Equilibrium and dynamo interplay in ProtoSphera and implications for diagnostics.

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Abstract

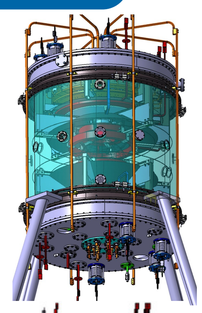
ProtoSphera is a unique plasma configuration consisting of two distinct domains: a plasma column surrounded by a low-aspect ratio torus. The plasma column is a screw pinch formed by a DC discharge (70 KA) between two ring shaped electrodes; the column shape is reminiscent of a double hourglass, resulting in a central expanded region, where an annular current structure (torus) is allowed to develop as a result of magnetic relaxation. Unlike other self-organized configurations, ProtoSphera lacks a flux conserver and is stabilized thanks to the presence of the central pinch.
The torus current is likely sustained through a dynamo mechanism and in particular through an outward helicity flux; helicity conservation typical of Taylor states is expected to hold in weaker form in absence of flux conserver.
The configuration topology and the foreseen equilibria will be discussed addressing in particular the time and spatial scales of dynamo mechanisms and helicity transport. In particular, time dynamics and space scale of MHD activity at the column-torus interface are critical to discriminate between discrete and quasi-stationary contributions for current drive in the torus, where discrete events are more detrimental in term of topology disruption and decrease in overall confinement. Besides, characterization of plasma temperature, density and transport is crucial to identify kinetic contributions to the dynamo field, as a results of particle diffusion or differential trapping.
The onset and permanence of a closed-surface magnetic domain is consistently found in fast camera data, in images as well as in tomographic reconstructions. On the other hand magnetic arrays and optical diagnostics are needed to fully characterize ProtoSphera dynamics and are still under finalization; notably, quantitative data are lacking on current distributions, density and temperature gradients, spectra of MHD perturbations.
Diagnostic design criteria adopted to maximize the achievable information, in particular to discriminate different dynamo mechanisms, are discussed in view of the foreseen step-up in the experiment performances.

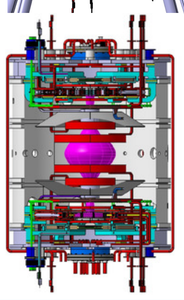
The Proto-Sphera experiment



Protosphera starts as a plasma pinch driven by annular electrodes [All+24], ≈2 m long. It is MHD stable for low n[Mic+10] even in absence of flux conserver. It features:

- Cylindrical vacuum vassel, orginally alluminium, now insulating material (policarbonate). *Sandwich* like assembly
- Annular anode/cathode assemblies. W filaments heated cathode
- "Toroidal coils" loop which closes the central column current
- Vertical field coils and plasma shaping coils: two squeezing assemblies to lock the plasma column, larger coils near the equator → double "hourglass" shape
- Conical limiter structures, mainly to suppress spurious plasma formation outside the pinch

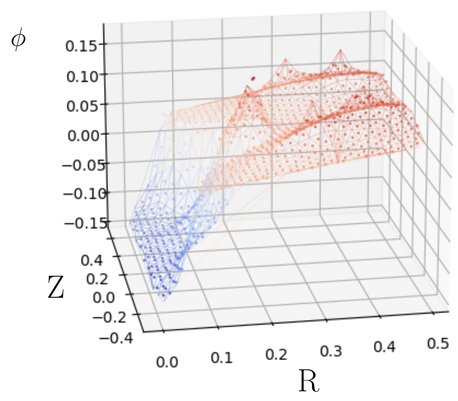




2D Equilibrium model

Assumptions:

- Equilibrium is approximated by a Force Free configuration ($JXB \approx 0; J \parallel B$); ∇P is either negligible or can be treated with a perturbative approach ($\phi_T = \phi_{FF} + \phi(P) \simeq \phi_{FF}$).
- In the two domains j, pinch and torus, B^j_θ, B^j_ϕ are described by a BFM: $B_\theta \propto J_1(\mu r), B_\phi \propto J_0(\mu r)$. Different μ_j translates in different current densities; [LGF18]
- The field pitch is continuous at the boundary r_B, no current sheets persist outside DRE $B^T_\theta(r_B)/B^T_\phi(r_B) = B^P_\phi(r_B)/B^P_\theta(r_B)$ (current density profile cannot be assumed to be strictly continuous → finite transition layer);
- Rotation is negligible; it can be accounted but only as a rigid body (constant Ω)



Model is under finalization, preliminary results

Equilibrium model is vital to determine:

- Safety factor profile (Magnetic perturbation localization, scale)
- Helicity and magnetic energy integrals and hence losses through DRE
- Diagnostics allocation/resolution etc

Equilibrium model shall be validated:

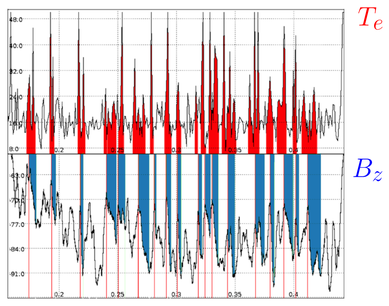
- Diagnostics data shall constrin B, J
- Sustainement by palusible, measured Dynamo mechanism

Plasma Phenomenology





- Limited diagnostic coverage: visible camera array (allow for 3D emissivity reconstrution [Pau+25]), Rogowski coils, Langumuir probe, dispersion interferometer (under commissioning).
- Kink instabilities documented by cameras, occurence depends on gas (resistivity/ionization ratio?).
- As current increases, plasma expands on the equator and a toroidal emissivity structure arises.
- Evidencies of Dynamo relazation events in magnetic flux and Langmuir T_e dynamics.



Torus dynamics and nature (separated domain, emissivity structure, hotter trapped particles in the mirror?) require an extended diagnostics set.
Topology recosntruction is crucial.

Dynamo Phenomenology and candidates

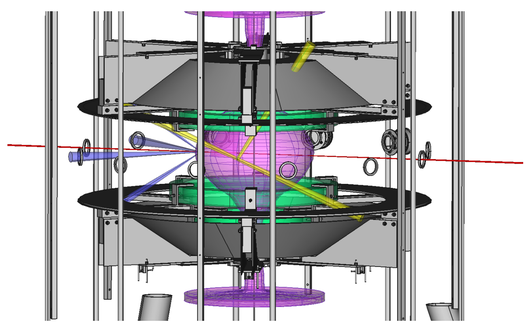
Evidencies of DRE in flux sawtooth; Eq model points out a dissipation in total magnetic energy $\int_V B^2/\mu_0$
Torus lifetime ($\approx 10ms$)is more than foreseen relaxation time ($\tau =$)
From equilibrium models trough a sawtooth, Global helicity $\int_V A \cdot B$ is not conserved; a radial helicity flux accounts for torus sustainment.
Candidates

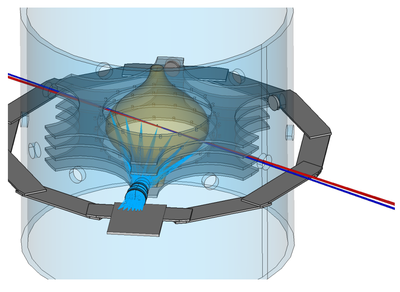
1. "Topological" Dynamo: current ropes gets snapped and reconnetted around the pinch, then merge with the torus [Pra99]
2. MHD turbulent dynamo; coupling between Torus and pinch[HZS06] instabilities
3. Kinetic dinamo: particles diffuse trhough the separatrix carrying current and momentum

External flux surfaces are expected to be ergodized in case 1 and 2 (Chirikov overlap); Case 2 may be associated to excitation of resonant perturbations in the torus (q factor evaluation becomes important)
Case 3 may be related to the presence of NT populations which carry a substantial part of current pinch [BP11]. Appears unlikely (pinch voltage is limited), however requires a quantification of electron kinetics in the pinch and at the boundary layer.
To conclude, the diagnostics setup shall address:

1. Conservation level of flux surfaces- (particle diffusion, kinetic gradients etc); topology reconstruction and filed line tracking. Tours and in particluar Boundary Layer are critical to assess equilibrium and field ergodization.
2. MHD activity, in particular for low wavenumber resonant perturbations; presence and lifetime of islands in the kinetic profiles.
3. Distribution functions of charge carriers (e^- in practice) in the pinch and at the boundary. Presence and characterization of trapped populations.

Laser diagnostics





- Ts ability to resolve cm-size flattening/peaking in the profile:
  $N_\nu(E = 1J, l_s = 1cm, n_e = 10^{19}, \Omega = 5 \cdot 10^{-4} \approx 500$ marginal, recoverable with multipass, laser energy raise, multiple collection optics. Double angle (multipass) also important to increase DOF in the electron DF reconstruction (NT populations, trapped particles in pinch).
- TS ability to measure current density J:
  Spectrum FWHM @ λ_i 1064 nm, 100 eV, $\theta = 70 \approx 64$ nm
  Spectrum shift $\delta_J \approx 2sin(\theta/2) \cdot \lambda_i \cdot v_J/c$; $v_J(J = 30KA/m^2, n_e = 10^{19}) = 5 \cdot 10^4 m/s$ $\delta_J \approx 0.6nm$;
  Photon budget $N_\nu \approx 500 \rightarrow \approx 100$ useful (on spectrum slope), out of two order of magnitude
  J measure is accessible only with Multipass/differential measure and multipulse averaging
- Polarimeter: Upper λ limit $\approx 0.5 - 1mm$ to control refraction, optics dimensions.
  Tangential View, single pass, 100 mT, 20 cm chord $n_e = 10^{19}, \lambda = 0.6mm$: Faraday rotation 0.02 rad, 1°.
  TBE (source power, S/N critical); no accesses → waveguides or SS sources

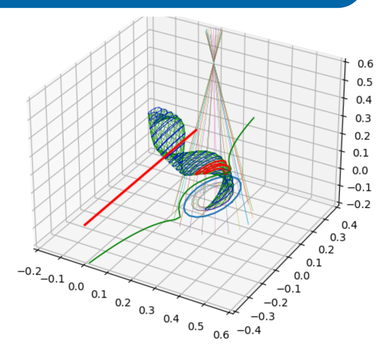
Xray

2D camera (quick and dirty), commercial 1" sensor. Brehmstrahllung preliminary estimation:
140 eV approx $N_\nu \approx 4 \cdot 10^{21} m^{-3} s - 1$;
pinhole 1 mm (Ω @$1m = 3 \cdot 10^{-7}$), magnification 10. QE < 0.1,
V≈ $10^{-5} m^3 \rightarrow N_{det} \simeq 10^4/ms$.

Some Hard Xray PHA for:

- NT electron population across DRE
- Target emission from divertor

To be dimensioned (APD + scintillator?)

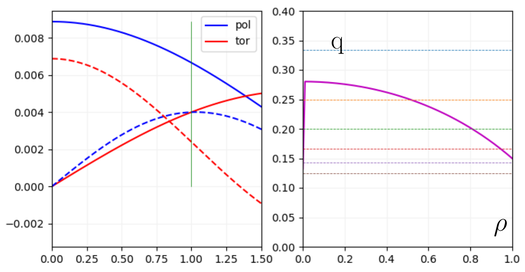


Magnetics

Pickup coils arrays resolution is determined by the minium wavenumber of interests

- indications form torus q set minium n > 8
- Only external equator is accessible, even so necessary to discriminate m=1 (kink in the torus) from m=0 (pinch displacements)

at least 4 x 10 array needed. Further array in the "bottleneck" regions for pinch?



B field tracking

- Preliminary lifetime estimation for a tangential injection $\tau_l(D = 0.3mm, n_e = 10^{19}, T_e = 200eV) \simeq 1 - 3ms$: [PTF77] $v_i \simeq 100m/s$ acievable with centrifugal injector. Limit in mass $m_p << m_t \quad D^3 dN_A/M_m : << \pi^2 i R_T^2 R_M n_e \quad D < 500\mu m$
- Field lines connection lenght can be probed by fast electron diffusion; Fast electrons are generated by laser-target ineractions and detected (on the divertor plates) by HXR [McL+03]. Energy threshold [Ray+17] $10^{13} W cm^{-2} \rightarrow$ parasitic to TS laaser.

Conclusions

Protosphera equilibria are not fully understood; equilibrium reconstruction and proper diagnostics coverage is mandatory to identify the dynamo mechanism at play. Diangostic coverage is at the moment lacking but a preliminary analysis is aimed at identfying and dimensioning the critical systems.

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