A Superconducting Cyclotron Accelerator Based Materials Test Center for Surface and Bulk Radiation Damage Studies

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Summary

A novel, superconducting cyclotron accelerator-based materials testing center is proposed for simulating bulk radiation damage in material (1-3 mm thick) and achieving at least 100 dpa per year proton dose or several hundred dpa/month heavy ion dose. The center will provide critical materials science that addresses fundamental questions related to radiation damage in fusion systems, by providing required data that approach those from full 14MeV neutron sources at a fraction of the cost of larger facilities (SNS, IFMIF). The center will exploit recent advances in superconducting magnets, advanced gas-jet cooling for heat removal, computer-aided design, rapid prototyping and manufacturing, as well as miniaturization, to design the smallest and cheapest proton, helium and heavy ion accelerators for the energy range of 30-100 MeV, which will achieve volumetric irradiation of materials. The three-beam center will allow independent variation of helium and proton dose rates (He/dpa ratio), while also providing static or dynamic active mechanical loading of material. The center will be fully equipped for sample production, irradiation, and subsequent analysis. Advanced instrumentation for analysis will include a full range of analytical analysis tools (SEM, TEM, FIB, Atom Probe, SIMS, etc.), aimed at direct visualization of radiation damage structures, and direct validation & verification of simulations of radiation damage in fusion systems.

1. Introduction: The study of materials in radiation environments is critical for the development of fusion systems. In fusion reactors, neutrons typically damage materials through two mechanisms: the displacement of atoms in the material, and the accumulation of helium from (n,α) reactions and α-decay of activated nuclei. These processes depend strongly on the neutron spectrum and the physical and nuclear properties of the material. Since neutrons have relatively long mean free paths, the damage occurs within the bulk of the material, causing changes to the material's atomic structure leading to macroscopic changes affecting its mechanical and thermal properties. The accumulation of helium eventually degrades the material on its own but also stabilizes voids, which aggravates swelling.

The ability to test fusion relevant materials in environments with high neutron fluxes is limited to research reactors and high energy accelerator based techniques, such as spallation and D-T target fusion. However, these methods induce radiation damage at similar or lower rates than the power reactors themselves. Since most materials in fusion applications must have lifetimes of several tens of years or greater, the development of new methods of testing materials with high neutron or neutron-like damage rates will greatly benefit the field of nuclear material science in that, done properly, accelerated damage rates can allow exploration of DPA regimes at end of life on substantially shorter timescales.

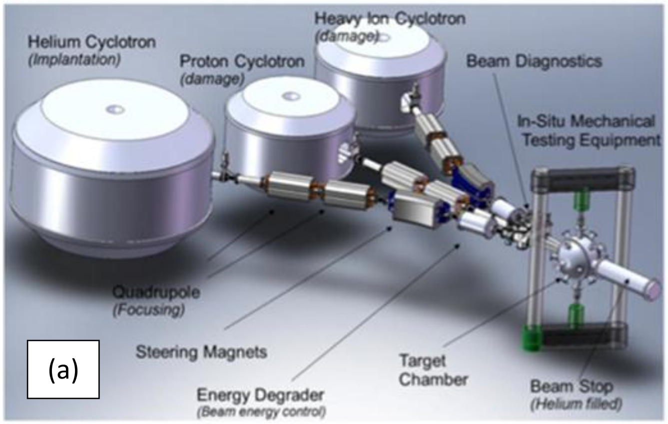
Simulation of neutron damage with ion irradiation is an established technique [1, 2]. The long range Coulomb interactions of the protons increase the damage rate per ion by several orders of magnitude as compared to neutrons. This allows for accelerated radiation damage rates when irradiating materials. However, these techniques are limited by the difficulty of heat removal from samples and are constrained by low energy (< 5 MeV) beams which can only produce near surface (< 100 μm) damage in materials. To simulate neutron-like damage effects that are uniform throughout the bulk of the sample, high energy proton beams (≈ 30-40 MeV) are required. With recent developments in accelerator technology, it is now possible to achieve these high energies with compact (∼2 m diameter) superconducting cyclotrons instead of linear accelerators (10-100m length).

2. Accelerator Based Materials Test Center

2.1 Beam Lines: There is a need for a materials testing facility that can accurately and quickly access material properties. In order to achieve relevant DPA values in a reasonable time, the facility would have to achieve at least 50-100 dpa per year. Currently, there are no fast spectrum or fusion material test facilities, and there are only two major thermal spectrum test facilities (ATR and HFIR). The International Fusion Materials Irradiation Facility (IFMIF) has been proposed for construction within the next decade. IFMIF would use a high energy deuteron beam and a tritiated target to produce fusion neutrons and would have the ability to test hundreds to thousands of samples at once. However, the projected cost of IFMIF is estimated to be several billion dollars, and it would be limited to damage rates on the order of 10-20 dpa per year of operation.

A novel accelerator based materials test center is proposed for simulating bulk radiation damage in material up to 1-3 mm thick. Superconducting cyclotrons will be used to accelerate three beams; helium, protons, and heavy ions. Protons can be used to simulate neutron damage, provided the Coulombic interaction is taken into account as needed to correlate with an equivalent level of neutron damage. Protons can be accelerated in a compact, superconducting cyclotron to high energies. A companion helium beam would allow for the uniform implantation of helium to simulate a second materials damage effect that occurs in fusion reactors. Independent control of the He/DPA ratio would thus be achieved. A third heavy ion beamline can provide for very rapid DPA rates for thin (<100 micron) samples. Figure 1 shows a schematic view of the three beam line facility. Also shown is a schematic of the target chamber. As mentioned above, the key features of the beam facility are the use of superconducting cyclotrons (high energy with small footprint) and gas jet cooling (high heat removal capacity). The high energy assures that the Bragg peak lies outside of the specimen, which results in uniform damage through the material of engineering significance.

2.2 Analytical Capabilities: The use of high energy beams will result in significant material activation. For this reason, the center will need facilities and a set of analytical instruments that can handle radioactive material. These instruments will include a complete analytical electron microscopy suite (Scanning Electron, Focused Ion Beam, Transmission Electron, Secondary Ion Mass, and Atom Probe Tomography). Specimen preparation, before and after irradiation, will be provided via a dedicated facility that includes hot cells (currently available via the MIT Nuclear Reactor Laboratory). In addition to post irradiation analysis, the center will allow for in-situ measurements during irradiation.



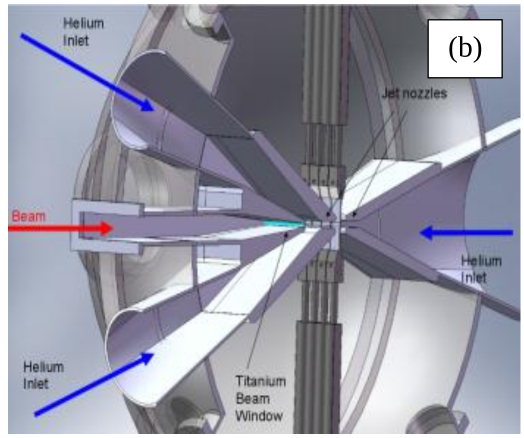


Figure 1. Triple cyclotron beam line for protons, helium, and heavy ions (a). Target chamber (b).

2.3 Additional Infrastructure: The proposed center would have the significant advantage of being co-located with several other facilities that would provide greatly enhanced overall capabilities when taken together. The combination of the MIT Nuclear Reactor Laboratory (hot cells, material handling experience), the Plasma Science and Fusion Center (overall fusion science expertise), Plasma Surface Interaction (PSI) Science Center (ion beam analysis capabilities), and the Alcator C-Mod Tokamak experiment along with the unique, industrial-like infrastructure (design, construction, operation of high performance vacuum systems) will result in a truly world class comprehensive fusion materials research nexus. Additionally, the infrastructure associated with these facilities and the experience in operating these facilities will serve to reduce programmatic risk as well as cost.

3. Other Considerations

3.1 Addressing Fusion-Specific Grand Challenges: The proposed center will provide a low cost approach to addressing the following fusion scientific grand challenges[1]:

1. CD1 - Develop a rigorous scientific understanding and devise mitigation strategies for deleterious microstructural evolution and property changes that occur in materials exposed to high neutron fluences and high concentrations of transmutation-produced gases from a 14 MeV peaked neutron source,
2. CD2 - Develop science-based design criteria that account for degradation of materials subject to severe time-dependent, thermo-mechanical, high temperature loadings, including effects of 14 MeV neutron irradiation,
3. CD3 - Comprehend and control the processes that drive tritium permeation, trapping, and retention in neutron radiation damaged materials with microstructures designed to store large amounts of helium in numerous, nanometer-scale bubbles.

3.2 Impact Beyond the FES Mission: While the center will be focused on the fusion environment, the variable energy nature and ion flexibility (He, Protons, heavy ions) would allow the center to simulate environments spanning fission and fusion reactors. The ability for

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[1] DOE/SC-0419, "Fusion Energy Science Advisory Committee Report on Opportunities for Fusion Materials Science and technology Research Now and During the ITER Era, Feb. 2012.

independently varying temperature, DPA rate, and He/DPA ratio, none of which could previously be decoupled in any other experiment, sets this facility apart from any other.

3.3 Context of Facility Related to World Effort in Fusion: The center would provide a "bridge" between what is currently available for radiation damage studies and what may be envisioned in the future. The center could be up and running in a fraction of the time required to build larger, non-accelerator based facilities. Needed data for fusion science could be obtained in a much more timely manner, which is critical to pushing the science forward. The center would become an international nexus for fusion materials science.

3.4 Construction and Operation Costs: The estimated capital total cost for the facility is $30M which includes the cost of the accelerator beam lines ($20M) and the analytical instrumentation ($10M). The estimated operational cost of the center is $7.5M/year. This includes staff and O&M.

3.5 Readiness of the Facility Concept: The keys to the success of the center are the successful design and construction of the compact cyclotrons using superconducting magnet technology and the successful design and construction of the target chamber. In particular, the heat removal concept using gas-jet cooling must be successful. Compact cyclotron technology is mature with the exception of the use of superconducting magnets. However, recent developments in this area indicate that this technology is ready and will be successful [4-6]. Gas jet cooling, while not used for the more conventional, low energy, LINAC machines, has been used in other applications in the fusion community and conservative analysis indicates that the heat removal capability will be adequate [7,8]. All other components are "off the shelf" items. We thus judge that the facility can be constructed successfully, but will require that the above engineering challenges be addressed to minimize programmatic risk.

4. Timescale: First beam in 2 years; full 3 beam facility in operation within 5 years.

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