Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro, April 11th-12th 2022

Nuclear Physics
Mid Term Plan in Italy

Development, characterization and modifications of materials for applied nuclear physics

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- Introduction
- Ion beam micro-analysis for nuclear targets development and cross section measurements for applied nuclear physics
- Ion-solid interaction and radiation damage of materials, detectors and devices
- Novel detectors development and test
- Conclusions

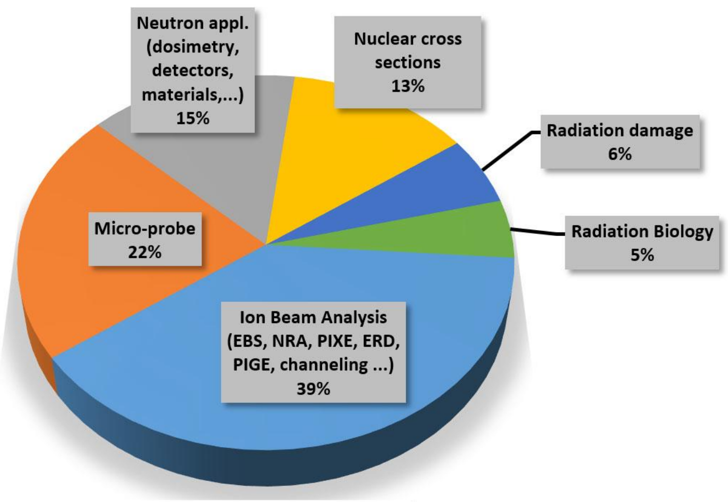
PRESENTATION TARGETS:

- Highlight our researcher knowledge improved in several years of work
- Actual experiments and future research perspectives
- Highlight the strong experience interconnections

Due to the large number of people involved in interdisciplinary experiments, in this presentation will be reported only some examples of activities carry out at LNL facilities based on Van der Graaf accelerators.

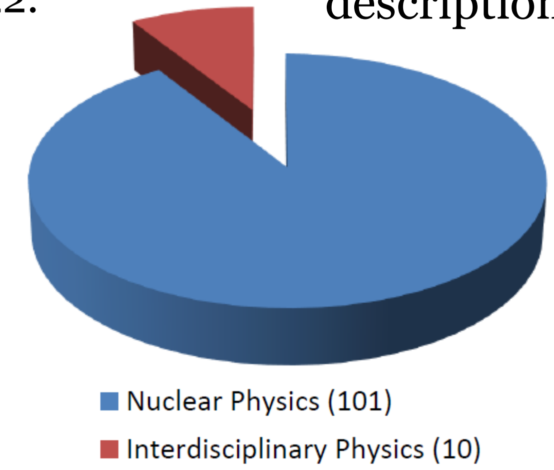
Average beam time (2016-2020) ~1000hr/year for each facility
Experiments proposed in 2022: **14@AN2000 and 17@CN**

AN2000 and CN beam time description



Experiments in 2022: **9 (~10days)**

TAP beam time description



Involved communities:

- LNL activities involve several communities interconnected to Nuclear Physics
- The **symbols** for different communities showed in each topic discussed in this presentation, want highlight the **strong interconnections of our researches**.

Nuclear Physics Community

Astrophysics Community

Electronics & Devices Community

Medical Community

Aerospace Community

Quantum Technology Community

Environmental & Geological Community

Cultural heritage Community

- Introduction
- **Ion beam micro-analysis for nuclear targets development and cross section measurements for applied nuclear physics**
    - **Targets production and IBA facilities**
- Ion-solid interaction and radiation damage of materials, detectors and devices
- Novel detectors development and test
- Conclusions

LNL Target manufacturing facilities

INFN experiments

LNL Target Service
- Evaporation
- Rolling

ISOL
- Sintering
- Additive manufacturing

LARAMED
- SPS
- HIVIPP

SALVIA
- Sputtering

Nuclear experiments

ISOL target

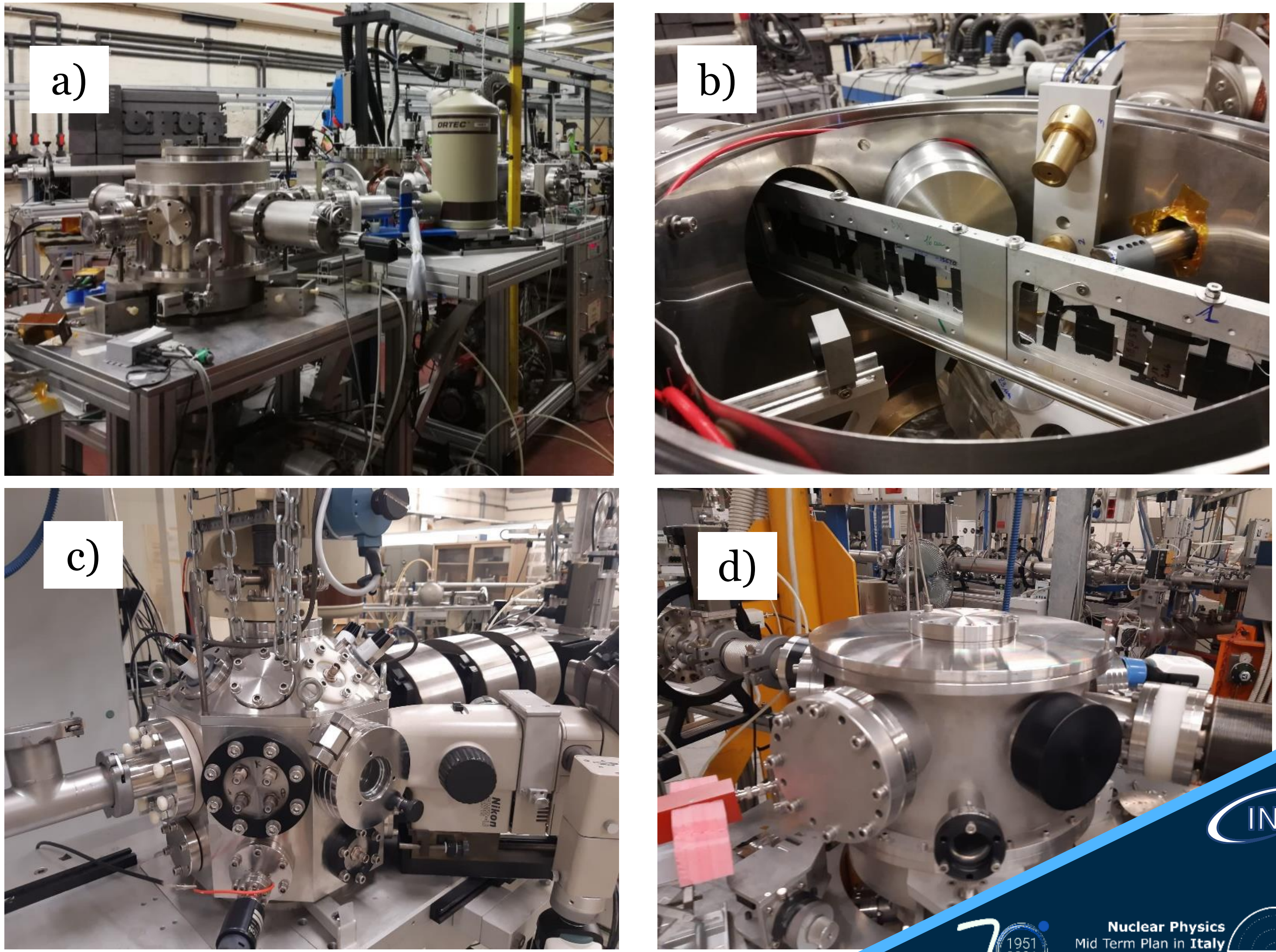
Medical and nuclear applications

Astrophysics

IBA facilities for nuclear target characterization

- ➢ quantitative determination of composition
- ➢ thickness measurements in terms of dose (at/cm²)
- ➢ depth profiles analysis

- ✓ non-destructive
- ✓ High accuracy and resolution



-15° beam line at CN facility [a), b)]
- EBS analysis
- PIXE analysis
- PIGE analysis

0° beam line (μ-beam) at AN2000 facility [c)]
- EBS analysis
- PIXE analysis

60° beam line at AN2000 facility [d)]
- EBS analysis
- ERDA analysis

- Introduction
- Ion beam micro-analysis for nuclear targets development and cross section measurements for applied nuclear physics
  - IBA: Some experiments
- Ion-solid interaction and radiation damage of materials, detectors and devices
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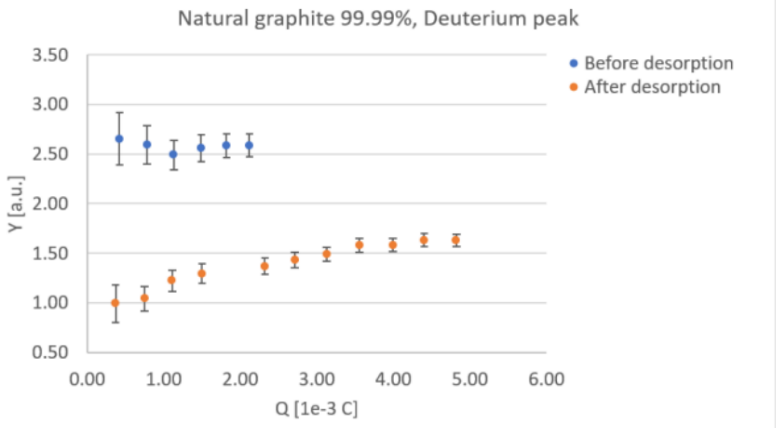
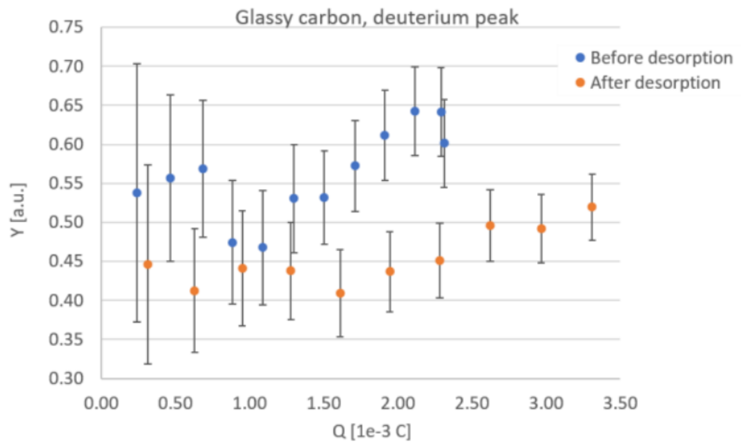
HEAT: Hydrogen dEsorption from cArbon Targets

INFN Grant for young researcher (CSN5 2018-2019 Rosanna Depalo)

- Study the Hydrogen desorption after a high temperature heating (up to 1200°) in different carbon substrate (graphite and glassy carbon)
- The ^{12}C- H reactions induces strong BIB that will compromise the xSm
- The Hydrogen reductions is mandatory for $^{12}C+^{12}C$ fusion cross section measurement (foreseen at LNGS LUNA-MV facility)
- ERDA and NRA $^{2}H(^{3}He,p)^{4}He$ analysis before and after heating for evaluation of hydrogen desorption



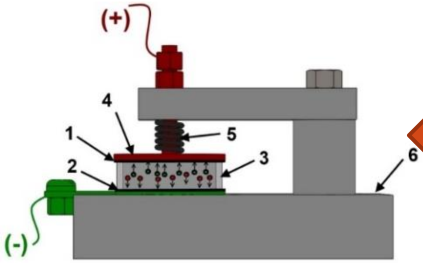


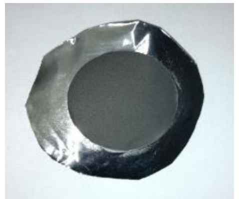
- **Next step: investigation of H desorption in HOPG (high oriented pyrolytic graphite) and other substrates**

HIX: characterization of HIVIPP targets for REMIX project

- HiViPP (High energy Vibrational Powder Plating) **new deposition technique**:
  - Compositional and dose measurements of all produced targets (process setting)
  - Targets are used for nuclear cross section measurements
  - IBA quantitative analysis are **essential** for nuclear cross sections measurement

HIVIPP technique

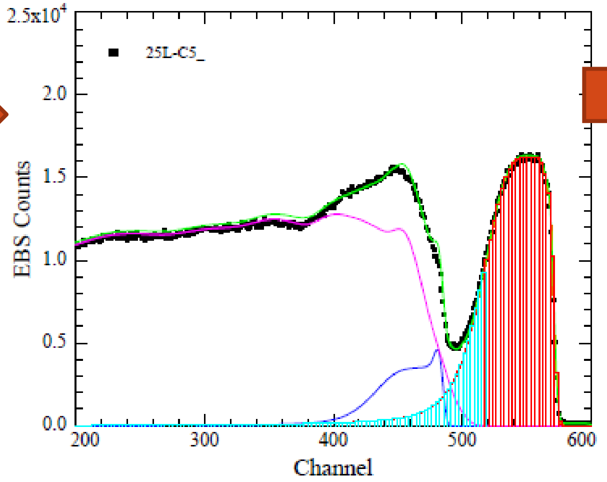




200-1000 μg/cm²

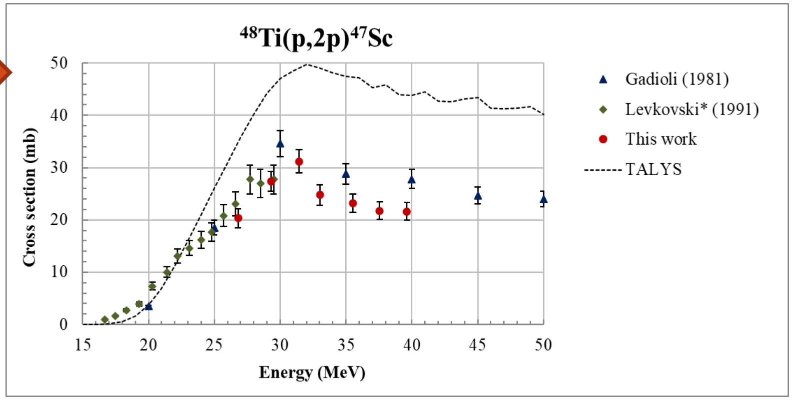
LNL (LARAMED)

IBA quantitative analysis



LNL
AN2000 and CN facilities

Nuclear cross section measurement



Actually irradiated @ ARRONAX
Next step @ SPES

Interested isotopes: **^{48}Ti, ^{49}Ti, ^{50}Ti** for **^{47}Sc** radionuclide and Gd for **Tb** radioisotopes

DES: Deposition of Elements on Substrates

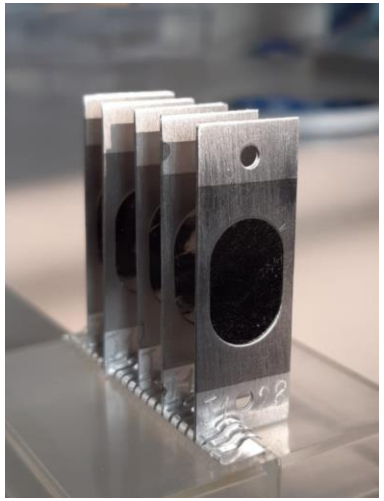
NUMEN, based in LNS-INFN,

- Measure the cross sections of Double Charge Exchange reactions
- Neutrinoless Double Beta Decay experiments to evaluate the Nuclear Matrix Element of the decay.

Target deposition~400nm

Buffer layer ~10nm

Highly Oriented Pyrolytic Graphite (HOPG) substrate 2μm



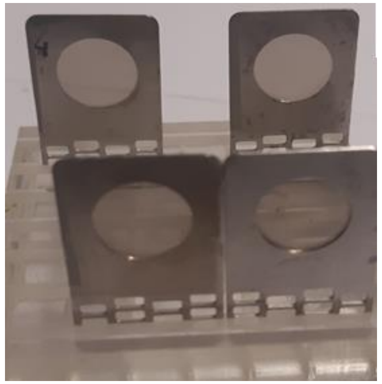
Analysis of:

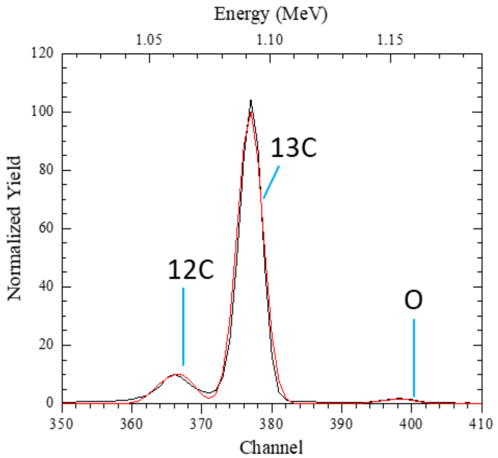
- average thicknesses of target, buffer and substrate can be evaluated at the same time
- elemental composition of the whole target system Target system prototypes characterized: Ge, Sn, Te, Se, Mo, Ca, HOPG substrates

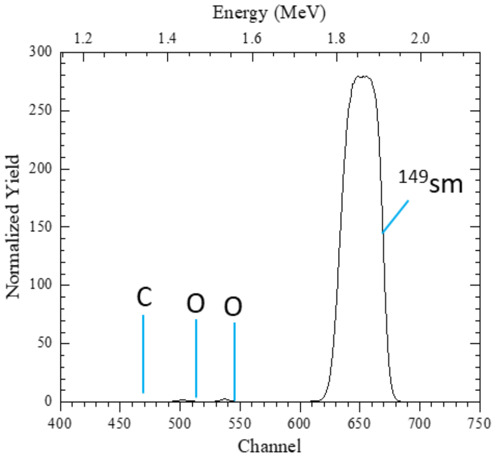
ANT: Advances Nuclear Target

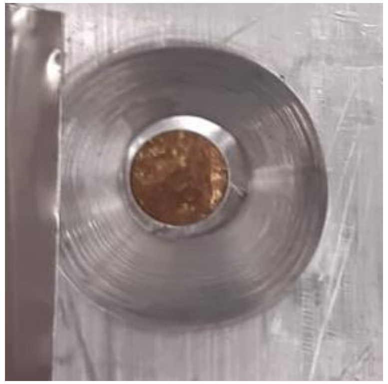
LNL "Targets for nuclear physics Laboratory" support:

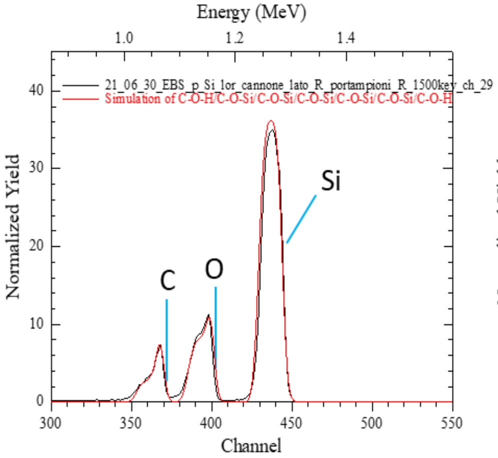
- target characterization, focusing on composition and layering of contaminants, in order to improve target production process

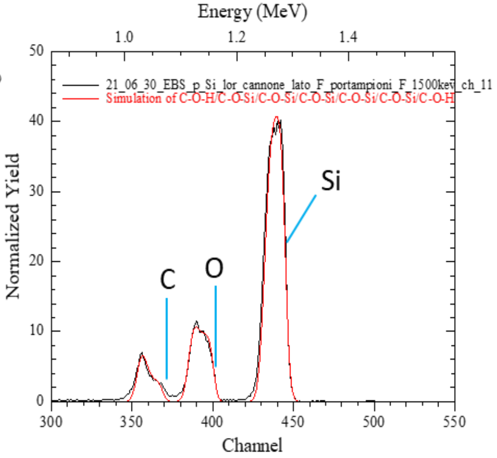












Further implementation:

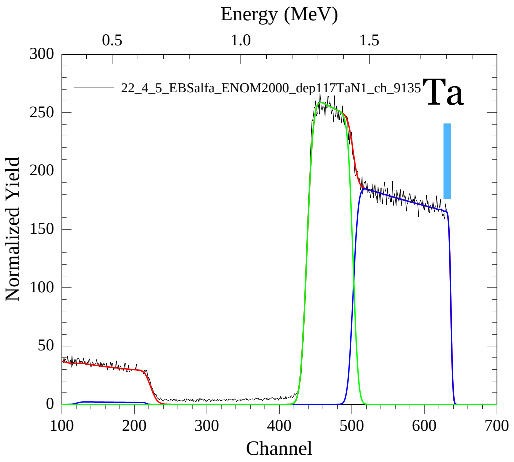
- **Dedicated beam line**
- **Integration of NRA and PIXE analysis**
- **Define a standard characterization procedure**

ANT: Advances Nuclear Target

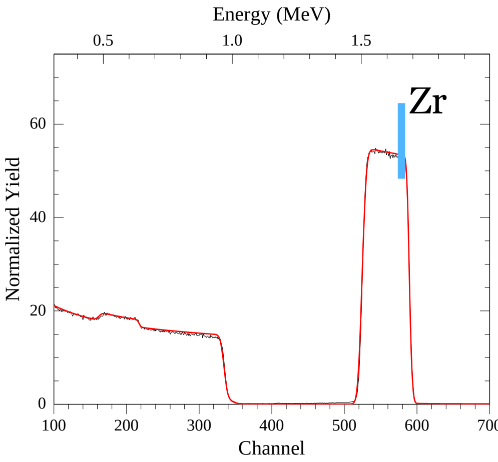
Nuclear target development and characterization in framework of **LUNA collaborations:**

- **Targets preparation for LUNA experiments** (nitrides, oxides, high purity metals)
- **Treatment and characterization of substrates** for contamination and γ background reduction (F,D,O,C…)
- Design and synthesis of single and nanostructured targets for **LUNA-MV (LNGS)** with low beam induced background (γ and neutrons)

High-Z metals nitrides for reduction of neutrons production for LUNA-MV

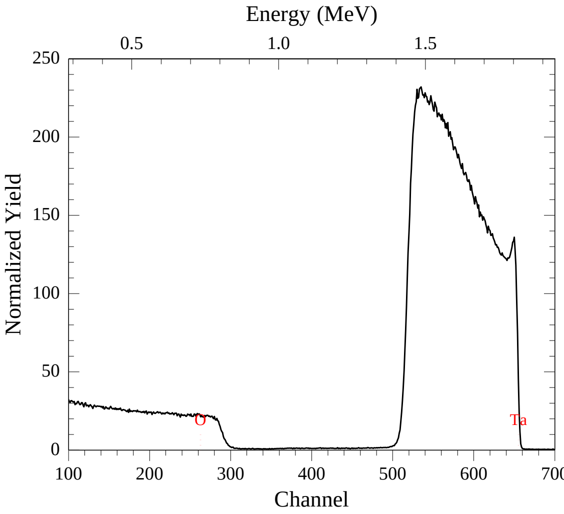


TaN 1320 atoms/cm²
deposited on
780 atoms/cm²
of high purity Ta interlayer
Silicon substrate

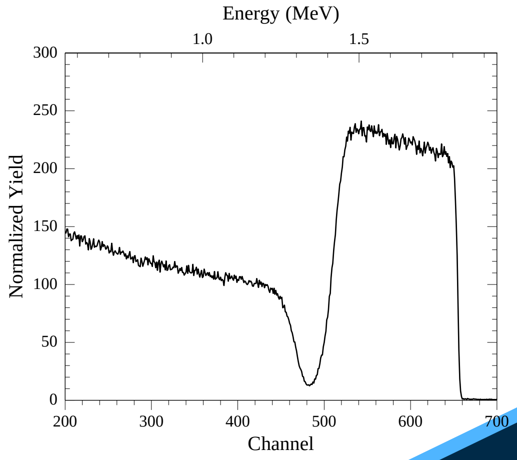


ZrN 1410 atoms/cm²
deposited
without interlayer
Silicon substrate

High purity Ta thick coatings for Fluorine contaminations reduction (γ background reduced ~10 times early tests at LNGS)



Multilayer for deuterium free backing in high purity metals (preliminary tests at LNGS)

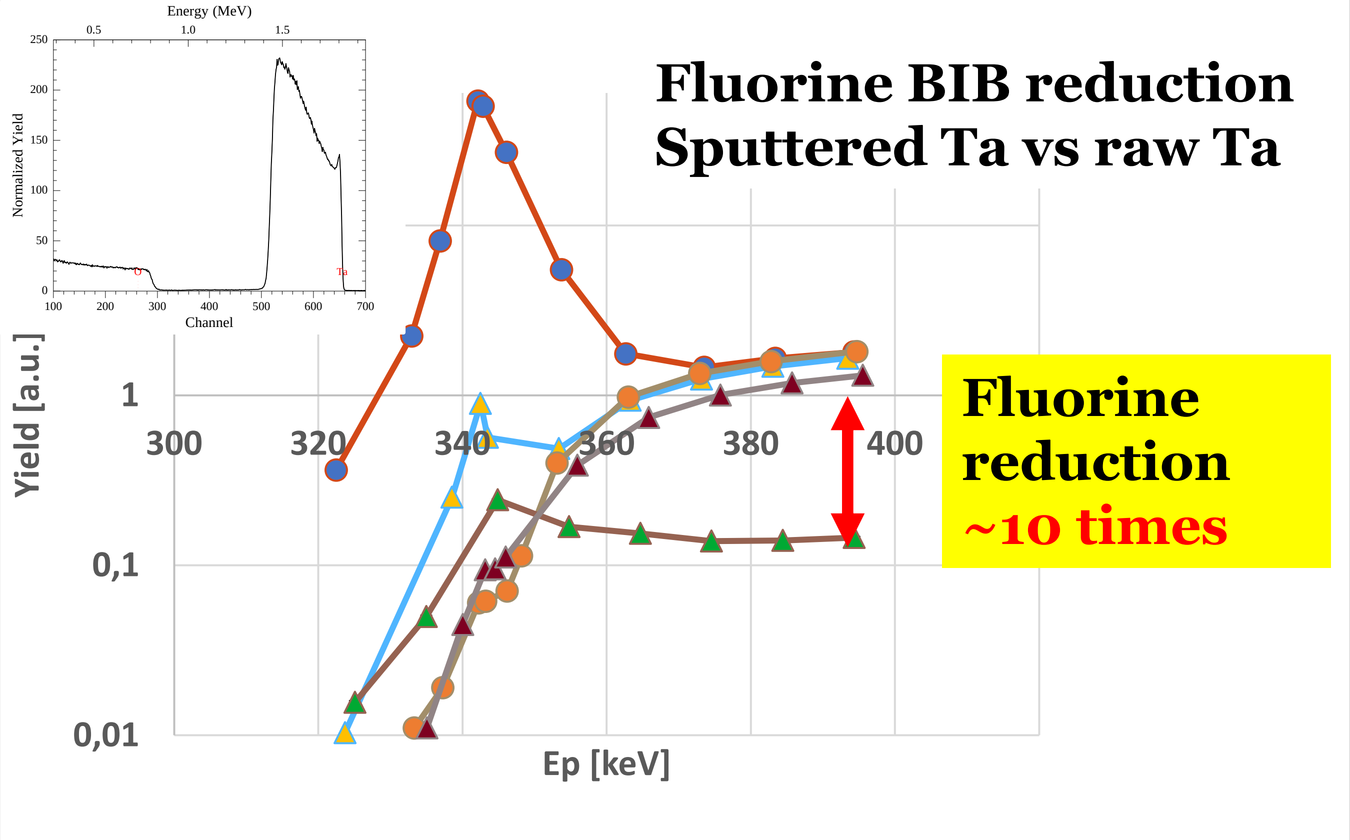


ANT: Advances Nuclear Target

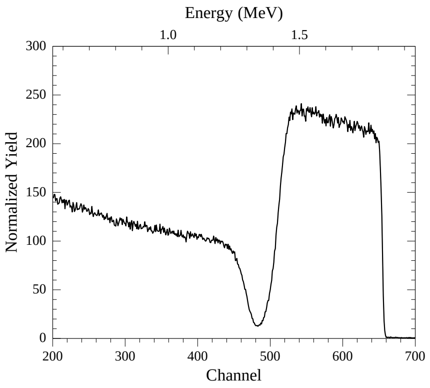
Nuclear targets development and characterization in framework of **LUNA collaborations:**

Contamination reductions: early results @LUNA400 (LNGS)

High purity Ta thick coatings for Fluorine contaminations reduction (γ background reduced)



Multilayer for deuterium free backing in high purity metals



Deuterium reduction Sputtered Me vs raw Ta backing

Ep [keV]	Target	RT [h]	Counts	Err	Yield [c/C]	Err
121	Ta	12.77	16	4	1.66	
121	Mo/Ta	13.23	4	2	0.44	

x 4

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  - IBA: cross sections measurements
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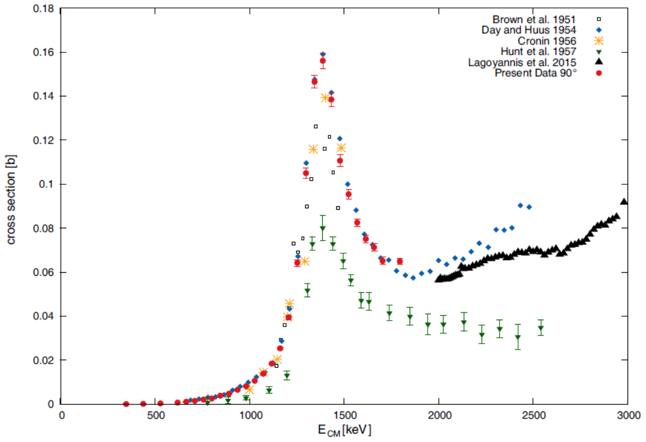
IBA: Cross section measurements for applied nuclear physics

Request:

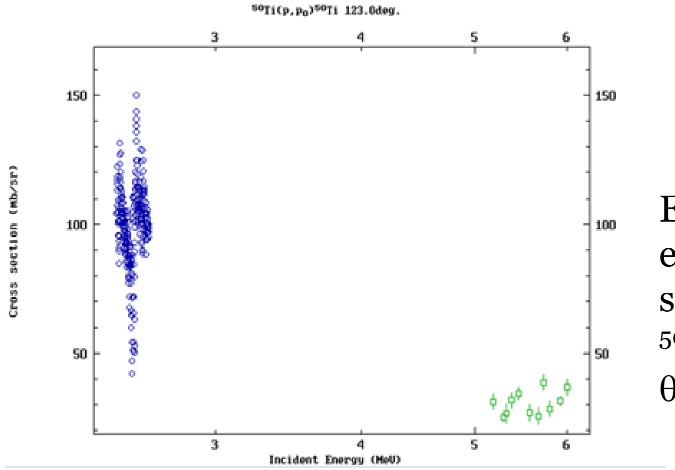
- Constant growth of isotope enriched nuclear target characterization with thickness up to ten microns (target for radioisotope production LARAMED, E-PLATE, REMIX, PASTA, COME)
- Accurate characterization of target for nuclear physics

EBS problems:

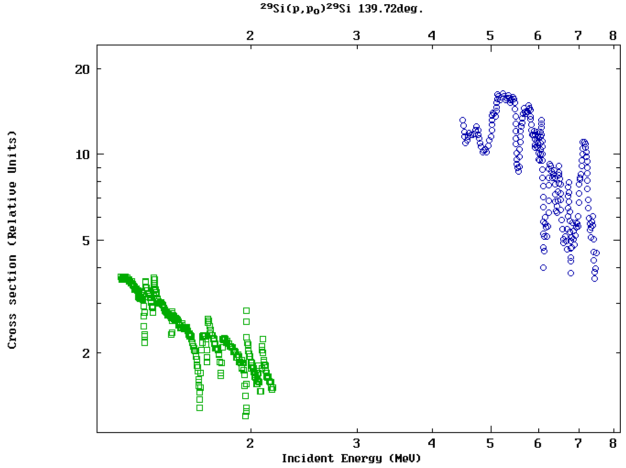
- Analysis of thick target (order of ten micron) required a full knowledge of proton elastic cross section for EBS analysis in up to 6MeV beam energy range.
- Lack of proton cross sections data in literature (energy and angle).
- Presence of large deviation from Rutherford, with resonances



$^{10}B(p, \alpha_1\gamma)^7Be$ cross section measured AN2000
Eur. Phys. J. A (2019) **55**: 171



Experimental elastic cross sections data of $^{50}Ti(p,p)^{50}Ti$ θ(123°)

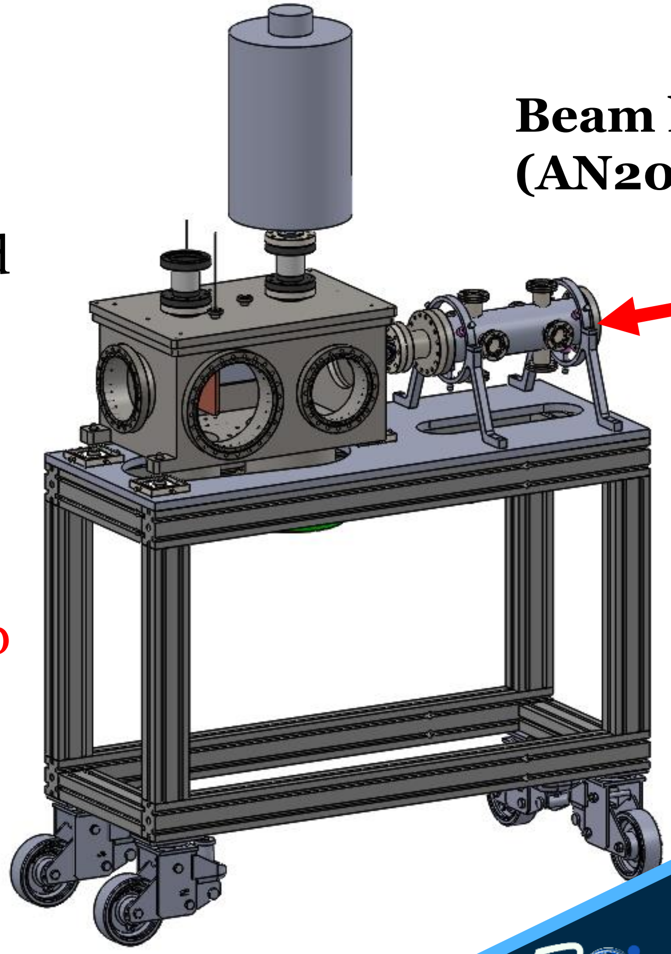


Experimental elastic cross sections data of $^{29}Si(p,p)^{29}Si$ θ(140°)

SALVIA: Setup for AnaLysis with MeV accelerators of Isotopic tArgets and their preparation

INFN Grant for young researcher (CSN5 2021-2022)

1. Characterization of nuclear targets (EBS, NRA and PIGE)
2. Study and measurement of unknown nuclear cross sections (EBS)
3. Ion beam calibration of actual accelerators (AN2000-CN) and new accelerator



Beam line (AN2000 and CN)

Chamber features:

- Up to 4 Si detectors with different orientations for EBS and ERDA measurements
- Cryogenic electrostatic electron suppressor for carbon build up reduction and high accuracy integrated charge measurements
- Polarizable sample holder)-> high resolution beam energy scanning (≈ 50eV in ±3.5KeV)
- XYZ + θ sample holder, up to 4 samples each run
- Integrated sample cooling system

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  - **Experiments**
- Novel detectors development and test
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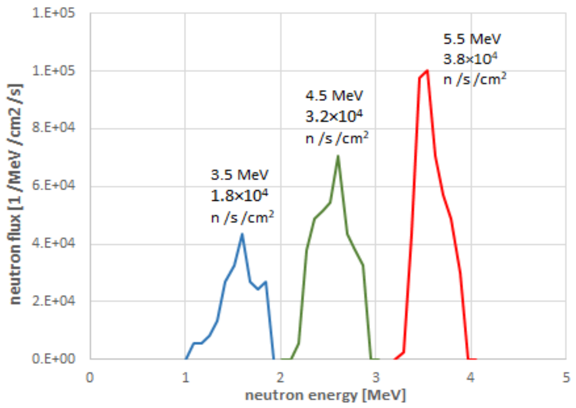
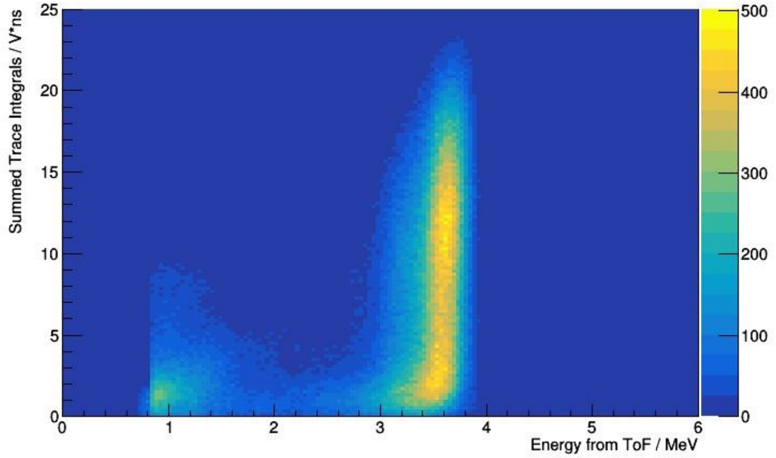
BELINA: QMN neutron beam source

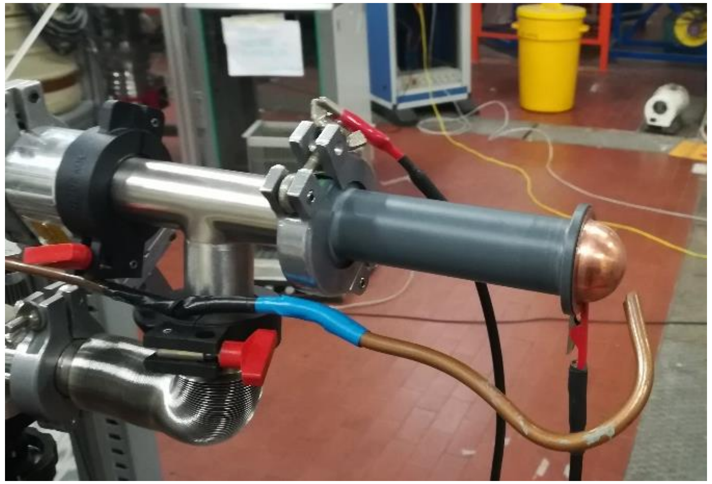
CN 0° beam line: protons on a thin (>20 μm) lithium target produce quasi mono-energetic (**QMN**) neutron beams with gaussian-like energy distributions

Simulated neutron spectra for different proton beam energies with 3 μA currents



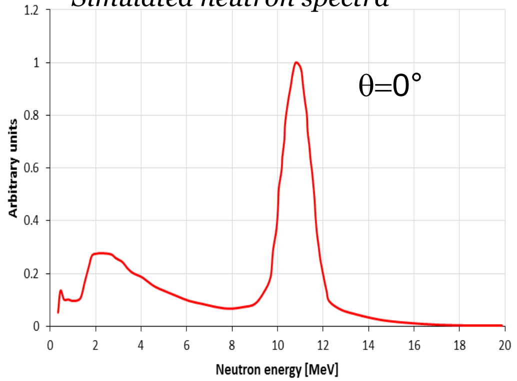
Experimental Energy spectra at 5 MeV proton on 50 um thick Lithium target



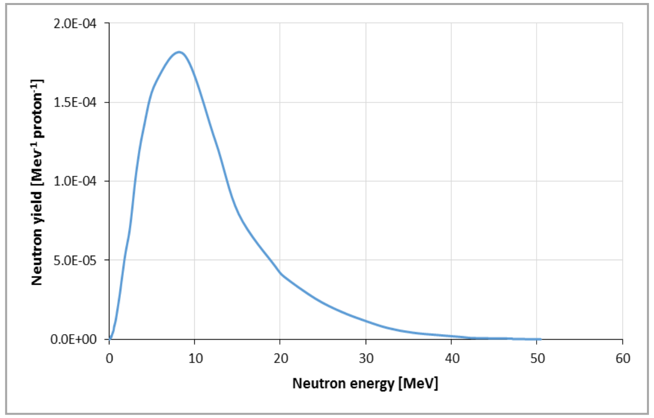


Tandem: further development of high energy neutron beams using inverse reactions

Simulated neutron spectra



- $^{1}H(^{11}B,n)^{11}C$ and
- $^{1}H(^{15}N,n)^{15}O$ nuclear reactions
- Gaseous H_2 target
- 5-14MeV neutron energy
- Flux: 4×10^4 n cm^{-2} s^{-1}

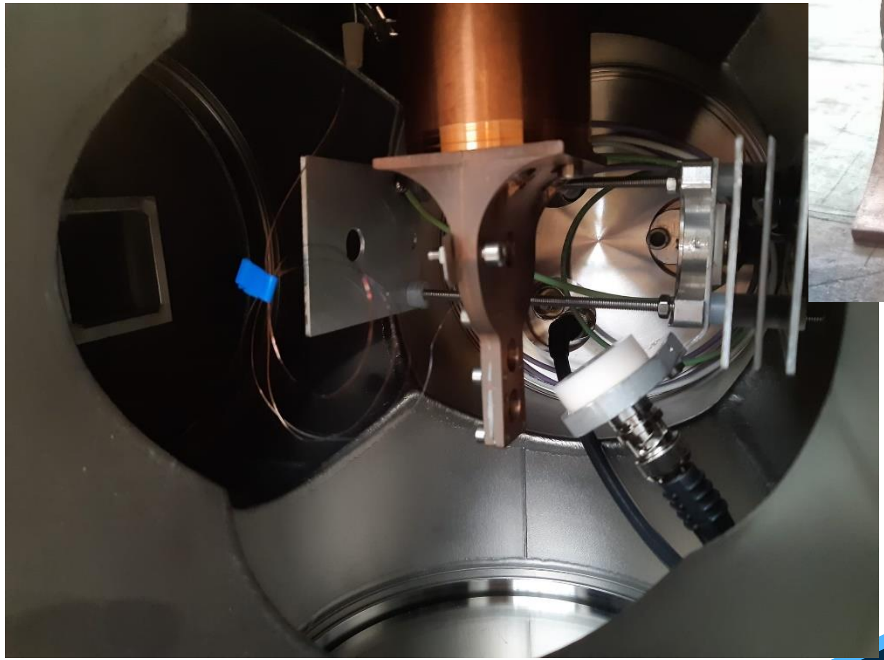


- $^{7}Li(^{14}N,n)^{20}Ne$ nuclear reaction
- 100 MeV ^{14}N beam on lithium thick target (5mm)
- wide continuous energy distribution in 3-20MeV range
- Flux: ~10^4 n cm^{-2} s^{-1}

HERETIC: HEat REsistance Test for Irradiated Cooled targets

Aim:
Test a new kind of thin, isotopically enriched target (~400 nm), backed by a 2 μm thick HOPG layer, suitable for **heavy ion beams with high intensity**.
The target has been developed within the **NUMEN Project**, in which Double Charge Exchange reactions will be studied with intense beams (~ 10^{13} pps).

Experiments:
Dedicated chamber has been designed for endurance test on novel targets.
A ^{16}O beam (1 μA), accelerated at 50 MeV by the TANDEM, will deposit the same power of NUMEN beams (~2 W) in the target/HOPG assembly. It will be used to test the thermal behavior of different targets under irradiation (Te on HOPG, Ge on HOPG, HOPG). **Radiation damages** in the target and in the backing will be evaluated as well.



- Introduction
- Ion beam micro-analysis for nuclear targets development and cross section measurements for applied nuclear physics
- **Ion-solid interaction and radiation damage of materials, detectors and devices**
  - ➢ **Irradiation facilities**
- Novel detectors development and test
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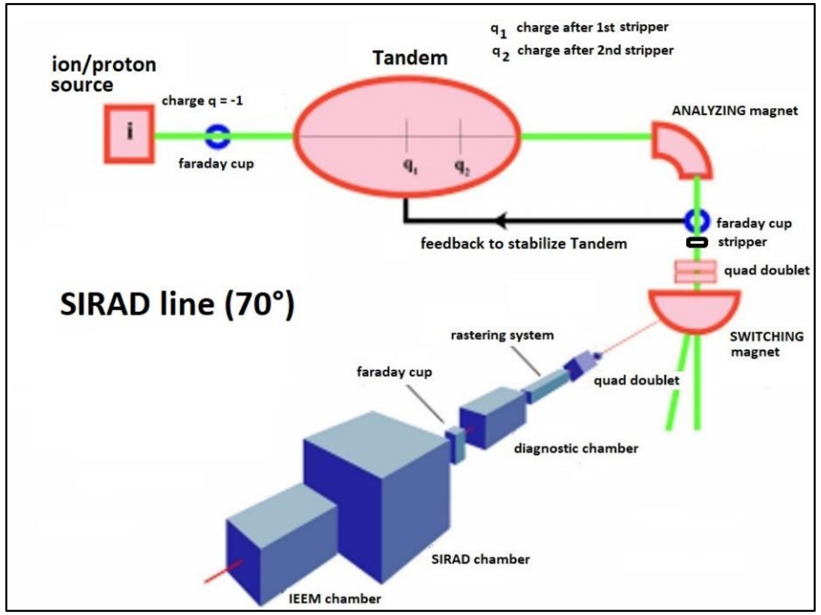
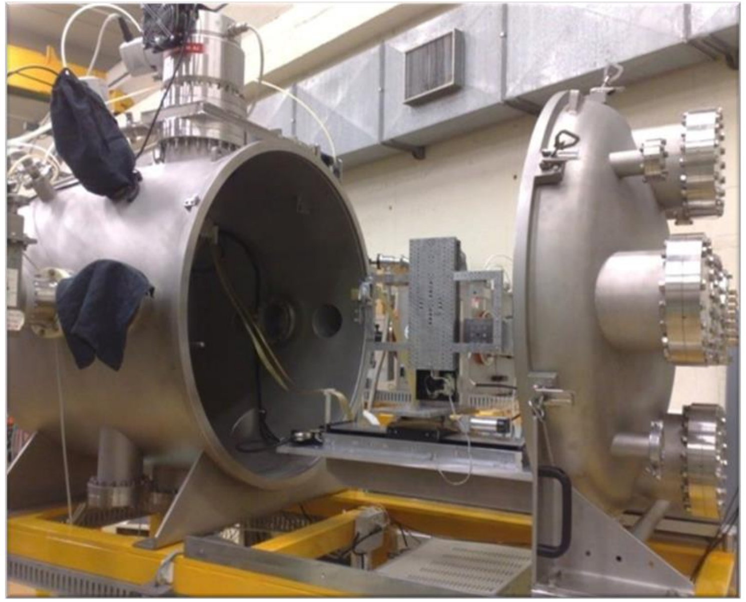
SIRAD irradiation facility at Tandem-ALPI complex





Light and heavy ion beams

Several upgrades:

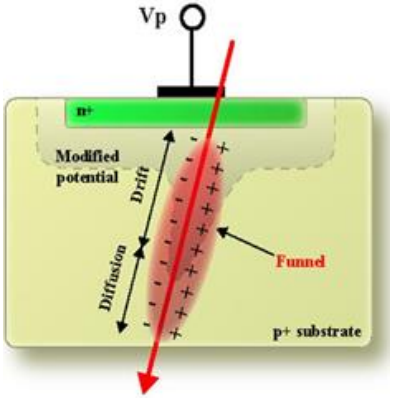
- Ion Electron Emission Microscope
- Post-acceleration stripping system

SIRAD irradiation facility at Tandem-ALPI complex

Experiments aims:
- Study irradiation effects on electronic components and material damage
- Improve endurance characteristics in detectors and electronic device
- Test next generation of detectors

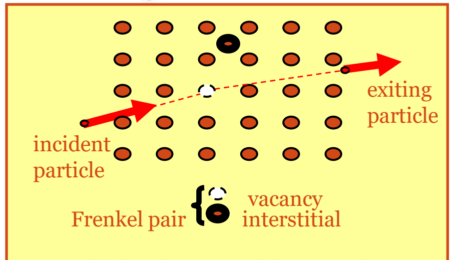
SEE - Single Event Effects

- Effects due to the passage of a **single** energetic ionizing particle
- Sudden large $\Delta E_{ionization}$ deposited in the “wrong” place at the “wrong” time (sensitive junction)



DDD - Displacement (Bulk) Damage Dose

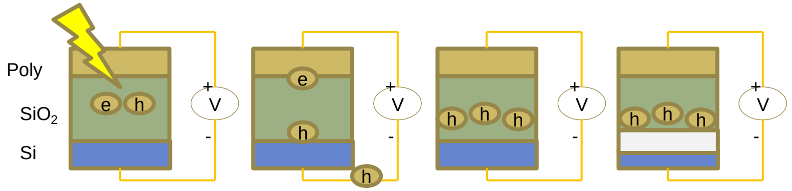
- Non-ionizing ΔE transfers to atomic nuclei (Coulomb nuclear interactions).
- Accumulation of displacement damage of lattice



Interstitial and vacancy defect creation.

TID - Total Ionizing Dose

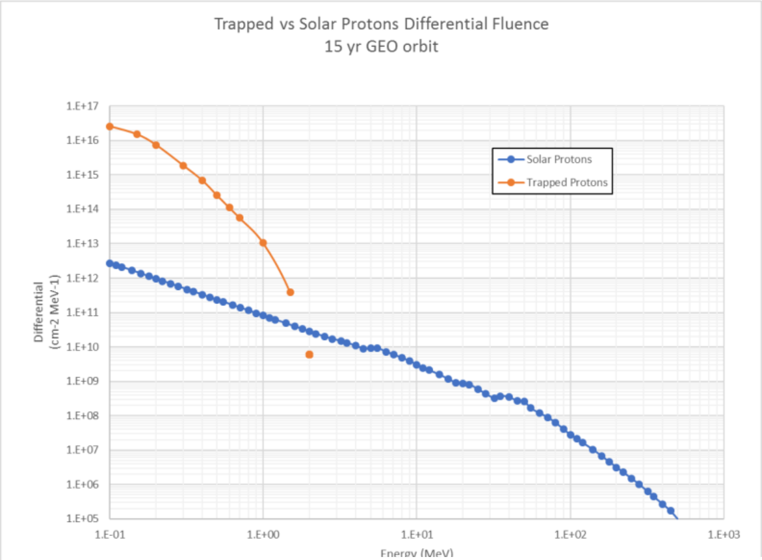
- Small $\Delta E_{ionization}$ deposited uniformly and delivered over a long time
- Accumulation of charge in SiO_2



6 different experiments approved in 2022:
- LiteBIRD
- FALAPHEL
- LiTE-DTU
- FAIRnet
- ARCADIA
- RReact

People involved: ~50

ASIF: ASI Supported Irradiation Facilities



BEAM FEATURES:

- Monochromatic Beams: 1H+, 4He+
- Energy: 0.2÷5.5 MeV
- Standard Beam Size: 2÷8 mm (FWHM)
- Beam Current: 1-400nA (typical)- (>400nA, <2μA energy dependent)

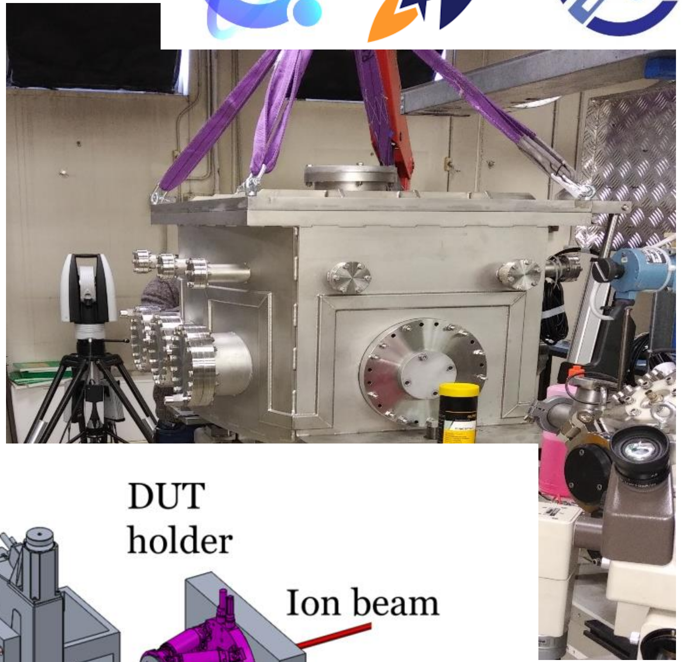
IRRADIATION OBJECTIVES OF THE NEW FACILITY

- Large area uniform irradiation of spacecraft materials and components in a wide range of energies and fluences
  - Fluence: $1x10^{9} \div 10^{16}$ cm^{-2}
  - Energy: 0.2÷5.5 MeV
- Large area
  - $\Delta X \cdot \Delta Y = 20x20cm^{2}$ @ 2 MeV, $\Delta X \cdot \Delta Y = 8 \cdot 8cm^{2}$ a 5.5 MeV
  - XY beam scanning
- Uniformity
  - Spatial uniformity: target ≤ ±1%
- Accuracy
  - Accuracy: base ≤ ±5% - target to ≤ ±3% (multiple Faraday cups)
- No Carbon build-up (cryogenic LN2 trap)
- Time for full irradiation
  - From 30s to several hours
- **Certification of irradiation: ESA/ASI compliant**

ASIDI: Advances in Single Ion Deterministic Irradiation

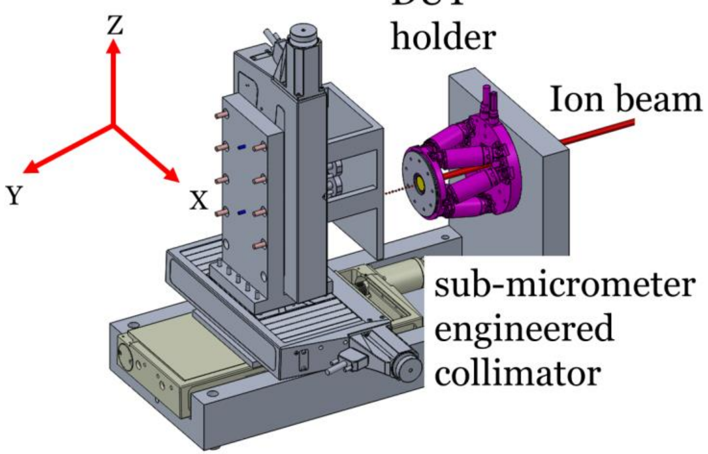
Goal:
Development of sub-micrometer ion beam collimation and related MeV ion beam diagnostics for precise low intensity irradiation of materials, micro-devices and detectors

- **Achromatic and sub-micron** features in a single device
- From single-ion hit to 10^4 ions/s - Energy: 200-2200keV
- AN2000 0° beam line



Increased demand of the physics community (mostly INFN) to perform experiments using MeV single ion techniques with sub-micrometer precision

- Detector tests (PIXEL, 3D, Microstrip, PDA …)
- Radiation damage studies (electronics, detectors)
- Characterization of the electronic features of micro-devices and detectors with unprecedented level of resolution
- Material modification, functionalization (semiconductors, SC oxides, SC thin films)
- Investigation of advanced SS material modifications at the sub-micron scale (QUANTUM)
- Localized implantation (color centers in diamond and other high band-gap semiconductors, lowD materials III-V – QUANTUM SENSING, SINGLE PHOTON SOURCES, QUANTEP …)



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- **Achromatic and sub-micron** features in a single device
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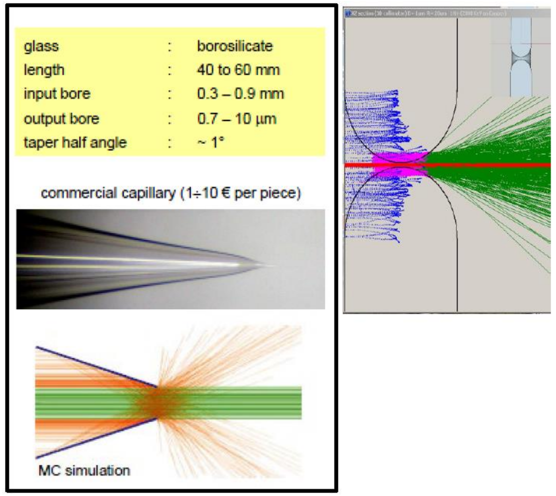
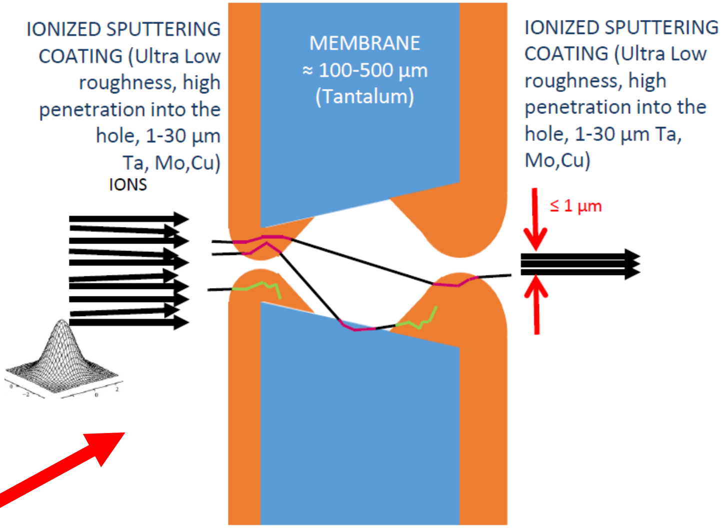
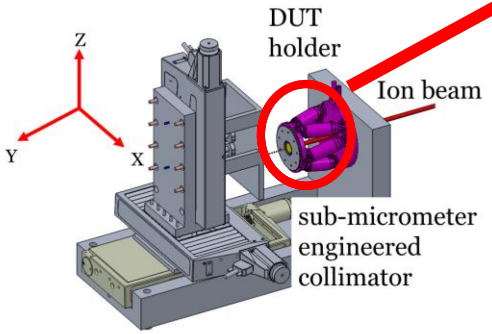
Standard collimator



ASIDI engineered collimator





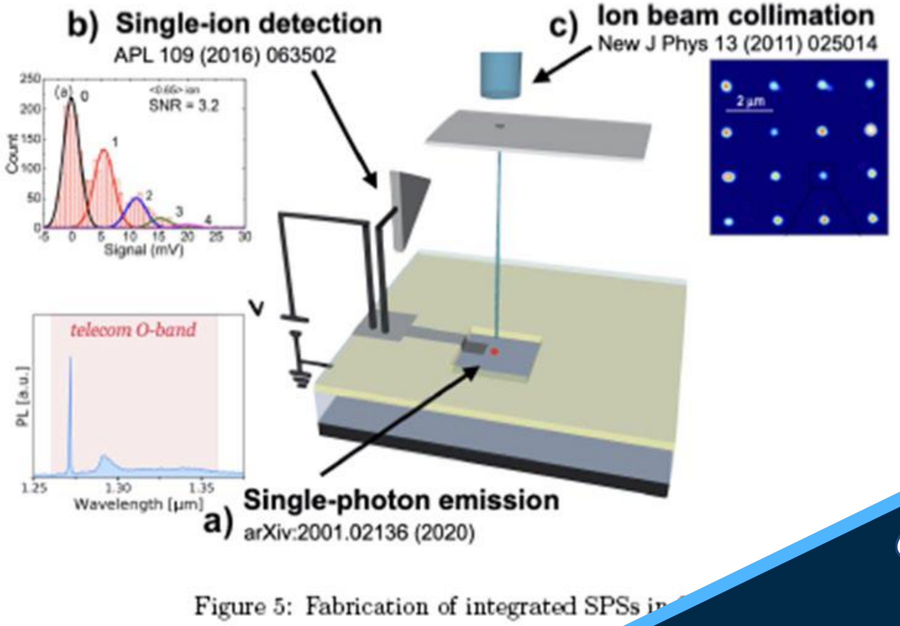
ENGINEERED COLLIMATOR

1. (pulsed) laser micro-drilling (5-30µm)
2. Focussed Ion Beam (FIB) debris cleaning
3. HiPIMS sputter deposition (both sides)
4. Focussed Ion Beam (FIB) refining (≤ 1µm)

QUANTEP

QUANtumTechnologies Experimental Platform

CNS5-INFN call of 2021-2023



- Introduction
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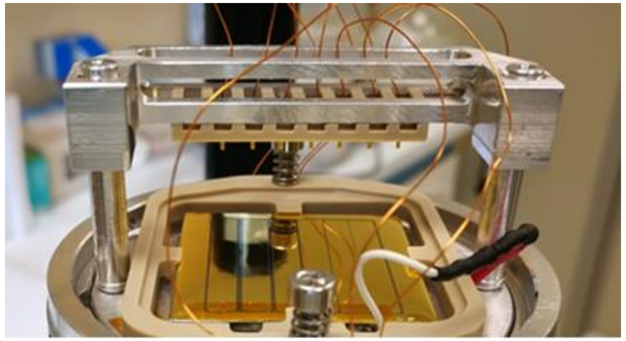
- **Novel detectors development and test**
  - **Some experiments: GAMMA**
- Conclusions

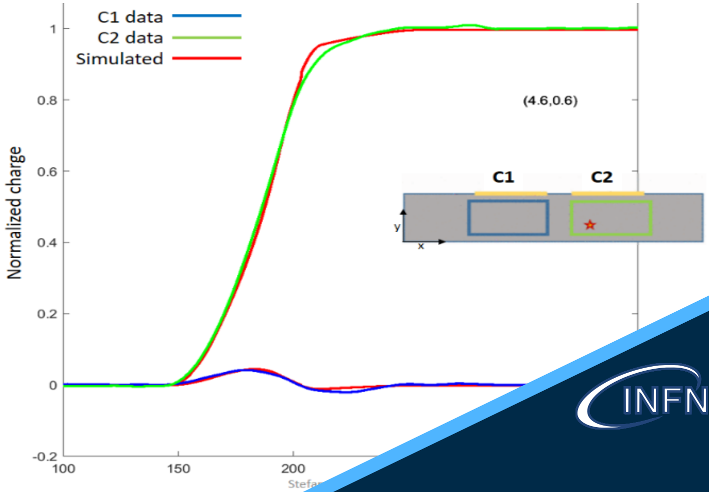
N3G: Next Generation Germanium Gamma Detectors

Technological research experiment of the CNS5-INFN call (21-23)

- Continuation: GAMMA activity about development of innovative processes for gamma tracking spectroscopy.
- Actual aim: Development of stable **p type segmented** coaxial detector exploiting pulsed laser melting technology.
- **Future goal: HPGe** coaxial detectors for high rate high damage environments in future spectroscopy experiments

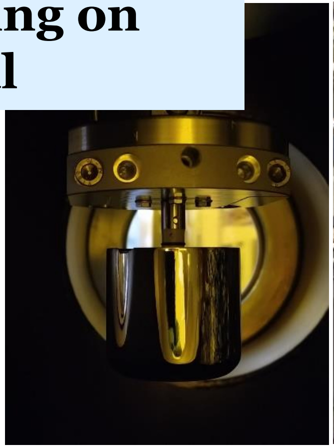
Planar detector prototypes



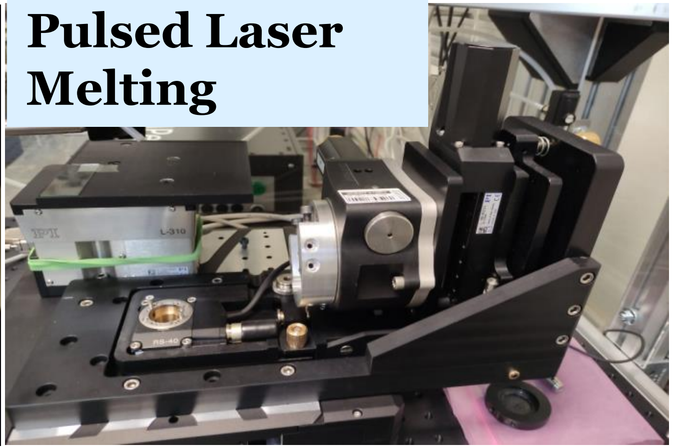


Upgrades to coaxial geometry

Dopant coating on HPGe Crystal



Pulsed Laser Melting



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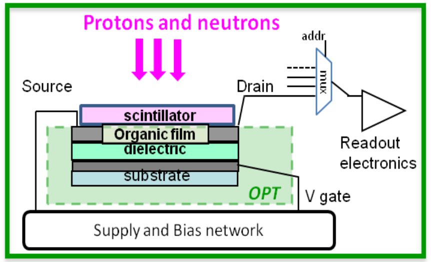
FIRE: The Flexible organic Ionizing Radiation dEtectors

Technological research experiment of the CNS5-INFN call of 2019-2022

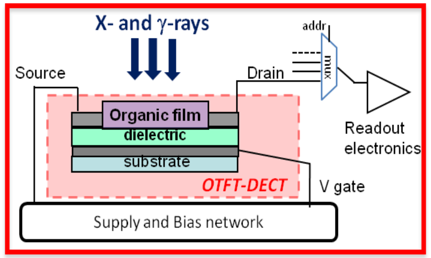
AIM:

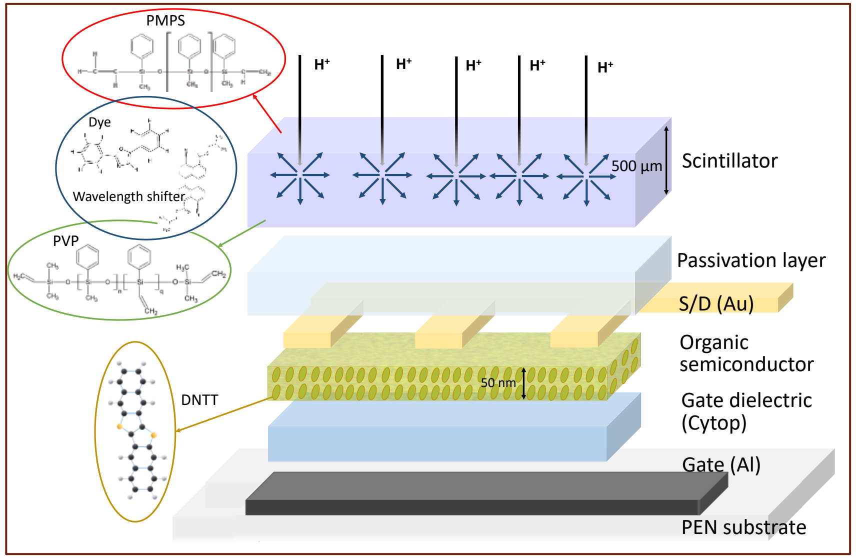
- Development of fully flexible devices for detection of X-, γ- rays, protons and neutrons either via DIRECT mode (PHOX) and INDIRECT mode (NEPRO)
- The LNL is involved in the development of thin and flexible polysiloxane-based scintillators to be coupled with OPT in NEPRO configuration
- DEMO: final expected device is a intracorporeal dosimeter during proton therapy session

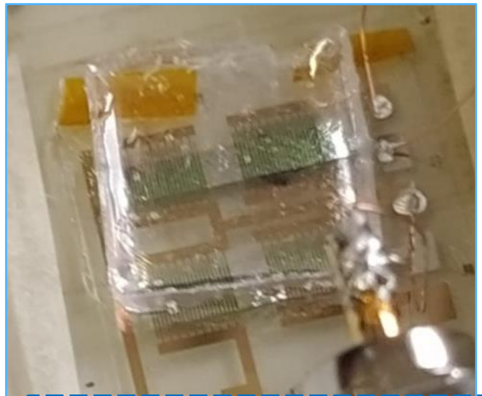
INDIRECT DETECTING SINGLE PIXEL (NEPRO)



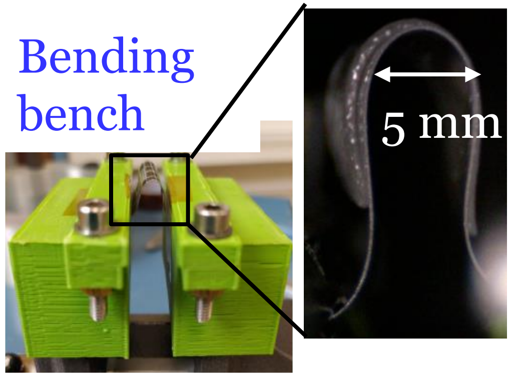
DIRECT DETECTING SINGLE PIXEL (PHOX)



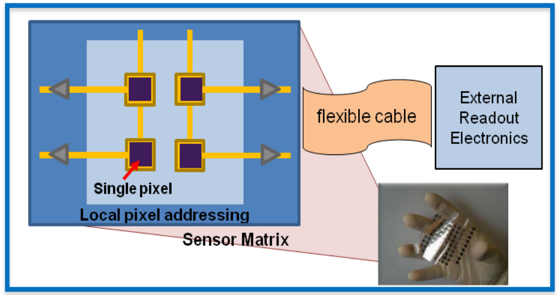




Bending bench



FULLY INTEGRATED FLEXIBLE DETECTING SYSTEM

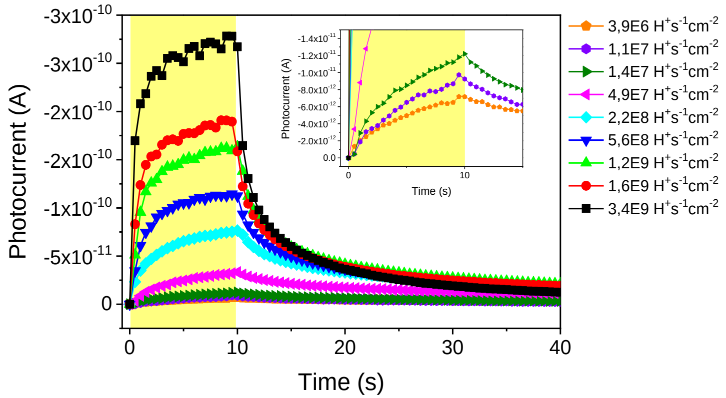


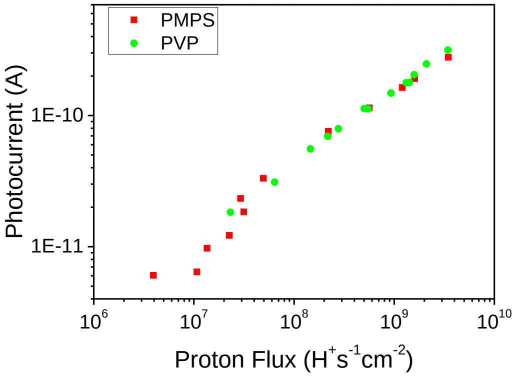
Hybrid detector: siloxane coupled to OPT ready for test under ion beam

FIRE: The Flexible organic Ionizing Radiation dEtectors

Technological research experiment of the CNS5-INFN call of 2019-2022

NEPRO test at LABEC: end-of-range test with H^+ 5 MeV extracted beam





Response of PSS100 to variable ON/OFF H^+ fluxes

- **linearity** of response with flux
- optimal **LoD** (1.9×10^4 H^+/cm^2 s for PVP-MPS → **0.026 Gy/min**)
- optimal **radiation hardness**: alternate shots ON/OFF beam on the same spot → negligible changes in response → results submitted to ***Nature Photonics***

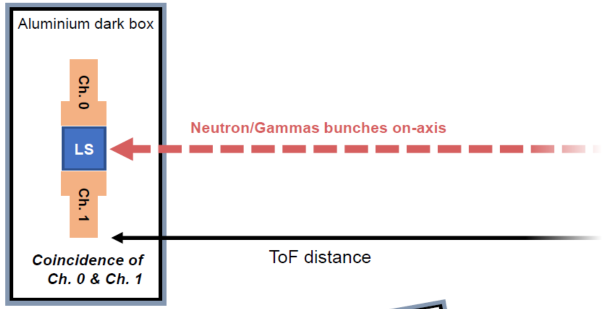
NEXT STEPS

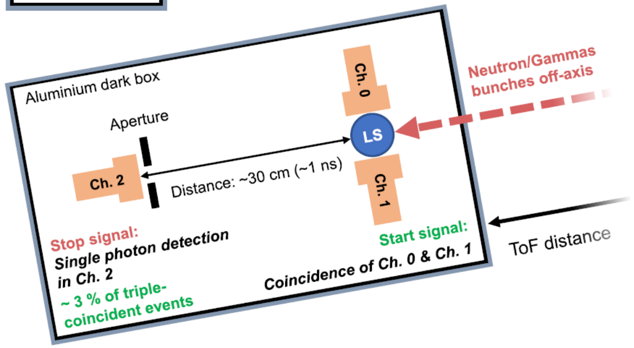
- test of **NEPRO** siloxane sensors for **thermal neutrons** @CN accelerator (LNL-INFN)
- installing **NEPRO** flex device into anthropomorphic phantom and **validation** under proton therapy run conditions @APSS (TN) , proposal submitted February 2022

NeuNuScint: Neutron Interactions in Scintillators for Neutrino detection

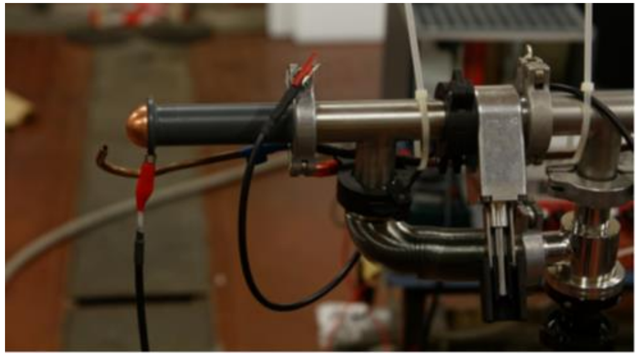
AIM:

- Study the quenching factor (QF) and background in Liquid Scintillator (LS) for neutrino physics experiments (JUNO, BOREXINO and SNO) induced by neutrons
- Test different scintillator formula and kind (***LiquidO opaque LS***)
- Apply the experimental results to improve the Neutrino-^{12}C model

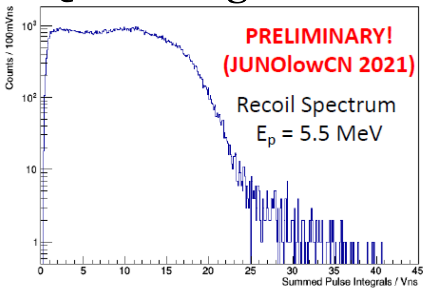




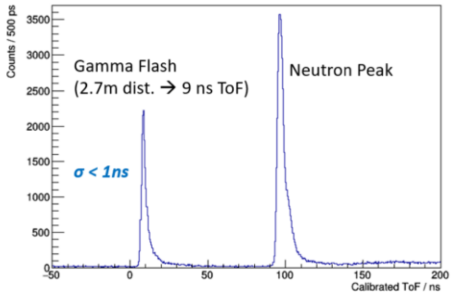
BELINA:QMN source

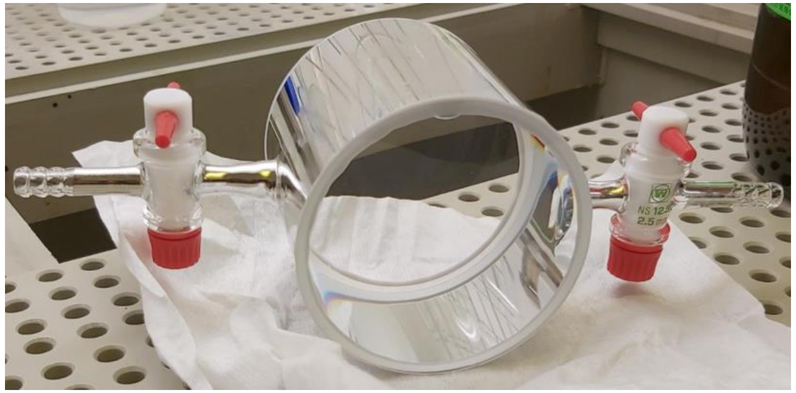


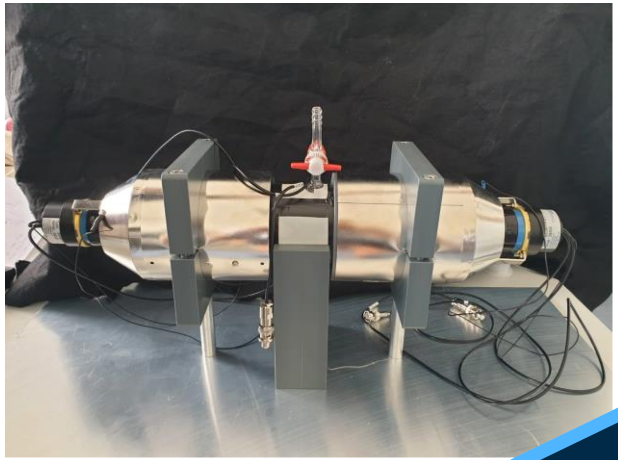
Quenching factor



Neutron and gamma
Pulse time resolved







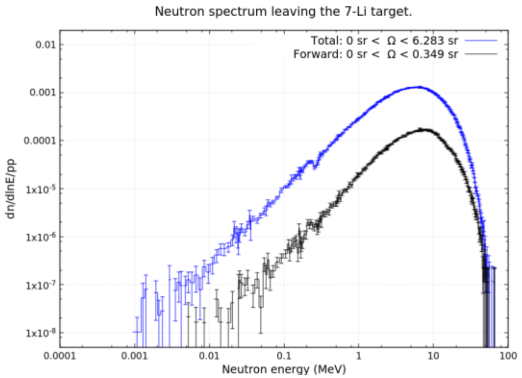
NeuNuScint: Neutron Interactions in Neutrino Scintillators

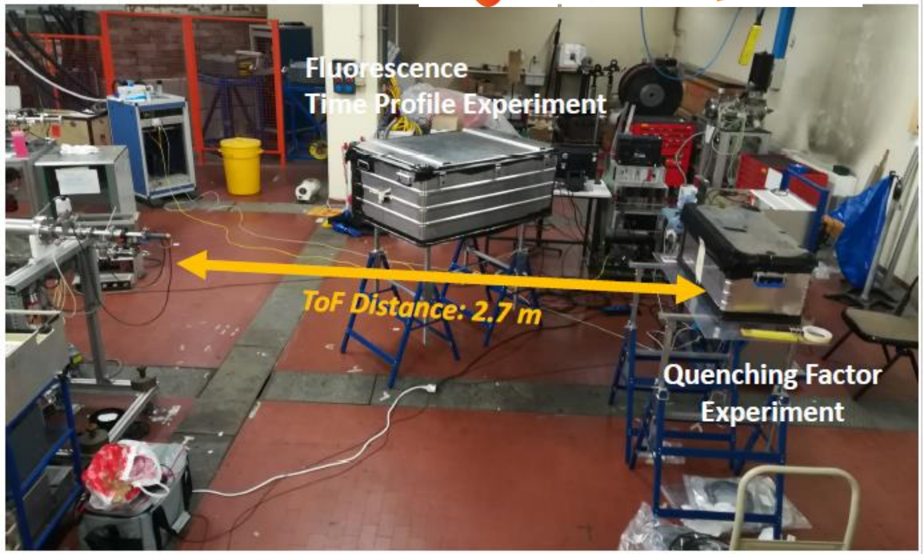
Further experiment:

Test LS at XTU-Tandem high energy neutron source beam

FANNILI facility (FAst Neutron production from NItrogen-14 on LIthium-7)

$^{14}N + {}^{7}Li \rightarrow {}^{20}N + n$

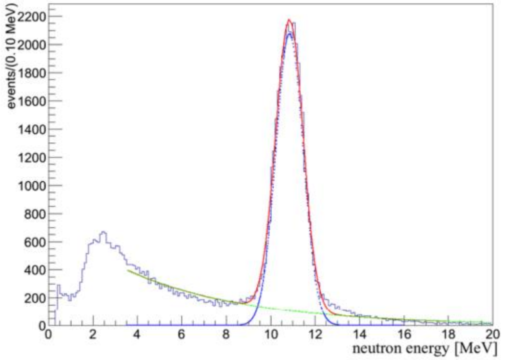


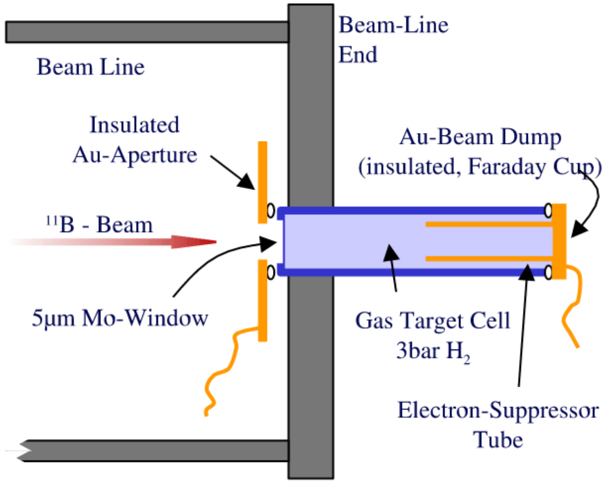


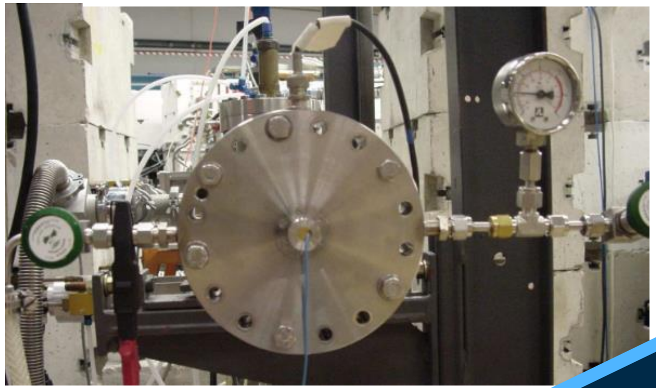
The LS Characterization Experiments in front of the Li-Target at the CN Accelerator

^{11}B on a Hydrogen-Gas Target

$^{11}B + {}^{1}H \rightarrow {}^{11}C + n$







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RREACT: Reliability and Radiation Effects on Advanced Components and Technologies

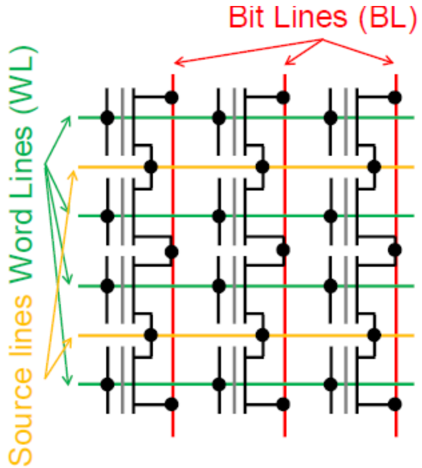
Aim: Particles detector based on NAND flash memories

Irradiation tests:

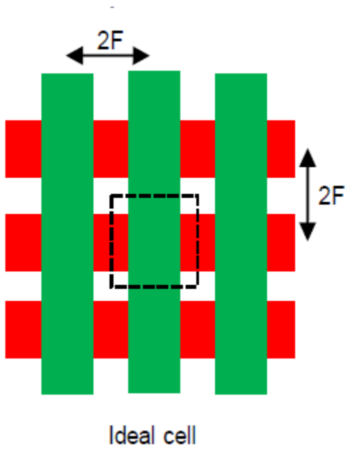
- Single Event Effects, Total Ionizing Dose, displacement Damage
- Synergy between different effects, between stress and radiation, etc.

Particle detection:

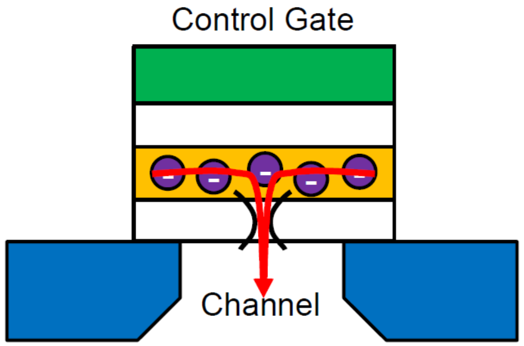
- Online tracing with continuous read/write of each memory cell (SEE)
- Off line: study the accumulate detector damage and dose



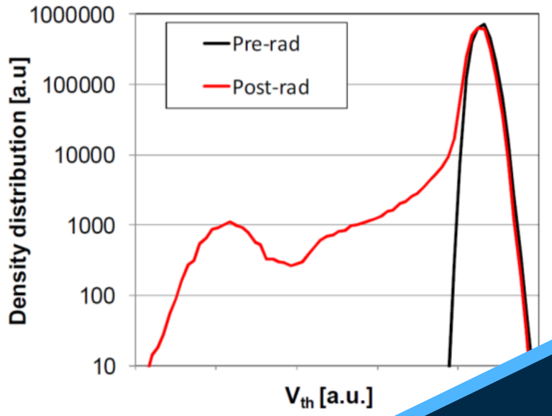
2D commercial flash memory



High density cell (2F ~ tens nm)



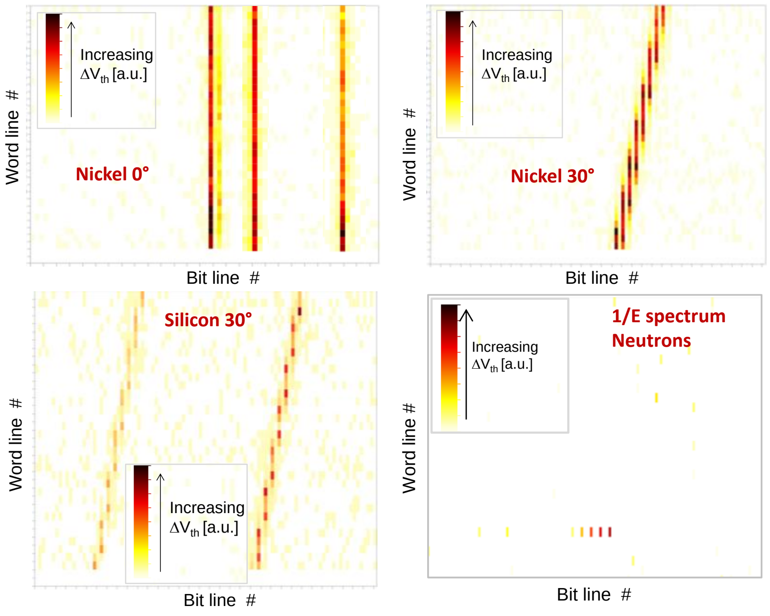
Heavy ion strikes can discharge the FG



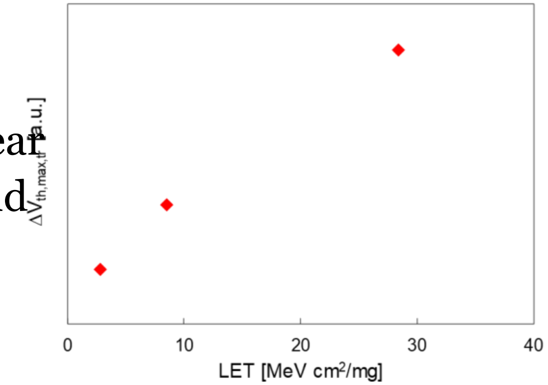
RREACT: Reliability and Radiation Effects on Advanced Components and Technologies

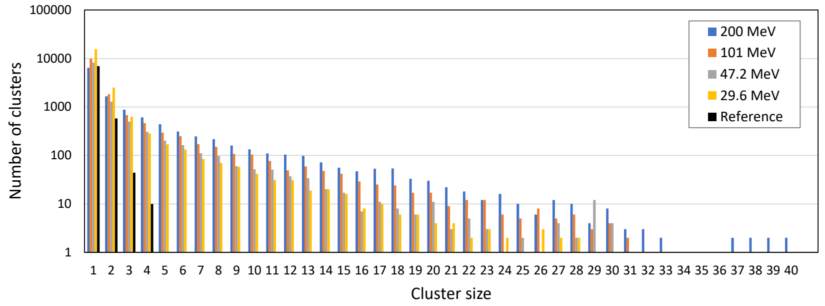
Further experiment: The application of **3D NAND** Flash-based as detector for particle tracing

Directly ionizing particles can be detected with very high efficiency (a single ion can affect tens of cells)

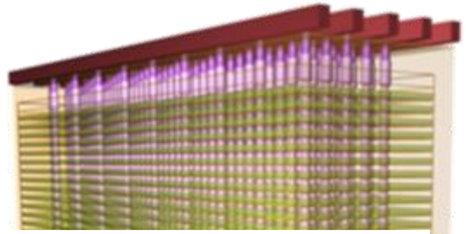


The ionizing power can be determined using ad-hoc algorithms, thanks to the linear relation between the threshold voltage shift and the LET of impinging ions

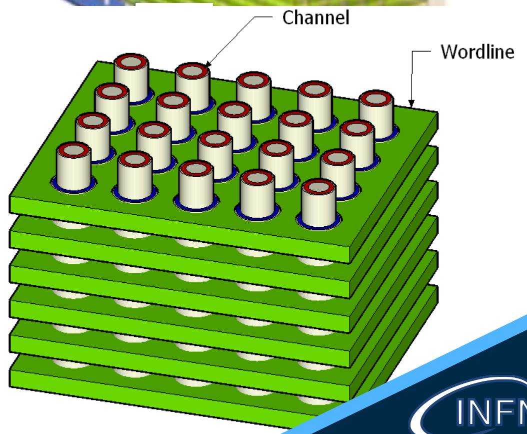




Indirectly ionizing particle beams (protons, neutrons) can be also detected, analyzing the number and features of secondary particles



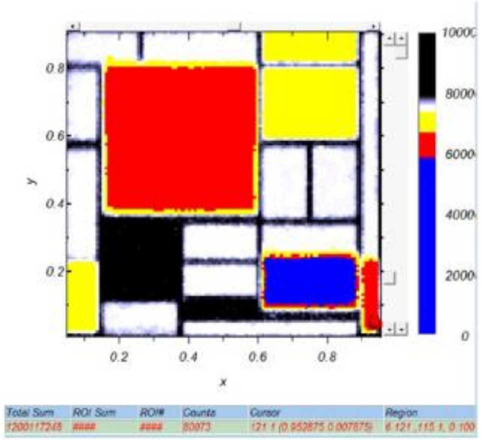
3D NAND Flash array with vertical-channel architecture



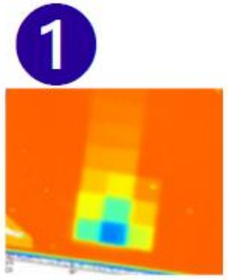
IBIC (ion beam induces charge): sensor development

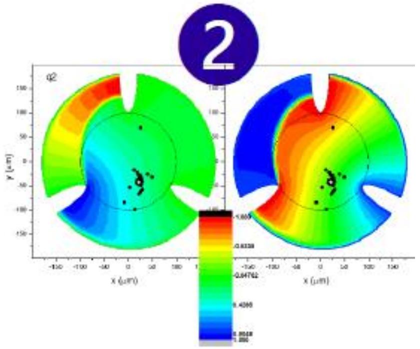
OBJECTIVE: Development of a sensors/systems to localize the sub-micrometer beam onto the image plane and to measure the spatial resolution **(ASIDI)**

- **Ion Beam Induced Charge (IBIC) injects charge through the surface into the electrically active regions of electronic devices**
- **Charge collection from device maps electrically active regions and shows recombination**



IAEA-CRP (2011-2016) "Utilization of Ion Accelerators for Studying and Modelling of Radiation Induced Defects in Semiconductors and Insulators" F11016:





Development of a new position sensitive detectors based on IBIC technique.

Two strategies:

1) Radiation detectors with micro-structures generated by local damage induced by ion beams

2) Localization of the ion beam impact position through the triangulation of charge signals induced in different sensitive electrodes.

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- Novel detectors development and test
- **Conclusions**

- **Several research communities are involved @ LNL**

- **Ion beam micro-analysis for nuclear targets development and cross section measurements for applied nuclear physics**
  - The nuclear target **IBA characterization** is an important supporting **tool** for nuclear physics experiments
  - **Without** a correct **characterization** (dose and compositions) **the cross section measurements are not possible or strong error affected**
  - IBA techniques **drive** the production process of high quality nuclear targets
  - **It's essential for INFN to focus on this field for the future high quality nuclear physics experiments**

- **Ion-solid interaction and radiation damage of materials, detectors and devices**
  - Several LNL research fields are involved on particle-matter interactions
  - The different facilities (already or soon available) will be used in future for test and development next generations of devices and detectors

- **Novel detectors development and test**
  - LNL is strong involved in **development of future generation detectors**

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A. Quaranta A. Mazzolari B. Fraboni R. Depalo