2016 US-Japan Workshop on Compact Torus

"Equilibrium studies and novel applications of compact toroids based on innovative confinement techniques: The future of Compact Tori"

August 22–24, 2016

at the Hotel Irvine

Irvine, California, USA

Hosted by

University of California, Irvine

Organized by:

Toshi Tajima (University of California, Irvine – USA)

Tomohiko Asai (Nihon University – Japan)

2016 US-Japan CT Workshop

Dates:

August 22–24, 2016

Venue:

Hotel Irvine
17900 Jamboree Road
Irvine, California 92614, USA
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CT2016 Workshop Website:

http://www.physics.uci.edu/US-JAPAN-CT2016/

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CT2016 Workshop Participants List

Name (Last, First)	Affiliation	Country
Asai, Tomohiko	Nihon University	Japan
Bao, Jian	University of California, Irvine	USA
Belova, Elena	Princeton Plasma Physics Laboratory	USA
Binderbauer, Michl	Tri Alpha Energy	USA
Cohen, Samuel	Princeton Plasma Physics Laboratory	USA
Gota, Hiroshi	Tri Alpha Energy	USA
Guttenfelder, Walter	Princeton Plasma Physics Laboratory	USA
Haw, Magnus	California Institute of Technology	USA
Horton, Wendell	University of Texas at Austin	USA
Hossack, Aaron	University of Washington	USA
Howard, Stephen	General Fusion	Canada
Kaminou, Yasuhiro	University of Tokyo	Japan
Kaur, Manjit	Swarthmore College	USA
Kishimoto, Yasuaki	Kyoto University	Japan
Laberge, Michel	General Fusion	Canada
Lau, Calvin	University of California, Irvine	USA
Lin, Zhihong	University of California, Irvine	USA
Magee, Richard	Tri Alpha Energy	USA
Masamune, Sadao	Kyoto Institute of Technology	Japan
Matsumoto, Tadafumi	Nihon University	Japan
McCollam, Karsten	University of Wisconsin-Madison	USA
McGuire, Thomas	Lockheed Martin	USA
Monkhorst, Henk	University of Florida	USA
Nagata, Masayoshi	University of Hyogo	Japan
Necas, Ales	Tri Alpha Energy	USA
Nehl, Colleen	Booz Allen Hamilton / U.S. Department of Energy	USA
O'Bryan, John	University of Maryland, Baltimore County	USA
Okada, Shigefumi	Osaka University	Japan
Omelchenko, Yuri	Trinum Research	USA
Paluszek, Michael	Princeton Satellite Systems	USA
Park, Jaeyoung	Energy Matter Conversion Corporation	USA
Putvinski, Sergei	Tri Alpha Energy	USA
Raman, Roger	University of Washington	USA
Ryutov, Dmitri	Lawrence Livermore National Laboratory	USA
Santarius, John	University of Wisconsin-Madison	USA
Schaffner, David	Bryn Mawr College	USA
Schmitz, Lothar	University of California, Los Angeles	USA
Sieck, Paul	Woodruff Scientific	USA
Steinhauer, Loren	Tri Alpha Energy	USA
Swanson, Charles	Princeton Plasma Physics Laboratory	USA
Tajima, Toshiki	University of California, Irvine	USA
Takahashi, Toshiki	Gunma University	Japan
Trask, Erik	Tri Alpha Energy	USA
Tuszewski, Michel	Tri Alpha Energy	USA
von der Linden, Jens	University of Washington	USA
Yamada, Masaaki	Princeton Plasma Physics Laboratory	USA
You, Setthivoine	University of Washington	USA

US-Japan CT2016 Workshop Program

August 22 – 24, 2016
at the Hotel Irvine, Irvine, California
Theater room

30 min/presentation (25 min talk + 5 min Q&A)

8/22 (Mon) - AM

Opening:

8:45 AM Opening Remarks: Toshi Tajima

Session 1: Transport & Confinement

Chair 1.1: Masaaki Yamada

9:00 AM Horton, Wendell (*Univ. of Texas at Austin*)
Comparison of the electron thermal transport between tokamaks and the C-2U FRC

9:30 AM Kishimoto, Yasuaki (*Kyoto Univ.*)
Tokamak/Stellarator vs. FRC: Transport and Other Fundamentals

10:00 AM Guttenfelder, Walter (*PPPL*)
Transport at high beta in spherical tokamaks

10:30 AM Break (20 min)

Chair 1.2: Wendell Horton

10:50 AM Trask, Erik (*TAE*)
Overview of Tri Alpha Energy's Experimental Program and Recent Progress on Transport Analysis

11:20 AM Schmitz, Lothar (*UCLA*)
Suppressed Ion-Scale Turbulence in the C-2/C-2U FRC – Recent Experimental and Simulation Results

11:50 AM Lau, Calvin (*UCI*)
Electrostatic drift-waves in the FRC: destabilized in the scrape-off layer, robust stabilization in the core

12:20 PM Lunch Break (1 hr 20 min)

8/22 (Mon) - PM

Session 2: Overview & Fusion/Reactor Research

Chair 2: Colleen Nehl

1:40 PM	McGuire, Thomas (*Lockheed Martin*) **Overview of the Lockheed Martin Compact Fusion Reactor (CFR) Program**
2:10 PM	Raman, Roger (*Univ. of Washington*) **Overview of Transient CHI Plasma Start-up Research in NSTX-U**
2:40 PM	Santarius, John (*Univ. of Wisconsin-Madison*) **Aspects of Advanced Fuel FRC Fusion Reactors**
3:10 PM	Break (20 min)
3:30 PM	Laberge, Michel (*General Fusion*) **Plasma compression experiments at General Fusion**
4:00 PM	Paluszek, Michael (*Princeton Satellite Systems*) **Fusion-enabled Pluto orbiter and lander**

Discussion 1: Transport & Fusion Research

Chair: Toshi Tajima

4:30 PM	Discussion (~1 hour)
5:30 PM	Session Closed

Reception & Banquet:

6:00 PM	Reception (~1 hour)
7:00 PM	Banquet

8/23 (Tue) - AM

Session 3: Spheromak-1 & Reconnection

Chair 3: Michel Tuszewski

9:00 AM	Yamada, Masaaki (*PPPL*) **Laboratory studies of magnetic reconnection: How can they be applied to CT research?**
9:30 AM	Belova, Elena (*PPPL*) **2D and 3D hybrid simulations of spheromak merging**
10:00 AM	Kaminou, Yasuhiro (*Univ. of Tokyo*) **Hall effect on flow structure in counter-helicity spheromak merging**
10:30 AM	Break (20 min)
10:50 AM	Omelchenko, Yuri (*Trinum Research*) **Asynchronous 3D HYPERS simulations of compact toroids and magnetoplasmas: spheromak merging, FRC formation, magnetized shocks, laser-produced plasmas and turbulence**
11:20 AM	Haw, Magnus (*Caltech*) **Extreme ultra-violet burst, particle heating, and whistler wave emission in fast magnetic reconnection induced by kink-driven Rayleigh-Taylor instability and measurements of forces, flows, and collimation in toroidal current channels**
11:50 AM	Lunch Break (1 hr 40 min)

8/23 (Tue) - PM

Session 4: FRC-1 & RFP

Chair 4.1: Shigefumi Okada

1:30 PM	Asai, Tomohiko (*Nihon Univ.*) **Topological Transition and Inductive Current Drive of a Translated Field-Reversed Configuration**
2:00 PM	Steinhauer, Loren (*TAE*) **Hybrid FRC equilibria with fully-kinetic ions and fluid electrons**
2:30 PM	Cohen, Samuel (*PPPL*) **Long-pulse operation of the PFRC-2 device**
3:00 PM	Break (20 min)

Chair 4.2: Masayoshi Nagata

3:20 PM	Magee, Richard (*TAE*) **Fast ion physics in the C-2U beam driven FRC**
3:50 PM	McCollam, Karsten (*Univ. of Wisconsin-Madison*) **Two-fluid magnetic relaxation in RFPs and initial CT injection experiments at WiPAL**
4:20 PM	Masamune, Sadao (*Kyoto Inst. of Technology*) **Evaluation of CT injection to RFP for performance improvement and reconnection studies**
4:50 PM	Break (10 min)

Discussion 2: Current and Future of Compact-Toroid Research

Chair: Loren Steinhauer

5:00 PM	Discussion (~1 hour)
6:00 PM	Session Closed

8/24 (Wed) - AM

Session 5: Spheromak-2, Helicity injection & Flow

Chair 5.1: Loren Steinhauer

9:00 AM	Hossack, Aaron (*Univ. of Washington*) **Sustainment of stable spheromaks with imposed-dynamo current drive**
9:30 AM	Howard, Stephen (*General Fusion*) **Experimental results from the SPECTOR device at General Fusion**
10:00 AM	Nagata, Masayoshi (*Univ. of Hyogo*) **Mulitiple plasmoid formation and flux closure during transient-CHI start-up process on HIST**
10:30 AM	Break (20 min)

Chair 5.2: Yasuaki Kishimoto

10:50 AM	You, Setthivoine (*Univ. of Washington*) **A field theory approach to plasma self-organization**
11:20 AM	von der Linden, Jens (*Univ. of Washington*) **Investigating the Dynamics of Canonical Flux Tubes**
11:50 AM	Kaur, Manjit (*Swarthmore College*) **Accelerated Taylor State Plumes on SSX**
12:20 PM	Lunch Break (1 hr 20 min)

8/24 (Wed) - PM

Session 6: FRC-2, Spheromak-3 & Compact Toroids

Chair 6.1: Sadao Masamune

1:40 PM Necas, Ales (*TAE*)
PIC Simulation of Thermal Distribution Driven Non-Maxwellian by Neutral-Beam Injection in a High Beta Plasma

2:10 PM Swanson, Charles (*PPPL*)
Extracting electron energy distributions from PFRC X-ray spectra

2:40 PM Sieck, Paul (*Woodruff Scientific*)
Design Point for a 1 MW Fusion Neutron Source

3:10 PM Break (20 min)

Chair 6.2: Samuel Cohen

3:30 PM O'Bryan, John (*Univ. of Maryland, Baltimore County*)
Numerical investigation of design and operational parameters on CHI spheromak performance

4:00 PM Matsumoto, Tadafumi (*Nihon Univ.*)
Compact Toroid Injection into C-2U FRCs for Particle Refueling

4:30 PM Takahashi, Toshiki (*Gunma Univ.*)
MHD and Hybrid Simulation Study of FRC Plasmas

Closing:

5:00 PM Closing Remarks: Tomohiko Asai / Toshi Tajima

CT2016 Workshop

Monday, August 22, 2016

Hotel Irvine – Theater Room

Session 1: Transport & Confinement

Session 2: Overview & Fusion/Reactor Research

Discussion 1: Transport & Fusion Research

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Comparison of the electron thermal transport between tokamaks and the C-2U FRC

W. Horton, T. Tajima, A. D. Beklemishev

In many magnetic confinement devices anomalous electron heat transport has been found. In tokamaks it arises from the densely spaced and overlapping drift wave eieng modes in the sheared magnetic field, which leads to radially extended streamers and the Bohm-like transport. In reversed magnetic field shear there appears a gap in the radial spectrum and greatly reduced transport[1] as confirmed in reversed magnetic shear experiments. The NBI driven FRC C-2U plasmas[2] have no magnetic shear and show energy confinement times that increase with electron temperature in sharp contrast to tokamaks and stellarators. We present arguments based on drift wave turbulent transport[3] and the FLR-MHD-Alfven wave stability conditions that are consistent with this sharp contrast of energy confinement scaling with electron temperature.

For the C-2U plasmas the following stabilizing elements for dirft waves are found: (1) the large ion gyroradii are stabilizing, (2) electron bounce frequency is high and only a small fraction of the electrons leave the core confinenment region, (3) the direction of the grad-B drift is opposite to the grad-n_e, and (4) the large temperature ratio such as $T_i/T_e > 5$. We use these contrasts between the toroidal confinement systems and the NBI driven closed magnetic fields of the C-2U plasmas to explain the key differences in the scaling of the plasma confinement with electron temperature. For the the C-2U plasmas, the energy confinement time $\tau_E \approx T_e^{\alpha}$ rather than the universal Bohm or gyroBohm toroidal system scaling where $\tau_E \approx 1/T_e^{\beta}$ decreases with increasing electron temperature.

[1] A. D. Beklemishev and W. Horton, *Transport Profiles Induced by Radially Localized Modes in a Tokamak,* Phys. Fluids B **4**, 200-206 (1992) and B **4**, 2176 (1992).

[2] M. Binderbauer et al., Confinement times in the Tri Alpha C-2U plasmas (2015).

[3] W. Horton, *Turbulent Transport in Magnetized Plasmas* (2012) ISBN: 978-981-4383-53-0 pp.172-180 and 188-199.

Work supported by the U.S. Department of Energy Office of Fusion Energy Sciences under Award No. DE-FG02-04ER-54742, Tri-Alpha Corp and the Budker Institute for Nuclear Physics.

Tokamak/Stellarator vs. FRC: Transport and Other Fundamentals

Y. Kishimoto[1] and T. Tajima[2,3]

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[2]University of California, Irvine, Irvine, CA 92697, USA
[3]Tri Alpha Energy, Inc., Rancho Santa Margarita, CA 92688, USA

Plasma, highly nonlinear medium consisting of ions and electrons, exhibits prominent characteristic, self-organization and structure formation, once several conditions are fulfilled. In some case, they are expectable and useful in achieving purpose while in some case accidental and eliminated. Fusion device, one of promising plasma applications for future energy resource, is designed so as to minimize macro and micro instabilities in achieving high stability and confinement, so that the characteristics are of specifically importance [1]. When we design some device, we usually reply on linear aspect while not sure whether the characteristics, i.e. the self-organization and structure formation, support the approach or lead contradiction.

Tokamaks and stellarators have strong toroidal magnetic fields and additional magnetic field, i.e. poloidal magnetic field, by plasma current in tokamaks and by external coil in stellarators, so that the latter is more rigid than the former, which possess more freedom in magnetic configuration. Such magnetic structures are designed to have magnetic shear in minimizing various instabilities from the linear aspect while is found to induce the overlap of drift-wave “islands” called streamers, i.e. global modes, and causes avalanche-like intermittent bursts leading to self-organized critical transport [2]. This is peculiar to so called L-mode that causes anomalous ion/electron diffusion known as the Bohm transport. A recipe to prevent such anomalous diffusion is to weaken and/or eliminate the magnetic shear by the reversal of magnetic shear or by the annihilation of streamers by the additional electric field generated shear, which leads to high confinement state, e.g. internal transport barrier.

We compare and understand that the presence of null magnetic shear in stellarator enhances its confinement, much the similar way to the above tokamak’s local shearlessness contributing to the enhanced confinement [3]. Namely, through the series of research on fusion devices with strong and then rigid guiding magnetic field, we found a *reciprocal relation* between linear stability and nonlinear turbulent transport as that the configuration with more unstable smaller magnetic shear plasma provides smaller turbulent transport nonlinearly than that with moderate shear. This suggests that softening the “rigidness” of the system is of importance for the plasma to be self-organized in keeping higher stability and confinement.

From this viewpoint, high-energy beam assisted FRC [4] is charming system. FRC is devoid of strong “shell-like” fields and thus is bound to be wobbly. First, the FRC core is devoid of magnetic shear (an agent of the radial extended transport channels). Secondly, the core is devoid of the instability driving mechanism of drift wave due to the finite Larmor radius (FLR), short electron connection length, and reversed grad-B drift. However, the beam-driven FRC has an entirely additional dimension. The beam introduces the backbone to the overall plasma that makes FRC globally stable, while enhanced FLR due to the beam further solidifies the FRC stability. The additional but not yet well-known robustness of the beam-FRC combo is the principle that the beam induced waves with high phase velocity cannot destroy the plasma confinement, just similar to the intense wake field not destroying the plasma accelerator. We are planning to check this point by our gyro-kinetic code of FRC.

[1] W. Horton, Rev. Mod. Physics **71**, 735 (1999).
[2] Y. Kishimoto, T. Tajima, W. Horton, M. Lebrun, J.Y, Kim, Phys. Plasmas **3**, 1289 (1996).
[3] A. Ishizawa, Y. Nakamura, Y. Kishimoto *et al.*, 26th IAEA-FEC, October 17-22, 2016, Kyoto.
[4] M.W. Binderbauer, T. Tajima *et al.*, Phys. Plasmas **22**, 056110 (2015).

Transport at high beta in spherical tokamaks

Walter Guttenfelder, *Princeton Plasma Physics Laboratory*

A key priority for spherical tokamak (ST) transport research is to understand the mechanisms responsible for confinement scaling at high beta (~20%), especially as collisionality is reduced towards that envisioned for future ST-based fusion nuclear science facilities. Previous research in the National Spherical Torus Experiment (NSTX) has indicated that heat loss through the ions is often close to collisional (neoclassical) transport limits. This is a consequence of the equilibrium configuration at high beta and large rotation shear suppressing electrostatic, ion gyroradius scale, drift wave turbulence mechanisms. Recent analysis and theoretical predictions have shown that a zoology of theoretical drift wave turbulence mechanisms are predicted unstable that can contribute to anomalous electron energy losses. Depending on location in the plasma and operating regime, these drift waves can be electrostatic or electromagnetic in nature, exist at ion or electron larmor radius scales, and exhibit unique sensitivities to plasma gradients (density, temperature) and equilibrium properties. In addition to gradient-driven drift waves, measurements and simulations predict the onset of global and compressional Alfven eigenmodes driven by the presence of energetic ions from neutral beam heating in high power discharges. These modes are predicted to cause large energy loss via stochasticized electron orbits, as well as redistribution of energy via coupling to kinetic Alfven waves damped further out in the plasma. Experimental evidence suggests these additional mechanisms may limit peak electron temperatures in NSTX. The upgrade to NSTX (NSTX-U) was recently completed to double the toroidal field strength (0.5→1.0 T), plasma current (1→2 MA) and neutral beam heating power (6→12+ MW). This will allow access to new parameter regimes while also providing increased flexibility to modify equilibrium current and rotation profiles, in order to better clarify our understanding of underlying transport mechanisms and validate theoretical predictions. Interestingly, NSTX-U also fills a gap in parameter space (β~20%, $A=R/a$~1.7, $\rho_*=\rho/R$~1/100, $M=v_{Tor}/c_s$~0.5) between compact toroids and conventional aspect ratio tokamaks, providing an opportunity to unify understanding of various instability and transport mechanisms. This work is supported by US DOE contract DE-AC02-09CH11466.

Overview of Tri Alpha Energy's Experimental Program and Recent Progress on Transport Analysis

E. Trask, M.W. Binderbauer, T. Tajima, S. Putvinski, M. Tuszewski, S. Dettrick, H. Gota,
S. Korepanov, A. Smirnov, M.C. Thompson, X. Yang, M. Cappello, and the TAE Team

Tri Alpha Energy, Inc., P.O. Box 7010, Rancho Santa Margarita, California 92688, USA

Tri Alpha Energy's experimental program has demonstrated reliable field-reversed configuration (FRC) formation and sustainment, driven by fast ions via high-power neutral-beam (NB) injection. The world's largest compact-toroid experimental devices, C-2 [1] and C-2U [2], have successfully produced a well-stabilized, sustainable FRC plasma state with NB injection (input power, P_{NB} ~10+ MW; 15 keV hydrogen) and end-on coaxial plasma guns. Changes to beam parameters and magnetic field profiles have synergistically led to improved confinement and stability of FRC plasmas and larger fast-ion build up. Our zero-dimensional power balance analysis detailing loss channel characteristics and plasma timescales show substantial improvements in equilibrium and transport parameters, in which electron energy confinement time strongly correlates with electron temperature, T_e; i.e., showing scaling with a positive power of T_e scaling for the confinement time in our experimental device.

This advanced beam-driven FRC state has been produced and sustained for up to 5+ ms in C-2U, which is longer than all characteristic system time scales and only limited by hardware and electric supply constraints such as NB and plasma-gun power supplies. To further improve the FRC performance the C-2U device is being replaced by C-2W featuring higher injected NB power, longer pulse duration as well as enhanced edge-biasing systems and substantially upgraded divertors. Main C-2U experimental results including recent transport analysis as well as key features of C-2W will be presented.

[1] M.W. Binderbauer *et al.*, Phys. Plasmas **22**, 056110 (2015).
[2] M.W. Binderbauer *et al.*, AIP Conference Proceedings **1721**, 030003 (2016).

Suppressed Ion-Scale Turbulence in the C-2/C-2U FRC - Recent Experimental and Simulation Results

L. Schmitz[1,2], D.P. Fulton[1], C. Lau[3], T. Tajima[1,3], M. Binderbauer[1], B.H. Deng[1],
H. Gota[1], I. Holod[3], Z. Lin[3], and the TAE team[1]

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Ion-scale modes are found to be stable in the core of the C-2 and C-2U neutral-beam-sustained Field-Reversed Configurations (FRCs) [1]. An inverted toroidal wavenumber spectrum is measured in the closed flux surface region via Doppler Backscattering (DBS). Local, electrostatic gyrokinetic simulations via the modified GTC code [2] attribute the absence of ion-scale core fluctuations to a combination of Finite Larmor radius effects, large ion- to electron temperature ratio (T_i/T_e ~5), short field line connection length, and the radially increasing magnetic field gradient. Near-classical ion energy confinement is inferred from transport analysis, in qualitative agreement with the observed lack of core turbulence. In contrast, ion-range and electron-range modes with an exponential wavenumber spectrum are observed in the FRC scrape-off layer (SOL), with radially increasing fluctuation levels ($2 \leq k\rho_s \leq 40$, $0.05 \leq k\rho_s \leq 0.45$, where k is the toroidal wavenumber and ρ_s, ρ_e are the ion-sound gyroradius and the electron gyroradius). Linear, electrostatic flux-tube gyrokinetic simulations confirm unstable SOL drift wave and trapped electron modes, driven by the radial electron temperature and density gradients, across a fairly wide wavenumber range. Electostatic passive or active divertor biasing of the SOL plasma (via plasma guns with a central biased electrode, passive annular divertor electrodes, or a large radius LaB_6 electron emitter) maintains sufficient $\boldsymbol{E}\times\boldsymbol{B}$ rotational shear just outside the FRC separatrix to establish an effective radial transport barrier with reduced radial turbulence correlation. SOL fluctuation levels are reduced substantially compared to unbiased FRCs, sustaining an increased radial density gradient. The measured SOL critical density gradient is comparable to the linear instability threshold predicted by local gyrokinetic simulations, but increases with $\boldsymbol{E}\times\boldsymbol{B}$ rotational shear, opening the prospect of active boundary and transport control in view of FRC reactor requirements.

[1] M.W. Binderbauer, T. Tajima *et al.*, *Phys. Plasmas* **22**, 056110 (2015).
[2] D.P. Fulton, C. Lau, I. Holod, *et al.*, *Phys. Plasmas* **23**, 012509 (2016).

Electrostatic drift-waves in the FRC: destabilized in the scrape-off layer, robust stabilization in the core

Calvin K Lau
University of California, Irvine

Gyrokinetic simulations using the gyrokinetic toroidal code (GTC) has been performed for the advanced beam driven C-2 field-reversed configuration (FRC) experiment. With pressure gradient drives up to $\frac{R_0}{L_n} = \kappa_n < 5$ and the range of wavelengths up to $k_\zeta \rho_e < 0.3$, radially local fluxtube simulations find that electrostatic drift-waves are stable in the core. The stabilization mechanisms include finite Larmor radius (FLR) effects, magnetic well (negative grad-B), and electron kinetic effects. In the scrape-off layer (SOL), collisionless electrostatic, ion-to-electron-scale drift-waves are destabilized by electron temperature gradients from resonance with locally barely trapped electrons. Collisions can suppress this instability, but a collisional drift-wave instability can still exist at realistic pressure gradients. These simulation results are in qualitative agreement with C-2 FRC experiments. In particular, the lack of ion-scale instability in the core is consistent with experimental measurements of a fluctuation amplitude spectrum showing both lower amplitudes than the SOL and a depression in the ion-scale. The pressure gradient thresholds for the SOL instability from simulations are also consistent with thresholds observed in experiments.

Overview of the Lockheed Martin Compact Fusion Reactor (CFR) Program

Thomas J. McGuire
Lockheed Martin

Abstract

The Lockheed Martin Compact Fusion Reactor (CFR) Program endeavors to quickly develop a compact fusion power plant with favorable commercial economics and military utility. An overview of the concept and its diamagnetic, high beta magnetically encapsulated linear ring cusp confinement scheme will be given. The analytical model of the major loss mechanisms and predicted performance will be discussed, along with the major physics challenges. Key features of an operational CFR reactor will be highlighted. The proposed developmental path following the current experimental efforts will be presented.

Overview of Transient CHI Plasma Start-up Research in NSTX-U

R. Raman (*University of Washington, Seattle WA USA)*

Transient Coaxial Helicity Injection (CHI) in NSTX has generated toroidal current on closed flux surfaces without the use of the central solenoid. When induction from the solenoid was added, CHI initiated discharges in NSTX achieved 1 MA of plasma current using 65% of the solenoid flux of standard induction-only discharges. In addition, the CHI-initiated discharges have lower density and a low normalized internal plasma inductance of 0.35, as desired for achieving advanced scenarios. The Tokamak Simulation Code (TSC) has been used to understand the scaling of CHI generated toroidal current with variations in the external toroidal field and injector flux. These simulations show favorable scaling of the CHI start-up process with increasing machine size.

CHI is implemented on NSTX and NSTX-U by driving current from an external capacitor bank source along field lines that connect the inner and outer lower divertor plates, which are electrically separated from each other. The discharge is initiated by first energizing the toroidal field coils and the lower divertor coils to produce magnetic flux, known as the injector flux. After gas is injected into the vacuum chamber, a voltage is applied between these plates, which ionizes the gas and produces current flowing along magnetic field lines connecting the lower divertor plates. In NSTX-U, a 20-50 mF capacitor bank charged to 2 kV (with a future upgrade to 3 kV) would provide this current, called the injector current.

CHI on NSTX-U will benefit from numerous upgrades. These are: (1) Improved design of the injector coil that increases the injector flux capability, and consequently, the generated plasma current, by a factor of over 2.5, (2) improved positioning of the upper buffer field coil to minimize the generation of undesirable current paths, (3) factor of two increase in the toroidal field increases the current multiplication factor, (4) the capability for a 1 MW ECH system that is projected to increase the electron temperature of the CHI discharge, and (5) more complete lithium deposition capability that will reduce the influx of low-Z impurities.

NSTX has undergone a major upgrade (to NSTX-U) to increase the capabilities of its toroidal and poloidal field coils and to add a second neutral beam line. Analysis of the NSTX results shows that the amount of closed-flux current generated by CHI is closely related to the initially applied injector flux. On NSTX-U the available injector flux is over 240 mWb, much exceeding the 80 mWb in NSTX. The modeling projects that it should be possible to generate considerably in excess of 400 kA of closed-flux current with CHI in NSTX-U. At this current level, TSC simulations suggest that the second more tangentially injecting neutral beam system in conjunction with bootstrap current overdrive should be capable of ramping-up the plasma current to the 1 MW steady-state current sustainment levels in support of a ST FNSF.

Experimental results and the NSTX-U plans for achieving full solenoid-free plasma start-up, and full non-inductive current ramp-up to sustained operating levels will be described. This work is an important outgrowth of early CHI research conducted on Spheromaks. The differences between CHI on a Spheromak and a Spherical Tokamak, and the CHI operating modes in these two concepts will also be discussed.

This work was supported by U.S. DOE contracts DE-FG02-99ER54519 and DE-AC02-09CH11466.

Aspects of Advanced Fuel FRC Fusion Reactors

John F. Santarius and Gerald L. Kulcinski

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This talk will focus on aspects of $p^{11}B$ and D^3He FRC fusion reactors in comparison with DT FRC and tokamak reactors. Developing attractive fusion power requires overcoming physics, engineering, safety, economic, and environmental obstacles. Low-neutron advanced fuels in combination with high-β concepts appear very attractive from the perspectives of engineering, safety, environment, and licensing, while cost remains to be determined. With regard to energy confinement, DT fuel is the easiest to burn, while burning advanced fuels requires continued, modest plasma physics progress, especially in energy confinement, along with development of the FRC or another suitable high-β innovative concept. Unfortunately, DT fuel faces daunting engineering obstacles, including tritium-breeding blanket design, neutron damage to materials, radiological hazard (afterheat and waste disposal), and frequent maintenance in a highly radioactive environment. The geometry of FRCs (Figure 1) also leads to significant engineering advantages over the tokamak related to power flows, direct energy conversion, magnet configuration, radiation shielding, coolant piping accessibility, and maintenance. This talk will summarize the issues mentioned above, and also discuss fusion power density, plasma-surface interactions, nuclear proliferation, non-electric applications, and ^3He fuel supply.

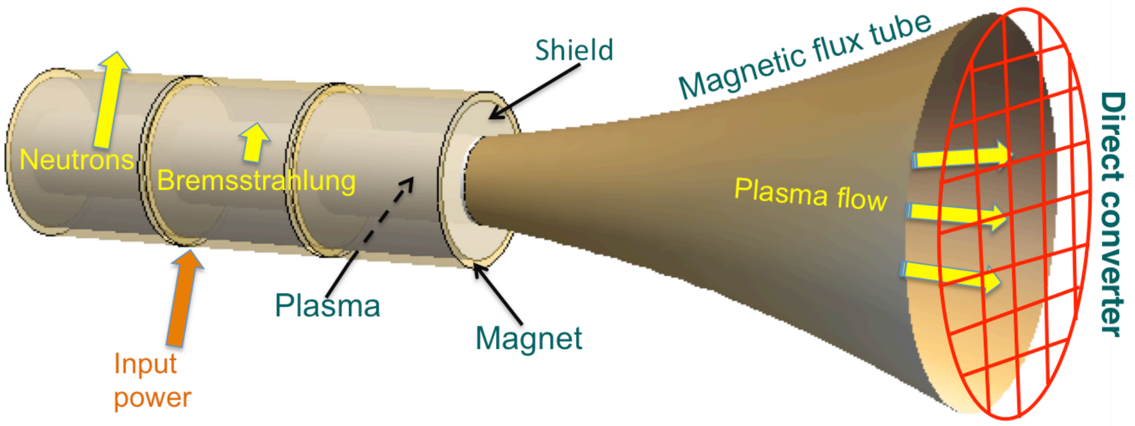

Figure 1. FRC fusion core key elements and major power flows.

Plasma compression experiments at General Fusion

Michel Laberge and the GF team. *General Fusion Inc, Burnaby, British Columbia, Canada.*

Abstract

General Fusion is developing an acoustically driven magnetized target fusion system. I will first describe the general idea and the parameters space where GF would like to operate. In order to test the compression of plasma without having to build an expensive compression machine, we are presently using high explosive to compress the plasma on a time scale similar to our planned acoustic driver. We have compressed spheromak and spherical tokamak. We initially lost the plasma by radiation due to impurity injection during the compression process. Shock less compression of the liner and switching from titanium gettering to lithium gettering fixed that problem. We now observe the rapid growth of MHD modes during the compression that terminates the plasma at low compression ratio (~2x radial). Our latest simulations indicate that a change of shape to a more self similar spherical implosion should improve the stability of the imploding plasma. We now have such SPECTOR plasma in operation achieving good results, and plan to compress it in the near future.

Fusion-enabled Pluto Orbiter and Lander

Michael Paluszek

The Princeton Field Reversed Configuration (PFRC) reactor is the basis for a small nuclear fusion rocket engine for interplanetary exploration. The engine is suitable for fusion power levels between 1 and 10 MW, which makes it ideal for both human and robotic exploration. PFRC, known as Direct Fusion Drive (DFD) in its space propulsion variant, is driven by odd-parity rotating magnetic fields and uses deuterium and helium-3 as fuels. Additional deuterium is introduced into the scrape-off layer on one end of the machine to provide variable thrust. The ionized gas is exhausted through a magnetic nozzle that has additional coils to provide plume steering.

The presentation will cover the Pluto mission in detail including the Pluto orbit entry propulsion phase. The spacecraft design will be presented. The mission launches on a single Delta-IV Heavy or comparable launch vehicle. Cost savings for this and other robotic missions will be discussed.

Details of the reactor design and balance of plant will be given including the recycling of the synchrotron radiation, bremsstrahlung radiation, neutron flux and wall thermal loads using a Brayton cycle power system; the reactor startup system; and the radio frequency and superconducting coil subsystems.

CT2016 Workshop

Tuesday, August 23, 2016

Hotel Irvine – Theater Room

Session 3: Spheromak-1 & Reconnection

Session 4: FRC-1 & RFP

Discussion 2: Current and Future of Compact-Toroid Research

Laboratory studies of magnetic reconnection: How can they be applied to CT research?

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Magnetic reconnection is a fundamental process in nature in which magnetic field lines change their topology in plasma and convert magnetic energy to particles by acceleration and heating [1]. It is one of the most fundamental processes at work in laboratory and astrophysical plasmas. For local aspects, we have recently reported our results on the energy conversion and partitioning in a laboratory reconnection layer [2]. A systematic study of the quantitative inventory of converted energy within a reconnection layer is presented with a well-defined, variable boundary. This study concludes that about 50% of the inflowing magnetic energy is converted to particle energy, 2/3 of which is transferred to ions and 1/3 to electrons. A question arises, whether there is a fundamental principle in the energy partitioning in a proto-typical reconnection layer. This talk presents our physics analysis of the energy conversion processes in the magnetic reconnection layer of two-fluid physics regime. The flows of electrons at the reconnection layer lead to a formation of strong electrostatic field in the reconnection plane causing ion acceleration and resultant ion heating. Based on the two-fluid features, a quantitative analytical model of energy partitioning will be presented. In this talk, we focus on a few laboratory experiments recently carried out regarding both local and global aspects of magnetic reconnection and discuss how the results should be applied to CT research.

[1] M. Yamada, R. Kulsrud, and H. Ji, Rev. Mod. Phy. **82**, 603 (2010).
[2] M. Yamada et al. Nat. Commn. **5**, 4474 (2014)

US-Japan Workshop on Compact Tori
August 22 - 24, 2016, Irvine CA

2D and 3D hybrid simulations of spheromak merging*

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Hybrid simulations of counter-helicity spheromak merging have been performed using the HYM code and compared with MHD and Hall-MHD simulations. The 2D hybrid simulations in the MHD-like regime, i.e. with relatively small thermal ion Larmor radius ρ_i/R_c~0.014 (R_c is the flux conserver radius), show remarkable difference compared to fluid results. It is found that for large resistivity (Lundquist number S~500), there are significant differences in reconnection rates and global spheromak dynamics. In particular, in the MHD runs, spheromaks move towards the midplane, and merge completely in about $10t_A$, whereas in hybrid simulations with the same plasma parameters, the spheromaks moved towards midplane initially, but then bounced back, and there was no complete reconnection. Unlike hybrid simulations, Hall-MHD simulations show global dynamics similar to that of MHD for these parameters. For lower resistivity with S~1500, the hybrid simulations show complete or nearly complete reconnection of spheromaks, and the FRC formation by $t\sim6t_A$, but the reconnection rates were much lower than in fluid runs. Comparison of results from hybrid simulations and MHD simulations shows thicker and shorter current layer in hybrid simulations. The hybrid simulations show an outward radial shift of the reconnection X-point which is related to generation of a quadrupole field, and has also been observed in 2D Hall-MHD simulations. Relatively large toroidal ion velocities up to $V_\varphi\sim2.5V_A$ are generated due to the 'sling-shot' effect both in fluid and kinetic simulations. Hybrid simulations also show much wider ion velocity profiles. Results of 2D and initial 3D hybrid simulations show that even in the MHD-like regime, there are significant differences between hybrid and MHD simulations of global reconnection, and demonstrate the need for a full kinetic description of plasma. These findings are in a sharp contrast with generally accepted paradigm that the inclusion of the Hall effects is sufficient to reproduce realistic reconnection rates of kinetic plasmas. Results of this study are also consistent with 2D full PIC and hybrid simulations of island coalescence, where it was found that fluid description including the Hall term does not describe reconnection in large systems correctly [1,2], unlike in the local current-sheet studies. It was shown that merging becomes increasingly ineffective for larger islands due to large gradients of the ion pressure tensor, broader ion diffusion region, and reduced outflow velocities [2], also demonstrating the importance of the kinetic ion description.

[1] H. Karimabadi, et al., PRL **107**, 025002 (2011); A. Stanier et al., PRL. **115**, 175004 (2015).
[2] J. Ng, et al., Phys. Plasmas **22**, 112104 (2015).

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Hall effect on flow structure in counter-helicity spheromak merging

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Counter-helicity spheromak merging[1] is an alternative method for forming a field-reversed configuration (FRC). The characteristic of the merging method is generation of strong toroidal sheared-flow due to magnetic reconnection of toroidal magnetic flux, and strong Hall effect in both merging[1] and relaxation[2] processes. For investigating the global Hall effect on formation of flow during merging process, we executed Hall-MHD simulation of merging counter-helicity spheromaks with various S* parameter (S* is the ratio of plasma characteristic length to ion skin depth). The simulation code adopts 2nd-order Adams-Bashforth scheme for time advancing, and 4th-order spatial central difference with 4th-order spatial smoothing (numerical diffusion). It was found that generated flow pattern in Hall-MHD cases were significantly different from that of MHD cases, and Hall current in downstream region of the magnetic reconnection generated the toroidal flow. In Hall-MHD case, negative toroidal flow is generated near the reconnection current sheet, and positive toroidal flow is generated in the downstream region by Hall current, while toroidal flow is generated at the edge of the current sheet in MHD case. The current sheet structure and flow acceleration region also changes with Hall parameter. We will talk about the characteristics of counter-helicity merging with the Hall effect.

References:

1. M. Inomoto *et al.*, Phys. Rev. Lett., **97**, 135002, (2006).
2. E. Kawamori and Y. Ono, Phys. Rev. Lett. **95**, 085003, (2005)

Asynchronous 3D HYPERS simulations of compact toroids and magnetoplasmas: spheromak merging, FRC formation, magnetized shocks, laser-produced plasmas and turbulence

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HYPERS (Hybrid Parallel Event-Resolved Simulator) is a dimension-independent (compile-time-configurable) quasineutral hybrid (fully kinetic ions and inertialess electrons) massively parallel code that scales to hundreds of thousands of processes and advances electromagnetic fields and particles asynchronously on time scales determined by local physical laws and mesh properties. To achieve high computational accuracy in complex device geometries, HYPERS employs high-fidelity Cartesian grids with masked (conductive) cells. The HYPERS model includes multiple ion species, energy and momentum conserving ion-ion collisions, and provides a number of approximations for plasma resistivity and vacuum regions. Both local and periodic boundary conditions are allowed. The HYPERS solver preserves zero divergence of magnetic field and utilizes the EMAPS (Event-driven Multiscale Asynchronous Parallel Simulation) technology that replaces time stepping with self-adaptive update events. As a result, local calculations are carried out only on an “as needed basis”. EMAPS (i) guarantees accurate and stable processing of physical variables in time accurate simulations, and (ii) eliminates unnecessary computation. This makes HYPERS a robust tool for modeling inhomogeneous plasmas with ion kinetic and Hall effects. The current capabilities of HYPERS are demonstrated on a number of applications of interest to fusion, space and astrophysical plasma physics. Future extensions to the asynchronous hybrid model are also discussed.

1. Spheromak merging

3D hybrid simulations of merging spheromaks indicate that a tilt-stable field-reversed configuration (FRC) can be achieved via fast merging and magnetic reconnection of spheromaks with opposite helicities. The simulations show that initially produced spheromaks must be delivered quickly enough to the collision point in order to avoid relaxation to the m=1 Taylor helix mode, which may lead to a severe loss of symmetry and ultimate disruption of the final FRC.

2. Theta-pinch formation of FRCs

The formation, spontaneous spin-up, and stability of theta-pinch formed field-reversed configurations have been studied self-consistently in 3D. The end-to-end hybrid simulations reveal poloidal profiles of implosion-driven fast toroidal plasma rotation and demonstrate three discharge regimes as a function of experimental parameters: the decaying stable configuration, the tilt unstable configuration, and the nonlinear evolution of a fast growing tearing mode.

3. FRC collisions with magnetic mirrors

Interactions of fast plasma streams and objects with magnetic obstacles (dipoles, mirrors, etc) lie at the core of many space and laboratory plasma phenomena ranging from magnetoshells and solar wind interactions with planetary magnetospheres to compact fusion plasmas. HYPERS simulations are compared with data from the MSX experiment (LANL) that focuses on the physics of magnetized collisionless shocks through the acceleration and subsequent stagnation of FRC plasmoids against a strong magnetic mirrors and flux-conserving boundaries.

4. Exploding magnetoplasmas

Results from hybrid simulations of two experiments at the LAPD and Nevada Terawatt Facility are discussed where short-pulse lasers are used to ablate solid targets to produce plasmas that expand across external magnetic fields. The first simulation recreates flutelike density striations observed at the leading edge of a carbon plasma and predicts an early destruction of the magnetic cavity in agreement with experimental evidence. In the second simulation a polyethylene target is ablated into a mixture of protons and carbon ions. A mechanism is demonstrated that allows protons to penetrate the magnetic field in the form of a collimated flow. The results are compared to experimental data and single-fluid MHD simulations.

5. Plasma turbulence

HYPERS simulations of externally driven plasma turbulence demonstrate the formation and evolution of coherent structures (current sheets) that play an important role in the dissipation of cascading energy. In the inertial range of scales magnetic spectra derived from hybrid simulations compare favorably with those from fully kinetic simulations. This match validates the hybrid model as a promising approximation for studying kinetic properties of large-scale (hundreds of ion inertial lengths) plasma turbulence.

Extreme ultra-violet bursts, particle heating, and whistler wave emission in fast magnetic reconnection induced by kink-driven Rayleigh-Taylor instability and measurements of forces, flows, and collimation in toroidal current channels

M. Haw, K. B. Chai, X. Zhai, and P. M. Bellan

We present two experimental investigations relevant to compact toroids:

1) We show experimental results observed when there is magnetic reconnection associated with a kink-driven Rayleigh-Taylor instability in a coaxial helicity injection source. The observations include i) a spatially localized energetic extreme ultra-violet (EUV) burst at the presumed position of fast magnetic reconnection associated with electron heating, ii) a circularly polarized high frequency magnetic field perturbation at some distance from the reconnection region indicating that the reconnection emits whistler waves, and iii) Doppler broadening of the plasma emission spectrum indicating ion heating.

2) We show 3D, time-dependent B-field measurements of a flared toroidal current channel. We observe significant axial JxB forces generating near-Alfvenic flows along the axis. These flows convect poloidal flux along the axis leading to collimation of the loop structure.

Topological Transition and Inductive Current Drive of a Translated Field-Reversed Configuration

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Because of its high-beta nature, effective additional heating technique for a FRC is primarily limited to a neutral beam injection. However, the FRC formed by a field-reversed theta-pinch (FRTP) method, the most effective formation technique of FRC, may not have enough poloidal flux to confine tangentially injected fast beam ions. In fusion experiments, center solenoid (CS) coil is widely employed in tokamak and RFP devices, while it requires torus-like plasma shape because the CS coil must locate inside of the plasma. There, topological transition of FRC from simply-connected to torus structure has been demonstrated for inductive current drive by a CS coil using the axial translation technique of FRC.

The series of experiments have been performed on the FAT facility at Nihon University. In the experiments, a “cantilever” CS with a conical point is installed on the geometrical axis of a quasi-spherical confinement region. The FRTP-formed FRC is translated into the confinement region with torus boundary at translation velocity in the range of Alfven velocity (100–200 km/s). Then it experiences a topological transition of magnetic configuration from a simply-connected to a torus structure. After this process, toroidal current is expected to be amplified by the loop voltage induced by applied CS current.

This dynamic translation/transition and poloidal flux amplification have been demonstrated successfully. The proposed technique may expand designing versatility of a FRC-based fusion reactor. Transiently observed toroidal magnetic field in the translated FRC will also be discussed.

Hybrid FRC equilibria with fully-kinetic ions and fluid electrons

Loren Steinhauer
Tri Alpha Energy

In view of large-orbit ions in field-reversed configurations (FRC), equilibria are poorly represented by fluid or even extended-fluid models. A realistic equilibrium requires, instead, a distribution function description of the ions. Moreover, since FRCs have a closed magnetic-field core, two ion populations are needed, one for ions more-or-less restricted to the *core* region, and those in the *periphery* that can access the open end. The latter have a probability of end loss whereas the former do not. While this distinction resembles the “inside” vs “outside” the separatrix regions in a fluid description, it is notably different since both “core” and “periphery” ions can invade, if only temporarily, the domain of the other.

The steady Vlasov equation governs the equilibrium distribution. In an axisymmetric electromagnetic field structure, the general solution is an arbitrary function of the two constants of motion: the Hamiltonian, namely the energy distribution, and the canonical angular momentum, related to toroidal rotation. The combined distribution embraces both core and periphery populations. The confinement boundary separating the two populations also happens to be a function of the constants of motion. Regarding Vlasov such solutions, only a small subset of them are realistic in view of collisions, which smooth the distribution, and instabilities, which reorganize the electromagnetic field structure. Both collisions and end loss can be accommodated by requiring the Vlasov solution to be roughly consistent with the demands of the Fokker-Planck (FP) equation. The Vlasov and FP formulations are very close if the collision frequency is low compared to dynamical frequencies.

Numerical construction of such equilibria requires solving both Ampere’s law for the magnetic flux function and the relatively ponderous task of a velocity-space integration at each point in space. The latter can be accommodated by the artifice of expressing the distribution function as the sum of simple “core” and “periphery” *elements* that have analytic moment integrals (e.g. density and current density). This is the case if the elements are truncated versions of the familiar rigid-rotor distribution. Moreover, summing of a small number of such elements gives the distribution function enough flexibility to access a broad range of realistic equilibria.

The foregoing procedure can be applied to plasmas with a combination of bulk ions as well as energetic beam ions resulting from neutral-beam injection. This merely adds a second ion distribution contributing to the current. The electrons, properly treatable as a fluid, also carry current, for which a simple model can be constructed. The numerical burden of computing such “hybrid” equilibrium is so modest as to take only a few seconds on an ordinary personal computer. The built-in flexibility of the distributions also allows the solver to “lock on” to routine observables in experiments. This allows rapid reconstruction of the evolving equilibrium in an experiment. Examples of such reconstructions will be presented.

Long-pulse operation of the PFRC-2 device

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Studies that resolve many time scales are important for understanding FRC physics. Perhaps the most difficult time scale to achieve is that of the classical inductive time, L/R, of the plasma. We have extended FRC plasmas to 300 ms, nearly 100x longer than the classical L/R, allowing studies of plasma stability and transport in a true steady state. Measurements of the time dependence of plasma density and electron temperature in long-duration plasma pulses were performed in the PFRC-2, a field-reversed-configuration device heated by odd-parity rotating magnetic fields at powers near 20 kW. Long-pulse operation is made possible by a set of eight high-temperature-superconductor BN-coated internal passive flux conserving rings, each with an inductive decay time of 1 sec and a critical current of 3 kA. With prefill hydrogen gas only, the line-average density rose to 2 x10^{12} cm^{-3} in less than 1 ms and the electron temperature typically reached 150 eV, as ascertained by X-ray emission. Under certain conditions the density decayed to near 0 in about 10 ms. Using a PV-10 gas valve modified to provide supersonic gas injection, we have found operational regimes where in-discharge fueling with a single 1-ms-duration hydrogen puff produced stable high density (2 x 10^{12} cm^{-3}) plasma discharges that persisted for 200 ms. Two or more 1-ms-duration gas pulses extended the pulse to in excess of 300 ms.

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Fast ion physics in the C-2U beam driven FRC

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and the TAE Team

In the C-2U experiment, a high beta field-reversed configuration (FRC) plasma with closed flux surfaces is embedded in a low beta, open-field line magnetic mirror plasma. Fast ions born from tangential neutral beam injection execute betatron-like orbits, sampling both regions of plasma as they orbit the magnetic axis. These large orbit particles sustain[1] and stabilize[2] the plasma and suppress turbulence.

Experimental evidence indicates that the fast ions in the FRC slow down classically via collisions with electrons. These fast ions accumulate in the core as they slow and exert a pressure on the mirror plasma comparable to the thermal plasma.

Measurements of magnetic fluctuations at the edge of the plasma, however, reveal the presence of multiple beam driven modes, indicating a non-classical interaction between the beam and the open field line plasma. These modes include a low frequency chirping mode, an Ion Bernstein-like mode, and a high frequency, compressional Alfven mode. Remarkably, none of these modes are observed to have a deleterious effect on global plasma confinement. In fact, the Bernstein mode has the beneficial effect of dramatically enhancing the DD fusion reaction rate by drawing a trail from the plasma ion energy distribution.

In this presentation, we experimentally characterize the fast ions in the C-2U FRC with data from multiple diagnostics including magnetics, spectroscopy, neutral particle analyzers and fusion product diagnostics. Results are compared to a particle-in-cell simulation in a simplified geometry.

[1] M. W. Binderbauer *et al.*, AIP Conference Proceedings **1721**, 030003 (2016).
[2] M. Tuszewski *et al.*, Phys. Rev. Lett **108**, 255008 (2012).

Two-fluid magnetic relaxation in RFPs and initial CT injection experiments at WiPAL

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US-Japan CT 2016 Workshop, Irvine, California

Experimental measurements in the MST device and nonlinear simulations with extended MHD models show the importance of two-fluid effects in magnetic relaxation, a key mechanism in the self-organization of RFP plasmas. In standard RFP experiments with a steady applied loop voltage in MST, both parallel current density and parallel flow equilibrium profiles are observed to relax concurrently with large bursts of magnetic fluctuations during quasiperiodic sawtooth crashes. The magnetic relaxation is due to a dynamo-like EMF generated by the nonlinear interactions of multiple tearing modes. In two-fluid MHD, this is expressed via a mean-field generalized Ohm's law including the fluctuation-induced EMF terms called the MHD and Hall dynamos. A Hall-like term also appears as a Maxwell stress in the mean-field parallel momentum equation (where it is accompanied by a Reynolds stress term), coupling magnetic relaxation to flow relaxation. Although single-fluid MHD simulations (Reusch et al., PRL 2011) reproduce the qualitative dynamical behavior of the magnetic equilibrium and fluctuations and the durations of sawtooth periods, the predicted magnetic fluctuation amplitudes are about twice as large as in the experiment. Additional effects, such as the Hall term and ion gyroviscosity used in extended MHD simulations (King et al., POP 2012) with the NIMROD code, might resolve such discrepancies. In MST, recent probe measurements of the Hall EMF for $r/a>0.6$ show a complex radial profile, similar to the results of recent nonlinear simulations of extended MHD with NIMROD.

CT injection experiments have recently been started at the Wisconsin Plasma Astrophysics Laboratory (WiPAL) by D. Endrizzi, C. Forest, and coworkers. With support and loaned equipment from the CT injection team at Tri Alpha Energy, Inc. and Nihon University (see, for examples, I. Allfrey et al., T. Matsumoto et al., T. Roche et al., APS-DPP 2015), the WiPAL team has begun injecting CTs into the 3 m diameter MPDX spherical vacuum vessel with and without background plasmas and with and without applied background magnetic fields. Initial results and preliminary analyses of these tests are presented.

Evaluation of CT injection to RFP for performance improvement and reconnection studies

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RELAX [1]（R/a=0.5m/0.25m, A=2, I_p~100kA、$T_e(0)$~100eV、n_e~10^{19}m^{-3}） is a reversed field pinch (RFP) machine whose research objectives include optimization of RFP geometry such as aspect ratio [1]. Some of the characteristic features of the equilibrium configuration have been described in ref. [2-4] in connection with the low-aspect-ratio nature of the machine. Feedback stabilization of a resistive wall mode (RWM) using saddle coils has resulted in improved plasma performance particularly in realizing discharge duration limited by the iron core saturation [5]. It has been found that we need further effort to reduce toroidal loop voltage particularly in the current rise phase for further improvement of the plasma performance. We will discuss the CT injection technique as a possible means for helicity injection to save flux consumption, and for fueling in RELAX.

[1] S. Masamune et al., JPSJ 76, 123501 (2007).
[2] R. Ikezoe et al., PPCF 53, 025003 (2011); R. Ikezoe et al., PPCF 55, 015005 (2013).
[3] K. Oki et al., PFR 7, 1402028 (2012); K. Oki et al., Fusion Sci. Technol. 63 (1T) 386 (2013).
[4] T. Onchi et al., JPSJ 80, 114501 (2011); K. Nishimura et al., RSI 85, 033502 (2014).
[5] H. Tanaka et al., PFR 9, 1302057 (2014); R. Ueba et al., PFR 9, 1302009 (2014).

CT2016 Workshop

Wednesday, August 24, 2016

Hotel Irvine – Theater Room

Session 5: Spheromak-2, Helicity injection & Flow

Session 6: FRC-2, Spheromak-3 & Compact Toroids

Sustainment of stable spheromaks with imposed-dynamo current drive

A. C. Hossack, T. R. Jarboe, K. D. Morgan, D. A. Sutherland, C. J. Hansen, C. J. Everson, J. M. Penna, B. A. Nelson, *University of Washington*

Inductive helicity injection current drive with imposed perturbations has led to the breakthrough of spheromak sustainment while maintaining stability. Sustained spheromaks show coherent, imposed plasma motion and low plasma-generated mode activity. Additionally, record spheromak current gain of 3.9 has been achieved with evidence of pressure confinement. The Helicity Injected Torus - Steady Inductive (HIT-SI) experiment studies efficient, steady-state current drive for magnetic confinement plasmas using a novel experimental method which is ideal for low aspect ratio, toroidal geometries and is compatible with closed flux surfaces. Analysis of surface magnetic probes indicates large $n = 0$ and 1 toroidal Fourier mode amplitudes and little energy in higher modes. Biorthogonal decomposition shows that almost all of the $n = 1$ energy is imposed by the injectors, rather than plasma-generated[1]. Additionally, much of the remaining nonaxisymmetric mode energy is part of the 3D equilibrium. Ion Doppler spectroscopy (IDS) measurements[2] show coherent, imposed plasma motion of ±2.5 cm in the region inside $r \approx 10$ cm ($a = 23$ cm) and the size of the separate spheromak is consistent with that predicted by Imposed-dynamo Current Drive (IDCD)[3]. Coherent motion indicates that the spheromak is stable and a lack of plasma-generated $n = 1$ energy indicates that the maximum q is maintained below 1 for stability during sustainment. Results from the HIT-SI3 experiment will also be presented. With three helicity injectors on one side of the flux conserver, the imposed mode spectrum can be varied to include $n = 2$ and 3 energy in addition to $n = 1$.

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[1] B. S. Victor *et al*., Phys. Plasmas **21**, 082504 (2014).

[2] A. C. Hossack, Ph.D. thesis, University of Washington (2015).

[3] T. R. Jarboe *et al*., Nucl. Fusion **52**, 083017 (2012).

Experimental results from the SPECTOR device at General Fusion

Stephen Howard, Michel Laberge, Russ Ivanov, Peter O'Shea, Ken Jensen, Adrian Wong, Curtis Gutjahr, Patrick Carle, William Young, Neil Carter, Ryan Zindler, Alex Mossman, Meritt Reynolds, Aaron Froese. *General Fusion Inc, Burnaby, British Columbia, Canada.*

Abstract

General Fusion (GF) is operating a new sequence of plasma devices called SPECTOR (**Sp**h**e**rical **C**ompact **Tor**oid) capable of generating and compressing plasmas with a more spherical form factor, avoiding the concave liner geometry used on previous compression tests at GF. SPECTOR forms spherical tokamak plasmas by coaxial helicity injection into a flux conserver (R= 19 cm, $\lambda_{Taylor} = 23.9$ m^{-1}, minor radius of 8.3 cm) with a pre-existing toroidal field created by $\leq$ 500 kA of current in an axial shaft. The initial poloidal flux of up to 30 mWb and toroidal plasma current of 100 - 300 kA is formed rapidly in the spherical flux conserver during a Marshall gun discharge (850 kA peak, 90 μs duration), and then resistively decays over a time period of ~1.5 ms. SPECTOR 1 has an extensive set of plasma diagnostics including a surface magnetic probe array, 3 interferometer chords, visible and VUV spectroscopy, multi-point Thomson scattering as well as a 4-chord FIR polarimeter system in development. SPECTOR 2, 3 are mobile test platforms that can be transported out of the lab for compression tests. Plasma facing surfaces include plasma-sprayed tungsten and bare aluminum, and can be coated with ~5 μm of vacuum deposited lithium for the purpose of gettering impurities out of the base vacuum and to reduce the gas recycling coefficient of the wall. Working gas has included helium and deuterium. Experimental characterizations have been made of formation dynamics, MHD mode activity, evolution of plasma profiles during its lifetime, and trends in FWHM magnetic lifetime with respect to system control parameters. Control of safety factor profile $q(\psi)$ can be achieved through a choice of the amount and axial distribution of poloidal gun flux and the amount of shaft current. Grad-Shafranov equilibria are reconstructed from the surface magnetic data using Caltrans/Corsica. Ideal and resistive MHD stability can be tested with DCON and NIMROD over a range of pressure and current profile parameters. Realistic compression scenarios have been simulated using the 3D MHD code VAC. The SPECTOR geometry is stable for a wider range of plasma parameters than previous experiments at GF. Relatively hot ($T_e \geq 350$ eV) and dense (~10^{20} m^{-3}) plasmas have achieved energy confinement times $\tau_E \geq 100$ μs and are now ready for field compression tests.

Multiple plasmoid formation and flux closure during transient-CHI start-up process on HIST

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The transient-Coaxial Helicity Injection (T-CHI) current drive without requiring for dynamo is a promising candidate for the non-inductive plasma start-up on Spherical Torus (ST). So far, the T-CHI method was successfully applied for HIT-II, NSTX and HIST devices[1, 2]. The flux closure during the short-time T-CHI process in ST is one of significant research issues that connect with the physics of fast magnetic reconnection. The recent MHD simulation[3] on T-CHI for NSTX predicts the formation and breakup of an elongated Sweet-Parker (S-P) current sheet and a transient to plasmoid instability. According to this simulation, the reconnection rate based on the plasmoid instability is faster than that by the S-P model and becomes nearly independent of the Lundquist number S. In this workshop, we will report the formation of multiple X-points (plasmoids) in the elongated current sheet has been observed in the T-CHI start-up on HIST.

The flux closure of T-CHI plasmas in the presence of the toroidal (guide) field have been measured by using the 2D internal magnetic probe arrays. The stronger toroidal magnetic field makes plasma less compressible and ion sound gyro-radius smaller, leading to slower reconnection time and longer current sheet even if the plasma resistivity is high. The long and thin current sheet in large size systems is unstable to the tearing mode. Recent experimental observation shows that two or three plasmoids are generated in the elongated current sheet with the narrow width comparable to the ion skin depth or the ion sound gyro-radius. We have measured the electron density and temperature profiles inside the current sheet by using the double electrostatic probes in order to estimate the S value. The one of plasmoids develops to a large-scale flux structure (closed flux) during the decay phase because the injected current diffuses into the plasmoid from the edge of the central open flux column. These findings indicate that the plasmoid instability in the elongated current layer in the presence of the guide field allows the formation of X-points and the fast flux closure via fast magnetic reconnection during the T-CHI start-up.

1) R. Raman *et al*., Phys. Rev. Lett. **104**, 095003 (2010).
2) T. Hanao *et al*., Plasma and Fusion Research **11**, 1402001 (2016).
3) F. Ebrahimi and R. Raman, Phys. Rev. Lett. **114**, 205003 (2015).

A field theory approach to plasma self-organization

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Self-organization is concerned with the spontaneous emergence of large-scale structures in physical systems. A fundamental conjecture, borrowed from the mathematics of topology, is the invariance of a global property during the process of self-organization: for example, a system relaxes to reduce energy constrained by a constant value of the helicity of the canonical momentum. This paper [1] presents a unifying field-theory framework that reformulates the single-particle, kinetic and fluid equations governing plasma dynamics as a single set of generalized Maxwell's equations and Ohm's law for canonical force-fields. The new Lagrangian includes terms representing the coupling between the motion of particle distributions, between distributions and electromagnetic fields, with relativistic contributions. The formulation shows that the concepts of self-organization and canonical helicity transport are applicable across single-particle, kinetic, and fluid regimes, at classical and relativistic scales. The framework shows that a species' canonical helicity is well conserved compared to the species' energy in shallow density gradients but not in steep density gradients (in the simplest case of an isolated, dissipative system). These results suggest that in the edge of multi-species, collisionless, kinetic plasmas, magnetic helicity can couple to ion canonical helicity, spontaneously generating flowing structures when density gradients are of the order of the ion skin depth. This field theory approach to helicity and energy evolution suggests that electrical engineering methods used for analyzing magnetostatic configurations can be extended to flowing magnetized (or non-magnetized) plasmas and flowing neutral fluids with finite vorticity. The driving circuits can be any combination of gravitational, pressure, kinetic or electrical supplies since these power supplies are simply enthalpy sources for a canonical Maxwell cicuit. This work is supported by by US DOE Grant DE-SC0010340.

[1] S. You, Phys. Plasmas, **23**, 072108 (2016)

Investigating the Dynamics of Canonical Flux Tubes

JENS VON DER LINDEN, University of Washington, JASON SEARS, Lawrence Livermore National Laboratory, ALEXANDER CARD, ERIC LAVINE, MANUEL AZURA-ROSALES, EVAN CARROLL, University of Washington, THOMAS INTRATOR†, Los Alamos National Laboratory, SETTHIVOINE YOU, University of Washington

Canonical flux tubes are flux tubes of the circulation of a species' canonical momentum. They provide a convenient generalization of magnetic flux tubes to regimes beyond magnetohydrodynamics (MHD). We hypothesize that hierarchies of instabilities which couple disparate scales could transfer magnetic pitch into helical flows and vice versa while conserving the total canonical helicity. This work first explores the possibility of a sausage instability existing on top of a kink as mechanism for coupling scales, then presents the evolution of canonical helicity in a gyrating kinked flux rope. An analytical and numerical stability space is derived by applying Newcomb's variational approach to idealized magnetic flux tubes with core and skin currents. The stability conditions indicate that as a flux tube lengthens and collimates, it may first become kink unstable, then a sausage may develop on top of the kink. A new analysis of 3D magnetic field and ion flow data on gyrating kinked magnetic flux ropes from the Reconnection Scaling Experiment tracks the evolution of canonical flux tubes and their helicity. These results and methodology are being developed as part of the Mochi experiment specifically designed to observe the dynamics of canonical flux tubes.

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LLNL-ABS-698041

† Deceased 3 June 2014

Accelerated Taylor State Plumes on SSX

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The typical plasma parameters of the Taylor plumes* in the SSX plasma wind tunnel are as follows: density $\approx 10^{15}\ cm^{-3}$, ion temperature $\approx 20\ eV$ and velocity $\approx 30 - 100\ km/s$. For producing a high velocity dense plasma, the Taylor plumes will be accelerated to over 100 km/s using pulsed theta pinch coils and will further be compressed to $10^{16}\ cm^{-3}$ using a stagnation flux conserver. For accommodating the pulsed theta pinch coils, the SSX device is modified by the addition of a 1 m long glass extension. In this configuration, the Taylor plumes are launched from a magnetized plasma gun and are allowed to flow to the main expansion volume downstream of the glass extension tube. The time of flight (TOF) measurements of these plumes are carried out during their passage through glass tube using a linear array of $\dot{B}$ probes (separated by 10 cm). With the glass boundary, the typical velocity of the unaccelerated Taylor plumes from TOF is found to be 25 km/s, accompanied by a fast plasma (50 km/s) at the leading edge. Magnetic field of the Taylor plumes in the expansion chamber is measured using a three-dimensional array of $\dot{B}$ probes and is found to be 700 G. The proton density of the plumes is measured in the expansion volume using a precision quadrature HeNe laser interferrometer and is found to be $\approx 6 \times 10^{14}\ cm^{-3}$. Ion temperature will be measured using a fast time response high resolution spectrograph which makes use of an echelle grading and a 32-channel photomultiplier tube to analyse the line shape of C III (impurity) ion at 229.687 nm. Some flux conservation of the Taylor plumes is provided by using a resistive liner (soak time = 3 μs) and a mesh flux conserver(soak time = 170 μs > discharge time) around the glass tube for improving the downstream Taylor state velocity, density and magnetic field. The results from all these different boundary conditions will be presented.

Work supported by DOE OFES and ARPA-E ALPHA programs.

*Gray, et al, PRL **110**, 085002 (2013).

PIC Simulation of thermal distribution driven non-Maxwellian by neutral-beam injection in a high beta plasma

A. Necas, R. Magee, B.S. Nicks, T. Tajima, and the entire TAE Team

Intense beam driven FRCs are the central focus of TAE's C-2U program [1]. It had been known that beam injection can stabilize some macro-instabilities such as the tilt mode and drift instabilities [2, 3]. In addition, in C-2U we now observe that intense beam drive (i) can excite robust kinetic micro-instabilities, (ii) causes no global plasma destruction, and (iii) can enhance the D-D fusion reactivity. These observations led to a new hypothesis beyond the large orbit paradigm: the robustness of waves with a high phase velocity and its consequences. This hypothesis shares the same philosophy as wakefield excitations [4]. To study the experimental behavior theoretically, we simulate beam-driven micro-instabilities that are non-destructive, but transfer energy from fast ions to the plasma, causing phase space bunching. Such a mechanism may explain an experimentally observed anomalous neutron signal (10–100× the predicted thermonuclear fusion yield), as other explanations have been eliminated (D in the beams, fast-thermal ion head-on collisions, and misinterpretation of T_i). We propose that the injected intense hydrogen beams generate an energetic ion population that then drives collective modes in the plasma, giving rise to an instability and increased fusion rate. A 1D3V PIC code [5] is used to simulate beam-plasma interactions and a two-body correlation function is employed to determine the computational D-D reactivity enhancement. Modifying the experimentally injected beam distribution supports this theory.

[1] M.W. Binderbauer et al., Phys. Plasmas **22**, 056110 (2015).
[2] N. Rostoker et al., "Physics of High Energy Particles in Toroidal Systems", eds. T. Tajima and M. Okamoto (AIP, NY 1994), p. 323.
[3] H. Naitou, T. Kamimura, and J.M. Dawson, J. Phys. Soc. Jpn. **46**, 258 (1979).
[4] T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[5] T.D. Arber et al., Plasma Phys. Control. Fusion **57**, 11 (2015).

Extracting electron energy distributions from PFRC X-ray spectra

Charles Swanson
Princeton Plasma Physics Laboratory

The PFRC is an odd-parity Rotating Magnetic Field (RMF) driven Field-Reversed Configuration plasma confinement experiment equipped with Si-PIN and SDD x-ray detectors. It is predicted that the electron energy distribution is non-thermal when the RMF is active. Using a novel Poisson-regularized inversion technique, we present full electron distribution functions as obtained ("spectrally inverted") from the x-ray Bremsstrahlung emissions. We present the results of high-power, long-pulse FRCs with measured temperatures of 50 eV – 150eV.

Design Point for a 1 MW Fusion Neutron Source

Paul Sieck, Simon Woodruff, Paul Melnik, James Stuber

Woodruff Scientific Inc.

Carlos Romero-Talamas, John O'Bryan

University of Maryland, Baltimore County

Ronald Miller

Decysive Systems

We are developing a design point for a spheromak experiment heated by adiabatic compression for use as a compact neutron source. Compact fusion neutron sources are currently serving important roles in medical isotope production and could be used for waste transmutation if sufficient fluence can be attained.

We use the CORSICA and NIMROD MHD codes as well as analytic modeling to assess a concept with target parameters R_0=0.3m, R_f=0.1m, T_0=0.2keV, T_f=1.8keV, $n_0=10^{19}m^{-3}$, and $n_f=10^{21}m^{-3}$, with radial convergence of $C=R_0/R_f=3$. These parameters are selected to achieve a target rate of 10^{19} n/s. We present results from CORSICA showing placement of the coils and passive structure to ensure stability during compression. Simulations of magnetic compression are in progress, using the NIMROD code to examine the role of rotation on the stability and confinement of the spheromak as it is compressed.

The power supplies consist of 4 separate banks of 2 MJ each; Pspice simulations and power requirement calculations will be shown. We outline the diagnostic set that will be required for an experimental campaign to address issues relating to both formation efficiency and energy confinement scaling during compression.

Work supported by DARPA grant N66001-14-1-4044 and IAEA CRP on compact fusion neutron sources.

Numerical investigation of design and operational parameters on CHI spheromak performance

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(University of Maryland, Baltimore County)

S. Woodruff, J.E. Stuber, C. Bowman, P.E. Sieck
(Woodruff Scientific, Inc.)

Nonlinear, extended-MHD computation with the NIMROD code is used to explore magnetic self-organization and performance with respect to externally controllable parameters (e.g. bias flux and injector current trace) in spheromaks formed with coaxial helicity injection. The goal of this study is to inform the design and operational parameters of proposed proof-of-principle spheromak experiment. The calculations explore multiple distinct phases of evolution—initial formation, relaxation/sustainment, and adiabatic magnetic compression—which must be explored and optimized separately. Our results indicate that modest changes to the design and operation of past experiments, e.g. SSPX [E.B. Hooper et al. PPCF 2012], could have significantly improved the plasma-current injector coupling efficiency and performance, particularly with respect to peak temperature and lifetime. Though we frequently characterize performance relative to SSPX, we are also exploring fundamentally different designs and modes of operation, e.g. flux compression.

This work is supported by DAPRA under grant no. N66001-14-1-4044.

Compact Toroid Injection into C-2U FRCs for Particle Refueling

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Hiroshi Gota[2], Toshiki Tajima[2,3] and the TAE Team[2]

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The compact toroid (CT) injector system [1] has been developed for the C-2U device [2] under the joint collaboration between Nihon University and Tri Alpha Energy (TAE) for several years. The first CT injector for a field-reversed configuration (FRC) particle refueling was deployed on the C-2 device at TAE.

Sustainment times of the FRC have exceeded 5 ms in C-2U. In long-lived FRCs, particles loss becomes a problem. Thus, the FRC needs a particle refueling system. As a particle refueling system, we have been developing the magnetized coaxial plasma gun (MCPG), which has coaxial electrodes. The MCPG accelerates the CT/plasmoid by Lorentz-force **J×B**. The CT reaches velocities such that it has a higher kinetic energy density than C-2U's magnetic field energy density; i.e., $\frac{1}{2}\rho v^2 \geq \frac{1}{2}B^2/\mu_0$, where ρ, v, and B are mass density of the CT, velocity, and magnetic field inside the C-2U confinement vessel. We have 2 CT injectors mounted on the confinement vessel around mid-plane, and they can be operated independently. They are installed on C-2U 180 degrees apart, slightly off-axis, and angled such that the injected CTs' trajectories intersect at the center of the confinement vessel. In order to refuel the FRC intermittently, a multi-pulse CT injection system is needed. Therefore, we have started to develop such system over the previous year [3]. Our multi-pulse CT injection system can inject 2 CTs with as little as 1 ms delay between them by using two capacitor banks on the MCPG. Using this technique, we are able to inject 3 CTs in a single shot. Furthermore, the CT injector needs a large amount of neutral gas to breakdown, and the neutral gas becomes a trailing gas that enters the confinement vessel; Thus, FRC is cooled down by the neutral gas. Therefore, we have developed a Pre-Ionization (PI) system to reduce the neutral gas as well as to improve a reliability of the MCPG breakdown.

In this talk, we will present the result of CT injection into C-2U, and the new techniques developed for the CT injector.

[1] T. Matsumoto *et al.*, Rev. Sci. Instrum. **87**, 053512 (2016).
[2] M. Binderbauer *et al.*, Phys. Plasmas **22**, 056110 (2015).
[3] I. Allfrey *et al.*, Bull. Am. Phys. Soc. **60**, BP12.00024 (2015).

MHD and Hybrid Simulation Study of FRC Plasmas

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T. Matsui[1], N. Mizuguchi[2], and T. Asai[3]

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3) College of Science and Technology, Nihon University, Tokyo, Japan

Field-reversed configuration (FRC) plasmas are extremely high-beta torus plasmas and those exhibit strong MHD activities. Experimental results of FRC plasmas sometimes are inconsistent with an MHD prediction for such as tilt mode stability; it implies that particle effects dominate FRC stability properties. Therefore, MHD and non-MHD natures can probably coexist in high-beta self-organized plasmas. Here, we will present simulation results for FRC plasmas of 1) translation and subsequent collision process, 2) poloidal flux amplification by neutral beam injection, and 3) spontaneous toroidal spin-up.

In the present abstract, we will show the MHD simulation result for collision process of two FRC plasmas. The obtained axial forces in the reconnection region are presented in Fig. 1, where the 2D profile is plotted on the top and the 1D axial profile on the field-null surface is shown on the bottom. We found from the bottom figure that an attracting force is acting on the plasma core and a repulsive force however is acting on the colliding front surface. Therefore, this repulsive force inhibits a merging process. Resultantly, we never observed the complete merging that unifies the two field-null points. We are now developing a 3D hybrid simulation code and plan to complete until next fiscal year to compare the results from different calculation models.

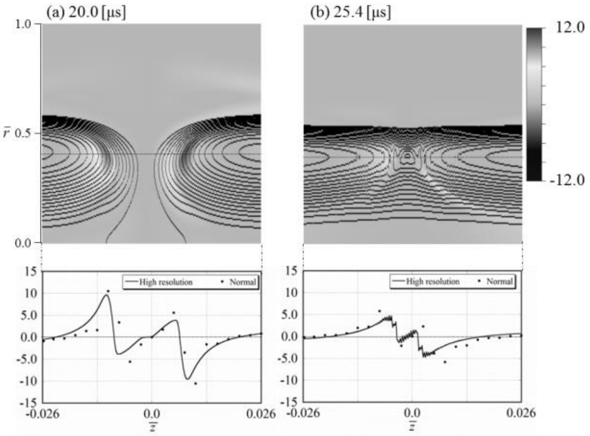


Fig. 1. (Top) 2D axial force profile in refined mesh region, (bottom) 1D axial force profile on a surface having the field-null points.

Author / Abstract Index

April 13, 2016

"Second Announcement"

2016 US-Japan Workshop on Compact Tori

Equilibrium studies and novel applications of compact toroids based on innovative confinement techniques: The future of Compact Tori

August 22–24, 2016
At the Hotel Irvine, Irvine, CA

Dear Colleagues:

Every other year the US or Japan host the Compact Toroid (CT) workshop series on alternate sides of the Pacific, a series that has continued for many years. This year is the turn of the US to host the event. We are pleased to make our second announcement for this year's workshop to be held in Irvine, CA on Aug. 22–24, 2016.

We would like to welcome your participation and possible presentation. The workshop objectives are to discuss equilibrium studies as well as applications of CTs and other innovative confinement concepts that share basic physics and/or experimental techniques with CTs. The future of compact tori will also be discussed.

A website of the CT2016 workshop is now open at the University of California, Irvine:
http://www.physics.uci.edu/US-JAPAN-CT2016/

Subpages on the workshop website such as Registration, Program/Abstracts, Lodging, etc. will also be updated shortly. You will be able to reserve a hotel room at a discount rate of $149 per night via the Hotel Irvine website (a special link will be provided shortly).

Workshop registration fee for a regular participant is currently estimated to be about $350, and $250 for students; this fee includes a banquet dinner and morning/afternoon coffee breaks.

Important Dates

Response for Participation	Deadline – May 10, 2016
Registration and Payment	Deadline – July 22, 2016
Hotel Reservation	Deadline – July 22, 2016
One-page Abstract Submission	Deadline – August 8, 2016
Workshop Dates	August 22–24, 2016

For any scientific/general inquiries please feel free to contact us via email at CT2016@uci.edu. For those of you who need an official letter of invitation to obtain a US visa or travel approval, please let us know at your earliest convenience.

Looking forward to hearing from you.

Sincerely yours,

Toshi Tajima
University of California, Irvine
ttajima@uci.edu

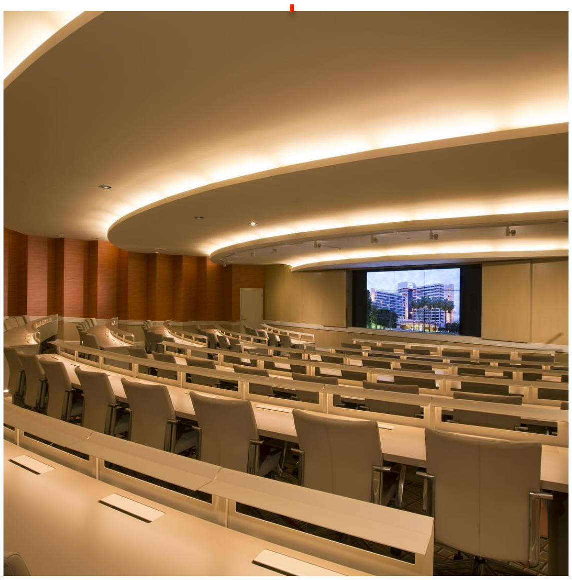
Hotel Irvine

Workshop Room: Theater

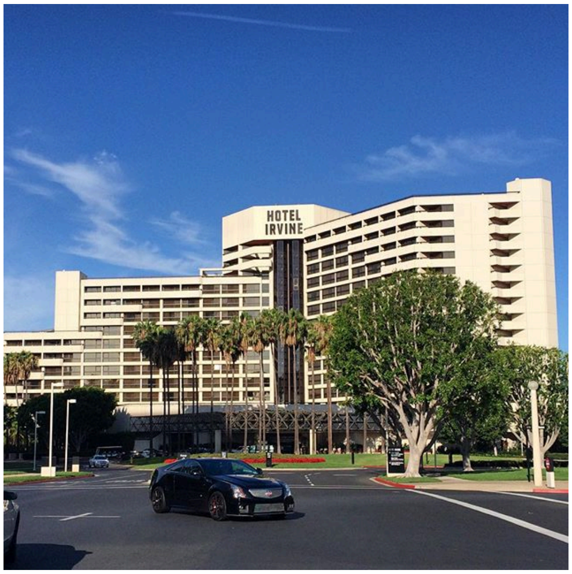
Banquet & Reception: Trabuco & Terrace

Wi-Fi: User Name – ct2016; Password – irvine

Hotel Map



Theater Room



Hotel Irvine