MODELING AND ENGINEERING APPLICATIONS FOR WEAKLY TURBULENT PLASMA

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Magnetic systems like the Field Reversed Configuration (FRC) and Spheromak (S), where a plasma is immersed in a linear external magnetic field geometry, called compact tori (CT) [1]. There are four all known FRC equlibria – spherical Hill's vortex [2], elongated Hill's vortex/ Solov'ev model [3], Steinhauer analytical equilibrium (SAE) [4] and quasy equilibrium (racetrack). The first one is described by

$$\psi_{HV} = -\frac{3B_e r^2}{4}\left(1-\frac{r^2}{r_s^2}-\frac{z^2}{l_s^2}\right),$$

where B_e is the field at ∞ , $k\equiv l_s/r_s$, r_s is the separatrix radius at z=0 plane, l_s is the half length.

Magnetic field flux inside the separatrix for the FRC SAE

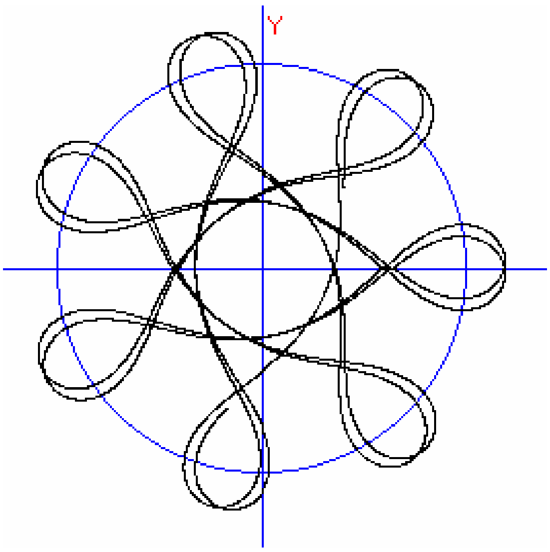
$$\psi_{SAE} = -\frac{Br^2}{2}\left\{1-\frac{r^2}{a^2}-\frac{z^2}{b^2}+\frac{1-N}{1+(6+N)(\varepsilon^2/4)+(1+N)(\varepsilon^4/4)+N(\varepsilon^6/32)}\right.$$
$$\left.\times\left[\frac{\varepsilon^2}{4}\left(1+\frac{\varepsilon^2}{2}\right)-(1-\frac{\varepsilon^4}{8})\left(\frac{\varepsilon^2 r^2}{4a^2}-\frac{z^2}{b^2}\right)-\left(1+\frac{\varepsilon^2}{4}\right)\left(\frac{\varepsilon^4 r^4}{8a^4}-\frac{3\varepsilon^2 r^2 z^2}{2a^2b^2}+\frac{z^4}{b^4}\right)\right]\right\},$$

where B is the nominal magnetic field, $\varepsilon= r_s/l_s$, N is the shape index (1 -HV and 0 - racetrack). First term is the elongated Hill`s vortex,second – the correction for the equilibrium flexibility. FRCs have the prolate shape while spheromaks more often use the oblate configuration. Even for recent compact tori experiments [5 and see Table I] with modest (for controlled fusion level) parameters: length, $l_s \sim 1$m; radius (or separatrix), $r_s \sim 0.4$ m; average beta, $\langle\beta\rangle \sim 20$ – 90 %; energy confinement time, $\tau_E \sim 1$ ms; ion temperature $T_i \sim 3$ keV; electron temperature, $T_e \sim 0.5$ keV; external magnetic field $B_e \sim 3$T and electron density $n_e \sim 10^{21}$ m^{-3}, the prolate form prevail over oblate. Last experiments have shown the weak turbulence in both plasma core and edge. CTs have charged particle transport losses which flow out the ends of the device. It is very crucial question because of plasma sustainment and getting power from high energy particles – the thermonuclear reaction products.

Table I. Compact Tori Experimental Devices (in alphabetical order). TF - toroidal field, TC – toroidal configuration, RMF – rotating magnetic field and MTF - magnetized target fusion

FRC:	*Spheromak:*
CBFR – UC Irvine, p-^{11}B reaction	BCTX–UCBerkeley,heating of a decaying S
FIREX-Cornell,Munsat/Boulder-Colorado	BSX,CT injection,Caltech - astrophysics jets
FIX–Osaka University, NUCTE-3 – Nihon	HIT-CT–Himeji,CTIX–UCDavis,accelerat.
FRX-L–LANL,MTF compres,high density	HIT-SI – UWashington, form S inductively
KT,BN,TOR–TRINITI,compres,translation	SPHEX – UMIST, PF structure, applied TF
Lebedev Physical Institute RAS, Moscow	SSPX – LLNL, high currents, confinement
MRX–PPPL,oblate flux-conserver,stability	SSSX–multi-probe,reconnection between 2S
TCSU,STX,TRAP,PHD–RMF, high T,flux	TS-3,4–Tokyo, merging of S, FRC,other TC

If we are looking for fusion products these are protons in D-T reaction and p and α–particles in D-^{3}He reaction. Particles trajectories are similar to both figure 8 and betatron orbits (Fig.1) may be Depending on initial (B, r, z, angles) and geometric parameters. There are two confinement favorites, possible improved confinement regimes – Hill's vortex and racetrack (SAE) was founded. Mainly it depends on birth point. The development of an approach considering of plasma parameters and magnetic field non-uniformity [6] and the analysis of physics properties of particles and energy of magnetized plasma are continued in this work.



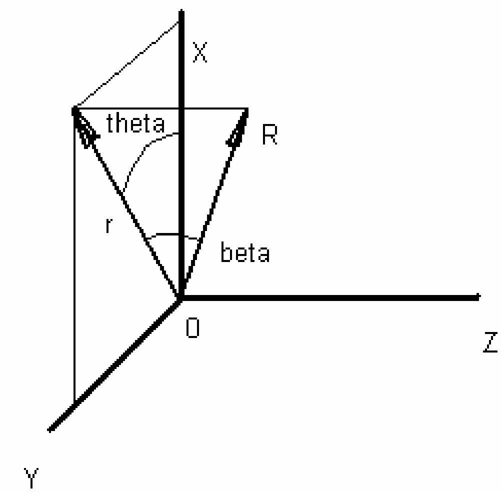


Fig.1. Protons (14.7 MeV) trajectory in X-Y plane. Typical example for particle orbits in SAE with initial parameters B=1 T, x=y=0.4 m, z=0, θ(theta)=90°, β(beta)=0°

It is known that the spheromak has a q-profile, not FRC.A toroidal field is developed in TCS-U [7] that gives FRC large safety factor ~ 2 (the edge value). This is the first known instance of a very high-β plasma with a safety factor greater than unity. The magnitude of toroidal field is less than ¼ of the external field, and does not affect the FRC beta. Another way to change the transport and turbulence is applying by magnetic field shear. So, approach using two fluid effects, poloidal flows and non linear waves in sheared flows are must be considered and tested.

Insight into compact magnetic confinement systems formation, confinement and sustainment should help in the design of future fusion experiments [8] such as the proposed ITER facility. Different applications of compact systems are very attractive [9]. Right now as neutron/proton source, plasma/ material technology [10], plasma-wall interactions, to test face components. Middle term application may include CT as energy source and plasma engine. Low turbulent plasma may be used as test facility, to support the tokamak (e.g. tokamak fueling). FRC and spheromak formation is also important for understanding plasma dynamics in the solar corona and astrophysical jets [11]. The proposed of a compact tori together with advanced fuel leads to the limitless source of clean energy for the future.

Burn dynamics is not well studied for MTF [13], where spherical/cylindrical plasma is compressed by guns and magnetic forces. The plasma to field energy density (beta) β determines the importance of the magnetic field in pushing the plasma around. Key difficulty is properly modeling the alpha-particle orbits and energy deposition.

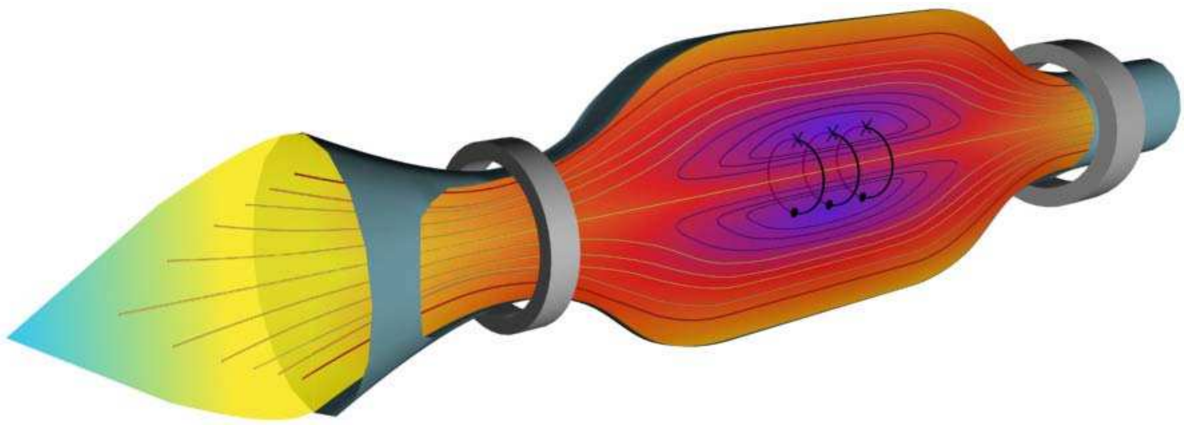


Fig. 2. Mirror nozzle, mirror coils and direct energy conversion (DEC) system for the prolate FRC (racetrack) as magnetic fusion rocket (space propulsion)

Three variants of Magnetic Fusion Rocket (MFR) model [12] based on racetrack, Hills vortex and elongated configuration were compared and it shown that the racetrack has more attractive parameters, including energy release and power density (Fig. 2, main solenoid is not shown here). Further development of the model in this direction is currently underway.

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