Abstract: We will review the role compact torus (CT) research has played in the OFES portfolio and propose a vision for the future for CT research within the Discovery Science program element. The current status of the program will be reviewed and priorities for the future in the ITER era will be discussed. First, CT research has been instrumental in studies of fundamental plasma science. The CT is a simple but non-trivial high-\( \beta \) plasma configuration that exhibits a wide variety of interesting kinetic and MHD behavior. These include fundamental phenomena such as plasma relaxation (of both spheromaks and FRCs), reconnection (from merging CTs), and turbulence (both MHD and kinetic). Second, CT research has played and will continue to play an important auxiliary role in fusion energy science research. These research contributions (falling within the Burning Plasmas: Foundations element) include helicity injection (as is now implemented on NSTX, for example) and non-disruptive central tokamak fueling by CT injection (as demonstrated on the TdV tokamak). Third, CT research facilities have been and will continue to be a productive training ground for students and postdocs. Over 40 undergraduate scientists have received their introduction to experimental plasma research at the SSX facility. Similar numbers have been trained on the PFRC and other CT facilities. Graduate students and postdocs currently working on OFES-funded projects got their start in the Bellan group at Caltech. Finally, we will propose priorities, initiatives, and ideas in CT research for the coming 10 years prior to the launch of ITER.

1 Introduction

A compact torus (CT) is a simply connected (i.e. topologically spherical), translatable, axisymmetric, high \( \beta \) magnetic plasma configuration that has been studied in a number of forms for over 50 years [1, 2]. The two principal members of the CT family are the spheromak and field-reversed configuration (FRC). A spheromak has both toroidal and poloidal magnetic fields with current flow parallel to the magnetic field (\( J \parallel B \)), with \( \Phi_{pol} \sim \Phi_{tor} \), and has \( \beta \sim 0.1 \). A spheromak typically has near unity aspect ratio. Spheromaks have been thoroughly reviewed in the book by Bellan [3]. An FRC has only
poloidal magnetic fields with current flow perpendicular to the magnetic field ($J \perp B$), and has $\beta \sim 1$. FRCs are typically highly prolate. Extensive reviews of early FRC experiments were presented by Tuszewski in 1988 [4] and of theoretical work by Steinhauer in 2011 [5].

![Diagram of FRC and spheromak configurations](image)

Figure 1: FRC configuration and spheromak configuration (from Figure 6 of ReNew [13])

In 1979, Rosenbluth characterized the stability of the spheromak (and coined the name) [6]. In the early 1980’s, spheromaks were fielded at Los Alamos (CTX) [7], Princeton (S1) [8], Livermore (Beta-II) [9], Maryland [10], among other laboratories. Similarly, FRCs were fielded at Los Alamos (FRX-C) [11] and Washington (LSX) [12]. Peak parameters for both FRCs and spheromak include $T_i \geq T_e \sim 0.5$ keV, $B \sim 1$ T, $n_e \sim 10^{20–21}$ m$^{-3}$.

The modern role of CTs was reviewed in the ReNew document in Theme 5 (Optimizing the magnetic configuration, p. 175) [13]. The emphasis in ReNew was the development of a CT reactor. From p. 213 of ReNew, “The mission of Compact Torus (CT ) research is to: Develop a compact magnetic fusion reactor without toroidal field coils or a central solenoid.” Some of the issues discussed include stability at large-$s$ for the FRC ($s \sim R_{FRC}/\rho_i$), and sustainment for the spheromak. Similarly, the FESAC Toroidal Alternates Panel report (TAP) states as a goal, “to demonstrate that a CT with a simply connected vessel can achieve stable, sustained or long pulsed plasmas at kilovolt temperatures, with favorable confinement scaling to proceed to a pre-burning CT plasma experiment.” Finally, Thrust 18 in ReNew (p. 379) is to “achieve high-performance toroidal confinement using minimal externally applied magnetic field.”

While these are admirable goals, we feel that in the near term pre-ITER era, the role of CTs will be in the Discovery Science realm with some aspects in the Foundations element of the restructured OFES as we discuss below.
It is notable that a large scale spheromak (SSPX at LLNL [14]) and a large scale FRC (TCS/LSX-mod at RPPL [15]) have been recently shut down.

2 Current status of the CT community 2014

Here we summarize the current state of the CT community (2014). Our work falls largely in the realm of Discovery Science including fundamental work on magnetic reconnection, turbulence, and relaxation physics. Some of our work is in the area of Foundation Science including understanding magnetic helicity injection, and CT fueling of tokamaks. In these smaller devices, our plasma densities range from $10^{18} - 10^{21} \text{ m}^{-3}$ with temperatures up to $T = 40 \text{ eV}$. Internal magnetic fields range up to 0.5 $T$. Importantly and because of the inherent translatability of CTs, flow speeds in many of these configurations exceed 100 $km/s$.

**Brown:** The SSX facility at Swarthmore is designed to merge and accelerate CT plasmas in order to study magnetic reconnection, relaxation, and turbulence. It has been in operation since 1994. Merging CTs in SSX exhibit a period of magnetic reconnection and relaxation followed by the observation of self-organized helical states in short cylindrical boundaries [16], as well as relaxed twisted Taylor states [17] in very long cylinders [18]. The SSX device is presently configured as a MHD plasma wind tunnel to study fundamental processes of turbulent relaxation [19].

![SSX MHD wind tunnel configuration. Shown is a simulation image using HiFi (Lukin) and placement of probes.](image)

**Bellan:** The solar simulation facility at Caltech uses CT plasmas to study processes relevant to solar and space physics. A coaxial plasma gun has been used to study the kink instability and subsequent poloidal flux amplification in an expanding CT plasma [20]. Experiments on a solar prominence two-electrode configuration showed that magnetically driven flows enabled collimation of magnetic flux tube structures [21, 22]. In a recent experiment, it was shown that the previously observed large scale kink instability could drive a small scale Rayleigh-Taylor instability [23].
Cohen: The PFRC facility at PPPL uses rotating magnetic field (RMF) current drive to sustain FRC plasmas up to 0.25 s duration. Experiments have demonstrated the formation of collisionless high-β plasmas by odd-parity RMF [24], and demonstrated excellent agreement with PIC simulations performed with the Lsp code [25]. In addition, plasma heating during RMF has been modeled [26]. A set of eight high-$T_c$ superconductors (BSCCO clad with BN) are used for long life-time flux conservers.

Hwang: The CTIX plasma accelerator at UC Davis [27] uses high velocity CTs to refuel or quench tokamak plasmas. Nondisruptive, central fueling was first demonstrated in the TdV tokamak by the injection of an accelerated CT [28]. The tokamak particle inventory increased by more than 30% without disruption. Since then CTs formed from non-recycling high-Z species have been studied for runaway electron cooling during tokamak disruption. Pure deuterium and tritium ions are useful for central fueling [29] while ions of higher atomic number (Z) have been shown theoretically to radiatively cool high-energy electron by the radiative and bremsstrahlung processes [30]. Conveniently, CTs of high atomic number can achieve high kinetic energy density at relatively low velocities compared to hydrogen CTs. This simplifies the design of a CT injector used for runaway electron suppression, as the penetration requirements can be satisfied with a CT injector.
operating at relatively slow time scales.

Figure 5: CTIX experiment at UC Davis. CT plasmas are accelerated to > 100 km/s for central tokamak fueling and disruption mitigation.

**Belova:** The Belova group has modeled FRC plasmas using the HYM framework. The HYM framework has a single-fluid MHD component, as well as two-fluid and hybrid options. She has modeled the tilt stability of prolate FRCs [31] as well as the formation, ion spin-up and nonlinear stability properties of FRCs in a collaboration with the SSX group [32].

**Jarboe:** The HIT and HIT-SI experiments at U Washington explore helicity injection into CT configurations. Over 150 kA of toroidal current was injected into the HIT device using DC coaxial helicity injection [33]. In the present configuration of HIT-SI, toroidal current is injected via steady state inductive (SI) helicity injection [34]. Toroidal currents up to 40 kA have been driven on HIT-SI.

We are a dynamic, responsive, and scientifically productive community. Our flexibility enables us to field ideas quickly. Our small devices can address scientific issues quickly and affordably (we employ the phrase “smarter not bigger”). For example, on the SSX experiment, a number of flux conserving boundaries (e.g. prolate, oblate) have been tried with turn-around times of a month or less. The Caltech experiment has fielded a number of helicity injection gun sources (e.g. planar, coaxial, bipolar). The PFRC facility at PPPL employs high $T_c$ superconducting loops in order to provide long-time flux conservation. We are a community willing to take risks. We are the paradigm of single investigator plasma research.

Finally, and importantly, we offer an ideal training ground for students. We offer a mix of experiment and simulation projects for graduate students, undergraduates, and postdocs. At Swarthmore College, over 40 undergraduate scientists have received their introduction to experimental plasma research at the SSX facility (including Geddes, Lukin, Landreman, Gray, Chaplin, Flanagan). Similar numbers have been trained on the PFRC and other CT facilities. Graduate students and postdocs currently working on OFES-funded projects got their start in the Bellan group at Caltech (including Brown, Kirkwood, You, Fredrickson, Hsu, Moser, Perkins, Yun).
3 Compact Torus Physics

Our plasmas generate physical phenomena of interest to non-fusion scientists (relaxation, turbulence, reconnection), while focusing on critical issues faced in fusion physics (helicity injection, fueling, disruption mitigation). Since a compact torus is a natural relaxed state of magnetized plasma, CTs can be formed in a number of ways either with electrodes (coaxial, planar, etc) or electrode-less ($\theta$-pinch FRC formation, HIT-SI scheme, etc).

The notion of relaxation to a minimum-energy state subject to some constraint is central to CT physics. It is well-established that spheromaks (and RFPs) relax to a minimum-energy state subject to constant magnetic helicity ($K = \int \mathbf{A} \cdot \mathbf{B} \, dV$) [17]. This model predicts relaxed states with zero $\beta$ and no flow, solving the Euler equation: $\nabla \times \mathbf{B} = \lambda \mathbf{B}$. Some CTs including FRCs could relax subject to a conserved generalized two-fluid helicity ($K_{\text{gen}} = \int (\mathbf{A} + m v/q) \cdot (\mathbf{B} + m \omega/q) \, dV$) [35]. This more general two-fluid theory predicts relaxed states with finite pressure and sheared flows. Here, $\mathbf{A}$ is the magnetic vector potential, $m$ is the particle mass (ion or electron), $v$ is the fluid velocity (ion or electron), and $\omega$ is the fluid vorticity.

4 The Future: CT priorities in the ITER era

As noted above, we feel that our role is to work within the Discovery Science and Foundations realms of the restructured OFES. Here are some specific initiatives and future plans.

4.1 Measurement Innovation

Since we are predominantly an experimental community, we feel we are in a position to develop innovative diagnostics. Our CT plasmas are accessible to a wide array of diagnostics (including internal probes). Many of us have developed clever diagnostics out of necessity. These include the use of LIF in a tokamak (Bellan [36]), the use of eschelle gratings and PMT arrays for ion Doppler spectroscopy (Brown [37]), the use of laser deflection to measure plasma density gradient (Hwang [38]), and the use of a transient internal magnetic probe (TIP) to measure magnetic fields on HIT (Jarboe [39]). We anticipate similar innovations in the future as measurement needs arise.

4.2 Experimentally validated simulations

Our CT geometries are simpler, and scales are smaller so detailed, experimentally validated simulations are possible. Indeed, a full-scale two-fluid validated simulation of a CT with Lundquist number $S = 1000$ is feasible, while a full-scale simulation of an RFP or tokamak is more challenging. Many of us have simulation collaborations or do simulations ourselves. Some
of us have participated in the OFES-funded Plasma Science and Innovation Center (PSI-Center) sited at the University of Washington. Recently, a modified astrophysical jet code was used in a highly resolved comparison between experiment and numerical model with excellent agreement [40]. We plan to continue to be an experimental testbed for simulation validation and verification.

The HYM code has been extensively verified versus analytical solutions, and in comparisons with other codes in modeling the tilt instability in FRC. It has been validated and currently is being validated in detailed comparisons with SSX experiments (MHD regime), TAE FRC experiments (kinetic regime), and ongoing comparisons with the NSTX measurements of the subcyclotron frequency Alfvén modes, i.e. global Alfvén (GAE) and compressional Alfvén (CAE) eigenmodes. This validation involves collaborations with the experimentalists, who provide the experimental data for unstable modes, i.e. measured structures, frequencies, amplitudes, growth rates, and unstable toroidal mode numbers, or implement synthetic diagnostics to use with numerically calculated data for experimental comparisons.

4.3 Connections outside OFES

The CT community have been leaders in reaching out to other scientific communities. The plasma science community is isolated so it is important to reach out to provide an OFES presence outside of the normal DPP and IAEA venues, reducing our isolation. Some of us are part of the astrophysical and space communities, and regularly participate in their meetings (e.g. IPELS, AGU, SHINE) and publish in their journals (e.g. ApJ, JGR). Some of us have connections with fusion energy science being conducted at private companies such as TriAlpha (TAE)[41, 42], General Fusion [43], Lawrenceville Plasma Physics [44], and Helion (Slough). We also have connections with the space propulsion community and attend their meetings. Finally, since CT research is conducted abroad, we have vibrant collaborations with Japanese, Chinese, Canadian, and Russian scientists. There is a regular US/Japan CT workshop that will next meet in August 2014 with the EPR group in Madison.

As an example of outside connections, the HYM code was also used to perform 3D simulations of the magnetic arc experiments in the Magnetic Reconnection Experiment (MRX), which is designed to study the solar flux ropes, and conditions for their eruptions. The HYM code has been modified recently to allow to model the flux cores with time dependent current in order to study reconnection in MHD-like regime in the FLARE experiment under development in PPPL (upgraded MRX).

4.4 Innovative Applications to ITER class tokamak

High velocity CTs can deliver dense ionized plasma to the magnetic axis of a tokamak, for either an existing device or a planned fusion reactor-grade
device such as ITER. Depending on the type of species injected (Z), CTs can be used either to fuel a tokamak (typically Z=1) or to provide ions for collisional and bremsstrahlung cooling of runaway electrons (typically Z ≫ 1). The latter application would be particularly important during the quenching phase of a major tokamak disruption. More recent findings show that CT acceleration can amplify the internal field of the CT, thus offering the possibility of modifying the local magnetic field of the target plasma [45]. Innovative development in these directions can strengthen applicable tools for tokamak fusion reactors.

The HYM code has been developed for the FRC studies, and therefore has unique capability to model toroidal devices using a fully kinetic description. This capability has proven to be critical for numerical studies of sub-cyclotron frequency Alfvén modes in the NSTX, where full kinetic description for the beam ions is necessary for modeling cyclotron resonances. Excitation of these modes by beam ions has a strong effect on the electron temperature profiles in the NSTX, and it can also be important for the beam heated plasma in ITER, and for studies of the effects of fusion alphas in ITER.

4.5 The EPR community

Finally, we are part of the broader EPR (Exploratory Plasma Research) community, promoting interactions with other parts of fusion energy science. The EPR community (formerly the ICC group) meets every 18 months and provides a venue for auxiliary fusion energy science research. Our next meeting will be in Madison in August 2014 with over 100 registrants. M. Brown serves as chair and the entire CT community participates. Included in the broader EPR group are representatives from the Long Pulse realm (US stellarators including HSX, CAT, and CNT), Foundations (LTX, Pegasus), and Discovery Science (MST).

References


