Proto-Sphera

A magnetic configuration based on magnetic reconnections

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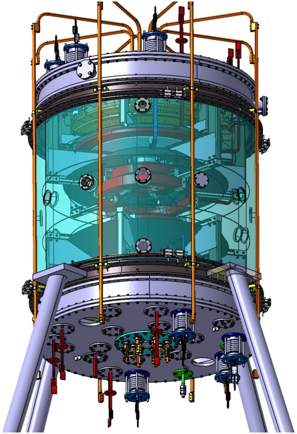
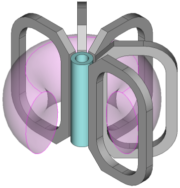
Overview



Background

- What if one removes the tokamak central column and closes the toroidail coils in a plasma column[a]?



[a] **Alladio˙2006**; **Tang˙2006**.

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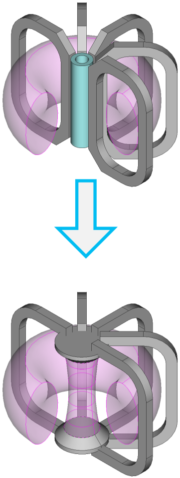
- Large electrodes to reduce local power density, hourglass shape of the central column.
- In absence of the central solenoid, inductive current drive is no more possible.
- The new configuration shall be sustained by some sort of dynamo: the result is more similar to a self organized configuration (Spheromaks, RFPs) than a tokamak



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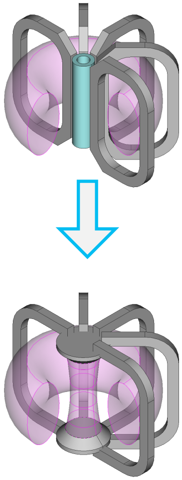
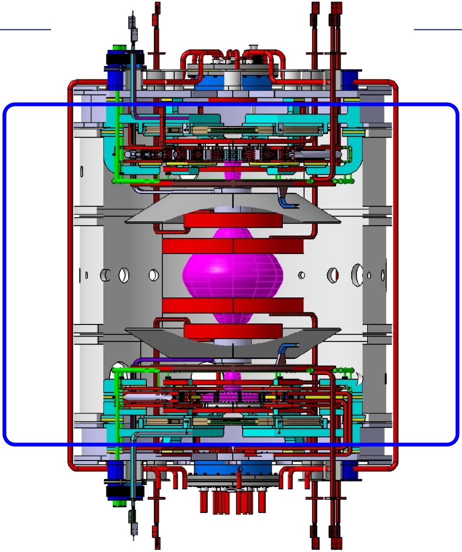


A little Hystory: Proto-sphera project was started in XXXX with PROTO-PINCH TO BE COMPLETED.

[a] Alladio˙2006; Tang˙2006.

Proto-Sphera Layout

- Cylindrical vacuum vassel, orginally SS, now insulating material (policarbonate); "sandwich" like assembly



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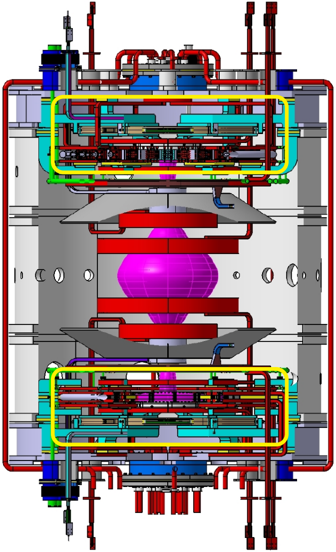

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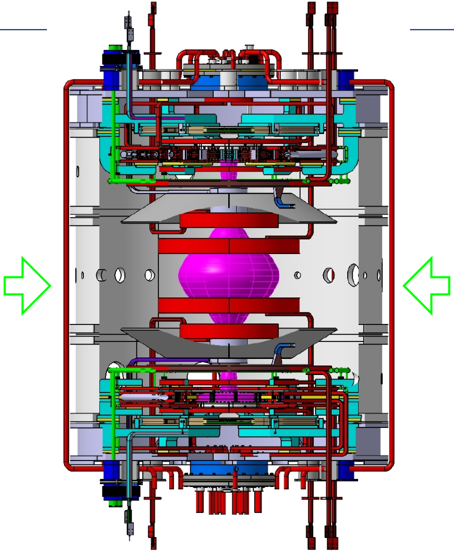

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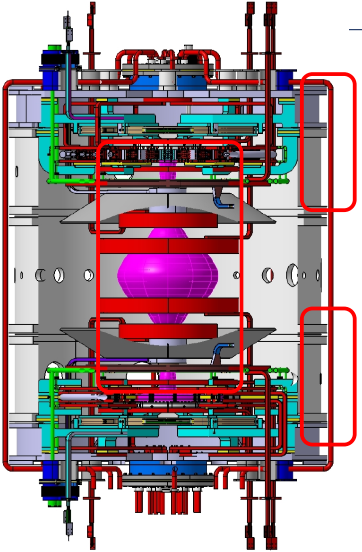

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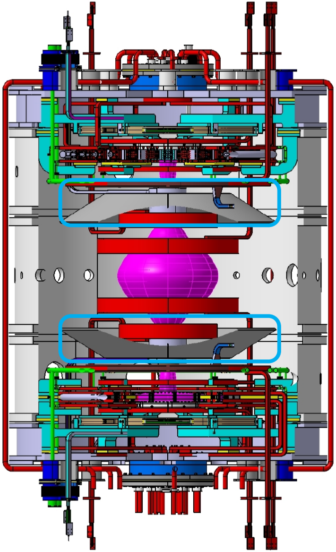
- Limiter structure, mainly to prevent spurious plasma formation around the electrodes



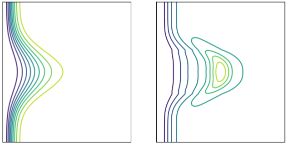
Equilibrium: general picture

Interpretation

- The configuration starts as a screw pinch, loosely confined at the equator
- The systems is almost force free $\nabla P \simeq 0 \rightarrow \mathbf{J}X\mathbf{B} \simeq 0 \quad (\mathbf{J}X\mathbf{B} = \mu \mathbf{J})$[a]
- $\mathbf{B}$ configuration tends to relax to low (magnetic, ∇P is negligible) energy: $\mathbf{B}_* = \mathtt{min}_B \int_V \frac{|\mathbf{B}|^2}{\mu_0}$
- Global magnetic helicity $K = \int_V \mathbf{A} \cdot \mathbf{B}$ is conserved to a certain degree; "weak" conservation is assumed in absence of flux conserver (radial K flux?)

[a]Buratti et al., 2020.

- The cental pinch builds up pitch until a relaxation it is energetically favoured; ψ_p and K are dissipated in the pinch.
- A net toroidal electric field $E_D = \frac{\delta \psi}{\delta t}$ arise as a consequence of DREs;
- K build up again in the pich $\frac{\delta K}{\delta t} = \int_A \mathbf{\Phi B} \approx VB_\perp$, while torus currents and fields decay.



Problem

- Can this mechanism be conitnuously substained?
- Does it result in the presence of an equatorial toroidal closed magnetic domain?
- Is MHD dynamo the only at play? Kinetic contribution[a]?

[a]Prager, 1999.

Equilibrium: GS solutions for poloidal flux

Pinch + torus equilibria be solved numerically, identifying a class of 2 domains maps of poloidal flux which solves the GS *Typically done via finite elements or via a multiparametric flux fucntion definition* classes of Anlytical equilibria has been identified[a] Under the assumptions

- current: $I \propto \psi, \quad I' = \frac{dI}{d\psi}, \mu = \mu_0 I'$
- pressure: $\mu_0 p' = \mu_0 \frac{dp}{d\psi} = \alpha/4\pi,$, which correspond to a FF state for $\alpha = 0$

The GS can be linearized
$$R^2 \nabla \cdot \left(\frac{1}{R^2} \nabla \psi \right) + \mu^2 \psi = -\alpha R^2 = 0 \quad (FF)$$

[a] Buratti et al., 2020.

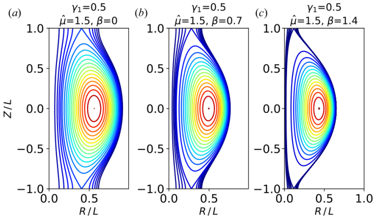


Figure: An. equilibrium variation as a β increases, left is FF - from[a]

[a] **Buratti¨2020**.

Introducing the amplification factor, as $A = \psi_{ma}/\psi_0$, and $\lambda \mid \nabla X\mathbf{B} = \lambda \mathbf{B}$ relaxation param, defines the 2D operational space of the machine.

Equilibrium: Currents, Stability

Global stability

To address stability (tilt stability), also torus elongation $e{=}h/a$ shall be accounted; elongation is a design parameter
Intuitively, torus tilts are stabilized by the pinch presence and by oblate vs prolate plasmas
A tilt acts against field lines tension in the pich and against volume expansion in an oblate torus [a]

$$f_T = \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0}$$

$$f_T = \frac{B^2}{\mu_0}\kappa, \quad \kappa = (\mathbf{b}\cdot\nabla)\mathbf{b}$$

b being the field versor, κ a curvature in field lines
This can be addressed formally[b]; stability decrease with A and e.

[a] Plasma bulk rotation may be stabilizing in an analogue way but is probably negligible

[b] L. G. Lampugnani, Garcia-Martinez, and R. Farengo, 2017.

1

Current patterns and Local stability

The parameter λ determines the shear of magnetic field, so the safety factor q inside the torus; other boudaries

- Total Z current in the pich is fixed
- *in absence of current sheets*, **B** pitch will varying continuously between pinch and torus

q profile and torus aspect ratio determine presence and position of resonances for CDM.
Torus modes dynamics shall necessarily be addressed, ifluencing

- Stability [a]
- Turbulence and transport
- Dynamo mechanism

[a] as in RFPs a saturation mechanism may intervene

[1] L. G. Lampugnani, Garcia-Martinez, and R. Farengo, 2017.

3D viscoresistive model

An axysimmetrics model is useful as a reference, but in order to follow properly the processes, axysimmetry must be broken
Attempts have been mabe to use fully 3D viscoresistive codes, optimized for other FF configurations[a])

- Boundary condtions, in particular the absence of a flux conserver and the presence of a vertical field
- Long time evolution → torus evolution, subsequent cycles, presence and dynamics of merging tori

[a] García-Martínez, Leandro Gabriel Lampugnani, and Ricardo Farengo, 2014.

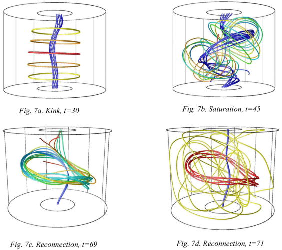


Figure: from[a]

The simulations catch the kink destabilization and the torus onset; open boundary to be addressed

[a] **Farengo˙2008**.

Pinch DREs and Tori evidences

Main Plasma Parameters in PS phase 1

- Pinch current 10 kA, Torus current $\approx$ 1kA, Discharge duration 0.5 s
- T_e 10-50 keV, $n_e \approx 10^{18} m^{-3}$

DRE can be traced as B_z crashes near the axis ("flux expulsion")

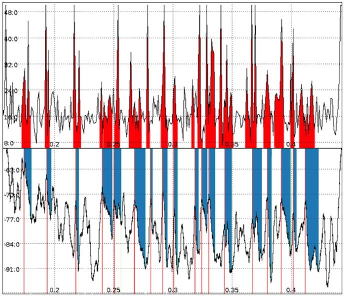


Figure: Negative $\frac{dB_z}{dt}$ phaseS correlate with T_e surges

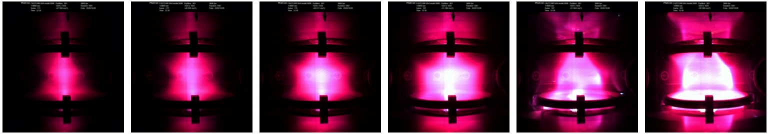
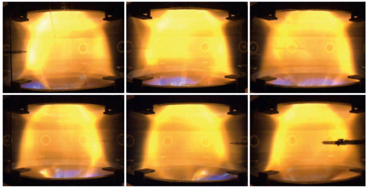


Figure: Argon pinch and torus formation in He

Visible tomography to track torus onset

Currently, to retrieve information on plasma topology, a visible camera tomography is used[a]:

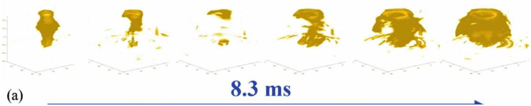
- 6 cameras, equatorial plane, looking through the transparent vessel
- numerical inversion to reconstruct the 3d emission pattern



(a)

Figure: single time cameras frames example

[a]Damizia et al., 2021; Pau et al., 2025.



An annular radiative scructure is detected[a]. Can this be interpreted as a torus?

1. Spacial Symmetry: a Kink $\rightarrow$ Reconnection dynamics is identified; cylindrical symmetry hardly achieved
2. Time evolution: is the radiative toroid stable beyond resistive diffusion time scale?

[a]Alladio et al., 2024.

Rationale of laboratory astrophysics and scaling laws

Plasma phenomena can be considered invariant under proper scale transformations[2], which involves length scale r, time scale t, magnetic field B, velocity v, pressure and density p, ρ

$$\mathbf{r} = a\mathbf{r_1}, \quad \rho = b\rho_{\mathbf{1}}, \quad \mathbf{p} = c\mathbf{p_1}$$

$$\mathbf{t} = a\sqrt{\frac{b}{c}}\mathbf{t_1} \quad \mathbf{v} = a\sqrt{\frac{c}{b}}\mathbf{v_1}, \quad \mathbf{B} = a\sqrt{c}\mathbf{B_1}$$

Once accounting dissipative phenomena, $\frac{\tau_A}{\tau_R}$ shall be conserved[3,4]

Just a recall: Why are we interested in scaled astrophysical models?

- lab plasmas are easier to diagnose, phenomenology are better understood
- numerical models can be benchmarked
- parameter space usually easier to explore

Note: A collaboration with INAF is ongoing

[2] Ryutov, Drake, and Remington, 2000.

[3] Bouquet et al., 2010.

[4] Ryutov, 2018.

Relevant astrophysical objects

which FOM shall be adressed in a lab astrophysics model?

- **Topology /simmetry**: plasmoid diven by reconnections in almost force-free enviroment)
- **Phenomenolgy** Reconnections, Dynamo

As for topology, any disk-jet configuration may be eligible, but

- Disk-jets are not raeally force free (gravity).
- They tend to average global K at 0 (twist is symmetrical with respect to equator).

Interaction/downflow regions of jets may be candidates[5], with plasmoid-like axisymmetric KH instabilities ;
Low collisionality in jet downstream $\rightarrow \tau_r/\tau_A$ scaling tends to be inconsistent
Solar/stellar atmosphere is a better phenomelogy candidate:

Quantity	PS	SA	scaling par value
Temperature eV	10-100	1-10	c/b= 0.1
Density m^{-3}	10^{13}	$10^{12} - 10^{16}$	b= 10
Lenght scale m	1	10^{6}	a= 10^{6}
Time scale s	$10^{-2} - 10^{-1}$	$0.3 - 3 \cdot 10^{4}$	$a \cdot \sqrt{\frac{c}{b}} = 3 \cdot 10^{5}$
B T	$10^{-2} - 10^{-1}$	$10^{-2} - 10^{-1}$	c=1
Flow v m/s	$< 10^{3}; expec. 10^{4}$	few $10^{4} \rightarrow 10^{5}$	$\sqrt{\frac{c}{b}} = 0.3$

Table: scaling from PS to SA

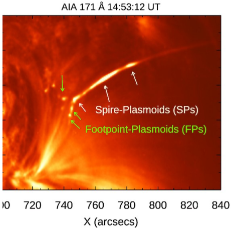


Figure: blobs and plasmoids in SA,[a]

[a] **Mulay˙2022**.

[5] **Christie˙2018**.

Current status and required upgrades

In order to be relevant as a fusion POP and a lab astro experiemnt, Proto-Sphera shall be upgraded

1. **Performances**: the toroid configuration shall be achieved continuously or quasy continuosly $\rightarrow$ higher K injection ratio $\rightarrow$ higher pinch current
2. **Diagnostics**: Information is needed on
   - Plasma equilibrium and topology (T_e, n_e, $\mathbf{B}$)
   - Plasma Kinetics
   - MHD activity

Currently, Pinch current is limited to 10 kA and the diagnostics set features:

- Visible cameras (fast and tomography)
- A single line dispersion interferometer @ 1064-532 nm
- An equatorial languir probe (T_e) and a Hall probe
- A visible spectrometers?

The experiment is currently being re-assembled in a wider experiment hall.

Phase II: foreseen operation

Major machine improvements addresses high current operation

- Pinch current from 10 kA up to 70 kA
- Cathode upgraded to widthstand higher current density
- Improvement of internal insulation $\Longleftrightarrow$ Probing of floating potential.

Main goal is to obtain stable tori in a reliable way

- Torus duration/extension statistics
- Scaling of torus current vs pinch current
- Dynamo Characterization (time dynamics, links with MHD, kinetics)
- Assessment of confinement and transport (scaling vs current and MHD activity)

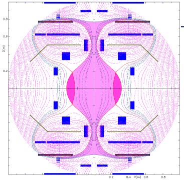


Figure: 10 kA equilibtrium model

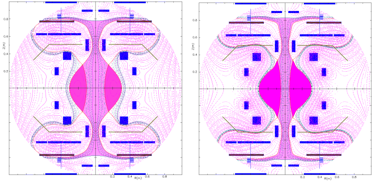


Figure: 30 to 70 kA equilibtrium model, A $\rightarrow$ 2

Longer run: atlernate/complementary torus sustainement techniques: Helicity injection by B modulation (OFCD,[6]) Alfven Wave Current drive ([7])

[6] McCollam et al., 2007.

[7] Elfimov, 1995; Torasso and Tataronis, 2022.

Phase II: required diagnostics

The current diagnostic setup is commissioning-focused and is unadequate to track properly the complex PS phenomelogy.

1. **Plasma equilibrium and Kinetics**
    - multipulse TS, recicled as possible from FTU, collinear with Interferometer (Xcalibration)
    - Internal **B** measurement, a multipass tangential polarimeter is being evaluated
    - Xrays detectors to get information on electron kinetics
2. **MHD activity**
    - 2D magnetic probes array covering at least a toroidal sector near the equator
    - a tracker pellet injector (centrifugal?): fast cameras can follow **B** pitch and plasma flow

The number of accesses (eq ports) is limited to 12 100 mm windows, careful integration is needed

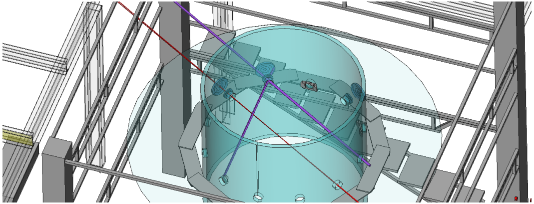


Figure: diagnostic layout TO BE UPDATED with LEGEND .

Conclusions and perspectives

- Proto-Sphera is a unique self organized experiement
- It is relevant to basic plasma phisics and as a laboratory astrophysics model.
- Phase II operations and improvements in the diagnostics coverage are crucial to assess the PS configuration physics
- Depending on plasma confinement scaling as power increases, it has to potential to be be a fusion relevant configuration
- In the framework of Frascati Research center, it is strategic for technology transfer and young scientist training
- We welcome collaborations, especially addressing modelling and diangostics.

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Thanks

APP1: toroids and astrophysical jet

Qua in appendice discuterei velocemente esempi di strutture jet-toro, scaling, trasporto momento (citerei MRI) e topologia ...