ADDRESSING CRITICAL TRITIUM CHALLENGES IN FUSION POWER PLANTS USING SPIN-POLARIZED FUEL

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Commercial fusion power hinges on solving tritium-related hurdles—securing a robust supply, operating with minimal circulating inventory, maintaining a sufficient Tritium Breeding Ratio (TBR), and mitigating neutron damage to magnets and other key components—all while enhancing total fusion power [1]. Here, we show how spin-polarized fuel (SPF) can help meet these challenges. By biasing (polarizing) the nuclear spins of fusion fuels, SPF favorably alters the fusion cross section σ_{DT} and emission spectra [2], enabling an ARC-class Fusion Power Plant (FPP) to more than double its net electric power and achieve plasma ignition, all with an 85% reduction in tritium startup inventory and a 5x boost in Tritium Burn Efficiency (TBE) [3] where TBE=$\dot{N}_{\mathrm{burn}}/\dot{N}_{\mathrm{in}}$ for tritium burn rate $\dot{N}_{\mathrm{burn}}$ and tritium injection rate $\dot{N}_{\mathrm{in}}$. Using high-fidelity tritium and neutronics simulations for a spherical tokamak (ST) FPP design with different polarization configurations, we observe dramatic gains in magnet survivability and increases in TBR. Building on prior research [4,5] demonstrating SPF's ability to enhance fusion power density, we focus here on extending these insights to address some of the most pressing challenges in fusion engineering, including more efficient tritium utilization, optimized reactor designs, and improved material survivability for commercial fusion systems.

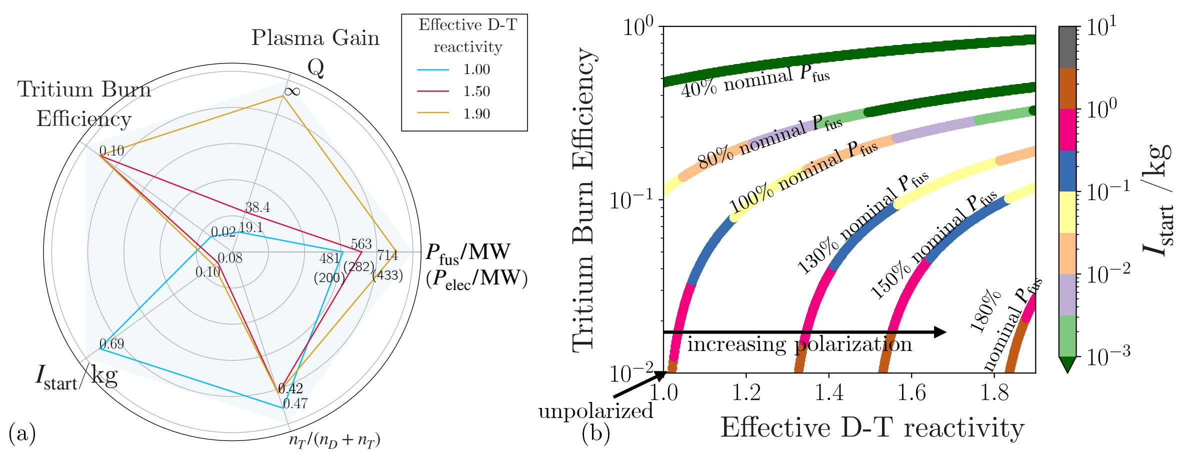

Figure 1: (a) Key tritium self-sufficiency and fusion performance for an ARC-class power plant, (b) dependence of minimum tritium startup inventory on Tritium Burn Efficiency and Effective D-T reactivity [6].

Using SPF to enhance fusion reactivity can increase TBE by an order of magnitude [6], offering an invaluable tool for addressing the tritium challenges facing FPPs [5]. By reducing (i) the tritium startup inventory, (ii) the required TBR, and (iii) the circulating tritium inventory, SPF relieves three critical bottlenecks in commercial fusion. Large FPPs can demand ~10 kg of tritium at startup—comparable to global tritium inventory—while ensuring TBR >1 remains a daunting engineering feat. At the same time, minimizing tritium stored in blankets, storage systems, and pumps is essential for safety and regulatory compliance. Fig. 1(a) shows that, for an ARC-class power plant [1,6,7], a 50% boost in effective fusion reactivity raises TBE from 1.6% to 10%, cuts tritium startup needs from 690g to 80g, doubles plasma fusion gain Q from 19 to 38, and increases net electric power from 200MWe to 282MWe. A 90% reactivity boost further lifts electric power to 433MWe, achieving plasma ignition. Meanwhile, Fig. 1(b) highlights the tradeoff between TBE and fusion power. Maintaining or exceeding nominal power while increasing effective reactivity (via higher polarization fractions) can elevate TBE from under 1% to tens of percent, reducing the breeding blanket's burden, shrinking overall tritium requirements, and simplifying plant design.

In standard fusion plasmas, deuterium (D) and tritium (T) spins are unpolarized and emission is isotropic (fig. 2(a)). Polarizing D and/or T changes crucial reaction parameters. In the perpendicular emission scheme (fig. 2(b)), fully aligning D–T spins boosts σ_{DT} by ~50%, directing alphas and neutrons largely perpendicular to the magnetic field

B. In contrast, the parallel emission scheme (fig. 2(c)) tensor-polarizes only deuterium; σ_{DT} remains unchanged, but emission shifts parallel to B. These polarization strategies open new routes for managing power density and reactor engineering constraints.

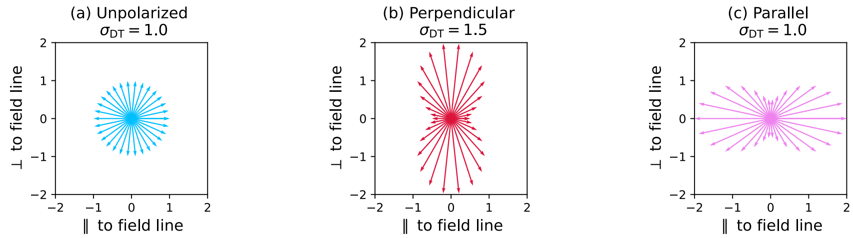

Figure 2: Emission from 3 polarization schemes. Arrows represent D-T differential cross section.

Controlling 14 MeV neutron fluxes remains a top priority in FPP design, as high-energy neutrons degrade materials, shorten component lifespans, and raise activation concerns. Integrated simulations [8] of the STAR [9,10] ST FPP using the FERMI framework [11] reveal how polarization dramatically reshapes neutron flux distributions. In the perpendicular scheme, inboard neutron fluxes jump by 70% (fig. 3)—likely unacceptable for an FPP—whereas the parallel scheme channels neutrons along B, reducing inboard flux by as much as 70% (fig. 3). This reconfiguration alleviates major engineering obstacles by steering neutrons toward more shielded regions. Motivated by these findings, we show that if the inboard blanket is removed and the design optimized for sufficient TBR, the parallel scheme significantly boosts fusion power at low aspect ratio, freeing space for more magnet windings and shielding.

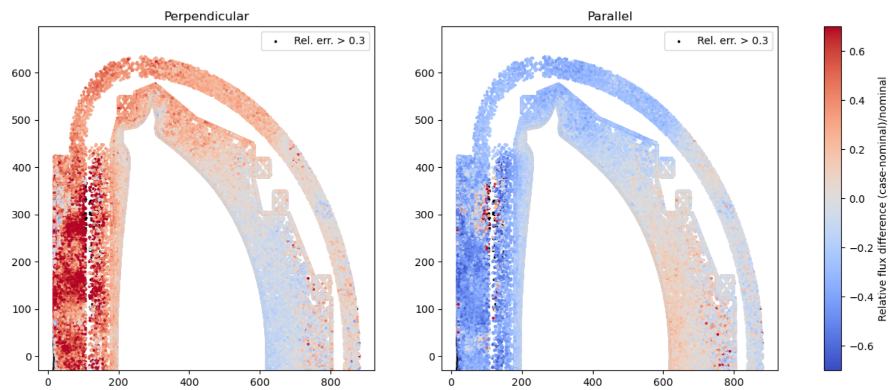

Figure 3: Relative neutron flux compared with nominal for perpendicular (left) and parallel (right) polarization schemes [8]. The total fusion power is constant.

Spin-polarized fuel provides a bold, orthogonal approach to many core challenges in commercial fusion energy. By shaping both total and differential fusion cross sections, SPF can increase TBE, decrease tritium startup burden, and mitigate neutron damage to critical components. There are significant challenges to overcome before SPF can be used in FPPs: high throughput polarized fueling and determining depolarization rates in plasma. Ongoing research focuses on refining SPF for reactor design, assessing depolarization by plasma waves, and performing experimental validation in relevant conditions. Demonstrating these benefits at scale would mark a significant step toward commercially viable FPPs. This work was supported by the U.S. Department of Energy under contract numbers DE-AC02-09CH11466, DE-SC0022270, DE-SC0022272.

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