

DEVELOPMENT OF INNOVATIVE FUELLING SYSTEMS FOR FUSION ENERGY SCIENCE

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Development of Innovative Fuelling Systems for Fusion Energy Science

Abstract

The development of innovative fuelling systems in support of magnetic fusion energy, particularly the International Thermonuclear Experimental Reactor (ITER), is described. The ITER fuelling system will use a combination of deuterium-tritium (D-T) gas puffing and pellet injection to achieve and maintain ignited plasmas. This combination will provide a flexible fuelling source with D-T pellets penetrating beyond the separatrix to sustain the ignited fusion plasma and with deuterium-rich gas fuelling the edge region to meet divertor requirements in a process called isotopic fuelling. More advanced systems with potential for deeper penetration, such as multistage pellet guns and compact toroid injection, are also described.

1. Introduction

In contemporary tokamaks, fuelling provides the required density level for a particular plasma experiment lasting typically from a fraction of a second to several seconds. Recently, the Oak Ridge National Laboratory (ORNL) development program has focused on meeting the International Thermonuclear Experimental Reactor's (ITER's) complex fuelling needs. For ITER [1] and fusion power plants, the fuelling system has to provide deuterium-tritium (D-T) fuelling for much longer pulse lengths, in the range of ~1000 s to steady state. The system also must serve multiple, diverse functions including control of the plasma ion density to maintain a specified fusion power, replenishment of the fuel burned in the D-T fusion reaction, establishment of a flow of hydrogenic ions into the scrape-off layer, and influence of plasma edge conditions for optimum divertor operation. The ITER fuelling system will use a combination of gas-puffing and pellet injection [2] to achieve and maintain ignited plasmas. This combination will provide a flexible fuelling source with D-T pellets penetrating beyond the separatrix to sustain the ignited fusion plasma and with deuterium-rich gas fuelling the edge region to meet divertor requirements in a process called isotopic fuelling [3]. Several advanced fuelling schemes for tokamak fusion reactors are under study. Technologies with potential for deeper penetration include multistage pellet guns and compact toroid (CT) injection.

2. Pellet Fuelling Systems

The baseline ITER pellet injector concept is the centrifuge acceleration device. A major objective of the development program is to improve the performance and reliability of the centrifuge pellet injection system. An existing centrifuge accelerator facility provides a test bed for experimental investigations and hardware development. In the present effort, a standard ORNL extruder and an innovative pellet punch mechanism have been fitted to the existing centrifuge accelerator facility. The new, punch-type pellet feed/cutter device is closely coupled to the arbor and is adjustable, including the capability to change pellet lengths remotely in 0.2-mm increments over the 1.6- to 2.8-mm range. Deuterium testing is being carried out to optimize system performance and reliability with a goal of retrofitting this feed and punch system on the Tore Supra centrifuge injector. To date, the feed system has

produced over 400 cylindrical pellets (2.3-mm diam by 1.6-mm long) at low repetition rates of 1 to 2 Hz. At higher repetition rates in the 10- to 20-Hz range, pellets sequences of several seconds length have been produced, the pulse length being limited by the ability of the centrifuge vacuum pumping system to maintain sufficient vacuum for thermal insulation of the extruder cryostats. This constraint can be removed by a separation of the cryostat guard vacuum from the centrifuge spin tank vacuum. Sequences of up to ~100 pellets have been accelerated to speeds of 500 m/s with a high fraction of intact pellets hitting the pellet target plate in the pellet injection line.

For the ITER application and fusion reactors, a feed system capable of providing a continuous supply of frozen isotopic hydrogen is required. A straightforward technique in which multiple extruder units of identical design operate in tandem is being developed for steady-state operation. The extruder design was updated with a version that doubles the available hydrogenic ice volume over the design used on the Joint European Torus and the Tokamak Fusion Test Reactor (TFTR) pellet injectors. A prototype consisting of three extruder units, each with a deuterium ice volume of $\sim 8 \text{ cm}^3$, is under assembly. Deuterium extrusions with a nozzle producing 4-mm-diam pellets were carried out recently on a single extruder assembly. The system performed as expected, providing a good ribbon of deuterium ice for multiple seconds. A transition piece that accepts the three individual feeds and outputs a single feed is the key new component that must be developed for this design. The equipment described here should be adequate to demonstrate steady-state feed rates required for pellet injector operation at frequencies up to $\sim 10 \text{ Hz}$ and pellet sizes in the 2- to 8-mm range.

A pellet injection system to test the thermal-mechanical properties of extruded tritium has been fabricated. This repeating, single-stage pneumatic injector, called the Tritium-Proof-of-Principle Phase II (TPOP-II) Pellet Injector [4], has a piston-driven mechanical extruder and is designed to extrude and accelerate hydrogenic pellets sized for the ITER device. In initial tests with deuterium feed at ORNL, up to 13 pellets have been extruded at rates up to 1 Hz and accelerated to speeds of $\sim 1.0 \text{ km/s}$. The pellets, typically 7.4 mm in diameter and 7 to 11 mm in length, are the largest cryogenic pellets produced by the fusion program to date. These pellets represent about a 5 to 10% density perturbation to ITER. In a series of successful experiments at Los Alamos National Laboratory, solid tritium was extruded and used to produce repetitive tritium and D-T pellets (Fig. 1). This is the first known extrusion of solid tritium.

ORNL, in collaboration with ENEA Frascati, has developed a repeating two-stage light gas gun [5] to evaluate the technology issues of a high muzzle velocity pneumatic injector utilizing an extruder-based pellet feed system. Figure 2 shows the results of many single pellet and repetitive deuterium pellet sequences; muzzle velocities of 2.5 km/s have been attained at repetition rates of 1 Hz.

The production of impurity pellets (Ne, Ar, Kr) has been demonstrated using the DIII-D and TFTR pneumatic pellet injection systems; such pellets will be used in experiments to optimize edge plasma/divertor conditions and evaluate rapid plasma shutdown capability for mitigation of the effects of a major plasma disruption.

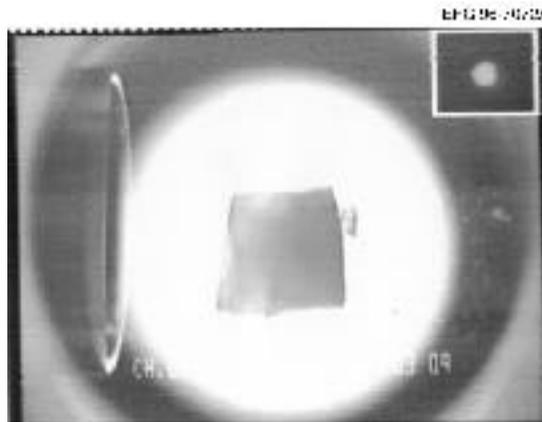


Fig. 1. Photograph of D-T pellet (7 mm in diameter by ~8 mm long)

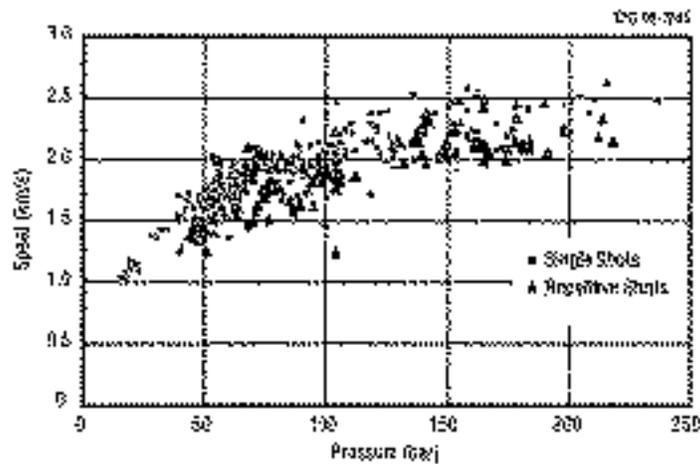


Fig. 2. Muzzle velocity as function of breech pressure for repeating two-stage pneumatic injector.

3. CT Fuelling

As tokamak parameters approach the fusion reactor regime, it becomes increasingly clear that the ability to centrally fuel a tokamak reactor is crucial to its overall efficiency. For example, a recent parametric study [6] of the ITER operating regime has shown that a centrally peaked density profile can lower the ignition parameter and the relative plasma pressure required for ignition. Spheromak-like compact toroids (SCTs) are self-contained, magnetized plasma structures that have an internal toroidal and poloidal magnetic field, with associated internal poloidal and toroidal plasma currents [7]. This CT type has been demonstrated to withstand great accelerating forces using coaxial electrodes [8]. Unlike CTs formed by reverse field processes, SCTs are low- β plasmas with relatively high magnetic binding energy per ion. This is expected to result in a more robust magnetized plasma with increased capability of remaining intact during the tokamak-CT interaction phase. The use of accelerated SCTs to centrally fuel tokamak plasmas has been demonstrated on experiments on the TdeV tokamak [9], during which central plasma penetration was obtained without any adverse effect to the tokamak discharge.

The first goal of the U. C. Davis experimental program is to understand the stopping mechanism of an accelerated SCT in a vacuum magnetic field. By assuming

that the SCT behaves as an incompressible, perfectly conducting rod, we can obtain a simple estimate of its penetration into a magnetic field. Taking mass density ρ_{ct} to be constant, the SCT kinetic energy density at velocity v is $K = \rho_{ct} v^2/2$, while the energy density required to exclude magnetic field B from the SCT volume is $P = B^2/2\mu_0$. The total energy $K + P$ is conserved, so that an SCT with initial velocity $v = v_0$ in a field-free region has final velocity $v_f = \sqrt{v_0^2 - 2P/\rho_{ct}}$ in the presence of a vacuum magnetic field. The condition that the SCT be stopped ($v_f = 0$) at final magnetic field B_f is therefore $\rho_{ct} v_0^2 = B_f^2/\mu_0$. Experimental data in general agreement with the equation for v_f are shown in Fig. 3. The extra SCT penetration at high fields may be caused by finite compressibility.

Using this model, SCT injection data to date can be summarized on a plot of mass density ρ_{ct} vs initial velocity v_0 , with an estimate of the parameter region needed to centrally fuel an ITER-class tokamak. Data for CT experiments at CTIX (U.C. Davis/Livermore), RACE (Livermore), MARAUDER (Phillips Lab), and CFFTP (TdeV) are shown in Fig. 4. Note that the energy density required for penetration of a 5-T magnetic field has already been obtained on the MARAUDER accelerator, using argon SCTs [10].

For an SCT injector to fuel a reactor-class tokamak, repetitive operation is essential because a discharge duration of ~ 1000 s is planned. Moreover, repetitive

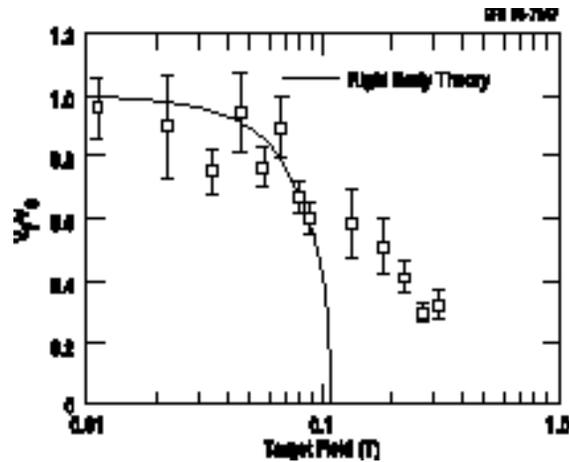


Fig. 3. Fitting of SCT vacuum field penetration to rigid body model.

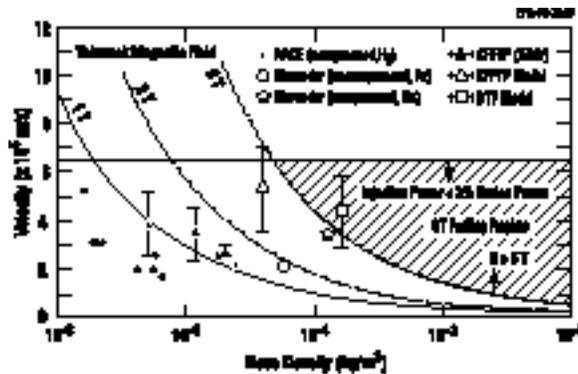


Fig. 4. Comparison of energy displacement model of SCT penetration with existing experimental data.

operation at a high repetition rate can minimize plasma disturbance by delivering a relatively small mass of neutral density per SCT injection. We have developed the first operating repetitive SCT injector by making use of fast gas-puffing and saturable core reactors, thus obtaining power switching without use of active external switching devices such as spark gaps or ignitrons. To date, this injector has produced up to 1000 consecutive shots into our small tokamak, DDT, which is pulsed in synchronism with the injector.

Another area of interest is the effect of repetitive pulse operation on SCT impurity content [11]. This effect is under investigation on DDT using time-resolved spectrometry. Repetitive SCT operation is expected to have the advantages of continuous electrode cleaning and maintenance of electrode surfaces at high temperatures, reducing impurity redeposition. Spectroscopic data of SCT impurities are measured with a gated visible optical multichannel analyzer (OMA). A total of 100 shots at 0.2-Hz repetition rate were recorded at a distance 91 cm from the SCT formation region, with the OMA gated on for 10 μ s, starting 5 μ s after SCT formation. O^{III} is the predominant radiation in the wavelength region studied (370 to 400 nm). The 100 shots show no dramatic increase in impurity radiation, despite significant wall dissipation and heating.

Time-resolved measurements with silicon X-ray photodiodes (Fig. 5, bottom trace) indicate that virtually all emission occurs during the 10- μ s OMA gating interval. Wall field measurements at the same location (Fig. 5, top and middle traces) indicate that most radiation is contained in the accelerating sheath, and not in

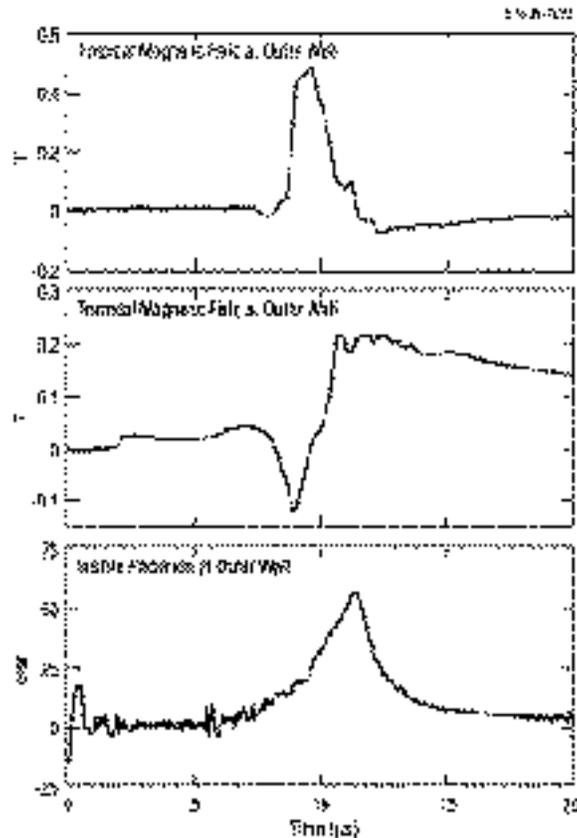


Fig. 5. SCT measurements at outer wall, 91-cm port. Top: SCT field (poloidal field), middle: accelerating field (toroidal field), bottom: radiation signal at outer wall (photodiode).

the SCT itself, because visible light is seen to peak after the poloidal field has significantly decayed from its maximum value. Because the radiating impurities are not contained within the SCT, they are not expected to penetrate the closed-field region of the tokamak plasma but will instead be swept away by the divertor action of the open-field-line region. The SCT plasma, of course, would penetrate deep into the discharge. The impurities associated with the acceleration plasma should therefore not contribute to contaminating the tokamak discharge.

In summary, we have shown that it is possible to form and accelerate SCTs by purely passive switching, greatly reducing the complexity associated with an actively switched injector. Experiments with other SCT devices have demonstrated disruption-free tokamak fuelling at directed energy densities close to that required for reactor fuelling. Together, these results suggest that the SCT is a viable candidate for tokamak reactor fuelling.

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