



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



1° Conferenza  
Italiana Plasmi

03-06  
Febbraio  
— 2026 —

Centro Ricerche  
ENEA Frascati

# PROTO-SPHERA: a “bridge” between laboratory and astrophysical plasmas

Paolo Micozzi and the PROTO-SPHERA Group



# PROTO-SPHERA : an "astrophysical" configuration

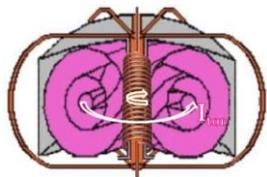


PROTO-SPHERA

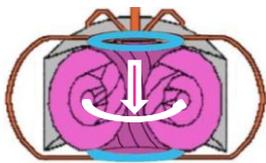


*Crab Nebula remnant*

# PROTO-SPHERA Vs Tokamak: the stationary state



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

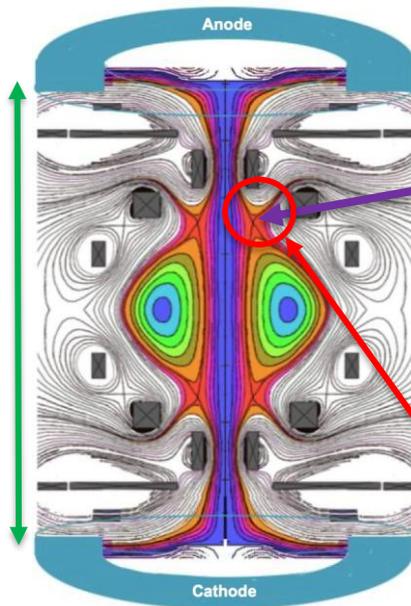


- Most efficient accelerators in the Galaxy are the PWNs (>25% of their released power is emitted in radiation)
- spectrum of e.m. emission extends beyond PeV ( $10^{15}$  eV)

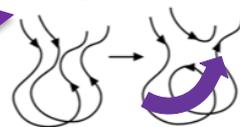
Acceleration of particles in PWN is open question: magnetic reconnections good candidate



Constant V between electrodes: stationary



X-points

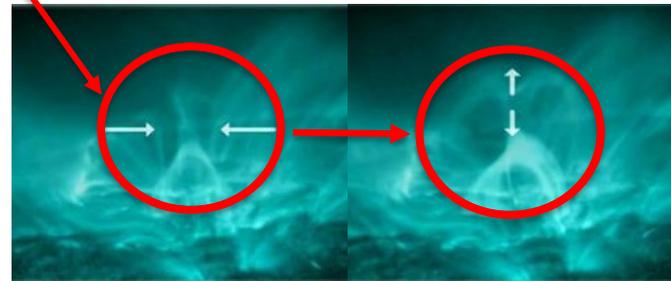


On the standard X-points reconnections are present: the Helicity Injection sustains the torus toroidal current

Which is the level of axisymmetry violations?

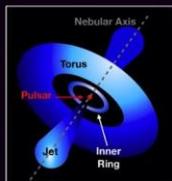
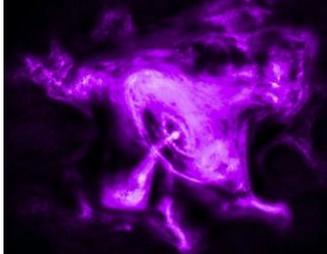
In the Sun probably the reconnections explain the coronal heating

Solar corona (millions °C)



Solar photosphere (~6000 °C)

CRAB PULSAR WIND NEBULA (PWN)



PROTO-SPHERA

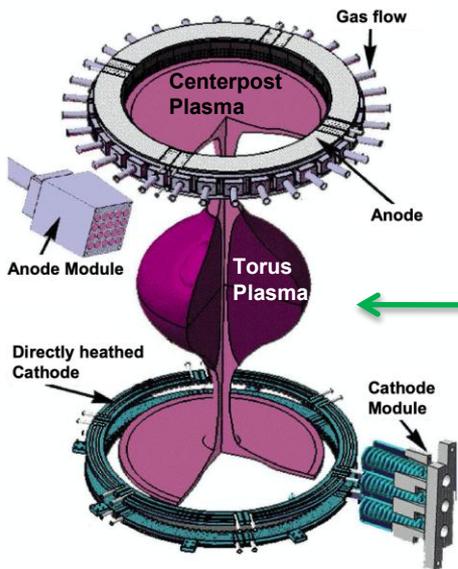
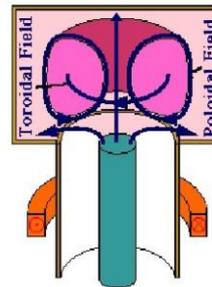


# PROTO-SPHERA and the SPHEROMAKS

## Flux-Core SPHEROMAKS

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

**Spheromaks are intrinsically pulsed devices**



## 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  
(Insulating/transparent Vacuum Vessel in PMMA)
- Annular electrodes, disk shape of the Pinch on interface (fluxed hollow Anode, directly heated (AC) Cathode: W at  $2900$  °C)
- Power density upon electrodes:  $P_e \sim 20 \div 30$  MW/m<sup>2</sup> (sustained for  $>1000$  discharges, 1 sec duration, on Proto-Pinch)

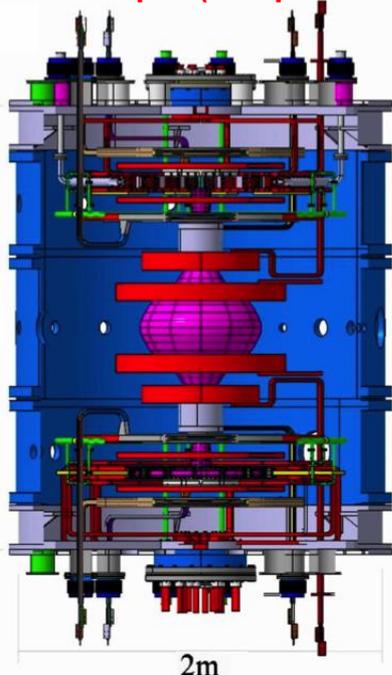
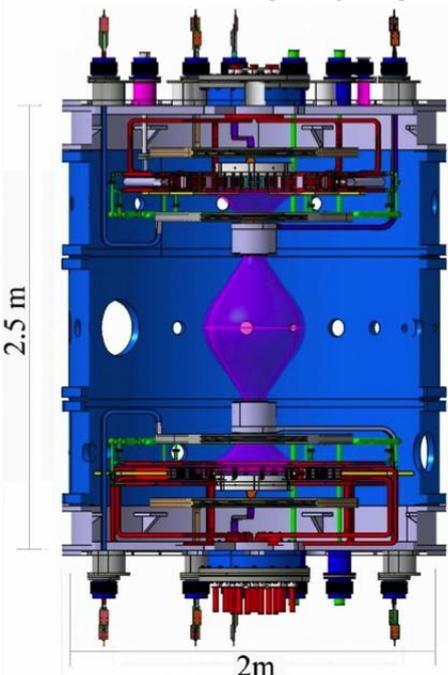


Proto-Pinch (2000)

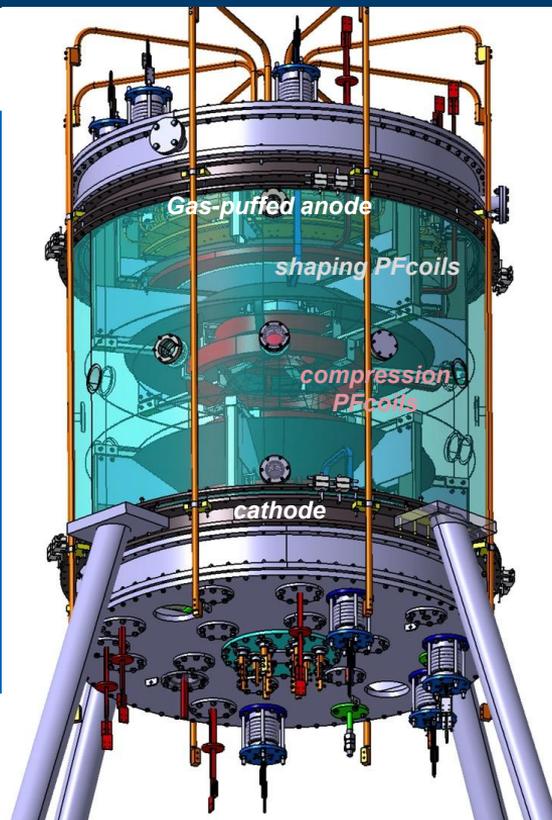
# PROTO-SPHERA: the machine

Phase-1:  
8 PF coils Group-B (shaping)

Phase-2: 8 PF coils + 6 PF  
Group-A (compression)



Vacuum Vessel of START (Culham)



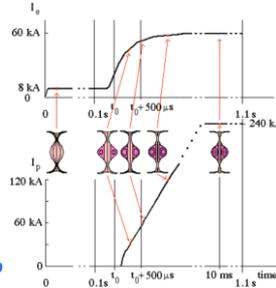
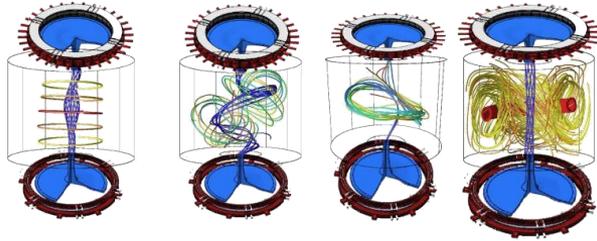
Pinch  $I_e = 10$  kA  
Spherical Torus  $I_{ST} = 6$  kA...!

Pinch  $I_e = 70$  kA  
Spherical Torus  $I_{ST} = 280$  kA

Insulating/transparent Vacuum Vessel in PMMA  
(since 2019)

# PROTO-SPHERA: what we learn from Phase-1.5 (reduced $I_e=10$ kA but “hand made” compression coils inside the vessel)

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



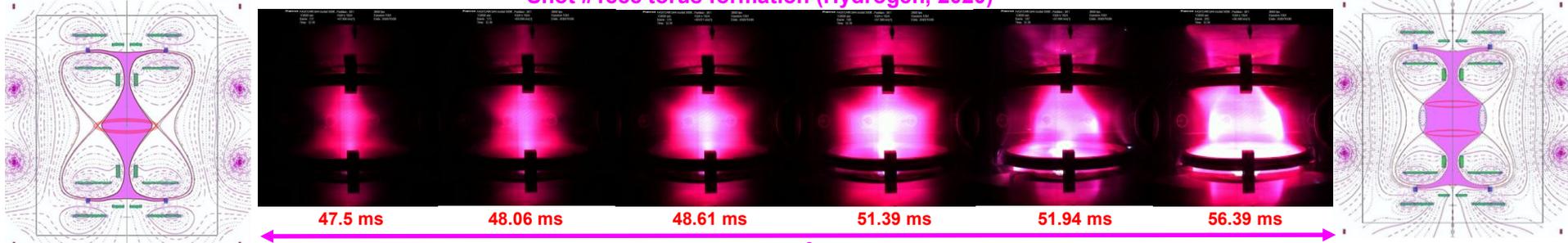
In origin (2001 Report) we planned to form the torus by destabilizing the Pinch ( $q_{pinch} < 2$ ) with a fast rise ( $< 1$ ms) of its current from 10 to 70 kA and “following” its evolution with the “Group A” compression coils: the coil flux gave a strong contribution to the  $I_{ST}$  rise during the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

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

2 circles of X-points on top and bottom of the equator indicate that a toroidal current exists

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  $I_e \leq 10$  kA. After destabilizing it “looks for” a stable configuration: the SP+ST one!

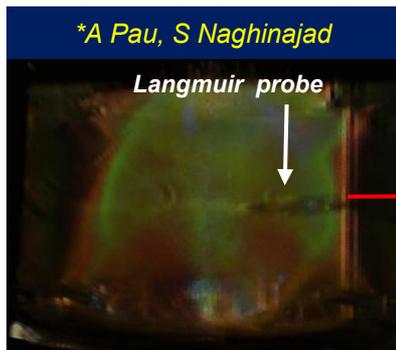
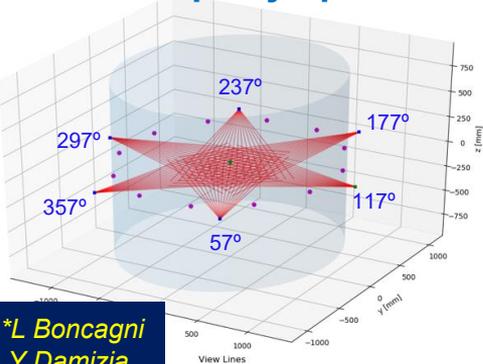
Shot #1888 torus formation (Hydrogen, 2020)



Therefore a fast rise of  $I_e$  and a fast Bv feedback are no more necessary for Phase-2

# 3D tomography reconstruction

6 equally-spaced cameras (600 fps) arranged around transparent vessel equator



3cm  $\varnothing$  copper bars are perfectly reconstructed

Since 2019: 18 PFcoils  
8 shaping PFC internal  
6 compression PFC internal  
4 PFC external  
to the vacuum vessel

\*L Boncagni  
Y Damizia  
M Iafrati

Vertical tomographic section

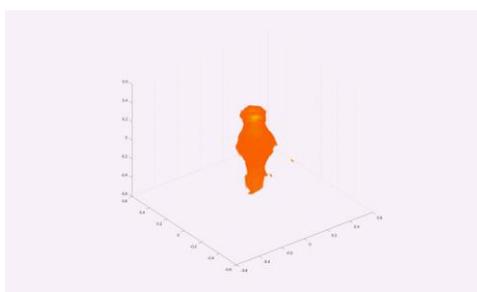
## Torus self-organization

## #2141 He, false colours

a kinked centerpost



forms the torus

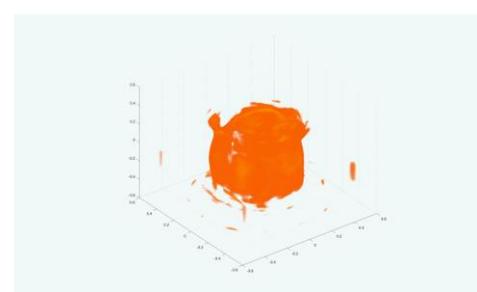


formation time <10 msec

& a kinked state

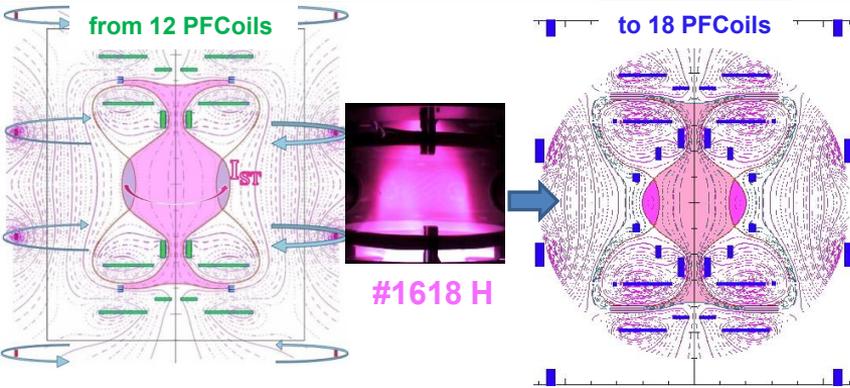


lets the torus to be re-born



re-birth cycle <10 msec 7

# PROTO-SPHERA from 2019 to 2024, evolution of torus up to 1 sec



2021, poor divertor  
plate insulation  
0.3 s tori always  
produced

2024, 1 s, better  
divertor plate  
insulation  
but tori not  
always produced

#2126 He

#2460 He

$I_{ST}=5$  kA tori: anode-cathode  $\Delta V$  grows by 20-30 Volts (10% of 200 V)

## 3D tomography allows to steal a glance inside the plasma cross-section

#2141 He

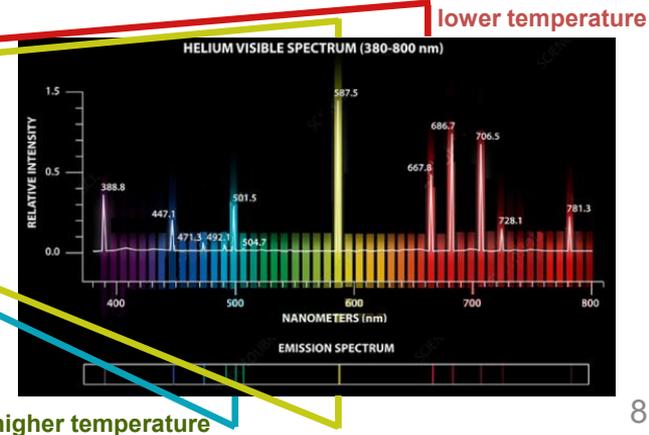
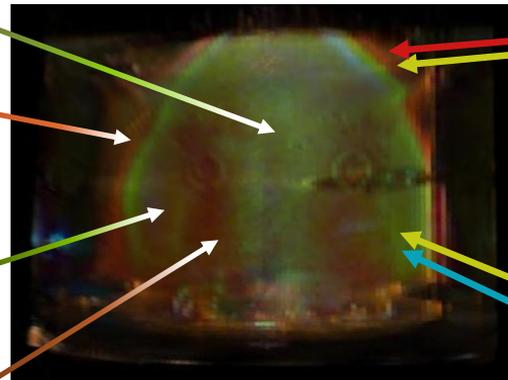
centerpost

outer edge  
(ionization)

torus plasma

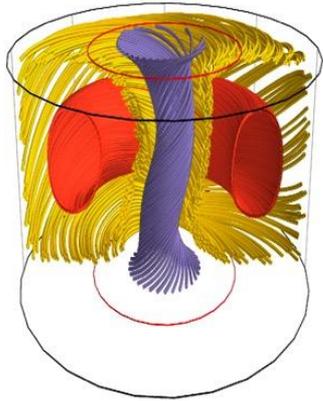
$t = 159$  msec

torus-centerpost gap



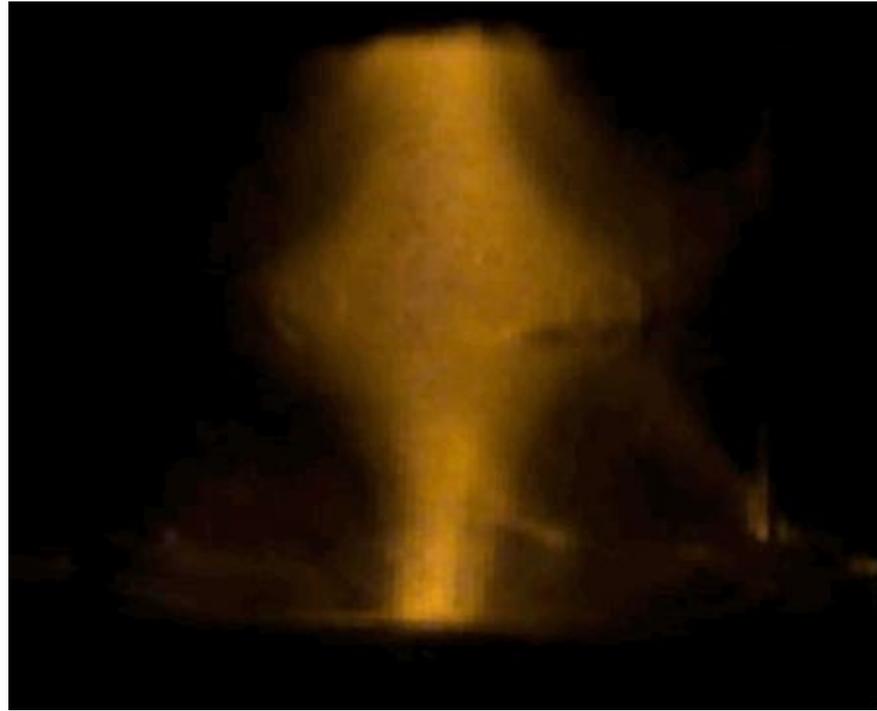
# Looking inside an Helium discharge: a restless, still enduring plasma

vertical tomographic cross section @ 357°



- **kinked plasma centerpost**

Farengo 2018  
*Physics of Plasmas* 25



**Surprise: PROTO-SPHERA**  
plasma spontaneous  
toroidal rotation ~600 rad/s  
(clockwise from top)

**Oblique rotator**  
(like Crab PWN)

**torus shaken by  
continuous unrest**

**#2141 He**

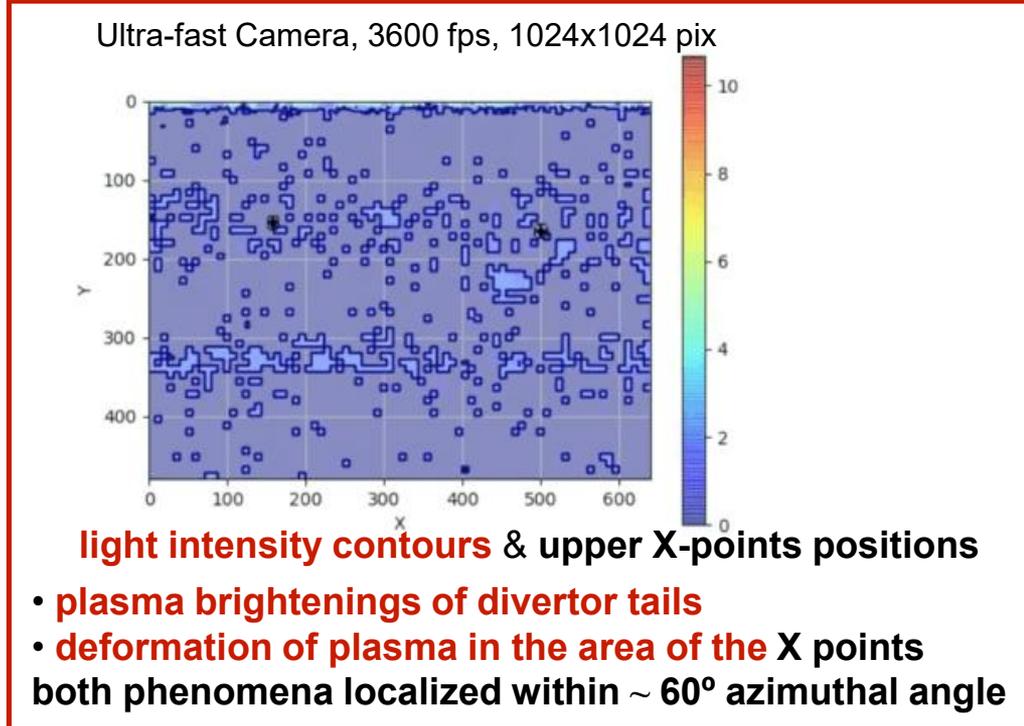
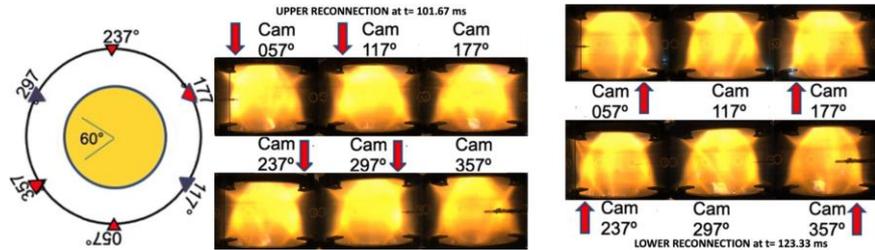
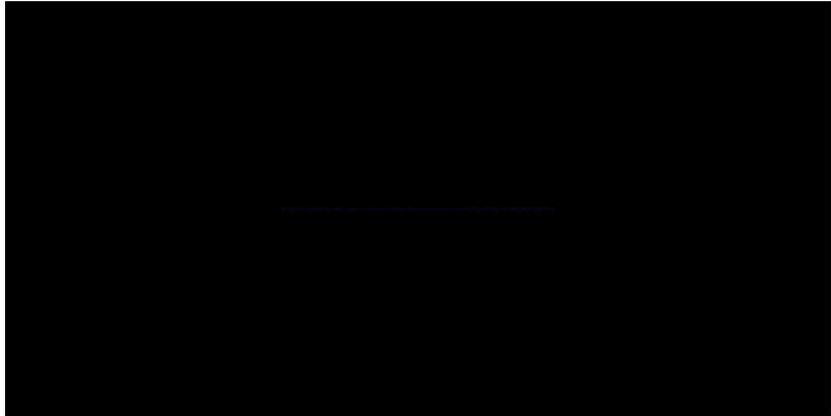


**centerpost plasma in continuous turmoil**

# Torus sustained: magnetic reconnections break axisymmetry *S Macera*

breaking of axisymmetry\* is required in order to inject current into the torus \*Cowling anti-dynamo theorem

6 cameras (600 fps, 640x480 pix) around vessel equator

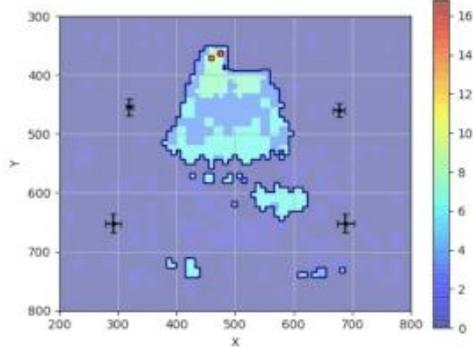


only 2 toroidally contiguous cameras observe brightening and deformation (& also the 2 opposite ones) but the other 2 cameras do not see anything

# Notwithstanding symmetry breaking, fair integrity of toroidal surfaces

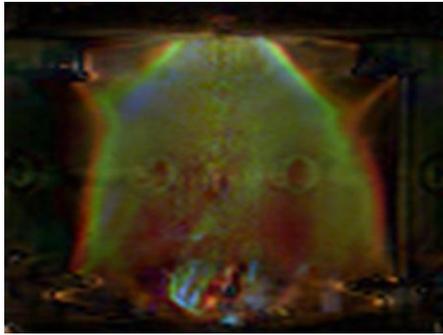
#2092 He

Ultra-fast Camera, 3600 fps, 1024x1024 pix

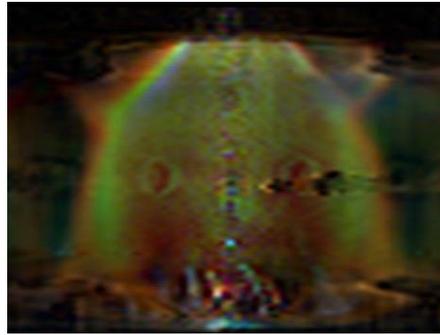


- notwithstanding X-points position oscillations
- nested & closed light intensity contours inside the torus

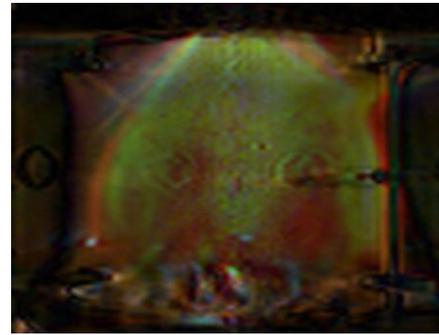
*3D tomography vertical cross sections at various angles suggest fair axisymmetry of torus, apart from oblique rotation*



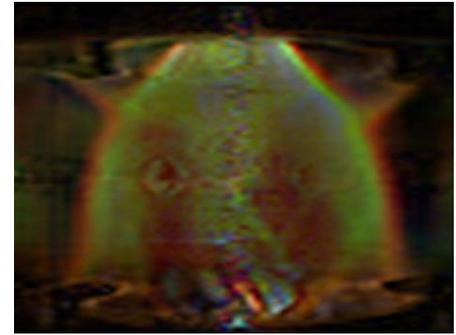
vertical section @ 0° azimuth



vertical section @ 45°



vertical section @ 90°

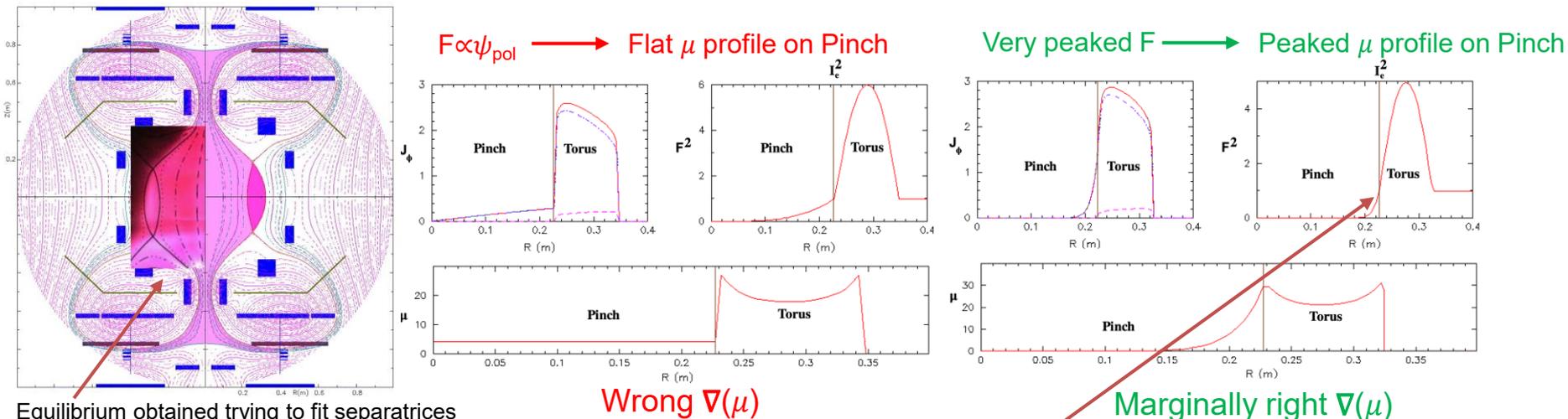


vertical section @ 135°

# PROTO-SPHERA: the “puzzle” of Phase 1.5

On Phase-1.5 any attempt to rise the  $I_{ST}$  by compressing the ST failed:  $I_{ST} \approx 4-6$  kA with  $I_e \approx 10$  kA is the limit

But the MHD equilibrium simulations show some incoherence, 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  $\mu \sim$  heat transfer equation)



Equilibrium obtained trying to fit separatrixes and external boundary (measured  $I_e$  & PF coil currents as input):  $I_e = 9.47$  kA,  $I_{ST} \approx 5$  kA

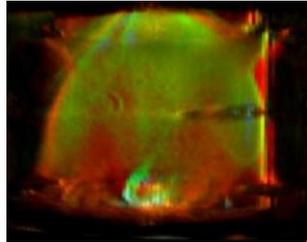
Such a peaked  $\mu$  profile, that means a “current layer” on Pinch, is unphysical  
Therefore a direct Helicity Injection from the Pinch to the Torus is also unphysical

Torus formation has a reasonable explanation, but what about the observed sustainment?

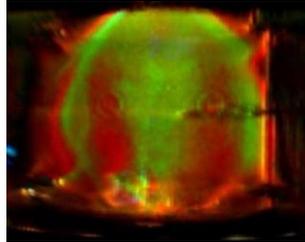
# 3D tomography gives some interesting suggestion: two kind of reconnections are observed

Vertical cross sections

Upper reconnection Lower reconnection



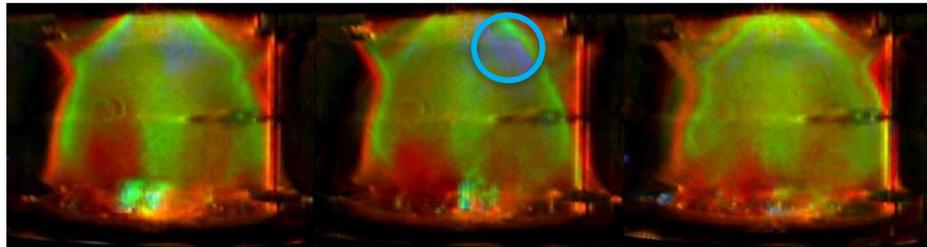
256.20ms



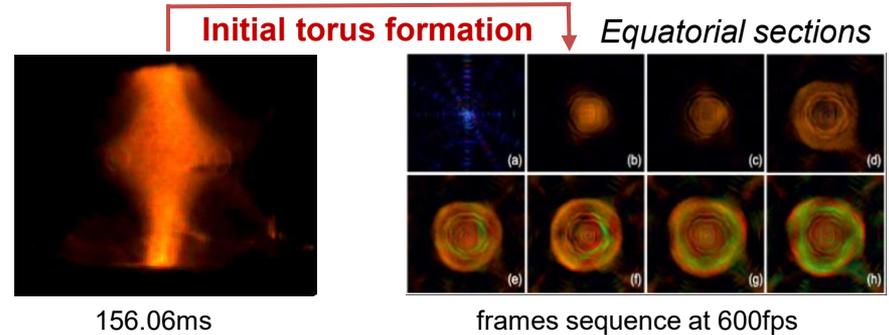
277.87ms

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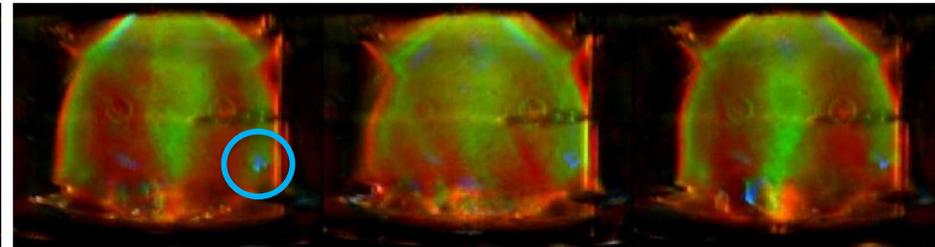
- The visible light emission has different spectra (different temperatures) in different regions of the plasma: torus, centerpost and ionization edge
- The hotter (green & blue) zones indicate where the reconnection appears, on the upper or lower X-point. Upper reconnections seem stroger



ENEА Upper reconnection sequence (~3-4ms)

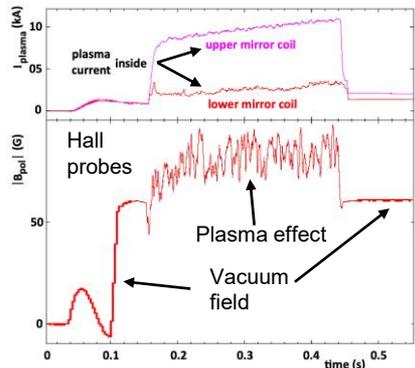


- Plasma centerpost and plasma torus are separated by an orange-brown (colder) region → torus and centerpost are not adjacent suggesting that a lower temperature plasma exists between the hotter plasma
- This unexpected observation suggests that the helicity transfer is not a phenomenon occurring between adjacent plasma centerpost and plasma torus, with  $\mu_{CP} > \mu_{ST}$



Lower reconnection sequence (~3-4ms)

# A possible explanation: spurious external currents

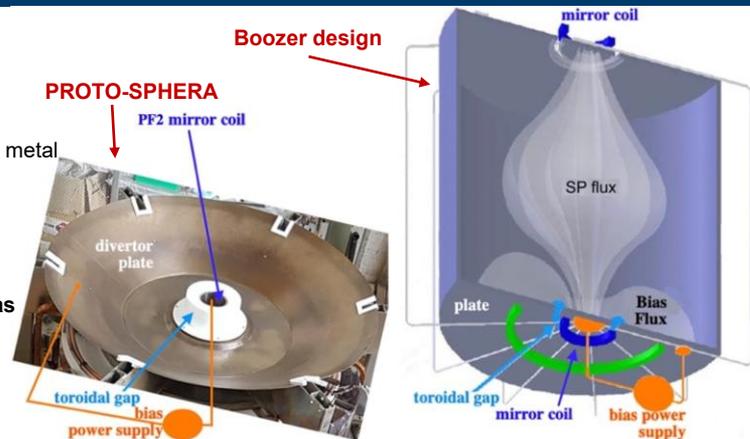


Plasma torus was **sustained only when**, while the full plasma centerpost current  $I_0$  delivered by the power supply always went **completely inside** the upper PF2 mirror coil, instead **up to 80% was missing** from inside the lower PF2 mirror coil

The missing centerpost plasma current **impinged instead** into the **lower metal divertor plate**, charged it electrically and created a **non-axisymmetric localized plasma current** coming out of the lower divertor plate and impinging into the metal case of the lower PF2 mirror coil

That behaviour reminds the **Hsu, Tang and Boozer design** of the “Tokamak with a Plasma Center Column”, which included **secondary bias polarization electrodes** for the unbuilt Los Alamos experiment

The missing current ended, **below the lower divertor plate** and the nearby PF2 and PF3 coils up into the underlying cathode, through **local discharges** occurring between metal components



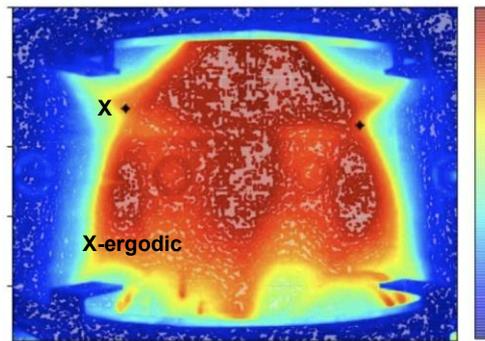
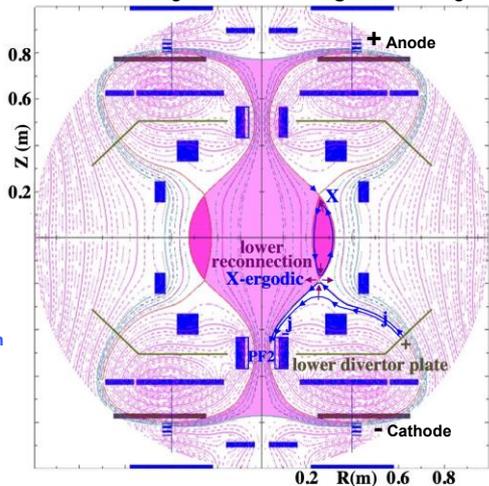
Unexpected azimuthally-localized plasma currents flow from the lower divertor plate to the lower PF2 mirror coil:

- 1) had to surround the torus completely and reconnect near the upper X-point circle
- 2) near the circle of lower X-points, did reconnect the azimuthally-localized plasma current with the current flowing on the inner side of the torus

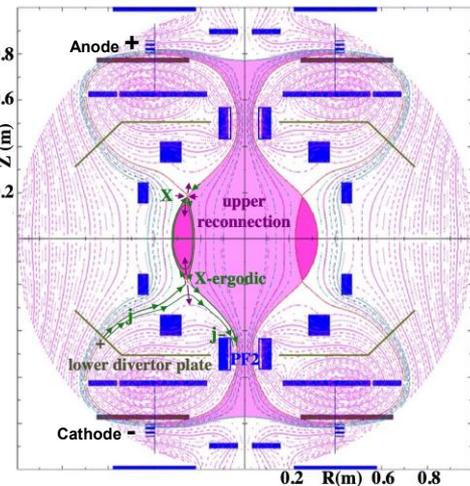
The two different localized current paths should have quite different effects:

Injecting current to the torus when the reconnection occurs near the upper X-point circle

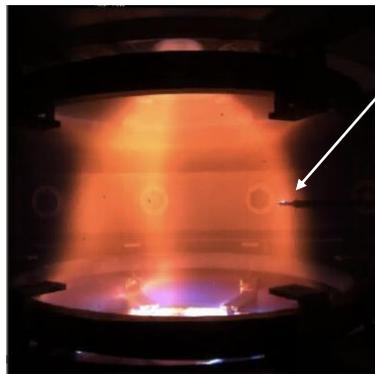
Ejecting current from the plasma torus when the reconnection occurs near the lower X-point circle



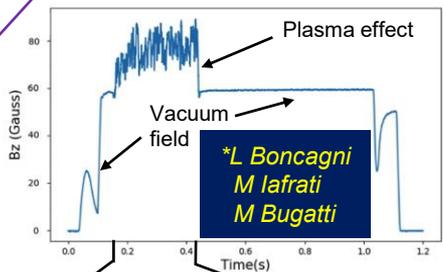
Add a power supply to control the external discharge...



# Hall probes ( $B_{Z\text{-vertical}}$ ) & Langmuir probes ( $T_e$ ) at torus edge: $\Delta B_{\text{vert}}$ bursts ( $\propto$ toroidal current $\Delta I_{ST}$ ) & $T_e$ spikes



Langmuir probe & Hall sensors\*

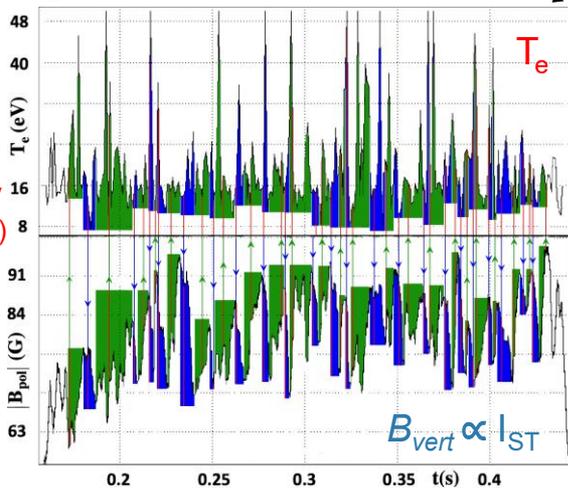


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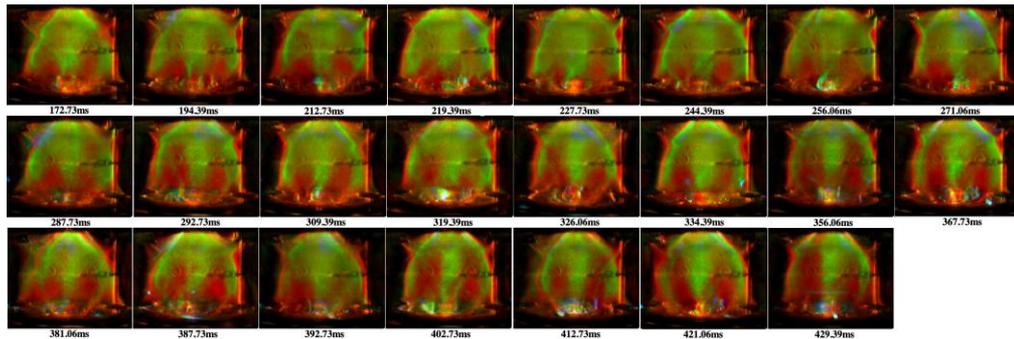
$T_e$  spikes coincide with  $\Delta I_{ST}$  bursts

$T_e$  spikes 20 eV  $\rightarrow$  50 eV (heating?/acceleration?)

$\Delta I_{ST}$  bursts  $\sim$  1-1.5 kA increase/decrease of  $I_{ST}$  (average  $I_{ST} \sim$  5kA)

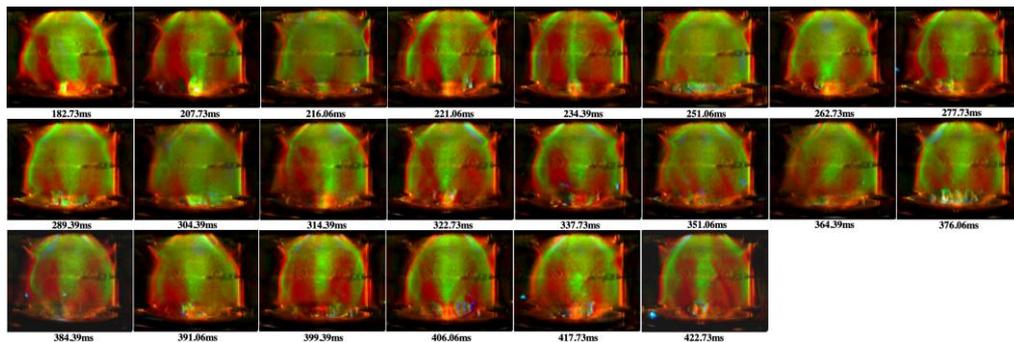


Vertical cross sections



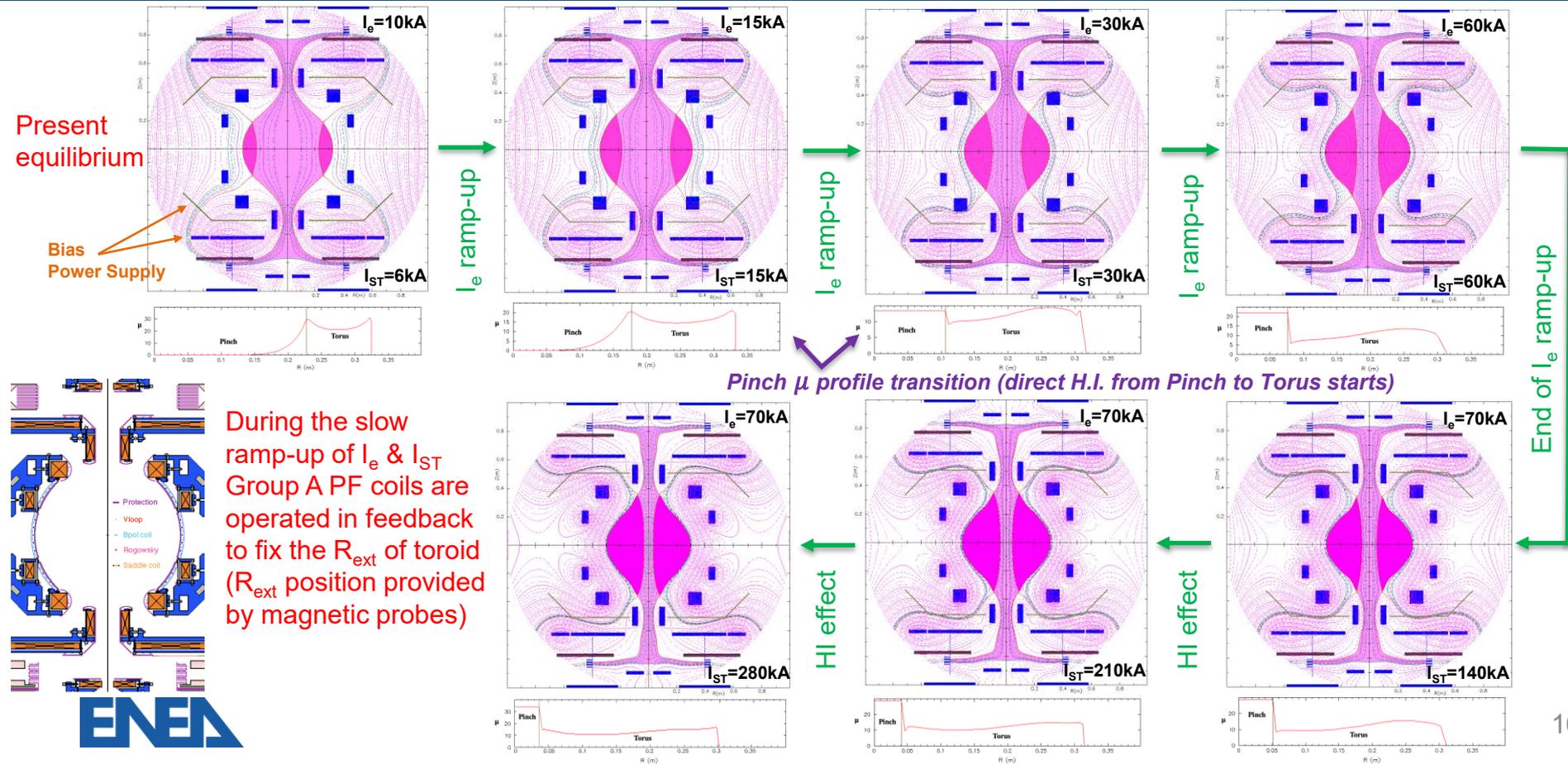
Upper strongest reconnections (23)

Good coincidence between 3D tomography and  $T_e$  &  $I_{ST}$  bursts



Lower strongest reconnections (22)

# PROTO-SPHERA: Phase-2 scenarios



# Conclusions

Design of PROTO-SPHERA was inspired by astrophysical examples (PWNe) and produced self-organized tori: a successful gamble to sustain for 1 sec a self-organized torus, with Alfvén time  $0.5 \mu\text{s}$ , resistive time  $<10 \text{ ms}$

## Results obtained up to now:

- very good ideal MHD stability (without any conducting shell near the plasma)
- torus is formed in a purely magnetostatic field
- He plasma viewed by 3D tomography shows different colors (torus+centerpost: green, edge: orange-brown)
- the plasma rotates in toroidal direction, acting as an oblique rotator, just as PWNe in astrophysics
- magnetic reconnections observed: not axisymmetrical & evidencing thermal/acceleration effects
- notwithstanding (slight) axisymmetry breaking, fair integrity of toroidal flux surfaces
  
- We find a **reasonable explanation** for the sustainment of the torus also at low Pinch current  $I_e \leq 10 \text{ kA}$ : the presence of spontaneous current paths also in the external part of the torus, no direct Helicity Injection from the central pinch
- We also find a reasonable way to slowly increase the Pinch current in Phase-2
- Phase-2 **without design uncertainties**, but with a **new Cathode** (already under construction for Phase-1.5) and an **additional power supply** to control the external current paths in the low  $I_e$  initial phase
- For Phase-2 the experiment has been moved in a different building with better facilities

Phase-2 of PROTO-SPHERA (~2.5 M€ needed) must prove the direct H.I. from the central pinch to the torus and assess the torus confinement quality in order to understand if this new configuration is viable for magnetic fusion but in any case can accommodate experiments of astrophysical interest

PROTO-SPHERA is the only magnetized plasma experiment in Frascati (in Italy?) until the DTT start-up: it can be a test facility for the DTT diagnostics and a “training facility” for the young researchers that will operate the new tokamak

# PROTO-SPHERA Group

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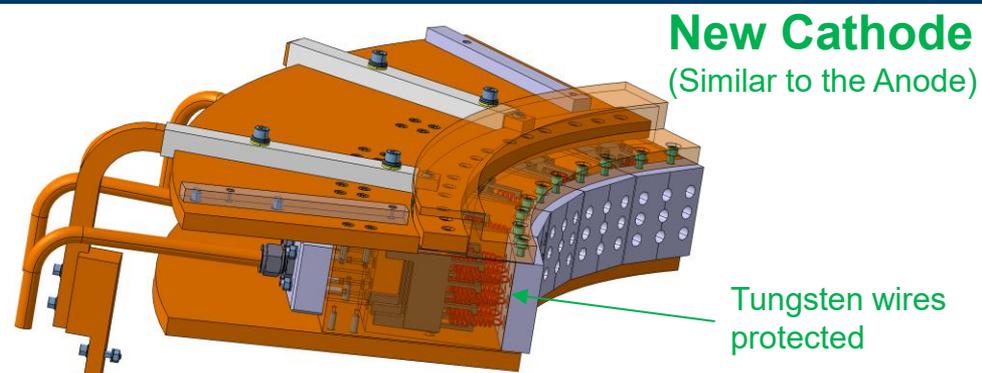
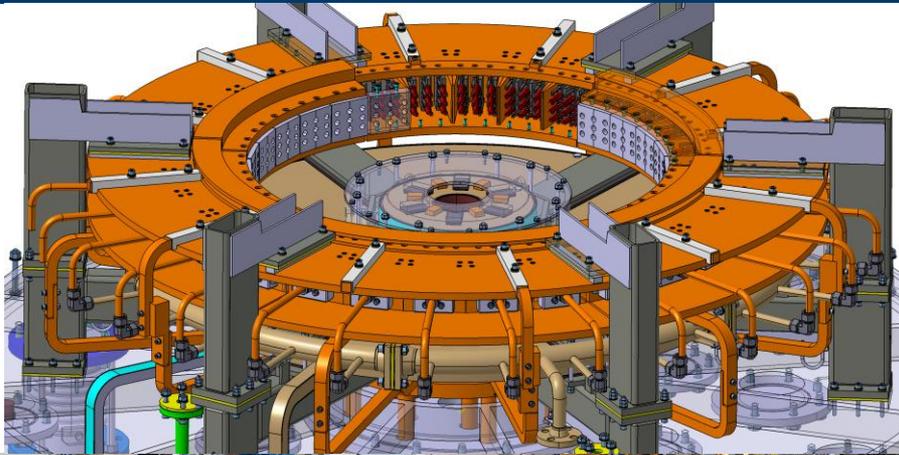
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**Samanta Macera**

*Pisa University*  
**Francesco Giammanco<sup>retired</sup>, Paolo Marsili**

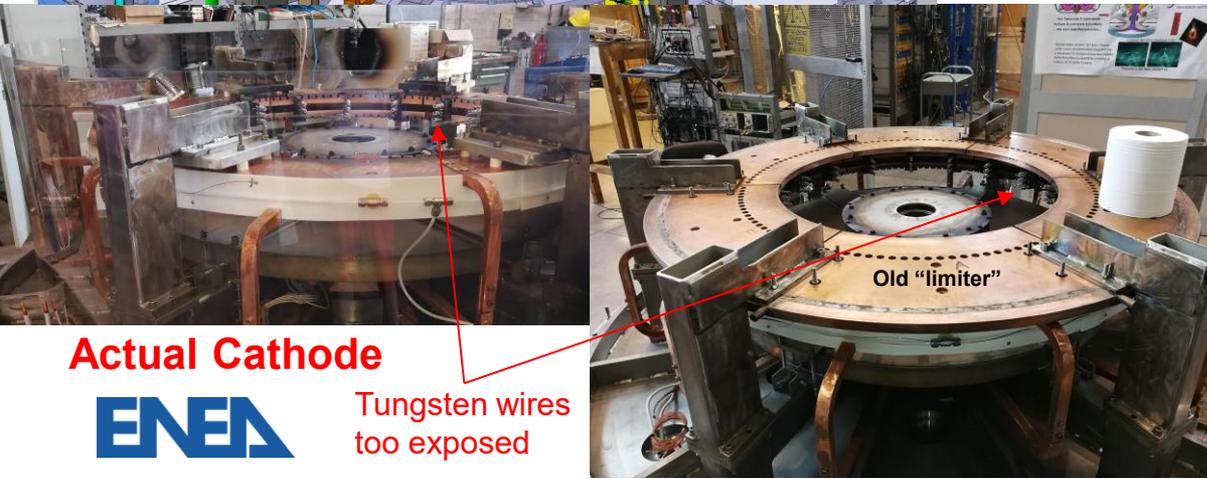
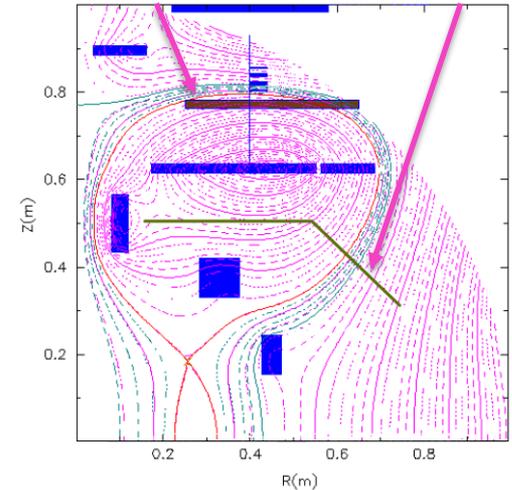
*Università di Roma-1 La Sapienza*  
**Annamaria Pau, Shayesteh Naghinajad Mohammadkhanlou, Yacopo Damizia**



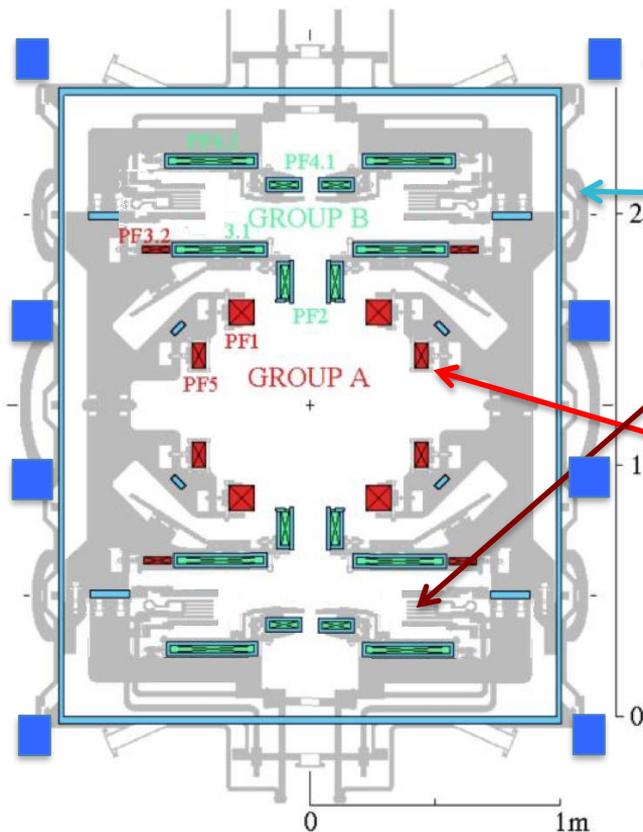
# PROTO-SPHERA: Phase-2 improvements



## New "limiter" & divertor



# PROTO-SPHERA: towards Phase-2



*Already built: Phase-1.5, June 2019 - July 2024*

PFext 8+12+12+8 wires, 240 mm<sup>2</sup>

Vacuum Vessen in PMMA

Cathode wires in W (54→270) (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** ( $I_{\text{cath}}$  10→70 kA) (conventional AC)
- **Pinch** ( $I_e$  10→70 kA) (Super-Caps and/or batteries)

Cost up to 2025

~ 2.5 M€

Cost for Phase-2

~ 2.5 M€ (including diagnostics)

# PROTO-SPHERA: the new location

Old location



Machine disassembled



Transport



New Torus Hall



During 2025, PROTO-SPHERA has been moved inside a better experimental Hall (the one of Frascati Tokamak FT); the transfer of its power supplies is still underway and the building and electrical renovation of the control room is not yet finished.