Rotamaks and Propagating Wave Effects in FRCs

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The rotamak uses an orthogonal set of coils excited by radio frequency power, phased in quadrature, to generate a “rotating” radial magnetic field. In combination with an external or axial bias field (similar in geometry to a mirror field), the rotamak can nonlinearly drive sufficient axis-encircling electron current to generate field reversal of the bias field, resulting in the generation of a sustained FRC.

The operating frequency of rotamaks can be either near the ion cyclotron frequency, here referenced to the external bias field at the radial boundary of the plasma, or several times the ion cyclotron frequency. RF power in these normalized frequency ranges has been used for many years in the tokamak, stellarator, and – especially relevant – the mirror program to heat ions and electrons via the excitation and damping of propagating wave fields. The polarization of the antennas used to generate RF magnetic fields in the rotamak is similar to antennas used during the mirror program to generate slow (shear) Alfven waves; examples are antenna sets utilized on the TARA tandem mirror at MIT, RFC-XX at Nagoya, and also the Uragan series of stellarators at Kharkov, Ukraine, where saddle coils were used for startup. Excitation of antennas in quadrature was less commonly utilized in mirrors, but the HIEI device at the University of Kyoto, and especially the Phaedrus-B tandem mirror at the University of Wisconsin, made use of antenna arrays operated in quadrature to preferentially excite either slow or fast (compressional) magnetosonic waves, through selective generation of either m=+1 or m=-1 azimuthal mode number rotating fields. The Phaedrus experiments were successful at exciting both shear and compressional magnetosonic waves with a single antenna structure (designed for the compressional wave) [Y. Yasaka et al., Nucl. Fusion 28, 1765 (1984)], since for realistic geometry the wave polarization is always mixed.

Despite the similarities between the rotamak system and RF heating systems in mirrors, and the far larger experimental and theoretical database which exists for RF heating, there have been virtually no linear analyses of RF wave excitation in the rotamak FRC. As the experiments become larger and denser, propagating waves will no longer be cutoff, and the device scale size will exceed the Alfven (and other characteristic) wavelengths. In addition, in the vicinity of the field reversal radius the local cyclotron frequency is reduced, so that the normalized frequency increases. Cyclotron resonances and mode conversion layers (in two ion systems) will exist. While it is possible that the rotamak can benefit from selective excitation of propagating waves for heating, etc., there are clear potential difficulties associated with wave excitation in the rotamak FRC. As an example, note that the phase relationships between the perturbed quantities (δb, δv, δn) differs in the far (wave) field from that in the near field, where rotamak drive occurs. A propagating wave also introduces spatial variations in the phase of the perturbed quantities. These phase variations in the linear wave fields will clearly affect, and could potentially even eliminate, nonlinear rotamak current drive.

Furthermore, propagating Alfven waves, kinetic Alfven waves, ion Bernstein waves (all of which can be accessed in the radially varying bias field produced as the field null is approached in an FRC) carry a nonzero Poynting vector. Power flow produced by propagating wave excitation therefore has a strong effect on the Q of the exciting antenna circuit, often reducing the circuit Q from ~ 100 to ~10 or less. The drop in antenna Q as a propagating wave is excited has long been used as a diagnostic of the eigenmode spectrum in tokamaks, for example. It would be difficult to efficiently employ rotamak current drive with antenna Q values as low as 10.

A dispersion relation calculation indicates that the UW rotamak, the Princeton rotamak, and the Prairie View (formerly known as the Flinders) FRCs, all operate, interestingly, in a density range where the radial scale size is comparable to the Alfven wavelength. In rotamak experiments at the Australian Nuclear Science and Technology Organization (ANSTO) [G.A. Collins et al., J. Plasma Phys. 40, 127 (1988)], it was concluded that the observed limits on density were due to the onset of fast magnetosonic wave propagation. The ANSTO experiments are unique in the rotamak community in considering propagating wave effects. Now, it may be possible to modify the rotamak antenna structure, or reduce the operating frequency, to avoid the excitation of propagating waves. But even the avoidance of propagating wave excitation requires analysis of the target FRC parameters to see if roots of the relevant wave dispersion relations are indeed absent.

It is therefore surprising that propagating wave effects are not mentioned as a "knowledge gap" in any of the white papers dealing with the rotamak FRC. Nor are experiments or theoretical analysis of wave effects identified as a "research need". Certainly the theoretical and experimental tools to address this issue already exist. As an example, the ANTENA code [B. McVey, MIT preprint PFC/RR-84-12 (1984 – note the date!)], which was extensively used in the mirror program, includes prebuilt antenna modules which allow the modeling of arbitrarily phased arrays of saddle coils. Rotamak coils of even or odd parity can be modeled by an appropriate array of saddle coils. Much more modern rf heating codes exist than ANTENA, and further codes are presently under development with funding through the SCIDAC initiative.

In summary, the problem of wave excitation in rotamaks remains a large and unaddressed gap in our knowledge of these devices, and an obstacle to future performance projections. The rotamak FRC community should consider an appropriate effort to address this problem.