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COMPARISON OF COMPACT TOROID CONFIGURATIONS

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INTRODUCTION

The IAEA Coordinated Research Project (CRP) on "Comparison of Compact Toroid Configurations" has participants from Argentina, Brazil, China, India, Israel, Italy, Japan, Russia, Ukraine (Dr. Yaroslav Kolesnichenko), UK, and USA. The results of a recent CRP meeting are summarized here.[1] Spherical tokamaks (ST) have very low aspect ratios, which facilitates attainment of high β. Spheromaks have both poloidal and toroidal fields, but no center post.[2] Field reversed configurations (FRC), have only poloidal magnetic fields.

PLASMA FORMATION AND SUSTAINMENT

Spherical tokamaks plasmas are usually produced and sustained inductively. Spheromak plasmas are usually produced by coaxial guns or by inductive flux cores. Field reversed configurations have been produced by theta pinches, by merging two spheromaks with opposite toroidal fields, and by rotating magnetic field (RMF) current drive. ST, spheromaks, and FRC will all need some current sustainment by non-inductive means, such as electromagnetic waves, neutral beam injection (NBI), or RMF.

EQUILIBRIUM, STABILITY, AND TRANSPORT

Typical beta values are 30% (ST), 10% (spheromaks), and 70% (FRC). Flow shear has a stabilizing influence in ST. Plasma shaping, profile control, and current drive have been done in ST, but not in spheromaks or FRC. Spheromaks are nearly in the "Taylor minimum energy" equilibrium, which is conducive to stability, and energetic beam ions are expected to help stabilize them. Toroidal rotation is predicted to stabilize external kinks of ST, and to stabilize the tilt instability of spheromaks and FRC. Flow may also help to suppress the tilt instability of FRC.

The dangerous instabilities in ST are disruption, ballooning modes, kinks, neoclassical tearing modes, and resistive wall modes. In spheromaks they are tilting and relaxation events, and in FRC, tilting and rotational modes. The experimental stability of FRC exceeds that predicted theoretically.

The H mode has been observed in ST, and internal transport barriers are expected. Transport in ST is somewhat understood in terms of microturbulence suppression by magnetic shear and flow shear and magnetic well. Transport in spheromaks is dominated by the dynamo reconnection phenomena and should improve at higher T_e. Transport in FRC is anomalous and not understood. Improved confinement is seen in decaying isolated spheromaks, but not the H mode or internal barriers. Most of the transport barrier in spheromaks and FRC is near the separatrix.

FUELING AND EDGE PHYSICS ISSUES

Edge physics studies have been done somewhat in ST, but spheromaks and FRC have not been sustained long enough for meaningful scrape off layers to develop. High power electrodes are used in ST for coaxial helicity injection and divertor biasing, and in spheromaks for plasma production. Tungsten alloy on copper substrate looks good for some electrode applications, and is being tested in Proto-Sphera. H mode tokamaks, spheromaks, and FRC all have difficulty with particle inventory control. Pellet injectors are useful for ST. The spheromak community has developed high throughput gas inlet valves, including hypersonic valves. Spheromaks and FRC have not yet operated at pulse lengths that require sustained fueling. Boronization may be a good technique for both spheromaks and FRC. Generally tokamaks run out of fuel, whereas spheromaks have too much.

ST EXPERIMENTS

Parameters of **National Spherical Torus Experiment (NSTX)** (Princeton, USA) are: R = 0.85 m, A = 1.3, k = 2.3, triangularity = 0.6, B_ϕ = 0.3 T for 3 s, and I_ϕ = 1 MA. The central column is insulated from the remainder of the vacuum vessel to facilitate coaxial helicity injection (CHI). There is also 6 MW of high harmonic fast wave (30 MHz), and 5 MW of neutral beam injection (NBI) at 80 keV. NSTX has achieved 1 MA toroidal current, 130 kA toroidal current using CHI, and performed initial experiments with high harmonic fast wave (HHFW) current drive, which showed excessive plasma loading of the antenna. At I = 1 MA, V_ϕ ~ 3-5 V, β ~ 9%, and τ_E ~ 25 ms.

The **MegaAmp Spherical Tokamak (MAST)** (Culham Laboratory, UK) has tested startup methods, demonstrated H-mode operation, and achieved I_ϕ = 1 MA using neutral beam injection (NBI). The 1 MA toroidal current was terminated abruptly by an internal reconnection event (IRE). Typical parameters are I_ϕ ~ 0.6 MA, n ~ 5×10^{19} m^{-3}, T_e ~ 0.8 keV. Vertical plasma motion control is essential to prevent machine damage. The power loading measurements indicate that 80-90% of the power goes to the outboard strike point, which is desirable since the outboard strike point has much more surface area than the inner strike point. The wall power loading for a 0.5 MA plasma with no NBI is 1 MW/m^2, but with high-power NBI the loading will probably increase by a factor of ten.

The **TST-2** spherical tokamak (University of Tokyo, Japan) has design parameters of R = 0.36m, a = 0.23m, B_ϕ = 0.4 T, I_ϕ = 0.2 MA, Φ_{OH} = 0.13 V-s. Parameters achieved so far are: B_ϕ = 0.2 T, I_ϕ = 0.09 MA, τ_{pulse} = 0.02 s, T_i = 100 eV (O V measurement). Internal Reconnection Events (IRE) have an abrupt increase in I_ϕ, a decrease in V_{loop}, and a 40% density decrease. Magnetic probes show a consistent growth of a 10 kHz perturbation and its harmonics. The RF system uses a Faraday-shielded comb-line antenna designed to excite a unidirectional HHFW. Low power (1 kW) RF propagation experiments performed so far indicate plasma loading of the antenna is much stronger than expected.

The **Globus M** spherical tokamak (Ioffe Institute, St. Petersburg, Russia) is in the start-up phase. Its current goals are to improve vacuum conditions (chamber baking at 200 C, glow discharge cleaning); to study plasma-facing materials; and to install diagnostics including soft x-ray, impurity ion spectrometers, microwave interferometers. A toroidal current of 84 kA was obtained with an associated loop voltage of 4V. The plasma duration of ~300 ms is limited by heat build-up.

The **ETE** spherical tokamak (Brazilian National Space Science Institute) is also in the start-up phase. It will have A = 1.5, R_0 = 0.3 m, B_0 = 0.4 T, I_ϕ = 0.2 MA, pulse length 10-15 ms, 7 kW ECH, 22 point Thomson scattering system, a 10 kV, 10-100 μA lithium beam probe, and a submillimeter interferometer with added HeNe laser to counteract vibration.

The **Sino-United Spherical Tokamak (SUNIST)** (Institute of Physics, the Chinese Academy of Sciences, and Tsinghua University) has: R = 0.3 m, A = 1.3, B_ϕ = 0.15 T, and initial I_ϕ = 50 kA. Plans include wall pre-conditioning, ECRH startup studies, wave-plasma interactions, and fast wave current drive, which should permit operation without OH coils.

The **Proto-Sphera** spherical tokamak experiment (Frascati, Italy) will use a vertical plasma current I_z = 60 kA along the geometric axis, instead of a solid center post, to produce the toroidal magnetic field. Expected parameters are R = 0.35m, I_ϕ = 120-240 kA, n = 10^{20} m^{-3}, Z = 2, T = 130 eV, τ_E = 2.3 ms. The cathode current density will be 100 A/cm^2. The machine is finished and cathode development experiments are underway on a prototype screw pinch experiment, where 700 A flows axially in an external axial magnetic field with B_z = 1.5 kG. For Proto-Sphera 850 kW of heating power will be needed to provide the required 60 kW of axial current.

SPHEROMAK EXPERIMENTS

The **Sustained Spheromak Physics Experiment (SSPX)** (Livermore, USA), which is beginning operation, uses a fast bank to initiate the discharge followed by a slow bank for sustainment, with the goal of obtaining 1 MA toroidal current for 3 ms. Experiments so far have shown that gettering reduces radiated power to less than 20% of total input power. A flat-top with 1.5 kG magnetic field has been achieved for 1.8 ms. A multi-point Thomson scattering system and a Transient Internal Probe (TIP) are being developed. The CORSICA code is being used to verify the plasma equilibrium by fitting surface magnetic probe measurements to a numerical prediction. A full 3D numerical MHD calculation using the NIMROD code shows evidence of Taylor relaxation and also evidence of the doughhook mode seen previously on the SPHEX device at the University of Manchester.

The **Berkeley Spheromak Experiment** (Berkeley, CA, USA) has B_{pol} ~ 0.3 T, n ~ 2-7x10^{20} m^{-3}, and T_e ~ 30-150 eV. It is investigating the application of 20 MW of 450 MHz lower hybrid heating via a slot in the flux conserver. Diagnostics include Thomson scattering, a 3.8 meter ion Doppler spectrometer, a HeNe interferometer, and magnetic probes. There is substantial MHD activity and the plasma decays after 100 μs. The device is fired sufficiently fast that the electrodes become hot. The critical issue for lower hybrid waves is the accessibility condition for wave penetration, which requires waves with very slow parallel phase velocity.

Unbounded spheromaks (California Institute of Technology, USA) are formed in a large vacuum chamber and photographed using high speed cameras. Formation of spheromak configurations without a flux conserver contradicts conventional theory, which requires the plasma to be bounded by a flux conserver. As with other spheromak devices, the spheromaks were formed over a distinct range of λ, the ratio of gun current to gun bias flux. Immediately after formation, the spheromaks convected away from the coaxial magnetized gun at a constant velocity and expanded self-similarly. The regime where λ was marginally insufficient to form spheromaks produced distinctive helically twisted flux tubes.

FRC EXPERIMENTS

The **STX** experiment (University of Washington, USA) has demonstrated: (1) enhancement of the rotating magnetic field (RMF) strength in the plasma relative to the vacuum field strength, (2) initial penetration of the RMF into the plasma on start-up and then exclusion to a surface layer as the plasma heats up, (3) a resistivity anomaly where the RMF appears to lower the resistivity, (4) beneficial properties of a flux conserver, (5) improved confinement with RMF, and (6) problems with uncontrolled increases in density. Current drive by RMF is analogous to an induction motor: a rotating magnetic field drags the electrons along until they rotate nearly synchronously with the rotating field and so constitute a toroidal current with associated poloidal magnetic field providing magnetic confinement. The larger **LSX** experiment, just starting, involves multi-megawatt RF power supplies. An FRC plasma, formed by standard high voltage theta pinch technology, is injected axially into a separate chamber section having RMF field coils. The goal is to sustain the FRC in this section using RMF drive. There have been problems so far with unwanted density increases when RMF is applied, and RMF drive becomes ineffective when the density exceeds a critical threshold.

The **FIX** experiment (Osaka University, Japan) generates a hot (T_e+T_i = 400 eV) FRC in a high-field formation section and then axially translates the FRC to a much lower field section, where the FRC reflects without significant losses from mirror coils at the far end of the low field section, resulting in collisionless shock heating and the appearance of a toroidal field. A 15 kV, 600 kW short pulse neutral beam is injected into the low density plasma. The hot injected ions are mirror trapped with large orbits. The plasma volume lifetime increases from 95 microseconds without NBI to 230 microseconds with NBI. RF power from a ringing capacitor bank at 100 kHz, coupled via a pair of azimuthal loop antennas that excite B_r and B_z wave fields, increases T_i by 25%, probably by excitation of a shear Alfven wave.

The **TS-3** experiment (University of Tokyo, Japan) has: $0.15\text{m} < R < 0.22\text{m}$, $1.05 < R/a < 2.0$, $B < 2$ kG, T_i = 10-200 eV, T_e = 10-40 eV, n = 0.5-10x10^{20} m^{-3}. FRC's are produced by merging two spheromaks with opposite helicity. The toroidal field is annihilated, 60-80% of the toroidal field energy is converted into ion heating, and $\beta > 0.7$. The **TS-4** device will have $0.4<R<0.55$ m, $1.2<A<1.9$, $3<B<5$ kG, and I_ϕ = 300 kA. The TS-3 and TS-4 devices can produce FRC, spheromak, ST, and reversed field pinch plasmas in the same device as they explore the β-q_0 parameter regime over wide ranges.

The **TRINITI** FRC experiment (Troitsk, Russia) has three sets of coils (main theta pinch coil, trigger coil, and mirror coil) to trigger reconnection and produce FRC plasmas via self-organization. Rotation and an associated instability can be reduced by using special formation techniques, and strong adiabatic compression results in T_i = 3kV. One formation sequence involves a "balloon" shape at the axial ends of the plasma, which causes the plasma to contract axially, producing shock heating in 0.5 μs. A toroidal field is spontaneously excited during the compression, but this field does not significantly affect the equilibrium.

Some features of hypothetical ST, spheromak, and FRC **fusion reactor**s are compared in Table.

SUMMARY

Plasma theory and simulation are developing a better understanding of stability and transport issues. Several new ST experiments will yield valuable data in the next few years, which should help to clarify many of the remaining experimental issues. Then a more powerful ST could become a volumetric neutron source for fusion materials testing. If compact toroids could fulfill their potential for simpler, compact reactors, then fusion energy production might be more reliable and less expensive than with large aspect ratio tokamaks. However, low budgets for Spheromak and FRC research make experimental progress in those areas very slow.

Table Hypothetical Reactor Features.

	ST	**Spheromak**	**FRC**
Dimensions	10-m diam. x 15-m high	5-m diameter	7-m diameter x 10-m long
n, m^{-3}	2x10^{20}	2x10^{20}	10^{20}
T_e, keV	10	10	10
β	0.4	0.1	0.7
Plasma Energy	1 GJ	0.1 GJ	0.2 GJ
Fusion Power	3 GW	0.3 GW	0.3 GW
Toroidal coils,	2 T	None	None
Poloidal coils controls	1.3T feedback for shape and MHD modes	4 T external flux and tilt control	1 T adjust for constant external flux
Plasma Current	25 MA toroidal + 25 MA poloidal	50 MA parallel current	20 MA diamagnetic current
Plasma Heating & Current Drive	50 MW HHFW (90% bootstrap)	Ohmic heating 40 MW CHI	100 MW RMF, maybe NBI or Alfven wave
Fueling & ash removal	Pellets $\tau_p \sim 5\tau_E$	Pellets	Central fueling?
Impurity control	Divertor closed to plasma	Natural divertor, DEC *	Natural divertor, DEC *
MW/m^2	Hi	Variable	Low
Disruptions / Terminations	Abnormal termination (disruption) possible	Flux decay, may be unstable at high beta	Tilt or flux decay. Energy lost out ends
Other issues	Center post lifetime & recirculating power. Single turn for easier replacement	Close fitting wall. Must have active soak in of B_{vert}	RMF antenna placement.

* DEC = possibility of direct energy conversion

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