Research Thrust on Advanced Plasma Fuelling

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1. Mission and Scope Summary

Steady-state Advanced Tokamak (AT) and ST scenarios rely on optimized density and pressure profiles to maximize the bootstrap current fraction. Under this mode of operation, the fuelling system must deposit small amounts of fuel where it is needed, and as often as needed, so as to compensate for fuel losses, but not to adversely alter the established density and pressure profiles. Conventional fuelling methods have not demonstrated successful fuelling of AT-type discharges and may be incapable of deep fuelling long pulse discharges that operate at high values of the bootstrap current fraction. The capability to deposit fuel at any desired radial location within the tokamak or ST would provide burn control capability through alteration of the density profile. The ability to peak the density profile would ease ignition requirements. An advanced fuelling system should also be capable of fuelling well past internal transport barriers. Compact Toroid (CT) fuelling has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input. In a reactor with high-Q, other than the balance of power needed for current drive, no other sources of input power are allowed. Under these conditions, precision fuelling provides a valuable method to optimize and control the fusion burn.

NSTX is a particularly good choice for the near-term studies. Besides having a large plasma cross-section and low toroidal field, NSTX is a spherical tokamak. As a consequence NSTX has a very large toroidal field gradient. The toroidal field on the inboard side is an order of magnitude higher than on the outboard side. Since the CT penetration criterion depends on the toroidal field, it means that on NSTX the CT stopping location is much more precisely defined. This makes NSTX or any large spherical tokamak an ideal candidate in which to study the CT penetration scaling laws.

On NSTX, Lithium is now being developed as a plasma facing component. The benefits from Li walls arise as a result of reduced recycling. To benefit from reduced recycling, it is necessary that the fuelling system deposit most of the fuel deep inside the separatrix. Thus for NSTX to benefit from the potential benefits of Lithium a core fuelling system is needed. CT fuelling technology is well suited for this purpose.

2. Closing Research Gaps for Advanced Fueling

This white paper addresses the following issues identified by the ***Greenwald Panel Report.***

From the Greenwald report:

> ***Greenwald 2.b.6.*** **Plasma Modification by Auxiliary Systems:** Establish the physics and engineering science of auxiliary systems that can provide power, particles, current and rotation at the appropriate locations in the plasma at the appropriate intensity.
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> Some of the more detailed wording states: *" ... The parameters to be modified include…density,..pressure profile, ….plasma fuel mixture ratio, …impurity content.."*
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> *Greenwald - c.* Fueling and Exhaust Control "The areas where further knowledge will be needed for DEMO are in fueling physics, isotopic control, steady-state operation, tritium handling, and technology reliability. ***New technological solutions for core fueling will most likely be needed, which should be first tested on test stands and later on operating devices such as ITER and other magnetic confinement devices."***
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> ***Greenwald - c.*** **Gap: Fueling and Exhaust Control**: "… fuel concentration in the core of the plasma be adjustable and renewable." ***"Develop new methods of Core fueling."***

This white paper also address the ***TAP panel Tier II issues for the Spherical Torus Concept.*** These are in the areas of Integration and Disruptions.

From the TAP report:

> The more detailed wording states,
> Integration: " …An ST based CTF is projected to require simultaneous achievement of plasmas with a degree of self-heating (Q ~ 1-2); ***with no inductively driven current (~50% bootstrap current); with profiles consistent with macroscopic stability and adequate confinement***; vanishingly low disruptivity and high, steady-state heat flux and particle control at low normalized density. Substantial research will be required to identify workable scenarios, control tools and measurement techniques."
> Disruptions: "***Disruption*** avoidance and ***mitigation for reliable continuous operation***"

The traditional method for deep fuelling has been through the use of cryogenic pellet injection, and this is the reference fuelling system for ITER. However, there is no data from present machines that demonstrates the capability of pellets to fuel AT discharges. In order for a pellet to penetrate deep into the plasma, it may have to be physically large in size. Large fuel pulses may be incompatible with high-bootstrap current fraction operation as it would alter the optimized pressure profile.

A Compact Toroid (CT) is a self-contained plasmoid with embedded magnetic fields. The structure is very robust and it can be accelerated to the high velocities needed for fusion reactor fuelling. With a CT fuelling system, the reactor density control system would control both the fuel deposition location and the amount of fuel deposited. This would provide capability for real-time density profile control. In addition to this, a tangentially mounted CT injector would provide a source of toroidal momentum injection. In a reactor with isotropic alphas for plasma heating this capability is desirable for controlling plasma stability limits. In reactors, the capability for deep fuelling with tritium should increase tritium burn-up and reduce tritium wall inventory and tritium inventory in the gas flow cycle.

The CT injection concept was first proposed by Perkins et al., [1] and Parks [2]. CT acceleration was first demonstrated on the RACE facility at the Lawrence Livermore National Laboratory, where accelerated CT velocities of up to 2000 km/s were achieved at high acceleration efficiencies [3]. Further experiments on the ITER scale MARAUDER device at a US Air Force laboratory demonstrated acceleration of mg sized CTs to velocities of over 300 km/s [4]. These are the parameters required for a reactor CT fueller. The accelerator design was further improved by the Canadian Fusion Fuels Technology Project (CFFTP) in collaboration with the University of Saskatchewan, Lawrence Livermore National Laboratory and the University of California-Davis, for the purpose of injecting these plasmoids into high temperature tokamak plasma [5]. This resulted in the first successful tokamak injection experiments being conducted on the TdeV tokamak [6, 7]. Subsequent experiments on the STOR-M and JFT-2M tokamaks showed that CT injection can also be used to trigger advanced confinement modes [8, 9].

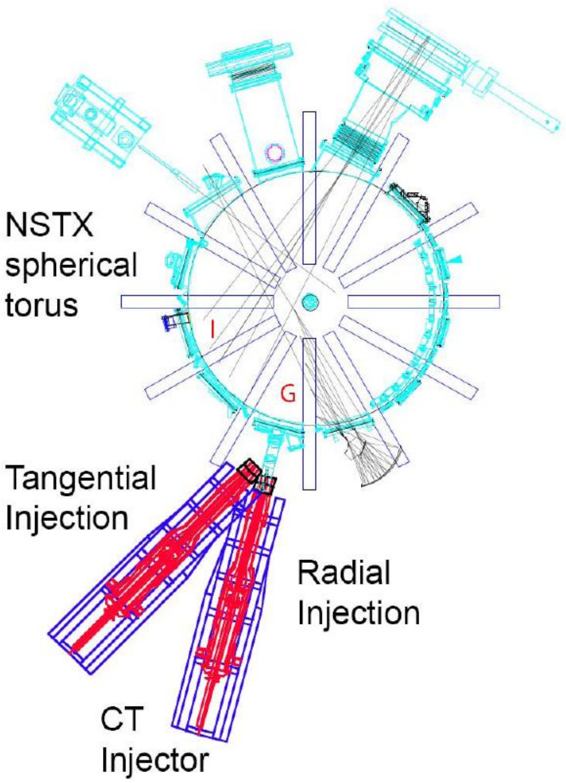

Figure 1: Proposed layout of the CT injector on NSTX.

Some of the *Advanced Fuelling* benefits of CT fuelling are:

2.1 Variable depth fuelling and profile control - The injector would typically operate at about 20 Hz. By controlling the mass and the radial location of fuel deposition at each of these fuel pulses the density profile could be maintained at the required levels without introducing strong perturbations to the required density and pressure profiles. This is because each CT pulse would introduce a total particle inventory per pulse (mass contained in the CT / total fuel mass in the target plasma) of less than 1%.

For a CT with a given mass density, by adjusting the voltage at which the accelerator is operated the CT velocity can be controlled. To first order, the combination of CT mass density and velocity determines where the CT would stop. Thus the plasma fuel control system, for each CT pulse by specifying the operating voltages for the gas valves and the acceleration sections of the injector controls the amount of fuel and the fuel deposition location.

2.2 Tritium wall inventory reduction - Without deep fuelling, the fuel must diffuse from the edge into the plasma. This also increases edge tritium losses to the walls and increases the burden on the tritium clean up systems, which are not yet well developed for ITER. Part of this is because tritium could be trapped in small difficult to access regions within the reactor vessel. Thus an improvement to the fuelling system that increases fuel burn-up, reduces tritium losses to the walls and reduces tritium inventory in the fuel gas handling circuits is very desirable.

A future 1 GW fusion reactor will burn on the order of about a kg of tritium/day. With shallow edge fuelling only a small amount of the injected tritium would be burnt, typically about 5%. This means that the gas control system must process on the order of about 20 kg tritium/day. Most of it simply being re-circulated to and from the reactor because of the very low fuel burn-up fraction. With deep core fueling relatively more of the injected fuel would be burnt and fuel burn-up fraction would be on the order of 10% or more [10]. Thus a core fuelling system such as CT injection would have the immediate impact of reducing the size of the tritium gas handling system requirements. There will therefore be less tritium inventory at any given time. This represents a significant improvement factor in the cost and maintenance of tritium systems in a reactor.

In addition to this reduction in tritium inventory, there are other tritium related benefits. The capability to vary the fuel deposition location inside the reactor allows capability for tailoring the tritium profile to reduce tritium inventory in the wall. To achieve this, the core of the plasma could be fuelled with a tritium rich mixture, while conventional fuelling systems, such as pellets, which are best suited for edge fuelling could inject deuterium. This should increase tritium burn-up in preference to deuterium burn-up and result in less tritium being exhausted and trapped in the walls.

2.3 Momentum injection - In reactors that do not need neutral beams for plasma heating during steady state operation, because alphas are isotropic, it is desirable to have a system for toroidal momentum injection to induce and maintain plasma rotation at the desired levels. A CT with mass *m* and velocity *v*, has a momentum equal to *mv*. An ITER-class CT fueller would inject 2.2 mg CTs at a velocity of up to 500 km/s. The directed momentum per CT is 1.1 kg m/s. At an operating frequency of 20 Hz it is 22 kg m/s. The CT injection power is 5.5 MW. The total number of particles injected per second is 1.05 x 1×10^{22} particles (D+T).

This shows the tremendous advantage of a CT fueller. In addition to fuel injection it injects substantial amounts of momentum. The momentum injection is so large that the CT tangency need not be very large.

Figure 1 shows the proposed layout of a CT injector for such a momentum injection test on the NSTX device.

2.4 Disruption Mitigation

Disruption is a serious issue for ITER. Present disruption mitigation technique for ITER is to rely on massive gas jet injection. However, it is not know at this time if this technique would scale favorably for ITER. This is primarily because the amount of gas that can penetrate the edge of ITER discharges is expected to be small. CTs have the potential to assist massive gas jet injection techniques by controlling the time at which the plasma could begin to radiate the stored thermal energy by injecting high-z doped CTs to the q=2 surface in ITER on a fast time. A test of this could be easily conducted on NSTX, and the related disruption physics is of significant interest to ITER, and such a proposal was supported by the ITER ITPA MHD group.

3. Elements of the Research Thrust

3.1 Localized fuelling: It is necessary to show that by altering the CT injector parameters, that the CT could be used to deposit fuel at an arbitrary location within the tokamak. CTs from the CTF-II device (used on TdeV) have the capability to penetrate 1T discharges. NSTX has large cross-section plasma at a nominal toroidal field of 0.5T. Thus there is adequate overcapacity in the present injector design to demonstrate this capability in NSTX***. The CT injector used on TdeV is in storage on site at PPPL and is available for installation on NSTX and is awaiting programmatic plans.***

3.2 Fuelling advanced confinement modes: An experimental demonstration of deep fuelling H-mode discharges is needed, a test which could be conducted on NSTX using the present CT injector.

3.3 Momentum injection: As shown in Figure 1, a tangential CT installation is possible in NSTX to demonstrate the momentum injection capability of the CT.

3.4 Repetition rate operation: CT injection from a 10-20 Hz injector into high temperature tokamak/ST plasma is needed. NSTX and NSTX-U are well suited for this purpose. It is useful to note that the present repetition rate achieved 0.2 Hz [11] is not an engineering limitation. The present off-the-shelf hardware capability for high current switches and capacitor banks is such that a 20 Hz system can be built without the need for further research development in pulsed power technology [12-15]. After single pulse injection experiments, the power supply can me modified for a high repetition rate test.

NSTX is a particularly good choice for the near-term experiments as neutral gas has considerable difficulty penetrating the torus. Besides having a large plasma cross-section and low toroidal field, NSTX is a spherical tokamak. As a consequence NSTX has a very large toroidal field gradient. The toroidal field on the inboard side is an order of magnitude higher than on the outboard side. Since the CT penetration criterion depends on the toroidal field, it means that on NSTX the CT stopping location is more precisely defined. This makes NSTX or any large spherical tokamak an ideal candidate in which to study the CT penetration scaling laws.

3.4 Variable isotope operation: The proposed CT injector has 10 gas injection valves. By using some valves for deuterium gas and some for Helium gas, it can be shown that the isotopic mix can be varied in the core injected fuel.

3.4 Disruption Mitigation: Inject CTs doped with high-Z impurities into NSTX to produce a controlled plasma disruption.

In summary, this white paper addresses the following specific recommendations from the Greenwald and TAP panels. The relevant journal published references are shown in brackets.

Greenwald Panel Recommendations:
Rotation control [15], Thrust No. 3.3
Particle control [13], Thrust No. 3.2
Fuel deposition at appropriate location at the appropriate intensity [15], Thrust No. 3.1
Plasma fuel mix ratio [14], Thrust No. 3.4
Density and Pressure Profile Control [13], Thrust No. 3.1 and 3.4
Tritium handling [14], 2.2 and Thrust No. 3.4
TAP Panel Recommendations:
Operate with profiles consistent with stability and bootstrap current fraction [13], 2.1 and Thrust No. 3.1, 3.2
Disruption Mitigation. Thrust No. 3.4

Finally, this white paper is consistent with the high level recommendations from the Greenwald panel that states, "***New technological solutions for core fueling will most likely be needed, which should be first tested on test stands and later on operating devices such as ITER and other magnetic confinement devices."*** and ***"Develop new methods of Core fueling."***

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