Helicity balance models and data analysis in the SPECTOR spherical tokamak plasmas

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Introduction

Here we present the analyses of helicity balance for the SPECTOR (SPhErical Compact TORoid) devices at General Fusion. SPECTOR devices are the reduced-scale plasma injectors at General Fusion designed to enable compression of stable, spherical magnetized plasmas. The toroidal magnetic field is applied by driving a current through the central shaft prior to the ignition of the plasma.

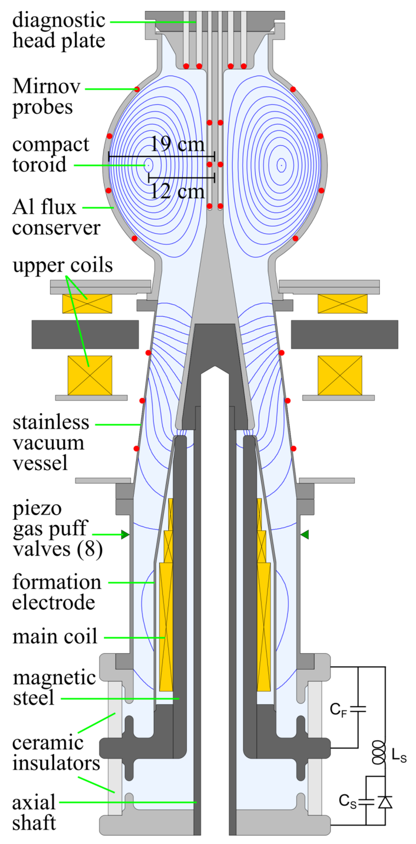

Fig 1. A schematic diagram of SPECTOR

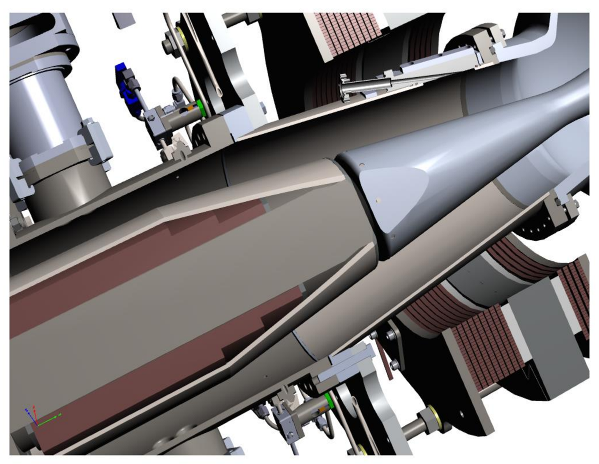

Fig 2. A cross-section of coaxial Marshal gun

- A spherical tokamak with Rinner = 3 cm, Router=19 cm
- Current through axial shaft is 0.5 MA
- Plasma density is $(1-2)x10^{14}cm^{-3}$
- T_e at plasma center is 350 – 450 eV
- Toroidal magnetic field is 0.5 T at plasma center
- Plasma current of 300-800 kA is induced using coaxial helicity injection
- Coaxial Marshall gun generates 80 μs long formation pulses of current up to 850 kA
- Magnetic gun flux is 10-20 mWb.
- Plasma current is not sustained and resistively decays for 1.5-1.9 ms
- The inner surfaces of the gun and inner wall of the flux conserver are coated with plasma-sprayed tungsten, the outer wall is bare aluminum.

Diagnostics:
- 41 magnetic probes on the inner and outer walls of the plasma vessel and in the Marshall gun
- Thomson scattering: YAG laser generates 1 pulse per plasma shot 6 radially resolved points are available
- Three-chord FIR heterodyne interferometer with two 118.8um methanol cavities
- Three-chord FIR polarimeter for measuring Faraday rotation
- SXR diagnostic using 2 filtered AXUV diodes
- Visible and VUV spectroscopy
- Ion-Doppler spectroscopy

Helicity Balance

Following [1], the helicity balance in a plasma produced by a gun is given by:

$$\frac{dK}{dt} = 2\,V_g\,\psi_g - 2\int_{sheath} \boldsymbol{E}\cdot\boldsymbol{B}\,d^3r - 2\int_{core} \boldsymbol{E}\cdot\boldsymbol{B}\,d^3r \qquad (1)$$

where V_g and ψ_g are the gun voltage and the poloidal flux, respectively, while the integrals take into account the dissipation in the plasma and in the sheath surrounding the plasma.

Eq. (1) can be rewritten as:

$$\frac{dK}{dt} = 2\,(V_g - V_{sheath})\,\psi_g - 2\int_{core-sheath} \boldsymbol{E}\cdot\boldsymbol{B}\,d^3r \qquad (2)$$

where V_{sheath} is the voltage drop across the sheath. The sheath is a region of open field lines that surrounds the well-confined plasma region with closed field lines. Note that for $V_g > V_{sheath}$ the sheath potential terms can be neglected in the balance, since V_g is about 6-8 kV during the sustainment phase in SPECTOR.

The plasma dissipation integrand can be written in a simple way as:

$$\boldsymbol{E}\cdot\boldsymbol{B} = \eta_{\parallel}\boldsymbol{J}\cdot\boldsymbol{B} \qquad (3)$$

Therefore, only the parallel current contributes to the core dissipation.

Constraints Deduced From Taylor State

Taylor's plasma relaxation has an important role in systems like spheromaks, but when there is a strong external toroidal magnetic field, the applicability of Taylor's paradigm is more uncertain.

However, assuming such a theory can be applied [2], the following eigenvalues can be obtained for the SPECTOR geometric configuration (a=0.014 m, b=0.19 m, L= 0.4 m) : $g_{1,1}$= 5. and λ_{eig}= 5. /b = 26 m^{-1} .

As discussed in [3], a gun can form a plasma if the following requirement is met :

$$\lambda_{gun} = \frac{\mu_o\,I_{gun}}{\psi_{gun}} \;>\; \lambda_{eig}$$

With a poloidal flux of 14 mWb and a gun current of 600 kA, the typical values in SPECTOR for λ_{gun} are about 45-50 m^{-1}. So, this condition is satisfied.

Another important condition discussed in [4], which guarantees the transport of helicity from the gun to the plasma core, is :

$$\lambda_{gun} > \frac{\mu_o\;I_{tor}}{\Phi} = \lambda_{tok}$$

where I_{tor} is the toroidal plasma current and Φ is the toroidal flux. Assuming a toroidal field of 0.9 T and a toroidal current of 300 kA, λ_{tok} = 3.5 m^{-1}, the above condition is also very well satisfied.

Unfortunately, the efficiency of helicity injection $\epsilon = {}^{\lambda_{tok}}/_{\lambda_{gun}}$, as defined in [4], is very low in SPECTOR compared to the efficiency of inductive current drive in tokamaks using an ohmic transformer.

As discussed in [5], plasmas are expected to have a hollow current profile when $\lambda_{gun} > \lambda_{eig}$, while peaked profiles are expected when $\lambda_{gun} < \lambda_{eig}$. Since λ_{gun} is slightly higher than λ_{eig} in SPECTOR, we expected to form plasmas with flat to slightly hollow plasma current profiles.

Comparison With Experimental Data

Following [8], the helicity balance equation can be rewritten in the following way:

$$\frac{dK}{dt} = 2\,V_g\,\psi_g - \frac{K}{\tau_k} \qquad (4)$$

where the helicity rate of change is the sum of the rate of gun generated helicity (1st term) and the rate of CT helicity decay (2nd term), with τ_k as the helicity confinement time of the system.

The product $V_g\,\psi_g$ is based on the real Spector data of the applied poloidal gun flux of 14.8 mWb and the voltage measured between the electrodes of the gun, is shown in Fig.1,

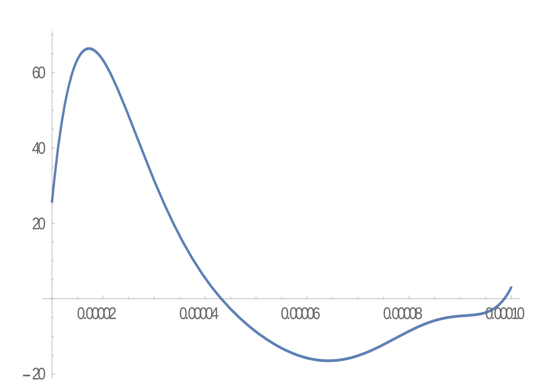

Fig 3. Experimental $V_g\,\psi_g$ vs. time (in sec)

Note, that this experimental waveform fades out around t=80 μs after the breakdown, close to the time that CT formation is complete.

The helicity vs time obtained by integrating Eq.(4) is shown in Fig.4 for two different time constants.

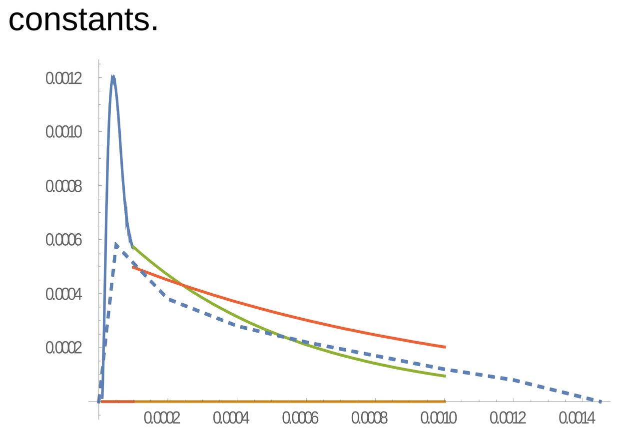

Fig 4. Helicity vs. time: The green and red curves have decay times of 0.5 and 1 msec respectively. The dashed line is the helicity obtained from a CORSICA reconstruction of the equilibrium based on surface Mirnov probes measurements from experiment.

It can be seen that the peak helicity content estimated by the CORSICA equilibrium code is about only a half of the electrostatic input of helicity calculated from the voltage and poloidal flux applied between the electrodes.

Analyses Of "Bubble-out" Threshold

Another interesting result that can be deduced by assuming a force-free Taylor state is the stretching current I_{st} threshold, the current required at the gun electrodes to push the poloidal flux into the flux conserving area. Assuming no external toroidal field, the relation obtained in [6] is:

$$I_{st} = \frac{8\,\psi_{gun}^2}{\mu_o^2\;d^2 I_{tf}} \qquad (5)$$

where d is the distance between the inner and outer electrodes of the coaxial gun and I_{tf} is the current through the central rod. This formula is plotted with 3 values of the poloidal flux and d=0.065 m in Fig.5a.

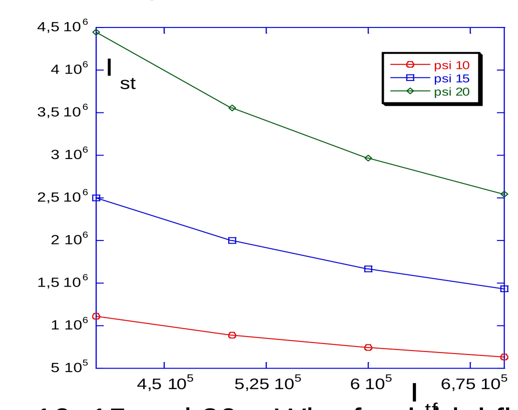

Fig 5a. I_{st} vs. I_{tf} for 10, 15 and 20 mWb of poloidal flux.

A formula that relates the shaft current I_{tf} and the gun current I_{gun} with different poloidal fluxes is presented in [7] without much explanation:

$$I_{st} = \frac{\lambda_{gun}\psi}{\mu_0}, \qquad (6)$$

where $\lambda_{gun} = \left(\lambda_{co}{}^2 + \lambda_R{}^2\right)^{1/2} - \lambda_R$

λ_{co}~λ_{eig} , and $\lambda_R = \frac{\mu_o}{\psi_{gun}}\,I_{tf}$

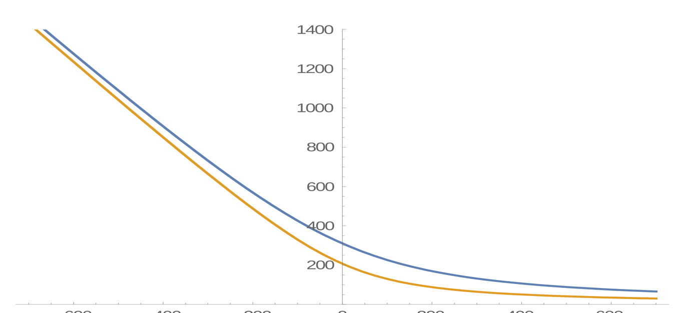

Fig 5b. I_{gun} vs I_{tf} for 15 mWb (blue line) and 10 mWb (orange line) poloidal flux. The currents are in kA.

Depending on the mutual directions of I_{gun} and I_{tf} , the toroidal magnetic field can "help" or hamper the bubble out. To push the same amount of flux, a shaft current with the same sign as the gun current is desirable because it reduces the required gun current considerably.

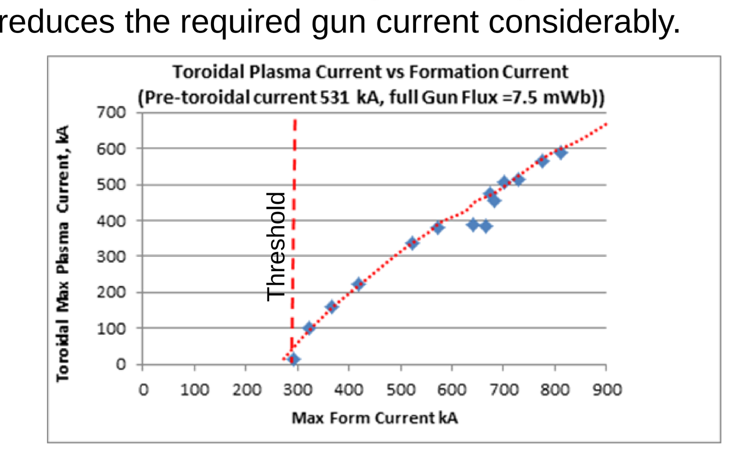

Fig 6. The 250 kA threshold for "bubble-out" determined by experiment in a smaller SPECTOR-type machine is consistent with the prediction of 270 kA by the formula (5). However, it is greater than the theoretically-predicted threshold of 114 kA by formula (6).

Helicity Balance And Plasma Resistive Dissipation

The helicity dissipation and the poloidal energy dissipation time scales can also be estimated from the Corsica simulations as:

helicity dissipation rate $d_K = \frac{1}{K}\frac{\Delta K}{\Delta t}\,[\mu s^{-1}]$,

poloidal energy dissipation rate $d_W = \frac{1}{W_{pol}}\frac{\Delta W_{pol}}{\Delta t}\,[\mu s^{-1}]$.

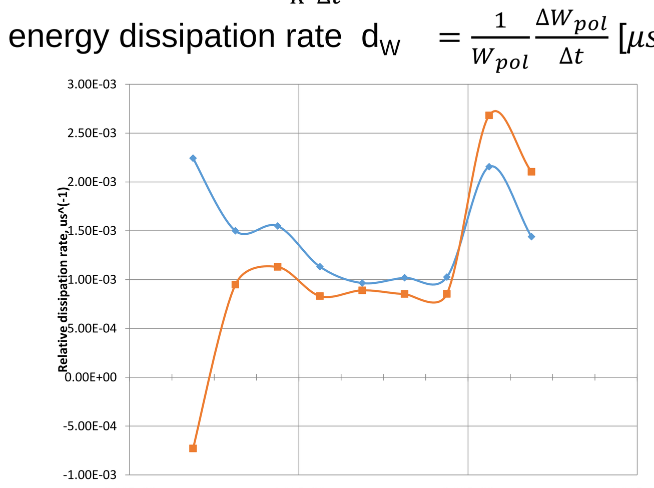

Fig 7. d_K (blue diamonds) and d_W (brown squares) vs. time as deduced from the CORSICA simulations.

The fact that the two time scales are similar is equivalent to the statement that the dynamo term is very small in this system. Therefore, there is likely no significant flux amplification effect. This is a reasonable result, since it is known that the dynamo is not strong in a tokamak-like plasma, unlike spheromaks and reverse field pinches.

It should be noted that an IRE (Internal Relaxation Event) occurred around t= 0.8 ms (Fig 7). During an IRE, the energy dissipation rate somewhat exceeds the dissipation of helicity, so associated dynamo activity in the plasma is possible.

The helicity dissipation deduced from Fig. 7 is in the range 0.3-0.6 s^{-1} (depending on time). On the other hand, when the formation of a CT is finished, the helicity dissipation can be estimated from the Ohmic parallel current term (see Eq.(2) and Eq.(3)).

$$\frac{dK}{dt} = 2\int_{core-sheath} \eta_{\parallel}\boldsymbol{J}\cdot\boldsymbol{B}\;d^3r$$

By assuming a simple constant J/B model [9] and the Spitzer resistivity given by:

$\eta_{\parallel}$ = Zeff $* 0.5 * 10^{-3} * T0^{-1.5} * (1 - r^{\alpha})^{-1.5}$ [W m]

with T_0 being the on-axis temperature in eV, and Z_{eff} , the effective dissipation integral over the volume can be calculated.

The results are plotted in Fig. 8 as a function of T_0 , for Z_{eff} = 2,3 and a= 2,4.

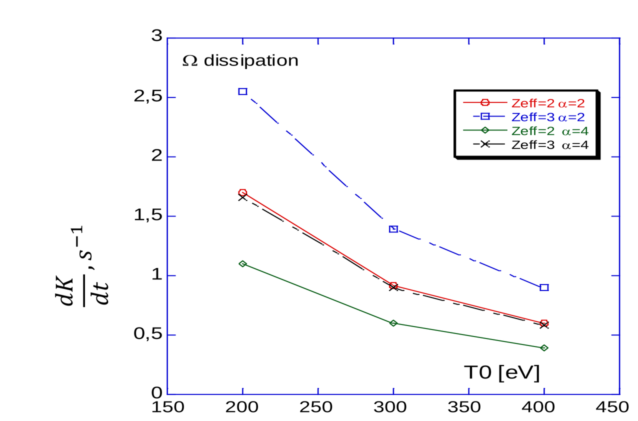

Fig 8. Volume integral of the ohmic helicity dissipation vs T_0.

The helicity dissipation deduced from Fig 7 $(0.4-0.6)s^{-1}$ is of the same order as the helicity dissipation deduced from ohmic dissipation (Fig 8). Since the values of Zeff (2-3) and T_0 (400-450 eV) are within the range measured in SPECTOR, Ohmic dissipation may account fully for the measured helicity dissipation without the need to invoke anomalous dissipation mechanisms or enhanced losses to the surrounding walls.

Discussion And Summary

We found that the helicity injected in the system is about 50% of the available electrostatic helicity.

The helicity and energy balance exhibit the same behavior, implying that flux amplification or a dynamo mechanism is small or absent (at least for times when the equilibrium reconstruction is reliable). High-q tokamaks do not seem to be prone to these effects.

We found that Ohmic dissipation is enough to account for the helicity losses without the need to invoke an anomalous mechanism.

We have begun to compare the experiment to different models for the amount of bubbled-out flux produced by a given gun current. More experiments oriented to this end are needed.

We found that during IRE the helicity is better conserved than energy (Fig.7), which, if confirmed, is an important fact from a basic physics point of view.

References

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