Sigla RIPTIDE
Durata proposta 3 anni
Area di ricerca rivelatori
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ABSTRACT

Neutron detectors are an essential tool for the development of many research fields, as nuclear, particle and astroparticle physics as well as radiotherapy and radiation protection. Not ionizing directly, neutrons are detected via nuclear interactions producing charged particles or electromagnetic radiation. Consequently, the detection efficiency depends on the probability of neutron interaction in the detector and on the escape probability of the reaction products. Fast neutron detection is often based on the neutron-proton elastic scattering reaction: the ionization caused by recoil protons in a hydrogenous material constitutes the basic information for the design and development of neutron detectors. Although experimental techniques have continuously improved, proton-recoil track imaging remains still at the frontier of n-detection systems, due to the high photon sensitivity required. To address this deficiency, we propose a novel recoil-proton track imaging system, RIPTIDE, in which the light output produced in a fast scintillator is used to perform a complete reconstruction in space and time of the n-p scattering event. In particular, we propose a setup combining a monolithic plastic scintillator coupled to CMOS technology imaging devices. The need for Micro Channel Plate (MCP) image intensifiers will be considered along the project development. Clearly, this system requires advanced and fast readout electronics, suitable for short exposure times at high frame rates.

By stereoscopically imaging the recoil-proton tracks the proposed apparatus can achieve neutron spectrometry capability enabling real-time analysis of the specific energy loss along the charged particle track. Consequently, the proposed system would allow the detector to retrieve the neutron direction and energy, without spoiling its efficiency. Moreover, the spatial and topological event reconstruction enables particle discrimination, a prerequisite of neutron detectors.

We propose to demonstrate the possibility to reconstruct with sufficient precision the tracks and the vertices of neutron interactions by developing and eventually building a first prototype with fully optical readout and transfer rate capability fully addressing the technological challenges. In addition to experimental activities, extensive Monte Carlo simulations will support the optimization and realization of the detection system, allowing to accurately study the detector performances in terms of efficiency and particle tracking. The development of analysis techniques of 2D images for the 3D reconstruction of tracks is also part of the project.

PROPOSTA SCIENTIFICA: stato dell'arte e obiettivi

Any experimental setup conceived for neutron detection consists of two components: a converter and a charged particle detector [1]. The converter (e.g. ^{3}He, ^{6}Li, ^{10}B, ^{235}U) can be external (radiator) or embedded in the particle detector. Though extensively used for environmental dosimetry, neutron-beam flux and energy measurements as well as beam profiling, such converters cannot provide neutron tracking, i.e. complete momentum reconstruction of the detected neutrons. Instead, this task can be accomplished by using kinematical properties of two-particle reactions (recoil neutron-detectors): in this framework the n-p elastic scattering is the simplest and promising interaction. In fact, the basic tool for full neutron momentum reconstruction in Recoil Proton Track Imaging (RPTI) detectors is the two-body kinematics, where the neutron energy E_n is related to the proton recoil angle and energy (ϑ_p,E_p) by the formula:

$$E_n=E_p/\cos^2(\vartheta_p) \qquad (1)$$

State-of-the-art approaches for neutron tracking by using neutron-proton single and double scattering have been proposed [2-6]. So far, they show limits in terms of detection efficiency, complexity, cost, and implementation. For instance, ref. [2] reports the feasibility study of a RPTI detector to be used for neutron spectrometry measurements, combining a gas scintillator (CF_4) with a real-time imaging device. The experimental setup was adjusted in a fixed angle scattering geometry by using a CH_2 foil, thus exhibiting a poor detection efficiency (10^{-6}). Moreover, the scintillation yield is weak, and several amplification stages are in place to enable a reliable proton track reconstruction on the image-intensified CCD camera. Fine tracks of the recoil protons were obtained, leading to a good energy resolution by proton range measurement in CF_4 (2.33% at E_n=14 MeV).

On the other hand, a different and more complex approach has been proposed either by the SONTRAC [7,8] and the MONDO [3,4,9] trackers (see [10] for an overview). Both systems are based on multiple n-p scatterings: SONTRAC is being developed for Solar MeV-neutron detection in spacecraft while MONDO aims to track fast neutrons produced in Particle Therapy treatments. In both cases the recoiling protons are detected using a matrix of plastic scintillating fibers and the produced light is either amplified using a triple GEM-based image intensifier or by Single Photon Avalanche Diode arrays (SPAD) in MONDO or read-out by Silicon Photomultipliers (SiPMs) in SONTRAC.

The MONDO collaboration has investigated the performance by Monte Carlo simulations, reporting an overall neutron detection efficiency in the range 0.1-1% for 10-400 MeV neutrons. In particular a sizable efficiency cut-off for the low energy range (10-100 MeV) is inherently due to the detector structure (matrix of scintillation fibers), while the high energy cut-off is related to the finite detection volume (capability to completely contain two subsequent recoiled proton trajectories). The SONTRAC collaboration has realized a first prototype and its performance is being studied [7,8] including issues related to the read-out of channels and data transfer. As discussed below, some limits of MONDO and SONTRAC would be mitigated in the detector proposed in this project, obtaining, at the same time, a much simpler (less expensive) and possibly more efficient detection geometry.

Recently, a neutron detector based on an array of segmented plastic scintillators NARCOS [11] has been proposed by the CHIMERA collaboration (CSN3) within a PRIN project. Similar to NEXT [12], its advantage is the capability of retrieving the interaction point of the neutron-proton elastic scattering. However, it is conceived to work in a fixed-target configuration only (i.e. the neutron source is known).

In summary, to our knowledge no neutron-tracker detector is in the data-taking phase right now, though several systems are under study or being developed.

Obiettivi

The objective of the RIPTIDE detector concept [13-15] is to detect fast neutrons, determine their energy, and most importantly retrieve their trajectory (i.e. momentum reconstruction). RIPTIDE is a RPTI detector (i.e. exploits Eq. 1) which aims at reconstructing with good efficiency the neutron momentum from:

- single n-p scattering, when the primary vertex of neutron trajectory is known (e.g. point-like target in fixed-target experiments);
- double or multiple n-p scattering in the detector active volume (general case).

It is worth mentioning that RIPTIDE is conceived for both cases depending on the application (unlike other systems like MONDO and SONTRAC which only exploit double scattering or NARCOS exploiting single scattering only).

We propose to build a first prototype of the RIPTIDE detector concept: a cubic plastic scintillator coupled to an optical system of lenses focusing the proton tracks into CMOS cameras. So far, we have carried out feasibility studies showing that the detector concept is valid (see refs. [13-15] and next section). Here, we propose to: (i) optimize the geometry through Monte Carlo simulations; (ii) improve the analysis procedure to reconstruct 3D tracks from the combination of 2D images; (iii) study a suited optical system which minimizes aberrations; (iv) experimentally benchmark the MC simulations obtained so far and (v) build and characterize a first prototype (this step includes the realization of an acquisition system for the synchronization of photos acquired by different CMOS cameras). Although MC simulations have demonstrated the viability of the RIPTIDE detector concept, the actual number of photons reaching CMOS cameras have to be assessed within this project in order to evaluate a possible use of MCP image intensifiers. In summary, this project might prove a novel neutron detection technique towards a new class of detectors with unprecedented efficiency and timing properties, together with track-reconstruction capabilities.

Metodologia della ricerca

A detector sketch, describing the RIPTIDE working principle, is shown in Fig.1, where single and multiple proton recoil tracks are seen by light sensors downstream of optical systems.

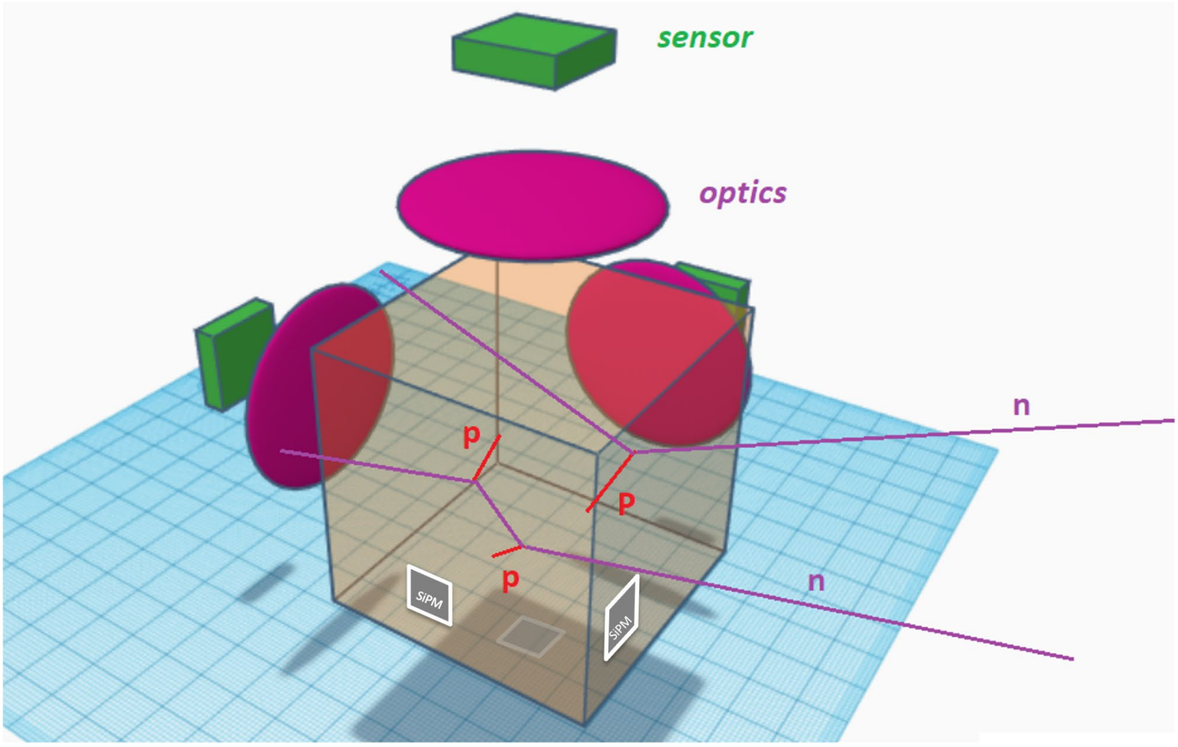

Fig.1 RIPTIDE working principle

The central plastic scintillator is surrounded by two (or more) optical systems coupled to CMOS cameras. If required, Micro Channels Plates imaging devices will be added to increase the number of photons reaching the CMOS cameras (this depends on the results of the first experimental tests proposed in this project). It is important to mention that “proof-of-principle” experiments for 3D tracking of charged particles by scintillation light successfully demonstrated its feasibility [16][17]. The novelty here is the application in the field of neutron detection systems. As a preliminary design for the RIPTIDE demonstrator, we propose a cubic active volume (BC-408/EJ-200 plastic scintillator of 216 cm^3) whose dimension results from a compromise between detection efficiency (Eff_n~10% at E_n=10 MeV) and geometrical constraints given by the wide-angle optics. In this first configuration, we expect to identify proton track lengths in the range $0.2 < R_p < 30$ mm ($4 < E_p < 50$ MeV).

From a preliminary feasibility study based on Geant4 MC simulations, we have estimated absolute detection efficiency with the full optics over the energy region of interest, see Fig. 2, and in addition we have studied the impact of carbon share in BC408, $^{12}C(n,n)$ being the most prominent [20]. Other kinds of background due to gamma rays and charged particles can be rejected by dE/dx track characterization (see Fig. 3 and Fig. 4). Figure 3 shows an example of a preliminary study of Geant4 simulated tracks of 30 MeV protons and the reconstructed track from the 2D images seen by a light sensor positioned downstream of a simple optical system. In Fig. 4, the Bragg peak obtained from the simulation of 30 MeV protons is compared to the reconstructed one, with the same procedure used in Fig.3. Clearly, both Fig. 3 and Fig. 4 show the viability of the idea, as the track is well reconstructed and the energy loss along the track can be determined with good accuracy.

In these studies, proton transport in the scintillator volume has been simulated at different energies, thus optical photons were collected at the surfaces of the plastic cube. Then, the optical system has been simulated in order to produce the set of 2D images to be analyzed downstream the apparatus. In the reported pictures, a single proton track is simulated and reconstructed - corresponding to a single-scattering neutron interaction. At this stage, single track reconstruction is obtained through effective use of the projections of the trajectory on the surfaces of the cube. Principal Component Analysis (PCA) method has been chosen as a reconstruction technique. The 2D data sets are composed of points useful for the reconstruction. They are projected onto the principal component and give a distribution yielding a Bragg profile, from which the range is easily obtained.

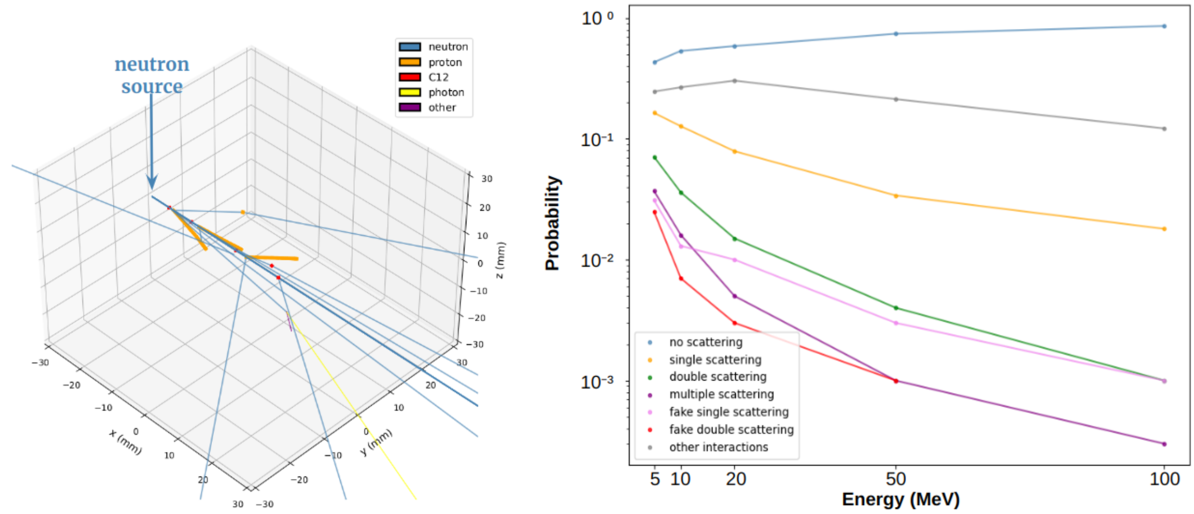

Fig.2 Example of neutron interactions in the active volume of RIPTIDE obtained with Geant4, together with interaction probabilities for neutrons with energy between 5 and 100 MeV.

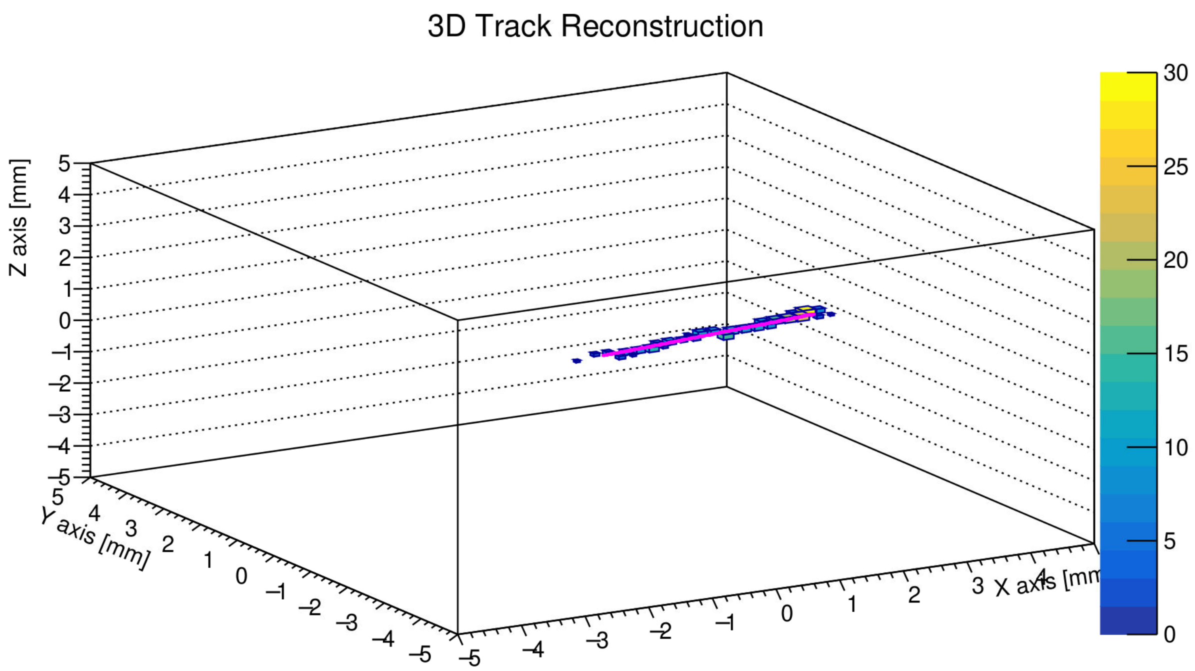

Fig.3 Example of a 3D track reconstruction compared to the original photon source according to Monte Carlo simulations.

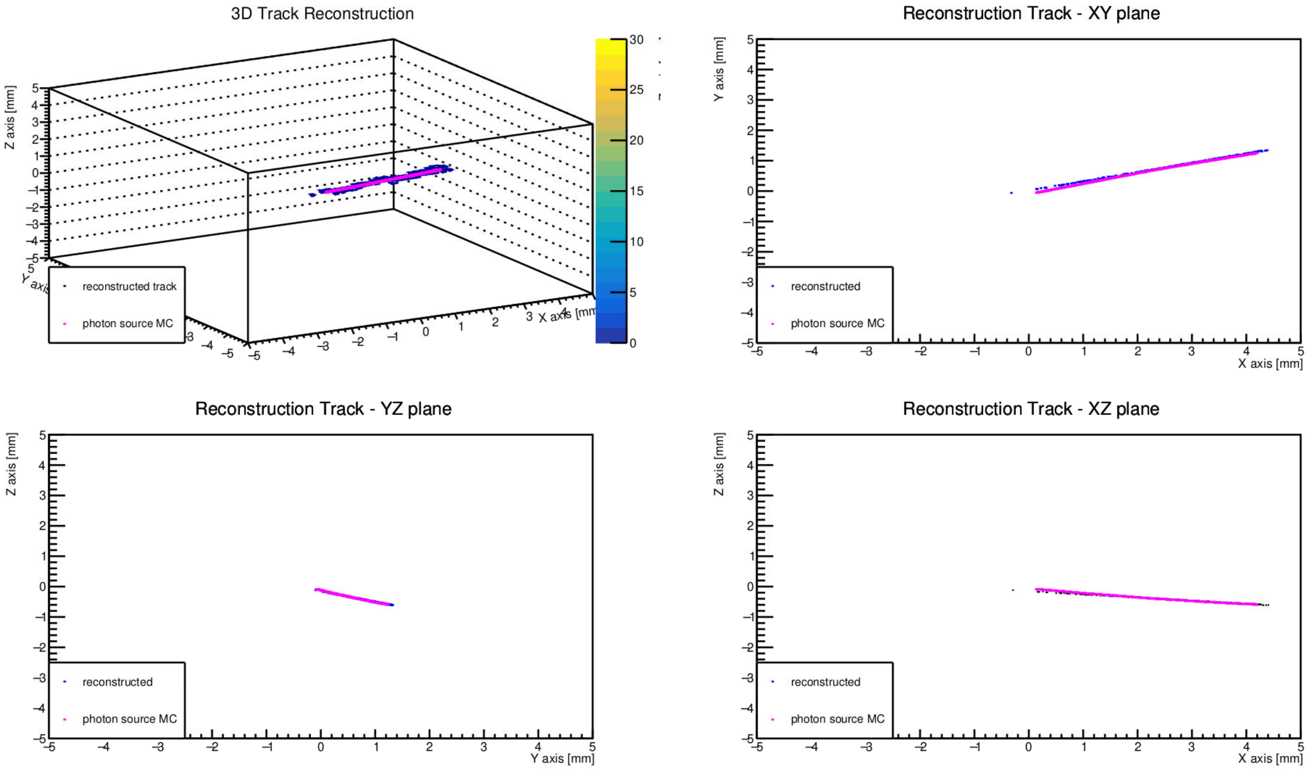

Fig.4 Projections at the CMOS camera (after a lens) onto 2D orthogonal surfaces. Monte Carlo simulated tracks produced by 30 MeV protons are purple, reconstructed tracks are blue.

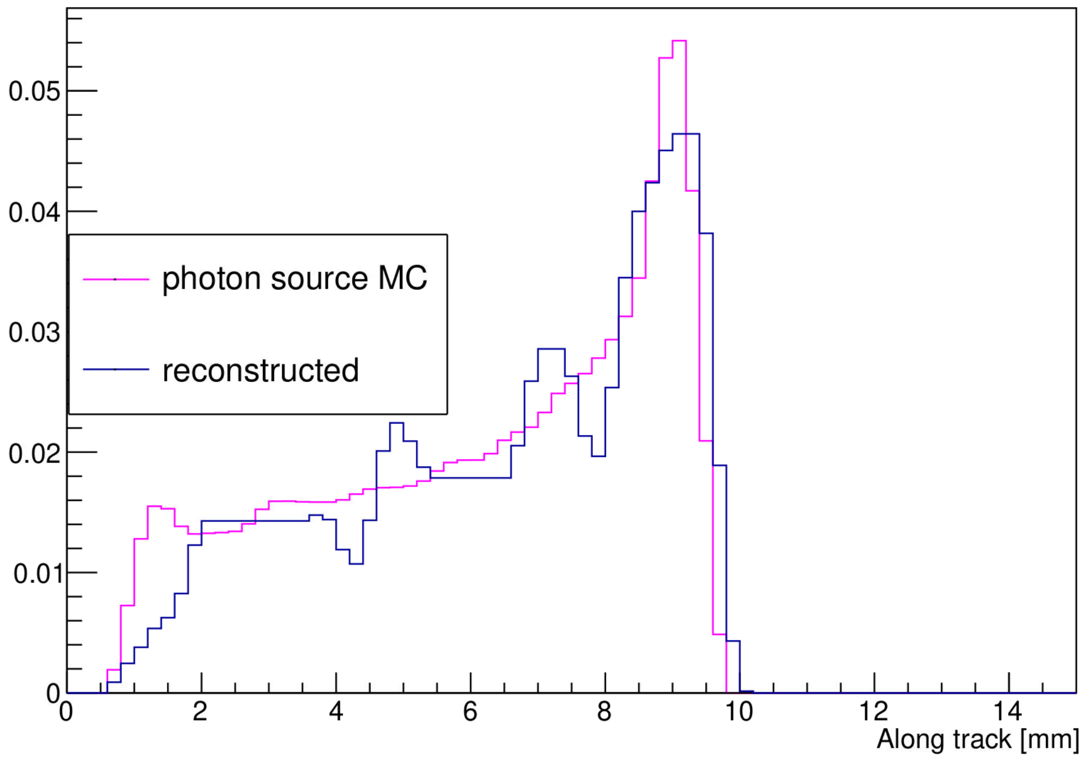

Fig. 5 Track reconstruction for a 30 MeV proton. Photon source simulated by Monte Carlo (purple) and reconstructed track (blue) are projected on the principal component.

The study of the optical system is part of the project. It will be coupled to the plastic scintillator in order to minimize light losses, while achieving the best compromise among depth of field, aperture and aberrations. Scintillation light transmittance will be measured according to the scintillator emission spectrum (peaking at 420 nm) thus selecting the best optical glass (borosilicate vs UV transmitting glasses). In addition, the readout systems for imaging will be investigated, in particular back illuminated, high-eff. low-noise CMOS devices (diag. size from 1/3'' to full-frame). If the number of photons reaching the CMOS sensor will be below the detection threshold, we plan to add MCP image intensifiers to reach the required sensitivity. Resolution (HxV) and pixel-size of the CMOS cameras should match the optics in order to obtain a 50-100 μm resolution in proton track reconstruction, and a reasonably small detection threshold for photons.
As the system requires the simultaneous acquisition of 2 or more pictures, an external fast trigger implemented by SiPM will provide a time reference for starting track-image selection and time-of-flight (ToF) measurement. The integrated light signal recovered by SiPM will be also acquired as a guess of the total energy released and used also within the first level trigger. Last generation back-illuminated CMOS sensors (monochromatic) have the advantage of high quantum efficiency in the required spectral range (60-70%) and single-pixel readout-noise approaching to single photon detection threshold (1.0 e- RMS; e.g. Sony IMX290 MM). CMOS are premium devices with respect to CCD because of faster readout, up to 3000 fps in full resolution, e.g. Cyclone 2000 [20], with data throughput for high resolution and high frame rate imaging as high as 50-100 Gbit/s. The large data rate obtained by the multi element imaging system must be treated in real-time, thus the associated hardware and software frontend must sustain image classification on the fly. The system has been conceived to process in parallel images acquired by at least two image sensors, with individual data size of the order of 1-4 MB at a frame rate exceeding 1 kHz. A couple of fast input channels for timing must be included in the input routing: one channel will be provided by a non-imaging fast device (e.g. SiPM) and the other one can be used in combination with an external timing reference signal. Therefore, the image sensors will be synchronized.

Dedicated analysis procedures will be developed during the project, in order to improve the analysis performed so far. In particular, we plan to improve PCA as well as state of the art AI techniques for the 3D track reconstruction from 2D images.

Organizzazione del Progetto

The full project is organized in three work packages:
- WP1: Simulation and event reconstruction;
- WP2: Detector, electronics, image acquisition and selection;
- WP3: Laboratory and beam tests.

The goal of WP1 is to define the geometry of the detector, including the optics and sensors and to provide all the software tools to process the sensor images to extract the physical information: neutron energy and direction.
The WP1 will provide a full detector simulation made in Geant 4, controlling neutron interaction inside the scintillating cube and photon generation, a code to simulate all the optical characteristics until the sensors. In addition it will provide a code processing images in at least two views trying to reconstruct the 3D characteristics of the scattered protons. The simulation, the optical transport code and the reconstruction code exist in their preliminary form and they have been used for the simulation results previously presented. However, future updates are necessary to properly describe all the intervening physical processes, in order to tune and make the simulations more reliable. In particular the reconstruction for the cases of multiple scattering in the scintillator has still to be studied in detail. At the end this WP concludes its work with the detector design together with the evaluation of the detection and reconstruction efficiencies as well as the expected performances. These activities will be supervised by Patrizio Console Camprini and Nicholas Terranova and will involve people from Bologna and Frascati.

The goal of WP2 is to build the actual detector by choosing the suitable components, optics, and image sensors. One of the aims of this WP is to have a fast image sensor reading and image preprocessing in order to select only relevant frames. This will involve a development of the firmware that can be loaded in the frame grabber. The code will have to fast process the frames, time-tag them, rejecting empty frames and saving only filled frames, possibly in time coincidence with a fast trigger signal coming from SiPM reading the light of the scintillator. These activities will be supervised by Alberto Mengarelli and Riccardo Ridolfi and will involve people from Bologna.

The WP3 will employ all the previous WP results with the aim of exposing the full detector on different beam test facilities. As a first step, the light yield of the scintillator, produced by radiative source and cosmic rays, will be measured.
A simple multianode PMT will be used to evaluate the relative sensitivity of the image sensor. The goal of this test is to assess the possible need of an image intensifier to enhance the signal amplitude. In this WP we will tune the frame grabber system to work simultaneously with at least two cameras and to check the correct working on physical events in the laboratory. Once all these phases will be carried out, the system will be exposed to a proton and a neutron beam to measure the track reconstruction capability and the final performances of the system. This measure will be performed in parasitic mode within the framework of either n_TOF or FOOT data takings. These activities will be supervised by Cristian Massimi and will involve people from Bologna, with external contributions from n_TOF Catania group (see next section).

Milestones:

31-12-2024 WP1: definition of all the geometry except the image intensifier
31-12-2025 WP1: reconstruction of the neutron kinematics in double-scattering events
31-12-2025 WP2: first prototype realization (without the image intensifier)
31-12-2024 WP3: light yield and multianode PMT measurements
31-12-2025 WP3: first laboratory tests with radioactive neutron source
31-12-2026 WP3: data taking with proton and neutron beams

Descrizione del gruppo di ricerca

The group consists of researchers currently working at FOOT and n_TOF and CNAF. Moreover, some of the people involved have a longstanding experience in High Energy Physics. For instance, the required innovative electronics for RIPTIDE has been defined by using the large experience developed by the people related to High Energy Physics experiments at CERN. The researchers from n_TOF have gained a consolidated experience in the field of neutron physics and related topics including Geant4 simulations with neutrons.
The researchers from FOOT have experience in Data Acquisition systems, detector developments and data analysis.

INFN Bologna

Name	Surname	Title	FTE
Roberto	Spighi	*Research Director*	0.5
Cristian	Massimi	*Associate Professor UNIBO*	0.5
Patrizio	Console Camprini	*Researcher ENEA*	0.5
Riccardo	Ridolfi	*Post-Doc. UNIBO*	0.5
Alberto	Mengarelli	*Tecnologo*	0.2
Francesco	Giacomini	*Primo Tecnologo CNAF*	0.1

INFN BO Totale = 2.3 FTE

INFN LNF

Name	Surname	Title	FTE
Nicholas	Terranova	*Researcher ENEA*	0.5

INFN LNF Totale = 0.5 FTE

Coinvolgimenti esterni alla CSN5

The idea of the RIPTIDE detector concept was proposed a few years ago in CSN3 by n_TOF, and FOOT (CSN3 experiments). In fact such a detector would open the way to new experiments in the two collaborations. However, the whole project from MC simulations to the construction of the first prototype of the detector cannot be funded by CSN3, we are now proposing to open the project in CSN5, while maintaining our close collaboration with colleagues from CSN3 who are part of the n_TOF and/or FOOT collaboration. More in detail, the development of RIPTIDE will be supported by:

- prof. Mauro Villa (FOOT) - INFN and University of Bologna
- prof. Agatino Musumarra (n_TOF) - INFN and University of Catania
- Dr. Maria Grazia Pellegriti (n_TOF) - INFN Catania.

Some experimental studies and readout/DAQ developments for RIPTIDE are in common with other n_TOF or FOOT activities. Therefore, we plan to work in full synergy with these people.

Indicare progetti in corso o finanziati negli ultimi cinque anni su tematiche analoghe

As mentioned above, the project received some funding in CSN3. In particular, in the last 2 years both n_TOF and FOOT received about 10 kE to perform a preliminary feasibility study. More in detail, CSN3 funded: (i) computing resources at CNAF, (ii) two plastic scintillators, (iii) several SiPM, (iv) a Cyclone 2000 CMOS camera and a frame grabber.

Descrizione dell'impatto e delle ricadute dei risultati della ricerca

So far, the signature of fast neutron interactions is obtained by fast plastic or liquid scintillators in combination with the ToF technique. More in detail, the light is collected towards PMTs or SiPMs, creating an electric pulse proportional to the deposited energy and, at the same time, providing excellent timing information of the event. On the other hand, only in ref. [18] the scintillation light has been exploited in order to traceback the spatial and topological reconstruction of the events. The idea in ref. [18] - so far never applied to fast neutrons - represents the key of the present project.

The spatial and topological reconstruction of the neutron-proton elastic scattering is currently unavailable. As discussed above, a few attempts of spatial reconstruction by means of double n-p scattering or track imaging in gas detectors can be found in the literature. However, in both cases these innovative techniques have in common an intrinsic limitation related to the very-small detection efficiency. Surprisingly, the potentially great tracking capability, which could be achieved by imaging the scintillation light with a fast camera, has not been exploited so far. Such an achievement is the objective of the present project. In fact, the continuous scientific and technological progress of an optical system based on CCD/CMOS segmented cameras cannot be underestimated. Thus, its use in combination with a scintillation material through lenses can be considered as a first step in a research field which could rapidly develop. In addition, a system working at the maximum of its current potential, could already achieve better results than any existing neutron detector in terms of time and space reconstruction, while maintaining a high detection efficiency.

In summary, if successful this project might represent a novel neutron detection technique towards a new class of detectors with unprecedented efficiency and timing properties, together with track-reconstruction capabilities.

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ULTERIORE DOCUMENTAZIONE

Curriculum del RN Roberto Spighi

Roberto Spighi has been a research director at INFN Bologna section since 2021. He has actively participated in four experiments: OBELIX, HERA-B, ATLAS and FOOT giving his contribution in different physics fields: nuclear physics at low energies (OBELIX), particle physics at high (HERA-B) and very high (ATLAS) energies and applied nuclear physics (FOOT). From the Scopus (SPIRES) database he is author of 1080 (1057) articles published in national and international scientific journals with an h-index of 125 (186). The following references are about the 10 selected publications. In the FOOT experiment of which he is currently a member, he has held various positions such as head of the editorial board, head of physics, member of the collaboration board and local manager. Over the past 3 years, he has participated in several statistical studies on the Sars-Cov-2 pandemic both within INFN and in collaboration with the hospital environment. An important project being studied under an agreement among INFN, University of Bologna and Policlinico Sant'Orsola of Bologna concerns the purchase of a cyclotron for the treatment of tumours through hadrontherapy. The project, with a cost of around EUR 50 million, has already been accepted by the hospital and is currently being examined by the Emilia-Romagna Region. If the project is accepted, Roberto Spighi would be the scientific responsible for INFN. Also in collaboration with the same hospital, a study aiming to develop software to provide donor-patient assignment for liver transplants in the Emilia-Romagna region is currently underway.
Roberto Spighi's research activity involved software, data analysis and hardware for detector development.

The main physics measurements he carried out are:

- branching ratio of antiproton-proton annihilation to two-body proton in the final state at the Obelix experiment. In particular $p\bar{p}\to\pi^+\pi^-$ both in liquid and gaseous target at NTP, $p\bar{p}\to k^+ k^-$ both in liquid and gaseous target at NTP, $p\bar{p}\to\pi^0\pi^0$ both in liquid and gaseous target at NTP, $p\bar{p}\to\pi^0\eta$ both in liquid and gaseous target at NTP, $p\bar{p}\to k_S k_L$ in both liquid and gaseous target at NTP and at low pressure (5 mbar) [1], which allowed the probability of annihilation from the various J^{PC} levels of the initial state to be determined;
- search for resonances with spin parity analysis in the p-channel $\bar{p}\to\pi^+\pi^-\eta$ carried out on both liquid and gaseous targets at NTP, with the aim of verifying the possible presence of a new meson around the mass of 1400 MeV/c2;
- measurement of the kinematic distributions (azimuth angle φ, Feynman-x and transverse impulse pT) [2] and polarization [3] of the J/ψ and ψ(2S) mesons carried out at the Hera-B experiment. For the first time, the polarization was evaluated in all reference systems in the literature (elicity, Collins-Soper and Gottfried-Jackson);

At the ATLAS experiment he participated in

- the measurement of the differential cross-section of direct and indirect charmonium production, measurement of the differential cross section of $t\bar{t}$ pair production with respect to the kinematic variables of the top or $t\bar{t}$ pair [4];
- the production of a $t\bar{t}$ pair in association with a Higgs Boson ($t\bar{t}H$)[5]. On this topic, Roberto Spighi was also the supervisor of Dr. Silvia Biondi's PhD thesis, which won the Conversi prize as best thesis of the year 2018 in INFN Group 1.

Within the framework of the FOOT experiment he got involved in

- integral and differential cross section measurements of the elements produced by a 12C beam on a target containing C and H [6].

In July 2021, Roberto Spighi was the initiator and person in charge of a data taking performed at GSI laboratory in Darmstadt (Germany) with an Oxygen beam at different energies on graphite and polyethylene targets. The measurement was funded by the European Space Agency (ESA) call for space radiation protection studies for the future human missions to Mars.

Moreover, Roberto Spighi actively joined statistical analysis of Covid-Sars-2 pandemic data. This work led to 5 publications and to the creation of a website (https://covid19.infn.it/) automatically updated every day. Among them, the article on ISTAT data about deaths over the last 5 years (the extension over the last 12 years is currently in progress) [7] is of particular interest.

Initially, the results were used within the INFN as an aid for decision-making, but they were soon also used to inform the relevant Ministries and regional crisis units about the development of the pandemic. Following these results, Roberto Spighi was asked to join the crisis unit of the Sant'Orsola hospital in Bologna to forecast the need for beds due to Covid emergency in the short term (1-2 weeks). The usefulness of these studies emerged in February 2021 when the hospital was alerted about the upcoming arrival of another Covid wave and it was able to prepare beds in advance to deal with the emergency.
Within a collaboration with the Sant'Orsola hospital in Bologna, he also got involved in the development of a software employing neural networks and artificial intelligence techniques to establish the donor-patient match for liver transplants. At present, the polyclinic has already made available a database of approximately 3,000 performed transplants as a train set for the network.

Regarding experimental activities, Roberto Spighi was involved in:

- development and optimisation of the electromagnetic calorimeter of the Obelix experiment [8]. Here, he worked on the reconstruction of electromagnetic clusters, the separation of charged from neutral clusters, the slow control software for high voltage system and gas fluxing, and the realization of the trigger system;
- development and optimisation of the scintillating fiber sampling calorimeter of the Hera-B experiment [9]. He collaborated on the management of both readout electronics and the trigger system, the implementation of a software to control data quality simultaneously providing a real-time alarm and warning system in the case of any malfunctioning, and the implementation of a system to separate signals from electromagnetic and hadronic clusters;
- development and optimisation of the Cerenkov LUCID detector to measure luminosity within the ATLAS experiment. He collaborated on the first phase of beam tests by analyzing the data obtained on prototypes of the detector: the analysis of the data made it possible to test the performance of the various prototypes and make the necessary modifications to obtain the best results in terms of both precision in measuring the amount of light and speed of response (a required feature since the luminosity has to be provided continuously during data acquisition). Of particular interest it is the study of the signal acquired by photomultipliers in its deconvolution between single and multiple photon contribution;
- development of a new method for the reconstruction of high transverse momentum tops where standard methods of jets reconstruction are highly inefficient. The method is based on a maximum likelihood criterion

between the jets reconstructed by the apparatus and a set of specially generated tops ('templates');

- optimisation of the performance of the FOOT apparatus through Monte Carlo studies and analysis of acquired data [10]. In particular, the studies carried out on test beams have made it possible to achieve absolute accuracy on time-of-flight measurements of less than 50 ps and relative accuracy on energy better than 2%;
- participation in the analysis on the discrimination of neutron-gamma signals through the use of a BC-501 plastic scintillator;
- participation in the Monte Carlo analysis to define the main characteristics of the RIPTIDE experiment, such as geometry, active volumes, associated optics and materials in order to make the detector as efficient as possible. The main backgrounds from collisions with the carbon in the scintillator were also considered (the RIPTIDE-related references can be found in the text).

From 2008 to 2013, Roberto Spighi held a course in mechanics at the University of Bologna in the Department of Computer and Energy Engineering. At the Department of Physics and Astronomy of the same university, he runs a course in *Electromagnetism* at the Physics Bachelor degree from 2019 and a course in *Application of nuclear physics to medicine* at the Physics Master degree. Student satisfaction for both courses exceeds 90%. The course at the Master degree is particularly popular among students, since many of them (15 per year on average) ask to do their thesis work in this field. In 2019-2020, he held also a hadrontherapy course for Physics PhD students. Roberto Spighi has also been involved in outreach events by organizing "La scienza si fa in 4" in 2009, the European Researchers' Night in 2014 and Masterclasses from 2011 to 2015 in Bologna. In collaboration with other colleagues, he won a science outreach project within the INFN Third Mission Coordination Committee "Physics Involving People - 2020" call, for the support of initiatives to disseminate scientific culture. This project, funded with 8,000 euros, is called PATH (Particles Accelerator Technologies for Health) and it aims to raise awareness of hadrontherapy. Over the past 15 years, he has held over 40 seminars in schools at all levels (from primary to university) explaining a wide variety of physics topics in various classes.

Pubblicazioni selezionate di Roberto Spighi

[1] OBELIX Coll. “Protonium annihilation into KS KL at three different target densities”, Phys.Lett. B386 (1996) 486
[2] HERA-B Coll. “kinematic distributions and nuclear effects of J/psi production in 920 GeV fixed-target proton nucleus collisions”, Eur. Phys. J. C60, 2009, 525
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[4] ATLAS Coll “Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in sqrt(s) = 8 TeV proton-proton collisions using the ATLAS detector” Phys. Rev. D 93 (2016) no.3, 032009 10.1103/PhysRevD.93.032009
[5] ATLAS Coll “Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector”, Phys.Lett. B784 (2018) 173-191
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[7] CovidStat Group “A statistical analysis of death rates in Italy for the years 2015–2020 and a comparison with the casualties reported from the COVID-19 pandemic.” G. Bonifazi et al. Infectious Disease Reports, Volume 13, 7 February 2021, doi:https://doi.org/10.3390/idr13020030, arXiv: 2102.01629
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[9] HERA-B Coll. “The electromagnetic calorimeter of the Hera-B experiment”, Nuclear Inst. and Methods in Physics Research, A 580 (2007) 1209
[10] FOOT Coll. “Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment”, G. Battistoni et al. Front. Phys. 8:568242. doi:10.3389/fphy.2020.568242

RICHIESTA FINANZIARIA

Richiesta finanziaria, dettagliata e per sede, per il primo anno di attività del progetto.

- Travel Expenses: 1 kE for 2 in-person meetings in Bologna (for the LNF researcher).
- Inventory and apparatuses construction:

1. 7.5 kE for a second CMOS high frame rate camera, similar to the CYCLONE 2000 already purchased;
2. 1.5 kE for 2 commercial optical systems (two Canon RF 35mm F1.8 IS MACRO ST macro lenses);

https://store.canon.it/canon-obiettivo-canon-rf-35mm-f1-8-is-macro-stm/2973C005/;

- Consumables:
1. 1 kE cables, connectors, supports, ecc.;
2. 1 kE realization of a black box to characterize light sensors;
3. 1 kE lens and mirrors to be used as alternative to commercial optics (item in the previous section);

Stima di richiesta finanziaria per gli anni successivi

The requests for the next two years may range between a few kE to a maximum of 50 kE. More in details:

- Second year: if required, the request for the MCP image intensifier is 30 kE. If required, the request for the third CMOS camera CYCLONE 2000 is 7.5 kE. Consumables 2 kE, missions 1 kE.
- Third year: missions 5 kE to perform tests at neutron facilities as for example n_TOF and/or hadrontherapy centers like CNAO. Consumables 1 kE.