Princeton Plasma Physics Laboratory

PPPL- 4686

PPPL- 4686

RF Plasma Heating in the PFRC-2 Device: Motivation, Goals and Methods

S. Cohen, C. Brunkhorst, A. Glasser,
A. Landsman and D. Welch

September, 2011

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

RF Plasma Heating in the PFRC-2 Device: Motivation, Goals and Methods

S. Cohen[a], C. Brunkhorst[a], A. Glasser[b], A. Landsman[c], and D. Welch[d]

[a]*Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544 USA*
[b]*Department of Aeronautics and Astronautics, University of Washington, Seattle, WA 98195, USA*
[c]*Institute for Quantum Electronics, Swiss Federal Institute of Technology, 8093 Zurich, SW*
[d]*Voss Scientific, LLC, 418 Washington Street, SE, Albuquerque, NM 87108, USA*

Abstract. The motivation for using radio frequency, odd-parity rotating magnetic fields for heating field-reversed-configuration (FRC) plasmas is explained. Calculations are presented of the expected electron and ion temperatures in the PFRC-2 device, currently under construction.

Keywords: FRC; rotating magnetic field; RF heating; fusion reactor development.
PACS: 52.50.Qy; 52.55.Lf; 52.65.Cc

INTRODUCTION

Difficulties anticipated with tritium, neutron, heat-load and size/cost issues contribute to a long period anticipated for tokamak reactor development.[1] Smaller *aneutronic* MFE devices could reduce these problems, accelerating reactor development, but would need to operate stably at higher temperature and β than tokamaks. Plasma heating, current drive, energy transport and stability physics in high-β devices will be different than in tokamaks, hence new research efforts are needed if these approaches are to be evaluated. This paper describes one such approach, the proposed sequence of four PFRC devices, shown Fig. 1, parametrized by size, r_s, and magnetic field, B_e, along with those parameters of other proposed *aneutronic* FRC reactors and D-T fueled ITER.

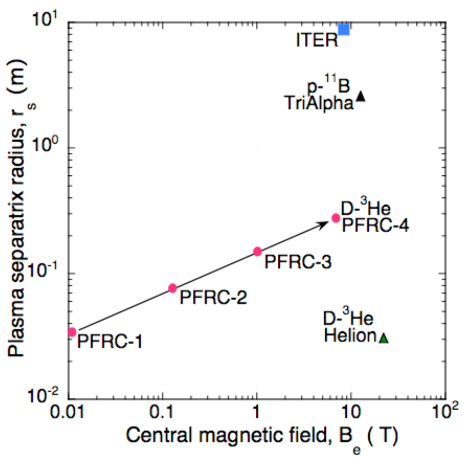

Figure 1. Separatrix radius and central magnetic field for four PFRC devices, a compressed FRC (Helion)[3], a beam-heated FRC (TriAlpha)[9], and ITER.

The FRC, the MFE device with the highest ⟨β⟩, has attracted scientific attention in the US [2, 3, 4, 5, 6] and Japan [7, 8] and financial support from governmental and private sources. The FRC class of devices is diverse, with heating method being a primary differentiating feature. Some propose a tokamak-like path using energetic neutral beams for heating. Because of the higher ion temperatures needed for *aneutronic* fusion, the neutral beams must be very energetic, hence the plasma must be dense and large to absorb the neutral beams. The main experimental effort in this arena is by TriAlpha, whose design for a p-^{11}B reactor shows $r_s \sim 2.5$ m and $B_e \sim 12$ T.[9]

Other groups are pursuing compressional heating, one by imploding a metallic liner[10] on an FRC, the other by injection of an FRC into a region of intense magnetic field[3]. These devices would produce a pulse of burning plasma having r_s = 0.5-5 cm. Advocates for the Helion compression approach[3] are concentrating on burning D-T for a variety of uses, *e.g.*, spacecraft propulsion, energy generation, and destruction of actinide waste produced by fission reactors, for which B_e = 10 T is sufficient. For *aneutronic* fuels, B_e would have to be increased a factor of 2-4.

RF plasma heating, in a form pioneered abroad[11,12] but most recently pursued in the US[2, 4, 5], targets steady-state operation. Our research on an improved RF method, odd-parity rotating magnetic fields (RMF_o), aims at midsized, $r_s \sim 25$ cm, D-^{3}He reactors with $B_e \sim 6$ T, promoting loss of the T^+ fusion product. That sized plasma would need far better energy confinement properties than the larger beam-heated FRCs. It is encouraging that the energy confinement midsized reactors need is less than classical, a value recently achieved in one FRC experiment.[6] Previous researchers[13] have pointed out reasons why plasmas in FRCs should have better confinement than the anomalous confinement common to electrons in tokamaks. In the next section we will add to their commentary.

PHYSICS OF THE RFM$_O$ METHOD

RMF_o is natural for FRCs. The FRC, too, has odd-parity magnetic-field symmetry about the z=0 midplane, critically affecting the physics as now described.

Energy confinement: That both the RMF_o and the FRC magnetic fields have odd-parity preserves closed field lines essential for good confinement,[14] if the RMF_o amplitude, B_R, is less than ~ 5% of B_e. In the PFRC-1, $B_R/B_e \sim 0.13$, so that condition is not fulfilled. However, it is a design feature of the PFRC-2, see Table 1, to operate at $B_R/B_e < 0.05$. Also essential for good confinement is a decrease in LHD turbulence predicted to be the primary cause of transport losses in FRCs.[15] The ratio of the electron drift speed to ion thermal speed, $\gamma_D \equiv v_{de}/v_{ti}$, is expected to control turbulence level. For $\gamma_D < 1$, confinement is expected to improve, which would occur with sufficient ion heating in the PFRC-2. Additionally and in contrast to beam heating, RMF_o is predicted to form truncated particle distributions, *i.e.,* without long high energy tails, see Fig. 2. Such distributions are absolutely stable,[16] which should further contribute to improved confinement.

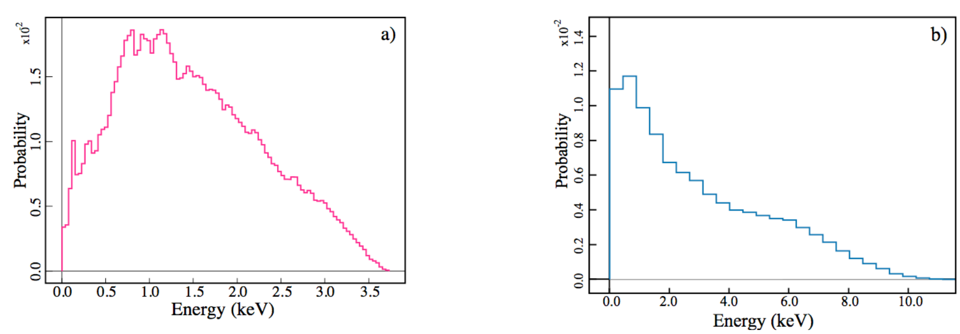

Figure 2. Sample particle energy distributions in the PFRC-2, *RMF* code: a) electron and b) ion.

Plasma heating and current drive: RMF_o generates a time-varying z-directed magnetic field, $\partial B_z/\partial t$, in the FRC's midplane, which also contain the O-point null line. $\partial B_z/\partial t$ creates a rotating azimuthal electric field that periodically accelerates then decelerates charged particles along the null line. Both Hamiltonian[17] and kinetic (PIC)[18] simulations show that most orbits periodically enter the betatron class, carrying most of the current during the high energy portion of their trajectory. Whether a Maxwellian-like distribution evolves depends on phase-mixing events along the trajectory, particularly collisions with particles or scattering from magnetic field inhomogeneities. Plasma heating in FRCs, a stochastic process with low threshold [19], is greatest when the RMF frequency, ω_R, is near the particle cyclotron frequency, $\omega_{ce,i}$. Though electrons always have $\omega_R/\omega_{ce} << 1$, they are, nevertheless, heated because of their low inertia. In the PFRC-1, RMF_o has been observed to heat electrons to a few hundred eV and to sustain kA currents for periods longer than 1000 τ_A, where τ_A is the Alfvén time.[5] For ions in the PFRC-1, $\omega_R/\omega_{ci} \sim 80$ and no ion heating was seen or expected. For PFRC-2, a combination of increased B_e and reduced ω_R will allow $\omega_R/\omega_{ci} \sim 3$. B_e will be increased by the combined effects of increased axial-field-coil current *plus* axial-field compression against the flux conservers (FCs) accompanying plasma pressure build-up. The expected PFRC-2's ion and electron average energies are shown in Fig. 2, *versus* $\omega_R/\omega_{ce,i}$ for a variety of B_R values. The PFRC-2 RMF_o system, rated at 200 kW for 0.1 s, can provide B_R up to 70 G.

Current-drive efficiency is important. In contrast to wave-driven currents in tokamaks, toroidal currents in high-β devices increase when RF energy is dissipated into plasma thermal motion. That is, diamagnetic currents are important when β is high. A large fraction of the plasma current will be carried by the betatron-orbit particles, which have low Spitzer resistivity because of their high energy.

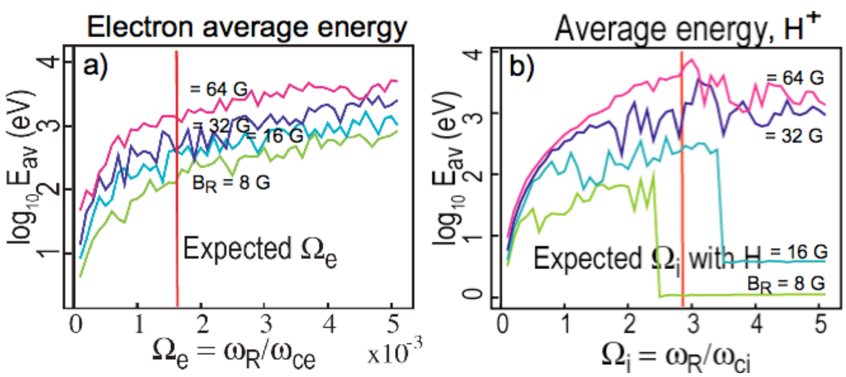

Figure 3. Predicted average a) electron and b) ion energies caused by RMF_o heating in the PFRC-2, *vs* $\omega_R/\omega_{ce,i}$, for four values of B_R.

Macrostability: MHD theory predicts that FRCs will be unstable to the internal tilt mode[20] and other modes[21]. As previously noted, RMF-heated FRCs are sustained for 1000's of τ_A, in contradiction to MHD theory. A commonly offered reason is that MHD is inapplicable to kinetic FRCs in which the ion gyroradius is comparable to r_s: $s_i \equiv 0.3\ r_s/\rho_i < 4$ or $S^*/\kappa < 3$, where $S^* = r_s\omega_{pi}/c$, ω_{pi} = ion plasma frequency and κ = elongation.[22] All PFRC devices are designed with $S^*/\kappa < 3$.

SUMMARY

Experiments on the PFRC-2 enter a regime where the benefits of the RMF_o/FRC symmetry and topology can be tested against these predictions. The key improvements over PFRC-1 are the reduced B_R/B_e which allows closed field lines and improved energy confinement and $\omega_R/\omega_{ci} \sim 3$ which permits ion stochastic heating. We also expect positive effects on current drive and stability. A positive outcome from these experiments will motivate the construction of the next RMF_o-heated device, the PFRC-3, and more extensive theoretical analyses of the physics.

TABLE 1. Parameters of the PFRC devices

	PFRC-1	PFRC-2	PFRC-3	PFRC-4
r_s (m)	0.033	0.07	0.12	0.25
κ	4	4	5	10
B (T)	0.012	0.13	1	6
Φ (mVs)	0.01	0.6	10	400
n_e (10^{19} m^{-3})	0.13	1	10	40
Ion species	H	H	H	D-^{3}He
T_e (keV)	0.2	1.0	7	40
T_i (keV)	$5\text{x}10^{-4}$	1.5	10	80
P_{RMF} (kW)	20	200	1000	2000
$\omega_R/2\pi$ (10^6)	14	4.1	1.1	0.5
B_R/B_e	0.13	0.05	0.013	0.002
τ_E (s)	$7\text{x}10^{-7}$	$2\text{x}10^{-4}$	0.004	0.4
s_e	4.1	39	200	1200
s_i	1.6	0.7	2.5	12
S^*/κ	0.04	0.24	0.75	1.9
γ_D	43	0.53	0.13	0.025

ACKNOWLEDGEMENTS

This work was supported by USDOE Contract No. DE-AC02-76-CHO-3073.

REFERENCES

1. Charles Seife, *Sun in a Bottle,* Penguin Books, New York 2009.
2. H.Y. Guo, A.L. Hoffman, and L.C. Steinhauer, Phys. Plasmas **12**, 062505 (2005).
3. J. Slough, G. Votrubek, and C. Pihl, Nucl. Fusion **51**, 053008 (2011).
4. T-S Huang, Yu. Petrov and F. Zhong, Plasma Phys. Control. Fusion **47**, 1517 (2005).
5. S.A. Cohen, B. Berlinger, C. Brunkhorst*, et al.,* Phys. Rev. Lett**. 98**, 145002 (2007).
6. M.W. Binderbauer, H.Y. Guo, M. Tuszewski, *et al.,* Phys. Rev. Lett. **105**, 045003 (2010).
7. M. Inomoto, K. Kinao, and S. Okada, Phys. Rev. Lett. **99**, 175003 (2007).
8. Y. Ono, M. Inomoto, Y. Ueda, *et al.,* Nucl. Fusion **39**, 2001 (1999).
9. H.J. Monkhorst and N. Rostoker, US Patent 6850011 (2005).
10. T.P. Intrator, G.A. Wurden, P.E. Sieck, *et al*., J. Fusion Energy **28**, 165 (2009).
11. H.A. Blevin and P.C. Thonemann, Nucl. Fusion: 1962 Supplement, Part 1, p. 55.
12. I. R. Jones, Phys. Plasmas **6**, 1950 (1999).
13. N. Rostoker and A. Querushi, Plasma Physics Reports **29**, 626 (2002).
14. S.A. Cohen and R.D. Milroy, Phys. Plasmas **7**, 2539 (2000).
15. N.A.Krall, Phys. Fluids **B1**, 1811 (1969).
16. R. C. Davidson, Phys. Plasmas **5**, 3459 (1998).
17. A.H. Glasser and S.A. Cohen, Phys. Plasmas **9**, 2093 (2002).
18. D. Welch, S.A. Cohen, T.C. Genoni, and A.H. Glasser Phys. Rev. Lett. **105**, 015002 (2010).
19. A.S. Landsman, S.A. Cohen, and A.H. Glasser, Phys. Rev. Lett. **96**, 015002 (2006).
20. M.N. Rosenbluth and M.N. Bussac, Nucl. Fusion **19**, 489 (1979).
21. L.C. Steinhauer and A. Ishida, Phys. Fluids **B2**, 2422 (1990).
22. E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, Phys. Plasmas **11**, 2523 (2004).

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov