Radio frequency sustainment and current drive for Compact Tori

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Introduction

Injection of radio frequency (RF) and neutral beam power are two approaches that are commonly considered for driving and maintaining the plasma currents that sustain Compact Tori (CT) configurations. We consider here some RF issues. One important parameter for a fusion reactor is large plasma pressure or $\beta = nT/(B^2/2\mu_0)$, where n, T, B are respectively the plasma density, temperature, and magnetic field. CTs such as spheromaks and Field Reversed Configurations (FRCs) operate at large $\beta > 0.3$-1, which allows large plasma pressure for a given expensive magnetic coil set and power supply.

Radio frequency Sustainment: The goal of RF sustainment of CT plasmas is to achieve efficient time-averaged current drive and heating.

Wave access to a CT

At large β, the plasma dielectric constant $\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \approx 50$-100 is also large, compared with the typical tokamak value of $\varepsilon \approx 1$. In the ion cyclotron range of frequencies, fast magnetosonic wave accessibility to a plasma core is limited to low ion beta ($\beta_i < 10\%$). On the other hand, several types of waves offer accessibility and large power absorbtion in large β plasma. These are High Harmonic Fast Waves (HHFW) between the ion cyclotron and lower hybrid ($\omega_{ci} < \omega < \omega_{LH}$) frequencies, Alfven waves at low frequency $\omega < \omega_{ci}$, and RMF at very low frequency $\omega << \omega_{ci}$. Other waves that undoubtedly exist in the Alfven spectrum include surface waves, and low frequency MHD instabilities such as current driven kink and pressure driven ballooning modes, and parasitic electrostatic waves driven by antenna voltages near the plasma separatrix.

RF power required

It is typically assumed that high RF heating power will be required for CT sustainment. However if confinement time exceeds 100 msec or so, ohmic dissipation for a 30MA CT, replenished by coaxial gun, RF heating and/or CD power could be substantially less than 100MW [Hagenson1987].

Status of RF in CTs

There have not been any investigations of RF heating or sustainment for spheromaks. Rotating Magnetic Field (RMF) or rotomak current drive has been exploited in several FRC experiments. RMF has been used successfully at low frequencies (<100kHz) for FRC sustainment, at densities $n \approx 10^{19} m^{-3}$, with magnetic field $B_\omega \approx 10$-20mT [Hoffman2000] [Guo2002] [Slough2000].

Research gaps for RF in CT's

We describe here some issues, advantages, and research gap unknowns, for radio frequency (RF) techniques. Considerations include antenna design, launch access, near and far field wave excitation, power limits, and hardware limitations. Experiments, theoretical analysis, and computational modeling of wave effects are a research need.

RMF drive in FRC
We would like to apply rotomak current drive to large, reactor scale plasmas. The average ion fluid toroidal force due to oscillating RF driven current density and magnetic field is $F_\theta = \langle j_z x B_r \rangle$, where j_z, E_z and B_r are all assumed to be in phase [Hoffman2000, eqns 4,15]. The existing scaling rules of thumb are based on a window in frequency and wavenumber space for rotomak drive in smaller FRC devices that operate in the antenna near field volume. The radial size is typically about the same order as the Alfven wavelength. Rotomak current drive is nonlinear in δv and δB for non rigid rotor models.

Excitation of propagating waves may alter the CD drive efficiency. For example it would be useful to model a large fusion plasma FRC with rotomak drive to see if the phase assumptions hold for time and/or volume averaged quantities using δj, δE, δv, and δB. Also Poynting vector energy transport away from the antenna can increase radiation resistance and lower the circuit Q. [Collins1988]. This might substantially raise the RF power required to produce a given perturbed B-field.

Antenna design
The typical RMF antenna resembles what we used to call a "Nagoya type 3" antenna. It has historically been used for helicon, and fast and slow Alfven excitations. Many mirror machine experiments have taken advantage of its propensity to excite multiple modes and field polarizations. Similar considerations are germane to spheromaks.

Improvements on antenna design may be possible. FRC's have small vacuum vessels with dielectric walls, and could accommodate a variety of antenna geometries not accessible on other devices, such as antennas mounted on the air side of the vacuum vessel. RMF type arrays with full 2π toroidal coverage, many more than quadrature sectors, with resonant transmission line type traveling wave structures could facilitate highly selective and directional toroidal wave number.

Research thrusts
There have been virtually no evaluations of what Alfvenic RF waves would do in a high $\beta \approx$ 20-100%) plasma. Several computer codes that could address this issue have been developed over the years, including

1. Cylinder r-z 2D mirror codes (some FLR, no mode conversion) ANTENA [McVey1984]
2. 1-D hot plasma higher order dispersion code CRF [Ignat1995]
3. Cylinder r-z 2D mirror codes that include antenna structures and sheath parasitic wave launch MORFIC [Mark Carter]

A survey of the wave characteristics with a 1-D hot plasma, finite FLR effect, dispersion code would tell us what to expect to lowest order. There might be ion Bernstein modes, quasi resonant damped modes, or kink modes. All these waves are likely to be affected by the plasma helicity, ie the handedness and field line pitch of the equilibrium magnetic field structure in 2D or 3D. Other codes with plasma profiles and more realistic magnetic and antenna geometry could be used later.

References

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