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## FUSION CONCEPT EXPLORATION EXPERIMENTS AT PPPL

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Small "concept exploration" experiments have for many years been an important part of the fusion research program at the Princeton Plasma Physics Laboratory (PPPL). This paper describes some of the present and planned fusion concept exploration experiments at PPPL. These experiments are at University-scale research level, in contrast with the larger fusion devices at PPPL such as the National Spherical Torus Experiment (NSTX) and the Tokamak Fusion Test Reactor (TFTR), which are at "proof-of-principle" and "proof-of-performance" levels, respectively.

### 1. CDX-U (Current Drive Experiment-Upgrade)

The CDX-U device is a modified version of the CDX device, and in the form of CDX-U was the first Spherical Torus (ST) in the US [1]. Since 1992 CDX-U has explored several innovative concepts in fusion physics; for example, it provided the first demonstrations of bootstrap current drive with electron cyclotron heating [2], DC helicity injection [3], and high-harmonic RF heating of an ST [4].

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The CDX-U machine was upgraded in 1998 and currently has the configuration shown in Fig. 1 and the parameters listed in Table 1. In addition to the existing 12 MHz, 100 kW RF system there is now an additional  $\approx 500$  kW of RF power available at a frequency of 0.5-1.0 MHz suitable for rotamak experiments. The machine also has an excellent set of plasma diagnostics for a concept exploration experiment; for example, it has a state-of-the-art ultra-soft x-ray imaging system based on multi-layer mirror technology built by the Johns Hopkins group [5].

Near term plans for CDX-U involve two main research areas: continued study of high harmonic fast wave heating (HHFW), and initial studies of electron Bernstein wave (EBW) emission. In the area of HHFW heating, the goals are to evaluate the heating mechanisms and plasma transport at the higher power level than previously, in particular using a new multi-point Thompson scattering system to measure the electron density and temperature profiles. In the area of EBW emission, the goal is to measure for these EBW waves using a probe inside the plasma, both to explore the physics of wave propagation, and also to develop a new technique for measuring the electron temperature profile in high beta plasmas [6].

Longer-term plans for the CDX-U facility include the following:

- 1) study of rotamak current drive in the ST configuration, using new a set of 8 antennas and the 500 kW low frequency RF power system. This should allow a significant extension of the initial ST rotamak results [7] to regimes of higher density, larger current, and longer pulse length, and a systematic study of the physics of rotamak current penetration into the plasma.
- 2) investigation of RF heating and stabilization of a field-reversed configuration (FRC), based on plasmas formed in CDX-U with little or no toroidal field. The plasma startup will be done by ECH and an ICRH slow

wave antenna, the current will be formed by the same rotamak antennas and power supplies used for the ST current drive study above, the ohmic system will be used for additional current drive, and the ICRH will be used for heating and pondermotive stabilization of instabilities.

3) tests of liquid lithium walls, either using a static or flowing "rail" limiter at one toroidal location, or a toroidally symmetric pool of lithium as a target plate in a single-null divertor configuration. These experiments would be done in collaboration with the PISCES group at UCSD [8], so that the issues relating to plasma-surface interactions can be studied in the linear steady-state PISCES experiment, while the issues relating to toroidal plasmas and lithium transport can be studied in CDX-U.

## 2. SPIRIT (Self-organized Plasma with Induction, Reconnection, and Injection Techniques)

SPIRIT is a proposed next-generation FRC physics and confinement experiment at PPPL, based on the reconnection experiments done on the MRX (Magnetic Reconnection Experiment) device at PPPL [9]. Novel features of SPIRIT would include a wide range of possible elongations, a broad range of the kinetic stability parameter (ion Larmor radius to the plasma's outer separatrix), new means for sustaining the plasma current by NBI, and flexibility to compare the FRC with other CT configurations in the same facility, such as a low aspect ratio RFP.

The proposed configuration of SPIRIT is shown in Fig. 2, and the tentative machine parameters are shown in Table 1. The SPIRIT FRC plasma will be formed by merging of two counter-helicity spheromaks produced by inductive discharges formed by the internal flux cores, similar to MRX [9]. This should produce a relatively large trapped magnetic flux (up to 50 mWb,

equivalent to 300 kA) over a wide range of the kinetic parameter  $s^* = R_s/\rho_i \approx 4-60$ . This in turn should allow a good test of MHD stability over a wide range of elongations  $\epsilon \approx 0.5-4.0$  at high  $\beta \approx 0.5-1$ .

An important goal of the SPIRIT experiment is to study the sustainment and confinement of FRCs and other CTs over times much longer than the resistive decay time, which has generally not been possible in previous experiments [10]. The primary means for plasma current sustainment in SPIRIT will be a 30-60 keV, 5 MW NBI system, which should generate a significant amount of current drive, with possibly more from the dynamo effect driven by radial plasma flow. A secondary current sustainment can be obtained by introducing an ohmic transformer through the plasma center, similar to the TS-3 experiment in Tokyo [11].

A major physics issue to be explored in SPIRIT concerns the MHD stability of the FRC configuration. Previous FRCs have been shown experimentally to be stable over many Alfvén times, despite the fact that they are usually unstable to ideal MHD tilt instabilities. The SPIRIT experiment will test the MHD stability of FRCs over a wide range of the theoretically important parameters of  $s^*$  and  $\epsilon$ , and test whether additional stability can be obtained through the effects of conducting shells, saddle coils, NBI-induced rotation and/or flow shear, or energetic ion stabilization.

A further feature of SPIRIT will be the flexibility to relatively easily change the configuration into other compact toroids such as a spheromak and reversed field pinch (RFP). A spheromak can be formed by reversing the direction of one of the flux cores, thus co-merging the helicity instead of counter-merging as in an FRC. A low aspect ratio RFP can also be formed by adding a small toroidal field through the core. Comparative studies of these

three configurations in the same device would clarify both the physics and the relative reactor potential of these three concepts.

### 3. MNX (Magnetic Nozzle Experiment)

The MNX magnetic nozzle experiment is a linear device at PPPL which is designed for studies of the rapid plasma cooling and the resulting recombination in the expansion zone of a nozzle whose shape is set by a magnetic field. This experiment is based on studies of plasma recombination made in the same device without a magnetic nozzle [12], which showed that plasma can recombine before hitting the wall due to the presence of neutral gas.

The MNX will explore fusion concepts relevant to reducing the plasma power fluxes on fusion reactor first wall, as well as basic plasma physics such as the phase transition from a magnetized plasma to a supersonic neutral jet, and plasma applications such as spacecraft thrusters [13] and plasma processing. The MRX configuration is shown in Fig. 3, and the machine parameters are in Table 1. The device is presently operational with a weak magnetic nozzle and heated by a helicon RF source.

The main physics goal of the MNX experiment is to understand the process by which a rapid expansion of plasma through a magnetic nozzle cools the plasma and enhances recombination of the plasma into neutral gas. There are several unresolved issues such as the equation of state in the cooling region, the formation of a double-layer, the process of energy transfer from electrons to ions, turbulence in the plasma and/or gas flows, and the atomic physics of recombination.

The main fusion relevant goal of MNX is to explore new methods for reducing the edge plasma power and particle exhaust problems which have been a major difficulty in fusion experiments and fusion reactor concepts. For example, the plasma heat load to the divertor plate in ITER is such that the erosion rate would require the development of *in situ* repair or replacement techniques. The most promising solution to this problem is a "detached" plasma which cools and recombines before striking the wall. The cooling in present tokamak experiments is attributed to collisional processes with neutrals; however, the presence of these neutrals may not be consistent with steady-state operation regimes or H-mode scenarios. The magnetic nozzle technique of plasma cooling to be tested in MNX may be applicable to bundle divertors at the outer midplane of low aspect toroidal systems, or (more naturally) to the open field line region of FRC or spheromak reactor systems.

#### 4. Summary

This paper described three fusion concept exploration experiments currently in operation or planned at PPPL. These experiments are valuable not only for their innovations in fusion research, but also for the their contributions to our basic store of knowledge in plasma physics. These small University-scale experiments can also contribute to the larger fusion experiments at PPPL in the areas of RF physics, MHD stability, edge plasma physics, and diagnostic development, and are excellent facilities for graduate education.

Table 1: Parameters of Concept Exploration Experiments at PPPL

	CDX-U ST	SPIRIT FRC	MNX
Status	running	proposed	running
Major radius	34 cm	35 cm	50 cm (length)
Minor radius	22 cm	30 cm	1 cm
Elongation	1.6	1 - 8	-
Toroidal field	2.3 kG	0	5 kG
Plasma current	150 kA	300 kA	1-100 A
Pulse duration	50 msec	1-10 msec	continuous
External power	400 kW (RF)	5 MW (NBI)	5 kW

## Figure Captions

Fig. 1: The CDX-U machine configured in its present form as a spherical torus. The machine can be reconfigured to create rotamak fields by adding antennas, and can also be modified to produce FRCs. An experiment on liquid metal walls is also being planned.

Fig. 2: The SPIRIT machine proposed as a new concept exploration experiment at PPPL. The plasma will be formed inductively on the flux cores, and fueled by NBI. The effect of variable shaping and passive stabilizers on MHD stability will be studied for an FRC configuration.

Fig. 3: The magnetic mirror experiment (MNX) machine configuration. The linear plasma flows through a magnetic nozzle and is allowed to expand into a large chamber (at the right hand side), thus promoting cooling and plasma recombination.

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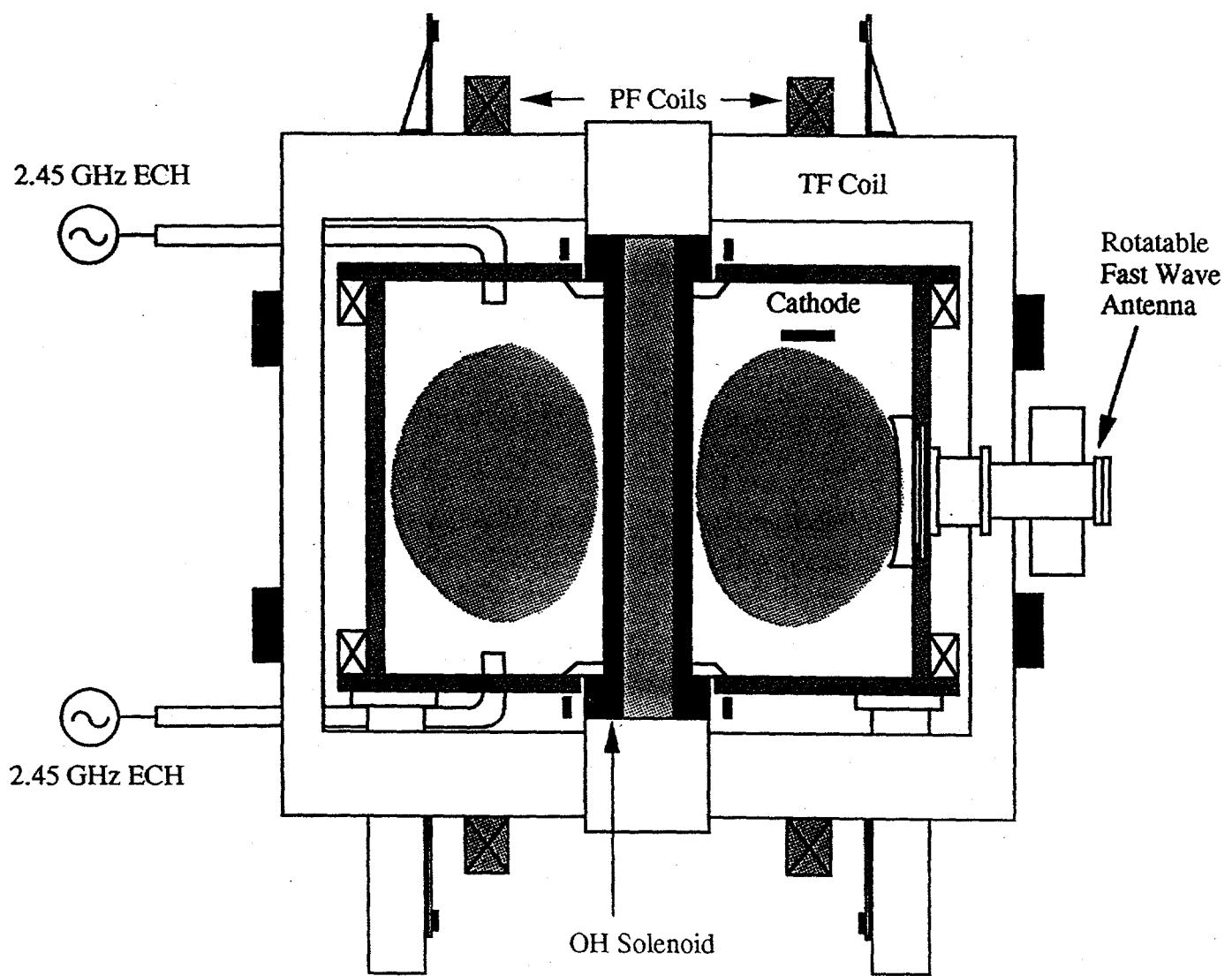


Fig. 1

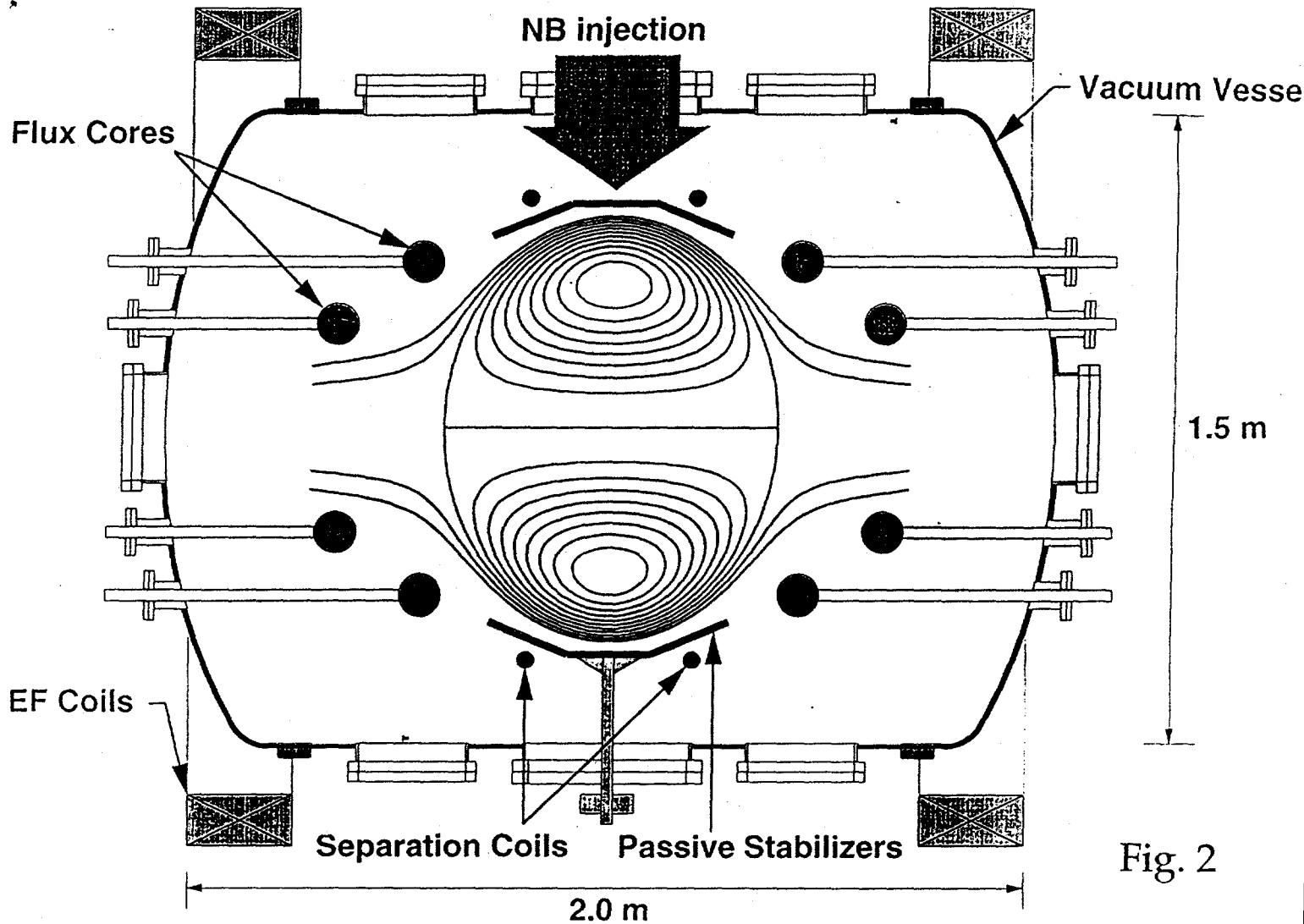


Fig. 2

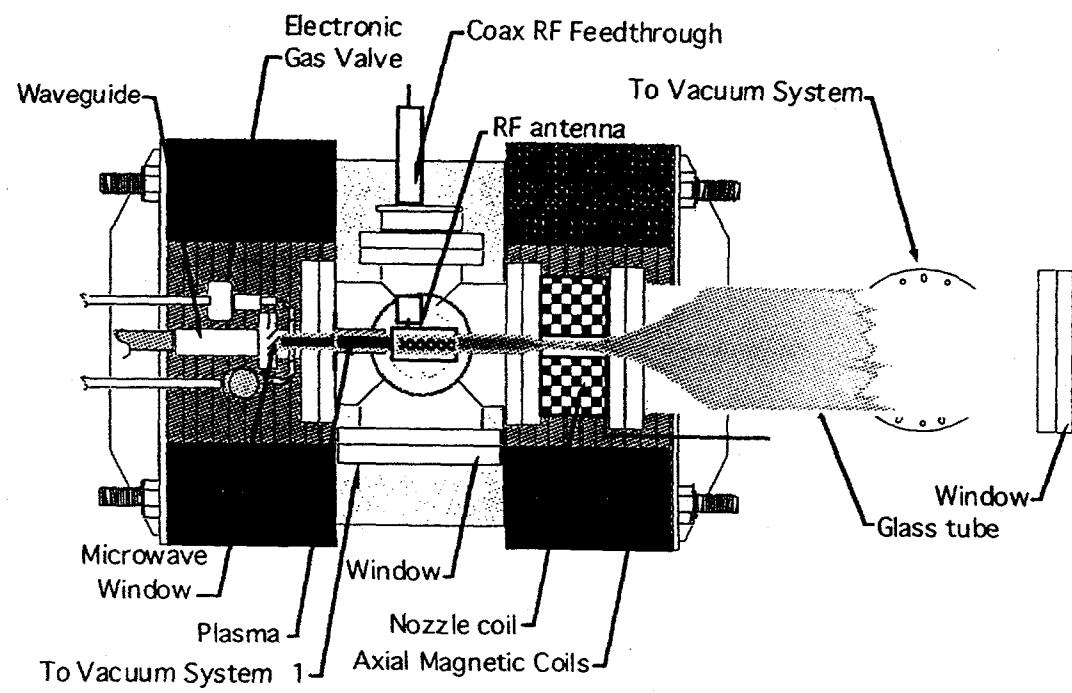


Fig. 3