SATIF-16 Shielding aspects of Accelerators, Targets and Irradiation Facilities

Tuesday, 28 May 2024 - Friday, 31 May 2024

INFN-LNF

Book of Abstracts

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PRELIMINARY RESULTS OBTAINED AT IFIN-HH USING THE TR19 CYCLOTRON

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Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), one of the biggest research institutes in Romania, owns one of the most reliable and advanced particle accelerators in Europe. This equipment and a radio-chemistry facility are part of the Radio-pharmaceutical Research Center at IFIN-HH, Magurele. The TR19 cyclotron can produce very stable proton beams with energy ranging 14 MeV to 19 MeV and is used to produce different medical radioisotopes such as: 18F, 64Cu, 89Zr, 99m Tc. The maximum proton beam current of 300 microA can be focused on different targets with minimum beam losses and with high precision using different water-cooled collimators. The cyclotron is equipped with two target selectors having the possibility to install four different targets on each of them. Attached to the cyclotron we use a six meters long beam line equipped with three powerful quadrupoles that ensures the optimal beam optics and transport. From January 2018, the Cyclotron Research Group started to develop new ways to operate the cyclotron in order to extract, scatter and focus proton currents in extreme conditions: very small proton currents through different transport systems. There were proton beams obtained with currents between tens of picoA and 100 femptoA used for radiobiology experiments with promising results. Using a COMECER Solid Target Station the 64Cu production was tested with good results related to production yields and beam alignment to the target- there were paper burn tests performed. We will also present a new equipment for production of new radioisotopes used in nuclear medicine: a neutron activator in line with the cyclotron. Preliminary results were obtained and will be presented.
This work was partially supported by a grant of the Ministry of Research, Innovation and Digitization, IFIN-HH DFNA PN project and 48UB/2023 project, University of Bucharest, Faculty of Physics
Keywords: radioisotope, cyclotron, nuclear medicine, neutron activator.

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A Monte Carlo Method to Calculate Residual Radiation with MARS Code

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Residual activation represents a significant issue in accelerator applications, in particular in intensity frontier experiments at Fermilab. In current version of the MARS code, several options are available for calculation of residual radiation. First, the residual dose is calculated on contact with surfaces of irradiated objects and is presented in output files by default. This approach is based on so-called ω-factors developed by M. Huhtinen et al. in the end of 1990s. There is also a FermiCord tool designed to calculate a spatial distribution of the residual dose. With this tool, the calculation is carried out in three stages: (i) a calculation of the distribution of secondary nuclides in boundary layers of dense materials is carried out on tetrahedral grids; (ii) temporal evolution of the nuclides is described with the DeTra code; (iii) particles emitted in radioactive decay of the unstable nuclides generated at the previous stages are used as a source for the final residual dose calculation. To tally the generated nuclides, this approach employs geometry regions occupied by different materials which imposes an essential limitation on its applicability.

When using the presented method, there is no need to generate the intermediate source so that the residual dose for different irradiation/cooling scenarios is calculated in a single run. Also, geometry during irradiation and cooling time may be different. Functions provided by CERN ROOT are used to dynamically change the geometry at runtime. Temporal evolution of generated unstable nuclides and particle emission in corresponding radioactive decays are simulated using the SandiaDecay library and database. By design, assessment of the spatial distribution of the residual dose can be performed on structured and unstructured grids. For this purpose, a specially developed track length estimator is used, the implementation of which is currently based on the VTK library. To construct boundary conformal meshes, external tools such as ANSYS, FreeCAD, or Salome can be used.

Test results of the developed tools – MCScores library – are presented by comparing calculated residual doses with experimental data from the SINBAD benchmark database. The suitability of the tools for practical application is demonstrated on the problems solved for the LBNF project.

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News of INCL, the Liège IntraNuclear Cascade model

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INCL is one of the intranuclear cascade codes that is still being developed and implemented in particle transport codes. It was last presented at a SATIF workshop in 2010. Since then, INCL has been updated and in this presentation, we propose to show the latest developments and perspectives.
The new capabilities of INCL are linked to the extension of the energy range, new projectiles and the addition of new quantum effects. INCL can be used with energies of up to ~20 GeV. This has been made possible by the implementation of multiple pion channels, then by the addition of eta and omega mesons, and finally by the ability to handle strange particles such as the Kaon meson and the Lambda and Sigma baryons. The projectiles available range from nucleons and pions to light (hyper)clusters with masses of 18 or less, including strange particles (K, Lambda, Sigma). Recently, a new type of reaction has been introduced, using antiprotons as projectiles. This has been driven by demand from people carrying out experiments at ELENA (CERN) with antiprotons at rest, and from people at FAIR (GSI) with antiprotons in flight. Concerning quantum effects, the possibility of low-energy nucleons in the target nucleus moving further away from the centre than a classical particle in a potential well has been made possible by a better description of the radial density distributions of nucleons based on a Skyrme interaction.
All these new capabilities are available in the Geant4 transport codes.
In addition to these extensions, a new study was launched in 2024: errors and associated uncertainties, and parameter optimisation. This project has been funded for four years by the French National Research Agency (ANR).
In a few words, we will present the objective of the project, what has been done previously and what will be done in the future.
This will provide an up-to-date picture of INCL.

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Status of the MARS code

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This report describes major features of the most recent version of MARS code as well as ongoing developments.
In addition to a basic CSG geometry, the CERN ROOT geometry package is used. The latter is especially effective for complex geometry models with in-depth volume hierarchies. For accelerator

applications, a beam line builder based on MADX is very helpful. In this case, a corresponding 3D geometry model of the tunnel with all the beam line components is built automatically, and the entire model follows the beam line itself. The automated built-in procedure needs a corresponding MADX input file and ROOT-based geometry models of the beam line components. Import of geometry models in GDML format is possible as well, in which case an extra tool is provided to perform processing for material assignments.
Structured and unstructured meshes can be used for scoring purposes. The scoring meshes can be overlapped. Unstructured meshes are especially helpful when correct description of borders between regions with different materials is important, for example, when studying energy deposition in a beam absorber with complicated water-cooling channels.
An update to the most recent version of TENDL nuclear data library provides detailed description of interactions with matter for a number of projectiles (p, d, t, ^3He, ^4He, and γ) at low-energies –from 250 keV up to 200 MeV. The library features both inclusive and exclusive distributions of secondary particles.
A recently implemented method to calculate residual radiation provides a possibility to get spatial distributions of residual dose in a single computer run without an intermediate source. Also, in the same run the calculations can be done for both irradiation and cooling geometries without an intermediate source.
Development of a new Python-based GUI is currently underway. Work on replacement of the LAQGSM event generator with a more recent code, DQGSM, developed at JINR (Dubna, Russia) is being performed. Also, work on replacement of obsolete features and improved modularity is ongoing.

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Photoneutron production at electron LINACs: testing performance of Monte-Carlo simulations and impact on relevant applications

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The production of neutrons in photon-induced nuclear reactions in the giant-dipole-resonance energy domain remains a topic of high interest for various applications, including the activation and decommissioning of electron accelerator facilities, the detection of illicit materials for homeland security, and the evaluation of neutron dose received by patients during radiotherapy treatments.

General-purpose Monte-Carlo (MC) simulation codes for particle transport are intensively used to account for photoneutron production in these applications. However, due to the current scarcity of measured photoneutron energy and angle distributions in the literature, experimental validation of MC-simulated photoneutron emission probabilities is not always feasible. Therefore, a critical benchmark among simulation results from various MC codes presently appears as the only option to systematically assess their capabilities in accurately simulating photoneutron production for nuclear reactions of interest.
In this work, neutron energy spectra from several targets under irradiation by 20 MeV photons are simulated, employing various state-of-the-art MC codes (FLUKA, Geant4, MCNP6, and PHITS) in their default or generally employed settings. A detailed analysis of the simulated neutron spectra allows one to not only assess the performance of various MC codes in applications such as those mentioned above, but also to partially gauge the incurred systematic uncertainty, and to highlight the present need for more comprehensive evaluated nuclear data in this domain.
New measurements of energy and angle photoneutron distributions recently performed using our Varian TrueBeam medical LINAC will also be presented.
Ultimately, this work suggests that more prudence is required when using MC codes for applications where photonuclear reactions play a dominant role and where not only the production rate but also the energy spectrum and angular distribution of the emitted neutrons matters.

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DOIN: a novel electronic personal dosemeter for neutrons

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Electronic personal dosemeters (EPD) are powerful tools for achieving ALARA (As Low As Reasonably Achievable) objectives in operational radiation protection. These offer real-time reading, time-resolved dose recording, alarm threshold settings and visible/audible alarms to prevent accidental exposures. EPD for photons are well developed and their performances usually comply with relevant Standards. By contrast, a very few commercial models exist for neutrons and their energy dependence is too large for using them without pre-information on the workplace neutron spectrum. Within the INFN-based DOIN (DOsimetro Indossabile per Neutroni) project, a new EPD for neutrons was prototyped, owing to a new patented design. The energy variability of the response is limited to about 2 when the energy varies from thermal neutrons up to the quality of 241Am-Be and monoenergetic reference neutron fields. The calibration coefficient is ~10^4 mSv^−1 in terms for H_p (10,0°) for the bare 252Cf source The response is nearly isotropic compared to actual commercial models. Finally, the parasitic photon sensitivity is lower than 2 mSv^−1 in the range 48÷205 keV.

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Experience during Ring Injection Dump Parts Exchange at the Spallation Neutron Source

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According to the accelerator operation plan of the Oak Ridge National Laboratory Spallation Neutron Source (SNS), the beam-stop and the proton beam window (PBW) assemblies of the existing Ring Injection Dump (RID) are replaced with fresh assemblies, when they have reached their end-of-life. End-of-life is determined by the stainless-steel beam-stop window having accumulated 10 dpa radiation damage. The exchange process took place during facility maintenance period that started in March 2023. Each of the spent assembles were put into specially designed storage containers for intermediate on-site cooldown. The spent beam-stop was predicted to be the part of highest activation that has been taken out of service at SNS. The exchange processes require good work planning to minimize radiation exposure to personal.
The SNS accelerator employs an H- charge exchange process to obtain sum-microsecond proton pulses in its accumulator ring. The H- beam passes through a set of two foils to strip away the electrons and produce a proton beam. Non-stripped or partially stripped parts of the beam are called waste beam and are directed to the ring injection dump (RID). This dump was designed to accept 10% of the main 2-milliamp and 1-1.3 GeV proton beam deflected into this beam dump, depositing up to 200 kW of energy in the copper plate assembly of the beam dump. During the years, operational

experience has shown that only about 5% of the main proton beam is going to the RID beam stop, however, this is still putting a large particle charge into the components during their lifetime and making them highly activated. The central part of the beam-dump, the beam stop, is heavily shielded by steel and concrete to keep radiation levels during accelerator operation under allowed limits.
The residual dose rate distribution is calculated using rigorous application of Monte Carlo code MCNPX together with Activation in Accelerator Radiation Environments script, which handles the transmutation analyses and prepares the sources for the residual dose rate calculations. Analyses are performed for each exchange step and the peak values of the dose rates are identified and were fed into the exchange work planning.
This paper gives an overview of the exchange process, describes methods for the neutronic analyses, some of encountered challenges, and gives the comparison of calculated vs measured dose rates during beam-stop assembly exchange.

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Investigation of residual nuclide inventory of the storage ring of the Swiss Light Source (SLS)

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The Swiss Light Source (SLS) is a third-generation synchrotron light source which employs electrons with energy of 2.4 GeV. The accelerator is currently being refurbished after 23 years of operation with an average annual operating time of more than 250 days, delivering X-rays for various applications. Information about residual nuclide inventory of materials is required for the radiological classification. In addition, this information can be used to calibrate measuring devices that are used for classification and triage measurements.
At the SLS, residual activation is expected due to the beam losses in the storage ring near the vacuum chamber, where extensive studies have been carried out to investigate the beam loss pattern and spatial distribution of residual activity. This work describes the results of the radiological characterization of the accelerator component material at the identified beam loss locations. The nuclide inventory was determined using various methods, including in-situ measurements in the beam loss region within the accelerator vault. Various samples were taken from the representative materials and analyzed in the laboratory. Additionally, activation studies were carried out with certified metal specimens in the area of localized beam losses.

The results of the experimental studies described in this work are currently used for a replacement and upgrade of the storage ring.

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Multifaceted, coded nuclear data libraries assemblage: TENDL-2023

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The multipurpose, multifaceted methodical nuclear data libraries coded by TALYS & databases, TEFAL, TASMAN as the Evaluated Nuclear Data Library TENDL has now been released every other year recently. Considerable experience has been acquired during the production years of global repetitive seven incident particles (neutron, proton, deuteron, triton, alpha, helium and gamma induced) multipurpose, application agnostic nuclear data libraries with covariance information up to 200 MeV incident energy on about 2850 (T½ > 1s) targets Z=1 1H to Z=115 291Mc. The library information is stored in the ENDF-6 data format explicitly below 30 MeV, implicitly above. The backbone of this achievement is completeness, quality, upgradability and, most of all, reproducibility and methodology. Since, TENDL has been comprehensively embraced by many, quite different applications (accelerator, astrophysics, fusion, fission, medical, experimental, decommissioning, etc.) that require multifaceted nuclear reaction data in various forms, primary and derived, for not only criticality but shielding, transport, radioprotection, transmutation, experimental interpretation, materials or earth sciences. The essential knowledge is not the TENDL libraries themselves, but rather the necessary physics models, databases and methods, processes, codes, tools and know-how that go into the making of every evaluation of the libraries. Recent efforts have focused on proper assessment of the underlying physics reproductible models coding and incorporation of databases information and metrics into the scientific T3 system.

Industry recognized traditional nuclear data libraries (ENDF/B-US; JENDL-Japan; JEFF-OECD, CENDL-China) have. are being assembled over decades by hand, 'evaluators'added nuclides/reactions/energies as and when it was deemed necessary for principally fission, low energy-based applications. The methodology is robust when high-quality, differential and integral experimental data are available

and can be successfully embedded in their making; however relative to the total set of target nuclides/reactions/energies and derived data needed for many other applications such as shielding, these libraries are small and incomplete. They generally do not contain any more than a very small fraction of the data, forms and observables needed for other non-operational fission, non-criticality applications: non-elastic double differential data, branching ratio, radionuclides production, gas, emitted particles and residual recoil spectra, etc. Since many (or most) reactions important for advanced; shielding, accelerators, fusion, instrumentation and manufacturing, security or astrophysics systems have few or no experimental differential information, one cannot rely on these traditional libraries, and a robust alternative is necessary to explore the broader nuclear application landscapes. TENDL-2023 fills the space between on-the-fly high energy collision models and low energy tables, leads the way scientifically and technologically into chartered and uncharted territory.

https://tendl.web.psi.ch/tendl_2023/tendl2023.html
https://www-nds.iaea.org/talys/

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From Bonner Spheres to real-time single-moderator neutron spectrometers

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Since 1960, Bonner Spheres (BS) admirably served as operational neutron spectrometers with wide energy interval in a variety of fields, from industry to medicine and research. They respond up to GeV energies, their operation is simple and their accuracy is well established. Nevertheless, they are cumbersome and very time consuming. In the last decade an INFN-based international collaboration led the evolution of Bonner spheres into a new class of single-moderator neutron spectrometers (SMNS). These devices condense the functionality of BS in a single moderator with specific geometry,

embedding multiple solid-state thermal neutron detectors in previously optimized positions. SMNS are similar to BS in terms of energy interval, operation, unfolding and performance, but they require only one exposure to determine the whole neutron spectrum. According to the specific measurement needs, various isotropic or directional SMNS have been developed. This work presents this evolution with special focus on the use of SMNS in large accelerators.

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Prompt gamma activation analysis of borated concrete at the radionuclide-based HOTNES facility

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Borated concretes are often selected as combined gamma-neutron shielding material for particle accelerators or nuclear plants. Accurate knowledge of the boron content in these materials is crucial for guaranteeing a realistic shielding design. Therefore, the concrete industry adopts specific QA/QC techniques, such as the prompt gamma activation analysis (PGAA), usually performed at research reactors. With the objective of reducing the cost and increasing the accessibility of this technique, an experiment was set up to evaluate the feasibility of a simplified PGAA, based on moderated neutron sources, and suited for the boron levels requested by the concrete industry. PGAA on borated concrete samples was performed at the HOTNES thermal neutron facility, established by ENEA and INFN at the Frascati research centre. The HOTNES irradiation cavity is completely characterised from both experimental and computational points of view. The useful thermal fluence rate is lower than 1000 cm-2 × s-1 but, due to the construction details, it exhibits unique uniformity features: the thermal fluence is constant within 1-2% across disks with diameter about 30 cm (iso-fluence surfaces). The tests were perfomed using a 0.5 cm3 CdZnTe gamma detector. To calibrate the technique, a series of standards made of borated UV resin with well-known compositions were manufactured. The Monte Carlo code MCNP 6.2 was used to determine the matrix correction factor. Quantities of Boron in the order of mg were measured with reasonable uncertainties in exposure times of hours. As the setup is rather simple and only requires a neutron source with emission rate

in the order of few 106 s-1, this technique could be easily displaced to construction or fabrication sites for inspection or quality control purposes.

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Measuring high photon dose rates with semiconductor dosimeters

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Gamma dose rates in the Gy/h to kGy/h range can be found at particle accelerators in hot points such as targets, bending magnets or interaction points. As these points constitute "source terms" in shielding design, a device to correctly measure these doses is desirable. Although a number of passive dosimetry techniques have been established in the past, very few or no direct-reading dosimeters are available for this purpose. In the framework of ENEA-INFN (Italy) collaboration, a test campaign was organized to evaluate the performance of semiconductor-based gamma detectors as active dosemeters for very high gamma dose rates. Gamma detectors based on Silicon, Silicon Carbide and GaAsP substrates were manufactured at the LEMRAP Laboratory (INFN Frascati) and tested at the ENEA Calliope 60Co gamma Facility (ENEA Casaccia) at dose rates up to few kGy/h. This communication reports the results of the tests focusing on sensitivity, radiation resistance and scalability to multi-dosemeter systems.

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The HOTNES thermal neutron facility

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HOTNES (HOmogeneous Thermal NEutron Source) is a thermal neutron irradiation facility jointly developed by INFN and ENEA at the ENEA Frascati research center. HOTNES was designed as a user facility for multi-purpose thermal neutron testing and detector calibration.

HOTNES consists of a polyethylene assembly with dimensions of 70 cm x 70 cm in square section and 100 cm in height, accommodating a cylindrical cavity measuring 30 cm in diameter and 70 cm in height with an 241Am-B source placed at the cavity's base. A cylindrical shadow-bar separates the source from the irradiation volume, so that neutrons can only reach the irradiation volume after multiple scattering with the cavity walls. Therefore, the spectrum in the useful irradiation volume is highly thermalized.

As a consequence of this design, the irradiation volume presents iso-fluence surfaces that are disks, parallel to the facility base, having about 30 cm in diameter. Across any iso-fluence surface, the thermal fluence exhibits remarkable uniformity, with deviations below 2-3%. The fluence rate can be easily varied by moving along the cylindrical axis, with attainable values in the range from 700 to 1000 cm−2 s−1.

The facility's design was previously optimized through Monte Carlo simulation and proven by experimental validation. This communication describes the facility design, the Monte Carlo simulations and the results of the validation measurements. Furthermore, it summarizes the experiments performed within the first external user program.

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Session 5 - Induced Radioactivity / 18

Challenges and strategies in planning Long Shutdown 3 for the HL-LHC Upgrades of the LHC experiments at CERN: a comprehensive overview

Authors: Davide Bozzato[1]; Robert Froeschl[1]; Tommaso Lorenzon[1]

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The CERN Large Hadron Collider (LHC) will undergo upgrades during the period of 2026-2028, known as Long Shutdown 3 (LS3) to become the High-Luminosity LHC (HL-LHC). These will allow for an increase in instantaneous luminosity by a factor from five to seven beyond the original LHC design value, thus allowing to increase almost tenfold the integrated luminosity by the early 2040s.

The four large LHC experiments will also be upgraded during LS3 accordingly to be able to cope with the increased collision rates and to withstand the harsher irradiation conditions posed by HL-LHC operation. These upgrades will entail the dismantling and decommissioning of large detector components, the refurbishment of existing ones, and the installation of new detectors and electronics. The execution of all these activities will require multiple and prolonged interventions in high-residual radiation environments and the handling of activated detector components of different nature. This poses complex radiological challenges that the CERN Radiation Protection group must address in a timely manner.

From an operational radiation protection point of view, the preparation of LS3 activities in the LHC experiments first requires a series of predictive studies aiming to estimate the residual radiation environment during interventions. This is necessary to preliminary estimate and then to properly reduce/optimize the dose to personnel for each intervention.

Furthermore, it is foreseen that a substantial amount of material will be removed from radiation areas during the shutdown. Detailed radiological characterization of evacuated equipment from the experimental caverns is essential for determining appropriate disposal paths and minimizing the duration of the dismantling activities as well as the waste disposal costs. It is also fundamental for ensuring and establishing the appropriate conditions for the transport off-site of activated components for their disposal or refurbishment.

This paper aims to provide a comprehensive overview of the challenges encountered in planning a long shutdown for the LHC experiments and the strategies employed to address these challenges, relying on advanced FLUKA Monte Carlo simulations. This will be illustrated by a series of case studies covering relevant applications at the LHC experiments.

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Session 5 - Induced Radioactivity / 19

Simβ-AD study: a methodology using active neutron detection and Monte-Carlo to improve radioactive waste management from cyclotron facilities

Authors: Jean-Michel Horodynski[1]; Nicolas Arbor[2]

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Radioactive waste management for French cyclotron facilities is facing an issue regarding the assessment of pure-β radionuclides emitters produced by activation from the secondary particles created during the production of medical radionuclides. An efficient methodology of activation assessment needs to be defined to improve the current situation, especially for dismantling activities.

The aim of the Simβ-AD study is to provide an activation assessment tool, easy-to-deploy and minimising the impact on the production, that couple innovative active neutrons detectors and a dedicated Monte-Carlo algorithm. Based on irradiation parameters, correlation factors $R_{\frac{\beta}{\gamma}}$ could be assessed by Monte Carlo calulations. Use of AlphaBeast compact neutron flux detectors enable a real-time validation of Monte-carlo simulations. CMOS technology has been selected to develop efficient and very compact detectors that can be easily used inside cyclotron vaults. Monte Carlo calculations can then be used in the radioactive waste management process to provide reliable radioactive characterization.

At the moment, several facilities will provide beam times for the experiment, including cyclotron for radionuclides production (CYRCé (Strasbourg), CYCERON (Caen)) and for protontherapy (CAL (Nice), CPO (Orsay)). Five Monte-Carlo codes will be used and benchmarked : FLUKA, MCNP6, PHITS, GEANT4/GATE and RayXpert.

This talk will present the current status of the study regarding the development of the AlphaBeast neutron flux detectors, benchmarking of codes on simple model and comparisons between experiment and calculations made for existing cyclotron facilities.

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Session 4 - Shielding and dosimetry / 20

Radiation Protection Studies for CERN's HI-ECN3 Facility

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The High Intensity ECN3 (HI-ECN3) facility in CERN's SPS North Area has been proposed. It shall be housed in the ECN3 underground cavern and offer unique opportunities in terms of intensity, energy and infrastructure for a potential high-impact particle physics programme. It's initial Technical Design Report (TDR) phase of the beam delivery and facility study has recently been approved.

The implementation of the HI-ECN3 facility in ECN3 has undergone comprehensive radiation protection (RP) studies. These studies focus on ensuring compliance with CERN's RP code and achieving radiation exposure levels for personnel, the public, and the environment that are as low as reasonably achievable (ALARA). The optimization process considers factors such as prompt and residual radiation, soil activation, transfer of activation products to groundwater, air activation, and environmental impact. Extensive simulations, utilizing the CERN FLUKA Monte Carlo particle transport code, have been conducted to assess these radiation protection aspects. The presentation will cover the current status of RP assessments and design optimization.

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Session 6 - Medical and industrial accelerators / 21

Enhancement of shielding properties of the maze for 10 MV linear accelerator

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Typical bunkers for radiation therapy with linear accelerators (LA) include mazes in order to minimize shield thickness of entrance doors while remaining allowed level of exposure outside them. Despite common general layouts, the design of each bunker is of individual approach depending on its location and type of LA. Sometimes there is inappropriate relative dimension of treatment room and maze due to lack or inaccuracy of data for LA exploitation such as dose rates, leakage values, workload, room dimensions, occupancy factors etc. One of those cases took place in Kyiv' s medical center, where the 10 MV LA «Elekta Infinity» was installed in the bunker dedicated for this machine and designed without neutrons consideration, that occasionally acceptable for the 10 MV accelerators. Nevertheless, the maze of this bunker was found to be too short in relation to the door's shielding against neutrons resulting to exceeding of prescribed by national regulator dose rate limit.

1[Fig.1 MCNP model of bunker and shielding plates inside the maze]

In order to reduce the dose rate near the door the measurements of gamma-ray spectra and neutrons flux were carried out inside the maze to get the radiation levels at reference points used in calculations for bunker design. The different variants of additional shielding inside maze were proposed and studied by MCNP simulations (fig.1). The plates of borated (5% by weight) paraffin with thickness of 40 mm on maze's walls were determined to be sufficient for reducing dose rate by ~50%. These plates were manufactured and installed, and the new neutron dose rate behind the door was measured to be 3,2 μSv/h, that was in a good agreement with expected one from simulations. It was shown that neutron flux inside the maze also decreased by factor of ~2 after installations of plates. Such passive shielding can be applied directly inside the treatment room minimizing neutron dose to patients undergoing therapy with high energy linear accelerators. The reported value of neutron' s doses during 10-18 MV gamma-therapy are in the range of 2-7 mSv/Gy, thus up to 20 mSv of extra dose to patient can be avoided.

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Session 5 - Induced Radioactivity / 22

Overview of recent activation benchmarks at the CERN High Energy Accelerator Mixed Field facility (CHARM) and the CERN Shielding Benchmark Facility (CSBF)

Author: Davide Bozzato[1]

Co-authors: Arnaud Devienne [2]; Patrycja Dyrcz [1]; Robert Froeschl [1]; Angelo Infantino [1]; Tommaso Lorenzon [1]; Marco Tisi [1]; Tsuyoshi Kajimoto [3]; Eunji Lee [4]; Noriaki Nakao [5]; Toshiya Sanami [4]; Stefan Roesler [1]; Markus Brugger [1]

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The CERN High Energy AcceleRator Mixed Field facility (CHARM) at CERN is designed to test electronic devices in high-energy and mixed radiation fields resembling particle accelerators, ground-level, atmospheric, and space environments. Located at the East Experimental Area, it receives a 24 GeV/c pulsed proton beam from the CERN Proton Synchrotron (PS), with pulses of 350 ms having maximum intensities of 8.0E11 protons per pulse: the extracted beam impacts on a 50 cm long copper or aluminium target. The intensity, energy spectrum and relative particle composition of the secondary high-energy and mixed field at the different irradiation locations can be for instance tuned by remotely changing the target and/or by inserting in the irradiation room concrete and iron shielding walls up to a thickness of 80 cm.
The CERN Shielding Benchmark Facility (CSBF) is located laterally above the CHARM target and incorporated within its roof shielding: it makes parasitic use of the beam conditions at CHARM for activation measurements, characterization of shielding materials and radiation detectors in high-energy neutron. Thanks to a 200 cm long custom-made removable sample-holder concrete block, it also allows for irradiation of passive detectors at various depths within the roof shielding.
During the operational year, one week of beam time is typically dedicated to radiation protection measurements and radiation benchmark studies. This paper provides an overview of benchmarks conducted at CHARM and CSBF over the past two years covering activation in neutron-dominated

radiation fields and mixed radiation fields. An example for the former case is the study of neutron streaming through the CHARM access maze using activation detectors in which experimental results were compared against FLUKA, PHITS, and Geant4 simulations. Several FLUKA benchmarks in the CHARM target room and in the shielding structure of CSBF will also be discussed: these focused on the production of medium- to long-lived radionuclides in commonly used materials for accelerator high-energy physics experiment components, ranging from copper and aluminium to steel.

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Session 5 - Induced Radioactivity / 23

Depth profiles of radioactive nuclides in bulky targets irradiated with heavy ion beams

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The activation of accelerator components represents the primary factor that restricts the allowable level of uncontrolled beam losses in heavy-ion accelerators. Monte Carlo heavy ion transport codes play a crucial role in evaluating the activation induced by beam losses. Measuring the depth distribution of radioactive isotopes in thick targets irradiated by heavy ion beams provides valuable experimental data for validating these transport codes. In this paper, we present and discuss the results of recent experiments involving bulky copper and aluminum targets irradiated by argon and uranium beams.

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Session 4 - Shielding and dosimetry / 24

Contamination density analyses at Fukushima-Daiichi Power Station using pinhole type gamma camera

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Co-authors: Hideo Hirayama [2]; Kohei Iwanaga [3]

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In Fukushima Daiichi Nuclear Power Station, various projects are currently working towards decommissioning. Radioactivity distribution measurement is indispensable to plan every project. These remained radioactivity information are also valuable for investigating accident procedure analyses. We developed contamination density estimation method using pinhole type gamma camera. 1),2) This method was extended to apply to measure 137Cs contamination density of SGTS (stand-by gas treatment system) pipe.
The SGTS pipes of unit.1 and 2 are highly contaminated by vent operation of unit 1 to release high pressure of PCV (Primary Containment Vessel) in the accident period. To decrease high dose rate by this piping at adjacent building, it was cut in 2022 and removed from original position and temporarily located on the unit 1 turbine building before cutting to small pieces for storage. We measured 137Cs contamination density of these SGTS pipes from the viewpoint of radioactive waste management and also get data potentially useful for accident procedure analyses.
Figure 1 shows 12 shot areas of unit 1 SGTS pipe took by gamma camera (Hitachi HGD-E1500). Figure 2 shows 137Cs contamination density distribution (GBq/cm2) of the pipe inner surface along the direction of gas flow. Contamination peaks were observed every ~5 meter that may be caused by rust at inner surface caused by surface alteration phenomena by welding at construction.

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Fig.1 12 shot areas of unit 1 SGTS pipe at unit 1 T/B roof

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Fig.2 137Cs contamination density of SGTS pipe

References
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2) K. Hayashi, H. Hirayama, K. Iwanaga, K. Kondo and S. Suzuki "Estimation of 137Cs Contamination Density of Wall, Ceiling, and Floor at Unit 2 Operation Floor in Fukushima Daiichi Nuclear Power Station Using Pinhole Gamma Camera"Nuclear Science and Engineering, 198, 207-227 (2024)

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Session 3 - Code benchmarking and intercomparison / 25

Intercomparison of Particle Production (5)

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In accordance with the discussion at SATIF15, we propose the same intercomparison problems of particle production from targets. Relatively large differences are observed for neutron and proton especially at small and large angles between Geant-4, PHITS, FLUKA-2021.2 and FLUKA 4-2.2. Results by using MARS and MCNP were desired to include in this intercomparison.

At SATIF16, we will present comparison between major Monte Carlo codes including MARS and MCNP concerning particle production with high energy protons.

"Inter-comparison problems of particle production (4)"

1. Incident particle
   Pencil beam of protons with the following energy
   (a) 1 GeV
   (b) 10 GeV
   (c) 100 GeV

2. Target materials and their sizes
   Target geometry is the cylinder.
   Source protons incident on the center of the cylinder bottom.
   Target detector distance from the center of the cylinder is 500 cm.
   (a) Al : length 40 cm, diameter 4.0 cm and density 2.7 g/cm^3
   (b) Cu : length 16 cm, diameter 1.6 cm and density 8.63 g/cm^3
   (c) Au : length 10 cm, diameter 1.0 cm and density 19.3 g/cm^3

3. Quantities to be calculated
   (1) Neutron, proton, pion+, pion- and photon spectrum above 20 MeV in particles/MeV/sr/proton at 0, 15, 30, 45, 60, 90, 120, 150 degrees with angular width plus/minus 0.5 degrees.
   Photons from produced radionuclides are not necessary to include.

(2) Angular integral spectrum above 20 MeV in particles/MeV/proton
(3) Energy integral neutron fluence for (1) and (2)

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Session 3 - Code benchmarking and intercomparison / 26

Neutron ambient dose equivalent measurements at the CERN Shielding Benchmark Facility (CSBF) platform

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The CERN Shielding Benchmark Facility (CSBF) is an installation embedded in the shielding structure of the CERN High Energy Accelerator Mixed field facility (CHARM), located in the East Experimental Area. At CHARM, the 24 GeV/c primary proton beam from the Proton Synchrotron is sent on one out of three possible targets to produce the desired secondary radiation field. The CSBF was specifically designed to allow for deep shielding penetration studies and characterization of material shielding properties. It was initially designed in 2013/2014 and further upgraded to its current layout during an extended year-end technical stop at the beginning of 2016. One of the currently available CSBF shielding configurations features a 1.2 m x 1.6 m measurement platform, shielded by 80 cm of iron and 320 cm of concrete, suitable for irradiations of active and passive detectors with deep shielding equilibrium neutron spectra.
During one week in 2022, measurements have been performed in several locations of the CSBF platform, employing a combination of various beam intensities, ranging from 2E11 to 6E11 protons/spill, and two of the available CHARM targets. Different active neutron ambient dose equivalent monitors, commonly used at CERN for radiation protection purposes, have been employed, and the measurement results were compared with the results of FLUKA Monte Carlo simulations. This activity is part of the experimental characterization of the neutron field available at the CSBF platform and allows for a comparison with the neutron field provided by the CERN-EU high energy Reference Field facility (CERF).

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Radiation Protection Studies of CiADS Linac

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The China initiative Accelerator Driven System (CiADS) is currently under construction at Huizhou, China, which represents a key capability in Accelerator-Driven System (ADS) R&D. The CiADS is composed of a high energy superconducting proton accelerator (Linac), a Lead-Bismuth target and a subcritical reactor. The driven Linac is the central component of the CiADS. It will accelerate protons up to the energy of 500 MeV with a maximum average current of 5 mA in CW operation mode. Operation of a proton accelerator at this high energy and high intensity produces strong secondary radiation caused by beam loss protons interacting with beamline components. In such case, the Linac can be a strong radiation source and poses a great risk to research workers and the public during the period of the accelerator commissioning. This paper will present radiation protection studies for the Linac by using the Monte Carlo Code, FLUKA. First, we built a complex geometry model with cryomodules, quadrupoles, mazes and ducts base on the final engineering design of the Linac. Second, we adopted a normal beam-loss conditions of 1 W/m to calculate the secondary flux in main accelerator components and prompt radiation field in the Linac tunnel. The simulation results indicated that high energy neutron is the priority in shielding design. Third, we made multiple deep penetration calculations to obtain the thickness of bulk shielding and local shielding based on the CiADS design criteria. Finally, we assessed the environment impact of the Linac. These simulation data is currently used to support CiADS construction and radiation protection system design.

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Session 5 - Induced Radioactivity / 28

Simulation supported, zoning concept using a novel BGO low-background setup for fast radiological classification

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CERN's accelerator and experimental facilities face activation due to the presence of radiation fields stemming from losses of high-energy beams. The characterization of this activation is complex, demanding the application of sophisticated methods to distinguish materials as radioactive or non-radioactive. Materials exhibiting activation levels near or below legal limits pose significant challenges to be classified correctly. To facilitate this process, CERN employs zoning samples sets of commonly used materials like aluminium, steel and copper to assess the activation of equipment caused by the radiation environments being present in the vicinity of the samples.

The threshold allowing to classify zoning samples as non-radioactive can be very low (e.g. 0.1 Bq/g for Mn-54 and Co-60) and therefore difficult to be measured. So far, gamma spectroscopy has been the primary tool for accurate classification. Recognizing the large number of zoning samples at CERN and acknowledging the time-intensive nature of this analysis, we have developed an innovative solution based on a pure counting measurement. This system integrates a shielded BGO detector and uses computer simulations (FLUKA and ActiWiz), enabling swift and precise classification for the vast majority of samples in less than 100 seconds.

The paper provides details about the shielded BGO setup and the simulation details of the energy dependent response functions of this detector system. Additionally, it details the ActiWiz/FLUKA-based calculations that establish measurement decision criteria, allowing for determining whether a sample is radioactive or non-radioactive. Notably, this integrated simulation-measurement approach extends its coverage beyond gamma-emitting isotopes, effectively encompassing pure beta emitters that are otherwise challenging to identify using conventional gamma spectroscopy methods.

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Poster Session / 30

Development of a Monte Carlo simulation workflow for the study of the radionuclide deposition process on the collection target in the context of Selective Production of Exotic Species (SPES) facility

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SPES (Selective Production of Exotic Species) is a second-generation ISOL facility for the production of Radioactive Ion Beams (RIBs), under completion stage at the Laboratori Nazionali di Legnaro of the Istituto Nazionale di Fisica Nucleare (LNL-INFN), Padua, Italy. The Isotope Separation On-Line (ISOL) technique is one of the most utilized methods for the production of high intensity and high purity RIBs, that are of high interest for both basic and applied nuclear physics research. In the case of SPES, neutron-rich isotopes will be produced with a $40\,\mathrm{MeV}$, $200\,\mu$A primary proton beam impinging on a $^{238}\mathrm{UCx}$ target, the expected reaction rate being about 10^{13} fission/s. Since the target is operated at high temperature (above 2000 °C), the produced radionuclides undergo in-target diffusion, effusion and ionization; the beam is then extracted, mass separated and delivered to the experiments. One of such experiments is ISOLPHARM (ISOL technique for radioPHARMaceuticals), a research activity dedicated to the development of innovative radiopharmaceuticals exploiting the high purity radionuclides produced in the SPES ISOL facility. For such scope, a dedicated system called IRIS (ISOLPHARM Radionuclide Implantation Station) will be coupled with the RIB line to handle the collection targets where radionuclides of medical interest are deposited. $^{111}\mathrm{Ag}$ is one of the most promising medical radioisotopes produced by SPES for its potential in therapeutic use. The deposition of radionuclides with mass number = $111\,\mathrm{u}$ and the radiological safety issues raised by such an amount of radioactive species are studied, by means of Monte Carlo codes FLUKA and PHITS. The work flow includes calculation of the in-target production due to ^{238}U fission, selection of isotopes forming the RIB and realistic estimation of their activities, and evaluation of the ambient dose equivalent rate around IRIS at different times during and after the production phase. The methodology provides a guideline for estimating the available activities at the end of RIB line, taking into account that all physical processes undergone by the RIBs before reaching the IRIS system present a specific efficiency. Furthermore, the obtained results will be used for the design of the shielding for the handling of the IRIS collection targets.

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The Beam Test Facility of the Laboratori Nazionali di Frascati

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The Beam Test Facility (BTF) of the National Laboratories of Frascati provides external users with positron/electron primary and secondary beams in various configurations for detector calibration purposes.
The BTF beam is organized into bunches, with a repetition rate of up to 49 pulses per second from the DAΦNE LINAC facility. Each bunch offers impressive flexibility, accommodating a multiplicity ranging from a minimum of 1 to 10^{10} particles per bunch (depending on the specific hall and line). For secondary beams, energy selection spans a wide range—from 30 MeV up to maximum energies of 750 MeV (for electrons) and 510 MeV (for positrons).
A notable strength of BTF lies in its user-friendly approach. Beam can easily manipulated in vary beam parameters to meet users specific needs, even during ongoing data collection. The facility comprises two experimental halls: BTFEH1 and BTFEH2.
Both experimental halls feature remotely controlled movable tables, beam diagnostics, and essential services to facilitate experiments. These services include data delivery of machine and detector parameters, laser alignment, networking support, high voltage assistance, and provisions for compressed air, fluids, and gas pipelines.

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Investigation of Unstructured Mesh Utilization in MCNP at LANSCE

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At the Los Alamos Neutron Science Center (LANSCE), we are exploring the application of Unstructured Mesh (UM) MCNP methodologies for various computational challenges, including the enhancement of shielding calculations. We work with a complex and detailed Target-Moderator-Reflector-Shielding (TMRS) geometry. Our analysis evaluates the impact of UM granularity on computation time and the quality of results in different calculation scenarios. We present the conversion from complex CAD designs to MCNP UM geometry and assess the computational costs associated with diverse computational strategies and versions of MCNP.

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Measurement of nuclide production cross sections via the 208Pb(p,X) reactions at GeV-energy proton incidence

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Nuclide production cross sections are key information to derive the residual γ-ray dose rate at accelerator facilities. To contribute the research and development of Accelerator-Driven System (ADS), a research program to measure the nuclide production cross sections was launched at Japan Proton Accelerator Research Complex. As of now, we already acquired the nuclide production cross sections by the reactions of GeV-energy proton incidence on various targets, which will be applied to

neutron-production target, coolant, accelerator-components, and proton beam window at an ADS facility proposed by Japan Atomic Energy Agency. Here, we selected ^{208}Pb as the target, which is planned to be contained in the neutron-production target and coolant at the ADS facility. By using ^{208}Pb instead of ^{nat}Pb, it is expected to simplify the nuclear reaction mechanism and gain the better understanding of it.
We present the measurement of the nuclide production cross sections via the ^{208}Pb(p,X) reactions at GeV-energy proton incidence. Additionally, the comparison among our present data, nuclear reaction models, and Japanese Evaluated Nuclear Data Library High Energy file 2007 is also presented to confirm the prediction accuracy.

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Recent radiological studies at NSLS-II using the Monte Carlo code FLUKA

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This work details some of the latest radiological studies performed at NSLS-II using the Monte Carlo particle transport code FLUKA.
In particular, it describes the radiation protection challenges posed by the anticipated NSLS-II facility upgrade, evaluating a selection of the various scenarios currently under consideration.
Also, it assesses the impact related to the eventual adoption of ambient dose as the external radiation exposure estimator of effective dose.
Lastly, a demonstration of synchrotron radiation transport is provided for an in silico beam line, from source to endstation, utilizing FLUKA's new X-ray reflectivity capabilities.

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Monte Carlo simulations for use of ions up to neon in the ion therapy synchrotron facility MedAustron

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The existing ion therapy facility MedAustron operates a synchrotron providing proton and carbon ion beams for treatment of tumor patients as well as research. The facility has one research irradiation room plus three treatment rooms (one proton gantry, one vertical beam line and two horizontal beam lines). From an accelerator point of view, it would be possible to deliver other ion species. However, the existing operating permit only allows use of protons and carbon ions. With the increasing interest from both research and clinical users of the machine in helium ions, and, in the future, possibly also oxygen ions, it was decided to apply for an extension of the operating permit. Since the expansion of ion species is a long-term project, different ion species might be deemed beneficial in future. To keep options open, all ion species up to neon were calculated and included in the permit application. Also, taken together, the results from multiple ion species reveal more insight into the physics behind the processes leading to dose outside the shielding.
FLUKA, with the FLAIR interface, was used to set up a generic, rotationally symmetrical room geometry with biased shielding walls (heavy concrete for the research irradiation room, standard concrete for the others). The annual dose equivalent at two "worst-case"scoring regions lateral to the target was evaluated for all simulations. The results for carbon ions were in the same range as those calculated 10 years previously for the more detailed geometry (Jägerhofer 2012), confirming that the generic geometry is sufficient to evaluate the shielding wall thickness for other ion species. As a result of the simulations, it was possible to generate conversion factors for dose equivalent per primary ion for heavy concrete and standard concrete irradiation rooms. Using these conversion factors, the dose resulting from all primary ions used in a year can be calculated and used for the annual reporting to the authorities. Previously, separate limits were used for each ion species, which would get unnecessarily complicated when the number of ion species are increased.
Additionally, air activation was simulated for all primary ions up to neon. These results were then used to estimate the dose received by personnel entering the room after irradiation in the form of inhalation dose as well as gamma submersion. Here the nuclides produced are very similar for all ion species, with slight differences in their activities. The resulting doses are therefore also very similar for the ion species considered and pose no more risk to personnel than the carbon ions already in use (for which the inhalation doses were already confirmed by measurements).
In summary, the results show that both prompt radiation and air activation are in the same order of magnitude for all primary ions up to neon and the shielding and other safety measures –which were designed for carbon ions and 800-MeV-protons –are sufficient for the use of any of these ions. A permit was granted to commission and use other ion species, setting the usage limit in the form of a total dose from all ion species instead of number of particles per ion species. Currently helium ions are in the final stage of commissioning for research purposes.

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Session 5 - Induced Radioactivity / 36

A Study on the Composition of the Concrete at the High Intensity Proton Accelerator in PSI

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The High Intensity Proton Accelerator (HIPA) at the Paul Scherrer Institut (PSI), Switzerland, just celebrated its 50th birthday. During these 50 years, the concrete shielding blocks are added, removed, or replaced constantly due to changing operational requirements, new experimental setups and/or structure damages. For the first time after 50 years, a thorough study of the concrete composition of the shielding blocks and walls in HIPA was carried out for a better understanding of the character and the performance of the concrete in order to keep a database up-to-date for a best estimation of the shielding during operation and of the radioactive waste volume in the case of decommissioning. The experience and the results of sampling, composition analyses, such as Inductively Coupled Plasma –Optical Emission Spectrometry (ICP-OES), Thermogravimetric Analysis (TGA), and Neutron Activation Analysis (NAA), as well as validations of Monte-Carlo simulations applying the analytical results with the thermal neutron images, taken in the thermal neutron radiography station, NEUTRA, at SINQ PSI, will be presented.

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Modeling tritium production and release in high-energy proton accelerators

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Tritium is a well-known byproduct of particle accelerator operations. To keep levels of tritium below regulatory limits, tritium production is actively monitored and managed at Fermilab.
We study tritium production in the targets, beamline components, and shielding elements of the Fermilab facilities such as NuMI, BNB, and MI-65. To facilitate the analysis, we construct a simple model and use several major Monte-Carlo radiation codes, such as FLUKA, MARS, and PHITS, to estimate the amount of tritium produced in these facilities. This analysis could also serve as an intercomparison between these codes related to tritium production. To assess the actual amounts of tritium that would be released from various materials, we employ semi-empirical diffusion models. The results of this analysis are compared to the experimental data whenever possible. This approach also helps to optimize proposed target materials with respect to the tritium production and release.

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Shielding Design and Environmental Dose Monitoring for the ALFA Laser-Plasma Accelerator at ELI Beamlines

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As the commissioning of the laser systems at the ELI Beamlines Facility of ELI ERIC progresses, its laser-driven particle acceleration experiments reach ever higher energies and intensities. Due to the uncertainties in the laser-matter interaction and the variability of the experimental setup, the actual dose rate maps could differ from the results of the Monte Carlo simulations. This requires additional radiation protection measures to ensure safe operation at all times.

One example of such occurrence is the ALFA user station, where electron beams of several tens of MeV are produced with laser wakefield acceleration (LFWA). The station utilizes the L1 Allegra laser which produces < 20 fs long laser pulses at 26 mJ power and 1 kHz repetition rate.

This work presents the Monte Carlo simulations performed with FLUKA v4-3.3 for the design and development of a novel shielding and the environmental dose measurements taken during operation.

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The use of MonteCarlo computation tools in the Hadron Therapy Facility MedAustron

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MedAustron is an accelerator facility with a synchrotron for cancer therapy and research located in Wiener Neustadt, 50 km south of Vienna. The facility provides protons up to kinetic energies of 250 MeV and carbon ions up to 400 MeV/u for medical applications. Additionally, protons up to 800 MeV kinetic energy can be used for non-clinical research purposes in a dedicated room.
The concept of the MedAustron particle accelerator was developed in cooperation with the European Organization for Nuclear Research CERN. The system is comprised of active beam scanning on fixed beam lines, as well as a proton gantry.
Since 2016, the MedAustron Particle Therapy Accelerator MAPTA is a CE-labeled medical product in accordance with the European medical device directive. In the same year, treatment of tumor patients, as well as research with protons, commenced, with more than 2300 patients having completed their treatment so far. Commissioning of helium beams has now also started –the associated operating permit is expected to be granted in 2024.
The use of Monte Carlo computational tools have played a crucial part since the beginning of the project, being used for various applications. The radiation protection group, for example, uses FLUKA to create detailed technical reports for complex authority approval procedures, such as the extension of the operating permit to accelerate stable ions between hydrogen and neon.
Just recently, a new Environmental Impact Assessment procedure was started for the extension of the facility with a commercially available cyclotron including a gantry system providing protons up to 230 MeV for patient treatment in a 5th irradiation room. This involved FLUKA simulations to ensure sufficient shielding and estimate activation of components and building parts, including a comparison to MCNP simulations of similar facilities performed by the vendor.
At the interface between Radiation Protection and Medical Physics, an ongoing project explores the use of voxel geometries of actual patients for a detailed assessment of clinical doses in cases where the transport of secondary particles (beyond standard treatment planning systems) is necessary for exact dose predictions (e.g. close to implants).
Additionally, smaller questions arising in daily operation are resolved with the help of the Monte Carlo Code FLUKA: optimization of bite splints for sinus irradiation, assessment of water activation in the water phantom using carbon ions, comparison of measurement and simulation of ambient dose rate in the room during patient treatment, etc.
The Accelerator Beam Physics group also uses FLUKA for the assessment of beam scattering in the dose delivery system by sampling measured beam profiles as source terms. Specific failure scenarios were assessed and collimators were designed to limit beam outside the intended beam scanning field, in order to achieve certification as a medical device in accordance with IEC 60601-2-64.
The Medical Physics Department has harnessed GATE/Geant4 across various domains, encompassing dose delivery monitor gain calibration, ocular beamline design, validation of the particle energy spectra look up tables in the TPS, or ripple filter development. An ongoing initiative seeks to replace patient-specific quality assurance measurements, typically conducted per field of each patient plan, with in-silico simulations employing GATE/Geant4. To ensure compliance with legal regulations, an Application Programming Interface (API) was developed for seamless integration with the commercial software platform myQA iON by IBA Dosimetry, which currently only supports proton beams via the MC engine MCSquare. This endeavor targets the optimization of beamtime allocation and enhancement of dose verification specificity, promising significant advancements in clinical practice.

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Optimization studies of radiation shielding for PIP-II project at Fermilab

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The Proton Improvement Plan-II (PIP-II) at Fermilab represents a significant advancement in the quest to answer some of the most profound questions about our universe using the world's most intense high-energy neutrino beam. The project requires the construction of a new addition to the Fermilab accelerator complex –an 800-MeV high-intensity superconducting linear accelerator. Ensuring the safety and regulatory compliance of this ambitious project is paramount, necessitating thorough dose rate assessments under both normal operational and accidental scenarios to align with the Fermilab Radiological Control Manual (FRCM) standards.
Our approach included a comprehensive update of the geometry model to incorporate new magnet and collimator designs, essential for reflecting the current state of PIP-II infrastructure. The implementation of high-resolution detector planes, despite their computational demands, enabled us to gather detailed radiation field data crucial for optimizing shielding configurations. To overcome the significant computational demands, we developed a branching code that drastically reduced simulation runtimes while maintaining statistical integrity. This was achieved through geometry splitting and the application of Russian Roulette techniques, tailored to prioritize regions of interest based on predefined importances and weight limits.

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Status of the ELI Beamlines facility

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The Extreme Light Infrastructure (ELI) is the world largest and most advanced high-power laser infrastructure. It is established as a European Research Infrastructure Consortium since 2021. The Czech Republic, where the ELI Beamlines facility is located is a founding member of the Consortium of which the ELI Beamlines facility became integral part in 2023.
ELI Beamlines aims at the development of high-brightness sources of X-rays and the acceleration of proton, electron, and ion beams, to be used both for fundamental and applied research. The commissioning of the various lasers and beamlines started has been going on in the last few years. The radiation fields generated by laser differ from conventionally generated fields in some key characteristics, such as ultra-short pulse length and ultra-high dose rates, which raise some challenges for the reliable implementation of radioprotection systems.
This contribution presents an update on the current status of the facility, the preparatory radioprotection works, and presents some of the output from the first experimental tests.

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Development of user-friendly verification tool of radiation shielding calculation

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Shielding calculation software was developed to assist the regulatory body in shielding calculation verification for shielding thickness required in different medical radiological departments; radiation diagnosis, nuclear medicine, and radiation therapy. It is user-friendly, simple and fast. It was mainly used for verification and validation process. The calculated values calculated by the calculation software were compared with those calculated manually and were accurate and precise. The calculation

software has proven to be an effective tool when it is used as an independent verification tool to minimize time of the assessor and reduce the possibility of human error.

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Ionizing Radiation from Laser Target Interactions: High Irradiance for SLAC MEC-U Project and Low Irradiance for Laser Material Processing

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Interaction of a high irradiance laser beam with matter creates a plasma on the target surface. The laser's electric field accelerates charged particles in the plasma, and the accelerated charged particles can produce ionizing radiation hazards. The spectrum and dose rate of ionizing radiation depend on the laser irradiance at the target, the average laser power and the atomic number of the target.

An overview of the radiation hazards for laser-matter interaction from two extreme irradiance cases is presented. High irradiances of up to 3x1021 W/cm2 create the ionizing radiation hazards for the SLAC Matter in Extreme Conditions Upgrade (MEC-U) project; the ionizing radiation hazards in laser material processing are created by low irradiances of ~ 1013 –1015 W/cm2.

MEC-U is a flagship laser facility under design for plasma physics and fusion science that will combine a high pulse energy (150 J), high peak power (1 PW at 150 fs pulse width), and high rep rate (10 Hz) laser with the X-ray free electron laser beam from the Linac Coherent Light Source (LCLS) at SLAC. The MEC-U laser-target interactions will accelerate electrons up to tens of MeV and protons up to ~120 MeV. Source terms calculated with particle-in-cell plasma code were used with the FLUKA Monte Carlo code in radiation safety analyses. In addition to the bulk shielding requirements, the design of large penetrations for HVAC and laser pipes, as well as maze entrances and equipment doors, are also studied. With its high rate operations, activation of the target chamber including optic, target handling system, and detector components inside the chamber, and environment (air, soil, and groundwater are also considered.

Many industrial laser material processing applications utilize ultrashort pulsed lasers, operating at high repetition rates of tens of kHz and pulse energies up to a few mJ. These systems can have irradiances of 1013 –1015 W/cm2 at the target material and accelerate electrons up to 10-30 keV with hot electron temperatures up to a few keV. The resulting shallow dose rates can be very high. Results of radiation measurements from laser material processing with laser irradiances in the range of (0.7 –28) x 1014 W/cm2 on a thin Tungsten target is presented. Measurements were performed with ion chamber survey meters and personnel dosimeters. The energy response of the survey meter and dosimeter were calibrated with irradiations using X-rays down to ANSI M-20 beam code (average energy 14 keV). Results of shallow and deep dose rate measurements are presented.

This work was supported by Department of Energy contract DE-AC02-76SF00515.

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Developments of the present and future FLUKA generations

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In this contribution, a selection of recent and ongoing FLUKA developments of relevance for various applications is presented, along with an update on the deployed strategy to ensure the long-term development and maintenance of the codebase.

The FLUKA v4 point-wise treatment of neutron interactions below 20 MeV is reviewed, emphasizing recently implemented physics and technical capabilities. An automatic region-importance biasing algorithm is presented, which greatly simplifies user settings for shielding applications. Furthermore, a recent partial-wave model for the nuclear elastic scattering of protons below 250 MeV (released in FLUKA v4-4.0) is discussed. Its impact on the production of single-event upsets in electronic devices under proton irradiation is highlighted. Moreover, an enhancement of FLUKA's deuteron reaction model is shown, leading to an improved account of (d,2n) yields from high-Z targets. An update of the FLUKA crystal tracking module is also provided, focusing on its ongoing reformulation in terms of a numerical solution of the equation of motion for positively charged particles in the electrostatic potential of bent crystals.

Concurrently, in the interest of ensuring its long-term sustainability, the FLUKA codebase is being redesigned and recast onto a modular C++ architecture, here referred to as FLUKA v5. The current status of the FLUKA v5 framework is presented. Prior to the full integration of FLUKA physics models, it already facilitates direct inter-comparisons with Geant4.

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Study and implementation of the shield around a beam dump of a new experimental trasport beam line at LNS

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The "Laboratori Nazionali del Sud" (LNS) of Italian National Institute for Nuclear Physics (INFN) are equipped with two accelerators, a Van de Graaff Tandem and a K800 Superconducting Cyclotron. The accelerators produced ions with atomic mass from 1 to 238 amu and energy until 100 MeV/amu. Following an upgrade of the beam currents up to 10^14 pps for some radionuclides from C-12 to Ne-20, a shield around the final beam dump of a new beamline equipped at the LNS, has been studied and implemented.

A study of materials to be used for the realization of the shield both in terms of secondary neutrons produced by the switching off of the primary beam on the beam dump and in terms of shielding power has been done.Furthermore, once the material for the realization of the beam dump shielding has been chosen, a study relating to the residual activation has been carried out.

The choice of the best materials to use has been carried out using Monte Carlo FLUKA simulations and other calculation programs.

The procedures for the choice of the materials and the Monte Carlo simulations are described.

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Optimal decommissioning planning of NPPs using validated neutron fluence calculations

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The last nuclear power plants in Germany have been shut down in spring 2023 and are in the process of decommissioning. For this process, it is necessary to estimate the different waste quantities and qualities, e.g. between activated, contaminated and material which can be released for further use. Part of the contamination due to deposits of radioactive particles on the surface can be removed by cleaning. However, the activation of the material by neutrons cannot be removed. This activation depends on the one hand on the possibility of neutron diffusion into the surrounding rooms and subsequent penetration into the components and on the other hand on the years of operation of the plant and the power history in the cycles. Therefore, neutron fluence is a basic and important parameter in the evaluation of possible activation of materials during decommissioning and should be calculated as accurately as possible.

For the calculation of the neutron fluence characteristics in components outside the pressure vessel, a very detailed 3D Monte Carlo (MC) model of a German pressurized water reactor was developed. In addition to the exact modeling, the neutron source used in particular for the peripheral fuel assemblies is very important. This was determined pin by pin on the basis of the real burn-up calculations. Both the model and the source were validated with the aid of metal foil activation measurements, which were carried out at different locations. Metal foil activation measurements, also known as neutron fluence monitors, have been used successfully in reactor dosimetry for many years and are an ideal method for obtaining information about the neutron fluence in an operating reactor or other facilities with denitrifying neutron radiation.

This presentation gives an overview of the MC model of the reactor and presents the foil activation measurement method. The results of the MC simulations and the experimental measurements are then presented, corresponding C/E (calculation/experiment) comparisons are shown and discussed.

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Session 4 - Shielding and dosimetry / 47

Shielding calculations for the Swiss Light Source upgrade

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The Swiss Light Source (SLS) has been in operation since 2001. Renovations are now ongoing for a major upgrade project, named SLS 2.0.

Key changes for the SLS 2.0 are the increase of the electron beam energy from 2.4 GeV to 2.7 GeV and a significant reduction of the beam emittance. In addition to this, the new lattice foresees the presence of two sets of collimators and of a dedicated beam dump. Beam losses will be concentrated at these three locations, posing new challenges to shielding design.

Simulations have been performed using the FLUKA.CERN Monte Carlo code and the results will be presented in this work.

The energy density on the beam intercepting devices could be very high, because of the small beam emittance. In particular, the expected energy density on the dump is challenging. To avoid damages, a strategy to distribute the bunches on the dump has been developed. The resulting energy density on the dump is calculated for different filling patterns.

Furthermore, there will be permanent magnets in the same straight sections as those of the intercepting devices. Notably, undulators will be located downstream of the collimators. These magnets are characterized by lower aperture compared to other machine components, so they are more exposed to radiation. The load on these components is evaluated and shielding strategies conceived.

The expected dose maps outside the SLS 2.0 bunker have also been calculated. Openings are foreseen in both collimation regions to host wave guides for the radiofrequency cavities, cooling pipes and cables. The expected dose in correspondence to these weak points has been evaluated and shielding reinforcements have been studied.

Finally, an accidental beam loss scenario will be discussed to assess the maximum possible dose in a gallery below the SLS 2.0 bunker, accessible during operations.

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Session 8 - Radiation damage to materials / 48

Material Damages and Burn-Through Detection for FEL Beams at LCLS

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The Linac Coherent Light Source (LCLS) at SLAC is operating with a normal-conducting Linac (up to 17 GeV, 120 Hz) and a new superconducting Linac (up to 4 GeV, 1 MHz, since 2023). Free Electron Laser (FEL) beams can be generated by two adjustable gap undulators: one for soft X-rays and one for hard X-rays.

FEL beams are capable of damaging materials and the mechanism of the damages from normal-conducting and superconducting beams are different. For normal-conducting beams, the ablation from strong pulses and thermal fatigue from repeated pulses are the source of damage. For superconducting beams with high repetition rate, the heat can be accumulated between pulses and thus the damage can also come from the combination of high temperature and large pulses. It is critical to detect such damages so radiation safety interlocks can shut off FEL beams before all safety layers are drilled through.

This presentation introduces the analyses of material damages and the designs of burn-through detection for stoppers, collimators, and other radiation safety devices, and shows the tests using normal-conducting and superconducting FEL beams to verify the analyses and designs.

*This work is supported by the Department of Energy Contract DE-AC02-76SF00515

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Poster Session / 49

X-ray Targets and Collimation system for Indigenously developed Linear Accelerators

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Linear accelerators can be used for various applications including radiotherapy, cargo inspection, industrial radiography, research etc. In this work the X-ray collimation system and targets for the indigenously developed linear accelerators having various applications have been designed and simulated using Monte Carlo based codes Fluka and Geant4. For 6 MeV medical accelerator and cargo scanner an X-ray target is designed and manufactured. Collimators are essential to accelerators as they define the shape of X-ray beam and restrict its size. They also provide shielding of leakage radiation and attenuation up to 0.1% of the primary beam. For 6 MeV medical accelerator a primary collimator and two sets of secondary collimators have been designed, fabricated and tested. These collimators are made of tungsten. Primary collimator defines the largest available circular field and has a conical opening. Secondary collimator provide a rectangular field at the iso-center. Both simulated and experimental results of beam profile measurements show a fully collimated X-ray beam. Cargo scanners requires a fan like beam to fully scan an object. For such shape a different kind of primary collimators of lead has been designed. The collimator consists of two parts. First is a cylindrical shaped collimator having a trapezoidal slit. The second collimator is rectangular with a trapezoidal slit and is placed at some distance from the first collimator. The cylindrical collimator defines the shape of x-ray beam along with the shielding from leakage radiation. The rectangular collimator only shapes the beam to a fan like structure. These collimators have been designed and simulated in Geant4 and are now in manufacturing phase. Another dual energy radiography system is being developed for which a collimator to focus the beam and to shield the detector system has been designed using theoretical calculations. For this system a dual energy target is also under research phase. The target would be of tungsten and copper brazed together giving maximum x-ray dose and a minimum electron leakage.
A 20 MeV beamline is also under design phase. For this a beam dump and its shielding is being designed using Fluka. A beam dump as the name suggests is a device where the unused beam from accelerator is dumped. It is designed to absorb all energy of the primary beam. Beam dump shielding is required so that the free electrons, neutrons and photons along with the radiation dose caused by the activation of beam dump is stopped.

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Session 4 - Shielding and dosimetry / 50

Overview of Radiation Shielding Design for HEPS Project

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The HEPS project is the first high-energy synchrotron radiation light source in China, comprising a 74-meter-long Linac (with a beam energy of 500 MeV), a 453-meter circumference Booster (with a maximum beam energy of 6 GeV), a 1360-meter Storage Ring (also with a beam energy of 6 GeV), and 17 beamlines in the phase I.

The radiation protection group in IHEP is in charge of the radiation protection design for the entire project, which includes radiation shielding design, dose monitoring system, personnel protection system, and the management of operational radiation protection. This report gives an overview of the project progress until now, and particularly introduces the radiation shielding design for the HEPS project, covering the calculation methods and results for prompt radiation shielding design and induced radioactivity calculation; shielding design schemes for items such as the beam dump, radiation shielding doors, and mazes; shielding calculation methods for the beamline hutches; measures for radioactive waste management; and an assessment of the ionizing radiation impact on workers and the public during the operation of the project.

Currently, the HEPS project is in the installation and commissioning phase, with plans to complete the tuning by the end of December 2025.

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Session 3 - Code benchmarking and intercomparison / 51

Benchmarking of FLUKA residual simulations for radiation protection at CERN's Large Hadron Collider

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Keywords: air ionization chamber, FLUKA4, dose rate measurement, area monitoring

The Large Hadron Collider (LHC) at CERN is the world's largest particle accelerator capable of accelerating protons beams up to 6.8 TeV. The operation of the LHC machine generates unavoidable high-energy mixed radiation fields due to the particle debris of proton-proton inelastic interactions and the consequent hadron/electromagnetic particle shower. Hence, this poses radiological challenges that the CERN Radiation Protection (RP) group needs to address. One of the challenges is the accurate prediction of the residual dose rate during the maintenance and intervention activities in the LHC tunnel to ensure that the exposure of personnel to ionizing radiation is as low as reasonably achievable (ALARA).

The reference simulation tool used for radiation protection aspects at CERN is the general-purpose particle interaction and transport FLUKA (version 4) 1 Monte Carlo code. FLUKA allows for predicting the activation levels and the associated residual ambient dose equivalent rate for a given source term and the corresponding irradiation profile. On the other side, the residual ambient dose equivalent rate levels at CERN are constantly monitored by a network of simple and robust ionization chambers that are installed inside CERN's accelerator tunnels, PMI 2 (trade name PTW, type 34031). These ionisation chambers are used for remote reading of ambient dose equivalent rate during beam-off periods.

A set of PMI positions inside the Long Straight Section of the LHC tunnel is selected to perform this study. These PMI are located in positions which are relevant for the most activated beam line elements in the LSS. Additionally, the RP group carries out the routine dose rate measurement surveys in the tunnel using the dose rate meter Automess 6150AD/6 (AD6) [3] unit. Hence, the comparison is also carried out for this type of instrument.

This paper provides a comparison of the residual dose rates simulated by FLUKA 4 and values measured by PMI and AD6 units. Specifically, the comparison focuses on the Long Straight Sections (LSS) 1,5,7 and 8 of the LHC. The LSS 1, 5 and 8 accommodate the experimental caverns of ATLAS, CMS and LHCb, respectively, while LSS 7 hosts the collimation section dedicated to betatron cleaning.

1 C. Ahdida et al., New Capabilities of the FLUKA Multi-Purpose Code, Frontiers in Physics, Volume 9, 2022, https://doi.org/10.3389/fphy.2021.788253
2 H. Vincke et al., Simulation and measurements of the response of an air ionisation chamber exposed to a mixed high-energy radiation field, Radiation Protection Dosimetry, Volume 116, Issue 1-4, 20 December 2005, Pages 380–386, https://doi.org/10.1093/rpd/nci088
[3] Dose rate meter 6150AD/6 (AD6), https://www.automess.de/en/products/productfamily-6150ad/dose-rate-meter-6150ad

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Poster Session / 52

Application of Machine Learning in Radiation Shielding at FRIB

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Radiation transport computations are an essential part of operating and maintaining an accelerator facility. However, these computations can be challenging because they require a significant amount of time and resources. Neutron transport analysis is an important computational requirement in heavy-ion facilities like the Facility of Rare Isotope Beams (FRIB) to support safe operation. At FRIB beam conditions (ion species, energy, power) vary widely, requiring frequent reevaluation of radiation environments and confirming shielding effectiveness. A Machine Learning (ML)-based approach promises to speed up neutron transport and shielding analysis.
The objective of this work is to predict the neutron differential flux at a given distance after shielding material of a certain thickness. To generate the required training dataset, we use the Monte-Carlo-based radiation transport code PHITS (Particle and Heavy-Ion Transport code System) to simulate the effects of mono-energetic and mono-directional narrow neutron beams impinging normally on a radiation shield of chosen thickness and material. The volume-averaged output differential neutron flux is used to generate the training set as a response function of a given incident neutron energy.
In view of the complexity of the problem, we have employed one-dimensional convolutional neural networks (1D-CNNs) as a candidate for our ML algorithm. The successful application of this tool in a proof of concept, albeit on a simplified problem, has provided us confidence about the suitability of this approach. We will present the required tool set and initial outcomes of our work.
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, operated by Michigan State University, under Award Number DE-SC0000661.

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Session 2 - Code status, development and model converters / 53

Bayesian Uncertainty Quantification for Radiation Transport Calculations at FRIB

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The Facility for Rare Isotope Beams (FRIB) has recently started operation and is gradually increasing its beam power towards the final design goal of 400 kW. Radiation Transport (RT) calculations contribute to ensuring safe power ramp up and operation of FRIB for science experiments. Understanding the accuracy of the RT simulation predictions for the wide range of radiation scenarios present at FRIB is important. RT calculations rely on multiple inputs, such as material composition, geometrical information, cross-sections, and physical models. Each of these inputs contains intrinsic uncertainties that are propagated to the output of the simulation. Therefore, when the input parameters exhibit a significant level of uncertainty, the results of the simulations may lead to erroneous conclusions. Uncertainty Quantification (UQ) methods, such as Bayesian analysis, are a powerful tool for investigating the correlation and influence of systematic uncertainties and, at the same time, for improving the interpretation of the simulation results. In this work, a UQ code based on Metropolis-Hastings Markov chain Monte Carlo was developed to perform an analysis of RT calculations. In particular, the method is applied for studying systematic uncertainties in shielding design and their propagation through burnup codes used to estimate activation and isotope production. Preliminary results and perspectives will be discussed in this talk.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, operated by Michigan State University, under Award Number DE-SC0000661.

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Session 1 - Source terms, new accelerator facilities and related topics / 54

Facility for Rare Isotope Beams: Never the Same Beam Twice

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The Facility for Rare Isotope Beams (FRIB) –a world-leading laboratory for providing exotic beams –is entering its third year of user operation. The facility produces rare-isotope beams through in-flight fragmentation of high-power beams of stable heavy-ion isotopes ranging from oxygen to uranium and at energies up to 200 MeV per nucleon. This year the facility will double its primary beam power from 10 to 20 kW on its multi-year ramp-up path to 400 kW.

The fact that beam conditions constantly change is a defining characteristic of the facility. Each rare-isotope setting usually requires a unique combination of three primary beam parameters: isotope, energy, and power. The variability among these parameters is even more dramatic for the resulting rare-isotope beams, along with the added complication of a large range of beam loss scenarios along the fragment separator depending on its setting required to produce a specific isotope. A final parameter contributing to the variability of beam conditions is the final beam destination, with each end-station having its unique circumstances.

This work gives a sampling of recent simulations by the FRIB radiation transport team to support the facility. The examples highlight the challenges and strategies involved for an accelerator complex that mixes and matches multiple components to make beams –one where the beam conditions almost never repeat.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, operated by Michigan State University, under Award Number DE-SC0000661.

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Session 6 - Medical and industrial accelerators / 55

Source term assessments for air activation in hadrontherapy facilities

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Hadrontherapy is a radiotherapy technique that exploits accelerated particles to treat oncological patients. Protons are the primary particles utilised in such treatments, although there are only a few centres worldwide where also carbon ions are adopted. One of these centres is The National Center for Oncological Hadrontherapy (CNAO), located in Pavia, Italy. The facility accelerates protons up to 250 MeV and carbon ions up to 400 MeV/u since 2011. In the near future CNAO has planned to install a new ion source that also enables the adoption of He-4, Li-7, O-16 and Fe-56 ions, for both clinic and research applications using the actual synchrotron.
Typical radiation protection issues of these installations include the activation of materials, water and air both due to the primary and secondary fields. Specifically, when the beam interacts with either the patient or the machine components, it generates a secondary neutron field, which is also capable of producing radionuclides in the surrounding materials.
In this study, the production of radionuclides in the air within a hadrontherapy environment is evaluated for the particles accelerated at CNAO as listed above. Subsequently, the simulations are validated through experiments conducted under reference conditions using particles that are currently available, such as protons and carbon ions.
Two kinds of source terms are assessed: the first addresses activation resulting from the beam's free path in air, while the latter considers radionuclides generated by secondary radiation, when the beam impinges on different targets. Source term calculations are performed using the Monte Carlo code FLUKA.
Those results are normalised and generalised in order to allow their utilisation as source terms for air activation in standard conditions. So that, they can be useful for raw valuations of air activation, in various conditions and across different kinds of accelerator facilities.

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The European XFEL after 6 years of operation - a status report

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An overview of the performance of the EuXFEL after more than 6 years of operation is given.
The second part deals with the challenges with regard to radiation protection.These arise mainly

from the high average power of the electron beam of a maximum of 300 kW per main absorber and the high energy content of the X-ray pulses of up to 10 mJ.

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Session 6 - Medical and industrial accelerators / 57

An Accelerator Based-BNCT facility radiation protection simulations

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A facility for Boron Neutron Capture Therapy based on a 30 mA, 5 MeV proton Radio Frequency Quadrupole Accelerator (RFQ) coupled with a beryllium target will be built at the University of Campania 'L. Vanvitelli' in Caserta (Italy). The National Institute of Nuclear Physics (INFN) is in charge of the technology and collaborates on the design of the facility in the framework of the PNC-PNRR ANTHEM project. The interactions of the neutron beam and the consequent production of secondary particles must be studied to assess their effects in terms of safety for people both inside

and outside the structure. For this reason, simulations were performed using the N-particle Monte Carlo transport code (MCNP) version 6.0. A prototype Beam Shaping Assembly (BSA) has been designed as reported by Postuma et al.1 for filtering, moderating and collimating the neutron beam, which has a flux to the patient of at least $(10^9 cm^{-2} s^{-1})$. This beam is used to assess the necessary shielding (i.e. material composition and structure of the facility walls) to keep radiation as low as reasonably possible outside of the irradiation room. The simulations are performed in two steps, first we evaluate the radiation protection issues while the beam is on target and there is no patient in front of the beam (i.e. open-beam to be conservative). A latter simulation is then used to evaluate the induced activation in the rooms (i.e. Ar-41 and walls) using PHITS monte carlo code coupled with DCHAIN2. Different materials and compositions of the facility walls, including Portland,baritic and borated Baritic concrete and borated polyethylene, were tested to evaluate their performance as shielding. Simulation results reported in equivalent ambient dose, were analyzed in representative areas of the facility and compared to ensure the best conditions for safety. Neutrons are not only produced on the Be target. It is pivotal to consider the contribution to the ambient dose due to proton losses along the beamline. These protons have sufficient energy to produce neutrons through nuclear reactions. This extra ambient dose is important in the accelerator room and in the adjacent technical room. For the simulation of beam loss, a source has been designed by extracting protons perpendicularly to the particle transport direction with an energy distribution depending on the position along the line, according to simulations provided by the accelerator scientists. The results show that the most advantageous wall structure consists of a three-layer configuration: the inner layer is made up of borated polyethylene, the second is a 20 cm baritic concrete thick layer and the outer of Portland concrete. Thanks to the structure of the BSA which collimates the neutron beam,the quantities relevant for the radioprotection are kept very low. Work is currently ongoing to design a new, more efficient BSA, which ensures the same beam quality, while guaranteeing a higher neutron flux also exploiting an innovative target design.

1 Postuma, Ian, et al. "A novel approach to design and evaluate BNCT neutron beams combining physical, radiobiological, and dosimetric figures of merit." Biology 10.3 (2021): 174.
2 Y. Iwamoto, S. Hashimoto, T. Sato, N. Matsuda, S. Kunieda, Y. Çelik, N. Furutachi and K. Niita, Benchmark study of particle and heavy-ion transport code system using shielding integral benchmark archive and database for accelerator-shielding experiments, J. Nucl. Sci. Technol. 59, 665-675 (2022).

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Session 4 - Shielding and dosimetry / 58

Shielding Assessment for Spallation Neutron Source Power Upgrade

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The Spallation Neutron Source (SNS) Proton Power Upgrade (PPU) project is in the last phase of accelerator and target equipment installation. Its goal is to double the proton beam power of the SNS accelerator facility from 1.4 to 2.8 MW in preparation for providing a 700 kW/15 Hz beam to a second target station. The SNS target station will receive a power upgrade from 1.4 to 2 MW beam power, with part of this power upgrade being achieved by the proton beam energy increase from 1 to 1.3 GeV.
While the target station was initially designed for 2 MW beam power and 1 GeV beam energy, numerous neutronics analyses were conducted to check the existing target station installations for compatibility with the changed parameters, primarily due to the proton energy increase. The analyses examined radiation attenuation of shielding, nuclear heating, material damage and associated component lifetime, and radionuclide inventories impacting waste streams and hazard scenarios.
The focus here is on shielding. Beside verifying the shielding of the existing facilities, such as soil thickness above the accelerator tunnel, target monolith, and neutron beamlines, including instrument enclosure shielding, the stub-out of the accelerator tunnel into the new STS proton beamline was assessed as it is part of the PPU project.

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Radiation shielding analysis for synchrotron radiation beamlines of 4th generation storage ring in Korea

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The 4th generation storage ring (4th GSR) facility has been planned and launched in Korea since July 2021. Storage ring circumference is 799.297 m and is composed of 28 symmetrical cells with a beam emittance of 62 pm.rad. The stored electron energy and current are 4 GeV and 400 mA, respectively. The facility includes a 200-MeV linac, a booster ring, and a storage ring (SR). Both SR and booster ring are located in the same tunnel.

In previous work, the bulk shielding calculations were performed 1. In this work, the FLUKA Monte Carlo code was employed to calculate the equivalent dose rates generated from Gas Bremsstrahlung (GB) and synchrotron radiation throughout the beamlines based on the current design conditions. GB which is produced by electron beam interaction with residual gases in the vacuum chambers in the SR is a source of high-energy radiation that penetrates the beamlines. The GB generates electromagnetic shower in beamline components and produces neutrons via photonuclear reactions, exposing high radiation doses so that it needs to be shielded properly. The injection efficiency into SR was assumed as 90%. Calculations were performed to optimize the wall thicknesses of optical and experimental hutches. A permanent dipole magnet was also considered in the front-end beamline components as a safety magnet. The safety magnet deflects all primary particles in case of any accidental situation. The dose rate was calculated around the beamline for an accidental scenario to confirm the safety magnet's role in the beamline. The appropriate shielding criteria were determined based on the Nuclear Safety Act in Korea and the ALARA principle. These simulations will provide an overall radiological framework for shielding the beamlines of the 4th GSR in Korea.

This research was supported in part by the Korean Government MSIT (Multipurpose Synchrotron Radiation Construction Project).

1 N. S. Jung, Radiation Shielding Evaluation of 4th Generation Storage Ring in Korea, 11th International Workshop on Radiation Safety at Synchrotron Radiation Sources (RadSynch23), ESRF, Grenoble, France 30 May-2 June (2023).

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Beam loss monitoring in NanoTerasu storage ring with active neutron dosimeter

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A compact 3 GeV synchrotron light source (NanoTerasu) has been in operation at Tohoku University's new Aobayama campus in Japan since April 2024. NanoTerasu provides both soft and hard x-rays from insertion devices installed in the 3 GeV storage ring [1,2]. At present 10 of the 28 beamlines

designed are available; the remaining 18 beam lines will be installed in the future. The storage ring is operated with a storage electron current of ~100 mA by a top-up mode injection for the maximum design value of 413 mA. In the accelerator commissioning, beam loss information of the storage ring is important not only for beam tuning, but also for radiation safety. We have measured secondary neutrons generated by electron beam loss to obtain information on the position, timing and amount of electron beam loss. Secondary neutrons produced by photonuclear reactions have a peak energy around 2 MeV and more isotropic than secondary photons emitted in the interaction between a high-energy electron and materials. The neutron dose in the accelerator tunnel attenuates simply with distance from the beam loss position regardless of the direction of electron beam. On the other hand, secondary photons as a bremsstrahlung have a strong forward peaking; the photon dose depends on not only distance from the beam loss position but also the direction of electron beam. We used a semiconductor-type active personal radiation dosimeter DMC3000 coupled with neutron module to measure neutron dose inside accelerator tunnels. The dosimeter was put in the NanoTerasu storage ring tunnel and continuously measure gamma and neutrons dose during accelerator operation.
We present some examples of dose distribution in the storage ring tunnel and an optical hutch during the accelerator commissioning.

1 A. Takeuchi et al., "Estimation of Absorbed Dose due to Gas Bremsstrahlung Based on Residual Gas in Electron Storage Rings", Nucl. Sci. Eng, vol. 2, issue 2, 2024
2 H. Matsuda et al., "Shielding design of NanoTerasu for gas bremsstrahlung and photonuclear reaction", J. Nucl. Sci. Technol., vol. 61, issue2, 2024

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Exploring the degradation of thin carbon-backed LiF target bombarded by 68 MeV 17O beams

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In our research, we aimed to uncover the causes leading to the destruction of thin, carbon-backed lithium fluoride (LiF) targets in Li-7 and O-17 fusion measurements. To achieve this, we estimated theoretically the lifetimes of carbon and LiF films, taking into account the effects of sputtering, thermal evaporation, and lattice damage, and compared them with the lifetime observed in the experiment. During the experiments, surface silicon barrier (SSB) detectors were used to detect elastically scattered target and beam ions, allowing for the monitoring of beam flux and target density degradation.
The investigation revealed that the primary causes of this destruction were not the expected factors of sputtering yields and thermal evaporation rates, which were found to be too low to significantly impact the target's integrity. Instead, lattice damage emerged as the main culprit behind the target breakdown. Lattice damage was analyzed by calculating displacements with Monte Carlo simulations, and target lifetimes were evaluated. The target lifetime due to lattice damage agreed well with the observed target lifetime during the experiment. For experiments that utilize thin LiF targets to trigger nuclear reactions, this research proposes strategies for estimating the lifespan of the LiF film, thereby optimizing the experimental protocol for enhanced efficiency.

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Monte Carlo Simulations for the Future TATTOOS Target Station at PSI

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TATTOOS (Targeted Alpha Tumour Therapy and Other Oncological Solutions) is a proton irradiation target station to be built at PSI as part of the IMPACT project. The design goal of TATTOOS is to produce a wide range of radionuclides for diagnostics and therapeutics. Currently, UCx (Uranium Carbide) and Ta (Tantalum) targets are under investigation. Both the UCx and the Ta target will be irradiated by up to 100 µA, 590 MeV proton beam. A portion of the 2.4 mA high-energy proton beam extracted from
the Ring Cyclotron HIPA will be directed towards the TATTOOS target, while the remainder will proceed to the muon production targets and the Swiss neutron source SINQ. Therefore, TATTOOS will

be able to operate in parallel to the muon production targets and SINQ by the use of an electrostatic splitter.

TATTOOS encounters various design challenges, notably the management of high power density distributed onto the target and the large shielding required against intense neutron and gamma radiation fields. Addressing the 25 kW power deposit on the 300 cm^3 target demands a bespoke cooling concept and innovative target design. Additionally, the confined space presents a formidable obstacle in devising shielding solutions for both the target station and the secondary ion extraction beamline.

In this paper, the Monte Carlo transport calculations for shielding and power deposition performed in support of the TATTOOS project will be presented.

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Neutron transport calculations in support of the PSI-NEUTRA instrument upgrade

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NEUTRA is the thermal neutron imaging instrument coupled to the Swiss Spallation source SINQ. Successfully completing 25 years of operation, the NEUTRA 2.0 upgrade project has been approved. The upgrade to NEUTRA 2.0 foresees a complete reconstruction of the instrument including a redesign of the shielding bunker. The inner space of the measurement bunker will be enlarged, enabling complex setups with bulky samples. Likewise, full access to an upstream measuring position, MP1, on the beamline will allow utilizing about half an order and one order of magnitude higher flux than at the currently accessible measurement positions MP2 and MP3, respectively. These measures

will enable higher temporal resolution neutron imaging and the use of state-of-the-art detectors and measurement techniques at NEUTRA.

In this paper, the Monte Carlo MC / deterministic transport calculations performed for the verification of the safety of the shielding concept will be presented. In addition, we will give an overview of the calculation methodology and the variance reduction techniques applied for improving the simulation efficiency. With the help of the numerical analysis the shielding design has been optimised, its corresponding dose rate distribution maps are computed, and it is shown that the required radiation dose limits will be fulfilled.

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Radiation damage in a power dump

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In applications like nuclear reactors or particle accelerators, mechanical components near a source of radiation develop radiation damage. This typically means a change in tensile properties and fracture toughness, which depends on the radiation dose (commonly measured in 'displacements per atom', or DPA). In addition to such radiation hardening, radiation damage can also cause swelling, which in turn can lead to additional stresses. These effects need to be taken into account in the design of components, to make sure they do not fail.

In this work, the risk of failure for a power dump is assessed. The purpose of this power dump is to absorb gamma radiation with approximately 1 MW of power. The radiation is emitted from a target that is irradiated by an electron beam. The power dump's primary constituent material can become very brittle after irradiation, so fast fracture was determined to be the most likely failure mechanism.

To ensure the structural integrity of this component in its radiation environment, FEM analysis in combination with Monte Carlo radiation transport codes was used. Our approach consisted of first modeling the irradiation parameters of the system using a radiation transport code (FLUKA). This includes accurate modeling of the radiation source term. From this the heat load and radiation damage production (DPA/s) were obtained. As a second step, these spatially dependent results were mapped to a detailed 3D FEM model (COMSOL). The FEM model has appropriate boundary conditions relating the DPA to swelling strain, and temperature to mechanical strain. This allowed assessment of stress-distributions over time. Some changes were made in the design to minimize stresses. By assessing and evaluating a conservative fast fracture criterium, it was then determined that the component is not likely to fail.

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Treatment of low-energy heavy particle fusion reactions in PHITS

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The changes in the results of calculations and comparisons with experimental data when fusion reactions are explicitly treated in low-energy heavy ion reactions in the transport calculation code PHITS will be discussed. The CCFULL model is used to obtain the fusion cross section. Fusion reactions have been output as a result of JQMD simulations and not been treated explicitly in PHITS, but the use of CCFULL allows for an explicit treatment of fusion reaction. When a fusion reaction was selected, a composite of incident and target nuclei is prepared, and for the composite nuclei evaporation calculations are performed by the statistical model GEM. Comparison was performed with data of low energy heavy ion induced fragment nuclei.

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Radiation-Induced Effects on Commercial 3D Printing Materials Exposed to High X-Ray Doses

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Non-metallic materials for 3D printing are of increasing interest for the realization of components operating in extreme radiation conditions, such as particle accelerators, nuclear facilities, medical field, space missions, and repositories for radioactive waste. For this reason, radiation effects on several categories of commercial printing materials must be evaluated.

Considering the incomplete and limited existing data on this topic, a new research activity is being developed to broaden the available knowledge about radiation effects on 3D printed parts, using a multi-scale approach. Four non-metallic materials commonly used for 3D printing have been selected for investigation: Poly(Lactic Acid) (PLA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Elastomer (TPE), and High Temperature Polyamide reinforced with Carbon Fibres (PAHT CF). The materials have been irradiated at the Hubert Curien Laboratory (LabHC), using X-ray tubes operating at a voltage of 160 kV. Monte Carlo simulations realized with PHITS and GEANT4 have been implemented to guide the optimization of the experimental setup and estimate the dose in the material.

Both raw filaments for 3D printing and samples printed in selected geometries have been irradiated and tested to assess the dependence of radiation effects on the printing process and on the sample geometry. Samples were irradiated at doses ranging from about 100 kGy[H_2O] to 1 MGy[H_2O] at a dose rate of 0.6 Gy[H_2O]/s, at room temperature and in air atmosphere. An additional set of samples has been irradiated at 0.2 Gy[H_2O]/s, to investigate the dose rate and the oxygen effect. The total absorbed dose has been measured during the irradiation duration with a set of FD-7 radiophotoluminescent glass dosimeters, whose readout, specifically adapted to high doses, is performed in collaboration with CERN.

Sample characterizations are jointly performed at LabHC and at the Materials Science and Technology Laboratory of the University of Brescia. The performed multi-scale investigations include thermal, mechanical and spectroscopical analyses, such as Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), tensile test, Dynamic Mechanical Analysis (DMA), Fourier-Transform Infrared spectroscopy (FTIR), and Raman spectroscopy, aiming at finding correlations between structural and macroscopic radiation effects.

Results of the irradiation campaign evidence a progressive evolution of the properties of the materials with dose. In addition, the collected data allow the different materials to be systematically compared, providing useful information for the selection of the most radiation tolerant ones. More details on the performed characterizations will be presented.

Future experimental campaigns will target the dependence of radiation effects on other parameters, such as temperature, environmental atmosphere, and dose rate in view of specific applications.

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MONTE CARLO CALCULATION CODE APPLICATIONS FOR THE SHIELDING DESIGN OF A TRANSPORTABLE POSITRON GENERATOR

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POSITHOT is a French startup issued from the fundamental physics institute of the French Atomic Energy Commission (CEA), which offers materials analysis using positron annihilation spectrometry. This technique of defect detection reaches the sensitivity level of a metrology, to the contrary of existing Non-Destructive Testing (NDT) solutions. The POSITHOT technology offers the capacity to quantify the lack of matter in the matter without radioactive waste.

The positrons used in this technology are created through the interaction between an electron beam and a tungsten target by pair production. The patented design of this innovative positron generator allows the realization of a compact and transportable equipment that furthermore does not activate the materials. The generator is then non-radioactive, but registered as an ionizing radiation source. In the physical reaction to produce the positrons, a substantial part of the incoming electrons spread in the vacuum vessel and the copper dump, producing secondaries emissions sources of X-rays. They complete the initial spectrum of X photons produced in the interaction target. As a result, this type of technology leads to very intense photon radiation due to the interaction between the incident beam and the constituents of the equipment. The resulting X-rays spectrum was at the origin of radiation protection issues for the shielding design of this generator.

The objective of the performed study was to design an effective shielding of the positron generator regarding to the French Nuclear Safety Authority (ASN) norms in order that the generator remains transportable.

Three steps were conducted:
- The 3D modeling of the generator that mixed CAD import and direct modelling,
- The evaluation of the initial shielding with a 3D dose mapping,
- The shielding optimization in respect of the generator transport limitations.

Calculations were performed with the Monte Carlo code RayXpert® developed by TRAD Tests & Radiations. In this presentation, it will be demonstrated that thanks to a first 3D dose mapping, it was possible to highlight the origin of dose leaks that led to non-compliance with the fixed dosimetric objective outside the generator. Due to the transportable limitations, radiation shielding was added as close as possible to the source in the respect of weight issues and equipment dimensions. The additional shielding enabled to reduce the dose by a factor of 25,000 for the most problematic direction. This step of the study was easily achieved thanks to the 3D conception interface of the software and its various features adapted to radiation protection issues.

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The Frascati Neutron Generator (FNG): capabilities and applications for radiation testing on electronic devices

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The Frascati Neutron Generator (FNG) is a 14 MeV neutron source with a maximum strength of $1\text{x}10^{11}$ s^{-1} designed and built by ENEA in the Frascati research center, in operation since 1992. It is a linear electrostatic accelerator in which an ion beam of D+ is accelerated up to 300 keV and 1 mA of current. 14 MeV neutrons are produced via the D(T, n)α fusion nuclear reaction using a tritiated target on which the ion beam impacts. FNG can, also, produce 2.45 MeV neutrons by replacing the tritiated target with a deuterated one, thus triggering the D(D, n)He^3 fusion reaction.
Thanks to its unique characteristics, FNG strongly supported the Fusion Neutronics program through benchmark experiments and nuclear data validation for over thirty years and is also employed in a wide range of other relevant scientific activities. Among them, one of the most significant activities is the investigation of radiation effects on electronic components under neutron irradiation. For

this purpose, FNG is involved in national and international projects such as RADNEXT, (RADiation facility network for the Exploration of effects for indusTry and research) and ASIF (Italian Space Agency Supported Irradiation Facilities).
RADNEXT is an H2020 INFRAIA-02-2020 (Interacting Activities for Starting Communities) infrastructure program with the objective of creating a network of facilities and related irradiation methodology for responding to the emerging needs for electronics component and system irradiation. ASIF is a national program aimed at coordinating irradiation facilities to support spatial mission needs. Additionally, an ENEA project called GENeuSIS (General Experimental Neutron System Irradiation Station), was recently launched to develop a modular and customizable irradiation station to be installed at FNG. It aims to study neutron induced Single Event Effects (SEE) on electronics by reproducing neutron and gamma energy spectra in specific ITER locations. The present work gives to the audience an overview of all the aforementioned activities and partnerships, along with their status, highlighting the capabilities of the machine in investigating the radiation effects on electronic devices.

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Spectral characterization with a Bonner Sphere Spectrometer of the Neutron Irradiation area for radiation hardness studies at the EPOS facility

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Among the radiation effects to detector and electronic components, the displacement damage due to neutron exposure is a key aspect. At ELBE an optimal neutron radiation source for radiation hardness studies is provided at the pELBE beamline at the ELBE Positron Source facility (EPOS), as secondary radiation with unique properties. The heart of EPOS is a 1 cm W target, which not only induces bremsstrahlung and then pair production in view of the positron selection, but is also, de facto, a photo-neutron source. This source provides a neutron field optimal for radiation hardness studies, due to the typical photo-production spectrum (which is peaked at 1 MeV), the high neutron fluence rate (up to 107 n per cm2 per second), and the negligible contamination due to the optimal shielding to the photon field provided by the lead cage.

Until now the neutron irradiation area at the EPOS facility has been characterized only via Monte Carlo simulations. With the aim to validate the Monte Carlo results, and to perform an accurate calibration of the area in view of future irradiation campaigns, a spectral characterization with a Bonner Sphere Spectrometer (BSS) has been performed. The Bonner Sphere Spectrometer of INFN Frascati National Laboratories, which consists of a set of 13 polyethylene spheres inside of which a Li6I(Eu) scintillator is inserted, was used.
Considering the EPOS neutron spectrum, a set of 9 spheres with diameter ranging from 2 in to 8 inches, adequate to cover the full energy range, was considered. The complete characterization was performed for three different points placed on the nELBE lead roof under the same irradiation conditions, which consists in the use of a 34 MeV electron beam whit a mean current of 2 nA, corresponding to 3x105 n/cm2/s estimated in the points of interest. Once obtained the counts for the entire set for each point considered and exploiting the knowledge of the response matrix, the unknown neutron field has been estimated using the default spectrum, produced through a Bayesian approach, and then the unfolding code UMG (MAXED and GRAVEL packages).

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Radiation load studies for the proton target area of a multi-TeV muon collider

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Muon production in the multi-TeV muon collider studied by the International Muon Collider Collaboration is planned to be performed with a high-power proton beam interacting with a fixed graphite target. Capturing the emerging pions and muons requires very strong magnetic fields that can only be reached with superconducting solenoids, whose properties are sensitive to long-term radiation damage. The design must ensure that the induced radiation damage is compatible with the operational lifetime of the muon production complex. One of the main concerns of the target area design is the displacement damage in the superconductor. Next to that, the fraction of the primary beam

passing through the target unimpeded must be safely extracted onto an external beam dump. In this study, we use the FLUKA Monte Carlo code to assess the radiation load to the target solenoids and we explore the spent proton beam extraction scenarios considering the desired muon spectrum.

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Session 4 - Shielding and dosimetry / 71

CALLIOPE GAMMA IRRADIATION FACILITY AND REX ELECTRON BEAM DOSIMETRIC INTERCALIBRATION

Authors: Beatrice D'Orsi[1]; Maria Denise Astorino[2]; Giulia Bazzano[2]; Rocco Carcione[3]; Ilaria Di Sarcina[3]; concetta ronsivalle[2]; Jessica Scifo[3]; Adriano Verna[3]; Alessia Cemmi[4]

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The Calliope gamma irradiation facility (ENEA Casaccia Research Center) is a pool-type facility, equipped with ^{60}Co gamma source in a large volume (7x6x3.9 m^3) shielded cell, involved in several research fields. At Calliope facility, several dosimetric systems such as Fricke solution, alanine-ESR, Red Perspex, radiochromic, Thermo Luminescent Dosimetry (TLD) and electronic RADFET are used, depending on the absorbed dose range of interest. In particular, by means of the Fricke absolute dosimeter, the relative secondary dosimetric systems are periodically calibrated and used when the Fricke solution is not applicable.

The REX (Removable Electron to X-ray) system (ENEA Frascati Research Center) is based on a pulsed (3.5 μsec pulse length, repetition frequency variable from 5 to 20 Hz) 5 MeV S-band electron linac and a removable head containing an electron to X-ray converter. It is employed in many research fields, from cultural heritage to space component testing, thanks to its customizable radiation beam. The linac extraction terminal and the X-ray converter are enclosed in a lead-shielded chamber (40x40x80 cm^3). The output radiation is routinely characterized by radiochromic films (EBT3, HD-V2), Markus type ionization chamber and Faraday collector. These types of detectors provide information on transverse homogeneity, radiation flux and machine reproducibility, but for an accurate dose estimate a comparison with an absolute dosimeter is necessary. This is especially true for the electron modality, characterized by a very high dose rate (100-400 kGy/h).

One of the most powerful dosimetric techniques is the alanine-ESR dosimetry method based on the detection, by the Electron Spin Resonance (ESR) spectroscopy, of stable free radicals induced by ionizing radiation (e.g. gamma rays or electrons) in the crystalline L-α-alanine amino acid. Thanks to its wide dose range and dose rate and energy independence for energies around few MeV, it is well suited for REX electron beam dosimetric intercalibration.

Dosimetric measurements for the dose rate distribution assessment inside the REX chamber have been performed by means of alanine-ESR dosimeters, calibrated with the absolute Fricke solution at the Calliope facility. In particular, alanine dosimeters were irradiated at the REX facility in different points of the REX chamber, with different irradiation times and at different distances from the electron source. The obtained results will be presented.

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Session 2 - Code status, development and model converters / 72

Particle and radiation transport simulations: tackling user needs via software architecture layer abstractions

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The design and safety assessment of nuclear installations and experimental setups are nowadays backed by accurate simulations, performed by dedicated numerical methods capable of representing the relevant physics involved. More specifically, the plethora of phenomena that come into play in these facilities should be analyzed from both the microscopic point of view, which in turn is related to the actual nuclear interactions, and the macroscopic scale, which is more connected to the engineering perspective of the plant installation. When dealing with neutronics studies in which the transport of neutrons and photons is the key objective, the microscopic scale is related to nuclear data and their evaluation, while the macroscopic level is connected to the actual engineering components.
In the past decades, a large collection of numerical solvers has been developed to address all the relevant physical problems ranging from these two different views. Moreover, each nuclear installation requires a peculiar and very demanding certification procedure, that justifies the need for costly verification and validation activities. This means the actual knowledge of the physical phenomena and the actual validity of their potential numerical representation is graved in the source codes.

At the same time, it may be noticed that the numerical software representation of a given problem may not be immediately understandable from an analyst interested purely in the final observable quantities. The principal reason is that the solver relies to a certain extent on a specific discretization of the equations governing the physical phenomena and their numerical stability with a given algorithm, while the analyst is typically interested in the real components of the system. Tackling the issue of connecting these two worlds is the main goal of this presentation.

Restricting the analysis purely to neutron and photon transport in fission (PWR and BWR) and fusion (tokamak and neutron generator) facilities, the presentation will focus on the software architecture options to develop efficient yet flexible solutions to decouple the development of simulation platforms. The analysis will be based on the application of systems engineering practices to capture relevant user needs and on the separation of responsibilities between the frontend and the backend. When constructing the potential software layers stack, special attention will be devoted to the object lifecycle, the ownership of data objects, and the implications of different choices. Eventually, some examples of specific problems (e.g. geometry and representation) will be proposed to provide insight into the effect of software architecture design choices on real cases.

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Session 5 - Induced Radioactivity / 73

Benchmarking study on induced activity of H-3 and Be-7 in water target at PAL-XFEL

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Water is considered as one of the candidates of beam dump material for high energy and high-power electron beam. A benchmarking study on a water target is conducted at Hard X-ray (HX) main beam dump bunker of PAL-XFEL to investigate the induced radioactivity concentration in the water target.
An irradiation experiment of the water target was conducted and the induced radioactivity concentrations of H-3 and Be-7 were measured. The electron beam energy during irradiation was 9.5 GeV. The average beam charge was 180 pC with a 60 Hz repetition rate (the average beam power: 10.9 W). The total irradiation time was 138.5 h. The water was contained in a cylindrical stainless-steel chamber and directly irradiated in front of the main beam dump of PAL-XFEL. The size of the

chamber was defined as a diameter of 26 cm with a length of 40 cm, considering the accessibility of PAL-XFEL beam dump space and handling of water chamber. After the irradiation, the water in the chamber was sampled and the radioactivity concentration of H-3 was measured by a Liquid Scintillation Counter and that of Be-7 was measured by an HPGe detector.
The water chamber and all the components in PAL-XFEL HX main beam dump bunker was simulated in the FLUKA 4-4.0 code to calculate water activation, taking all the reactions and scatterings in the bunker into account. The induced radioactivity in the water target was calculated considering the beam irradiation condition and compared with measured results.
The discrepancy between the simulated and measured results of H-3 and Be-7 was less than a factor of two. The detailed comparisons between simulated and measured induced radioactivity concentrations will be discussed.

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Session 8 - Radiation damage to materials / 74

Evaluation of Radiation Heating and Damage for the Preliminary Design of Second Target Station Monolith Inserts

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The Second Target Station (STS) Project 1 at Oak Ridge National Laboratory (ORNL) is currently working to complete preliminary design of components within the Target Monolith by the end of calendar year 2025. This includes the rotating water-cooled tungsten target, the two liquid hydrogen moderators, and many other components. After the completion of the Proton Power Upgrade (PPU) 2 of the Spallation Neutron Source (SNS), the proton accelerator will produce 1.3 GeV protons at a repetition rate of 60 Hz. A quarter of these pulses will deliver 700 kW of power to the STS target. A lot of work has focused on analyzing radiation heating and damage to the target monolith components. These analyses result in preliminary design estimates of cooling requirements for major components, like the target segments and surrounding shielding blocks, and component lifetimes, like the proton beam window.

The majority of instrument systems components will reside outside the target monolith. However, the monolith inserts, which hold the first section of neutron guide for each neutron beamline, is a notable exception. The monolith inserts extend from the outer surface of the target monolith to less than 1 m from the liquid hydrogen moderators. Therefore, the effects of radiation heating and

damage also need to be quantified for the preliminary design of these components. The expectation of the authors before this analysis began is that the portion of the monolith inserts nearest the moderators will need to be actively cooled and that the radiation damage will not be the limiting factor of the monolith insert lifetimes. This presentation will include details of this analysis and conclusions for the preliminary design based on the results.

1 ORNL, "Spallation Neutron Source Second Target Station Conceptual Design Report Volume 1: Overview, Technical and Experiment Systems,"S01010000-TR0001, R00, Oak Ridge National Laboratory (2020).
2 ORNL Neutron Sciences Directorate, "Final Design Report Proton Power Upgrade Project,"ORNL/TM-2020/1570-R0, Oak Ridge National Laboratory (2020).

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Session 3 - Code benchmarking and intercomparison / 75

The Shielding Integral Benchmark Archive Database (SINBAD) Task Force

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In 2021 the oversight and future development of the Shielding Integral Benchmark Archive Database (SINBAD) was transferred to the SINBAD Task Force (TF) supervised by the OECD NEA Expert Group on Physics of Reactor Systems (EGPRS). The TF consist of shielding experts, experimentalists, and benchmark evaluators from the EGPRS and other invited experts. It was originally mandated to operate for three years until February 2024. Given its success in establishing new processes and reestablishing communities of practice, it was decided during the last EGPRS meeting in February of 2024 to continue its operation.

Since its inception, the TF has established its own unique process and procedures to develop, review, and publish SINBAD benchmarks. This includes using a unified benchmark report format (or template), moving development and review of benchmarks to a Git repository hosted by the NEA Data Bank, and development of SINBAD maturity levels that make the process of developing and reviewing SINBAD benchmarks modular. Some of these details have been presented in the past 1, so this presentation will provide an overview of these details and focus on recent changes. Some of

the important changes are including the concept of Quality Reviews developed by I. Kodeli and E. Sartori 2 and opening the SINBAD Git repository to all SINBAD licensees. In order for a SINBAD benchmark to reach maturity level 4, a quality review will need to be completed and a grade (1, 2, or 3 stars) assigned to the benchmark. Opening the Git repository to all SINBAD licensees represents a monumental shift in the development of benchmark evaluations. This will allow licensees to create Git issues that are essentially "bug reports"to the maintainers of the Git repository. If licensees are so inclined, they can help address these issues themselves. Licensees can also submit simple additions to the repository, like adding a new radiation transport code input file. Finally, allowing all SINBAD licensees access to the Git repository means that licensees will have immediate access to newly published or revised entries in SINBAD.

If you or your colleagues have interest in participating in the SINBAD TF, please contact the authors of this paper.

1 T. M. Miller, O. Buss, and M. Fleming, "The Task Force to Reinvigorate SINBAD,"Proceedings of the 14th International Conference on Radiation Shielding and the 2022 Topical Meeting of the American Nuclear Society Radiation Protection and Shielding Division, Seattle, Washington, September 25-29, 2022, https://doi.org/10.13182/ICRSRPSD22-39408 (2022).
2 I. Kodeli and E. Sartori, "SINBAD –Radiation shielding benchmark experiments,"Ann. Nucl. Energy, 159, 108254, https://doi.org/10.1016/j.anucene.2021.108254 (2021).

Scientific Topic 1:

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Session 6 - Medical and industrial accelerators / 76

CNAO RADIATION PROTECTION STUDIES FOR A FACILITY MADE OF AN A-BNCT FACILITY AND TWO SYNCHROTRONS

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The National Centre for Oncological Hadrontherapy (CNAO) stands as one of the few facilities in the world capable of treating oncology patients using both protons and carbon ions accelerated by a synchrotron. In the near future, this machine will undergo an upgrade, incorporating a new ion source that allows the exploitation of helium, lithium, oxygen, and iron ions for both therapeutic and research purposes. Additionally, new accelerators will be added to the facility, i.e. a proton

synchrotron with rotating gantry and an accelerator based BNCT facility.
All the accelerators are built within a single building, in a small area (about 30,000 m^2), and the particular location, near urban construction, such as hospitals, research institutes, and apartment buildings at a few hundred meters of distance, poses some particular issues when handling the radiation protection problems for the facility.
For these reasons, many peculiar solutions have been found to minimize the doses around the shielding of the machines and to assess new ions workloads inside the current shielding. Furthermore, extensive assessments have been carried out to minimize the production of neutron absorption gammas of radioactive gases released by the exhaust and by choosing ad hoc materials e.g. boronated concrete, barite boronated concrete in the construction of the BNCT facility.
The evaluations have been developed by deep-diving into some hypotheses that are usually taken as granted, by building a very precise Monte Carlo modeling of the facilities and by taking into account also the magnets self-shielding and by cross checking different Monte Carlo softwares for better robustness of the data. Particular attention was paid to the dispersion of radionuclides in the atmosphere involving a comparison between existing literature models and introducing an original Monte Carlo implementation of the Gaussian Plume model.

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Session 8 - Radiation damage to materials / 77

Nuclear design of a shielded cabinet for electronics: the ITER Radial Neutron Camera case study

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Co-authors: Alberto Previti [1]; Andrea Colangeli [1]; Antonio Maffucci [2]; Basilio Esposito [1]; Cristina Centioli [1]; Daniele Marocco [1]; Davide Flammini [1]; Domenico Marzullo [3]; Francesco Belli [1]; Fulvio Pompili [1]; Gennaro Di Mambro [2]; Giada Gandolfo [1]; Jerzy Kotula [4]; Marco Riva [1]; Michele Lungaroni [1]; Nicola Fonnesu [1]; Rafal Ortwein [4]; Rosaria Villari [1]; Ryszard Kantor [4]; Salvatore Podda [1]

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The Radial Neutron Camera (RNC) is a diagnostic system located in the ITER Equatorial Port #1, probing a poloidal section of the plasma through a set of fan-shaped Lines of Sight (LOS). The RNC is designed to provide spatial and time-resolved measurement of the neutron and α particles source profiles as well as the total neutron source strength, as a result of reconstruction techniques applied to the line-integrated neutron fluxes.
The uncollided 14 MeV and 2.5 MeV neutrons, generated through deuterium-tritium (DT) and deuterium-deuterium (DD) fusion reactions, are measured by means of an array of neutron flux detectors located in dedicated cassettes at the end of the collimated LOSs. Signals from RNC detectors (i.e. fission chambers, single Crystal Diamonds and scintillators) need preamplification because of their low amplitude; consequently, the preamplifiers have to be located as close as possible to the detectors in order to minimize the detrimental effect of signal degradation on the RNC measurement performances. On the other hand, the electronic devices must be protected against the severe radiation environment during normal operating conditions, due to the intense neutron streaming directly from the plasma and the effects of secondary gammas generated through the interaction of neutrons with the surrounding machine components.
The solution adopted is to host the preamplifiers in a shielded cabinet located in a dedicated area of the Port Cell, behind the Bioshield Plug.
The overall design of the cabinet must ensure the necessary magnetic, thermal and nuclear shielding and, at the same, satisfy weight and allocated volume constraints and maintain its structural integrity. The aim of the present work is the nuclear design of a suitable shielded cabinet, performed by means of 3D particle transport calculations (MCNP), taking into account the radiation streaming through the Bioshield penetrations and the cross-talk effect from the neighboring Lower and Upper Ports. The assessment of its nuclear shielding performances is presented, as well as the analysis of the compliancy with the alert thresholds for commercial electronics in terms of neutron flux and cumulated ionizing dose.

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Poster Session / 78

Radiation safety study for the upgrade of LINAC injector for the SOLEIL II low emittance storage ring project.

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The Synchrotron SOLEIL, the French 3rd generation synchrotron light source, will be upgraded to a 4th generation ring, based on multi-bend achromat lattice to achieve a very low emittance electron beam (~80 pm.rad) and a much more brilliant and coherent synchrotron light source.

To achieve this and allow the filling and top-up operation of SOLEIL II new storage ring, the injector, made of a LINAC and a BOOSTER synchrotron must be upgraded too. Regarding Radiation Protection aspect, the upgrade of the LINAC will result by the enhancement of the electron beam energy delivered to the BOOSTER from 110 MeV up to 150 MeV. To comply with the French Nuclear Regulation Authority (so call ASN) requirements, a complete Radiation Safety study of the upgraded LINAC has been done and will be submitted to ASN approval soon.

This paper presents the methodology, measurements and Monte Carlo calculations that have been conducted to assess the radiation fields generated by the upgraded LINAC and to define the potential additional shielding requirements and new beam stoppers. Monte Carlo calculations were performed with the FLUKA particle transport code for both normal beam losses and operation and "reasonably predictable"abnormal beam losses.

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Session 2 - Code status, development and model converters / 79

Advancing the MCNP Unstructured Mesh Calculations at ORNL's Second Target Station

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The Second Target Station (STS) at Oak Ridge National Laboratory (ORNL) Spallation Neutron Source is designed to become the highest peak-brightness source of cold neutrons in the world. A preliminary design of the STS consists of a rotating tungsten spallation target driven by a short-pulsed 1.3-GeV, 700-kW proton beam and two coupled parahydrogen neutron moderators at 20 K surrounded with a water premoderator and a beryllium reflector. To advance the STS design in a timely manner and complete a large volume of supporting neutronics calculations, we employ the most efficient computational tools that are currently available. Key among these tools is the Unstructured Mesh (UM) geometry capability of the radiation transport code MCNP6.2 1 and the latest Attila4MC 2 mesh generator and variance reduction modules. The UM geometry capability allows us to convert the computer aided design (CAD) models into high-fidelity models for neutronics calculations, evaluate the performance of the moderators, calculate the dose rates throughout the facility, and deliver

heating profiles in the beam intersecting devices with high spatial resolution for the subsequent structural stress, thermodynamic, and other engineering analyses.

This talk focuses on several practical applications of the UM geometry capability within the scope of the STS. We discuss the use of Attila4MC's Part-by-Part Mesher and Cottonwood, a new variance reduction solver designed to be used with discontiguous (complex) meshes. These highly efficient tools were used to carry out radiation shielding calculations, including streaming through the gaps, for a few cases involving prompt neutron and shutdown gamma radiation. Problems encountered and their resolution will be presented.

1 C. WERNER (ed.), et al. "MCNP User's Manual, Code Version 6.2,"LA-UR-17-29981, Los Alamos National Laboratory (2017).
2 Attila4MC 10.2 Overview of Core Functions, Silver Fir Software, Inc., Gig Harbor, WA, USA, SFSW-UR-2020-OCF102 (2020).

Scientific Topic 1:

Source terms, new accelerator facilities and related topics

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Status of the development of FLUKA MC dedicated radiation sources and estimators for the design and commissioning support of the high-power, high rep-rate LCLS-II electron accelerator

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Since the inception of the Linac Coherent Light Source (LCLS) at SLAC in 2009, significant advances in multidisciplinary science have been achieved with hard X-ray Free Electron Lasers (FELs). In such facilities, a low emittance electron beam from a linac goes through an array of undulators, where bright and coherent light is generated via self-amplified synchrotron emission. The next evolution, aimed at maximizing data-taking, among other features, involves increasing the average laser brightness through more powerful linacs, typically utilizing superconducting cavities to meet high RF demands. This is the case of the European XFEL (since 2017), LCLS-II (currently under commissioning), or SHINE (under construction). Computational models to describe some of the radiation challenges that can arise with these facilities are described here.

High RF fields at LCLS-II and especially LCLS-II-HE will enhance undesired electron extraction from superconducting cavities' surfaces via the tunnel effect. These field-emitted electrons, lacking the correct phase and energy for full acceleration, are eventually swept away by magnets or lost at apertures and chicanes, thus leading to radiation terms that can be dominant in some contexts. Source routines with interfaces via input cards to the FLUKA input file have been developed and refined for FLUKA to help predict such hazards. These computational capabilities are also crucial for designing dedicated cryomodule test facilities.

Ion chambers, whether point or elongated detectors, can experience pile-up and self-screening due to relatively low ion mobility compared to the high repetition rate and power of LCLS-II-type accelerators. Consequently, new beam loss monitors, such as synthetic diamonds based on hole-electron pairs generation, or Cherenkov optical fibers coupled to photomultipliers, have been adopted for LCLS-II and its successors. In the context of the ongoing LCLS-II commissioning, alongside attention to the aforementioned field-emitted electrons, recent developments of the FLUKA models that predict the response of such detectors while addressing the intrinsic statistical challenges of such small detectors are presented.

This work is supported by the Department of Energy Contract DE-AC02-76SF00515

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Session 5 - Induced Radioactivity / 81

Evaluation of decommissioning of proton therapy centers based on the selection of shielding materials at the building stage of the facility

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Introduction
Proton therapy centers are growing fast, both in Spain and all around the world. Prompt radiation attenuation is essential to achieve legal dose limits, but not enough to develop efficient radiation protection of these facilities. Activation of mechanical elements, ambient (air, water, ground), and of course, the shielding, is a relevant issue, linked with radiation protection conditions, as well as future dismantling and management of radioactive materials. To estimate and reduce decommissioning costs, a sensitive part of total investment, it is essential to study the cycle of life of the facility, thus,

the goal of this work was to carry out comparative analyze of neutron activation in shielding of three compact proton therapy centers, depending on the concrete used.

Methods
Calculations were developed using two Monte Carlo codes (MCNP and PHITS), in three types of proton therapy centers, similar to those working now or planned for Spain, and four types of concrete (conventional, high-density with magnetite, high-hydrogen-content, and low activation). Considering the energy of neutrons, up to 230 MeV, and the generation of radioisotopes through capture and spallation reactions, both, several physics models, and nuclear data libraries were used and benchmarked, namely, ENDF/B VIII.0, JENDL-4.0, JEFF-4T2 and TENDL2017/19.

Results
From the activation point of view, best concretes are those with low impurities. The type of activation, and the isotopes present, depend on the channel of the reaction. From the attenuation point of view, the four concretes largely meet the necessary dose attenuation conditions.

Conclusions
Induced radioactivity remains in the walls of centers for several years, even decades, after their closure, therefore, a good inventory estimation, depending on the choice of the shielding material, could be advisable in the early stages of projects. Considering the flux and neutron spectrum in each area of the center, it would be more suitable to use different concrete for each area, optimizing the selection based on attenuation, activation, and cost.

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RP Commissioning of the LCLS-II linac at low power

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The LCLS-II at SLAC represents a significant upgrade over its predecessor, introducing advancements in X-ray laser technology to provide a deeper understanding of atomic structures. The commissioning of the linac includes a series of surveys that are performed at different steps while ramping up energy, power and parking beam at different locations of the beamline. This presentation details the findings of the Radiation Physics commissioning of the LCLS-II, structured into two main sections: RF-only operations of the gun and cryomodules & operations with low beam power.

In the first part we focus on radiations produced by RF-only operations. We aim at better understanding the accelerator field emissions and their origin. Field emissions are undesirable electron discharges from the superconducting cavities, which integrate with the main beam, affecting its quality, potentially disrupting the beam's characteristics, and posing risks of radiation hazard as well as to the accelerator's components. The identification and quantification of these emissions are important to design mitigation strategies, enhance operational safety, and optimize the accelerator's beam performance.
The second part is related with low power beams purposely lost at different locations in the accelerator enclosure and associated residual doses.
Through a series of tests in 2022 and 2023, the RP group has collected data by monitoring radiation through different operational modes to validate the adequacy of the designed radiation mitigations and better understand our capacity of measuring radiation from different sources with optical fibers, solid state diamond detectors, ion chambers and average current monitors.
Next phases of LCLS-II commissioning will be related to higher power beams.

This work is supported by the Department of Energy Contract DE-AC02-76SF00515

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FLUKA: status and new developments

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The status of the FLUKA code and many important physics developments occurred after SATIF15 will be presented.

The FLUKA photonuclear interaction models as developed in the 90's by A.Fassò were a breakthrough for the community. Nowadays new data and better theoretical understanding allow for a better and more complete description of photonuclear interactions. Therefore the FLUKA photonuclear interaction models have been completely reworked. The previous implementation was replaced with a completely new approach for all energies above the quasi-deuteron region. The talk will describe how the new models have been implemented, comparing with cross section data ranging from proton to uranium targets. The description of photon interaction is no longer based on transforming the incoming photon into a pseudo-$\pi 0$, but in the resonance region the photon is directly treated as such, combining gamma-nucleon interactions, two and three nucleon absorption, in a framework where the Delta resonance modifications in the nuclear medium are now properly accounted for. At higher energies, where the VMD approach takes place, the photon is now treated as a virtual vector meson, taking into account the corresponding hadronic resonance interactions and decay in nuclei. At the same time the GDR cross sections for many important isotopes have been revised and updated taking into consideration the most recent data and evaluations.

Pointwise S(α,β) treatment for neutron in the thermal energy range is now implemented with a FLUKA specific algorithm. Incoherent inelastic [S(α,β)], incoherent elastic, and coherent elastic are all supported within a fully continuous approach.

Important developments for photon interactions will also be described, in particular the implementation of complex refraction indexes for X-ray reflection at boundaries. Ortho-positronium annihilation in 3 photons is now supported with the proper matrix element: the relative probability of ortho- and para-positronium annihilation can be changed by the user in order to study possible effects of the chemical environment of the material where the annihilation takes place.

On a more technical side, the latest ICRU/ICRP conversion coefficients are now available in FLUKA, as well as state-of-the-art spectra for Galactic Cosmic Rays, along with built-in sampling for some popular neutron sources, 252Cf, Am-Be, Am-B, D-D and D-T.

For all these topics examples will be given assuming the time will be enough.

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Monte-Carlo simulations of the ESS accelerator radiation environment using kernel density estimation techniques

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The Spallation Physics Group at the European Spallation Source (ESS) maintains a detailed model of the ESS accelerator for Monte-Carlo simulations. This model can be used together with the codes PHITS, MCNP6, and FLUKA for calculations of prompt dose rates and nuclide inventories produced

around the accelerator. This includes problems involving for example deep-penetration of neutrons through the berm, skyshine at the boundary of the facility, activation of cooling water, and streaming of radiation through chicanes and ducts. These types of simulations are however computationally challenging and require the application of variance reduction techniques to make them possible. One approach is to divide the full simulation into smaller simulations by creating intermediate source terms at specified locations in the geometry. This approach can however suffer from simplifications made in the production of the intermediate source terms. In this work we highlight results of investigating the usage of kernel density estimation techniques with the software package KDSource for intermediate source term creation for accelerator radiation transport applications at the ESS.

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Computational fluid dynamics investigation of the dispersion of radioactive cloud in the surroundings of an urban center

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Plume dispersion into the atmosphere of radioactive cloud emitted by a source can be affected by the presence of buildings and obstacles modifying the velocity and the spatial distribution fields respect to the classical Gaussian Plume Model. The Gaussian Plume Model (GPM) is often used to assess the submersion dose resulting from an emission stack. The dispersion of the radioactive cloud is determined by computing the Brigg's coefficients, which are influenced by meteorological factors such as wind speed and atmospheric stability. Huber et al. 1 has proposed a simplified model to estimate the increased dispersion caused by obstructions and buildings. This is achieved by incorporating modified parameters into the Gaussian Plume Model (GPM) framework. The model created by Huber includes modifications to the dispersion parameters and Brigg's coefficients to account for the looping movement of the plume in the lee of the buildings. This looping movement is caused by vortices generated in the flow field around the obstacles. Huber model simply takes into account

basic characteristics, such as the maximum height of obstacles, without considering the actual geometry of the domain.
An accurate estimation of the dispersion of a radioactive plume can be obtained by recurring to computational fluid-dynamics (CFD) models. Furthermore, the dispersion of radionuclides can be incorporated into the Monte Carlo code FLUKA to enhance the accuracy of dose evaluation. Computational Fluid Dynamics (CFD) models are very valuable for assessing conditions in close proximity within urban environments, where the assumptions or the Gaussian Plume Model (GPM) cannot be used. This is especially crucial for nuclear medicine and hadrontherapy centers located in densely populated areas, in which GPM models might significantly overestimate radiation exposure. The model includes a chimney releasing radioactive gases together with adjacent buildings of an urban agglomeration of a hadrontherapy center. Accurate meshing of the domain for the CFD-simulation has been considered with settings of refinement size for calculation cells near the obstacle surfaces. The study focuses on comparisons between Gaussian plume and fluid dynamic models to assess their performance at both short and long distances. The Reynolds Averaged Navier-Stokes equations and the k-ω turbulence closure model are used 2 and adapted in order to consider atmospheric stability, temperature stratification, and ground roughness effects. Numerical results have been obtained by considering various stability atmospheric conditions. Comparisons with the Huber approximation are reported.

1 Alan H. Huber, "Evaluation of a method for estimating pollution concentrations downwind of influencing buildings", Atmospheric Environment, 18(11), 2313-2338, 1967.
https://doi.org/10.1016/0004-6981(84)90003-9
2 Breedt, H. J., Craig, K. J., & Jothiprakasam, V. D. (2018). Monin-Obukhov similarity theory and its application to wind flow
modelling over complex terrain. Journal of Wind Engineering and Industrial Aerodynamics, 182, 308-321.

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Diagnostic beam dump design for the EuPRAXIA@SPARC_LAB project

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EuPRAXIA is the first European and world-wide project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology. The project EuPRAXIA@SPARC_LAB, which will be built at the Frascati National Laboratories, aims at constructing a FEL radiation source based on RF linear accelerator combined with a plasma module. The linear accelerator consists of two fundamental components: a 3 m long accelerating cavity in S-band located at the beginning of the line, which accelerates electrons up to 300 MeV, and a subsequent series of 8 X-Band accelerating structures that allow accelerating the primary beam up to 800 MeV, in an intermediate section of the line, and up to 1.2 GeV at the FEL entrance. According to the design parameters, the EuPRAXIA@SPARC_LAB FEL will provide more than 1011 photons/pulse with a pulse duration of less than 50 femtoseconds. A wide class of experiments will benefit from these brilliant, soft X-ray FEL pulses using X-ray absorption and emission spectroscopies and X-ray resonant Raman scattering. The energy range of this FEL beam will allow performing spectroscopic experiments looking at the K-edges of "light"atoms, such as carbon and nitrogen, and at the L-edges of "heavy"atoms, including some 3d transition metals.
In this work, some of the radiation protection studies conducted for the realization of the authorization procedure are reported, focusing particularly on the diagnostic beam dumps design placed along the LINAC, which are used in alignment operations and primary beam studies.
Part of these studies, performed by the Monte Carlo code FLUKA, involves the analysis of three different cases corresponding to the different energies that can be reached during acceleration (300, 800, and 1200 MeV). The spatial distributions of the photon and neutron ambient dose equivalent were estimated through Monte Carlo simulations, assuming scenarios of interaction between the primary electron beam and the diagnostic beam dumps. The structure of the proposed dumps was designed to achieve ambient dose equivalent values below 1 μSv/h in areas near the bunker, thus enabling their classification as freely accessible areas or, at most, as supervised areas, according to the provisions of the current national regulations (Legislative Decree 101/2020).

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Development of TLD thermo-luminescence dosimeters by doping with a rare earth element

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Dosimeters based on thermoluminescent materials are an optimal solution over an extended range of applications.This work has been motivated by the difficulty, in my country, to access industrial TLD dosimeters on the international market, and by the resulting need to develop solutions that rely

on local available and possibly cheap materials, without missing the goal to reach a high sensitivity, linear dose response, low background and low rate of fading.
We developed a method to prepare Dysprosium doped calcium sulphate (CaSO4:Dy) dosimeters, and we investigated the response of the TLD at different Dy concentrations. The manufactured samples were exposed to a Cs-137 source at doses up to 20 mGy. and the glow curves of the undoped and doped samples were studied.
The results showed an ideal thermal brilliance curve with a good peak of brilliance for all concentrations taken, which range between 0.07 mol% and 0.4 mol%, and for all doses.
CaSO4:Dy is therefore confirmed as good solution to prepare not expensive TLD dosimeters for a wide range of dosimetry purposes.

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Source terms for the HED science in short-pulse experiments with solid target, and further perspectives

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In the facilities dedicated to the investigation of the matter under extreme conditions, without production of accelerated proton/ion or electron beams, the radiation protection assessment is primarily driven by the electron dynamics in the plasma. In the case of ultra-short relativistic laser pulses hitting a solid target, the radiation source term is given by the electrons escaping from the sheat field in the target, coupled with the pure Bremsstrahlung produced by the electrons recirculating within the sheat field. At the Helmholtz-Zentrum Dresden-Rossendorf, after a previous simulation and experimental work (presented at SATIF-15) done to characterize the pure Bremsstrahlung component, the developed radiation concept has been applied to assess the radiation protection for the next generation of experiments at the HED Instrument at the European XFEL.

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Shielding and activation experiment in the downstream of the JLAB beam dump with several GeV electron beam

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For advanced shielding design of high energy electron accelerators, accuracy of nuclear model and data base used in the theoretical simulations should be validated with the experimental data. For this purpose, shielding and activation experiment with secondary particles generated from the beam dump was performed using 2.2, 4.3, 6.4 and 8.45 GeV electron beams at JLAB. The beam dump consists of aluminum and circulated water coolant. In the concrete shield upstream of the beam dump, there are three vertical penetration holes reaching the beam line level 10 m down from the ground level. The concrete shield thicknesses at the three holes are 91, 273 and 570 cm, and aluminum or graphite activation samples were placed in the penetration holes during the irradiation. After the irradiation, gamma rays from the produced radionuclides of Na-24 from aluminum and C-11 from graphite were measured and attenuation profiles of the production rates through the shield were experimentally obtained. Monte Carlo simulations with the experimental conditions were also performed, and they were generally agreed within a factor of 2.
This experiment project is performed as the collaboration between KEK and JLAB under the support by the USA-DOE.

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Advanced features of ALEPH2 depletion code applied to radioprotection of nuclear facilities

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The SCK CEN in-house ALEPH2 depletion code is designed to combine the Monte Carlo codes (MCNP or PHITS) for spectral calculations with the advanced depletion module realizing RADAU5 implicit Runge-Kutta algorithm for evolution calculations. The versatility of the code allows using it for time behavior simulation of various systems ranging from one single pin model to full-scale models of conventional reactors, accelerator driven systems and high energy proton accelerators. The radiation protection calculations of two world-renowned projects of SCK CEN (MYRRHA and RECUMO) rely on the ALEPH2 code. Besides that, in several running projects ALEPH2 is a key code for characterization of nuclear waste (CHANCE project), decommissioning calculations of end-of-life projects for nuclear plants (e.g., BR3 reactor), cyclotrons (e.g, 40 MeV Medical Cyclotron of VUB in Brussel), hot cells, laboratories and etc.
ALEPH2 has several advanced features making it attractive and user-friendly among other depletion codes. An important feature in terms of user's convenience is automatic generation of MCNP input files with the delayed particle spectra from previous irradiation or decay steps. The delayed particle spectra are used as new source distributions for subsequent delayed radiation transport calculations to obtain biological dose due to alpha, beta and gamma radiation in most accurate way.
This work summarizes the features and example applications of ALEPH2 code.

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Decay Heat and Radionuclei inventory in ISIS TS1 target: measurements in tungsten core and tantalum cladding based on 2 dif-

ferent experimental methods and comparison with FLUKA predictions

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The TS1 spallation target operated at ISIS between 2014 and 2019 for the production of neutrons by high energy protons (700-800 MeV) is made of 12 tungsten plates cladded with tantalum and water-cooled. Residual radioactive nuclei can be produced in the target either as a direct product of the spallation process or as a result of secondary low energy neutron absorption.
This work presents the indirect measurement of the decay heat deposited in the tungsten core and tantalum cladding of each ISIS TS1 target plate, by using two different experimental approaches: the first one, for the tungsten core, is based on the temperature rise measurement by thermocouples located in the centre of each plate and the second one, applied to the tantalum cladding, is based on the gamma spectrometry measurements. The experimental assessed values have been compared with the Monte Carlo FLUKA-CERN predictions at different cooling times, showing a good agreement for both the tungsten core and the tantalum cladding. This benchmarking gives confidence in the FLUKA model we built to predict measurable physical quantities relevant for the engineering thermal design of the target/reflector and moderator (TRAM) assembly. In addition, it also provides indirect evidence of the accuracy of the simulated spallation physics and neutron interaction through all the TRAM assembly.

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Multi-Probe Tomography for Scientific Applications and Nuclear Safeguards

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Advanced diagnostic imaging techniques like tomography have become indispensable within scientific experimentation in fields such as applied nuclear physics and studies of condensed matter. Multi-probe tomography represents a cutting-edge modality that utilizes a range of probes, spanning from keV to MeV X-rays, thermal to MeV neutrons, electrons, protons, and more. As these various probes interact differently with matter, they provide complementary information, enabling accurate extraction of key observables such as material identifications, densities, and their distributions in the items. The realization of multiprobe tomography has been made possible through the parallel development of sophisticated algorithms for data fusion, including reconstruction from sparse data sets encountered in experiments with limited viewing angles. In this presentation, we will delve into the concept of multiprobe tomography and its practical applications. We will discuss our results of dual-probe tomography (neutron and X-ray) for studying the electrochemical features of Zn-based battery technologies. Based on that, we will then discuss the applicability in nuclear safeguards and nonproliferation, and in other relevant scientific fields.

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Ultrafast instabilities in shortpulse laser-solid interactions revealed by XFEL measurements and particle-in-cell simulations

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Ultra-intense lasers that ionize atoms and accelerate electrons in solids to nearly the speed of light can lead to kinetic instabilities that alter the laser absorption and subsequent electron transport, isochoric heating, and plasma expansion. These instabilities can be difficult to characterize, but a novel approach using X-ray scattering at keV photon energies allows for their visualization with femtosecond temporal resolution on the few nanometer mesoscale. Our experiments on laser-driven flat silicon membranes show the development of such structures on these previous unaccessble scales, which is relevant e.g. for laser particle acceleration, inertial confinement fusion, and laboratory astrophysics.

Combining the XFEL experiments with particle-in-cell (PIC) simulations provides a rich picture of the structural evolution of ultra-fast laser-induced plasma density development, indicating the excitation of plasmons and a filamentation instability. I will briefly introduce the concept of PIC simulations and present results that confirm that the measured signals are due to an oblique two-stream filamentation instability.

Future developments include a combination of several XFEL probe methods, e.g. resonant scattering, imaging, or spectroscopy, that require advancements in modeling the plasma ion excitations in PIC. I will briefly touch on our latest addition of an atomic physics module in PIConGPU that form the basis for such capabilities in the near future.

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Forty years of neutron activation in the ISIS Target station 1 monolith

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December 2024 will mark 40 years since the first operation of the ISIS spallation neutron source. Whilst many components have been changed and updated the Target station 1 void vessel and shielding monolith have remained in place throughout that time. This makes these components some of the most irradiated in a spallation spectrum in the world. It is important to understand the neutron activation and damage to inform lifetime assessments with ISIS planning to operate until to 2040s and to inform eventual decommissioning activities.
As well as the steel void vessel, steel monolith inner shielding and concrete outer shield there are also various penetrations and ducts for engineering services as well as the instrument beamlines and heavy shutters.
A new Monte Carlo model has been built using the most accurate CAD model available to include all these features and allow the most accurate calculations of neutron activation to be performed. The CAD to Monte Carlo geometry conversion has been performed using GeoUned which allows conversion to MCNP, OpenMC and PHITS compatible geometry.
Given the very thick shielding significant variance reduction methods are needed to reduce the statistical uncertainty. A variety of global variance reduction methods have been tried to develop global weight windows along with targeted variance reduction methods for some of the penetrations.
One of the issues with older facilities is the loss of information such as material specifications or even drawings of some of the component details. As a result there was also a need to perform sensitivity calculations for different impurity levels in the steel.
Many of the heavy shutters have been changed over time as instrument requirements have changed. As they are movable components they see different neutron irradiation conditions in terms of flux and spectrum in different positions.

This talk will give an overview of the history of the monolith irradiation by different neutron targets, calculations of neutron activation, dose rates and radiation damage rates. It will also discuss the approach for moving components such as the heavy shutters and the use of facility operations data to inform the irradiation history for use in the neutronics calculations.

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