Opportunities with Nuclear Fusion Using Spin-Polarized Fuel in Tokamak Reactors

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I. EXECUTIVE SUMMARY

The use of spin-polarized fuels in a tokamak reactor can in principle boost fusion power, owing to larger reaction cross-sections for specific fuel spin orientations. Realizing such benefits depends on whether fuel polarization can persist in a plasma environment for periods comparable to the confinement time. Favorable theoretical predictions have existed as early as the 1980's, but no experimental test has ever been attempted. In the recent decades, various advances in nuclear physics, fusion science, and small-scale R&D efforts all indicate that the tools are finally available to pursue an experimental test of spin-polarized fusion (SPF). We describe in this document the scientific principle of SPF and the current R&D status towards the first in-situ test of SPF in a tokamak plasma. Additional R&D efforts are needed, focusing on optimizing the production and storage of polarized deuterium and polarized ^{3}He suitable for fusion, cryogenic injection of these materials and the monitoring of their polarizations, and detection of the resulting charged fusion products. The success of this next phase of R&D requires expertise and support from Nuclear Physics.

II. SCIENTIFIC OPPORTUNITIES

There is no greater challenge facing our planet than the development of carbon-free, zero-emission energy production that will mitigate the current climate crisis while meeting the demands of modern societies on a broad scale. Providing energy from **Nuclear fusion** is a central goal of the DOE Office of Fusion Energy Sciences and is regarded as one of the *Grand Challenges for Engineering in the 21st Century* [1]. The thermonuclear fusion of deuterium (D) and tritium (T) is the most investigated for large-scale energy production. After decades of research, the first large scale tokamak, ITER (the *way* in latin), is under construction in France as a multinational scientific project, aimed at paving the way towards the first large fusion-power reactor. In parallel, the USA is pursuing smaller-scale tokamak designs with the Compact Fusion Pilot Plant (FPP) project [2], while various national laboratories and private companies are studying alternate fusion energy schemes [3–5].

Our focus here is Spin-Polarized Fusion (SPF), which has the potential to significantly facilitate the ignition of a burning plasma, because of two factors: First, the reaction rate for D + T $\rightarrow \alpha$ + n is 50% larger when the spins of the deuterium and tritium nuclei are parallel to the local field [6], a significant gain over randomly oriented unpolarized fuel. Second, the increased fusion rate will produce more plasma heating owing to increased α particle production, further boosting the net power output (Q), without any additional requirement on plasma confinement. With these enhancements, the same power goals could be achieved with a reduced magnetic field. Since plant costs scale roughly with the plasma volume and the square of the confining field, fuel polarization could offer a major benefit to fusion energy.

In a tokamak reactor, a relatively small fraction of the injected fuel mass undergoes fusion while confined in the plasma core. For SPF to be effective in practice, the polarization of the fuel must survive long enough

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compared with its confinement time. This has in fact been the predicted expectation since the 1980s [6, 7], although concerns persisted regarding the cumulative impact of ions cycling out and back into the plasma after interacting with the material in the plasma-facing wall. However, extensive simulations conducted for the ITER design have shown that such wall recycling is irrelevant in large-scale power reactors [8], making SPF a potential game changer. Our present goal is the first in-situ measurement of fuel-polarization lifetime in a tokamak plasma.

A collaboration involving General-Atomics/DIII-D National Fusion Facility, Jefferson Lab, and the University of Virginia has started preparing for the first direct *in-situ* test experiment of SPF. This would utilize the reaction D + ^{3}He → α + p, the mirror reaction of the standard D + T fusion reaction [9] and be conducted in the DIII-D tokamak in San Diego, California. Using ^{3}He eliminate the complication of working with radioactive tritium, while D + ^{3}He tests the same nuclear reaction physics as D + T. In the next section, we describe briefly the technical details and R&D that would require expertise and support from Nuclear Physics.

III. TECHNICAL DETAILS AND WHAT IS NEEDED FROM NUCLEAR PHYSICS

The key requirements of an in-situ test of SPF are (a) the preparation of pellets containing polarized D and polarized ^{3}He, in a form suitable for tokamak injection, with sufficiently long relaxation times to accommodate transfer to a pellet injector, along with the capability of monitoring their polarization, (b) cryogenic injection of polarized pellets deep into a plasma, and (c) charged fusion-product detection at the outer plasma-facing wall that is sensitive to fuel polarization and injected spin orientations. Tokamak injection of solid deuterium at liquid helium temperatures has been thoroughly developed [10], and modifications to include magnetic holding fields to maintain pellet polarization are not overly complex. The detection of charged-fusion products at the tokamak wall is routine, and a simulation for the DIII-D tokamak has projected substantial sensitivity to the polarization lifetime [11]. However, the preparation of polarized fuel pellets is completely outside the expertise of the fusion community and requires an active collaboration with Nuclear Physics.

Polarized materials have been used in Nuclear Physics studies for several decades, and their applications in medical imaging have become standard diagnostic tools. Nuclear Physics experiments using D and ^{3}He nuclei *hyperpolarized* to 60% or higher are now common [12]. Our goal is to leverage these techniques in a cost effective SPF demonstration experiment. While new laser-driven methods project the capability of eventually feeding a reactor with ≈ 100% polarized fuel [13, 14], the crucial question of polarization survival must be addressed before investing in the development effort.

Deuterium can be prepared as either dynamically polarized lithium-Deuteride (LiD) [15], fabricated as solid pellets, or as frozen-spin Hydrogen-Deuteride (HD), permeated as gas into hollow glow-discharge polymer (GDP) shells [16] and subsequently frozen and polarized [17]. While GDP shells can also be used to convey ^{3}He gas, polarized ^{3}He is typically produced by spin-exchange optical pumping, a technique involving high-powered lasers and alkali vapor, and thus ^{3}He must be polarized prior to permeation. Once filled, hyperpolarized nuclei naturally depolarize due to interactions with their surroundings. This has been well studied, with the exception of the ^{3}He depolarization as it permeates through material. We have completed an initial study and found that ^{3}He can retain a large fraction of its polarization during permeation through GDP shells, and further R&D is required to study and optimize ^{3}He pellet filling and storage.

Fuel pellets prepared by the aforementioned techniques all have long polarization decay times (≈ 6 minutes for LiD at 2 K, ≈ 2 months for HD at 2 K, and ≈ 3 days for ^{3}He at 77 K), all far greater than a plasma shot in a research tokamak such as DIII-D (≈ 20 s). Pellets of both species can be propelled from a single cryogenic injection gun. Signals of 15 MeV protons would provide a clean signature of D+^{3}He fusion. Polarization alters both fusion yields and the angular distribution of fusion products, and each of these provides a potentially strong signal. In a selection of shots with similar plasma characteristics, the expected ratios of yields from shots with fuel spins parallel and antiparallel range from 1.3 (HD+^{3}He) to 1.6 (LiD+^{3}He), and detailed tracking simulations for a high ion-temperature hydrogen plasma in the DIII-D tokamak confirm that this large signal should persist over a wide range of poloidal angles (normal to the toroidal field). Simulations also find strong sensitivity to fusion product angular distributions, as reflected in the pitch angles of protons and alphas reaching the plasma facing wall [11].

As can be seen from above, realizing the first in-situ test of SPF in a tokamak will require close collaboration between Nuclear Science and Fusion Energy Science. Specifically, we need to build upon existing polarized material technologies, adapt them for the production of polarized fuel pellets suitable for tokamak injection, and develop methods for monitoring the fuel polarization just before injection. We thus suggest the following texts, or a varied form with the same general spirit, to be adopted by the 2023 NSAC Long Range Plan for Nuclear Science:

> **We recommend strong nuclear physics support for the first in-situ demonstration of spin-polarized nuclear fusion in a tokamak plasma, along with the R&D effort needed to prepare such an experiment.** Specifically, the require R&D effort would include optimizing the production and storage of polarized deuterium and polarized ^{3}He suitable for fusion, cryogenic injection and polarization monitoring of the fuel, and detection of the resulting fusion products.

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