SHINE Ion-Beam-Driven Polywell Fusion Prototypic Neutron Source

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Executive Summary: SHINE, in collaboration with EMC2, has explored a technological solution to support DOE FES's Bold Decadal Vision for Commercial Fusion Energy. Our approach combines SHINE's expertise in fusion neutron source commercialization with EMC2's technology leadership in high-density Polywell plasma operation to develop a compact high displacement rate Fusion Prototypic Neutron Source (FPNS). To achieve a high neutron flux, we will replace the gas target in SHINE's current neutron generator design with a Polywell plasma target, enabling a higher ion beam power density and greater neutron yield efficiency. Our preliminary design is based on a compact system with a diameter of 20 cm which delivers a displacement rate of 5–15 dpa/cy to samples from DT fusion neutrons. The system will operate with 5–6 MW of ion beam power injected into a 500 eV Polywell plasma target confined by magnetic fields between 2–3 T. The Polywell plasma system operates with inwardly converging magnetic field shapes for high-power ion beam injection and outwardly diverging field shapes for handling heat flux, addressing two of the most difficult technical barriers for a compact FPNS design. In our cost estimate, the system size and the input beam power are two critical parameters to achieve a total capital cost of an FPNS facility under $500M. Additionally, SHINE's expertise in tritium handling, neutron utilization, and safe and reliable nuclear facility operation will be crucial in constructing and delivering the FPNS facility. While the preliminary system design looks promising, the team acknowledges many scientific and technical gaps that must be addressed to bring up the technology maturity suitable for a "go" or "no-go" decision to meet DOE's needs for an FPNS facility. Included here is a technical R&D plan for the next 24 months, including hardware demonstration, to achieve between TRL-4 and TRL-5.

Technical Overview: SHINE is a nuclear technology company which manufactures neutron generators for medical isotope production, neutron imaging, nuclear fuel rod verification, and radiation effects testing. SHINE uses an ion beam incident upon a gaseous target to produce a steady-state high flux of 14 MeV DT fusion neutrons. In 2019, SHINE demonstrated operation of a neutron generator for 132 hours with higher than 99% uptime and set the world record for steady-state fusion output of 4.6×10^{13} n/s shortly thereafter [1, 2]. This design is used in the medical isotope production facility shown in Figure 1(a).

Despite its high neutron output, the existing SHINE neutron generator can produce a displacement rate of only 1.7×10^{-3} dpa/cy, which is insufficient for use as an FPNS. Although SHINE has made progress by using plasma window technology and a multiple beam line arrangement to enhance neutron flux [3, 4, 5], we have determined that a high-density warm plasma target is required to meet the needs of DOE's FES program [6] within the given time frame of this RFI. There are three primary reasons for this. Firstly, a compact FPNS with a dense target is preferable to produce a high displacement rate on the sample. For instance, only 350 kW of fusion power output would be required to produce 10 dpa/cy on the sample if the FPNS diameter were 20 cm, as opposed to 35 MW for a 2 m diameter. Secondly, a solid or gas target would transform into a plasma target due to the high input power requirement for a compact, high

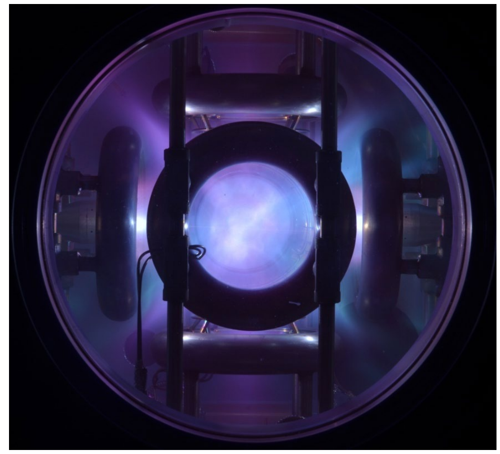

Figure 1: (a) SHINE medical isotope production facility driven by DT fusion neutrons and (b) Image of a high-density plasma target confined in a six-coil Polywell system [11].

displacement rate FPNS. Finally, incident ion beams can generate a higher number of fusion reactions in the warm plasma target compared to the gas target due to reduced beam slowdown at a plasma temperatures above 100 eV.

SHINE has evaluated various plasma target options and identified EMC2's Polywell design, shown in Figure 1(b), as the best choice for the following reasons: The Polywell is capable of operating at high density within a compact size due to its utilization of a magnetic cusp configuration, a well-established system known for its ability to provide plasma stability [7, 8]. The open field nature of the Polywell allows for more efficient ion beam injection, rather than less efficient and more complex neutral beam injection. Additionally, the naturally diverging magnetic field structure of the Polywell system is beneficial for handling intense heat exhaust from a compact FPNS. Although further testing and R&D is necessary to validate the Polywell approach's potential for fusion energy production, the theoretical and experimental foundation supporting the Polywell system as an enabling confinement system to produce a warm plasma target is substantial and sound [7–12]. As a result, SHINE and EMC2 will collaborate to provide a technical solution for an FPNS facility to meet the needs of DOE FES.

Technical Approach: Figure 2 shows the schematic of an ion-beam-driven Polywell neutron generator utilizing a 6-coil magnetic cusp system. The high-density plasma target (depicted in bright orange) is created within the magnetic coils through the utilization of plasma injectors [11]. Following the formation of the plasma target, ion beams with an energy 150–200 keV are injected via one or multiple cusp openings (shown in light blue). These ion beams generate fusion reactions upon colliding with the dense plasma target. The required ion beam injection power is dependent on the required displacement rate at the sample location. The ion beams also provide heating as they slow down within the plasma target. The Polywell system's plasma confinement efficiency determines the plasma target's operating temperature for a given ion beam power, which controls the fusion reactivity of ion beams. The inwardly converging magnetic field lines, shown as dotted lines, guide and collimate high power ion beams toward the plasma target. During steady-state operation, the injected power to the plasma target is balanced by the exhausted power out of the Polywell system, primarily via cusp openings. The outward diverging magnetic field distributes the heat flux from the plasma target (shown in light pink) across large surface

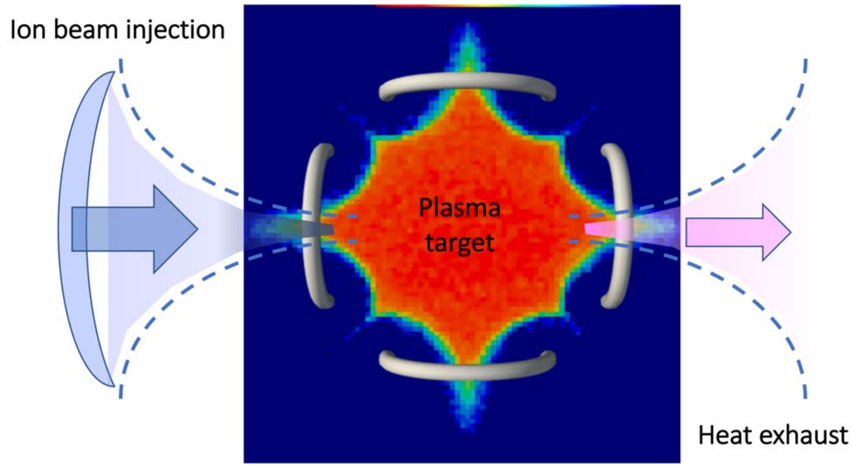

Figure 2: A cross-sectional view of an ion beam driven six-coil Polywell FPNS, showing converging-diverging magnetic field structure for beam injection and heat exhaust. The figure highlights only two of the 14 cusp openings.

areas where the plasma flow encounters the material walls, known as Plasma Facing Components (PFCs). The diverging magnetic field structure of the Polywell is advantageous in keeping the heat flux to PFCs below 5 MW/m^2 during steady-state operation.

Currently, SHINE is exploring various options regarding the placement of samples in relation to the magnetic coil structure. Once the optimal sample placement is determined, thermocouples will be used to monitor sample temperatures, which will be regulated using flowing helium coolant and resistive heating elements. In addition, the sample neutron flux will be measured in real time using external neutron detectors, and the ion beam current will be adjusted to keep the sample neutron flux constant. Finally, the team is considering an optional tritium breeding blanket testing, although the tritium burn rate will be less than 50 g/year.

Expected Performance: The following are preliminary design parameters and expected performance of an ion beam driven Polywell FPNS:

- Plasma target radius: 8.5 cm
- Plasma target temperature: 500 eV
- Magnetic field strength: 2–3 T at boundary, 4–5 T on surface of coil casing
- Ion beam energy: 150–200 keV
- Ion beam power: 5–6 MW
- Fusion power output: 350 kW
- Displacement rate: 10 dpa/cy at 10 cm sample radial location
- Neutron energy: 14 MeV DT fusion neutrons
- Sample volume: 50–500 cm^3
- Steady-state heat flux to PFCs: below 5 MW/m^2

The team considers the size of the proposed FPNS as the most critical parameter. The Polywell technology pioneered by EMC2 was selected primarily because of its ability to form and sustain a high-density plasma target in a compact system. With an operating magnetic field of 2–3 T, the estimated plasma target density is 10^{22} m^{-3}, which is comparable to the density achieved in the EMC2's previous test device [11] and approximately 100 times denser than the average plasma density of the ITER tokamak fusion reactor. The use of a high-density target is essential for generating 10 dpa/cy neutron flux for the sample with a modest output fusion power at 350 kW. The ion beam energy is chosen to be between 150 keV and 200 keV to maximize fusion neutron yield during the slowing down of beam ions in a plasma target operating at 500 eV, while confining the beam ions inside the Polywell device without hitting the coil surface. The estimated plasma target temperature of 500 eV for the proposed FPNS is determined by equating the ion beam input power of 5–6 MW with the estimated Polywell plasma loss rate based on the ambipolar plasma loss condition. This estimate assumes that the ion and electron loss rates are the same and that the ion loss rate is proportional to the ion transit time and the square of the ion gyro-radius. Previous studies have shown plasma confinement scaling consistent with this estimate [8, 9, 11]. Based on the achieved Polywell confinement efficiency in the test device during the next 24 months, the team will modify the size of the FPNS system and the input ion beam power accordingly to produce needed displacement rates on the sample. It is noted that the placement of the sample system within the compact Polywell device is a major uncertainty in the displacement rate estimate since even small changes in the sample placement can significantly impact the displacement rate on the sample surface.

Estimated Project Schedule, Budget, and Milestones: The proposed FPNS system has a substantial database to establish its feasibility for each subsystem, but the overall system has limited technical maturity currently estimated at TRL-3. The "small" FPNS approach to meet a high displacement rate requirement of 5–15 dpa/cy is a clear case of a high-risk, high-return project. Therefore, the team proposes the following R&D activities for the next 24 months to mitigate risks and increase the maturity level to between TRL-4 and TRL-5, enabling a "go" or "no-go" decision to build a working TRL-6 prototype over an additional 24 months.

- Task 1: Experimentally demonstrate high density plasma target formation and sustainment for a 20 cm radius plasma target by retrofitting an existing 6-coil Polywell system and including installation of new plasma injectors and ion beam injectors.
- Task 2: Conduct Polywell confinement scaling experiments in a compact plasma target as a function of magnetic field and beam input power.
- Task 3: Reduce the plasma target size by a factor of two and repeat task 1 and 2 with a 10 cm radius plasma target
- Task 4: Characterize ion beam injection efficiency and heat exhaust properties in two different Polywell plasma target sizes
- Task 5: Conduct first-principles plasma simulations and benchmark the simulation results with experimental data to establish ion beam driven Polywell FPNS scaling for making a "go" or "no-go" decision
- Task 6: If needed, add electron beam injectors and other actuators to improve the Polywell confinement efficiency for a 5–15 dpa/cy FPNS system.
- Task 7: Design megawatt-scale ion beam injector, integrated engineering for a magnetic coil and sample temperature control system and handling of heat exhaust.
- Task 8: Design FPNS facility, including supporting systems such as tritium handling, shielding, etc.

The estimated R&D cost for the above tasks for the first 24 months is $20M. Upon successful completion of these tasks to reduce the technology risks, the team will work with DOE to develop a plan for building a TRL-6 prototype and designing and operating an FPNS facility. Keeping the facility small will ensure timely delivery and control costs.

Overview of SHINE Team and Ability to Raise Capital: Ross Radel (SHINE) is the CTO and PI with 20 years of nuclear technology experience, including four years on the technical staff at Sandia National Laboratory. SHINE's expertise in nuclear engineering, tritium handling, complex nuclear facility development and navigating nuclear regulatory environments make the company well-positioned to deliver an FPNS facility in support of DOE's FES program. In February 2023, the Nuclear Regulatory Commission issued the Final Safety Evaluation Report related to SHINE's DT fusion driven medical isotope production facility, concluding that the technical requirements for an operating license have been met. This was the first time a non-power generating facility received such an approval in 35 years.

SHINE has a proven record in fundraising with a total of $750M to date. SHINE and EMC2 will work with University of Wisconsin-Madison to design a sample holder and temperature control system. SHINE is in the process of identifying other partners.

Capital costs for the FPNS facility, including the ion beams, Polywell, tritium handling system, cooling systems, and shielding are estimated at $250–300M. Operating costs, which are dominated by electrical costs to operate the ion beams and Polywell coils, are expected to be $20–25M/year.

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