Summary of US–Japan Exchange 2004: New Directions and Physics for Compact Toroids

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Scientists from research institutions in the United States of America and Japan attended a USA Department of Energy sponsored joint international workshop on the subject of Compact Toroids (CT) in Santa Fe, NM, USA in September 2004. We outline here a summary of the topics that were discussed, some of the implications, and new directions that are likely to follow from this research. Experimental, theoretical and computational results were presented. The experimental devices and concepts, along with the theory and computational models comprise investigations of fundamental plasma physics, fusion science, and approaches to fusion energy that require magnetized plasmas.

KEY WORDS: compact torus; fusion energy; plasma physics; fusion science; large beta; innovative confinement concept; magnetic reconnection; flux rope; field reversed configuration; spheromak; reversed field pinch; magnetized target fusion; spherical tokamak; helicity injection; kink stability; three-dimensional data visualization; magnetohydrodynamics; relaxation; self organization; flow; angular momentum; current drive; compact torus power plant; jet collimation.

INTRODUCTION

This exchange workshop was an open meeting during 14–16 September 2004 coordinated by the USA representative T. Intrator from the P-24 Plasma Physics Group at Los Alamos National Laboratory, and the Japanese representative M. Nagata from University of Hyogo. It took place at LaFonda Hotel, Santa Fe, NM. The scientists were assembled from institutions in the US and Japan, who are researching the various and complementary types of Compact Toroids (CT). The list of participants is provided in Table 1.

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The following is a summary of the topical presentations and discussions. Many concepts, including both experimental and theoretical investigations, were represented. The range spans Field Reversed Configuration (FRC), spheromak, Reversed Field Pinch (RFP), spherical tokamaks, linear devices dedicated to fundamental physics studies, and hybrid transitions that bridge multiple configurations. The participants represent facilities on which significant experiments are now underway: FRC Injection experiment (FIX at Osaka University), Translation Confinement experiment (TCS at Redmond Plasma Physics Laboratory, University of Washington), Nihon-University Compact Torus Experiment (NUCTE), (Helicity Injection experiment (HIT-SI at University of Washington), Steady Inductive Helicity Injection (HIT-SIHI at University of Washington), FRC experiment – Liner (FRX-L at Los Alamos National Laboratory), TS-3/4 (High Temperature Plasma Center, University of Tokyo), Sustained Spheromak Experiment (SSPX at Lawrence Livermore National Laboratory),

Table 1. List of Participants

Last	First	Institution	Nation
Bellan	Paul	Caltech	USA
Dorf	Leonid	LANL	USA
Fujino	T	Nihon University	Japan
Furno	Ivo	LANL	USA
Geren	Preston	University of Washington	USA
Gerhardt	Stefan	PPPL	USA
Gota	Hiroshi	Nihon University	Japan
Guo	Houyang	University of Washington	USA
Hoffman	Alan L.	University of Washington	USA
Hsu	Scott	LANL	USA
Intrator	Thomas	LANL	USA
Ji	Hantao	PPPL	USA
Kanki	T	Coast Guard Academy	Japan
Kawamori	E	University of Tokyo	Japan
Miller	R	Self	USA
Milroy	Richard D.	University of Washington	USA
Nagata	Masayoshi	University of Hyogo	Japan
Okada	Shigefumi	Osaka University	Japan
Renneke	Richard	LANL	USA
Ruden	Edward L.	AFRL	USA
Ryutov	Dmitri	LLNL	USA
Sieck	Paul	University of Washington	USA
Slough	John	University of Washington	USA
Steinhauer	Loren	University of Washington	USA
Takahashi	Toshiki	Gunma University	Japan
Takahashi	Tsutomu	Nihon University	Japan
Tang	Xianzhu	LANL	USA
Zhang	Shouyin	LANL	USA

Relaxation Scaling Experiment (RSX at Los Alamos National Laboratory), Helicity Injected Spherical Torus (HIST at Himeji Institute of Technology), Caltech Spheromak. Some experiments are in the design process such as the Magnetic Reconnection Experiment (MRX-FRC at Princeton Plasma Physics Laboratory), Pulsed High Density experiment (PHD at University of Washington).

Several new directions and results in CT research have recently emerged, including neutral-beam injection, rotating magnetic fields, flux build up from Ohmic boost coils, electrostatic helicity injection techniques, CT injection into other large devices, and high density configurations for applications to Magnetized Target Fusion (MTF) and translational compression of CT's. CT experimental programs in both the US and Japan have also shown substantial progress in the control and sustainment of CT's. Both in theory and experiment, there is increased emphasis on three-dimensional (3D) dynamics, which is also related to astrophysical and space physics issues. The 3D data visualization are now frequently used for

experimental data display. There was much discussion of the effects of weak toroidal fields in FRC's and possible implications for transport and relaxation.

A variety of key themes surrounding the physics of CT's were found to recur during this conference. These included questions and answers touching upon magnetic flux build up in CT's, generalized relaxation processes with finite beta and pressure gradients that extend beyond the Taylor picture, the importance of plasma flows, toroidal magnetic fields in FRC's, and CT power plant considerations. This document briefly outlines the tenor of these discussions. More details can be found at http://wsx.lanl.gov/CT_workshop_2004.

FLUX BUILD-UP IN COMPACT TOROIDS

A key technological challenge in CT research is the provision of sufficient magnetic flux to reach more reactor relevant parameters (i.e., large ratio of

scale length to ion gyro-radius). In some cases, it is even a problem to provide enough flux to efficiently utilize neutral beams for current drive or stabilization experiments. The methods of forming high beta FRCs and low beta spheromaks are different due to their different magnetic field topologies, but the scale of each is governed by its poloidal flux. An attractive method of increasing the flux, discussed at this workshop, is the temporary use of a central flux core, and then translating the CT off the flux core so that it would regain the desirable properties of a singly connected object.

FRC

In FRCs the plasma pressure nT where n is the density and T is the total temperature must balance the poloidal field forces. If purely Ohmic processes are relied on to heat the plasma, the heating scales as $P_{ohm} \sim \eta j^2 \sim \eta (B_{pol}/r)^2$, where η is resistivity, j is current density, B_{pol} is the poloidal magnetic field, and r is the minor radius. Radiated power scales as $n^2 \sim (B_{pol}^2/T)^2$ so that as B_{pol} is increased it is easy to encounter radiative collapse unless the temperature also rises rapidly. Rapid, non-Ohmic heating occurs in fast theta-pinches, which is why high temperatures, high densities, and high beta are easily achievable by that method, but the technology becomes difficult when scaled above the 10 mWb flux level. Combining opposite helicity spheromaks, where the merging occurs rapidly, is a recent method of forming FRCs, but it remains to be seen how much poloidal flux can be obtained in this manner. Rotating Magnetic Fields (RMF) can also be used to form FRCs at low densities and, if the impurity level can be kept low, it should be possible to have the Ohmic heating surpass radiative losses, allowing higher temperatures and magnetic fields than in present devices.

FRCs are also candidates for pulsed, high density fusion. The amount of flux required for favorable energy balance will scale inversely with B_{pol} to some power between 1 and 2 (depending on lifetime scaling). If theta-pinch formation is used and operation at non-destructive magnetic field pressures is desired, it will be essential to maximize flux trapping during the theta-pinch formation and flux retention during the subsequent compression process.

Spheromaks

Spheromaks can be formed in a similar manner to FRC's using flux cores. Since the configuration is nearly force free, the densities will be lower and the formation timescales can be longer with reduced requirements for externally applied power. It is not known at what size this will become impractical. Most spheromaks are formed using coaxial guns with a given initial poloidal flux. However, by continually injecting toroidal flux and helicity, the poloidal flux can be increased through flux conversion. This process involves electrodes and significant 3D turbulent processes, so it may be difficult to build the flux up beyond a certain level even though the plasma density may be kept low. A unique, electrode-less inductive helicity scheme is currently being developed.

Inductive Flux Build-Up

While theta-pinch formation methods supply GW of power, most spheromak formation processes involve ~100 MW, and RMF supplies MW level auxiliary power. It is thus difficult to imagine non-Ohmic methods, such as radio frequency waves or neutral beam injection, that would be powerful enough to add much to the existing heating or flux build-up. An Ohmic method being proposed is the use of an inner coaxial flux core to add flux. The previous concerns about radiation rates exceeding Ohmic heating will apply, but if the initial density can be kept low it should be possible to overcome low Z radiation barriers, similar to what is done for standard tokamak startup. RMF produces low density FRCs, and experiments will soon be underway to minimize impurities. Internal flux cores have also been proposed for use in spheromak merging experiments, either to increase the flux of the initial spheromaks or to be applied to the resultant FRC.

GENERAL RELAXATION TO A FINITE PLASMA PRESSURE PLASMA

Finite Beta

Taylor relaxation [1,2] to a minimum-energy state is a well-known principle that applies, in part, to certain classes of plasmas. However, it predicts force-free states, whereas even the configurations to which the Taylor theory applies best, spheromaks and RFPs, have finite β and pressure gradients. A more general relaxation theory is based on the two-fluid model (rather than Taylor's single fluid) and has two helicity invariants instead of one. Analyses of these states [3] show that (1) finite β appears in states with

significant flow and (2) the Taylor states are a subclass of the more general states.

Experimental Evidence of Relaxation

Results from TCS [4] and FIX indicate that the poloidal flux of the plasmoid increases significantly in the course of its injection into the confinement chamber. Cowling's theorem [5] states that such a transition requires 3D dynamics, such as in a relaxation. Moreover, the electron helicity is roughly conserved despite the extreme violence of the plasmoid ejection and stopping. Velocity measurements to date are too incomplete to determine if the ion helicity is conserved. Axial magnetic compression of the compact toroid would increase the toroidal field if poloidal flux were conserved, but increased toroidal field is *not* observed in FIX. This may reflect the conversion of toroidal to poloidal flux.

Tracking "Conserved" Quantities

The "electron" (or magnetic) helicity can be inferred from magnetic probe measurements, as routinely done in spheromaks and lately in low-density FRCs. However, tracking the ion helicity also requires measurements of the velocity fields. Successful measurements of the toroidal flow pattern have exploited the Doppler shift of impurity lines. However, poloidal flow measurements have not been made in CT. More complete measurements will be essential in the future to determine if the relaxation is regulated by both helicities. These measurements will also clarify the 3D transitional mechanism (e.g., internal kink modes) by which the initial state relaxes to the final state.

Self-organization in Helicity-driven Systems

A new research area of Taylor relaxation has been discovered in helicity-driven toroidal systems. The helicity-driven relaxation theory [6], extending beyond closed systems, predicts various kinds of driven-relaxed states such as spherical torus (ST) plasmas, spheromaks with a central rod, low-aspect-ratio RFPs, and tokamaks. The experimental finding on HIST [7] provides, for the first time, evidence for the existence of the flipped ST state predicted theoretically for negative polarity of the external toroidal field and from the conservation of the sign of magnetic helicity. Self-organization during the transition from normal to flipped relaxed states is closely related to magnetic reconnection of the helically kinked open field lines. New approaches to achieving finite plasma pressure plasmas are now being investigated in helicity-driven systems. Equilibrium calculations based on a two-fluid model show that there is a diamagnetic low safety factor (q) ST with higher beta than a conventional ST. Important future experimental work will drive fast ion flow (e.g., CT injection) for plasma formation.

Jets, Collimation, Mass Ingestion Intrinsic to Spheromak Formation

Experiments on the planar coaxial spheromak source at Caltech [8] show that MHD forces ingest plasma (i.e., mass) from the gas puff valves. The ingested mass convects frozen-in toroidal flux linking the poloidal flux established by the bias coil. Thus mass ingestion is directly associated with helicity ingestion. Because of stagnation of the ingested mass flow, there is a concommitant pile-up of the frozen-in toroidal flux associated with the flow. This toroidal flux concentration results in increased toroidal field and hence increased pinch effect which collimates the current channel (poloidal current) so that a long narrow jet of dense hot plasma is formed. When this jet becomes sufficiently long it satisfies $q = 1$ and becomes kink unstable [9]. The nonlinear kink converts toroidal flux into poloidal flux and leads to creation of a spheromak.

Role of Kink Instabilities

The most successful theoretical approach to relaxation of a turbulent magnetohydrodynamic (MHD) system is the Taylor hypothesis [1,2] that magnetic energy is minimized subject to the constraint of constant global magnetic helicity. Since this is essentially a thermodynamic argument, the actual 3D dynamics underlying the relaxation process remain unexplained. For example, in coaxial gun spheromaks a dynamo mechanism can convert injected toroidal flux into required poloidal flux. Cowling's theorem [5] requires non axisymmetric processes to accomplish this. In many situations in the laboratory and in nature, kink-like instabilities are observed to deform an axisymmetric plasma configuration into a 3D one [9]. Examples of this were also shown in RSX [10], in which helical deformations soon dominate the evolution of initially straight current channels.

There was a general appreciation that relaxation is a common effect for many of the CT concepts, and that the development of kink instabilities seems to be a common thread in many situations. Many Innovative Confinement Concept (ICC) approaches contain large plasma beta and pressure gradients and therefore are far from force free and clearly are not relaxed in the Taylor sense. One possible scenario for pulsed or cyclic CT operation might be to charge the configuration with magnetic flux and subsequently wait while it relaxes and dissipates this flux, and then repeat the cycle.

ROLE OF SMALL TOROIDAL FLUX IN FRCs

The general sentiment among the participants was that the influence of toroidal fields on FRC behavior should have a high priority in FRC research, in theory, numerical simulations, and experiments.

Ideal FRC

In its "idealized" form, the FRC is assumed to have no regular toroidal field. An equilibrium is entirely determined by the poloidal field with field nulls situated in the O-point and in (usually two) X-points. As has recently been shown [11], the magnetic structure in the "poloidal field only" configurations is very sensitive to possible non-axisymmetric perturbations of the magnetic field. Perturbations with low mode numbers, even if their amplitude is very small, cause large radial wondering of the field lines, comparable to the separatrix radius. This may lead to an increase of transport, especially electron heat transport. The magnitude of this increase depends on the electron collisionality. In high-density MTF experiments as well as other present-day experiments in which the plasma collisionality is high because of relatively low temperature, the effect is smaller than in low-collisionality systems, such as steady-state FRCs.

Transport

For non-axisymmetric perturbations introduced by external sources (e.g., RF perturbations intended for the current drive), one can substantially reduce radial transport by maintaining a proper parity of perturbations [12]. The analysis of the electron heat transport in FRCs was presented at the Workshop

[11]. It was shown that substantial reduction of the electron heat transport can be reached by introducing a regular toroidal magnetic field that exceeds by a factor of a few the amplitude of the magnetic field perturbations. For example, for perturbations of a relative amplitude of 3% ($\sim 0.1\%$ in terms of the magnetic energy), the toroidal magnetic field with an amplitude $\sim 10\%$ of the poloidal field will already suppress the electron thermal conduction. From a magnetic energy standpoint 10% toroidal field is too weak to cause any substantial changes in the plasma equilibrium; in other words, the FRC remains quite different from a spheromak, where the toroidal field is much larger, approximating force-free low-β configuration. In order to have a substantial effect on the transport, the weak toroidal field must have an even parity with respect to the equatorial plane of FRC.

If a toroidal field is present, a new loss channel appears [11], which is somewhat reminiscent of a neoclassical transport in other toroidal devices. This time it acts mostly on the ions. In the strongly collisional case this transport mechanism becomes unimportant. In the case of a strongly elongated FRC (with $E = L/d \gg 1$, where L is system length, d is minor radius) even a weak toroidal magnetic field, $B_t/B_p \sim 1/E$, may have a strong effect on the gross stability. This happens because the q value scales as $E \cdot B_{tot}/B_{pol}$ and may become of order 1 even at a weak toroidal magnetic field (provided it is an even function with respect to the equatorial plane). At the same time, the toroidal field has only a minor effect on the FRC equilibrium, $\sim 1/E^2 \ll 1$. Very little (if anything) is known about the MHD stability in this setting. The issue deserves some attention of the theorists. In the discussions during the Workshop, it was noted that, in the situation where q becomes of order 1, the magnetic field perturbations lead to formation of "canonical" islands and may lead to confinement degradation if the islands are thick enough. Stochastization of the magnetic field by overlapping higher-order islands is also possible.

Experimental and Computational Results

In FRC's the spontaneous generation of weak toroidal fields is known to be a rather common occurrence. The formation of a toroidal field [13] with an even parity has been reported. At this workshop [4], an interesting evolution of the toroidal magnetic field in the translation-reflection experiment was reported: initially, the plasmoid initially has little

poloidal flux but retains strong toroidal flux at the ends with odd parity. In a numerical study [14], formation of toroidal field with odd parity was reported. After super-Alfvénic reflections from the end magnetic mirrors, the plasmoid settles down into a near-FRC state. Most of the oppositely directed toroidal flux was annihilated, with only a reduced unidirectional toroidal flux remaining (the parity becomes even). Substantial flux conversion from toroidal to poloidal occurs with approximate preservation of the magnetic helicity. This is a tribute not only to the robustness of FRCs, but to the tendency of an FRC to assume a preferred plasma state. The elongation at this stage is ~ 10, so that the observed toroidal field $B_t \sim (1/5)B_p$ can already create the situation with $q \sim 1$ over most of the FRC, with a strong shear near the $B_{\mathrm{pol}} = 0$ flux surface. The flux lifetime of these FRCs is significantly better than predicted by the conventional non-translated FRC scaling.

Further evidence comes from the RMF formed and sustained FRCs. FRCs have been formed and sustained for up to 50 normal flux decay times by RMF in TCS [15]. During these longer pulse FRCs, a sudden transition to a higher performance mode occurs, accompanied by the spontaneous generation of toroidal fields. The toroidal fields are predominantly concentrated near the field null, with local q values significantly greater than unity. In MRX-FRC at Princeton [16], provisions are made to create FRCs with arbitrary toroidal flux. In the context of the aforementioned issues, this would be a very interesting experiment.

Existence of Intermediate States Between FRC and Spheromak

It was noted during the meeting by several participants that it is unclear whether there exists a continuum of long-lived configurations spanning from the "idealized" FRC at one extreme (zero toroidal field, beta ~ 1), and the "idealized" spheromak configuration at the other (comparable toroidal and poloidal fields, relatively low beta). The question was formulated: "Do there exist intermediate configurations with beta, say, equal to 0.3?" Experimental evidence to date casts doubt on this possibility. A range of CT have been generated in the same facility (TS-3/4), but a clear gap is observed between FRC-like and spheromak-like states. Transitional states appear in the theory of two-fluid minimum energy states [17], but the transitional states may or may not

be "attractors" in the nonlinear dynamics of the relaxation. If there is a continuum between stable FRCs and spheromaks and possibly spherical tokamaks this would be an important step to advance the understanding of generalized relaxation.

FLOW

Stabilizing Effect of Flow

The importance of equilibrium flows in plasmas is now broadly recognized. It has appeared in contexts as widely ranging as the L to H transition in tokamaks to the rotational instability in FRCs. Rotational flow in FRCs has long been known and occasionally measured because of its destabilizing effect. However, the possible stabilizing effect of flows, especially sheared flows, has only recently emerged as a result of studies of two-fluid minimum-energy states. Poloidal flows may impart a rigidity to the plasma, which combined with rotational (toroidal) flow, may give gyroscopic stabilization [18].

Flow Measurements

Methods for measuring flows are not nearly as mature as those for magnetic fields. Yet, the flow field, both poloidal and toroidal, must be known in order to track the evolution of the ion helicity, and to understand instabilities (e.g., kink modes) that serve to reorganize the plasma and possibly spawn further self-generated flows. The physical mechanisms for these transitions, including two-fluid and gyroviscous effects, also need to be illuminated. For instance, we know almost nothing about the magnitude of plasma viscosity. A concerted laboratory based effort to realize successful techniques to measure flow would have a large scientific payoff in the ICC and CT communities. Technologies to drive flow, such as biased electrodes and plasma gun methods, will also be useful not only to take advantage of different equilibria that may be accessible but also to investigate the physics systematically.

Angular Momentum

The influence of angular momentum conservation needs further study. This includes determining what boundary conditions either promote or compromise its conservation. If angular momentum is essential for stability, then practical methods for

assuring adequate rotation should be explored. Flow drive and current drive may require different approaches.

IMPORTANCE OF CURRENT DRIVE, FLUX MAINTENANCE

Current Drive

Current drive is a key concern for all current-carrying toroidal devices. However in CTs as there is no Ohmic transformer. Since the boundaries are less established than in toroidal devices, it is usually more appropriate to talk about poloidal flux maintenance. The power required will depend on the resistivity of the plasma. In FRCs the toroidal current is all diamagnetic, so the resistivity will be anomalous, i.e., not Spitzer like. For a radial force balance $J_{tor} \times B_{pol} = dp/dr$, the current density required to support a given pressure gradient is minimized for large β_{pol}, $J_{tor} = B_{pol}/(2\mu_0 \beta_{pol})$. For a given ion temperature, B_{pol} has a lower limit if we wish to confine ion gyro orbits. For spheromaks, RFPs, and to some extent STs, the currents that must be maintained are quite large.

Flux Maintenance in FRCs

The only two methods proposed for sustaining FRCs are RMF and Tangential Neutral Beam Injection (TNBI). RMF generally drives current near the separatrix, while TNBI is most efficient near the field null. The two methods should probably be used together since they supply momentum in opposite directions and could conceivably be used to influence both current profiles and toroidal velocity shear. The physics of RMF drive has been fairly well developed. On the other hand, while neutral beams have been injected into FRCs, the FRC flux levels have been too low to trap the resultant high energy ions inside the separatrix. Thus, the utility of TNBI for FRC current maintenance has not yet been tested.

Flux Maintenance in Spheromaks and RFPs

Helicity injection has been considered as a method for maintaining flux and current in both spheromaks and RFPs. In spheromaks toroidal flux is supplied by a coaxial gun injecting poloidal current at the edge, and a dynamo process maintains toroidal

current in the center. In RFPs, poloidal flux is supplied through an Ohmic transformer, but this is not a true steady state method, and current maintenance for longer than the transformer flux swing time may be very difficult. In either case, reliance on the relaxation principle [1] to provide the desired flux ratios may result in turbulence which unfavorably affects plasma confinement.

CT POWER-PLANT CONSIDERATIONS

Only a modest amount of recent work has been performed on CT-related fusion power-plant topics. There remains a general appreciation of the flexibility of the CT class in addressing the perceived needs and opportunities of future power stations. A detailed assessment of the competitive position of CTs relative to mainline MFE and IFE candidates must await further development of the various CT approaches. The potential for achieving high values of plasma beta in some CTs allows anticipation of advanced-fusion-fuel (e.g., D-3He) applications with high-efficiency direct conversion of charged-particle energy. Such systems result in greatly reduced neutron production and associated neutron damage of structural materials, with favorable consequences for the power-plant operational availability and radioactive-waste disposal. For D-T fueled systems, high plasma beta may result in high power density. On the positive side, a high-power-density fusion system may reap direct-cost savings. Adverse consequences include possible high 14-MeV neutron wall loads coupled to fluence-limited structural lifetimes and high surface heat fluxes.

Fortunately, the geometries of CT systems may more easily accommodate certain mitigating technologies (e.g., liquid walls) than can tokamaks and stellarators. Operationally, CT systems range from steady-state to pulsed. The ability to translate certain CTs allows physical separation of the plasma formation apparatus from the burn chamber. Adiabatic compression (possibly liner driven) may allow heating to ignition. Various combinations of these features have resulted in a number of power-plant embodiments over the years.

Pulsed systems require extra fusion gain [Q ~ fusion yield divided by invested (plasma) energy] to compensate for the dwell time between pulses. High yields require clever stand-off schemes and/or cheap and rapid remanufacture of destroyed components

and may be accomplished in IFE-type chambers protected by thick-liquid falls.

SUMMARY

This CT workshop provided an opportunity for a small subset (25–30 people) of the ICC community to get together and discuss issues that are directly related to CT physics. Many of our fusion reactor scenarios are intrinsically pulsed or cyclic, operate at large beta. This path to fusion reactors has not received the attention or support enjoyed by the proponents of a steady state approach. The physics of relaxation and equilibrium with large beta and and pressure gradients still needs much further study. Moreover, there is a strong connection between the fundamental science that is crucial to all the CT concepts and many interesting questions in space physics and astrophysics. We hope that this workshop continues in future years. Information is posted at our website http://wsx.lanl.gov/CT_workshop_2004.

ACKNOWLEDGMENTS

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