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A Physics model of the rotating halo current during VDE disruption

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Motivation

- From the 2016 campaign, We have observed that n=1 halo toroidal asymmetric current rotate during VDE disruptions.
- The rotation frequency is about several hundreds and is far less then the plasma toroidal flow velocity. The rotation directions are mostly counter-flow & IP and some times the rotating direction flipped opposite direction. It's real puzzle.
- Other devices (DIII-D, JET, etc.) also reported the same phenomena
- Resonant coupling of the rotating EM force to the machine structural vibration might be destructive
- ITER is also concerning this phenomena for safe operation
- No plausible model to explain the phenomena.
- We propose a physics model based on the precession of the angular momentum

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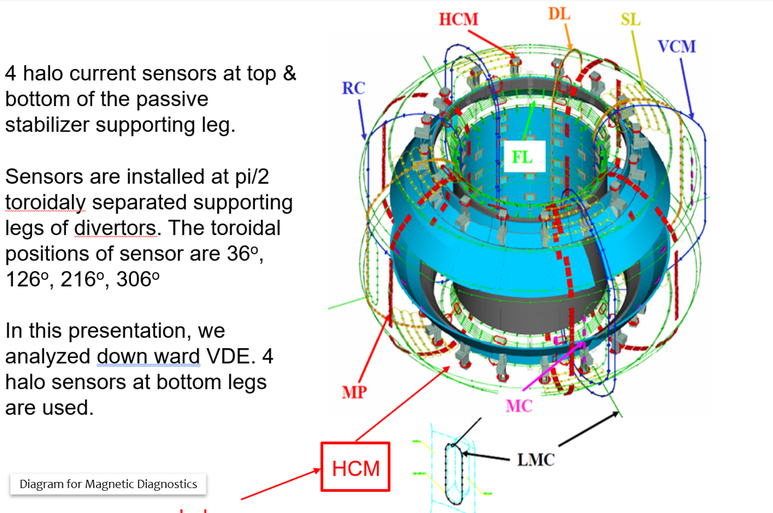
Magnetic Sensors in the Analysis (halo current)

- 4 halo current sensors at top & bottom of the passive stabilizer supporting leg.
- Sensors are installed at pi/2 toroidaly separated supporting legs of divertors. The toroidal positions of sensor are 36°, 126°, 216°, 306°
- In this presentation, we analyzed down ward VDE. 4 halo sensors at bottom legs are used.



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Time series of data during VDE disruption

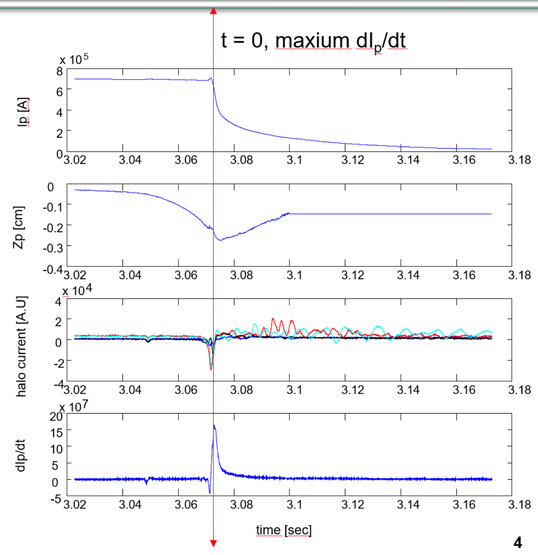
Data used for analysis

Ip : for disruption identification

Zp : VDE direction

Halo Current : Data for analysis

dIp/dt : disruption time identification



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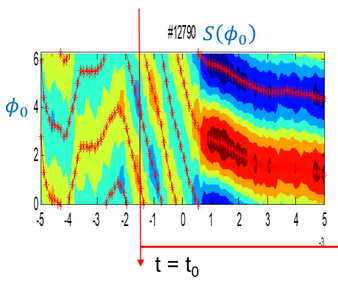
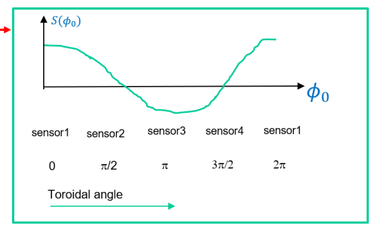
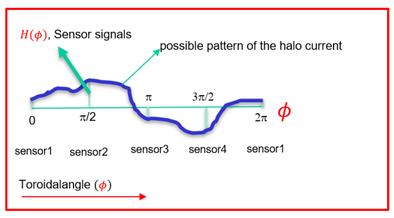
Toroidal Phase of the n=1 Halo Current (from 4 sensors)



- Subtract n=0 component from each signals
- Inner product with the signals of 4 sensors with sinusoidal function having shifted phase of ϕ_0





$$S(\phi_0) = \int_a^{2\pi} H(\phi) \times \sin(\phi - \phi_0)\, d\phi$$

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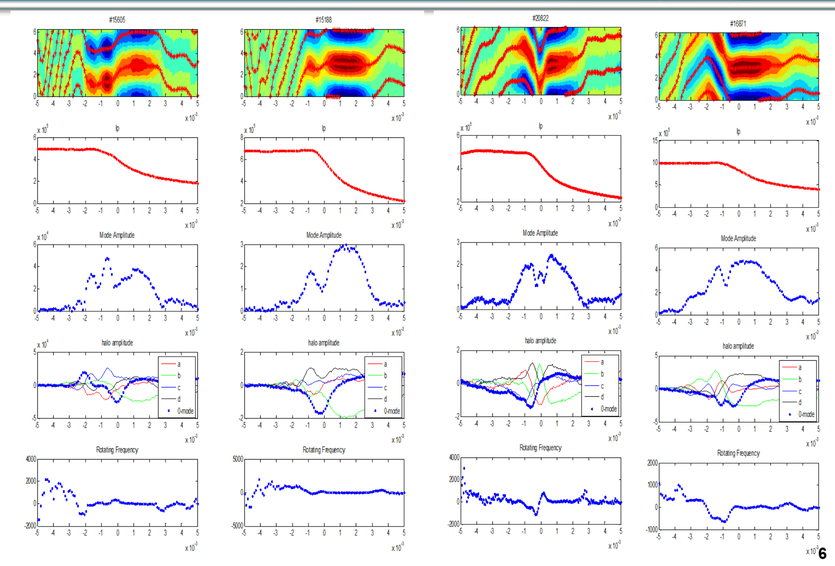
Examples (many turns and rotation flipping)



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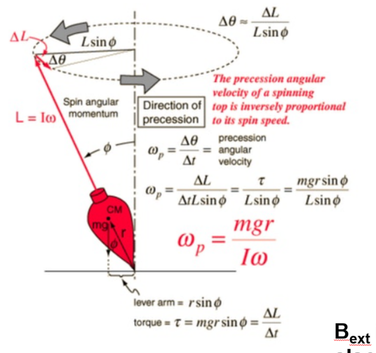
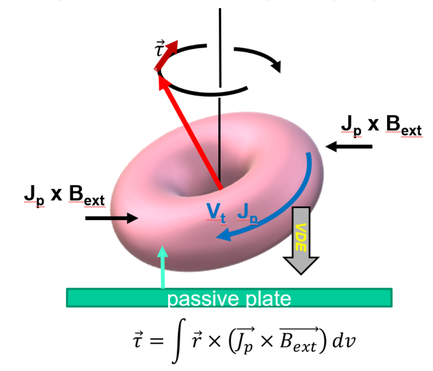
A physics model of the rotating halo current

- **Tokamak plasma has the angular momentum likewise spinning Top**
- **If once it is tilted and an external torque exerted on this spinning Top then the top goes precession.**





B_{ext} include not only magnetic field by PFs but also wall current

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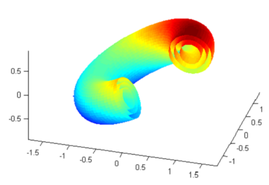
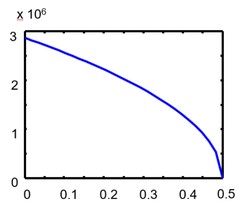
Assumptions for this model

- During violent disruption phase, the equilibrium torus a little tilted by some reason
- Plasma behaviors like solid body with the angular momentum
- Only toroidal plasma current is used in this analysis
- Plasma current on the nested circular torus
- Simple toroidal plasma current profile is used
- Toroidal magnetic field, B_R, B_Z by PF's coils and the induced current on the passive plate are used for $J_{Ip}XB$ force and the torque calculation





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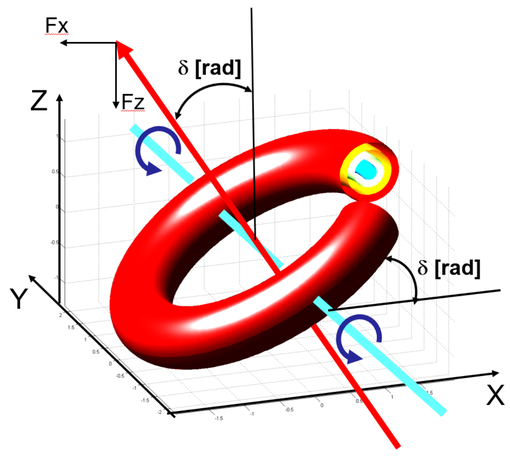
Forces, Torques for the tilted toroid



- Once torus is tilted, then various forces and torques are appear.
- Suppose the torus is tilted around y-axis
- Torque in y-direction gives precession
- Fx, Fz generate y-directional torque and are responsible to the precession of the torus

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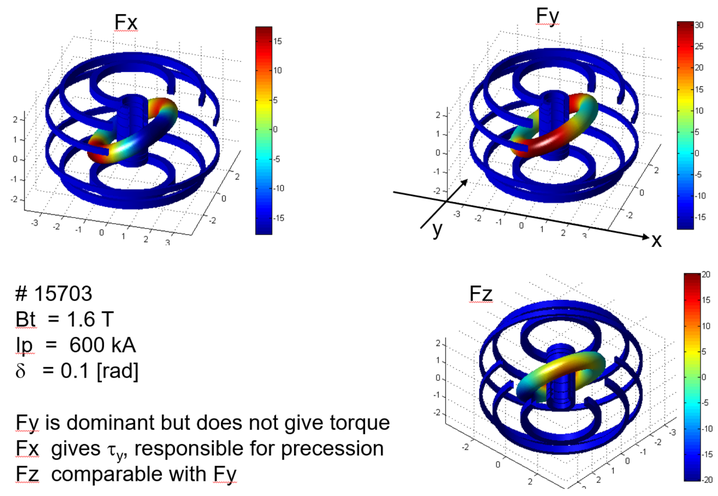
Forces, Torques for the tilted toroid by PFs



# 15703
Bt = 1.6 T
Ip = 600 kA
δ = 0.1 [rad]

Fy is dominant but does not give torque
Fx gives τ_y, responsible for precession
Fz comparable with Fy

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Co-Ip precession predicted without passive plate

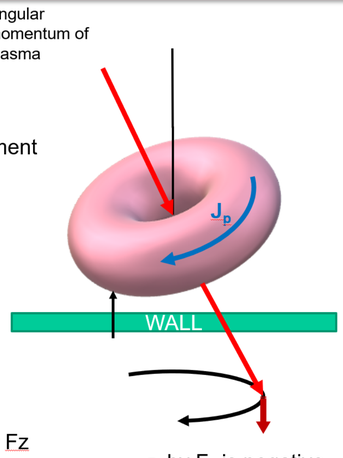
➢ Torque from PF coils

Z = 0
τ_y ~ -10^4 [NM] -> too strong to explain experiment
$\tau_x = \tau_z = 0$

✓ Negative τ_y gives co-current precession
✓ But #15703 halo current in counter-Ip

➢ Torque from passive plate should be considered

✓ wall prevent from free fall of the plasma by Fz
✓ The torque by the wall force ~ Fz
✓ Torque by P.P force give positive τ_y , P.P. effect gives counter-Ip precession



τ_y by F_x is negative -> co-Ip precession

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Induced current on the passive plate must be considered

Why?

- Down force by PFs and TF coil is enormous considering the fact that mass of the plasma is very light.
- But the measured velocity of the VDE is about several 10s meter/sec
- It seems that the passive plate prevent from free falling by J_PxB (PFs, TF)
- Meaning there is almost the same upward force by the passive plate.

How?

- Passive plate assumed as a thin conductor with characteristic conductivity.
  - VDE event occurs for < 10 msec
  - do not need to consider full thickness of coopered plate because there is no time current diffuse to deep inside
  - The characteristic conductivity considered as the cooper plate with the skin depth determined by the VDE time

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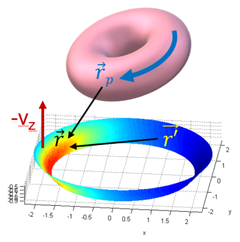
Induced current on the passive plate must be considered

$$-\frac{\partial \vec{A}(r)}{\partial t} = \frac{\mu_0}{4\pi}\vec{V}\cdot\nabla\int_{plasma}\frac{\vec{J}(r_p)}{|r-r_p|}dv_{plasma} - \frac{\mu_0}{4\pi}\int_{p.p}\frac{\frac{d\vec{J}'}{dt}}{|r-r'|}dv'$$

external source by moving plasma current

Self & mutual inductance mutual interaction of each current elements



- Time dependent integration of the equation of the motion should be performed for realistic analysis.
- Here, we deal with the external source (moving plasma current) only for fast check of feasibility.
- Electro motive force on the passive plate by moving down of the Ip can be calculated equivalently by supposing the passive plate is moving up for the simplicity of calculation.
- And the scalar potential is obtained by forcing the divergence free condition of the total electric field on the passive plate.

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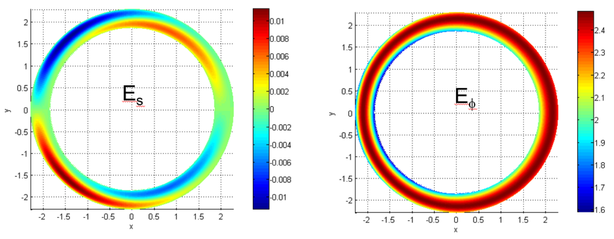
Total Electric field on the passive plate for various conditions (tilt angles, vertical positions) are calculated.

δ = 0.125 rad
Z = -0.3
Vz = 20 m/s



- The total electric field patterns are not sensitive to the tilting angle and vertical position of the plasma
- In this model, the current on the P.P. proportional to the total electric field on P.P.
- The toroidal current on the P.P. has positive – opposite to the plasma current -> upward force
- Even though we don't have enough information of the VDE velocity and realistic conductivity of P.P., The upward force would be balanced with the down force by the PF and TF field.
- By equating these two vertical forces, we can rescale the induced current on P.P and Torque by the P.P.

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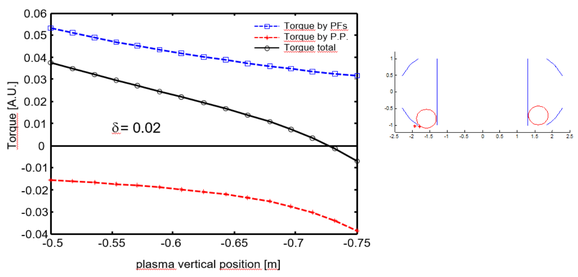
Preliminary results, Total torque τ_y (which gives precession)



- Torque from P.P. obtained by rescaling of induced current to make upward force equal to downward force.
- The sum of PFs and P.P. EM force gives positive y-torque which result in co-IP precession but as the plasma close to the P.P. the total torque inverted implying counter-Ip precession. (reversed halo current can be explained ?)

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Summary & Discussion

- Resonant between the rotation of the halo current and the structural vibration can be a potential danger during VDE disruption
- A physics model (spinning top) to explain the halo current rotation and the direction is proposed
- Controlled experiment show that halo rotation is higher in Ohmic discharge (low angular momentum)
- Higher halo frequency with lower angular momentum is qualitatively agree with the model.
- Rotation reversal when the plasma approach to the P.P. is predicted in this model.
- Passive plate effect will be rigorously considered in future works (time dependent analysis if it needs)

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