PPPL- 4572

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November, 2010

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Princeton Plasma Physics Laboratory
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DEVELOPMENT OF AN EXTREME ENVIRONMENT MATERIALS RESEARCH FACILITY AT PRINCETON

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The fundamental understanding of material response to a neutron and/or high heat flux environment can yield development of improved materials and operations with existing materials. A concept has been advanced to develop a facility for testing various materials under extreme heat and neutron exposure conditions at Princeton. The Extreme Environment Materials Research Facility comprises an environmentally controlled chamber (48 m^3) capable of high vacuum conditions, with extreme flux beams and probe beams accessing a central, large volume target. The facility will have the capability to expose large surface areas (1 m^2) to 14 MeV neutrons at a fluence in excess of 10^13 n/s. Depending on the operating mode. Additionally (deuterium) beam line power of 15-75 MW/m2 for durations of 1-15 seconds is planned. The facility will be housed in an existing test cell that previously held the Tokamak Fusion Test Reactor (TFTR).

I. INTRODUCTION

The motivation for an Extreme Environment Material Research Facility is the need to expose large surface areas to extreme radiation and heat fluxes (up to 75 MW/m^2). The situation and need has been summarized in recent publications and the multiple references therein (1,2,3,4). Extreme environments can have a major impact on everything from the operation of nuclear reactors to satellites in space, and high-intensity proton accelerators. The change in material properties and the interplay between effects such as radiation-induced embrittlement, swelling and deformation of materials, including fatigue and fracturing that occur in response to thermal shocks presents unique materials challenges.

In response to this need, plans for an Extreme Environment Materials Research Facility are being advanced at Princeton. The facility will provide a large volume, 48 m^3, environmentally controlled chamber that can expose various targets to high heat, via deuterium beam injection, and neutrons over a square meter of material. The materials will be analyzed with in situ beam probes and instrumentation. The combination of high neutron energies and intense fluences in the facility is designed to enable the study of material(s) exposure to extreme conditions on an accelerated time scale, producing aging effects that would take decades to produce in a fission reactor, instead of days

A survey of existing centers for extreme environment material research reveal that few have capabilities for exposing large surfaces and objects comparable to those proposed for the subject facility, which could also provide for accelerated aging, thermal shock and integrated mechanical stressing. In the U.S., the closest comparisons in terms of research goals can be made with the Purdue University Center for Materials Under Extreme Environments (CMUXE) and the Oak Ridge National Laboratory facility for Materials in Extreme Environments, while internationally, extreme materials are studied at IPP Garching and by the Extremat collaboration. The concepts discussed herein have been utilized in the past, such as the use of D-T generated neutrons for small-scale intense sources in the Rotating Target Neutron Source. However, it is not clear that a facility exists to provide the environments to large sample(s) commensurate with the radiation and heat exposures required for accelerated time lapse testing.

II. DISCUSSION OF SCIENCE NEED

Facilities for testing materials under thermal environments are a key element in enabling the development for new materials for many applications. High-energy physics, fission and fusion reactor design, aerospace and mechanical engineering and other fields are confronting technical challenges related to material properties in extreme environments and the need for exposing materials to prototypical conditions for developing high-temperature radiation-resistant materials has been documented.[4]

The list of needs is extensive. The next generation of nuclear power reactors will require corrosion resistant alloys, which will be exposed to temperatures in excess of 1000 ^{o} C for extended periods of time. First wall surfaces in pulsed (5Hz – 16 Hz) direct drive and indirect drive inertial fusion energy (IFE) reactors will be subjected to temperatures exceeding 800 ^{o} C with the added complication of being subjected to He ion implantation. Diverters in magnetic fusion reactors will be subjected to thermal power loads along the strike points on the order of 15 MW / m^2 to 20 MW / m^2 for long-term duty cycles.

The consequences of high neutron fluences on materials are also seen in the basic energy science research. At the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, 7 TeV proton beams will be collided at an intensity of $10^{34}/cm^2/s$ yielding 10 year integrated radiation doses of 10 MRad delivered to the particle detectors.

Data is needed for refining predictive failure modes (modeling) in extreme environments, as well as providing a technical platform for the development of new solutions, including the investigation of repair mechanisms. There is a need to investigate and understand damage evolution mechanisms that lead to material failure under extreme heating. Additionally, a need exist to perform such analysis under accelerated temporal parameters as many material failure concerns appear after decades of expose to stresses and other environmental factors. New models of high-temperature deformation and fracture are needed for creep-fatigue interaction and elastic-plastic, time-dependent fracture mechanics. Similar needs exist for materials with low ductility, pronounced anisotropy, composites and multilayers.

The opportunity to explore the interplay between environments and the impacts on properties will be needed if future materials and alloys deployed in extreme environments are to be identified. For example, exploring high heat flux sources and mechanical stressing in large volume rarified gaseous environments will provide unique capabilities for aerospace engineering material studies with implications for the design of re-entry vehicles.

III. FACILITY DESCRIPTION

The Extreme Environment Materials Research Facility will integrate an environmentally controlled chamber with extreme flux beams and probe beams accessing a central, large volume target. A sketch of the layout is depicted in Figure 1 and a schematic view of the chamber is presented in Figure 2.

The proposed Facility will harnesses the capabilities of a test cell that previously hosted the United States most powerful (MFE) fusion reactor, the Tokamak Fusion Test Reactor (TFTR). The TFTR test cell was developed for radiation and safety controls with extensive loading and assembly infrastructure. The deuterium beam line heat source originate from the TFTR.

To generate neutrons from a focused square centimeter metal titride target, obtaining fluxes up to a few times 10^{13} n/s. The proposed facility aims at expanding this technology to square meter surfaces with up to an order of magnitude larger average beam power. The neutrons produced by the deuterium beams would provide for vacancy and interstitial generation, and helium generation from neutron-alpha nuclear interactions. Opposing mechanisms for self-healing or vacancy-interstitial recombination are important in understanding how to develop highly radiation resistant materials.

Target chamber diagnostics will include infrared cameras, residual gas analyzer (RGA), thermocouples, and other instrumentation as part of the baseline diagnostics employed during material heating operations. High-energy deposition in either acute or continuous mode of operation is also achievable, thus providing a range of testing protocol conditions. The target chamber will be lined with actively cooled backing (armor) plates in support of these high-heat flux deposition capabilities.

By sustaining high temperatures through environmental controls and repeated beam pulsing, the conditions that effect materials in medium-range extremes of heat flux and exposure duration can be explored using the heat source alone. Accelerated defect generation can be induced with neutron exposure, and the combination of radiation exposure and the high peak power heat fluxes that provide the unique capability in the propose facility.

IV. BEAM PROBE DESCRIPTION

While the concept of D-T generated neutrons was successfully utilized in the past for small-scale intense sources, such as the Rotating Target Neutron Source - 2 (RTNS-2), there is no materials research facility that has kept up with the pace of increasing radiation and heat exposures confronted by the current generation of research and engineering challenges.

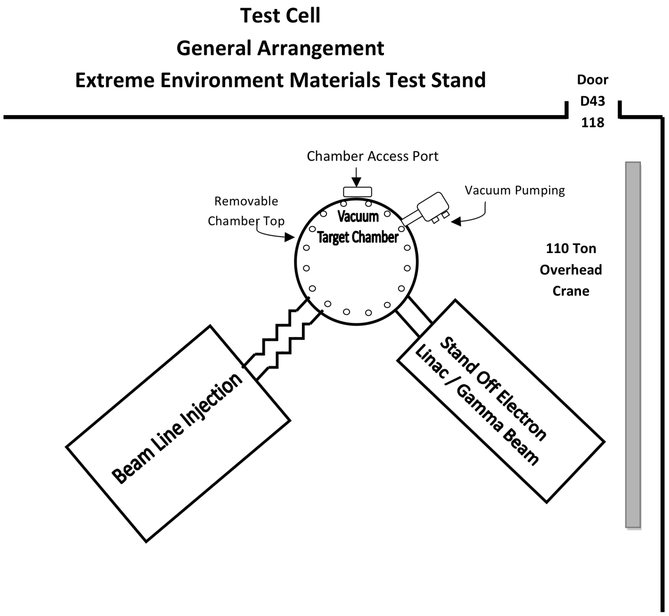

Figure 1. Depiction of Proposed Facility Layout

Hydrogen (deuterium) beams will provide up to 75 MW/m^2 of pulsed heat for durations up to 2 seconds. High-energy, neutron-induced radiation damage will be provided with a deuterium beam injector incident on metal titride or liquid lithium targets providing a flux of 14 MeV neutrons in excess of 10^{13} n/s. The deuterium beam line operates in the energy range of 80-120 keV providing optimal kinematics for high flux deuterium-tritium (D-T) neutron production. The RTNS-2 project exploited this property to generate neutrons from a focused square centimeter metal titride target, obtaining fluxes up to a few times 10^{13} n/s with an average beam power of approximately 40 kW on target. The facility aims at expanding this technology to square meter surfaces with up to an order of magnitude larger average beam power. The neutrons produced by the deuterium beams would provide for vacancy and interstitial generation, and helium generation from neutron-alpha nuclear interactions, and as noted, the self-healing mechanism is critical for achieving highly radiation resistant materials.

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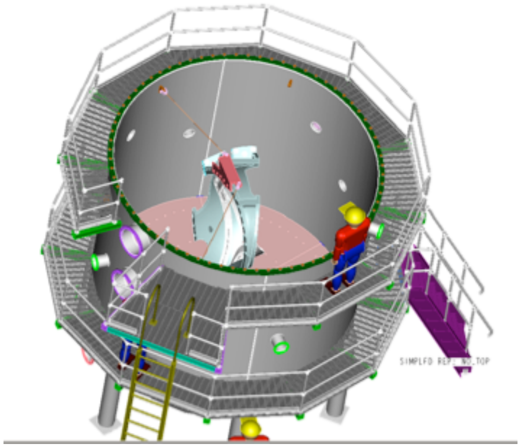

Figure 2. Schematic view of the target chamber

The facility will incorporate probe beams that access the target chamber and provide data to evaluate the target materials in situ during exposure. A number of advanced structural analysis methods have been developed using photon, neutron and electron and positron particle beams. Neutron beams are useful for deep penetrating structural analysis, especially if one has control of the source location and wavelength.

The configuration of the probe beam is depicted in figure 3. It is planned that the facility will incorporate a configurable source of neutrons using photonuclear interactions, which has been demonstrated using a diverse number of gamma ray production methods. In parallel asymmetric electron-positron collisions, a novel technique borrowed from high-energy physics research will also be exploited for producing stress on target materials.

V. HEATING , NEUTRONS, GAMMA

The energy of deuterium beam injectors, 80-120 keV, is optimal for 14 MeV neutron generation via the deuterium-tritium fusion interaction. The highly successful RTNS-2, exploited this property to generate neutrons from a focused square centimeter metal tritide target, obtaining fluxes up to a few times 10^{13}n/s with an average beam power of approximately 40 kW on target. Our facility aims at expanding this technology to square meter surfaces with up to an order of magnitude large average beam power. The purpose of the energetic neutrons is to provide large cross sections for vacancy and interstitial generation, including helium generation from neutron-alpha nuclear interactions.

Alternative sources for neutrons include: PET cyclotrons with MeV protons (the reaction ^{18}O(p, n) ^{19F} produces 14 MeV neutrons), Unstable Isotope Sources (AmBe, Sr, Cf), nuclear reactors (High Flux Isotope Reactors), GeV proton beam lines/spallation sources and photo-nuclear interactions. In the case of PET cyclotrons, the need for MeV beams makes the scalability of the beam power unfeasible for large surfaces and high flux rates. Isotope sources are limited in strength and come in only a handful of energy spectra. Nuclear reactors are abundant sources of neutrons, but the neutron energy spectra are limited. An integrated fluence of 10^{18}n/cm^2 for 1 MeV and higher neutrons takes on order 20 years to generate through the beam hole nozzles of a HFIR, and, for comparison, would take less than a day if not hours at our facility. Conversely, GeV proton beam/spallation sources do have substantial flux and energy spectra capabilities, but these devices require large-scale infrastructure greatly exceeding available university infrastructure constraints.

For probe beam design, there are a number of existing technologies that produce gamma rays: Inverse Compton Scattering (using GeV electron beams and power pulsed lasers), Bremsstrahlung (produces 1/E spectrum), positrons on target (produces a combined 1/E spectrum with a full-energy monochromatic energy peak) and unstable isotope sources (^{137}Cs, ^{60}Co, etc.). The GeV beams and laser system of the inverse Compton scattering system requires large-scale investment, and for typical beam will limit the photon energies to 15 MeV at the Compton edge. Bremsstrahlung is an abundant source of gamma rays, but the 1/E spectrum limits the high-energy gamma flux. Positrons on target is an effective source of monochromatic photons on top of a 1/E spectrum, but the flux rates are limited by the need to cool the positrons before injecting them into a linac. This facility will provide gamma rays from Bremsstrahlung and positrons on target and further develop this novel technique for gamma ray production.

The principles of the gamma-ray beam technology proposed are based on well-known techniques applied at large-scale national accelerator and collider facilities used for the study of high-energy physics. What is novel about this approach is the use of a compact, highly asymmetric electron-positron collider for the production of a tunable source of MeV-scale gamma-ray beams. The benefit of collider techniques in this application is the ability to produce MeV-scale gamma rays from MeV-scale electron beams, commercially available in nearly table-top (4 meter length) turn-key systems.

The physics for gamma ray production comes from the large electron-positron annihilation cross-section for low center-of-mass energies, the scale being set by the classical electron radius and the corresponding Thomson cross-section of 0.6 barns. The scattering process of electron-positron annihilation into two photons above relative velocities characteristic of a positronium bound-state are computed using u- and t-channel electron propagator exchange. The kinematics of this process differ greatly from the photons produced from positronium annihilation at rest, which is known to give an isotropic distribution of two back-to-back photons of 0.511 MeV. The forward scattering process above the positronium center-of-mass energy is a 2-to-2 scattering process with a forward-peaked angular dependence going as $1/\theta^2$ For forward scattering, the energies of the outgoing gamma rays correspond to the energies of the incident electron and positron. Therefore for the scattering of a 4-45 MeV electron on a low energy positron will yield an outgoing gamma ray with the energy of the electron. The angular spread of the gamma ray beam is further collimated by a Lorentz contraction factor of $1/\gamma$, narrowing the beam by an order of magnitude relative to the nominal $1/\theta^2$ cross section dependence.

The configuration of the proposed system is shown schematically in Figure 3. The 10 MeV/0.5 mA mode of the electron linac will serve as the incident beam for positron production. Alternatively the electron beam operating in its variable-energy mode of 4-45 MeV will be deflected into a collinear interaction region whereby the high-energy electron beam passes through the slow positron flux produced from the target. The rate of electron-positron annihilation and energy spectrum of the produced gammas will be measured in a calorimeter downstream of the interaction region. For the production of neutrons through the Giant Dipole Resonance, a target material of $PbWO_4$ will provide the lead target material for the generation of 12-15 MeV neutron while being a transparent, inorganic scintillator to serve as a self-calibrating flux measurement for the neutron production rates. The estimated Lead GDR neutron yield is 10% per incident 12-15 MeV gamma ray. Alternatively, the photo-nuclear target can be configured as needed with 1 millibarn cross sections down to 2.5 MeV from deuterium and beryllium, 100-500 millibarn cross sections for Lead in the 12-15 MeV region and 10 millibarn cross section out to 20-30 MeV for mercury and titanium. Thermal neutrons can be derived from high flux methods, such as bremsstrahlung photons interacting with BeD_2 and thermalized with polyethylene moderators, as previously demonstrated as a potential source for use in Boron Neutron Capture Therapy (5). Further cooling of neutrons could be achieved with total internal reflection methods.

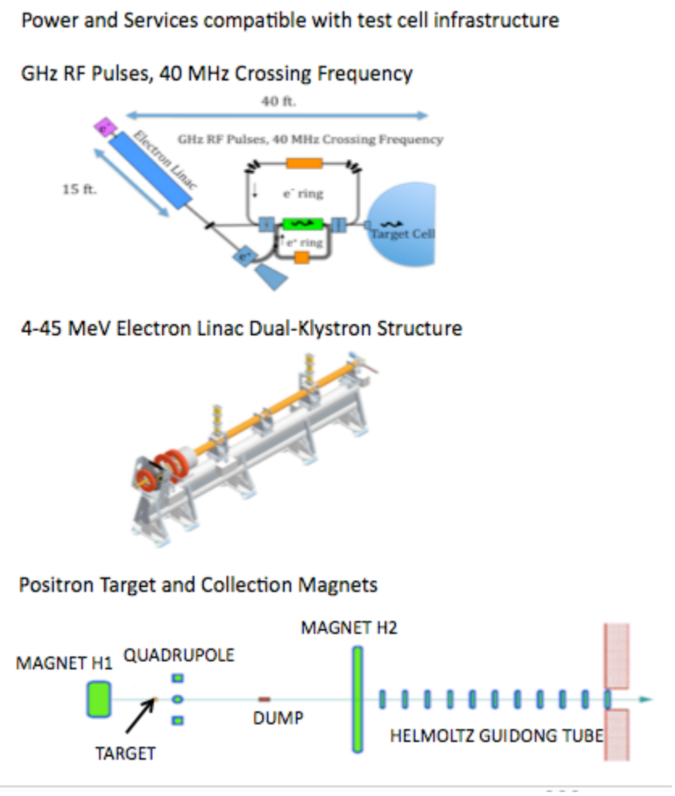

Figure 3. Layout of the probe beam components, depicting the dual-klystron electron linac, the positron production.

VI. SCIENCE EDUCATION OPPORTUNITIES

The described extreme material test facility will provide educational opportunities, both during development and operation. Indeed, the inherent concept on an extreme environment is to consider what happens in conditions that are completely unfamiliar to common everyday experience, inspiring imagination and new methods of scientific investigation.

For greater than 20 years the Princeton Plasma Physics Laboratory has directed award-winning science education programs, tailored to facility-oriented high-tech research, with a particular emphasis on encouraging participation from disadvantaged or underrepresented groups (6). These programs have provided opportunities for students and teachers at high schools from local and regional institutions and for undergraduates throughout the country to engage in scientific inquiry in ways that enhance their understanding of science concepts and scientific ways of thinking. The programs provide innovative opportunities for educators to work together with scientists and engineers to enhance science teaching and learning, and reach out to all students and teachers, particularly those previously excluded from educational opportunities. The proposed facility will serve as a technical education platform.

VII. CONCLUSION

Existing infrastructure at the Princeton Plasma Physics Laboratory provides a unique physical and economical opportunity for placing an extreme materials test facility. The need for such a facility is required for the development of new materials for use in extreme environments associated with fusion, fission, aerospace, and in other extreme environments. In addition to developing candidate materials for extreme engineering applications the proposed facility is will provide educational opportunities for the next generation of scientist and engineers.

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