



Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

ISTW 2022

Status of the PROTO-SPHERA experiment: evidences of plasma tori production and sustainment and progress towards Phase-2

Paolo Micozzi and the PROTO-SPHERA Group

PROTO-SPHERA Group

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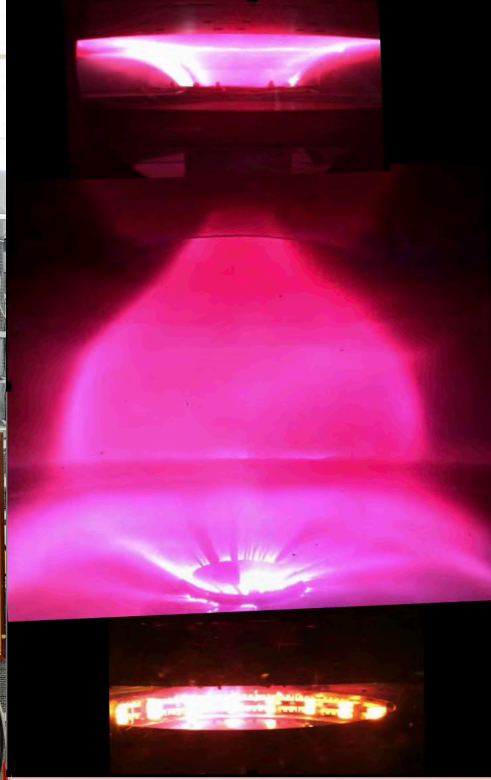
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Università di Padova e Consorzio RFX and FSN Department, CR-ENEA Frascati

Giuseppe Galatola Teka

PROTO-SPHERA : an "astrophysics" configuration

(more details in F. Alladio presentation)

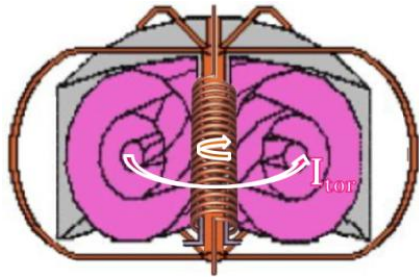


PROTO-SPHERA

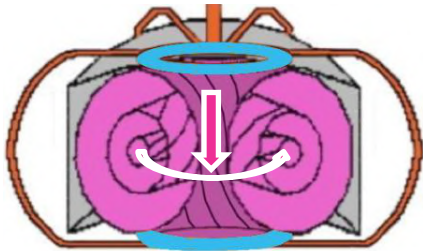


Crab Nebula remnant

PROTO-SPHERA Vs Tokamak: the stationary state

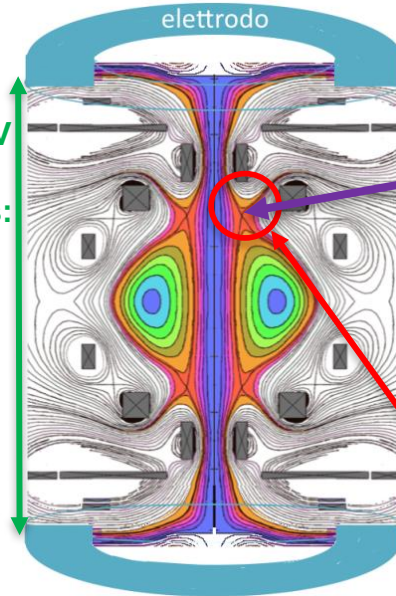
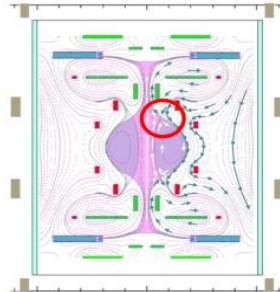
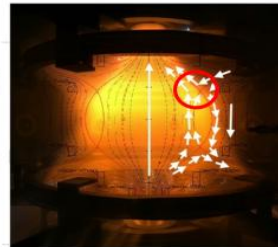


On Tokamaks the central solenoid induces the toroidal current ... but is not stationary

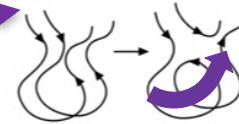


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Constant V between electrodes: stationary



X-points

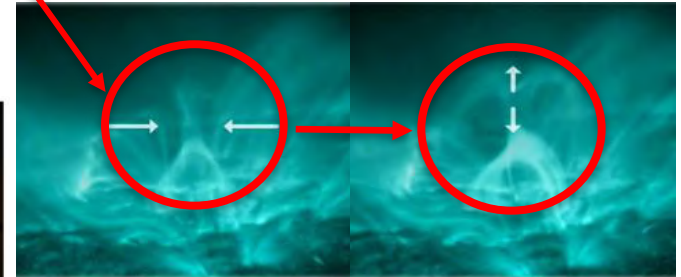


On the standard X-points reconnections are present: the Helicity Injection sustains the torus toroidal current

Which is the level of axisimmetry violations?

In the Sun probably the reconnections explain the coronal heating

Solar corona (millions °C)

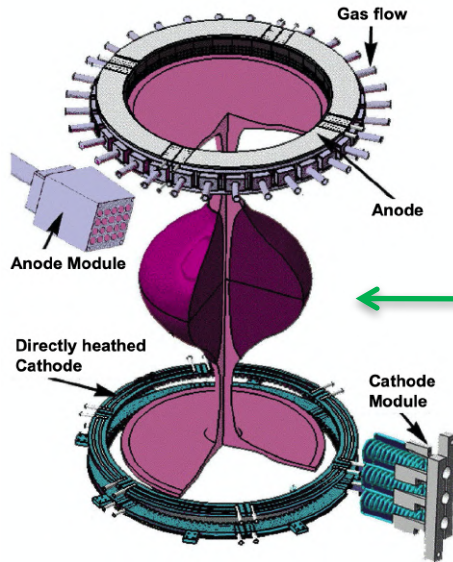
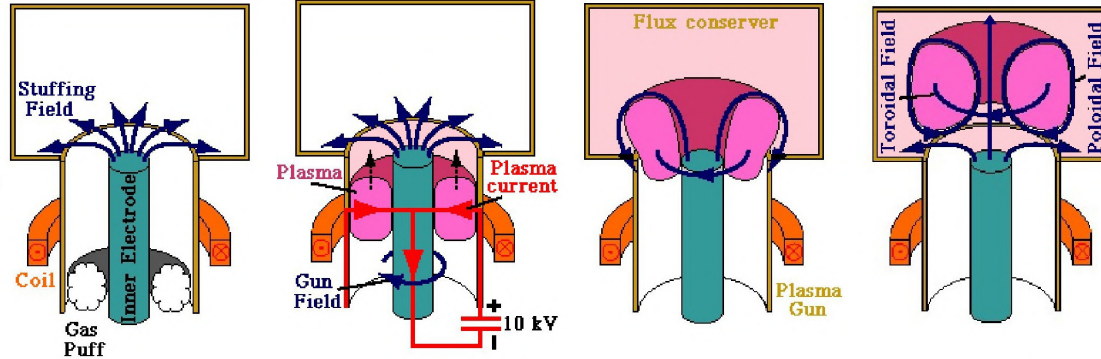


Solar photosphere (~6000 °C)

PROTO-SPHERA and the SPHEROMAKS

Flux-Core SPHEROMAKS

- Formation: injected by plasma gun
- Voltage ~ 10 kV between electrodes
- High pressure gas filling
- Flux conserver (no PF coils)



PROTO-SPHERA

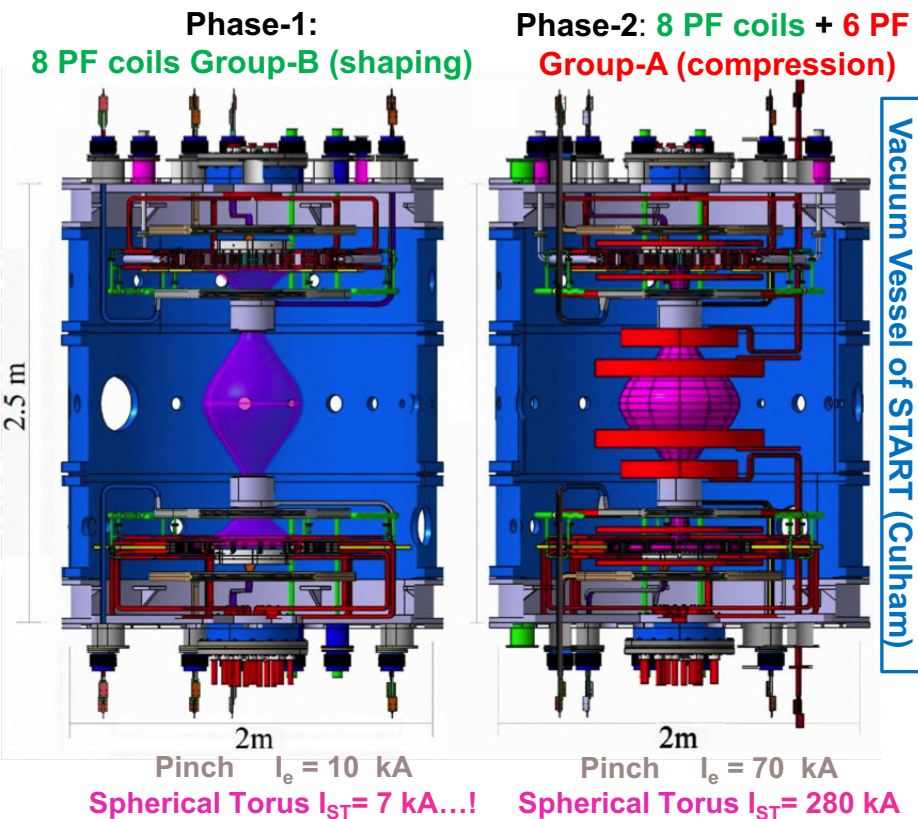
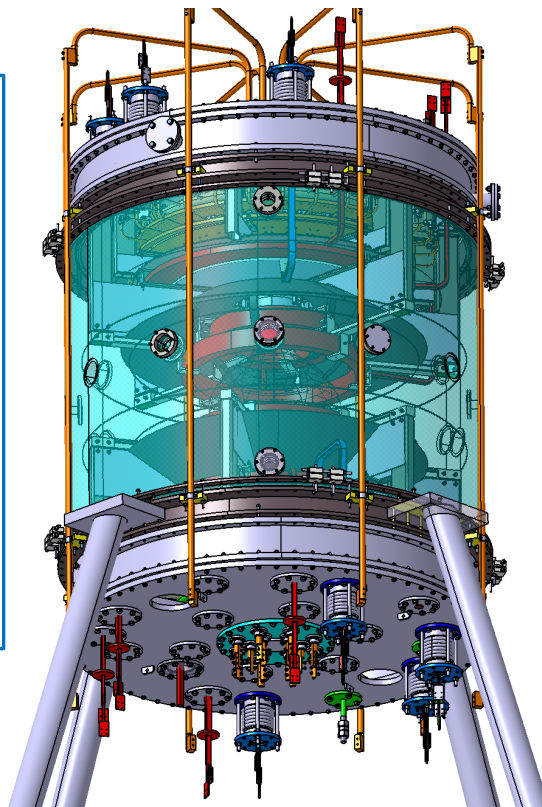
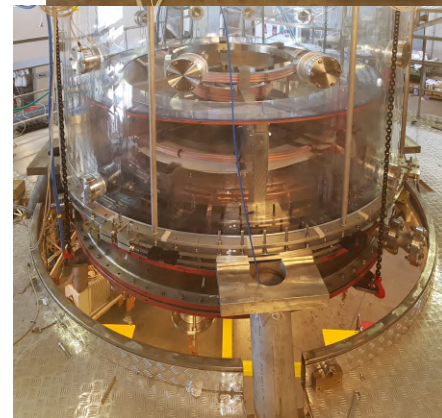
- Formation: MHD instability of the Pinch
 - Voltage $\sim 100 \div 200$ V between electrodes
 - Tokamak-like gas filling ($10^{-3} \div 10^{-1}$ mbar)
 - Confined by PF coils
- in absence of conducting walls close to the plasma

- Annular electrodes, disk shape of the Pinch on interface (fluxed hollow Anode, directly heated (AC) Cathode: W at 2900°C)
- Power density upon electrodes: $P_e \sim 20 \div 30 \text{ MW/m}^2$ (sustained for >1000 discharges, 1 sec duration, on Proto-Pinch)



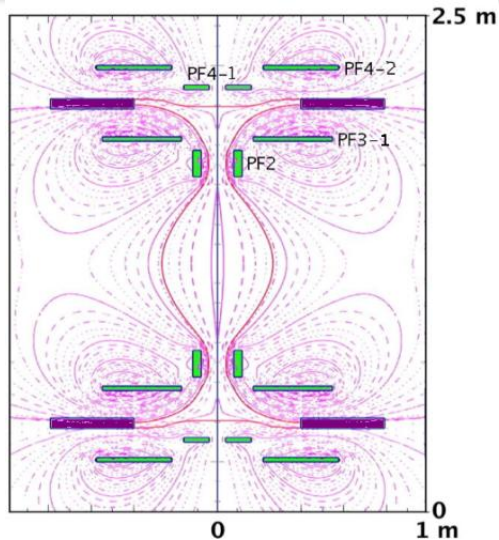
Proto-Pinch (2000) 5

PROTO-SPHERA: the machine



PROTO-SPHERA: Phase-1

*Magnetic field inside the
Al vacuum vessel (thickness 4 cm)*



*January 2018:
all Phase-1 targets obtained*



*Anode-Cathode voltage:
90 V at break-down, ~200 V at 10 kA flat-top*

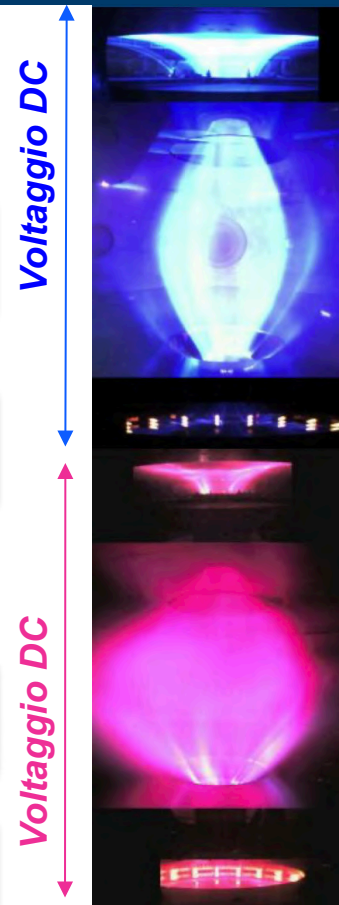
*Argon, electronic density (line averaged):
 $\langle n_e \rangle \propto I_e$ $\langle n_e \rangle = 4 \cdot 10^{20} \text{ m}^{-3}$ at $I_e = 10 \text{ kA}$*

*Plasma rotation $\omega \sim 2\pi$ (500) rad/sec
($\mathbf{E} \wedge \mathbf{B}$ effect: no arc anchoring on the Anode)*

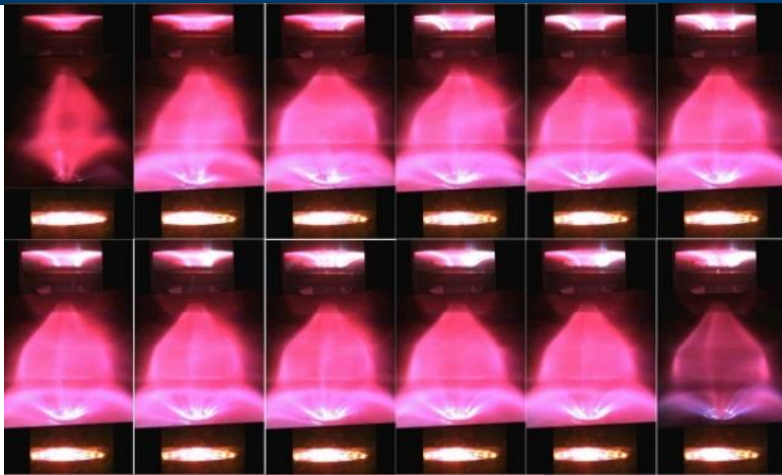
*Anode-Cathode voltage:
~320 V at break-down, ~220 V at 10 kA flat-top*

*Hydrogen, electronic density (line averaged):
 $\langle n_e \rangle \sim 1.5 \cdot 10^{20} \text{ m}^{-3}$ at $I_e = 10 \text{ kA}$*

High field Tokamak densities!

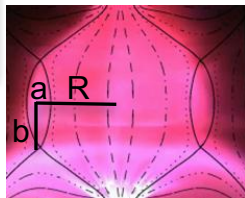


PROTO-SPHERA: the Phase-1 toroids

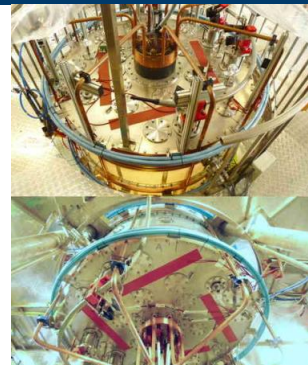
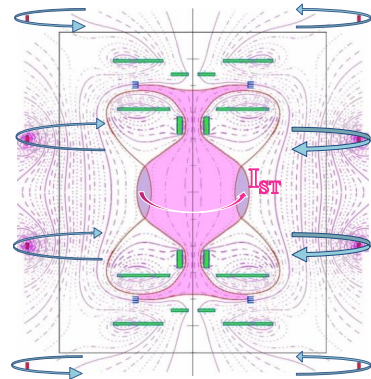


Static magnetic field!

“Slim” tori **aspect-ratio $A=R/a\sim 7$**
& elongation $b/a\sim 3.5$
...impossible in a Tokamak!
($I_e=10\text{ kA}$; $I_{ST}\sim 7\text{ kA}$)



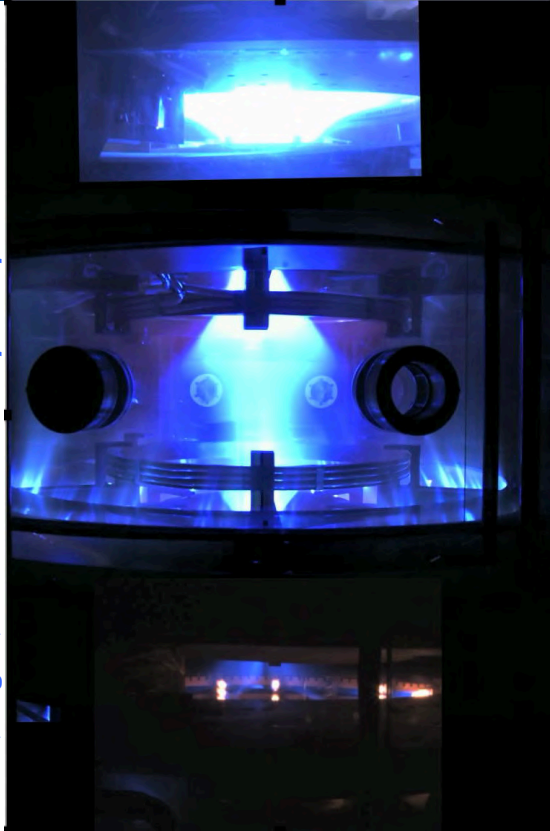
DC Voltage



Compression PF coils
external to the vessel

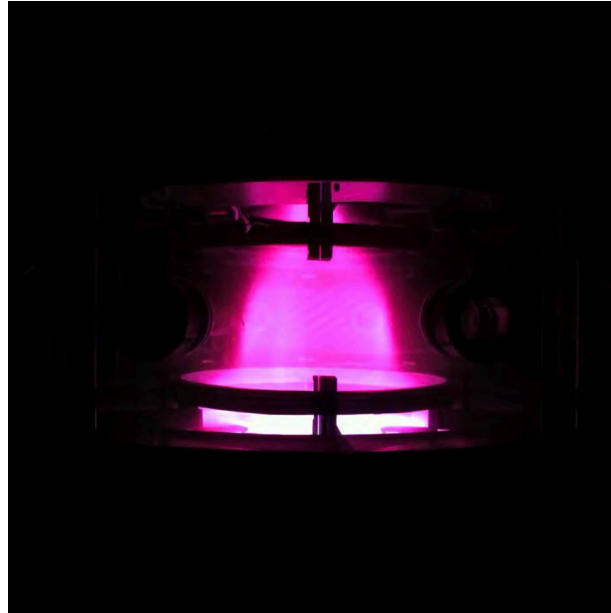
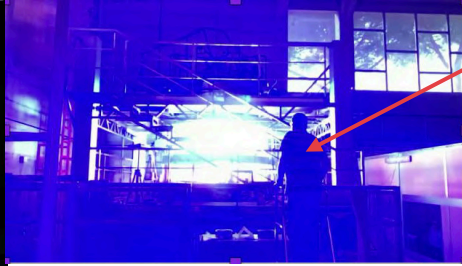
PROTO-SPHERA: Phase-1.5 (2019 campaign)

#1555, Argon, duration 0.5 sec: "quasi-spherical" torus ?



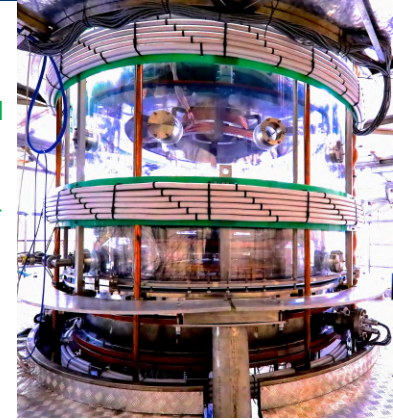
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#1618, Hydrogen, duration 1 sec: larger R/a

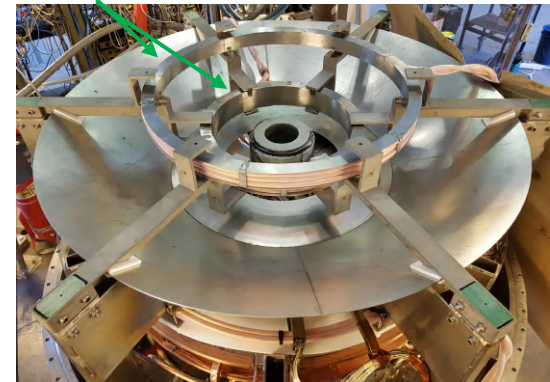


Franco Alladio! 🤖

Transparent-insulating Vacuum Vessel
and new "improved" PFext



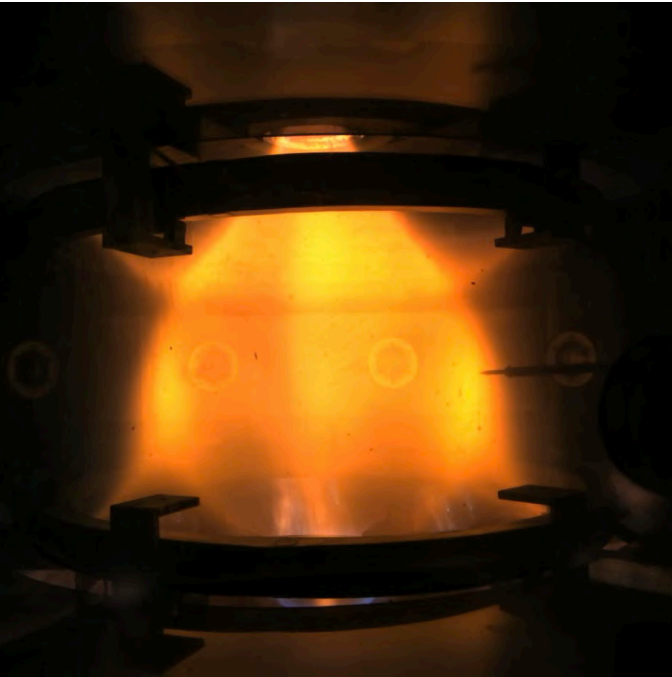
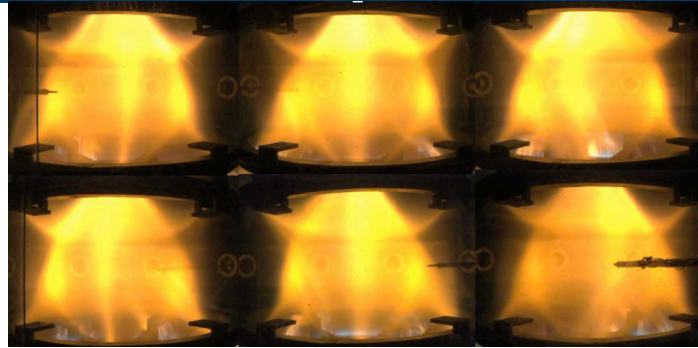
PF coils inside the VV for "compression"



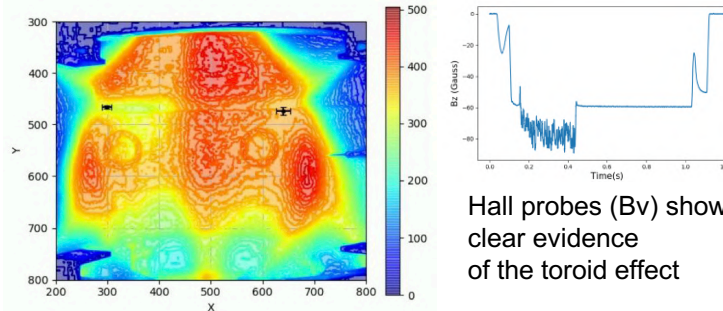
Powered with Super-Caps

PROTO-SPHERA: Phase-1.5 (2020, 2021... and '22)

After insulation improvement: better tori
But impurities limit the discharges to 0.3 sec
and problems of up/down asymmetry persist



#2141 Helium: 6 fast cameras (600 fps)
Toroidal rotation & 3D reconnections (*S. Macera presentation*)
Helicity Injection from quasi-periodic bursts (3-5 ms period) similar to sawteeth in Tokamaks



- Nested and closed light emission curves inside the torus
- Oscillation of the X-points position



Insulation in Teflon
on up & down divertor

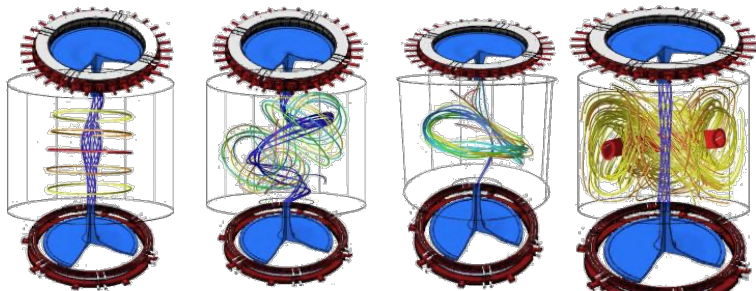


Gas injection
also from cathode

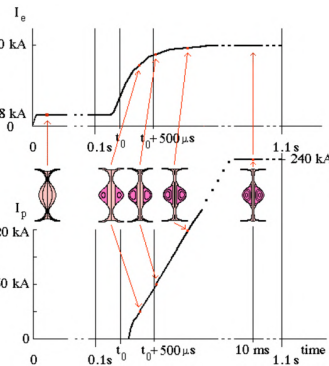
2022

PROTO-SPHERA: what we learn from Phase-1.5

Spontaneous formation of toroids in a static B field is a good surprise!

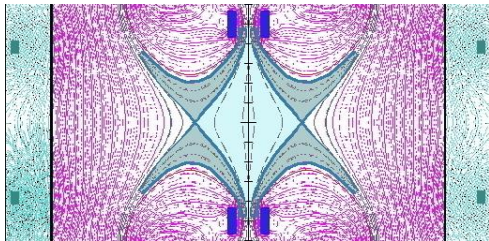


Resistive MHD simulations of ST formation by Ricardo Farengo (ISTW2008-Frascati)



In origin (2001 Report) we planned to form the torus by destabilizing the Pinch ($q_{pinch} < 2$) with a fast rise ($< 1\text{ms}$) of its current from 10 to 70 kA and “following” its evolution with the “Group A” compression coils: the coil flux gave a strong contribution to the I_{ST} rise during the fast phase. After that, the torus sustenement should rely upon Helicity Injection

The toroid formation in a static B field could be explained by the shape of the field itself: the initial Pinch is very “thin” and therefore unstable ($q_{pinch} < 2$) even at $I_e \leq 10\text{kA}$. After destabilizing it “looks for” a stable configuration: the SP+ST one!



Vacuum field



47.5 ms

48.06 ms

48.61 ms

51.39 ms

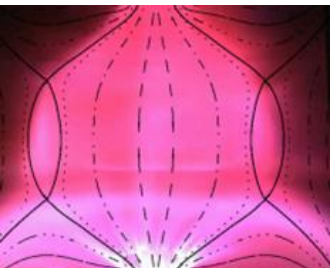
51.94 ms

56.39 ms

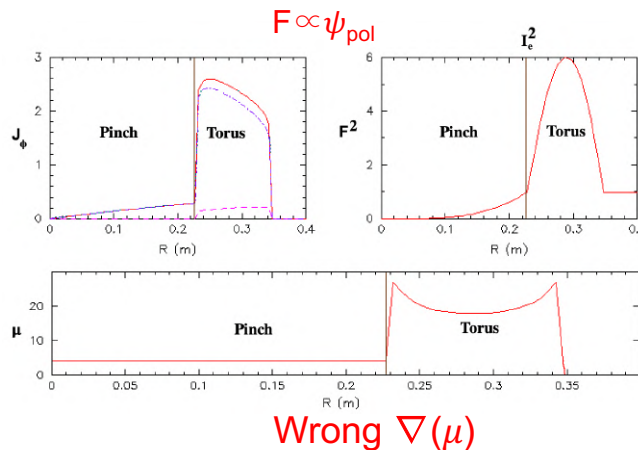
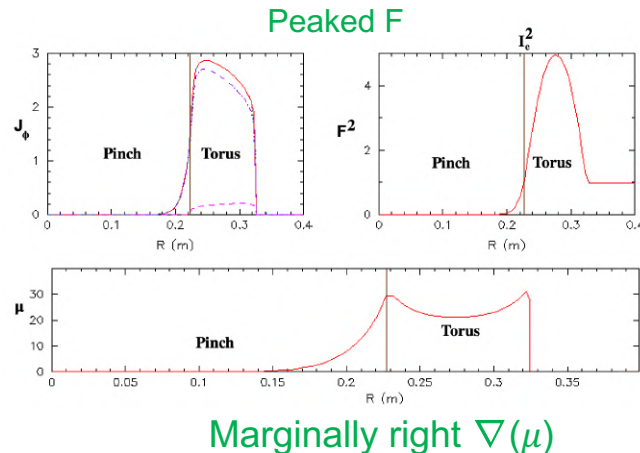
PROTO-SPHERA: what we learn for Phase-2 (cont.)

On Phase-1.5 any attempt to rise the I_{ST} by compressing the ST failed: $I_{ST} \approx 5-7$ kA with $I_e \approx 10$ kA is the limit

But the MHD equilibrium simulation give us some interesting suggestion, taking into account that the source of Helicity Injection is $\nabla(\mu)$, where $\mu = \mathbf{J} \cdot \mathbf{B} / B^2$ (i.e. Helicity flows from higher to lower μ)



Equilibrium obtained trying to fit separatrices and external boundary (measured I_e & PF coil currents as input): $I_e = 9.47$ kA, $I_{ST} \approx 6$ kA

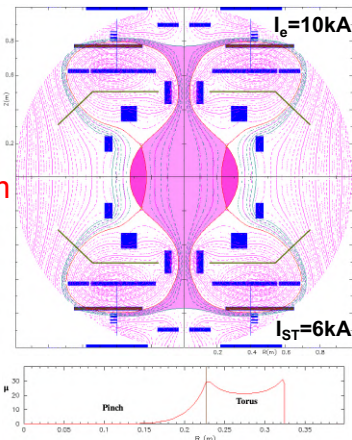


Therefore there are indications of a “skin current” inside the Pinch, and that the HI is marginal at low I_e
Probably the SP+ST equilibrium “rearranges” to maintain a stationary configuration

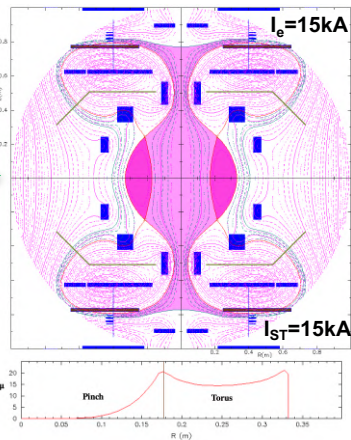
Some evidences from plasma diagnostics: in particular the line averaged density decreases of a factor of 3 when toroids are present

PROTO-SPHERA: Phase-2 scenarios

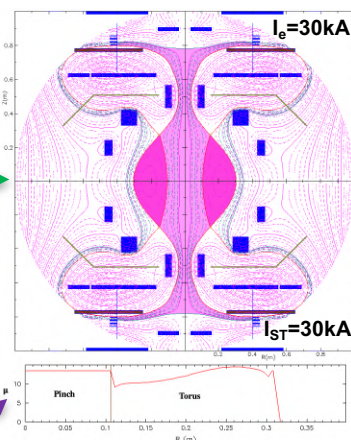
Present equilibrium



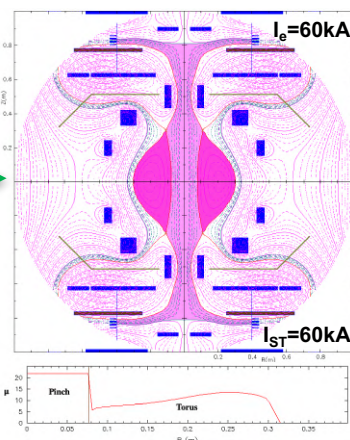
I_e ramp-up



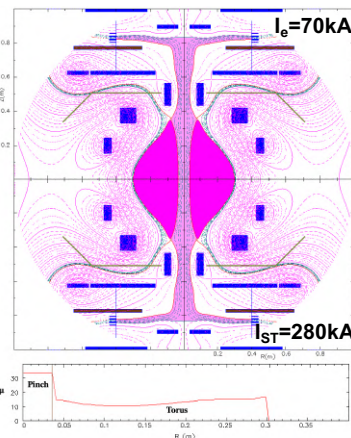
I_e ramp-up



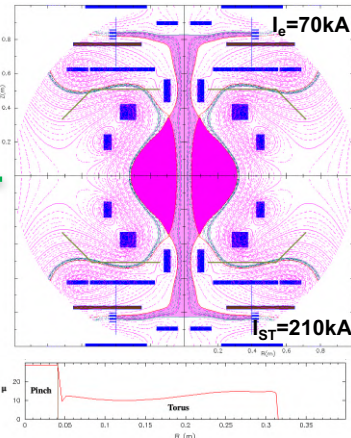
I_e ramp-up



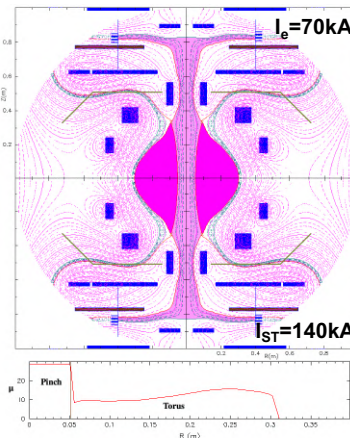
μ profile transition



HI effect

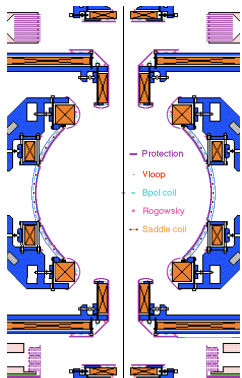


HI effect

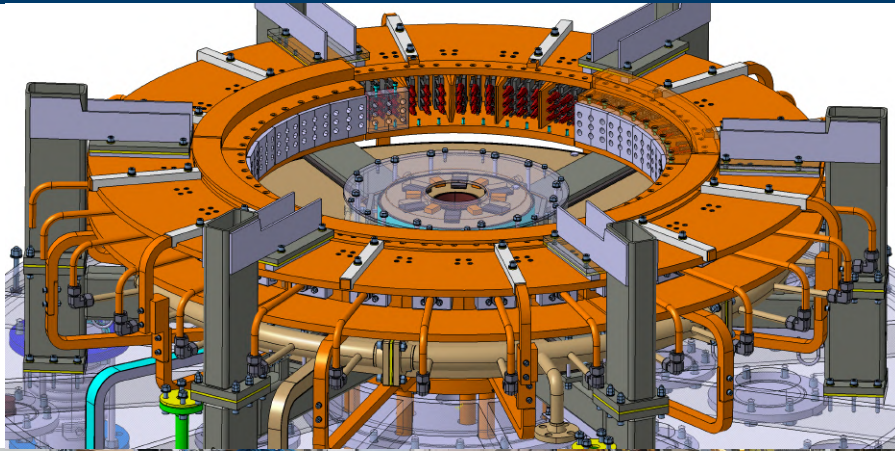
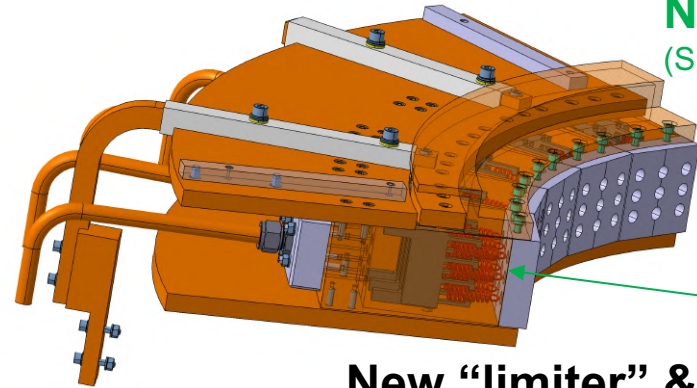


End of I_e ramp-up

During the slow ramp-up of I_e & I_{ST} Group A PF coils are operated in feedback to fix the R_{ext} of toroid (R_{ext} position provided by magnetic probes)



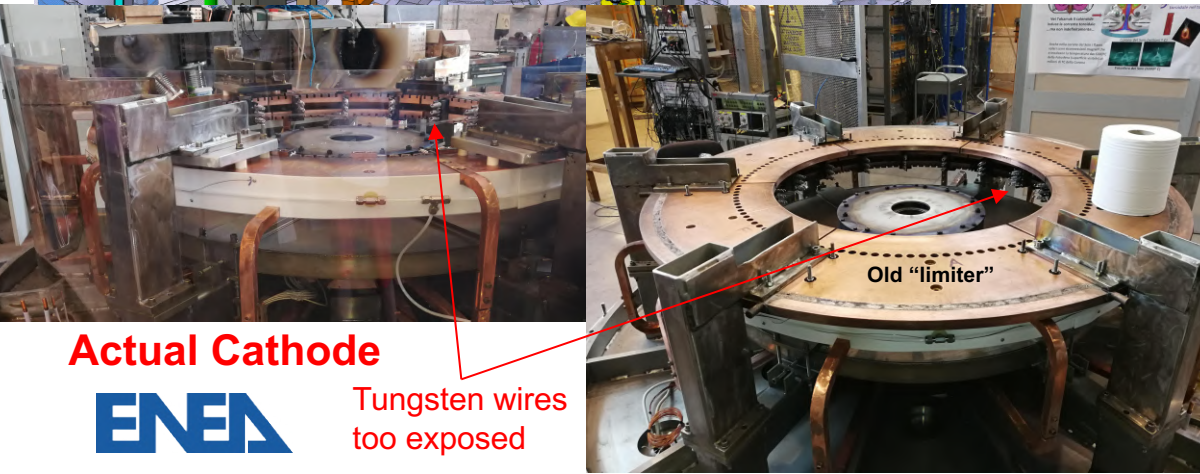
PROTO-SPHERA: Phase-2 improvements



New Cathode
(Similar to the Anode)

Tungsten wires
protected

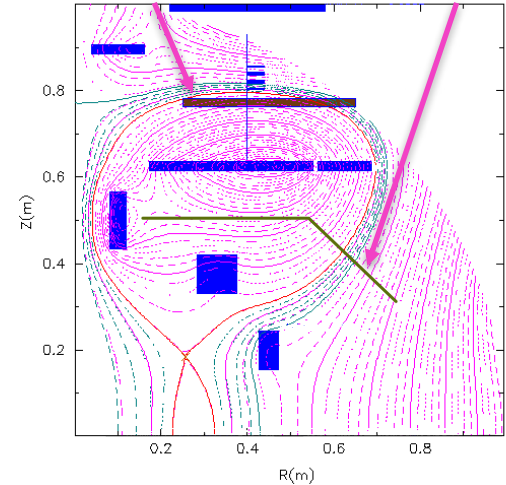
New “limiter” & divertor



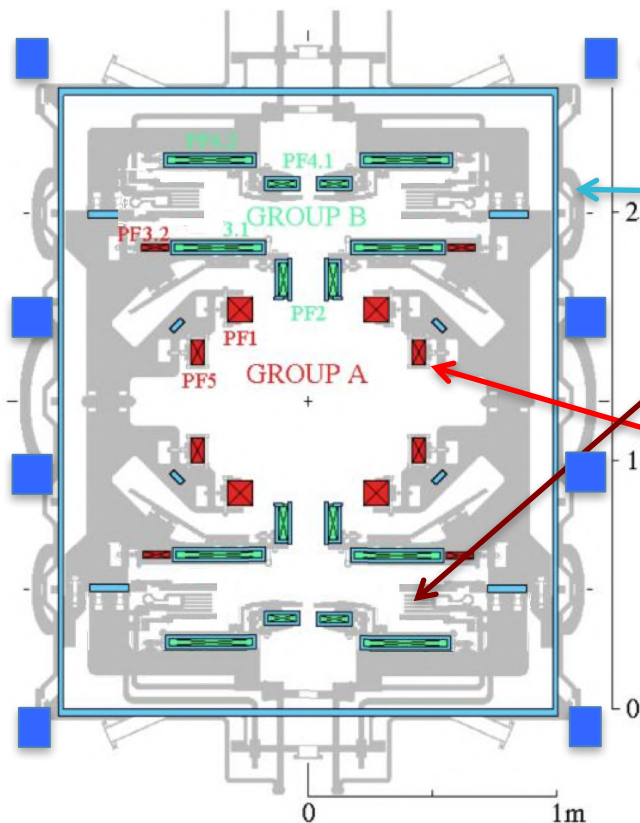
Actual Cathode

Tungsten wires
too exposed

Old “limiter”



PROTO-SPHERA: towards Phase-2



Already built: Phase-1.5, June 2019-Dec. 2022

PFext 8+12+12+8 wires, 240 mm²

Vacuum Vessen in PMMA

Cathode wires in W (54→378) (54 utilized up to now)

To be built, after the end of Phase-1.5

Group A: compression PF coils (3+3 in series)

Power Supplies

- **Compression Group A** (Super-Caps)
- **Cathode** (I_{cath} 10→70 kA) (conventional AC)
- **Pinch** (I_e 10→70 kA) (Super-Caps and/or batteries)

Cost up to now (2022) ~ 2.5 M€

Cost for Phase-2 ~ 2.5 M€ (including diagnostics)

PROTO-SPHERA: Conclusions

- **The machine** does not aim at refining previously achieved results, but to be **ground-breaking**
- **The magnetic configuration** of the experiment has ***astrophysical basis***
- Until now **the physics ideas seem sound**: Phase-1 aims were achieved & tori were sustained (*with the good surprise to produce and sustain them in a static magnetic field*)
- We find a **reasonable explanation** for the impossibility to obtain higher I_{ST}/I_e ratio at low Pinch current
- We also find a reasonable way to slowly increase the Pinch current in Phase-2
- Phase-2 **without design uncertainties, with limited corrections on Cathode**
- For Phase-2 the experiment will be moved in a different building with better facilities
- Fusion might be a dream, but **magnetic reconnections studies must aim at world excellence**
...& must accommodate experiments of astrophysical interest