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Advanced Fuelling System for use as a Burn Control Tool in a Burning Plasma Device

Roger Raman

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Roger Raman

University of Washington, Seattle, WA, USA

ABSTRACT

Steady-state Advanced Tokamak (AT) 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 ELM-free discharges in ITER. The capability to deposit fuel at any desired radial location within the tokamak would provide burn control capability through alteration of the density profile. The ability to peak the density profile would ease ignition requirements, while operating ITER with density profiles that are peaked would increase the fusion power output. 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. Experimental data needed for the design of a CT fueller for ITER could be obtained on NSTX using an existing CT injector.

1. INTRODUCTION

Early fusion plasmas relied on edge gas puffing for plasma discharge fuelling. While this method worked well to a certain extent, it is not expected to meet the fuelling requirements of fusion reactors. The advantages of depositing fuel in the core (where it is needed) motivated pellet injection research. During the past twenty years, this method has become a highly developed fuelling tool and is used in conjunction with edge gas fuelling in present experiments.

As the fusion plasma cross-section increased, and the quality of the plasma discharge approached conditions that would exist in a reactor (high core and edge plasma temperatures with the presence of fast particles and energetic electrons, and edge toroidal rotation velocities of over 100km/s), pellet injection from the outboard side was found to be inadequate even for present large machines. The pellet simply ablated well before it could get to the core. The limitations of pellet fuelling a burning fusion reactor was recognized as early as the 1980s, in particular by Perkins[1] et al. and Parks[2] who proposed the idea of injecting high velocity Compact Toroids (CTs) for reactor deep fuelling.

Experimental[3] [4] and theoretical work indicates that deep fuelling of magnetized fusion reactors can be achieved by CT injection. The advantages of deep fuelling include avoiding edge density limits by fuelling well beyond the transport barriers, profile peaking to reach ignition, profile control for attaining high-beta stability limits and high-bootstrap current fraction drive, low tritium inventory and others.

A CT is a self-contained toroidal plasmoid with embedded magnetic fields. The injector consists of the formation region, compression, acceleration and transport regions[5]. Fuel gas is puffed into the formation region, and a combination of magnetic field and electric current ionizes this gas and creates a self-contained plasma ring (the “CT”). Then a fast current pulse compresses and accelerates the CT by electromagnetic forces. The accelerated CT will travel at a speed of over 30cm/μs and for reactors will create a particle inventory perturbation of <1% per pulse.[6] For the CT to penetrate a magnetic field, to first order, the CT kinetic energy density ($\rho V^2/2$) must exceed the target magnetic field energy density ($B^2/2\mu_0$).

2.0 THE CONVENTIONAL METHOD FOR DEEP FUELLING

The traditional method for attaining deep fuelling is through the injection of cryogenic deuterium pellets. Penetration of pellets into fusion plasmas is dependent on the plasma parameters and in particular on the presence of energetic particles in the discharge. In conventional large aspect ratio tokamaks, large diameter pellets have been shown to do good core fuelling when injected from the outboard side. However as the neutral beam power is increased the pellet penetration considerably degrades. In 1996, a new invention that of injecting pellets from the inboard side (high field side) considerably improved pellet penetration even during neutral beam injection[7]. The physics behind this improved penetration is the formation of a high beta cloud that is transported radially out towards the low field side because of increased magnetic pressure on the inboard side. The same mechanism that made it difficult for pellets to fuel the core (when injected from the outboard side) now naturally helped fuel the core. However, here too, there is a limit on how high the edge temperature could be for deep penetration of a pellet in ITER.[8]

3.0 ADVANCED TOKAMAK SCENARIOS

Advanced Tokamak scenario discharges rely on high bootstrap current fraction with non-inductive sustained current drive. To understand why the fuelling requirements for AT discharges are different compared to present day discharges, it is necessary to understand the magnitude of fuelling perturbations in present experiments and its implication for fuelling AT discharges. On JET and on DIII-D, pellet fuelling typically produces a 50% total particle inventory perturbation[9] [10]. To achieve such a large fuelling perturbation, the pellets must be large in size. A large pellet can penetrate much deeper because even if the outer layers are ablated during penetration, some pellet mass can still be arranged to be available for core fuelling. Indeed such strong particle inventory perturbations are credited for producing the well-known "PEP" modes on JET, however, this is a transient mode, which is incompatible with steady-state operation. The confinement degradation in the JET experiments was attributed to a reduction in plasma temperature and to a degradation of the neutral beam heating profile. By reducing the pellet size and optimizing the delivery sequence the degradation in the plasma performance was reduced. Unfortunately this level of particle inventory perturbation is inconsistent with AT scenarios. Because, AT scenarios rely on optimized density and pressure profiles and fuelling that adversely alters these profiles is unsuitable.

To develop pellet fuelling that is consistent with AT scenarios, the ASDEX-U group has a program focused at reducing the pellet mass and increasing the pellet injection frequency. Pellet induced particle inventory perturbations on ASDEX-U are on the order of about 10%, but even this may be too high to sustain AT discharge profiles. Furthermore, since the pellet continually ablates as it propagates inward, the pellet does not locally fuel the discharge. In addition experiments on JET, ASDEX-U and DIII-D inject pellets at an angle with respect to the horizontal because of inacceability issues for injection of pellets from the midplane, for a true radial injection. Injection of pellets from the top or at an angle of 45 to 90 degrees with respect to the horizontal is not as favorable as mid-plane injection as the higher velocity of the ablated plasmoid can move it away from the trajectory of the pellet[7]. Maximum pellet velocities for inboard side injection appear to be limited to about 500m/sec, limited by the pellet inertial strength[7].

Additionally, there is yet no good data on fuelling Reverse Shear discharges using small pellets. Injection of a large pellet from the inboard side of JET into Reverse Shear discharges caused the barrier to be temporarily destroyed[9]. Finally, mechanical centrifuge pellet injectors that are used for high frequency pellet injection are inflexible as far as arbitrarily varying both the pellet mass and the pellet velocity as required for feedback control of the density profile. AT scenarios would greatly benefit from a fuelling system capable of varying the fuel mass, composition and the fuel deposition location as required by the reactor plasma control system.

4.0 FUELLING STEADY STATE PROFILE DISCHARGES USING CT INJECTION

Fuelling steady state AT discharges requires the ability to deposit small amounts of fuel at the desired location and as often as needed, so as to compensate for diffusion of fuel, but not to adversely alter the established density profile.

These requirements are particularly well suited for a CT injection system. Design studies for ITER conducted as part of an ITER-Task, resulted in particle inventory perturbations of about 0.3% per pulse[6]. At this level of perturbation, the total particle inventory perturbation is small allowing established steady state profiles to be maintained. CT systems are also fully electrical, with the only moving part being the high reliability gas valve. Electrical systems are generally more reliable than mechanical systems. In addition, in a CT injector, because of the electrical nature of the injector it is relatively easy to alter the fuel mass and deposition location. Altering the accelerator voltage alters the CT kinetic energy density, thereby changing the depth of penetration and the fuel deposition location. Changing the amount of gas puffed into the injector region alters the mass of the CT. Changing the fuel composition is also easy as some of the gas injection valves could be controlled by the operating system to dope the fuel with needed isotopes. The CT injector pulse recycle time can be as short as several ms, resulting in an operating frequency capability of over 100 Hz. Again, because of the electrical nature of the injector, it would be possible to alter the CT mass and velocity on the tens of ms time scale, giving the reactor fuel control system full feedback control capability of the density profile.

5.0 MOMEMTUM TRANSFER BY CT INJECTION

In present experiments, neutral beams are used for plasma heating. An added benefit is that the tangentially injected beams transfer momentum to the plasma and provide plasma rotation. The velocity shear helps sustain transport barriers. In a reactor, fusion product alphas will provide the needed heating thus neutral beam heating will not be needed during the sustained operation phase. Alphas being isotropic cannot provide preferential plasma rotation and velocity shear. A fuelling system that can also provide a source of toroidal plasma rotation, while fuelling the discharge as needed would be highly desired. The CT injector on STOR-M is mounted tangentially with the objective of momentum transfer[11]. For the case in Reference 6, a fuelling system based on CTs would inject on the order of about 5 x 10^{21} particles (D + T) per second at a velocity of about 300 km/s to provide the required core fuelling. For a tangentially mounted CT injector, the imparted toroidal momentum to the reactor plasma would be the same as that provided by a 500 keV, 40 MW neutral beam system. A 40 MW neutral beam operating at 500 keV, however, would provide only 2 x 10^{20} particles per second, or about 5% that of the CT based system.

Present experiments use numerous tools to produce and sustain a plasma discharge. These include a combination current drive systems (Ohmic, LHCD, ECCD, NBI, others) and a combination of heating systems (NBI, LH, EC, others). The goal of these tools is to produce a plasma discharge that approaches reactor relevant conditions. Since the entire discharge is governed by these auxiliary tools, in present experiments these tools can also be used to shape and control the profile of the discharge. The fuelling issue, unfortunately, is thus given much less importance in present machines.

In an ignited plasma, there is no need for the heating tools to heat the plasma. This then also takes away any plasma control capability these offer in present machines. An important byproduct of NBI heating, namely that of toroidal momentum input is also lost. In AT discharges, the use of a very high bootstrap current fraction, implies the need for much less auxiliary current drive. Thus, a burning plasma with high Q has little besides fuelling that can control the internal profile for stability, bootstrap current and beta[12].

6.0 EXPERIMENTAL STATUS

A number of small tokamak injection experiments have been conducted. These are: experiments on the ENCORE tokamak[13 14], the TdeV tokamak[15 16], the STOR-M [11 17] tokamak and the JFT-2M tokamak[18 19]. Supporting experiments have been conducted at UC-Davis[20 21] and at NIFS[22]. Notable is the demonstration of efficient acceleration of CTs[23] and the non-disruptive fuelling from CT injection in the TdeV tokamak[3]. Spectroscopic and bolometric measurements indicated that the impurity content was low and that most of the injected impurities were C and O; these are not expected to be a problem in a continuously operating injector, as the electrode surfaces are expected to clean up under repetitive operation. The MARAUDER device[24] has demonstrated an acceleration efficiency of over 30%, generation of 1-2 mg CTs, greater than 50% coupling of the injected gas to the CT, and velocities of 400 km/s. These are the CT parameters projected for a reactor.

6.1 CT Penetration Early theoretical work by Perkins et al.[1] and Parks[2] studied the penetration, slowing down and reconnection processes of a CT penetrating a tokamak plasma. A primary condition in these models is that the CT should have sufficient kinetic energy density ($\rho V^2/2$) to exceed the target magnetic field energy density ($B^2/2\mu_0$) so that the magnetic field lines could be pushed aside during CT penetration. More recently Suzuki et al.[25] have conducted three dimensional simulation studies to investigate the dynamics of CT penetration in to a tokamak plasma. The TdeV results show that CTs can be sufficiently clean for the purpose of tokamak fuelling. As shown in Ref. 3, during the fuelling of a 1.4 T single null divertor discharge the tokamak plasma was not adversely perturbed. While some fuel was deposited deep inside the separatrix, there was no localized fuelling and a large fraction of the fuel was deposited near the edge. This is an inherent difficulty with small tokamaks because the CT axial dimensions are comparable to the tokamak minor radius. In small tokamaks, gas following the CT can also contribute to edge fuelling, further complicating the analysis. As Figure 1 indicates, these issues can be avoided by selecting a larger cross-section target plasma. CT fuelling is a concept that is easier on larger cross-section plasmas because of the difficulty in producing very small CTs as is needed for the smaller machines. The details of the physics of CT fuel deposition is not well understood because of the lack of adequate experimental measurements. MHD simulations[25] indicate that the fuel would be deposited on tokamak field lines on which the CT magnetic fields reconnect. Reducing the dimensions of the CT should reduce the size of the reconnecting region. If the CT dimensions are sufficiently less than the minor diameter of the tokamak, then the region of reconnection and subsequent fuel deposition should be localized, however, detailed experimental measurements are needed to adequately understand this process.

The TdeV results show that it is not possible for localized deep fuelling with the CTF-II/TdeV or similar combination. Injection of CTs from a CTF-II sized injector into a larger cross-section plasma, as shown in Figure 1, would allow for a localized deep fuelling test, which is the required next step for the development of the CT fuelling concept. The CT injector used in experiments in the TdeV tokamak is at present in storage at the Princeton Plasma Physics Laboratory. Installation of this device on NSTX would allow the following experimental data to be obtained.

- Demonstration of localized deep fueling: The attained CT velocities are much more than NSTX's needs, as the CTF-II parameters translate to equivalent CT kinetic energy densities in the 1 to 2T range.
- The corresponding momentum injection is equivalent to a 100ms neutral beam pulse (at 1MW, 50keV). This level of momentum injection is sufficient to conduct initial demonstration tests of the ability of a CT to inject momentum.
- Demonstrate ability to alter fuel mass and deposition location.
- Demonstrate ability to fuel advanced confinement mode discharges.

- After initial tests with the single pulse power supply, upgrade the power supplies for a 10Hz CT injection test.

Experimental data from these tests should be adequate to proceed with the design of CT system for ITER, while in parallel experimental effort on JT60-U or on JET could be initiated.

In summary, for the viability of the CT fuelling concept, three key objectives need to be demonstrated. These are the demonstration of localized deep fuelling, ability to alter fuel mass and deposition location in a tokamak plasma and the ability to fuel advanced confinement mode discharges and AT discharges.

7.0 SUMMARY

Advanced Tokamak discharges rely on high bootstrap current fraction with non-inductive sustained current drive. Fuelling these discharges requires the ability to deposit small amounts of fuel at the desired location and as often as needed, so as to compensate for diffusion losses of fuel, but not to adversely alter the optimized density profile. Injecting small amounts of fuel also avoids cooling the plasma, which is generally accompanied by degradation in confinement. Ultimately, a burning plasma with high Q has little besides fuelling (and a source for current drive) that can control the internal profile for stability, bootstrap current and beta.

The capability to deposit fuel at any desired radial location within the tokamak would provide burn control capability through alteration of the density profile. The ability to peak the density profile would ease ignition requirements, while operating ITER with density profiles that are peaked would increase the fusion power output. An advanced fuelling system should also be capable of fuelling well past internal transport barriers. Compact Toroid fuelling has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input.

The electrical nature of a CT injection system, and it's potential to arbitrarily alter the fuel mass and the fuel deposition location, while simultaneously providing a source of momentum input for plasma toroidal rotation makes it a very attractive advanced fuelling concept. As a next step, large tokamak experiments are needed to establish localized fuelling and to demonstrate multi-pulse fuelling capability. A fuelling system that provides a source of toroidal momentum input, while fuelling the discharge as needed for maintaining plasma stability limits and current drive would increase the operational window of ITER.

Pellet fuelling has made important contributions to fusion research. While it continues to play an important role in present experiments, it is not clear if it will extrapolate favorably for fuelling AT discharges and reactor fusion plasmas. It is prudent for large tokamaks to consider and develop other backup options to meet the fuelling requirements of a steady state fusion reactor. Experimental data needed for the design of a CT fueller for ITER could be obtained on NSTX using an existing CT injector.

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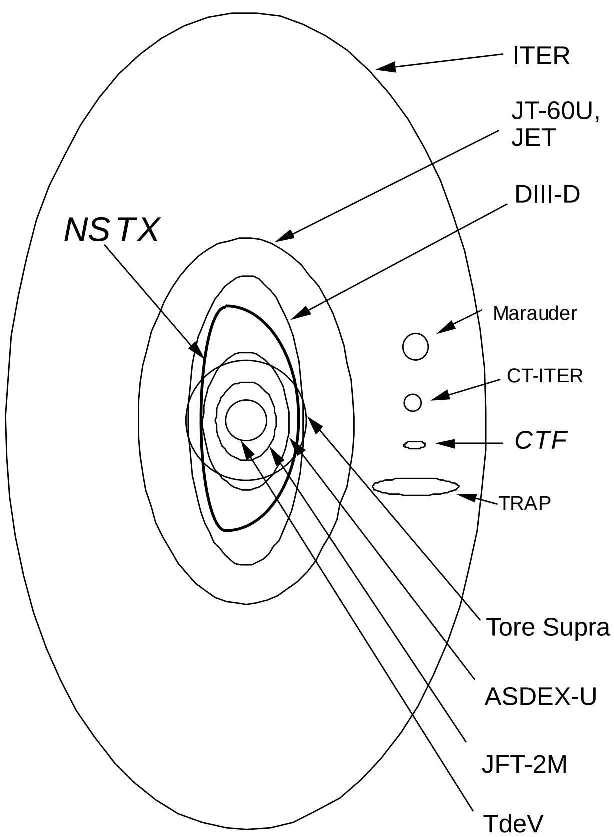
Figure captions:

Figure 1: Relative sizes of various tokamak plasma cross-section and CT plasmoids. Note that a CTF sized CT plasmoid can do far more localized fuelling on larger cross-section tokamak plasmas than it can on TdeV.



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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov