Title of the Thesis: Detector developments for radiation physics applications at GIP Arronax

Context :

The Arronax facility, located at Saint-Herblain (Nantes-France), posses ahigh energy, high intensity muti-particle cyclotron that can accelerate protons, deuterons and alpha particles. The cyclotron has been designed for radionuclide production for nuclear medicine applications[1]. The beam is composed of bunches of ions with duration of 3ns and separated by 33 ns each. The maximum energy available is 70 MeV for alpha particles and protons and 35 MeV for deuterons. Beam intensity can range from a few ions/s up to several hundred of µA. The injection part of the cyclotron is equipped with an home-made beam pulsing system that can remove a specific number of bunches and as a result, the beam can be delivered with a train of bunches with a minimum duration of 1µs and a maximum repetition frequency of around 10 kHz. After injection and acceleration, the beam can be sent in different vaults based on the application foreseen.

One Vault, named AX, is dedicated to applied research. The large range of energies, beam intensities, temporal structures and light ions, enables research in various fields as for example preclinical studies in radiotherapy and in particularly to study the Flash effect linked to the sparing of healthy tissue by irradiation at ultra-high dose rates for short duration. The Arronax beam can simulate the protons present in cosmic rays, the solar wind and the belts around the Earth. Therefore, it is possible to characterize the radiation hardness of electronic components and detector for space missions. Finally, the high energy beam is suitable to perform ion beam analysis on cultural heritage objects such as silver coins, paintings and statuettes. For all these applications, to ensure accurate irradiation, the beam parameters, intensities, geometric profile and beam energy within the irradiated samples, must be precisely controlled.

Proposed thesis topic: DETECTORS DEVELOPMENTS

The goal of this work will be to accommodate on our beam lines several detectors to be able to get precise on-line measurements over a wide range of intensity, projectile and energies. A Faraday cup with a guard ring placed in a vacuum chamber is used to measure beam intensity as a reference and allows to calibrate all the detector prior their use.

Low beam intensity regime (≤ 1nA)

Intensity ranging from 1pA -1nA range is measured using a commercial thin ionization chamber or by measuring the fluorescence of X-rays emitted by metal foil. We have developed another method that uses a photomultiplier (PM) that detects the UV-visible fluorescence emitted by the nitrogen in the air exited by the passage of the beam. It is working near 1nA and above. The advantage of this method is that it does not interfere with the incident beam. Despite the signal of the PM is fast (rise time 2ns), the probability of detecting one bunch is low because the UV-visible production cross section is small. This technique needs to be developed further in order to determined its lower intensity limit.

A new detector based on a thin diamond semiconductor is being developed in collaboration with the "Laboratoire de physique subatomique et corpusclaire" in Grenoble -France. The diamond response is very fast (100ps rise time) with a high detection efficiency [2], enabling individual bunches to be detected and the number of particles per bunch to be measured. Questions about defaults created by irradiation needs to be tackled.

High beam intensity regime (up to 20 µA)

The method based on the PM described above is very suitable to monitor a continuous high intensity beam. The number of protons per bunch is large and each bunch can be detected above 1µA. Studies with various intensities has shown the linearity of the PM response over a wide range of intensities [3]. Using the pulsing system present in our cyclotron to send train of bunches, the number of protons in a train and its duration can be accurately measured. In parallel, diamond detector with a dedicated electronic is being developed to measure the train (protons number and duration) for beam intensities from 1 nA to 1µA. The two methods are complementary, and we want to equip our beam lines in AX with PMs placed near the exit window, where high beam intensity is expected, and with diamond prototypes, near the sample where beam intensity of less than 1µA is expected. The integration of these 2 detectors and the characterisation of the capabilities of the system will be part of this work.

Beam profile measurement

For low intensities (1pA to several nA), a transparent beam profiler, called PEPITES, developed in collaboration with the "Laboratoire Leprince Ringuet" in Palaiseau and the CEA-Saclay have been installed on our beam line. The detector is based on the emission of secondary electrons from a nanometric gold layer deposited on a thin layer of polymer and composed of two plans of strips with an active area 10 cm^2. The total water equivalent thickness of PEPITES is less than 10 µm. Therefore, disturbing of the beam, energy loss and angular spread, is negligible.

For high beam intensity (> 1nA), a new beam profiler, based on the detection of air fluorescence with several PMs, is under development in collaboration with the "Laboratoire Subatech - Nantes". The goal of the work will be to finalize these developments, characterize their performances and integrate them on our beam line as these two profilers are complimentary and cover the wide range of beam intensities available on our research beam line.

Beam range measurement

Finally, in some applications, it is mandatory to verify the beam range for proton beam. At the moment, this is checked with a commercial ionisation chamber (Markus, PTW) placed in a water tank. The tank is mounted on a translator axis (10µm precision) to scan the deposited energy along the beam axis. The Bragg curve is measured and compared with Monte-Carlo simulations to deduce the beam energy. This method is commonly used in proton therapy centers to check beam quality. In the case of an inhomogeneous medium, such as small animals, there is no method for tracking beam energy within the target. At Arronax, we have begun investigating the possibility of using the X-ray bremsstrahlung emitted by the irradiated medium and correlating it with the deposited dose. First results obtained on PMMA layers are encouraging [5]. The next steps are to verify the feasibility with real phantoms and to build an X-ray camera suitable for small animals. This system will then need to be integrated on our beam line.

Associated to all these detector developments, data acquisition system will need to be developed to facilitate the use of these different detectors for external users coming to Arronax to make experimental campaigns.

Supervisors: C. Koumeir and F. Haddad

Date of start: October 2024 **Duration** 3 years

Location: The PhD work will be conducted at the GIP Arronax (St Herblain, 44) in collaboration with Subatech (PRISMA team)

Competences :

We are looking to a student in physics or engineering with interest in physics, electronics, detector developments. Knowledge on computing is also mandatory (Python or C++)

REFERENCES

[1] F. Haddad et al, 2008. ARRONAX, a high-energy and high-intensity cyclotron for nuclear medicine. Eur J Nucl Med Mol Imaging 35, 1377–1387. https://doi.org/10.1007/s00259-008-0802-5

[2] S. Curtoni et al, 2021. Performance of CVD diamond detectors for single ion beam-tagging applications in hadrontherapy monitoring. Nucl. Instrum. Methods Phys. Res. A 1015, 165757. https://doi.org/10.1016/j.nima.2021.165757
[3] N. Servagent et al, 2022. PROTON BEAM FLASH ONLINE MONITORING AT ARRONAX CYCLOTRON. Physica Medica 94, S44-S45. https://doi.org/10.1016/S1120-1797(22)01529-0
[4] B. Boyer et al, 2019. Development of an ultra-thin beam profiler for charged particle beams. Nucl. Instrum. Methods Phys. Res. A 936, 29-30. https://doi.org/10.1016/j.nima.2018.09.134
[5] F. Ralite et al, 2021. Bremsstrahlung X-rays as a non-invasive tool for ion beam monitoring. Nucl. Instrum. Methods Phys. Res. B 500-501, 76-82. https://doi.org/10.1016/j.nimb.2021.05.013
[6] G. Saade et al, 2023. Ultrahigh-Dose-Rate ProtonIrradiation Elicits Reduced Toxicity in Zebrafish Embryos. Advances in Radiation Oncology 8, 101124. https://doi.org/10.1016/j.adro.2022.101124
[7] Y. Ghannam et al, 2023. First evidence of in vivo effect of FLASH radiotherapy with helium ions in zebrafish embryos. Radiotherapy and Oncology 187, 109820. https://doi.org/10.1016/j.radonc.2023.109820
[8] G. Blain et al, 2022. Proton Irradiations at Ultra-High Dose Rate vs. Conventional Dose Rate: Strong Impact on Hydrogen Peroxide Yield. Radiation Research 198, 318–324. https://doi.org/10.1667/RADE-22-00021.1
[9] A. Gillon et al, 2023. Elemental analysis by XRF and HE-PIXE on silver coins from the 16th-17th centuries and on a gilded crucifix from the 12th century. Phys. J. Plus 138, 945. https://doi.org/10.1140/epjp/s13360-023-04570-5
[10] M. Hazim et al, 2020. High energy PIXE: New experimental K-shell ionization cross sections for silver and gold and comparison with theoretical values from ECPSSR/RECPSSR models. Nucl. Instrum. Methods Phys. Res. B 479, 120-124. https://doi.org/10.1016/j.nimb.2020.06.028