Design and evaluation of a repetitive-fire compact toroid fuelling system for ITER

Executive Summary

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March 2, 2007

1 Compact Toroids

Compact toroids (CTs) are semi-stable plasma rings with embedded toroidal and poloidal magnetic fields and currents, similar in structure to the tokamak. In 1982 it was proposed to use a device known as a Marshall gun to accelerate CTs to high speed (on the order of 100s of kilometres per second) and inject them into a fusion plasma for purposes of fuelling. CTs are typically modelled as perfectly conducting spheres with embedded magnetic dipoles. This allows models of the trajectory of a CT inside a magnetized plasma to be developed.

2 Application to ITER

It has been proposed in the past to use CTs as a fuelling method for the ITER tokamak. ITER is a large experimental fusion reactor which is currently being built in France under the cooperation of several nations. The ITER design, which was finalized in 2001, specifies 400 Pa m^3 s^{-1} of fuelling from the edge, and 50 Pa m^3 s^{-1} of central fuelling using a high-velocity pellet injector. The purpose of this project is to design a compact toroid injector to replace the pellet injector in the ITER (2001) reactor design. The ITER (2001) tokamak has a major radius of 6.2 m, a minor radius of 2.0 m, and a toroidal magnetic field strength of 5.3 T. The CT injector was chosen to operate at a rate of 50 Hz in order to synchronize with the European power grid, implying that each CT (composed of 90% tritium and 10% deuterium) has a mass of 1.29 mg.

3 CT Trajectory Modelling

To describe the motion of the CT inside the tokamak, a model incorporating six degrees of freedom (three spatial, three rotation) was developed and solved numerically using a finite element modelling system. The operating conditions (*i.e.* density, ion and electron temperature) for ITER in Hybrid #1 mode (one of three proposed modes) were used as a basis for the solution. The embedded CT magnetic field strength was chosen to be 0.4 T, concordant with the highest measured CT magnetic fields in past experimental work. The injector angle and initial speed were chosen by optimizing the CT trajectory so that alignment of the CT dipole and the tokamak magnetic field occurred when the CT was near the centerpoint of the reactor. The currently-accepted model holds that reconnection and fuel deposition occurs at this time. The results of this optimization were that the injector should be placed at a poloidal angle of 90° (that is, at the top of the reactor), angled 60° in the toroidal direction and 30° poloidally, with a muzzle velocity of 300 km s^{-1}.

4 Design Overview

The physical size of the gun is dictated by the CT radius, which is chosen (based on the minimum achievable size in past experimental work) to be 0.1 m. The injection velocity and angle were obtained by modelling the CT trajectory in the tokamak as described in Section 3. The length of the drift tube is dictated by the condition that the injector be installed in the ITER upper port, with the main body of the gun outside the bioshield for maintenance purposes. Based on extrapolation from previous experiment, the power consumption of the gun is calculated to be approximately 14.5 MWe. Figure 1 shows an overview of the proposed injector design.

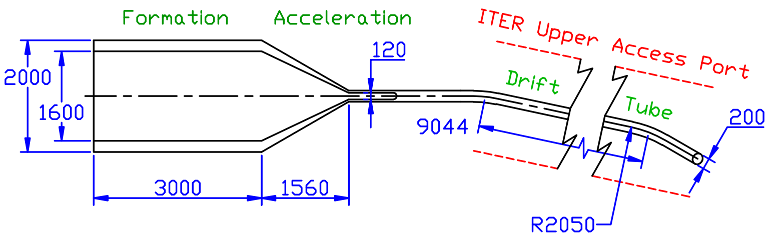

Figure 1: Overview of proposed gun design showing formation and acceleration regions, as well as drift tube and end section. All dimensions in mm.

The barrel and electrodes are constructed of a high-conductivity material such as copper with a tungsten coating. The tungsten is necessary to ensure that the gun walls do not ablate due to sputtering and arcing as the CT passes. It has been estimated that the tungsten content in the ITER reactor must be less than 7×10^{15} m^{-3} in order to limit bremsstrahlung losses. Experimental results from CT injection using tungsten-coated walls imply that W entrainment can be up to 0.002% (by mole), implying that at most (*i.e.* assuming no diffusion of tungsten out of the divertor vent), 2.66×10^{18} W ions will be in the reactor at the end of a 1000 s discharge. This corresponds to a final W content in the reactor of 5.4×10^{15} m^{-3}, below the required limit.

5 Comparison to Alternative Systems

Though the edge gas fuelling system is larger, the absolute rates are not directly comparable because inward fuel transport is limited by diffusion for edge fuelling. In contrast, fuel injected to the center is efficiently coupled to the fusion reactions.

There are several advantages of the proposed CT injector over the current status-quo pellet injection system. The CT fueller is mechanically simpler than any pellet-injection system, including centrifuge, pneumatic acceleration, and gyrotron acceleration. This is largely due to the requirement that solid deuterium/tritium 'ice' pellets be formed with a pellet injectoin system. Futhermore, the CT injection system provides better localization of fuelling than the pellet injection system, due to its higher injection speed (300 km s^{-1} for CTs vs. up to 3 km s^{-1} for gyrotron-accelerated pellet injection) and faster deposition.

6 Discussion & Conclusions

Some approximations were made in the development of the model of CT motion in Section 3. First, CTs are actually prolate ellipsoids, not spheres. Second, they actually *are* penetrated by the tokamak magnetic field, though on a time scale slow enough that most of the fuel deposition process will have occurred by the time the magnetic field penetrates. Certain extrapolations made from previous experiments were made, such as the ability of the CT to travel through a curved drift tube, the entrainment of tungsten from the gun walls into the CT, the efficiency of acceleration, and the ability of the gun to compress the CT. A more detailed feasibility study will have to be conducted before actually building the device.

The proposed fueller design is a viable option for delivering 50 Pa m^3 s^{-1} of 90%T/10%D fuel to a region approximately 1 m across in the center of the ITER (2001) tokamak. The fueller will not introduce an excessive amount of high-Z impurities to the plasma. Power consumption should be approximately 14.5 MWe. Despite this large power consumption, the flexibility and control characteristics of the CT fueller make it an attractive choice compared to current choices for central fuelling.