ACCELERATOR-BASED NEUTRON DAMAGE FACILITY USING LEDA*

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Abstract

An accelerator based neutron damage facility (AND) is proposed to generate a high-dose fast neutron flux for testing of advanced reactor materials. The facility will be implemented in two stages. In AND-1, the 350 MHz LEDA RFQ will be re-commissioned to deliver 100 mA CW proton beam at 6.7 MeV. The beam will be targeted on a sheet-flow of Lithium to produce fast neutrons. Samples located at a target station behind the sheet flow will receive up to 10 dpa/year of neutron damage with a mean neutron energy of 2.37 MeV. In AND-2, the LEDA beam will be modulated to produce three 116 MHz bunch trains where they will be injected to three 100 MeV strong-focusing cyclotrons (SFC). The beams extracted from the three cyclotrons will be targeted 120 degrees apart onto sheet-flow Pb targets. Twenty one tensile samples located in the space between the three targets will receive up to 150 dpa/year of fast neutron damage with mean neutron energy ~8 MeV. AND-1 and AND-2 can provide the fast neutron flux needed for life-cycle damage studies for advance reactor technologies and for first-wall simulations for fusion systems.

INTRODUCTION

A design for an accelerator-based neutron damage (AND) facility has been devised to test advanced reactor materials. Since Three Mile Island there have been no new licenses issued for new construction in the US until just recently (2 reactors). Materials testing is one of the biggest hurdles and is of the utmost importance for two reasons: 1) The original lifetime for a nuclear power plant is 40 years and thus the current fleet has only remained operation due to lifetime extension every ten years, and 2) New reactor designs (Gen 4 and ADS systems) that are more efficient and clean require materials that remain unproven up to 200 dpa (displacement per atom). Currently, testing of materials to be used in advanced reactors is underway at facilities around the world such as HFIR and BOR60. However to reach 200 dpa within the sample takes over 15 years domestically and 10 years internationally. A decade long evaluation process enormously extends the selection process and material evolution.

As a consequence of this timeline, nuclear engineers have turned to the only method readily available, ions. Ions produce significantly more dpa per incident particle than neutrons. However, the mechanisms that ultimately dictate how the material swells and embrittles function differently for the two flavors of particles. Defect production, defect migration, defect annealing, production of interstitial clusters and loops, and H and He production, as well as how damage induced is effected by their presence, are all different for neutrons vs. ions. *Much has been learned about mechanisms that control damage from ion studies, but one cannot predict the damage a given neutron spectrum and dose will produce in a new material solely by experiments with ion damage.* Therefore, without a fast, high fluence neutron source, the ultimate lifetime and failure modes for materials to be used in advanced reactions cannot be ascertained.

Texas A&M Accelerator Research Lab (ARL) has devised an accelerator that can produce 200 dpa via neutron bombardment on several samples in less than 16 months, while also providing control of the temperature and chemical environment of the samples during exposure (problematic in reactors). The spectrum can be tuned to fully mimic conditions anticipated in future fission and fusion (currently not possible) reactors.

AND OVERVIEW

AND is comprised of two stages that utilizes several technologies developed by several groups. In the first stage the LEDA accelerator will be re-commissioned at ARL and send a 100 mA 6.7 MeV proton beam to a liquid Lithium sheet target similar to that developed by ANL. The second stage takes the proton beam from LEDA and accelerate 45 mA of the beam to 100 MeV using a set of 3 flux coupled Strong Focusing Cyclotrons (SFCs) developed at Texas A&M. The three beams are then directed to liquid Lead targets. The result of these two stages is a facility that can generate ~150 dpa/year using fast neutrons. An image of the facility is shown in Figure 1.

AND – PHASE 1

LEDA

The Low Energy Demonstration Accelerator, or LEDA, is one of the few RFQ accelerators that have achieved high current CW operation [1]. Initially built as the front end of the Accelerator Production of Tritium (APT), the accelerator was commissioned in 2003 and achieved in accelerating ~100 mA of beam to 6.7 MeV. In 2004, LEDA was decommissioned and remains in pristine condition within a high strength support structure, to maintain internal alignment among the cavity sections, while in storage (Figure 2). The current state of LEDA should assure that the time to re-commission at low power should be less than a year. Los Alamos National Lab (LANL) has agreed to make a 10-year loan of the LEDA system to Texas A&M University. ARL plans to move LEDA to Texas A&M along with pulsed RF power source, power supplies, transformers, and waveguides from LANL. The RF power loaned will be a pulsed system, but A&M has received commitment from CERN for two 1 MW 350 MHz CW power sources.

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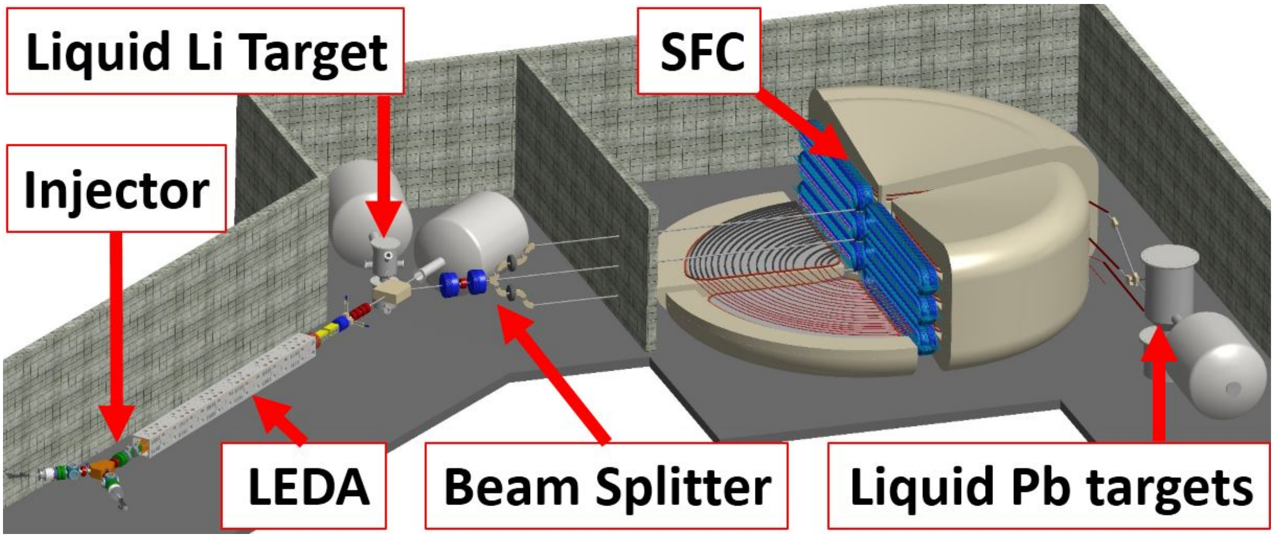

Figure 1: A diagram of the AND facility which identifies the critical system components. The LEDA and liquid Lithium target comprise Phase 1 and the SFC and Lead targets would be added to as Phase 2.

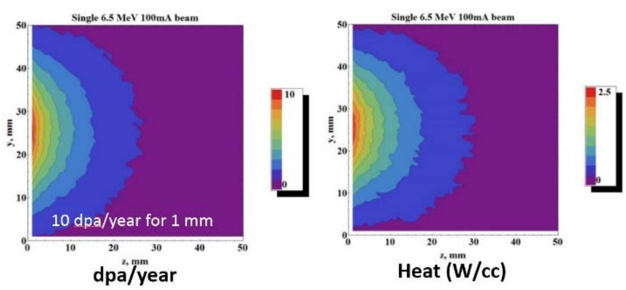

Figure 2: ~10 dpa/year is generated through a thickness of 1 mm. Such a rate is equivalent to current US capability.

Liquid Lithium Target

The 100 mA proton beam will be directed to a windowless liquid Li target to generate the neutrons for Phase 1. Li is used at this energy because the cross section is very large compared to other materials. The target must be molten so it can support the ~700 kW delivered by the beam. The Li is forced through a slit forming a flowing sheet of molten metal approximately 5 cm wide into a reservoir tank. The liquid in the tank is pumped through a heat exchanger and then pumped back to the slot iris. This approach has been developed at ANL and is planned to be used at facilities such as FRIB and RIKEN, but for stripping purposes. The AND system can produce at most 1.5 MW/cc. This power density is substantially lower than the 4.1 MW/cc electron beam used to test the device [2].

Neutron Damage – AND Phase 1

The Li window is ~2 mm thick and contains the Bragg peak of the protons and thus only neutrons bombard the sample. Dpa calculations were performed using a modified Kinchin and Pease model as is performed in the code SPECTER. The mean neutron energy for the AND-1 is 2.37 MeV and produces 10 dpa/year within the first 1 mm of the sample.

AND - PHASE 2

In Phase 2 the 350 MHz, 100 mA beam is split into 3 separate 116 MHz 15 mA beams. Each beam is then sent to TAMU100, a flux coupled stack of three strong focusing cyclotrons (SFCs). Using the SFC the beam is accelerated to 100 MeV and delivered to a molten Pb sheet flow target.

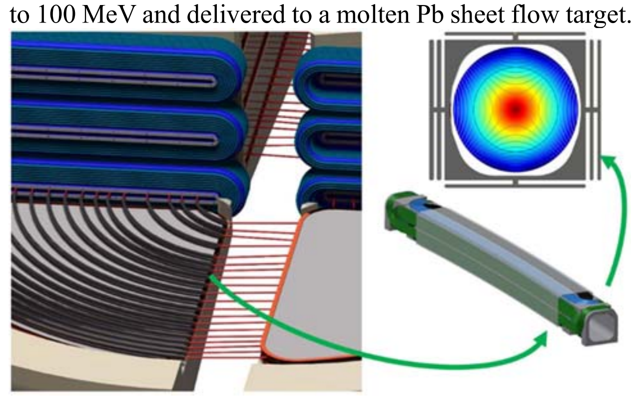

Figure 3: Left: SRF cavities (blue) and quadrupole channels are shown covering the proton projected orbits. Right: Detail of quad and the focusing field produced.

SFC – Strong Focusing Cyclotron

The SFC design incorporates three innovations (Figure 3) to bring the benefits of strong focusing to the cyclotron: 1) flux-coupled sector dipoles that permits one to stack multiple cyclotrons with a common footprint. 2) high-gradient superconducting RF cavities to increase the beam energy enough in each orbit (~2 MV/cavity) such that the succeeding orbits are fully separated; 3) As a consequence of the large separations, a set of beam transport channels are inserted in the aperture of the sector dipoles [3].

Each sector magnet has a pair of windings that each have a cold iron flux plate and generate ~1 Tesla. The sector dipoles of successive cyclotrons can thus be stacked upon one another and share a common warm-iron flux return. All magnet windings utilize MgB_2 superconductor, operating

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in the temperature range 15-20 K. The stack of flux plates is supported within a warm-iron flux return using low-heat-load tension supports in a magnetic design that cancels the Lorentz forces above and below each flux plate.

Each SRF cavity accelerates the 24 spiral orbits simultaneously, providing a minimum orbit separation of 5.6 cm for curved beam transport channels located in the aperture of each sector magnet. Each transport channel houses a pair of alternating-gradient Panofsky quadrupole lenses to provide an F-D strong-focusing doublet, and a window-frame dipole winding to facilitate correction of the dipole field for isochronicity. These winding also provides a built in septa for low-loss for injection and extraction.

The beam transport channels in the SFC are used to control beam size and achie ve transport of lar ger beam current. Our simulations show that these innovations will provide reliable low-loss acceleration and transport of a 15 mA proton beam to 100 MeV in each SFC by using emittance management provided by the beam transport channels.

The beam is t hen extracted from each cyc lotron and delivered to three m olten Pb tar gets similar in nature to those described in the Lithium target section.

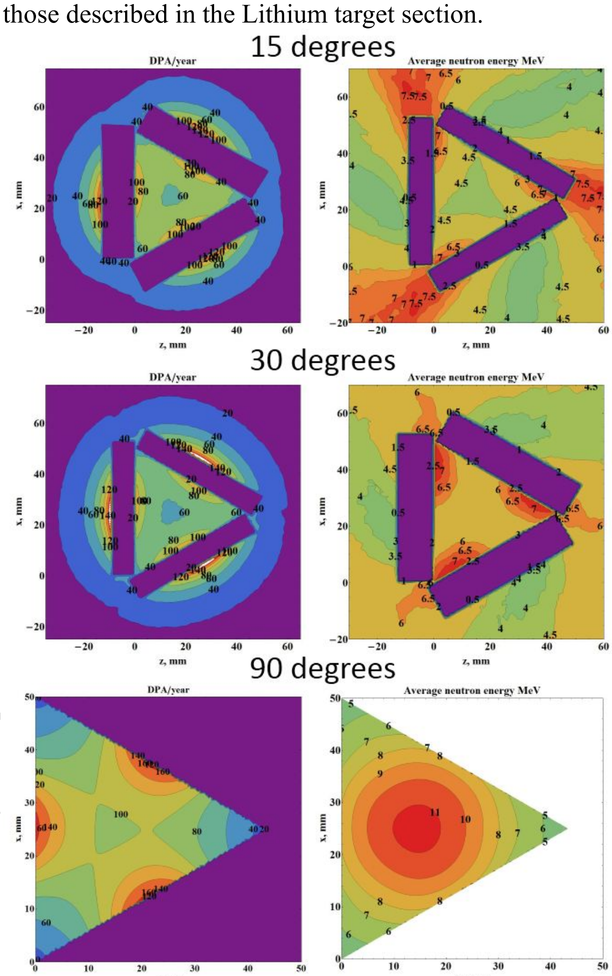

Figure 5: Angle dependence of damage and mean energy.

Neutron Damage – Phase 2

The angle at which the beam is brought to the Pb target has a dramatic effect on the mean energy and damage produced in the 21 tensile samples that are located within individually controlled environments (temperature and chemical). Three angles a re shown in Figure 5. The 15º version produced an average neutron energy of 4.5 MeV and a minimum of 50 dpa/year. The 30º had 5.5 MeV mean -60 dpa/year minimum, and the 90º case produced 8 MeV and a maximum of 160 dpa/year.

Comparing these results to the available user facilities, AND has higher fluence and average energy. If fact, AND would provide for t he first time the capability to study neutron damage produced at the first wall of fusion reactors (14 MeV). AND out performs existing and designed (IFMIF) facilities at a fraction of the cost (Figure 4).

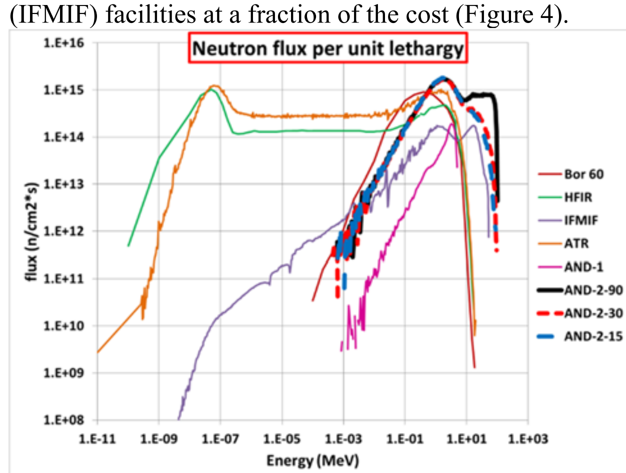

Figure 4: Comparison of AND 1&2 to other facilities around the world that are used for neutron irradiation.

SUMMARY

Ions are unable to predict damage type, ultimate lifetime, mechanical properties, and failure modes of ca ndidate materials for advanced reactors. A high fluence fast neutron source is needed to provide critical data and reduce decade long experiments to ~1 year. ARL has devised such a facility u sing LEDA, SFCs, and liquid metal targetry. AND facility can provide over 150 dpa/year of d amage (level needed for advanced reactors) on samples located with individually controlled environments that would uniquely support the advanced materials development for both fission and fusion.

ACKNOWLEDGMENT

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