Reactor considerations for Compact Toroids

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All fusion reactor concepts must allow engineering solutions for tritium breeding blankets, shields, vessel maintainability, duty cycle availability, radiation damage and activation, plasma particle and power balance, current drive, plasma surface interactions, and integration of systems. Operations must facilitate inspection and maintenance. Compact Toroids (CT: spheromaks and FRCs) simplify the solutions to many of these problems. A large improvement in the fusion reactor cost follows from the following features of the CT:

- CT power plants balance reactor engineering attractiveness against physics/technical risk.
- Radial build of integrated blanket-coolant-shield-coil modules determines the minimum practical radius of the first wall, and leads to a compact reactor size.
- Higher engineering β: lower cost coils for a given plasma pressure
- Simply-connected first wall with no toroidal field coil leads to simplified and modular blanket-coolant-shield-coil designs. Purely poloidal fields at the boundary allows coolants to flow parallel to the magnetic field hence there no MHD drag on liquid metal coolants. Better cooling may allow higher wall loading.
- Naturally diverted particle and heat flux allow particle-heat wall loads to be spread out to the optimal area and plasma wall loading can be in different locations from the neutron wall loading. This allows attractive divertor designs.
- Good confinement: closed drift surfaces from toroidally-symmetric closed-flux equilibria.
- Compact tori are translatable and allow separation of formation and reactor volumes.

For these reasons major fusion leaders have pursued the spheromak CT, including H. Furth, M. Rosenbluth, and K. Fowler. Because of these advantages OFES should have a strong program to understand the physics of sustainment and confinement of CTs.

Radial build key factor in cost and complexity

The nominal plasma-blanket standoff varies widely with the blanket concept invoked for use with 14MeV fusion neutrons. To efficiently utilize the first wall, blanket, shield, and coil the smallest dimension of the plasma must be larger than this thickness. For a toroidal vacuum vessel this dimension is the minor radius. For a CT this dimension is the full radius of the spheroidal first wall. The nominal radial build extent is 1.5-2 meter [El Guebaly2003], and the minimum first wall location which is the inner surface of the radial build, must also be at least of this order. This minimum area and also the minimum cost for the CT is smaller by a factor of six to ten depending on the aspect ratio of the tokamak. This leads to a considerably more compact reactor size than any tokamak or stellarator design. The wall loading may also be limited by the cooling capacity, but for the CT the heat and neutron loads can occur in different locations.

Simpler magnets for a given plasma pressure

The large beta (β) leads to efficient use of magnetic field created with expensive magnets and power supplies. Without toroidal magnets, or ohmic stack trapped connections, a simply connected, linear cylindrical vessel facilitates the design of cylindrically symmetric modules that contain the radial build of the first wall, breeder blanket, shield, and magnet. It will be straightforward to add, remove, or repair single integrated modules.

Furthermore, a large decrease in coil cost occurs when the engineering β becomes large enough that a normal conducting coil can be used. Not only is the normal conducting coil less expensive but it needs less shielding so the first wall, blanket, shield, and coil layer can be thinner allowing a smaller optimized reactor.

Simplified blanket-coolant-shield-coil designs

Without toroidal magnets, or ohmic stack trapped connections, a simply connected, linear cylindrical vessel facilitates the design of modular first wall-breeder blanket-shield-magnet modules. It will be possible to add, remove, or repair single integrated modules that contain the first wall, blanket, shield, and magnets. For liquid metal or salt blankets and coolants, the reduced flow path length from smaller size allow reduced hydraulic pressure drop. Coolant flow parallel to B fields eleminates MHD forces on liquid metal coolant flows.

Tokamak designs like FIRE and STs use a simply-connected blanket and shield and a normal conducting TF coil to get a very large decrease in capital cost compared to a normal tokamak design. However, the power lost in the normal coil and the increased maintenance cost due to neutron damage in the unshielded part of the coil offset the capital cost savings in a reactor. Elimination of the TF-coil removes this offset and gives a further decrease in capital cost for the CT.

Separate particle-heat and neutron wall loads

The particle and heat flow that escapes the separatrix leads to a heat loss flux that can be spread out to different locations than the neutron flux. The tough engineering problems associated with each type of wall loading can thus be separately solved. Divertor heat / area loads are reduced by field line expansion outside the separatrix, and the more demanding plasma surface heating (compared to the volume heating of neutrons) can be handled with components that will not be seriously degraded due to neutron damage. Elimination of the TF-coils makes this possible. This also opens the possibility of direct conversion of the diverted plasma energy.

Disruptions

It is not known whether steady state CT's will disrupt like tokamaks and quench all the energy into small peak regions at a divertor or first wall. There are CT instabilities that can grow and terminate the plasma state, but investigations of potential disruption scenarios remain an important research need.

Neutron wall load

CT geometry allows a large coverage fraction for tritium breeding [Santarius2000], albeit at high neutron flux. This may allow a solid breeder layer without recourse to a Beryllium neutron multiplier. This in turn would permit operation with water coolant without risking hydrogen production via Be-water reactions. Operations with liquid walls could be much easier than tokamak geometries, and should be investigated more. Dual coolant blankets including melted salt cooling/breeders (eg FLiBe, or PbLi) with complicated and additional Helium cooling loops can be avoided. If heat loss and neutron fluxes occur in different locations, each engineering solution can be separately and better optimized.

Reactor design comparison

The Table shows the results of a system analysis of a steady state spheromak reactor (CSR) [Hagenson1985] and of an advanced tokamak reactor ARIES-AT. The spheromak analysis makes the large extrapolation in physics of assuming that a spheromak can be sustained with good confinement and uses more conservative assumptions about materials and technologies. The tokamak analysis makes modest extrapolations in tokamak physics and more aggressive technology assumptions. Since the tokamak case uses the more advanced technologies one would expect that the cost per tonne would be at least as high as the spheromak case. Therefore, the decrease in mass per megawatt electric conservatively estimates the relative decreased cost associated with the CT fusion power core (FPC), which is about a factor of six. ***The spheromak has optimized neutron and plasma wall loadings while the tokamak has less than optimal neutron loading and more than optimal plasma loading.***

Parameter	Tokamak (ARIES AT)	Spheromak (CSR)
Mass utilization M_{FPC}/Pe (tonne/MWe)	5.2	0.81
Neutron wall loading (MW/m^2)	3.3	19.8
Peak diverted plasma wall loading (MW/m^2)	14.7	5
Thermal conversion efficiency (%)	60	35
Volume averaged β (%)	9	10
Blanket structural material	SiC	Steel
Coolant	PbLi	PbLi
Coil type	High Temp. SC	Copper
Electrical output (MWe)	1000	1000

Table I. Comparison of ARIES-AT tokamak and spheromak reactor designs.

CT path forward

There are reasons for optimism that a CT can be sustained with sufficient confinement for fusion purposes. CT equilibria are toroidally symmetric with closed flux and closed drift surfaces and are, therefore, capable of good confinement. Low neoclassical effects further increase their potential for good confinement. Compact tori are translatable and allow separation of formation and reactor volumes. Steady-state inductive methods have formed and sustained both spheromaks (30 kA) and FRCs (100 kA) (invited talks at 2007 APS/DPP). High power pulsed formation methods have produced decaying spheromaks with $T_e = 0.5$ keV, and FRCs with $T_i = 1.5$ keV. Recent experiments, theory, and numerical calculations have shown many avenues (minimum-energy states, rotation, kinetic particles, RMF pondermotive forces) for achieving full stability, even in FRCs. Spheromaks have ideal-MHD-stable, high-β equilibria. The use of ultra high vacuum techniques, have resulted in low input power steady-state CTs with $T_e > 100$ eV and overall confinement improving rapidly with temperature.

Research thrusts

Although CT funding has traditionally been a small part of the alternate concepts program, both CT configurations have made substantial plasma physics progress in recent years. Research thrusts require experiments, diagnostics, theory, computational modeling, to investigate CT sustainment, confinement, helicity injection and current drive, whether disruptions exist. We need viable CT reactor studies to supplement the modest efforts thus far. All this knowledge and expertise will be necessary for a breakthrough bridge to commercially attractive fusion power while maintaining USA world leadership in CT research.

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