SPIN-POLARIZED FUEL TO INCREASE FUSION GAIN

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1. TECHNOLOGY TO BE ASSESSED

The reactivity of a nuclear fusion reactor can be increased if the spins of the fuel nuclei are aligned parallel to each other. For 100% polarization of both deuterium and tritium, the fusion cross section is 50% larger [1]. Simulations for ITER have shown additional non-linear gains from increased alpha-particle heating, leading to a potential 75% power increase in large scale machines. For ITER-scale tokamaks, fuel polarization could lower the requirements to reach ignition, and compensate for ~10% reductions in torus field, which could extend useful reactor life by mitigating field degradation from the neutron fluence at the super-conducting coils. Fuel polarization could reduce plant costs by about 20% for future tokamak reactors, which would represent huge savings.

2. APPLICATION OF THE TECHNOLOGY

Spin polarized fuel could potentially be prepared by optical pumping of molecular deuterium-tritium (DT) gas with two lasers. The polarized material could be loaded into polymer pellets and cooled to the solid phase. The polarized pellets could be injected into a fusion device using versions of existing cryogenic pellet injectors, modified to provide continuous magnetic holding fields in the injector and guide tube during injection. As a result of a tokamak’s high magnetic field, it is projected that the polarization of the fuel nuclei should survive injection and subsequent ionization and collisions [2,3].

3. CRITICAL VARIABLE

The realization of the benefits of fuel polarization rests on the survival of spin polarization for periods comparable to the burn-up time. Interest in polarized fuel options had an initial peak of activity in the 1980s [4], where calculations predicted that polarizations could survive a plasma environment. However, concerns were raised regarding the cumulative impacts of fuel recycling from the reactor walls. In addition, the technical challenges of preparing and handling polarized materials prevented any direct tests. Over the last several decades, this situation has changed dramatically [5]. Detailed simulations of an ITER plasma have projected negligible plasma fueling from wall recycling in a high power reactor where the scrape-off layer is opaque to neutrals from the walls [6,7]. In addition, a combination of advances in three areas – polarized material technologies developed for nuclear and particle physics as well as for medical imaging, polymer pellets developed for Inertial Confinement Fusion (ICF), and cryogenic injection guns developed for delivering fuel into the core of tokamaks – have matured to the point where a direct in situ test is possible.

While no fundamental obstacles are anticipated in the polarization of DT, polarizing scenarios are not yet developed and will require significant research and development (R&D), due to the complications involved in handling tritium. Furthermore, the use of tritium in research tokamaks is extremely limited. However, a proof-of-principle polarization survival experiment can be carried out equally well using the isospin mirror reaction, D + ³He → α + p, which embodies all of the same nuclear and spin physics. In an envisioned test using current nuclear and medical physics technology, separate pellets of D (polarized to 40%) and ³He (polarized to 65%) can be injected into a high-performance hydrogen plasma, with temperatures comparable to the projected ITER plasma. The resulting energetic protons from fusion would have large gyro-radii and would rapidly leave the plasma and be detected at several wall locations.
Radio frequency (RF) manipulations can be used to orient D and $^3$He spins either parallel or antiparallel relative to the local field. Assuming fuel polarization survival in the plasma as expected, a 30% enhancement is anticipated in the ratio of proton yields for plasma shots with fuel spins parallel and antiparallel. In addition, detailed tracking simulations for the DIII-D tokamak have projected a significant dependence on poloidal angle (Fig. 1), providing an important additional constraint on systematics in such a test experiment.

4. DESIGN VARIABLES

Since the first critical step towards the potential utilization of the gains from fuel polarization is the verification of polarization survival in a realistic plasma, the focus is on the requirements of a D + $^3$He → α + p demonstration experiment. There are three main components to the experiment.

(1) Filling a thin-walled gas-discharge-polymer (GDP) shell with high pressure hydrogen-deuteride (HD), and creating a small version of a Nuclear Physics (NP) target – Thomas Jefferson National Accelerator Facility (JLab) has extensive experience in polarizing materials and unique capabilities in the production of polarized HD. Molecular HD can be diffused into GDP shells, which are routinely produced by General Atomics (GA). These can be cooled to a solid and transferred to an existing dilution refrigerator + superconducting magnet system, where they can be polarized at about 12 mK and 15 Tesla. With time, the spins become frozen, and can be cold transferred to another cryostat, where RF can be used to increase the deuteron polarization by transferring H spin to D. A deuteron polarization of at least 40% is expected, with a polarization-decay time in excess of a year. These pellets can then be shipped in a suitable cryostat to San Diego, CA. Apart from the filling of a thin-walled GDP shell with high pressure HD (which is routine ICF technology), this stage creates a small Nuclear Physics (NP) target with standard technology. However, new equipment tailored to the manipulation and transfer of polarized GDP fuel pellets will have to be developed.

(2) Filling GDP shells with polarized $^3$He – The University of Virginia (UVA) and JLab have considerable expertise in preparing polarized $^3$He and permeating the gas into GDP shells. Hybrid spin-exchange optical pumping (SEOP) is commonly used in NP and in medical imaging experiments to create highly polarized $^3$He. With this technique, a glass cell containing pressurized $^3$He and small amounts of alkalies ($\sim 10^{14}$ cm$^{-3}$) are heated to over 200° C. The alkalies are polarized with lasers, and collisions between the alkali atoms and helium transfer polarization to the $^3$He. After about 15 hours, the $^3$He polarization is saturated at about 70% and the temperature of the polarizing cell is lowered; the $^3$He can be extracted from the polarizing cell and used to fill a GDP pellet. (The alkalis’ concentration at 20° C is negligible.) Because the $^3$He must be polarized first, its polarization must survive permeation of the GDP wall, and the polarization decay time within the pellet must be sufficiently long to allow for transfer to a pellet gun and injection into the plasma. The permeation and polarization properties of $^3$He in GDP shells are now actively being studied by a UVA-JLab team. A 1.5 Tesla commercial MRI scanner at the UVA School of Medicine is being used to track the filling process by generating 3D polarization images of GDP shells during permeation (Fig. 2).

Preliminary results have demonstrated $^3$He polarization survival during the permeation process, and indicated a $^3$He polarization lifetime within GDP shells of about 5 hours at liquid nitrogen temperatures. These times scales require a polarizer on site at the tokamak, and dedicated equipment optimized for this purpose will need to be developed at UVA. With such a scenario, five hours is sufficient to fill pellets, transfer to a 77 K cryogenic pellet injector, and fire them into the tokamak.

![Fig. 1. The poloidal distribution in DIII-D for the ratio of proton yields, following D+$^3$He fusion with initial spins anti-parallel and parallel, from detailed tracking simulations](image-url)
(3) The synchronized injection of polarized D and $^3$He: The final component of a spin-polarized fusion (SPF) demonstration experiment is the synchronized injection (to within a few ms) of polarized D, as HD pellets from a 2 K cryo-gun, and polarized $^3$He pellets from a 77 K cryo-gun, into the plasma.

The polarizations must be maintained by a guiding magnetic field (typically less than a kilo-gauss) throughout their flight path to the outer edge of the tokamak. Both species are in frozen-spin configurations. Injection velocities are typically ~$10^3$ m/s. This and the inevitable tumbling motion down the guide tube are orders of magnitude slower than the Larmor frequencies of either D or $^3$He. As a result, the D and $^3$He spins will follow the local magnetic field throughout injection and in the tokamak. The anti-parallel configuration can be prepared using an RF transition (an adiabatic fast passage) to flip the sub-state population so that the spin of the $^3$He (or the D, but not both) is aligned against the local magnetic field.

As described above, the signal of spin survival consists in comparing proton yields from successive plasma shots, in which D and $^3$He are injected with spins alternatively parallel and anti-parallel. While fueling from wall recycling is not expected on the ITER scale, care must be taken for a demonstration experiment in a low-power research machine. Such an experiment requires an H plasma to avoid dilution of the average deuteron polarization, and this will require development of a high-performance plasma with hydrogen (instead of the usual deuterium plasma). The typical technique of boronizing reactor walls has been shown to dramatically extend the energy containment time. This needs to be coupled with the use of a hydrogen plasma with small or non-existent edge localized modes to increase injection efficiency. The reduced dwell-time on a boronized wall, coupled with modest energy confinement times in research machines such as DIII-D (~ 0.2 s), is expected to be effective in keeping wall depolarization at a minimal level for a program of spin-polarized fusion studies.

5. RISKS AND UNCERTAINTIES

For a polarization survival demonstration experiment, the signal is directly proportional to the fuel polarization. Polarizations of 40% for deuterium and 65% for $^3$He have been assumed in the above discussion, leading to an expected demonstration signal of 30% in the ratio of fusion product yields with D and $^3$He spins oriented parallel and antiparallel.

A 40% deuterium polarization is consistent with what can be achieved in large scale (50 mm) NP targets, using RF transitions to enhance the D signal by moving spin population in HD from H to D. While the theoretical maximum polarization achievable with this method is 67%, in practice, this technique has been limited by spatial uniformity requirements on the RF field. This is likely not to be an issue in preparing polarized GDP pellets, which are an order of magnitude smaller than NP cells. Nonetheless, 40% D polarization has been conservatively assumed for planning purposes.

The 65% polarization assumed for $^3$He is close to the maximum that is routinely attained in SEOP. However, in contrast to the deuterium polarization process where GDP pellets are first filled and then polarized, the polarization of $^3$He must be done outside the pellet, and the polarized gas must be permeated through the pellet wall. While initial tests are encouraging, further R&D is needed to maximize the post-permeation $^3$He polarization. Furthermore, due to polarization decay times that are significantly shorter than D, dedicated $^3$He polarizer and pellet filling systems need to be developed and located on site at the fusion facility for producing polarized $^3$He-filled pellets.

Existing cryogenic injection guns at existing facilities will need to be modified to accommodate both the polarized D pellets (at 2 K) and the $^3$He pellets (at 77 K). A plan for such engineering needs is being evaluated, for which the current obstacle is funding needed for such development.
The recent advances in spin-polarized fuel can be viewed as a byproduct of the vast development and progress made in nuclear physics and medical imaging techniques, which have used polarized material to study the intrinsic spin structure of the proton and the neutron in the case of NP research, and lung cancer studies in the case of medical applications. There are no institutional, regulatory, or societal obstacles to the development or use of spin-polarized fusion that can be foreseen. On the contrary, this will be a new example of how fundamental scientific research can be used to benefit the whole of society.

6. MATURITY
The technical readiness for the proposed application is already described in the sections above. In the last 30 years, no other progress has been made on a demonstration test or on the realization of SPF apart from the R&D reported here. The projected development rate is described in the next section.

7. TECHNOLOGY DEVELOPMENT FOR FUSION APPLICATIONS
Simultaneous innovations required to reach technical readiness: The following steps are needed to prepare a $\text{D}+\text{^3He}$ demonstration experiment. These could be completed within three years, given adequate funding.

- Develop a $\text{^3He}$ polarizer optimized for SPF at UVA and assemble at fusion facility
- Develop (ICF-like) systems for the rapid permeation of HD and $\text{^3He}$ into polymer pellets
- Develop ancillary equipment to utilize existing JLab facilities to polarize HD pellets and transport them to fusion facility
- Retrofit existing pellet launchers and guide tubes with holding fields for polarized pellets
- Test and optimize guide tube geometry for injection
- Deploy a polarization measurement (probably an in-line Squid) on the pellet injectors
- Install a polarization flipper to anti-align the polarizations
- Build and install detectors that are sensitive to the yields and poloidal distributions of fusion products from $\text{D}+\text{^3He}$

To capitalize on SPF in future reactors, subsequent R&D would be required in the following main areas: the polarization of tritium, the mass production of polarized pellets, and the automation of injection systems. A demonstration of polarization survival with $\text{D}+\text{^3He}$ would motivate such R&D.

Time horizon: Active research toward SPF has been initiated with the limited R&D funds discussed below. Based on our progress to date, additional support can enable a TR3 level to be reached in one year, at which point a cost analysis would have been completed for each of the above steps required for the SPF demonstration experiment. Assuming commensurate funding, the $\text{D}+\text{^3He}$ demonstration experiment could be completed in three additional years. This would constitute a TR 5 or 6 level in the development of SPF.

Resources, public and private: Tracking simulations for SPF in DIII-D have been supported by internal R&D funding from GA. The aforementioned R&D project on pellet performance of polarized $\text{^3He}$ has been funded by a UVA College of Arts and Science Faculty Initiative fund. Additional support is required to take this work to the next level of readiness.

Other nations: Interest in SPF has been rekindled in recent years \[8\], but as far as we know there is no actual R&D work on a proof-of-principle in-situ test of polarization survival in a tokamak. If the US invests in SPF, we will be significantly ahead of other nations.

8. REFERENCES

