US-Japan Workshop 2002

New Directions in Controlling and Sustaining Compact Toroids

September 9-11, 2002

Abstract Book

Osaka University
Suita, Osaka

Program

Monday Sept. 9

13:00-13:15	*Opening Session*	S. Okada, L. Steinhauer

Afternoon Sessions (Chair:A. Ishida)

Overview

13:15-13:40	*Historical overview to the next step of FRC at Osaka*	S. Goto
13:40-13:55	-----15 min break-----	

Global Behavior

13:55-14:20	*Control of an FRC translation velocity by a resistive metal liner*	Tsutomu Takahashi
14:20-14:45	*Numerical Investigation of Reflection Process of FRC*	T. Kanki
14:45-14:55	-----10 min break-----	
14:55-15:20	*Development of curved drift tubes for the vertical CT injection*	N. Fukumoto
15:20-15:45	*Overview of High-density FRC Research on FRX-L at Los Alamos National Laboratory*	M. Taccetti
15:45-16:00	-----15 min break-----	

Theory

16:00-16:25	*Effect of angular momentum on FRC minimum energy states*	P. Geren
16:25-16:50	*Proof of non-invariance of magnetic helicity in ideal plasmas and a general theory of self-organization for open and dissipative dynamical systems*	Y. Kondoh

Tuesday Sept. 10

Morning Sessions (Chair: L. Steinhauer)

Spheromak

09:00-09:25	*Experimental Study of the bifurcated relaxation of merging spheromaks into an FRC*	E. Kawamori
09:25-09:50	*Spheromak merging and FRC formation studies at SSX-FRC*	C. Cothran
09:50-10:00	-----10 min break-----	
10:00-10:25	*Processes that govern helicity injection in the SSPX spheromak*	C. Cothran (in S. Woodruff's stead)
10:25-10:50	*Recent progress of compact RFP experiment in TS-4 device*	M. Tsuruda
10:50-11:05	-----15 min break-----	

Stability I

11:05-11:30	*Self-generation of Hollow Current Profile and Tilt Instability in Field-Reversed Configurations*	H. Ohtani
11:30-11:55	*Global Motion of Field-Reversed Configuration Plasma*	K. Fujimoto
11:55-13:15	-----LUNCH-----	

Afternoon Sessions (Chair: S. Okada)

Stability II

13:15-13:40	*Nonliner and non-ideal effects on FRC stability*	E. V. Belova
13:40-14:05	*Comment on two fluids effect*	A. Ishida
14:05-14:20	-----15 min break-----	

Heating and Current drive

14:20-14:45	*Global Eigenmodes of Low Frequency Waves in FRCs*	N. Iwasawa
14:45-15:10	*Accessibility to Equilibrium with Shallow/Deep Penetration in Rotating Magnetic Field Current Drive*	M. Ohnishi
15:10-15:35	*Recent results from and proposed changes to the TCS rotating magnetic field FRC generation experiment*	H.Y. Guo
15:35-15:50	-----15 min break-----	

Panel Discussion I (Chair: H. Y. Guo)

15:50-16:50	Panel Discussion on Current drive, Steady state
19:00-	Banquet

Wednesday Sept. 11

Morning Sessions (Chair: Y. Ono)

Transport and Confinement

09:00-09:25	*Cross-Field Particle Transport due to Electromagnetic Fluctuation in a Field-Reversed Configuration*	Toshiki Takahashi
09:25-09:50	*Self-consistent electric fields and flows in the edge plasma of FRC*s	L. Steinhauer
09:50-10:15	*Investigation of Electron Heating Effect in NB-injected FRC*	M. Inomoto
10:15-10:30	-----15 min break-----	

Panel Discussion II (Chair: Y. Ono)

10:30-11:30	Panel Discussion on Physics issues toward CT reactors (Stability, Transport, and New ideas)
11:30-	Closing

Historical overview to the next step of FRC study at Osaka

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The world-wide fusion research has steadly continued for a half century, but the international situation on politics, finance, economy, industry and so no is dramatically changed. This kind of social transitions must stress some modification or turning-over of the research activity since a plenty of finance from the government has been no more expected for the fusion experiment. Therefore, we have to make deep considerations on why the fusion research, especially the FRC study should be maintained and also on how its experiments must be sustained and supported, although we need very long term development for the purpose.

Here the discussion on “why” may be excluded because there exist many complex issues, but only the FRC study of our laboratory has been refered according to the experimental footmark over forty-five years of the magnetic fusion plasma research at Osaka University. This historical consideration may give us a possible solution on “how” in near future. The key words are high beta physics and fast bank technology up to now. The latter should be replaced to be a modern one at least.

My presentation will be then summarized in the following. The significance of the high beta plasma must be advanced particularly in the university scale. Technologically speaking, the cheaper experiment is essential for long term continuity of development, and basically the power supplier have to be regenerated by power semiconductors. This technical progress may also give some spin-off effects in industrial developments through the plasma engineering and related diagnostics, if a part of our attention could be focused for the social support of plasma researches.

The 2002 US-Japan Workshop on

"New directions in controlling and sustaining compact toroids"

Control of an FRC translation velocity by resistive metal liners

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ABSTRUCT

Successful translation experiments on a field-reversed configuration (FRC) plasma have been achieved in several facilities. In such experiments, translation velocity is adjusted by a magnetic field of a translation region. An internal energy of the plasma is converted to the kinetic energy of the translation plasma. The translated plasma is settled down by inelastic reflections of a magnetic mirror. Though a part of kinetic energy is thermalized and the plasma temperature increases at the reflection, the internal energy of the FRC plasma doesn't conserve in the translation. It is necessary to improve the translation technology without the loss of the internal energy.

We propose a translation experiment using resistive metal liners for an acceleration and a deceleration. The metal liner is installed in a theta pinch coil to control a magnetic reconection and to ensure a position of the plasma formation. By adjustments of a penetration time and the position of the metal liner in the coil, uneven magnetic reconnection is triggered and the axial motion is initiated. The velocity is dependent on the penetration time and the field strength and configuration of the coil at the liners. In preliminary experiment, a plasma with the mass of $2x10^{-8}$kg and the radius of 5cm and the length of 60cm is accelerated to the velocity of10-40km/s by SUS304 liners with the thickness of 0.3mm, the diameter 127mm and the penetration time of about 5-15μs.

When the plasma injects in the liner with the penetration time, which is much longer than a plasma transient time through the liner, a magnetic field excluded by the plasma is anchored to the liner. A current flow is also induced in the metal liner. The plasma is decelerated by the energy loss worked by the magnetic pressure and the joule heating loss of the liner. From the simple model calculation, the FRC plasma with the velocity of about15km/s and the above plasma parameters will be settled down by the above metal liners of 0.3m length located in the magnetic field of 0.35T.

Numerical Investigation of Reflection Process of FRC

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Many translation experiments of field-reversed configuration (FRC) plasma [1] have been performed intensively to establish the convenient way of separating formation, heating, and burn regions in a fusion reactor design. On the FRC Injection experiment (FIX) machine [2] at Osaka, the FRC translation has been successfully accomplished by empirically adjusting a magnetic guide field in a confinement region. However, it is observed in the first reflection from the downstream magnetic mirror field imposed at the end of the confinement region that the separatrix radius of the FRC expands excessively, and that more energy of the translated FRC is lost in the case where the translation velocity is larger and the magnetic mirror ratio is smaller. Details concerning how such a reflection process of a FRC plasma is performed by interaction with the magnetic mirror field remain unclear. Under this experimental background, the purpose of this study is to investigate the fundamental physics of reflection dynamics of a FRC plasma by means of an axisymmetric numerical simulation. In particular, we will focus our attention to examine the time evolution of the poloidal flux contours and the plasma pressure distribution. For this purpose, we have developed the two-dimensional (r, z) MHD simulation code [3]. In this code, the full set of MHD equations are solved on a rezoned Lagrangian mesh which employs an adaptive algorithm to concentrate the grid in regions of sharp plasma pressure gradients. As the initial value for the simulation, we use a MHD equilibrium configuration such as is typically observed in the FIX experiment. We give an appropriate initial velocity for this equilibrium configuration. It is shown from the simulation results that during the reflection process the FRC still maintains most of its closed magnetic filed configuration even when injected with supersonic velocity into the magnetic mirror region, showing the robustness of the FRC against external perturbations. Also, it is found from time evolution of the average axial velocity on the midplane that the formation of the discontinuous front may be caused by a shock wave when the FRC with supersonic velocity is reflected by the magnetic mirror.

[1] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[2] H. Himura *et al*., Phys. Plasmas **2**, 191 (1995).
[3] T. Kanki *et al*., Phys. Plasmas **6**, 4612 (1999).

Development of curved drift tubes for the vertical CT injection

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We have researched on the most effective CT injection method for fuelling a tokamak. Recently, we have carried out for the first time the experiment on CT transport through a curved drift tube, which is used to change direction of a moving CT, with a view to injecting a CT vertically into a tokamak. We have observed that a CT is transported through a curved drift tube with a 45º bend and with a 90º one without interferential effect on CT passage. Magnetic field, electron density and speed of CTs transported through both 45º and 90º bends show as similar time evolution as one of CT transported through a linear drift tube.

So far, we have injected CTs into the JFT-2M tokamak from the horizontal direction on the midplane of the devic. In this case, CTs were transported through a linear drift tube from CT source. In order to realize CT injection into a tokamak with higher efficiency, we have tried to optimize a direction of CT injection. When a CT is injected horizontally from the outside of a device, it is forced to decelerate due to the magnetic pressure gradient of the toroidal field since the field intensity varies inversely as a major radius of the device. If a CT is vertically injected from a port at the bottom of the device, it may more easily enter into the tokamak core region than it horizontally injected, since the magnetic field is constant on the line of CT locus. Recently, Suzuki et al. presented the result of calculation that when a CT with a speed of 300 km/s is injected vertically into a toroidal field of 0.8 T, the penetration length of the CT is longer than horizontally [1]. This result indicates that the vertical injection of CT into tokamak has an advantage over horizontal one.

We have a plan to inject CTs vertically into the JFT-2M tokamak plasma using a curved drift tube. In order to experimentally demonstrate CT transport through a curved drift tube, we have taken the initiative experiment in the HIT-CTI2 at Himeji Institute of Technology as the first trial. Initially, we measured poloidal and toroidal magnetic fields B_p and B_t, electron density n_e and speed of CTs transported through the straight drift tube with inner radius r = 66.9 mm and successively through the curved drift tube with a 45º bend and a 90º bend of curvature R = 190 mm and the same inner radius as the straight drift tube. B_p decreases similarly as the distance from the measurement port in front of the bend entrance without regard to an angle of the bend. Furthermore n_e indicates the same tendency as B_p. Each speed of CT estimated from the CT transition is 37 km/s (θ=0º), 41 km/s (θ=45º) and 37 km/s (θ=90º), respectively. The deceleration of CT due to the bend of the curved drift tube was not observed. The profile of B_p and B_t before and after passing the 45º bend were observed. It has been confirmed that a plasmoid at the final port had a typical spheromak configuration and the CT was transported without destruction after passing the bend.

[1] Suzuki, Y., et al., Nucl. Fusion **41** (2001) 873.

Overview of High-density FRC Research on FRX-L at Los Alamos National Laboratory*

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We provide an overview of the FRX-L (Field Reversed configuration eXperiment – Liner) experiment at Los Alamos National Laboratory, including the design goals, plasma physics, engineering and diagnostic approach, and the most recent data. FRX-L is a magnetized-target injector for magnetized-target fusion (MTF) experiments. It was designed with the goal of producing high-density (n~10^{17} cm^{-3}) FRCs and translating them into an aluminum *liner* (1-mm thick, 10-cm diameter cylindrical shell) for further adiabatic compression to fusion conditions. Although operation at these high densities leads to shorter FRC lifetimes, our application requires that the plasma live only long enough to be translated and compressed, or on the order of 20-30 μs. Careful study of FRC formation in situ will be performed in the present experiment to differentiate between effects introduced in future experiments by translation, trapping, and compression of the FRC. A review of the MTF concept and how FRX-L applies to it is presented, along with current results on the optimization of the FRC formation process on FRX-L.

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Effect of angular momentum on FRC minimum energy states

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All stable equilibria are stationary-energy (SE) states of some form. Thus finding the SE states considerably simplifies the search for stable plasma equilibria. This is particularly so in the case of flowing equilibria for which finding any kind of equilibrium is exceedingly complicated. A previous analysis found SE of a two fluid plasma by minimizing the ordered energy W_{MF} (flow + magnetic field energy) subject to constraints on the two integral constants of motion for a two-fluid, the ion helicity K_i and the electron helicity K_e . By expanding the flow and field vectors in a complete basis set of divergence-free vectors, the problem was reduced to a system of algebraic equations. Solution of the equations led to the prediction of SE states that are a two-point spectrum of the basis set, i.e. *double-mode condensates*.[1] Once these states are found the important functional relationship W_{MF} (K_i,K_e) follows, allowing the minimum energy state to be identified.

The foregoing analysis has been extended to include the effect of another constant of motion, the angular momentum, L_z. In the case of an axisymmetric system with suitable boundary conditions (constant magnetic flux boundary, no flow through the boundary, free-slip condition) the angular momentum is an integral constant of motion. Incorporating this additional constraint leads to a more complicated system of equations. Instead of a two-point spectrum of SE states, all *axisymmetric* mode elements are represented except in exceptional cases, although the spectrum tends to concentrate in certain ranges. An important consequence of angular momentum conservation is that the solution is axisymmetric, i.e., tilted equilibrium states are disallowed.

Inspection of the form of the spectrum reveals potential pathological behavior, which must be carefully dealt with in numerical calculations. A method for removing the pathologies is presented and applied. Investigation of the equations indicates that there are two regimes for the SE states, a "no-root" region in which all modes contribute to the conserved quantities, and a "root" region in which the spectrum may collapse to a one- or two-point spectrum. Calculations of the functional form W_{MF} (K_i,K_e,L_z) will be presented for both cases.

[1] L.C. Steinhauer, Phys. Plasmas **9**, October 2002 (in press)

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Proof of non-invariance of magnetic helicity in ideal plasmas and a general theory of self-organization for open and dissipative dynamical systems

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It is proved that the global magnetic helicity is not invariant, even in an ideally conducting MHD plasma, with the use of the generalized Ohm's law for a fully ionized plasmas. This proof resultantly confirms that global constraints using helicity has no power to limit the relaxation process to lead to any self-organized states in plasmas, as has been reported that all theories using helicity do never explain results of experiments and simulations in the boundary regions. A novel general theory is presented in which a variety of self-organized states in open and dissipative dynamical systems with various fluctuations can be found. This theory is based on the principle that the self-organized states must be those states for which the rate of change of global auto-correlations for multiple dynamical field quantities, which depend on multidimensional mutually independent variables, is minimized. One of the important points of this theory is that the original generalized dynamic equations are embedded in the final equivalent definition for the self-organized states, and therefore the equations deduced from the final equivalent definition include all the time evolution characteristics of the dynamical system of interest. Since states derived from the Euler-Lagrange equations with the use of variational calculus have minimal rates of change of the global auto-correlations, they are most stable and unchangeable compared with other states. We have shown three applications to solitons by the Korteweg-deVries equation with a dissipative viscosity term, to two dimensional incompressible viscous fluids with the periodic boundary condition, and to compressible resistive and viscid MHD fusion plasmas, in order to demonstrate that the new general theory of self-organization is very useful for various dynamical systems

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Experimental Study of the bifurcated relaxation of merging spheromaks into an FRC

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It is found that the merging spheromaks relax either into a high beta Field-Reversed Configuration(FRC) or into a spheromak in TS-3, depending on whether the initial magnetic helicity is smaller or larger than a threshold value. [1] In order to study ion kinetic effect for the bifurcated relaxation, the counterhelicity merging experiment was carried out in the TS-4 device with various ion species such as hydrogen and helium, argon plasmas. Under the various ratios of the initial poloidal fluxes Ψ_{left} /Ψ_{right} of the merging spheromaks, the poloidal eigen value $\lambda \equiv I/ \Psi$ of a new spheromak was measured and compared among the above ion species. Here I is the current flux function. As a result, also in the TS-4 device, the bifurcated relaxation to a high beta configuration(FRC like) and a force-free configuration(Taylor state) was identified. The clear difference among the plasmas of these ion species was observed in the sustaining time of the λ~0 configuration. We also compare the behavior of troidal mode amplitudes during the relaxation among these ion species.

[1] Y. Ono, A. Morita, T. Itagaki, and M. Katsurai, Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1992), Vol. 2, p. 619; Y. Ono, Fusion Technol. 27, 369 (1995).

Spheromak merging and FRC formation studies at SSX-FRC

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We report the results of coaxial co- and counter-helicity spheromak merging studies at the Swarthmore Spheromak Experiment (SSX). The present configuration of SSX is optimized to study FRC formation and stability by complete counter-helicity spheromak merging. In forthcoming experiments the merging will be magnetically restricted with a pair of midplane coils to determine how the stability of the resulting magnetic configuration, a doublet-CT, depends upon the quantity of toroidal flux annihilated from the initial spheromaks.

The diagnostic set at SSX, featuring the capability of measuring up to 600 magnetic field components at 800~ns time resolution, permits detailed studies of the dynamic three-dimensional magnetic structures resulting from these merging experiments. A compact array of magnetic probes has been used for local reconnection measurements, while a distributed array of probes has been used to examine global magnetic structure. Counter-helicity merging produces an FRC that persists for many Alfvén times before an instability grows at a rate much slower than ideal. The oppositely directed toroidal field of the initial spheromaks does not completely annihilate. Co-helicity merging produces a single elongated spheromak that evolves on similar time scales and tilts. In addition to the magnetic activity, plasma flows and heating are being studied with a new mach probe and soft x-ray detector.

Processes that govern helicity injection in the SSPX spheromak

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The physical processes that govern the gun-voltage and give rise to field generation by helicity injection are surveyed in the Sustained Spheromak Physics experiment (SSPX[1]) using internal magnetic field probes and particular attention to the gun-voltage. SSPX is a gun-driven spheromak, similar in many respects to CTX, although differing substantially by virtue of a programmable vacuum field configuration. Device parameters are: diameter=1m, I_{tor}~400kA, T_e~120eV, t_{pulse}~3ms. SSPX is now in its third year of operation and has demonstrated reasonable confinement (core $\chi_e \sim 30 m^2/s$ [2]), and evidence for a beta limit ($\langle\beta_e\rangle_{vol} \sim 4\%$), suggesting that the route to high temperature is to increase the spheromak field-strength (or current amplification, $A_I = I_{tor}/I_{inj}$). Some progress has been made to increase A_I in SSPX (A_I=2.2 [3]), although the highest A_I observed in a spheromak of 3 [4] has yet to be beaten. We briefly review helicity injection as the paradigm for spheromak field generation. SSPX results show that the processes that give efficient injection of helicity are inductive, and that these processes rapidly terminate when the current path ceases to change. The inductive processes are subsequently replaced by ones that resistively dissipate the injected helicity. This result means that efficient helicity injection can be achieved by harnessing the inductive processes, possibly by pulsing the gun. A pulsed build-up scenario is presented which gives A_I>3 and emphasizes the need to maintain reasonable confinement while the field of the spheromak is being built.

[1] E.B. Hooper, L.D. Pearlstein, R.H. Bulmer, Nuclear Fusion **39**, 863 (1999)
[2] H. S. McLean *et al* Phys. Rev. Lett. **88** 125004 (2002)
[3] S. Woodruff (submitted as Phys. Rev. Lett.)
[4] Fernandez *et al* Nucl. Fusion **28** 1555 (1988)

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W7405-ENG-48.

Recent progress of compact RFP experiment in TS-4 device

M. Tsuruda, E. Kawamori, Y. Ono, M. Katsurai

We produced a compact RFPs with R ~ 0.5m and A ~ 2.3 for the first time. It had (F, θ) = (-0.7, 1.4)-(-1.2, 1.8) and center q = 0.3-0.4 much larger than the conventional RFPs. We also studies axial merging of two CTs with equal toroidal fluxes for the future heating and current drive of those CTs. The axial merging doubled the toroidal flux Ψ, while it maintained the poloidal flux as it was. A new finding is that the poloidal flux as well as the n=2 mode increased by 20% right after the cohelicity merging. Since the CTs have extra toroidal flux after the merging, some dynamo activity is considered to convert the extra toroidal flux to the poloidal flux. We will present more detailed study of the dynamo activity, especially the possible relationship between the flux conversion and n-mode activities.

Self-generation of Hollow Current Profile and Tilt Instability in Field-Reversed Configurations

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NIFS and Earth Simulator Center[A]

Two-dimensional electromagnetic particle simulation is performed to investigate the profile relaxation from a magnetohydrodynamic (MHD) equilibrium to a kinetic one and the physical property of the kinetic equilibrium in the field-reversed configuration. The radial oscillation is excited in order to relax an excess energy in the MHD equilibrium. After this profile oscillation, the system spontaneously relaxes toward a kinetic equilibrium, in which the electron current profile becomes hollow as a result of the combined effects of the gradient-B drift near the field-null line and the E$¥times$B drift generated by the ion finite Larmor radius effect near the magnetic separatrix. On the other hand, the ion current profile becomes peaked due to the effect of the ion meandering orbit near the field-null line. The stability of the obtained kinetic equilibrium against the tilt mode is also studied by means of three-dimensional full electromagnetic particle simulation. It is found that the growth rate of the tilt instability in the case of the hollow current profile is smaller than that in the case of the peaked current profile.

Global Motion of Field-Reversed Configuration Plasma

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It is known that a field-reversed configuration (FRC) plasma produced by a negative-biased theta-pinch method oscillates slowly radially (wobble motion) and axially (vertical displacement) around the equilibrium position, that are called global motions. It is considered that the kinetic energy of the motions is introduced into the plasma at the formation phase. Closed field lines to confine the high temperature plasma are formed at the end regions of the theta-pinch coil through a magnetic reconnection between a bias field and a main field. When the magnetic reconnection progresses naturally, non-uniformity of a preheated plasma and a wall contamination of a discharge tube disturb the symmetrical reconnection to form the closed lines. In this case, a momentum to trigger the global motions is generated.

If the magnetic reconnection is executed at the fixed axial position with good azimuthal symmetry, the FRC will keep the equilibrium position through the configuration lifetime. For this purpose, thin metal liners that consist of SUS304 with 0.3mm thickness and 0.3m width are installed along the discharge tube near mirror regions of the coil. A skin time of the liners is adjusted as they affect only the magnetic reconnection during the formation phase. For example, the skin time is about 10μs at preliminary experiment, which corresponds to about tenfold of a pinch time and a half the time till the equilibrium phase.

By installing the liners, the amplitude of the wobble motion becomes less than 50% of that without liners. That is, the radial shift of the separatrix axis from the coil axis is controlled within 10% of the separatrix radius. Clear results about the vertical displacement are not obtained at present. Since the displacement is also controlled by strength of the mirror field and a distance between the mirror regions and the plasma, a careful analysis of the motion is needed.

Nonliner and non-ideal effects on FRC stability

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New computational results are presented which advance the understanding of the stability properties of the Field-Reversed Configuration (FRC). We present results of hybrid and two-fluid (Hall-MHD) simulations of prolate FRCs in the strongly kinetic and small-gyroradius, MHD-like regimes. The n=1 tilt instability mechanism and stabilizing factors are investigated in detail including nonlinear and resonant particle effects, particle losses along the open field lines, and Hall stabilization. It is shown that the Hall effect determines the mode rotation and the change in the linear mode structure in the kinetic regime; however, the reduction in growth rate is mostly due to finite Larmor radius effects. Resonant particle effects are important in the large gyroradius regime regardless of the separatrix shape, and even in cases when the large fraction of particle orbits are stochastic. Particle loss along the open field lines has a destabilizing effect on the tilt mode, and contributes to the ion spin up in toroidal direction. The nonlinear evolution of unstable modes both in the kinetic and the small-gyroradius FRCs is shown to be considerably slower than that in MHD simulations. Our simulation results demonstrate that a combination of kinetic and nonlinear effects is a key for understanding the experimentally observed FRC stability properties.

Global Eigenmodes of Low Frequency Waves in FRCs

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A heating experiment of a Field-Reversed Configuration (FRC) plasma by low frequency waves has been performed in Osaka University [K. Yamanaka *et al.*, Phys. Plasmas **7**, 2755 (2000)]. A fluctuation of the magnetic field propagating through the plasma was observed in the experiment. Also, increase of the plasma energy was observed. In addition, the results showed that the energy of the applied field could be absorbed mainly by the ions. However the mechanism has not been explained.

Solving the linearized single-fluid MHD equations, global eigenmodes of the low frequency waves in FRC plasmas have been obtained in this study. One-dimensional FRC equilibria with peaked, flat, and hollow current profile are used here. The dispersion relation and the global wave fields of the eigenmodes are shown for the azimuthal mode number $m = 0$ (the same mode number as that for the applied field in the experiment). The results are compared with the results of the heating experiment. The possibility of the ion heating by the transit-time magnetic pumping is discussesd.

Accessibility to Equilibrium with Shallow/Deep Penetration in Rotating Magnetic Field Current Drive

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Kansai University

and

A. Ishida

Niigata University

The stability of the rotation rate of the electron fluids was recently studied in regards to the balance of the forces exerted on the electrons by the resistive friction and the rotating magnetic field (RMF). The linear stability analysis including the effects of ion rotation and separatrix radius change due to the flux conservation within the flux conserver gave analytically the stability conditions in the equilibrium of the shallow penetration. The stability conditions derived from the present experimental parameters indicate that the equilibrium may be marginally stable. The accessibility to the equilibrium with the shallow/deep penetration of the RMF into an FRC is studied by numerically integrating the rate equations for the ion and electron rotations with the perturbed initial equilibrium values. When the initial angular frequency of the electron fluid is less than the equilibrium value which satisfies the stability conditions, the electron angular frequency stays near the initial value to achieve the equilibrium of the shallow penetration. The initial electron angular frequency barely larger than the equilibrium brings rapidly the angular frequency close to the RMF frequency and results in the full penetration of the RMF. On the other hand, when the equilibrium is unstable, the smaller initial value than the equilibrium electron rotation leads to the continuous current decay and does not sustain the configuration. The larger initial value results in the rapid full penetration of the RMF similarly to the case of the unstable equilibrium. Both of the perturbed initial values do not keep the electron angular frequency near the initial equilibrium value. When the equilibrium, therefore, is unstable, the full penetration may be observed in the experiments. However, when the equilibrium is stable, the full penetration cannot be accessed, as is observed in the present experiments, from the electron rotating state non-synchronous with the RMF. The study on the dynamic behaviors of the electron angular frequency clarifies the accessibility to the equilibrium of the shallow/deep penetration and the means to control the degree of the penetration of RMF.

Recent results from and proposed changes to the TCS rotating magnetic field FRC generation experiment

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FRCs have been generated and sustained in steady state from preionized gas fills using Rotating Magnetic Fields (RMF) in the TCS device. These FRCs are limited to sub 100 eV temperatures by at least several percent impurity content. Hot FRCs have also been translated and expanded (axial confinement field dropping from ~10 kG to ~0.5 kG) into TCS from the LSX/mod theta pinch. These FRCs reflected off the end mirrors of TCS and their high supersonic directed energies were rethermalized to close to the original formation temperatures, but at less than one tenth the density (~10^{20} m^{-3} as opposed to ~10^{21} m^{-3} formation densities). Typical trapped FRCs had separatrix radii of ~25 cm inside 47 cm radius flux conserving coils. RMF applied to these FRCs altered the internal field $B_z(r)$ profiles and could stabilize the n=2 rotational instability, but could not sustain the flux due to a surrounding layer of ionized quartz vapor ablated from the quartz plasma tube walls. Ablation was caused by lack of centering of the reflected FRCs and the resultant vapor absorbed most of the RMF power and significantly reduced its amplitude. Smaller, less energetic FRCs would sometimes remain centered and exhibit excellent confinement scaling (much better than the $\eta_\perp \sim 16/(x_s n_m(10^{20}\ m^{-3})^{1/2}$ $\mu\Omega$-m) obtained at high FRC densities), but these FRCs had electron rotation rates higher than our present RMF frequencies and were thus not candidates for RMF sustainment. A modification to the TCS device will add internal metal flux conserving rings to shield the quartz insulating wall from hot plasma. Also a small diameter quartz transition tube between LSX/mod and TCS (previously used for FRC acceleration experiments) will be changed to a large diameter metal section and multipole fields will be provided to better center the translated FRC. In addition, discharge cleaning and wall conditioning will be added, which should maintain the good vacuum environment found necessary in all other quasi steady-state devices.

Cross-Field Particle Transport due to Electromagnetic Fluctuation in a Field-Reversed Configuration

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The cross-field particle transport in a Field-Reversed Configuration (FRC) due to the electromagnetically fluctuating fields is investigated. The fluctuation is described by the toroidal and poloidal mode numbers. We trace orbits of many ions numerically and observe the temporal change of the canonical angular momentum for the ions in the fluctuating field; this quantity is a constant of motion in axisymmetric and non-fluctuating FRC and is a good measure for the location of the guiding center. In order to estimate the cross-field transport coefficients, the first and second cumulants of the canonical angular momentum are calculated. From the evolutions of the first cumulant of the canonical angular momentum, it is found that the cross-field drift of plasma ion can be neglected safely. The fluctuation, however, causes the diffusive flow near the separatrix, where the density gradient is large. The dependences of the diffusion coefficients on the various parameters are studied. We examine the fluctuation effects in the lower frequency range than ion cyclotron frequency. It is found that the fluctuation with higher toroidal mode and lower frequency affect the cross-field particle diffusion deleteriously. The scaling of the particle confinement time is estimated with respect to the stability parameter $S \equiv (r_s - R)/\rho_i$, where r_s, R and ρ_i are the separatrix radius, the radius of magnetic axis, and the Larmor radius, respectively. It is found that the particle confinement time is proportional to $S^{3.156}$. It appears that about two times stronger dependence on S is obtained compared with the experimental results.

Self-consistent electric fields and flows in the edge plasma of FRCs

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The shorting of open field lines where they intersect external boundaries strongly modifies the electric field all along the field lines.[1] However, it doesn't simply force the radial electric field to zero. The self-consistent electric field is found by an extension of the familiar Boltzmann relation for the electrical potential. The resulting electric field vector is actually pointed *outward*, away from the field-reversed configuration (FRC). With this field, the electric drift can be found. The rotational flow for the self-consistent electric field is applied to three aspects of FRCs: (1) the plasma rotation rate; (2) the particle-loss spin-up mechanism; and (3) the sustainability of rotating magnetic field current drive.

The outflow of plasma along open field lines is also analyzed using a double-adiabatic model. The outflow is represented as that in a magnetic "duct" extending from the side of the FRC proper out through the jet. The effects of double-adiabaticity (different parallel and perpendicular ion temperatures) and the conservation of angular momentum may explain the anomalously slow outflow of particles as inferred from experiments.[2]

[1] L.C. Steinhauer, Phys. Plasmas **9**, September 2002 issue (in press)

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Investigation of Electron Heating Effect in NB-injected FRC

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Recent results of neutral beam (NB) injection experiments on the FIX-FRC device are presented. The NBI is considered as an attractive candidate for FRC sustainment, such as plasma current drive, heating and fueling. Previously performed NBI experiment on the FIX device proved that the NBI worked to improve the FRC confinement significantly [1]. A probable mechanism for this improvement will be the electron heating caused by NBI [2].

To investigate the mechanism of beam-plasma interaction, measurement of the FRC plasma parameter is essential, and especially the electron temperature measurement is required to understand the heating effect and the mechanism of confinement improvement. For this purpose, we have constructed the YAG Thomson scattering measurement system that provides spatial multipoint analysis.

Experimental results have shown that the NB-injected FRC plasma had relatively higher electron temperature in comparison with the FRC without NB. This higher electron temperature resulted in the longer flux and plasma volume lifetimes remarkably observed in the earlier period of the FRC discharge in the FIX confinement region. Detailed evaluation will be presented at the workshop.

[1] T. Asai, et al., Phys. Plasmas, 7, 2294 (2000).
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