ERASMUS MUNDUS MASTER IN NUCLEAR PHYSICS
Academic Year 2024/2025

MASTER THESIS PROPOSAL

TITLE: Transport solutions for I-LUCE: the INFN-LNS laser-driven acceleration facility

SUPERVISOR: Dr G A Pablo Cirrone

SUPERVISOR contact- email: pablo.cirrone@lns.infn.it
Telephone:

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT
(just few lines 5-10 explaining briefly the idea of the proposed work and the place where it will be developed).

** This is a thesis work envisaging experimental measurements campaigns at International laboratories

ABSTRACT

Plasma-based accelerators use the strong electromagnetic fields that can be supported by plasmas to accelerate charged particles to high energies. Accelerating field structures in plasma can be generated by powerful laser pulses or charged particle beams.
At INFN-LNS a new high-power short-pulse laser system will be installed in the next years. It will be part of a new facility (I-LUCE: INFN Laser induced particle acceleration) where the laser will be dedicated to particles (electrons and ions) acceleration.
Accelerated particle must be then transported in vacuum and air up to the irradiation point where irradiations will be performed.
The work here proposed is related to the study and implementation of new transport solutions of laser accelerated particles. The developed solutions will be then implemented in the new facility that is in construction at INFN-LNS.

TITLE: Modelling parameters of interest in radiobiology (LET, RBE) using a Monte Carlo approach at both macro and micro-dosimetric scale.

SUPERVISORs: Dr G A Pablo Cirrone, Dr Giada Petringa

SUPERVISOR contact- email: pablo.cirrone@lns.infn.it; Giada.petringa@lns.infn.it

Telephone:

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

A reliable prediction of the spatial Linear Energy Transfer (LET) distribution in biological tissue is a crucial point for the estimation of the radiobiological parameters on which are based the current treatment planning. Nowadays, the accuracy and approach for the LET calculation can significantly affect the reliability of the calculated Relative Biological Effectiveness (RBE).

Monte Carlo (MC) technique is considered the most accurate method to account for complex radiation transport effects and energy losses in a medium. However, as a computation method, the accuracy and precision of the MC calculation result strongly depend on the physics interaction cross sections applied as well as the simulation algorithms used and the transport parameters are chosen. In this framework, the goal of the project consists of the development, study and validation of a completely new open-source tool based on Geant4 code for the calculation of the LET-track, LET-dose and RBE distributions of therapeutic proton and ion beam completely independent of transport parameters.

TITLE: **INVESTIGATION OF THE ANEUTRONIC PROTON-BORON FUSION REACTION IN PLASMA FOR ENERGETIC STUDIES**

SUPERVISORs: Dr G A Pablo Cirrone

SUPERVISOR contact- email: pablo.cirrone@lns.infn.it;
Telephone:

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

The interaction of protons with 11B atoms triggers the following aneutronic fusion reaction:

$$11B + p \rightarrow 3\alpha + 8.7\ \text{MeV}$$

In such reaction, the final product is the generation of three energetic α-particles having a large energy spectrum strongly peaked around 4 MeV. In particular a main resonance occurs at 675 keV proton energy in the lab frame, with a maximum cross section of 1.2 barn [1].
The absence of produced neutrons makes the pB fusion reaction particularly appealing involving the possibility to build an ultraclean nuclear-fusion reactor where no activation of the material and no radioactive wastes are expected [2]. Recently, the pB fusion reaction has become an interesting topic also for applications in the space domain as well as for the medical physics with the possibility to use the alpha particles generated by the reaction to improve the biological efficiency of protontherapy [3].
In this context, a huge effort of the researchers has been addressed on the possibility to induce the pB fusion reaction in plasma using the high power-laser matter interaction. The extremely high flux (up to 1012 p/s) typical of laser-accelerated proton beams [4], is indeed a great advantage allowing to enhance the reaction rate and the alpha particle production yield, which might be interesting also for the applications previously mentioned. Moreover, the theoretical as well as the experimental investigation of the energy and angular distribution of the reaction products, i.e. alpha particles, are particularly interesting for the study of the fusion reaction in plasma induced by high power lasers. Many experiments have been carried out so far demonstrating the increase of the alpha particle production (up to1011) in the laser-induced pB reaction in comparison with the classical scheme [5,6]. The activity here proposed, regards the experimental study of the pB fusion reaction in plasma and of the alpha particles yield, angular and energy spectrum using innovative detectors through the systematic variation of the following fundamental parameters: laser energy and pulse duration, contrast, target thickness, target material and structure. A particular effort will be addressed to develop new solutions for the on-line and simultaneous diagnostics of protons and alpha particles. A part of the experimental as well as theoretical (through Monte Carlo simulations) activity could also be dedicated to the study the possible modification on the stopping power values of protons and ions when traversing extremely high-density and hot plasma.

References

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[2] H. Hora et al., Energy Environ. Sci. 3, 479 (2010).
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[4] A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys. 85, 751 (2013)
[5] A. Picciotto et al., Phys. Rev. X 4, 031030 (2014).
[6] L. Giuffrida al., Phys. Rev. E 101, 013204 (2020).

TITLE: Study and simulation of transport and diagnostics of very intense lasers for plasma-based acceleration of particles

SUPERVISORs: Dr G A Pablo Cirrone; Josè Suarez

SUPERVISOR contact- email: pablo.cirrone@lns.infn.it; jose.suarez@lns.infn.it

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

High-intensity lasers are used for particle (ions and electrons) acceleration in plasma-based interactions using different media, like gaseous and solid targets. Shortly, a high-power (>350 TW), ultra-short (<24 fs) laser facility will be established at the Laboratori Nazionali del Sud of INFN in Catania (Italy) with the main goals of developing new acceleration approaches and to study the laser-generated plasma behaviour. To have maximum efficiency and produce acceptable levels of numbers and energies of particles, we need to investigate the transport, focusing and general properties of such laser beams. The complexities of the transport system, including the vacuum tubes and chambers, diagnostic methods that assess energy density, pulse width, divergence, etc., need to be investigated through simulation and small-scale optical analogue studies. The student will need to develop model prototypes of the transport system and simulate the interaction of the high-intensity beams with different optical media along its path to the target. This is key to understanding how the beam properties are modified along its path, and what to expect when different design strategies are implemented. They also need to study the measuring systems based on the optical properties that need to be understood and simulate the expected parameters that will lead to an optimal interaction for secondary particle production.

TITLE: Towards the I-LUCE facility: Cutting-Edge PIC Simulation of Laser-Plasma Interactions in LWFA

SUPERVISORs: Dr G A Pablo Cirrone; Sahar Arjmand

SUPERVISOR contact- email: pablo.cirrone@lns.infn.it; sahar.arjmand@lns.infn.it

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

At the heart of the I-LUCE (INFN Laser indUCEd Radiation Facility) lies a high-power laser system with the capability to provide an astounding 500TW of laser power. This formidable power level facilitates robust interactions with matter and allows for particle acceleration. A pivotal feature of this laser system is its ultra-short pulse duration, clocking in at less than 25fs, coupled with a substantial energy output of 12J and a frequency of 10Hz. These exceptionally brief pulses are indispensable for realising high-intensity interactions and promoting effective particle acceleration.
In the pursuit of advancing laser-driven particle acceleration, this research employs Particle-In-Cell (PIC) simulation techniques to unravel the intricacies of Laser-Plasma Interaction within the Laser Wakefield Acceleration (LWFA) framework. This investigation is specifically tailored for the anticipated I-LUCE, where cutting-edge experiments in plasma physics

will be conducted. The PIC simulation is characterised by its high precision, leveraging advanced numerical algorithms and adaptive mesh refinement to model phenomena such as relativistic effects and non-linear plasma responses. The code's scalability ensures efficient utilisation of high-performance computing resources, aligning with the scale of experiments envisaged at the I-LUCE Facility. Diagnostic tools, including spectroscopic diagnostics and imaging capabilities, have been incorporated to glean comprehensive insights from the simulation results. The user-friendly interface enhances accessibility and collaboration among researchers, facilitating the exploration of various simulation parameters. Validation against experimental data is an integral aspect of this study, ensuring the reliability and accuracy of the simulated outcomes.
By expanding the frontiers of knowledge in laser-plasma interactions within the LWFA paradigm, this PIC simulation emerges as a crucial tool in readiness for experiments at the I-LUCE Facility. It constitutes a substantial contribution to the domain of advanced plasma physics research. The solutions derived from this simulation will then be implemented at the state-of-the-art facility currently under construction at INFN-LNS.

TITLE: Dosimetric approaches and detector developments for "Flash radiotherapy"

Towards the I-LUCE facility: Cutting-Edge PIC Simulation of Laser-Plasma Interactions in LWFA

SUPERVISORs: Dr Josè Suarez, G A Pablo Cirrone

SUPERVISOR contact- email: suarez@lns.infn.it; pablo.Cirrone@lns.infn.it

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

This is a thesis work envisaging experimental measurements campaigns at International laboratories

ABSTRACT

In the last decades, ion acceleration from laser-plasma interaction has become a popular topic for multidisciplinary applications and opened new scenarios in the protontherapy framework, representing a possible future alternative to classic acceleration schema. The high-intensity dose rate regime that can be obtained with this approach is also strongly attracting the radiation oncologist community thanks to the evident reduction of the normal tissue complication probability, this new radiotherapy technique was called "flash radiotherapy". One of the many challenges to bring laser acceleration to a clinical setting consists in the development techniques and technologies that allow for accurate dosimetry of a short and intense ion bunch length.

In comparison with conventional accelerators, dosimetry of laser-accelerated beams is an ambitious task. Conventional accelerators typically operate at quasi-continuous milliampere currents rather than proton bunches with a temporal structure of the order of nanoseconds. Several international collaborations and experiments have been launched in the last years aiming at exploring the feasibility of using laser-driven sources for potential medical applications. A collaboration between the LNS-INFN, ELI-Beamlines (Czech Republic) and Queen's University (Ireland) was recently established to develop and investigate new devices for diagnostic and dosimetric purposes for laser-driven ion beams.

TITLE: Modelling DNA damage with Geant4-DNA Monte Carlo simulations and comparison with radiobiological data.

SUPERVISORs: Dr Serena Fattori, Dr. G A Pablo Cirrone

SUPERVISOR contact- email: serena.fattori@lns.infn.it; pablo.Cirrone@lns.infn.it

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

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ABSTRACT

DNA damage studies are key investigations to understand the efficiency of radiotherapy treatments and move forward in improving them.
The Monte Carlo (MC) technique is considered a valid approach to estimating the DNA damage induced by radiation, both in a direct way, through physical interactions with the biological medium, and in an indirect way, through chemical reactions producing free radicals, that subsequently attack the biological medium.
However, as a computation method, the accuracy and precision of the MC calculation result strongly depend on the physics interaction cross sections applied, as well as the simulation algorithms used and the transport parameters chosen. In this framework, the goal of the project consists of realizing a series of Monte Carlo simulations reproducing DNA damage in different experimental conditions, varying the cell type and/or the radiation modality. The simulations will be performed with the use of the Geant4-DNA toolkit and the output of the simulation will be benchmarked against experimental data.

TITLE: Study of the water radiolysis effects in UHDR irradiations with the Geant4-DNA toolkit.

SUPERVISORs: Dr Serena Fattori, Dr. G A Pablo Cirrone

SUPERVISOR contact- email: serena.fattori@lns.infn.it; pablo.Cirrone@lns.infn.it

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

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Recent experimental research conducted on animal models has shown that radiation therapy utilizing an ultrahigh-dose rate irradiation (UHDR, i.e. ≥40 Gy/s) significantly boosts the radioresistance of healthy tissues while the control of tumours remains comparable to that achieved with traditional therapies. This increased radioresistance in normal tissues, known as the "FLASH" effect, might allow for treatment approaches that involve a substantial escalation of doses delivered to tumour areas.

However, the connection between the high-density energy deposition during a short time and biological responses is still not fully understood. Several hypotheses are under investigation, many of which look into the radiochemistry processes deriving from the radiation-matter interaction.

Radiation chemistry focuses on the chemical impacts of radiation on matter, including the indirect damage that may occur to biological systems through chemical reactions involving DNA or other biomolecules.

In this context, the investigation of the water radiolysis effect of UHDR irradiations is a very promising research field that could provide key information in the understanding of the FLASH effect.

In this framework, the goal of the project consists of realizing a series of Monte Carlo simulations to track the evolution of free radicals in the water radiolysis process under different irradiation conditions. The simulations will be performed with the use of the Geant4-DNA toolkit and the output of the simulation will be compared with literature data.

ERASMUS MUNDUS JOINT MASTER DEGREE IN NUCLEAR PHYSICS

UNIVERSIDAD DE SEVILLA

Co-funded by the Erasmus+ Programme of the European Union

TITLE: Machine Learning assisted Multiscale Simulation of Radiation-induced DNA Damage in Human Cells.

SUPERVISORs: Dr. G A Pablo Cirrone, Dr. Alberto Sciuto, Dr Serena Fattori

SUPERVISOR contact- email: pablo.Cirrone@lns.infn.it; sciuto.a@lns.infn.it, serena.fattori@lns.infn.it

UNIVERSITY/RESEARCH CENTER: Istituto Nazionale di Fisica Nucleare

ABSTRACT

ABSTRACT

In medical physics, radiation-induced DNA damage in human cells is crucial and of great interest. Simulation techniques have improved, but DNA-scale interactions remain difficult to represent. Macroscopic simulations like Geant4 have revealed radiation interactions, but they cannot capture the minute details of direct DNA damage and radiolysis-generated radicals. Geant4DNA, a Geant4 extension, captures these microscopic interactions but functions independently. This creates a gap in our understanding when visualizing radiation-induced damage at multiple scales.

This proposed research uses machine learning as a novel post-processing mechanism to bridge this gap. We hope to establish an indirect but powerful connection between macroscopic and microscopic views without intensive direct multiscale simulations. The study also plans to add particle types to increase simulation complexity and applicability. Combining computational physics and advanced machine learning should help us fully understand how radiation affects things on many levels, which will lead to better prediction models and treatment plans.