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ANEM: The future neutron production target for Single Event Effect studies at LNL

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Summary. — The design of a fast-neutron ($E > 1\,\mathrm{MeV}$) irradiation facility, devoted to investigating neutron-induced Single Event Effects in microelectronic devices and systems, is under development at the 70 MeV, 0.7 mA SPES proton cyclotron at LNL (Legnaro, Italy). Here we report on the progress in the design of ANEM (Atmospheric-Neutron EMulator): a water-cooled rotating target capable of producing neutrons with an energy spectrum similar to that of the neutrons present at sea level. In ANEM the protons from the cyclotron alternatively impinge on two circular sectors of Be and W of different areas; the effective neutron spectrum is a weighted combination of the spectra from the two sectors. Thermal-mechanical Finite Element Analysis calculations of the performance of the ANEM prototype indicate that ANEM can deliver fast neutrons with an atmospheric-like energy spectrum in the 1–65 MeV energy range with a maximum integral flux $\phi_n(1\text{–}65\,\mathrm{MeV}) \simeq 10^7\,\mathrm{n\,cm^{-2}s^{-1}}$ at 6 m from the target, a very competitive value for Single Event Effects testing.

PACS `61.80.Hg` – Neutron radiation effects.
PACS `61.82.Fk` – Radiation effects on semiconductors.
PACS `29.25.Dz` – Neutron sources.

1. – Introduction

A new variable energy high-current proton cyclotron (35–70 MeV; 0.75 mA) is being commissioned at the LNL SPES facility [1] in Legnaro, Italy. The proton beam can also be used to operate a compact NEutron and Proton IRradiation facility (NEPIR) [2].

The original purpose of NEPIR is to study Single Event Effects in electronic devices and systems induced by atmospheric neutrons (neutrons present at flight altitudes and at sea level, generated by cosmic rays), and by solar protons. At present the NEPIR project

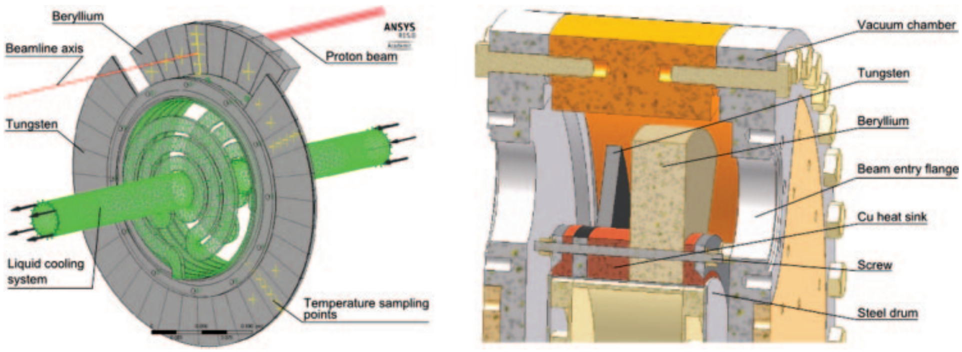

Fig. 1. – Left: Rendering of the rotating target layout: in red the proton beam striking the Be sector, the green highlighted volume is the water cooling circuit. The markers indicate the position of the temperature sampling points used in the transient simulations. Right: Close up view of a section of the rotating target.

foresees three different tools: the Atmospheric Neutron EMulator (ANEM), described in this work, a multi-purpose Quasi Mono-Energetic (QMN) beam with a controllable discrete energy peak in the 20–70 MeV energy range (by degrading the minimum 35 MeV energy protons) [3], and a direct proton beam in the same energy range.

2. – ANEM: the Atmospheric-Neutron EMulator

ANEM is a specialized neutron production target capable of delivering a continuous energy neutron beam, with an atmospheric-like energy spectrum in the 1–65 MeV energy range, uniform on a 60 cm diameter area 6 m downstream. The ANEM system (fig. 1) is a composite target made up of two complementary sectors, one of Be, the other of W, mounted on a rotating steel drum cooled by the water cooling circuit. These two separate sectors alternatively intercept the proton beam (fig. 1, left). A 2 cm thick copper ring, brazed on the drum surface and sandwiched between the coaxial rings of the two sectors, insures the thermal contact with the cooled drum (fig. 1, right).

The 5 mm thickness of the W has been chosen to fully contain the proton beam. On the contrary, the Be thickness (24 mm) was chosen to allow the protons to exit, to avoid blistering; the spent protons are stopped by a 2 mm thick copper plate located 4 cm downstream.

The effective neutron spectrum is then shaped to resemble the atmospheric one in the 1–65 MeV range by optimizing the relative areas of the two sectors via MCNPX simulations [4]. The best solution uses 19% Be and 81% W.

3. – Finite Element Analysis with ANSYS

The goal of ANEM is to achieve a maximum integral flux $\phi_n(1\text{–}65\,\text{MeV}) \simeq 10^7\,\text{n cm}^{-2}\text{s}^{-1}$ at a distance 6 m from the target, achievable with a 26 μA proton current, a power of 1.8 kW in a small volume. Calculations to optimize the target design were performed using the ANSYS CFX module of the ANSYS Workbench Platform [5].

We started by calculating the time-averaged regime temperature reached by the different sectors by performing steady state simulations. The deposited heat (fig. 2 left) was modeled as a power density source located in the volume defined by the intersection of the

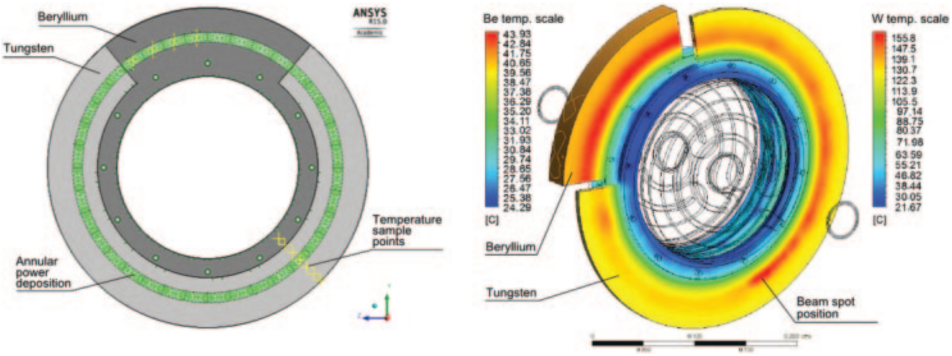

Fig. 2. – Left: Schematic representation of the power deposition in the steady state simulations. Right: Snapshot of the temperature map of the W sector during a transient simulation. Notice the position of the beam heating the target at 5 oclock and the heat trail deposited by the beam while the target rotates counter-clockwise.

two sectors with the time-averaged beam, an annulus ($R_{min} = 12.5\,\mathrm{cm}$, $R_{max} = 13.5\,\mathrm{cm}$) centered on the rotation axis. In the plane of the target the power deposition was uniform. To model the power deposition inside the target along the direction of the proton beam, each sector was divided into slices. Different amounts of energy were deposited inside each slice according to the Bethe-Bloch ionization profile of the protons.

This energy deposition is effectively a worst-case scenario as it results in a more concentrated energy deposition: the transverse profile of the flat energy deposition is narrower than that of a gaussian profile with a FWHM = 1 cm, and there is no lateral spreading as the beam propagates into the target.

This approach gives the time-averaged temperature of the Be and W sectors as it neglects the temporal effects induced by a gaussian pencil-like beam (FWHM = 1 cm) striking a spot on the rotating target.

Using a conservative reference value for the delivered power of 2.5 kW (proton current of 35 μA), a rotation speed of 60 rpm and a cooling water temperature of 10 °C, the calculated maximum temperature values are 44 °C for the Be sector and 153 °C for W. The time required for the two sectors to reach 90% of these temperatures, starting from room temperature, are 3 minutes for the Be sector and 2 minutes for the W one. In the 0.5–5.0 kW power interval, the maximum temperatures of both sectors are directly proportional to the delivered power. Preliminary ANSYS modelling indicates that the prototype can conservatively handle the 2.5 kW delivered by such a beam [6].

4. – Transient analysis

To eventually estimate the stress induced by the thermal expansion of the heated elements, a series of transient simulations were performed including effects induced by a rotating gaussian beam spot (FWHM = 1 cm). The quantity to evaluate was the range of the temperature oscillation induced by the periodic passage of the beam on the Be and W sectors and the dependence on the rotation speed. This information will be eventually used to determine the stress and fatigue experienced by the target and to choose a suitable rotation speed and cooling water flow.

The starting value of the rotation speed in the transient simulation was one revolution per second (1 Hz). The circular annulus of fig. 2 used for the steady state analysis was

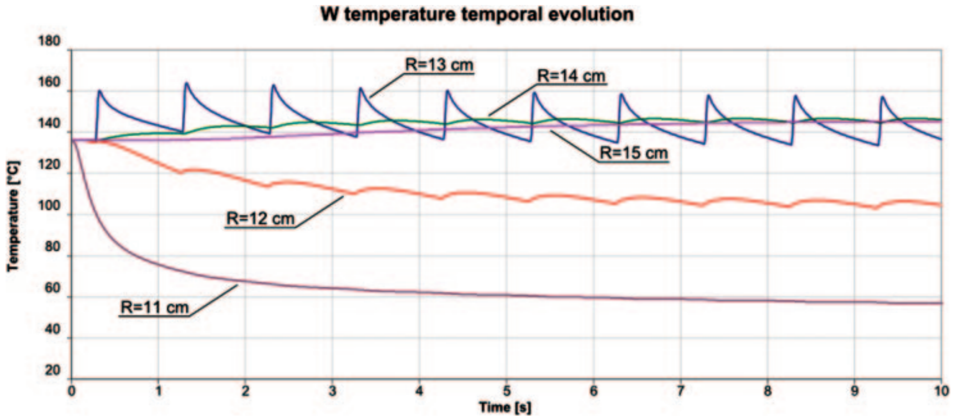

Fig. 3. – Temporal evolution of the temperature of the W sector sampled in points with different distance for the rotation axis (indicated in the callout) along the same radius (fig. 1).

segmented into 36 portions (10° wide) and the 2.5 kW power of the proton beam was deposited sequentially, one at a time, into the corresponding sector segments. On each segment the beam deposits energy for 27.8 ms (1 s/36 segments): the so-called beam-On time. The ANSYS timestep parameter chosen for this simulation was 1/3 of the beam-ON time. This kind of simulation requires very long times and an accurate optimization of the ANSYS timestep parameter. To speed up the evolution towards the regime conditions, the initial temperatures of the whole Be and W sectors was set to be uniform and equal to 90% of the time-averaged temperatures calculated with the steady state simulation. Figure 2, right shows a snapshot of the temperature map of both Be and W sectors, taken when they are close to the regime temperature. The position of the beam is at 5 oclock and it is moving clockwise; the heat trail of the deposited energy is clearly visible.

Figure 3 shows the temperature recorded within the W sector in points aligned along the same radius (fig. 1, left) at different distance from the rotation axis as a function of time. The point located at 13 cm from the axis, where the beam strikes the sector, experiences the most important temperature oscillations: 24 °C. Sample points located at greater distances from the axis experience smaller oscillations around the same time-averaged value: 148 °C, very close to the 153 °C value calculated with the steady-state analysis. The temperature of points located closer to the axis quickly converge to their regime temperature. The same plot for the Be sector shows a maximum temperature oscillation of 4 °C around an average value of 48 °C (the steady-state calculation foresaw 44 °C). For both sectors, the temperature oscillation decreases linearly with increasing rotation speed; it is lower by a factor ~ 7 for a rotation frequency of 10 Hz.

5. – Conclusion

This contribution is a status report of the ANEM target at the SPES 70 MeV, 0.7 mA proton cyclotron. The goal is to deliver an atmospheric-like neutron beam with a maximum integral flux $\phi_n(1\text{–}65\,\text{MeV}) \simeq 10^7\,\text{n cm}^{-2}\text{s}^{-1}$ at distance 6 m from the target. This can be achieved with 19% of the target area made of 24 mm thick Be and 81% of 5 mm thick W, with the cyclotron at full energy and with a proton current of 26 μA (1.8 kW proton beam power on the target). ANSYS was used to evaluate the temperature distribution inside the target and its oscillation due to the target rotation. We will use this moded to evaluate the mechanical stress inside the materials and to optimize the rotation speed and cooling water flow. Thermal tests on a realistic prototype will be performed to validate and tune the simulations.

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