Proto-Sphera

A magnetic configuration based on magnetic reconnections

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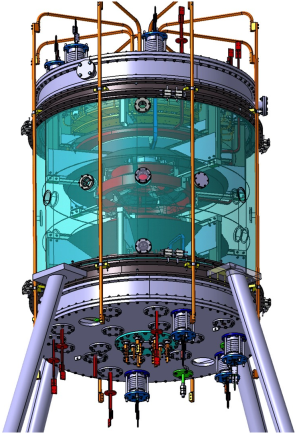
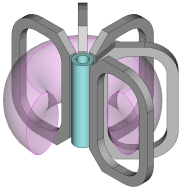
Overview



Background

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



[a]F. Alladio et al., 2006; Tang and Boozer, 2006.
[b]Franco Alladio, Grosso, et al., 2000.

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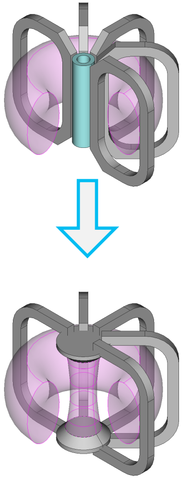
- Large electrodes to reduce local power density, hourglass shape of the central column.
- In absence of the central solenoid, inductive current drive is no more possible.
- The new configuration shall be sustained by some sort of dynamo: the result is more similar to a self organized configuration (Spheromaks,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



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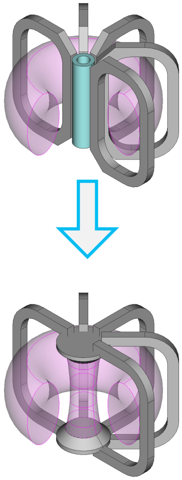
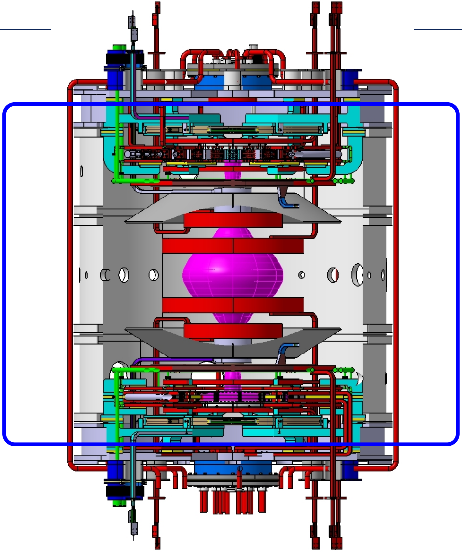


A little Hystory: Proto-Sphera design started in 90's; assembled in 2000's with arrival of START VV from Culham and with PROTO-PINCH experiement ($\approx$ 20 cm, 600 A)[b]

[a] F. Alladio et al., 2006; Tang and Boozer, 2006.
[b] Franco Alladio, Grosso, et al., 2000.

Proto-Sphera Layout

- Cylindrical vacuum vassel, orginally alluminium, now insulating material (policarbonate). *Sandwich* like assembly



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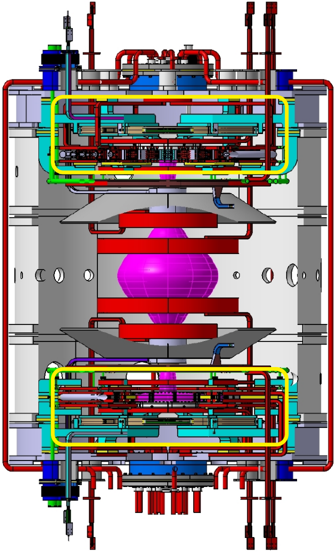
- Annular anode/cathode assemblies. W filaments heated cathode



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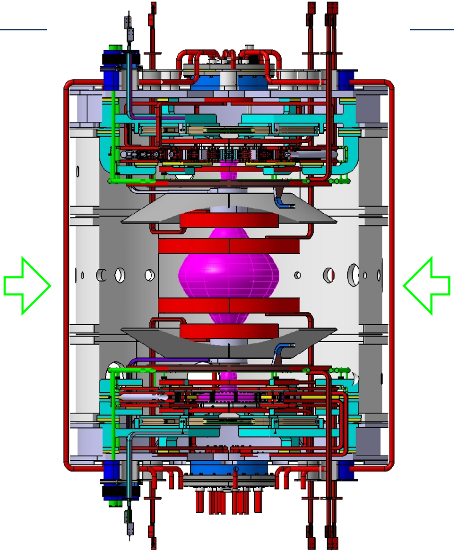

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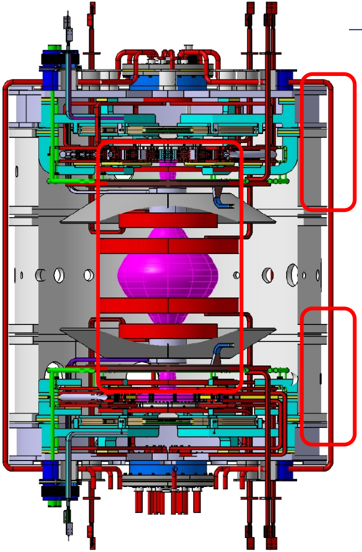

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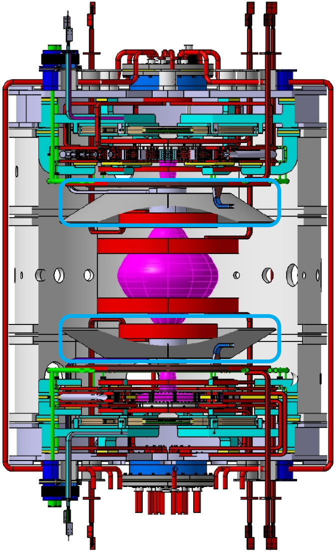
- Conical limiter structures, mainly to suppress spurious plasma formation outside the pinch



Equilibrium: general picture

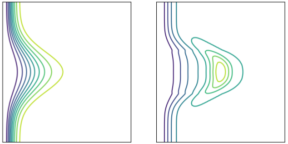
Interpretation

- 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: $\mathbf{B}_* = \min_B \int_V \frac{|\mathbf{B}|^2}{\mu_0}$: Taylor state.
- Global magnetic helicity $K = \int_V \mathbf{A} \cdot \mathbf{B}$ is conserved to a certain degreee; "weak" conservation is assumed in absence of flux conserver
- Radial K flux assumed in the description. Dynamics in the pinch external surface/region considered critical

[a]P. Buratti et al., 2020.

Cycle

- The central 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 $E_D = \frac{\delta\psi}{\delta t}$ arises as a consequence of DREs. Global K conserved since $\frac{dK}{dt}\frac{1}{K} \approx \tau_r >> \tau_{DRE}$;
- K builds up again in the pinch $\frac{\delta K}{\delta t} = \int_A \Phi\mathbf{B} \approx VB_\perp$, while torus currents and fields decay.



Problems

- Can this mechanism be continuously sustained?
- 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 GS have been solved numerically[a], identifying classes of 2 domains ψ maps.
Semi-analytical equilibria calculation possible[b] assuming:

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

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

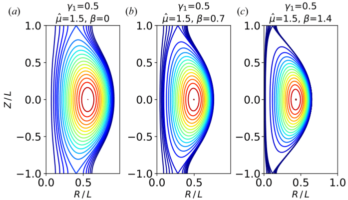


Figure: S. An. equilibrium variation as a β increases, left is FF - from[c]

[a] F. Alladio et al., 2006.
[b] Tirozzi and Buratti, 2021.
[c] P. Buratti et al., 2020.

Num. solutions obrained via finite elements or multiparametric flux fucntion definition

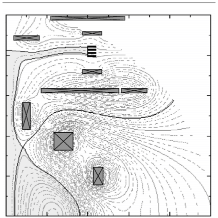


Figure: Num. eq.; high $A = 3 \quad I_p = 60kA$, from[a]

Ultimately, the machine operational space is defined by:

- $A = \psi_{ma}/\psi_0$, amplification factor, ψ_{ma} on torus axis
- $\lambda \mid \nabla X\mathbf{B} = \lambda\mathbf{B}$ relaxation parameter

[a] F. Alladio et al., 2006.

Equilibrium: Stability, q

Global stability

Intuitively: Torus elongation $e=h/a$ and *pinch/torus* ratio; elongation is a design parameter.

- Torus tilts are stabilized by the pinch presence and by oblate vs prolate plasmas; limits exist due to kink ($n=1$) destabilization of pinch plasmas[a]
- A tilt acts against field lines tension in the pich and against volume expansion in an oblate torus [b]
  $f_T = \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0} = \frac{B^2}{\mu_0}\kappa, \quad \kappa = (\mathbf{b}\cdot\nabla)\mathbf{b}$
  b being the field versor, κ a curvature in field lines.
- Semi-analytical approach[c]: Torus stability decreases with A and e
- Numerical approach[d]: I_p limit and β role ($\beta_{lim} \propto I_p/I_t = 1/A$), also confirm stability with respect to N=2,3 modes

[a] P. Micozzi et al., 2010.

[b] Bulk rotation may be stabilizing in an analogue way but probably negligible, v_{rot} fews $10^2 m/s$

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

[d] P. Micozzi et al., 2010.

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 vary 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, influencing

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

Measurements needed

[a] as in RFPs a saturation mechanism may intervene

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]). Open points:

- Boundary conditions, in particular the absence of a flux conserver and the presence of a vertical field
- Full geometry of pinch, featuring also electrodes region
- Long time evolution $\rightarrow$ torus evolution, subsequent cycles, presence and dynamics of merging tori (pinch/torus interface)

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

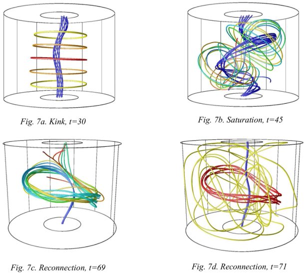


Figure: Frames from[a]

- The simulations catch the kink destabilization and the torus onset
- Collaboration ongoing to address open boundary problem.

[a]Farengo et al., 2008.

Pinches, DREs and emerging Tori

Main Plasma Parameters in PS phase 1

- Pinch current 10 kA, Torus current $\approx$ 4kA, Discharge duration 0.5 s
- T_e 10-50 eV, $n_e \approx 10^{18} m^{-3}$

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

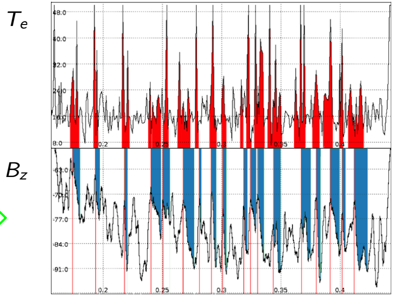


Figure: Negative $\frac{dB_z}{dt}$ phaseS correlate with T_e surges

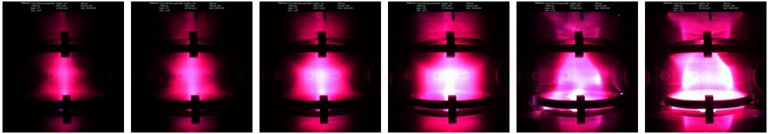
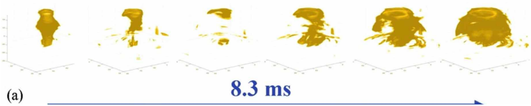


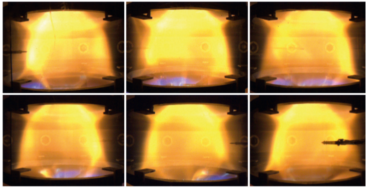
Figure: Argon pinch and torus formation in He

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 → Reconnection dynamics is identified; cylindrical symmetry hardly achieved
2. Time evolution: is the radiative toroid stable beyond resistive diffusion time scale?

[a] Franco Alladio, Paolo Micozzi, et al., 2024.

Rationale of laboratory astrophysics and scaling laws

Plasma phenomena can be considered invariant under proper scale transformations[1], which involves length scale r, time scale t, magnetic field B, velocity v, pressure and density p, ρ

$$\mathbf{r} = a\mathbf{r_1}, \quad \rho = b\rho_1, \quad \mathbf{p} = c\mathbf{p_1}$$
$$\mathbf{t} = a\sqrt{\frac{b}{c}}\mathbf{t_1} \quad \mathbf{v} = a\sqrt{\frac{c}{b}}\mathbf{v_1}, \quad \mathbf{B} = a\sqrt{c}\mathbf{B_1}$$

Once accounting dissipative phenomena, $\frac{\tau_A}{\tau_R}$ shall be conserved[2,3]

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

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

[2] Bouquet et al., 2010.

[3] Ryutov, 2018.

Relevant astrophysical objects

Which Figure of Merit 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 really 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[4], 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 another possible phenomelogy candidate:
Ionization ratios in SA and SJ? Ongoing work

Quantity	PS	SA	scaling par value
Temperature eV	100 ev	2-300 eV	c/b= 0.5-1; c= 10^4
Density cm^{-3}	$10^{12} - 10^{13}$	$5 \cdot 10^8$	b= 10^4
Lenght scale m	1	10^6	a= 10^{-6}
Time scale s	$10^{-3} - 10^{-2}$	100-1000	10^{-5}; $a \cdot \sqrt{\frac{b}{c}} = 10^{-6}$
B T	$10^{-3} - 10^{-2}$	$10^{-2} - 10^{-1}$	0.1; $a \cdot \sqrt{c} = 10^{-4}$
Flow v m/s	$< 10^3$	$10^4 \rightarrow 10^5$	10^{-2}; $a\sqrt{\frac{c}{b}} = 10^{-6}$

Table: scaling from PS to SA

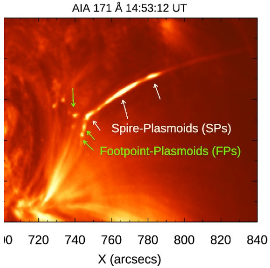


Figure: blobs and plasmoids in SA,[a]

[4] Christie et al., 2018.

[a] Mulay et al., 2022.

Current status and required upgrades

In order to be relevant as a fusion POP and a lab astro experiement, 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 LOS dispersion interferometer @ 1064-532 nm
- An equatorial languir probe (T_e) and a Hall probe
- A fiber-coupled visible spectrometer

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)

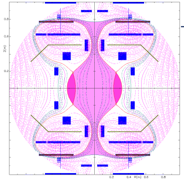


Figure: 10 kA equilibtrium model

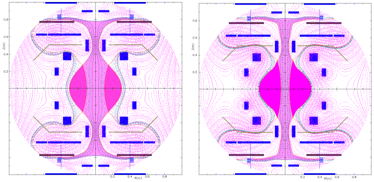


Figure: 30 to 70 kA equilibtrium model, A $\rightarrow$ 2

Longer run: atlernate/complementary torus sustainement techniques: Helicity injection by B modulation (OFCD[5], Alfven Wave Current drive ([6])

[5] McCollam et al., 2007.

[6] 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.

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

1. **Plasma equilibrium and Kinetics**
   - Multipulse TS, recicled as possible from FTU, collinear with Interferometer (X-calibration)
   - Internal **B** measurement, a multipass tangential polarimeter is being evaluated
   - Xrays detectors to get information on electron kinetics

2. **MHD activity, Dynamo**
   - 2D magnetic probes array covering at least a toroidal sector near the equator
   - Tracker pellet injector (centrifugal?): combined with fast cameras can reconstruct:
     - **B** pitch
     - plasma flow v

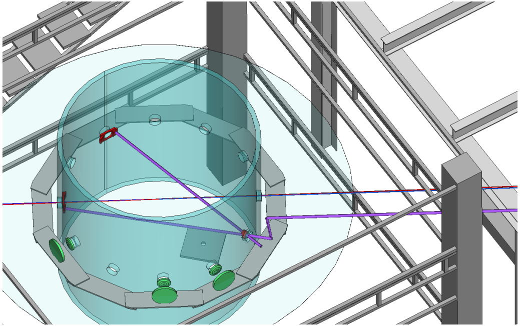


Figure: Possible layout for laser diagnostic: red and blue, TS and DI beams, green TS collection optics, purple POL beams

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 ...

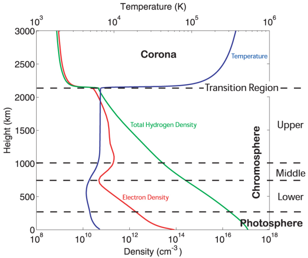

Figure: P. Song 2017 ApJ 846 92, 10.3847/1538-4357/aa85e1

Quantity	PS	SA	scaling par value
Temperature eV	100 ev	2-300 eV	c/b= 0.5-1; c= 10^4
Density cm^{-3}	$10^{12} - 10^{13}$	$5 \cdot 10^8$	b= 10^4
Lenght scale m	1	10^6	a= 10^{-6}
Time scale s	$10^{-3} - 10^{-2}$	100-1000	10^{-5}; $a \cdot \sqrt{\frac{b}{c}} = 10^{-6}$
B T	$10^{-3} - 10^{-2}$	$10^{-2} - 10^{-1}$	0.1; $a \cdot \sqrt{c} = 10^{-4}$
Flow v m/s	$< 10^3$	$10^4 \rightarrow 10^5$	10^{-2}; $a\sqrt{\frac{c}{b}} = 10^{-6}$

Table: scaling from PS to SA

Quantity	PS	SJ	scaling par value
Temperature eV	100 ev	0.1-1 keV	c/b= 0.1; c= 10^6
Density cm^{-3}	$10^{12} - 10^{13}$	$10^4 - 1010^6$	b= 10^7
Lenght scale m	1	$10^9 - 10^{10}$	a= 10^{-9}
Time scale s	$10^{-3} - 10^{-2}$	1-10y $10^8 s$	$10^{-10}, 10^{-11}$; $a \cdot \sqrt{\frac{b}{c}} = 10^{-9}, 10^{-10}$
B T	$10^{-3} - 10^{-2}$	10^{-8}	$10^5 - 10^6$; $a \cdot \sqrt{c} = 10^{-6}$
Flow v m/s	$< 10^3$	$few 10^5$	10^{-3}; $a \cdot \sqrt{\frac{c}{b}} = 10^{-9}$

Table: scaling from PS to SJ[a]

[a] Rodríguez-Kamenetzky et al., 2025; Gerrard, Federrath, and Kuruwita, 2019.