CERN ATS seminar on 30/03/2023: https://indico.cern.ch/event/1265906/

High Power Targetry R&D program with the RaDIATE Collaboration and target perspectives in the framework of Snowmass

by Frederique Pellemoine (FNAL)

Number of participants: 25 persons in the Kjell Johnsen Auditorium (30/7-018) + 2 people connected through Webcast

A recording is also available on the indico site

Frédérique started by presenting the activities ongoing at FNAL and reminding that for the Accelerator Neutrino Program, scientists create muon neutrino beams by smashing protons from the main injector accelerator into a graphite target.

For the neutrinos at the Main Injector (NuMI), the target station is able to operate with 1-MW proton beam since FY21 (120 GeV/c proton beam into a 1.2 m long graphite target).

Neutrino target NOvA / AIP (0.7 / 1 MW) operates since 2012. The target is in a canister with Helium atmosphere to avoid the oxidation of the graphite and presents Be windows.

Future neutrino target LBNF-DUNE (1.2-2.4 MW) will be made of a graphite target in a Ti-alloy based container **=> 2.4 MW target will require significant R&D to guide design and material choice**

High power targetry 6 challenges:

- **Heat removal**
- **Physics performance**
- **Operational safety**
- **Thermal shock**
- **Radiation damage**
- **Storage and disposal**

Radiation damage and thermal shock

- Radiation Damage: Displacements in crystal lattice expressed as Displacements Per Atom (dpa) leads to physical property and microstructure changes
- Thermal Shock: Sudden energy deposition from pulsed beam, stress waves may lead to plastic deformation, cracking and fatigue failure
- Thermal Fatigue: Cycling loading environment leads to early failure and reduced lifetime

Then Frédérique passed to the 2nd topic of her seminar that was the presentation of the RaDIATE Collaboration for which she is the Program Manager. **RaDIATE collaboration = RAdiation Damage In Accelerator Target Environments, since 2012 with FNAL as leading institution**

- Objective
  - ★ Harness existing expertise in nuclear materials and accelerator targets
  - ★ Generate new and useful materials data for application within the accelerator and fission/fusion communities
- Activities include
  - ★ Analysis of materials taken from existing beam-line as well as new irradiations of candidate target materials at low and high energy beam facilities
  - ★ In-beam thermal shock experiments

RaDIATE common materials of interest: Ti, C, Be, Si-SiC, High Z (including Tungsten etc.), Novel Mat. => Many more materials: Mo-alloys, SS, Al-alloys, Ni-alloys, Ir, etc.

1st approach at FNAL: autopsy and examination of used target (failed graphite neutrino production target) => Radiation damage was indeed the cause of the failure for such a target

- Slide12: from their computation, the issue should appear at ~ 0.7 dpa and they measured ~ 2-5 dpa, so there are other effects which are not included in their simulations
- Slide 13 confirmed the amorphization of graphite in the beam erea
- Slide 14: NuMI beam windows made of Be were also analyzed and radiation damage were also observed (significant change in hardness even at 0.1 dpa, transition from transgranular fracture to grain boundary/mixed mode fracture)

High-power targetry 4 R&D approaches at FNAL

- **In-beam studies**
  - ★ BNL-BLIP (Brookhaven Linac Isotope Producer), with Post-Irradiation Examination (PIE) at PNNL (Pacific Northwest National Laboratory)
  - ★ 6 RaDIATE participants including CERN, over 200 specimens
  - ★ World 1st high-cycle fatigue testing of irradiated Titanium at FNAL
  - ★ Collected valuable experimental data with several materials from several participants, CERN (with HiRadMat). For in-beam thermal shock experiment with pre-irradiated specimens compared with non-irradiated one
- **Alternative methods** => low energy Ion Beam Irradiation to High dpa; Plans for materials irradiation studies with Birmingham MC40 Cyclotron; Graphite irradiation studies with heavy ions; He implantation of Beryllium and graphite; World 1st response of irradiated materials to thermal shock by high intensity proton beam at CERN's HiRadMat facility. HRMT60 – RaDIATE experiment completed in 2022 with ~120 material specimens tested (graphite, Ti alloys, Beryllium, Nanofiber mats, High-Entropy alloys, Sigraflex, TFGR tungsten, SiC/SiC composite). Disassembly completed Tuesday and post-irradiation examination planned at several institutions
- **Novel target materials** => DOE Early Carrier Award to cover development of High-Entropy Alloy (HEA) development with UW-M (University of Wisconsin – Madison) and Nanofiber electro-spinning at FNAL

- **Modeling** => Ab Initio and molecular dynamics material modeling; Analysis and mitigation of thermal issues in a nanofiber target;

Summary

- Future high-power beams present critical target facility challenges
    - ★ Understanding material behavior under intense multi-MW beams is high priority
    - ★ Need for in-beam tests to enable next-generation multi-MW target facilities
        - ✳ Autopsy and analysis of failed targets
        - ✳ Prototypic beam irradiation
        - ✳ Alternative beam irradiation
        - ✳ Thermal shock tests at CERN's HiRadMat facility
- Materials R&D essential to help design robust targetry components and maximize primary beam power on target and secondary particle production
    - ★ Globally coordinated R&D activities are producing useful results
    - ★ Alternative irradiation facilities, material testing and characterisation methods essential to support R&D program
    - ★ Explore Novel material to support future high-power Targetry components

In the third and last part, Frédérique briefly reported about the SnowMass2021 process => AF7 - Targets report (https://snowmass21.org/accelerator/technology/start), for which Frédérique acts as co-convener with Charlotte Barbier (ORNL)

- Reminder: P5 (Particle Physics Project Prioritisation Panel) makes recommendations on the next 10 years of the US particle physics program within the 20 year context to HEPAP (High Energy Physics Advisory Panel), which advises DOE and NSF. It builds on the extensive community involvement in the Snowmass study
- 5 workshops and 4 white papers
    - ★ Kavin Ammigan et al., Novel Materials and Concepts for Next-Generation Targetry Applications, 2022 Snowmass White Paper, https://doi.org/10.48550/arXiv.2203.08357
    - ★ Barbier C. et al. Modeling Needs for High Power Target, 2022 SnowMass22 white paper, https://doi.org/10.48550/arXiv.2203.04714
    - ★ F. Pellemoine et al., Irradiation Facilities and Irradiation Methods for High Power Target, 2022 SnowMass22 white paper, https://doi.org/10.48550/arXiv.2203.08239
    - ★ K. Yonehara, Radiation hardened beam instrumentations for multi-Mega-Watt beam facilities, 2022 Snowmass22 white paper, https://doi.org/10.48550/arXiv.2203.06024
- **Main messages**

★ Development and validation of alternative beams to simulate high-energy proton irradiation

★ Development or upgrade Post-Irradiation Examination (PIE) facilities that will allow to test novel materials or extend the database for more materials (unirradiated and irradiated)

★ Development and validation of numerical tools to predict radiation damage

★ Development of radiation-resistant sensors for better numerical validation of the structural and thermal simulations and for potential Machine Learning (ML) and Digital Twin applications, and target health monitoring

★ Strengthen the high power target community through the RaDIATE collaboration and High Power Targetry workshop

★ Leverage the synergy with other communities facing similar challenges (light source facilities, Accelerator Drive System or ADS, and fusion/NSUF)

★ Development of DOE sponsored user facility program for irradiation stations and PIE facilities within the US

Q&A session

Following a question from Roberto Losito about the low temperatures operation of target, Frédérique answered that in the future with LBNF they will use He for cooling to have higher temperatures.

Following a question about the total power inside the target, Marco Calviani clarified that it is not the full power from the beam and that usually it is ~ 10-15%. Note from Frédérique: power deposited in target could be between 5 to 25 % of primary beam power depending on the target.

A question was raised about what is more important: the Bragg peak or dpa (slide 26)? => They avoided the Bragg peak (see top right picture) to have a more homogeneous dose in the depth of studied material (0 to 4 microns): it would be better to work at the peak but they cannot reach it.

Question from Antonio Perillo Marcone about slide 12 and the comparison between predicted and measured dpa. Frédérique reminded that, simulation predicts dpa in materials, there are also some other defects due to transmutation gas production (embrittlement), fatigue, corrosion, etc., which are not taken into account from MARS. The variation of the G band position is a great tool to predict the true defect amount compared to equivalent dpa.

Discussion about slide 38 and question if we expect the same effect with nanomaterial. With air inside the media, with 1 pulse the damage observed is probably due to the air rapid heat from beam and fast expansion inside the media (explosion?). It is confirmed on slide 31, similar behavior was observed in the Sigraflex specimen. We need more investigation to mitigate this effect.

Alessandro, Elias, Michele, Thierry (and Frédérique)