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RMF_O-FORMED COLLISIONLESS HIGH-β PLASMAS: YESTERDAY, TODAY AND TOMORROW*

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The field-reversed configuration (FRC) is a high-β plasma confinement concept that possesses many attractive features favoring its development into a practical fusion reactor. To reach this goal, physics research must find viable methods to achieve adequate energy confinement, to maintain plasma stability, to drive plasma current for sustaining the configuration, and to heat the plasma to fusion-relevant temperatures. The rotating-magnetic-field (RMF) technique, conceived[1] as a method to generate plasma current, also has the potential to heat and stabilize plasma.[2-4] RMF research should be performed at low Coulomb collisionality, ν_c^*, to explore the physics regime relevant to fusion reactors.

Plasma formation by even-parity RMFs (RMF_e), the geometry pioneered in the 1980's in the rotamak series of experiments,[5] has not been successful in producing collisionless FRC plasmas, sustaining only warm electrons, $T_e < 50$ eV, in relatively dense and large plasmas, even for heating powers in excess of 2 MW. Some attributed the limitation to a radiation barrier, though Bellan[6] showed that the energy loss from RMF_e-heated devices was at a rate consistent with ion-acoustic flow, evidence for open field lines predicted by theoretical work. Six years ago, theoretical analysis demonstrated that low-amplitude transverse fields of odd parity would maintain the closure of an FRC's field lines.[7] Soon after, theoretical research showed that fully penetrated odd-parity RMFs (RMF_os) could effectively heat ions and electrons in collisionless FRCs.[2,3,8]

Electron energy is a natural measure of confinement quality and heating physics. The experiments described herein were performed in a device named the Princeton FRC experiment (PFRC). Non-invasive diagnostic techniques were used to measure $\langle\beta\rangle$ and electron density and energy in plasmas generated by RMF_o, testing the hypothesis that this new symmetry-preserving class of rotating magnetic fields can effectively heat electrons at low ν_c^*. Our novel results[9] include the RMF_o generation of small-radius (~3 cm), low-ν_c^*($\sim 10^{-3}$), high-$\langle\beta\rangle$ (~0.8) hydrogen plasmas with electron temperatures well above 100 eV, sustained for more than 10^3 τ_{Alfven} and with the RMF_o fully penetrated to the major axis. No radiation barrier was encountered. The ratio of the RMF strength to the static axial magnetic field strength is generally less than 0.1, more than a factor of three less than conventional RMF_e experiments.

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The electron heating results have been compared with numerical simulations based on Hamiltonian techniques. Though the average energies agree well with the experiment, the detailed electron distribution functions do not.

The PFRC device extensively employs COTS (commercial, off-the-shelf) hardware, in line with a philosophy for developing a practical reactor design. The RMF_o heating method, non-invasive diagnostics, internal flux conservers, and two remote divertor chambers, see figure 1, were required for control of plasma recycling, neutral density and plasma density, necessary for the achieving the best plasma performance.

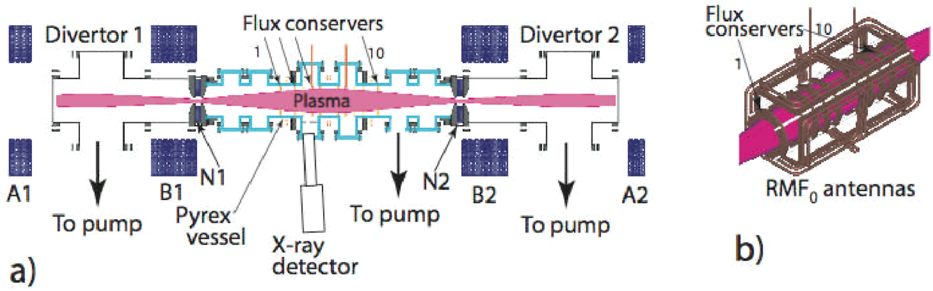

Figure 1 - Schematic of the Princeton FRC experiment. a) Cross section of the entire device. The total length is about 2 m. b) Close-up perspective view of the RMF_o antenna region.

Theoretical and computational studies of ion heating, again based on numerically integrating Hamiltonian particle orbits, show excellent confinement and explosive heating. These simulations are being used to design the next-step experiment. The scientific motivations for a larger superconducting next-step RMF_o device, operating at ten times higher axial field (to 1.5 kG), will be described, as will a path to the development of relatively small fusion reactors.

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