Introduction to Compact Torus

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Outline of Presentation

1. Compact Torus (CT)
2. Magnetized Target Fusion (MTF)
3. Compact Torus Injector

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Starting From Nuclear Fusion

In order to make fusion energy a viable economic alternative, significant improvements in concept design need to occur.

- We want the device to be **Simply connected**. Meaning that there is no material linking the center of the device, making the first wall either a sphere or a cylinder.
- By removing the center material of the device, the cost decreases and the engineering becomes simple.
- Compact Torus suits this purpose very well.

Well Studied CTs

- Compact torus is a toroidal magnetic configuration with a simply-connected geometry that are self-stable.

The following configurations fall into the category of compact torus:

- Spheromak.
- Field-reversed configuration (FRC).
- Particle ring. (Not in active research today.)

Spheromak

- Spheromak is a toroidal confinement with toroidal and poloidal fields.
- Toroidal field is completely generated by plasma currents.
- The current is toroidal at the core and poloidal at the surface.
- The current is parallel to **B** in spheromak, $\nabla p = \mathbf{j} \times \mathbf{B} = 0$.
- Ideally it is always MHD stable. In reality, spheromak has finite pressure and due to different decay rates of toroidal and poloidal fields, current driven kink modes will be developed.

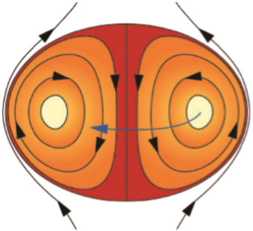

Figure 1: Spheromak configuration. [2] The arrow lines are magnetic field lines.

[2] Z.Gao. *Compact magnetic confinement fusion: Spherical torus and compact torus.*

Spheromak Issues [2]

- Due to absence of toroidal field coils, it is difficult to generate large toroidal fields in spheromak.
- Due to absence of ohmic coils, it is difficult to obtain long pulse discharges.
- The above issues indicates: it is hard to achieve good confinement simultaneously with an efficient current drive. The drive of plasma current will break the magnetic surface and induce high-level heat losses.

Spheromak Successes [3]

- Tokamak-like transport measured in the SSPX experiment by suppressing fluctuations.
- Multi-pulsed build-up of magnetic energy in a spheromak demonstrated in SSPX.
- SSX merged spheromaks and detailed magnetic reconnection and generation of energetic plasma flows, FRC formation by merging.
- TS-3/4 shows means for forming various toroidal configurations by merging.

Field Reversed Configuration (FRC)

- FRC is a toroidal confinement with poloidal field only.
- Bulk currents of FRC are diamagnetic, leading to a high beta ~ 1.
- FRC equilibrium cannot be described by Grad-Shafranov equation. Two-fluid or kinetic theory is needed.
- FRC's magnetic topology indicates that it is unstable to most ideal MHD modes, but robust stability can be obtained in experiments.

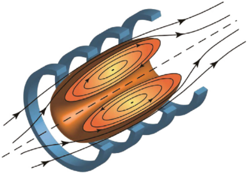

Figure 2: Field reversed configuration. [2] Arrow lines are magnetic field lines.

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FRC Issues [2]

- It is believed that Finite Larmor radius (FLR) effect contributes to the stability, but this effect is not effective in large-size FRC.
- Sheared flows and large orbit of energetic ions may improve stability but theoretical explanations and experimental evidences are not well convincing.
- FRC provides a big challenge in equilibrium and stability of plasmas at the extreme.

FRC Successes [3]

- Formation and Sustainment of long-lived FRCs in the TCS device (10 ms).
- Production of low-density FRCs with enhanced confinement in Osaka FIX experiment.
- Production of high density FRCs in the FRX-L device. FRCs have been formed with an equilibrium density $n_e(\sim 1-2)10^{16}\text{cm}^{-3}$, $T_e < T_i \sim 250\text{eV}$, and excluded flux $2-3\text{mWb}$.
- Formation, acceleration to $M > 1$, and collisions of FRCs in the IPA device.

Comparison Among Configurations

- CT can be used in fusion technology.

	ST	Spheromak	FRC
Scientific advantages	• High beta • Good MHD stability • Good confinement	• Force free	• High beta (~1)
Scientific disadvantages	• Difficulty in non-inductive startup and current drive	• Relative low plasma performance • Difficulty in the coexistence between good confinement and effective current drive	• Relative low plasma performance • Difficulty in realizing long life time for high pressure plasma • Unclear physics in equilibrium, stability and transport
Technological advantages	• Compact • High effective TF coils	• Compact • Simply-connected vacuum vessel and no TF coils	• Compact • Simply-connected vacuum vessel and no TF coils • Natural linear divertor
Technological disadvantages	• Relative low magnetic field at axis • Narrow center post • Intense wall loading		

Figure 3: Advantages and disadvantages of Spherical Tokamak (ST), spheromak and FRC for fusion. [2]

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Plasma Performance Achievements

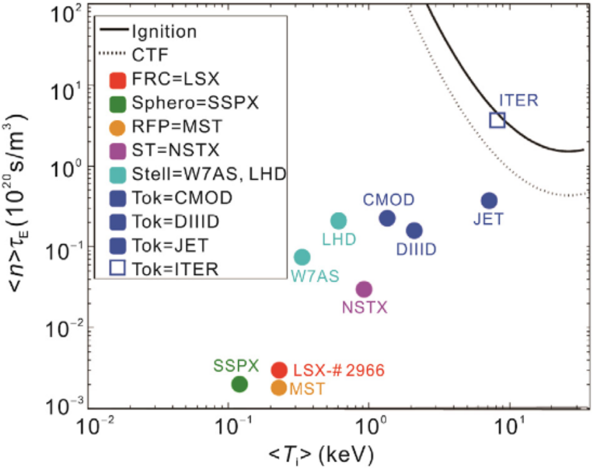

Figure 4: Plasma performance achievements of various concepts. [2]

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Magnetized Target Fusion (MTF)

- To obtain high pressure in magnetic confinement fusion (MCF): need to improve confinement time and/or enlarge the machine size.
- To obtain high pressure in inertial confinement fusion (ICF): compress small size plasma to ultra-high density but stability degrades the compression efficiency.
- MCF is a combination of MCF and ICF: compressing a magnetically confined plasma.

MTF Concept

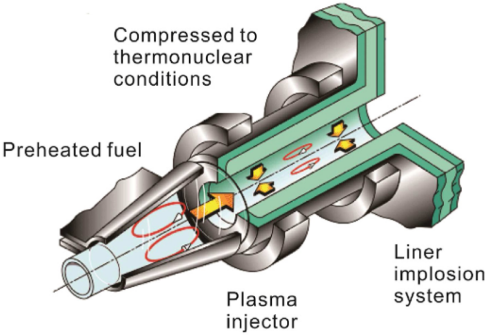


Figure 5: Schematic of MTF concept. [2]

[2] Z.Gao. *Compact magnetic confinement fusion: Spherical torus and compact torus.*

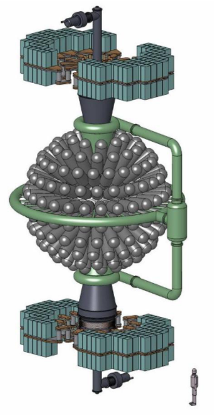


Figure 6: General Fusion's Acoustic Magnetized Target Fusion Reactor Concept. [1]

The early MTF concept in General Fusion involves the compact torus.

- The deterium-tritium fuel is supplied as a pair of CTs (spheromaks).
- CT accelerators are at the poles.
- Injected CTs travel to the center and merge to form a stationary compressible plasma target.
- The target is compressed by acoustic pressure.
- The acoustic pulse is generated mechanically by hundreds of pneumatically-driven pistons.

[1] M. Delage, A. Froese, D. Blondal, and D. Richardson. *Progress towards acoustic magnetized target fusion: An overview of the r&d program at general fusion.*

Outline of Presentation

Central Fuelling of Tokamak

Central fuelling can:

- control plasma density and pressure profiles.
- make plasma to achieve high fuel burn-up rate and low tritium recycling.
- improve tokamak confinement.

However, conventional fuelling technologies (peripheral gas admission, and frozen pellet injection) have drawbacks:

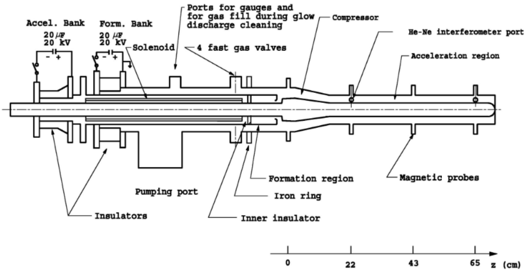
- relatively low pellet speed prevents the direct fuel deposition beyond the separatrix in reactor-grade tokamak such as ITER.
- Energetic neutral beam injection is economically inefficient.

Compact Torus Injection

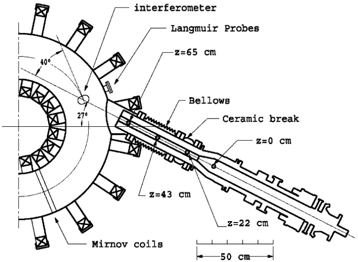
New injection technology, CT injection has some benefits:

- CT can be accelerated to hundreds of kilometers per second.
- Tangential CT injection may transfer CT momentum to tokamak plasma to induce and sustain toroidal rotation, good for stabilizing the locked mode and resistive wall mode.
- It is observed that tangential CT injection into STOR-M tokamak induces H-mode discharges.

Tangential Compact Torus Injection Setup



(a) Schematic diagram of USCTI. [4]



(b) Arrangement of CT injection experiments on the STOR-M tokamak. [4]

[4] C.Xiao, A. Hirose, and S.Sen. *Improved confinement induced by tangential injection of compact torus into the saskatchewan torus-modified (stor-m) tokamak.*

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