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Construction of the PFRC-2 Device

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Abstract. The PFRC-2 device is being constructed to achieve goals set for compact toroids by the DOE ReNeW process: formation of stable, quasi-steady-state, high-β plasmas with *keV* temperatures. In this paper we describe a number of novel technologies that have been incorporated into the PFRC-2 to enable and accelerate research towards small, clean, practical fusion reactors. These technologies include polycarbonate as the vacuum vessel material and high-temperature superconducting internal passive coils for plasma equilibrium and stability.

Keywords: FRC; rotating magnetic field; high-temperature superconductor; polycarbonate.
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I. INTRODUCTION

The Princeton field-reversed configuration device now under construction, the PFRC-2, is the second[1, 2] of a planned four-step research path towards small RF-heated D-^{3}He-fueled prototype fusion reactors. The PFRC-2 was designed to perform experimental tests of plasma physics kinetic theory[3, 4, 5] specific to small FRC devices heated by odd-parity rotating magnetic fields (RMF_o),[6] a radiofrequency method. The primary scientific questions to be addressed relate to goals for compact toroids stated in the ReNeW report[7], namely generating and sustaining stable *keV* plasmas.

The PFRC approach avoids entering the MHD regime wherein macro-instability, especially the internal tilt mode, would be a major concern. The chosen kinetic regime requires that the ion gyroradius, ρ_i, be not much smaller than r_s, the plasma radius, $s_i < 4$, or satisfy the criterion $S^*/\kappa < 3$,[8] see Table 1. To accomplish this, we plan to make relatively small plasmas with high ion temperatures, $T_i \sim 1.5$ *keV*. Small plasmas require ion-heating systems different than those useful for larger plasmas. We opt for RMF_o which has already shown the capability to heat FRC electrons well.[1] RF power systems in the required MHz range are highly efficient and extrapolate to full-scale reactor devices. Using this RF method necessitates a non-conducting vacuum vessel for RF field penetration because reactor designs call for external RF antennae. We have chosen polycarbonate, a readily machinable and tough material with good vacuum properties. Sustaining the plasma for many energy confinement times places demands on the coils that provide the confining, predominantly axial, magnetic field. For good control of the plasma's radial position and to reduce plasma contact with the polycarbonate vessel walls we chose internal passive coils, with their current arising inductively, in response to changes in plasma current and size. These

Table 1. PFRC-2

r_s (m)	0.07
Elongation, κ	4
B_e (T)	0.13
Φ (mVs)	0.6
n_e (10^{19} m^{-3})	1
Ion species	H^+
T_e (keV)	1.0
T_i (keV)	1.5
P_{RMF} (kW)	200
$\omega_R/2\pi$ (10^6)	4.1
B_R/B_e	0.05
τ_E (ms)	0.09
$s_e = 0.3r_s/\rho_e$	39
$s_i = 0.3r_s/\rho_i$	0.7
$S^* = r_s\omega_{pi}/c$	0.97
$\gamma_D = v_{de}/v_{ti}$	0.53

coils – one-turn rings – are called flux conservers (FCs). Simple rings of ordinary copper are too resistive to sustain induced currents for longer than a few *ms*. For the PFRC-2 we have developed high-temperature superconducting (HTS)[9] FCs, allowing for much longer pulse lengths. Section II describes details of the vacuum vessel, Section III of the HTSFCs and Section IV of the upgraded RF system.

II. VACUUM VESSEL

The three main issues for the vacuum vessel were material availability, structural properties and vacuum properties. Analyses of vessel distortion under atmospheric pressure load showed that for acceptable levels of deflection and stress, penetrations for diagnostics must be smaller than a certain size, *ca.* 3" x 3", and that a 5/8" wall was required. Conventional suppliers for the required polycarbonate pipe were not found so we turned to the Plastics Manufacturing Center at the Pennsylvania College of Technology who manufactured the pipe to the desired dimensions and shipped it to PPPL. There 87 penetrations and the required 66 port covers were fabricated. The assembled vessel was then evacuated using a 50 *l/s* turbo pump and reached a base pressure of 2×10^{-6} *T*, predominantly of H_2O, corresponding to an outgassing rate of $1.5\times10^{-8}\,T\,l/s\cdot cm^2$. The PFRC-2 will have a pumping speed of ~500 *l/s*, making that outgassing rate acceptable. The measured axial (+0.011") and radial (-0.005") deflections of the vessel under vacuum agreed with the numerical simulations, one example of which is shown in Fig. 1.

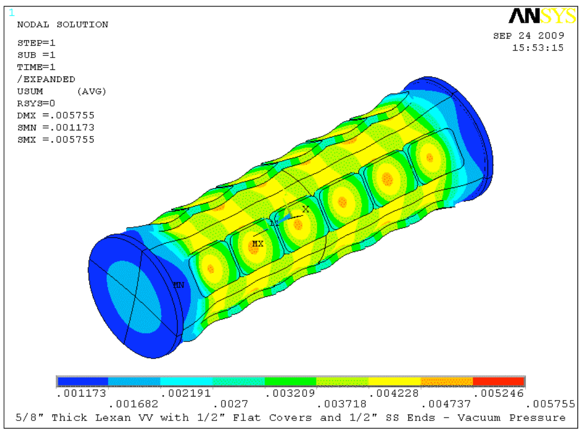

Figure 1. Calculated deflection of polycarbonate vessel, with port covers attached, under vacuum load.

III. FLUX CONSERVERS

The most relevant characteristic times for the PFRC-2 plasma are: 1) ion and electron energy confinement; 2) particle thermalization and heating; 3) inductive, *e.g.,* field penetration and current ramp-up and decay; 4) equilibration of recycling; and 5) macro-instability growth. In the PFRC-1, the longest characteristic time is due to recycling and is near 2 *ms*. For the PFRC-2 we expect the instability, heating, energy confinement, and inductive times be much less than 1 *ms*, under which conditions τ_p = 100-*ms*-duration plasmas would be adequate for attaining steady state. To prevent changes in the plasma due to decaying currents in the FCs, we required their L/R "skin" time to exceed $\tau_{FC} = 10\tau_p = 1\ s$ and accomplished this goal by

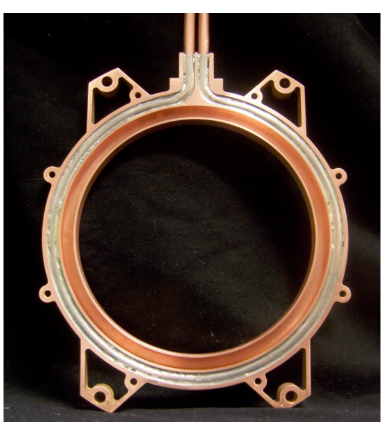

Figure 2. Copper mandrel for the outermost FC, prior to embedding the HTS. The ID is ~ 13 cm.

embedding HTS tapes[10] in copper mandrels, cooled by liquid nitrogen flowing through ¼" copper tubing, silver soldered into the circumference, see Fig. 2. Twenty-five turns of HTS tape were placed in the inner trough, see Fig. 2, and soldered in place with Pb-Sn eutectic rosin-core solder. A wide range of τ_{FC}, up to 1200 s, was achieved by varying the HTS winding pattern, with critical current being inversely related to τ_{FC}.[7] At the selected τ_{FC} = 1 *s*, the critical current, I_c, of each FC is 2 *kA*, sufficient to support the plasma parameters listed in Table 1.

The FCs are clad in 1.25-mm-thick boron nitride (BN) shields, to reduce the thermal radiation and plasma heat loads on the HTSFCs and also to lower the Z of impurities sputtered into the plasma. We deem it fortuitous that sputtering will produce p-B plasma. Eight FCs are arranged in a coaxial linear array, separated from each other by about 5 cm. Four alumina rods, used to align the FCs, pass through guide holes in the copper mandrel located at r ~ 10 cm and extend the length of the array.

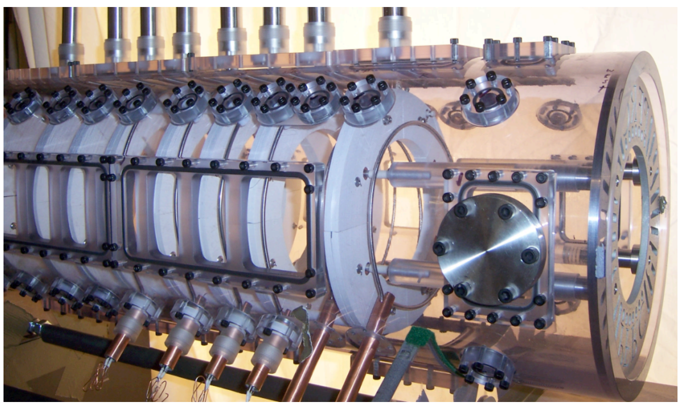

Figure 3. Photographs of the PFRC-2's polycarbonate vessel with port covers, diamagnetic loops, and BN-covered HTS FCs.

The fully assembled vacuum vessel, with six diamagnetic loops and eight BN-covered HTSFCs installed, is shown in Figure 3. The viton-sealed port covers are held in place by black nylon screws, to avoid their heating by the RF.

IV. RF SYSTEM

Hamiltonian[2, 3, 4] and PIC[5] modeling show that plasma heating, current drive, energy confinement and stability all benefit from the use of RMF_o. Based on these, we estimate that the PFRC-2 requires an RMF_o system capable of producing a rotating field strength up to B_R = 65 *G* at 4.1 MHz, corresponding to 200 *kW*. For τ_p = 0.1 *s*, power dissipation in the RF cables, antennae coils, and tank capacitors limits the duty factor to ~1%. Changes in plasma impedance during a pulse necessitate real-time changes in RF system frequency by 0.5%. This is consistent with common Q values, *ca.* 100, for RF tank circuits in the *MHz* range.

The selected five-element train of RF source *plus* amplifiers is shown in Fig. 4. The SRS DS345 is a digital, accurate, highly stable, tunable frequency source. Three commercial amplifiers follow and feed the 200 kW final stage whose output is passed through a 90° hybrid splitter which also provides phase control and isolation from load changes. This is a narrow band device, ±2.5% of the center frequency for a power imbalance of 5%. It consists of capacitors with a reactance of $-j2Z_o$ and a coupled inductor with a reactance of jZ_o. The hybrid is made tunable with vacuum variable capacitors and by changing the number of ferrite cores on the coupled inductor. The splitter is a 4-port device: input, ±45° outputs, and an isolated output. A useful feature of 90° hybrids is that when the load reflection coefficients are equal all reflected power is diverted to a dummy load. The source will be able to keep the forward power constant despite loading changes. The matching network must transform the impedance of the plasma and RMF coils, a few tenths of an Ohm, to 50 Ohms and survive voltages and currents of 25 kV peak and 1000 A rms when no plasma load is present. RF will be delivered to the RMF_o coils *via* RG-211 coaxial transmission lines. The matching network consists of a combination of variable and fixed vacuum capacitors. At 4.1 MHz, about 2500 pF is needed. The system has been constructed and tested into a dummy load to 195 kW for 5-ms pulses.

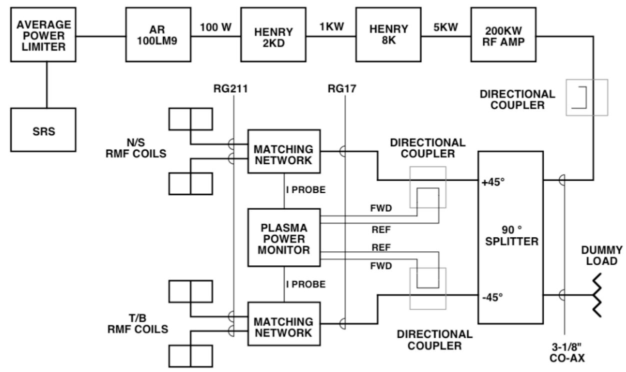

Figure 4. PFRC-2 200-kW RF system schematic.

V. SUMMARY

A 22.7-cm-ID polycarbonate vacuum vessel has been fabricated for the PFRC-2. It has sufficient penetrations and ports for extensive diagnostics, cryogenic and electric feedthroughs and vacuum pumping to meet the demanding standards at this stage of FRC research. High-temperature superconductor internal coils, cooled by liquid nitrogen and covered with BN shields, have been fabricated and tested. They have skin times of 1 *s* and critical currents near 2 *kA*, the latter necessary to increase the in-pulse FRC magnetic field above 1 *kG*. Both τ_{FC} and I_c are sufficient for sustaining quasi-steady-state FRC plasmas with *keV* ion and electron temperatures. The RF power system has been upgraded from 20 to 200 kW. Kinetic calculations predict that the combined effects of larger vessel size, stronger magnetic fields, and higher RF power are necessary for the creation of plasmas with kilovolt electron and ion average energies.

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