Oblate FRC concept with NBI for experimental studies of large-s FRC formation, stability, current drive and transport

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1. Research Goals

An oblate FRC experiment is considered to address several major FRC issues identified in the TAP report [1], namely large-s FRC stability, current drive, fast particle effects, and confinement. The choice of oblate/small-elongation shape allows the elimination of *n*=1 tilt stability issue in the large-s MHD regime, while utilizing the FRC formation method based on the counter-helicity spheromak merging. NBI will enable active control of plasma stability and provide current drive and heating. The suggested experiment provides a unique opportunity to advance the FRC concept, and provides important experimental tests of NBI effects on FRC stability and sustainment.

2. Approach

The oblate FRC-NBI concept is based on previous experimental and theoretical research performed in support of the SPIRIT project [2]. The main features are: (1) formation of FRC plasmas with large flux (50mWb) by counter-helicity spheromak merging; (2) flexibility to assess FRC stability properties by varying the plasma shape and kinetic parameter, by using passive stabilizers and external field shaping, and by injecting energetic ions; (3) sustainment of the FRC for a time significantly longer than the energy confinement time using a central ohmic-transformer stack and/or neutral beam injection (NBI). FRC formation by merging two spheromaks with opposite helicities has been successfully demonstrated by several experimental facilities in US and Japan. Significant advantages of this formation scheme include the ability to form large flux, large-s FRCs, and conversion of toroidal field energy into plasma internal energy during formation. (Here s is the FRC kinetic parameter equal to the number of ion Larmor radii between the field null and the separatrix) This method has been used in recent MRX-FRC experiments, where oblate FRC plasmas have been obtained with poloidal flux up to 10mWb [3]. NBI will be used for active control of plasma stability through direct beam stabilization as well as NBI-induced toroidal rotation, and also provides current drive and heating. An ohmic transformer can be used to sustain and amplify poloidal flux in the initial phase of this experimental study, allowing build up of sufficient flux to confine the NBI ions, and investigate their effects on stability, as well as the effects of the anomalous resistivity. This approach would separate FRC sustainment from stability and transport studies, and therefore allows addressing these critical physics issues before a full sustainment by the NBI can be studied. The experimental design and data analysis will benefit from computational support and existing state-of-the-art numerical tools, and experimental data will be used for validation and further improvement of the predictive models.

3. Global Stability and Effects of NBI

Numerous MHD studies and several recent small-elongation FRC experiments have demonstrated that in the MHD-like regime, the FRC is strongly unstable to the *n*=1 tilt mode. In a prolate FRC, the n=1 tilt mode is an internal mode which in the large-s (s~30) regime can only be stabilized by a very strong plasma rotation (Mach number order of one or larger), or, possibly, by a strong ion beam with the beam current comparable to the thermal plasma current. On the other hand, the tilt mode in an oblate FRC can be stabilized using a close-fitting conducting shell or strong external field shaping, even in the MHD regime [3,8]. The global stability properties of oblate FRCs have been investigated numerically using the HYM code [3,4,8] in support of the SPIRIT concept. It is found that all $n \geq 1$ interchange modes can be stabilized for a class of pressure profiles with a finite separatrix beta [8]. The n=1 tilt mode is stabilized by close-fitting conducting shells, but additional means of stabilizing the n>1 co-interchange modes are required. This can be achieved by injection of energetic beam ions. It was shown that the n = 1and n = 2 MHD modes can be effectively stabilized by a combination of conducting shell and beam ion effects, and that the residual weakly unstable n > 2 modes saturate nonlinearly at low amplitudes. The resulting configuration remains stable with respect to all global MHD modes, as long as the FRC current is sustained [4]. In addition to direct stabilization, the NBI would also induce plasma rotation with toroidal velocities of up to $V_{\text{Alfvén}}$, which would in turn help stabilize the global MHD modes.

Guided by these theoretical results, a series of MRX experiments studying the dependence of FRC stability on the plasma shape and passive stabilization have been carried out using a conducting center column, a pair of shaping coils, and an extensive set of magnetic probe arrays [3]. It is found that the passive stabilizer is not only crucial for formation of FRC by counter-helicity merging of spheromaks, but also to suppress n=1 tilt and shift modes. The plasma shape is controlled largely by the shaping coils, allowing for the plasma elongation varying from a moderate oblate shape of E=0.6 to an extremely oblate shape of E=0.35. The plasmas stability and lifetime is significantly improved when the elongation is extremely small. The kinetic parameter *s/E* of these plasmas is relatively large, and thus, these FRC plasmas are MHD-like.

4. Current Drive and Sustainment

Efficient current drive/flux sustainment is one of the critical issues in FRC research. An important method to sustain FRC plasmas against resistive decay is by injecting energetic beam ions, which is one of the key elements of the FRC-NBI concept. In order to confine the NBI ions, FRCs with large poloidal flux are required. For example, 20-30 keV hydrogen ions require a flux on order of 20 mWb. The maximum flux achieved in MRX is only a factor of 2-3 away from the required value [3]. A complementary way to sustain the FRC flux is to use an ohmic transformer, as demonstrated in TS-3 and recently in MRX [5]. In the SPIRIT experiment, for example, NBI of 3-5 megawatts was proposed in order to extend the lifetime of the plasma beyond ten milliseconds, by maintaining the plasma stability with toroidal rotation, additional beam heating and fueling.

5. Basic Study of the FRC Transport

One of the near term goals should be measurement of the flux dissipation rate in FRC with respect to collisionality, s and toroidal flow. The radial magnetic profile of an FRC at the magnetic axis is very similar to that of a typical reconnection layer (neutral sheet) without a guide field. The large cross-field current in FRC can excite electrostatic and electromagnetic lower hybrid waves [6] and other high frequency instabilities which can enhance flux dissipation rate [7]. If the scaling observed in MRX is applied, the magnetic field dissipation could be greatly enhanced in the collisionless regime [$l_{mfp} >> R$]. However there is an important difference between the FRC current center and a reconnecting neutral sheet, namely, in FRC, magnetic reconnection and dissipation occur around an O-point (often highly elongated), while in MRX reconnection without a guide field, it occurs around an X-point. In an FRC the exit channel is not open, but rather enclosed by magnetic field lines (in a 2D description). Thus plasma would not be ejected out freely as in the case of reconnection layer; the reconnection rate of an FRC is therefore expected to be smaller. An experiment supported by a high time-resolution ($\delta t < (\omega_{LHW})^{-1}$) 2-D PIC calculation in the FRC geometry is needed in order to assess this important issue. In addition, the injection of high energy ions could stabilize these modes. Thus NBI should be an important component of the FRC experimental campaign.

6. FRC Research Gaps and Proposed Thrust

The described oblate FRC-NBI experiment will serve to address critical FRC research gaps by providing long-needed experimental data regarding large-s FRC formation, stability and sustainment, and the effects of NBI on FRC properties.

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