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Fuelling Requirements for Advanced Tokamak operation*

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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. Compact Toroid (CT) fuelling has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input.

1. Introduction

Experimental[1 2] 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.

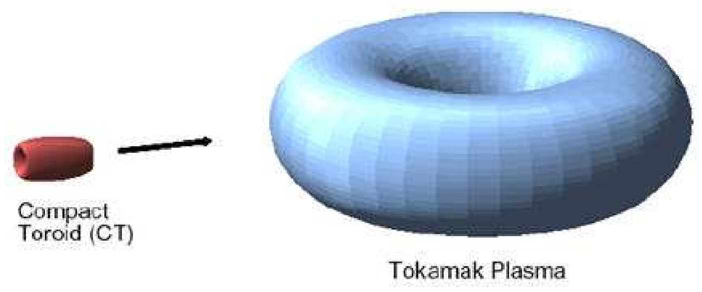

Figure 1: Pictorial representation of CT Fuelling. The CT velocity is about 300km/s. Other relevant time scales are: CT penetration time of a few micro-seconds, CT dissipation time inside the tokamak of about 100 microseconds and density equilibration time of > 1ms.

Perkins[3] et al. and Parks[4] proposed injecting CTs of dense DT plasma into tokamaks to achieve deep fuelling. 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 (please see Figure 1) 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. Fuelling steady-state discharges using CT injection

Fuelling steady state Advanced Tokamak (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 < 1% per pulse. At this level of perturbation, the total particle inventory perturbation is small, which should allow the required 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 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, thus 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. While pellet fuelling has made important contributions to fusion research, it is not clear if it will extrapolate well to burning plasma devices, in particular for feedback control of the density profile.

3.0 Momentum injection capability

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 and improve plasma stability limits. In a reactor, fusion product alphas will provide the needed heating thus neutral beam heating will not be needed during the sustained burn 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. For the case in Reference 6, a fuelling system based on CTs would inject on the order of about 5×10^{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 2×10^{20} particles per second, or about 5% that of the CT injection based system.

Present experiments use numerous tools to sustain a plasma discharge. These include a combination current drive systems (Ohmic, LHCD, ECCD, others) and a combination of heating systems (NBI, LH, EC, others). The goal of these tools in large machines 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 provide a large amount of control capability and can be used to improve plasma stability limits and to control the profile of the discharge.

An ignited plasma does not require the heating tools used in present machines. In an ignited device, this then takes away any plasma control capability these tools offer in present machines. An important by-product of NBI heating, namely that of toroidal momentum input is also lost. In AT discharges, the use of high bootstrap current fraction implies the need for much less auxiliary current drive. Thus, a burning plasma with high Q and with a source for current drive, has little besides fuelling that can control the internal profile for stability, bootstrap current and beta[7].

4. 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 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 favourably 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.

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[1] R. Raman, et al., "Experimental demonstration of tokamak fuelling by compact toroid injection," Nucl. Fusion, **37**, 967 (1997)

[2] T. Ogawa et al., "Compact toroid injection experiment in JFT-2M," 17th IAEA Fusion Energy Conference, IAEA-F1-CN-69/Exp1/16, Yokohama, Japan, 19-24 October (1998).

[3] L.J. Perkins, S.K. Ho and J.H. Hammer, "Deep penetration fuelling of reactor grade tokamak plasmas with accelerated compact toroids," Nucl. Fusion **28**, 1365 (1988).

[4] P.B. Parks, "Refuelling tokamaks by injection of compact toroids," Phys. Rev. Letter **61**, 1364 (1988).

[5] J.H. Hammer, et al., "Experimental demonstration of acceleration and focusing of magnetically confined plasma rings," Phys. Rev. Lett. **61**, 2843 (1988)

[6] R. Raman and P. Gierszewski, "Compact toroid fueling for ITER," Fusion Engineering and Design **39-40**, 977 (1998).

[7] T. R. Jarboe, private communication.