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

21th International Spherical Torus Workshop (ISTW 2022), Tsinghua University, Beijing, China, Oct. 31-Nov. 4 2022

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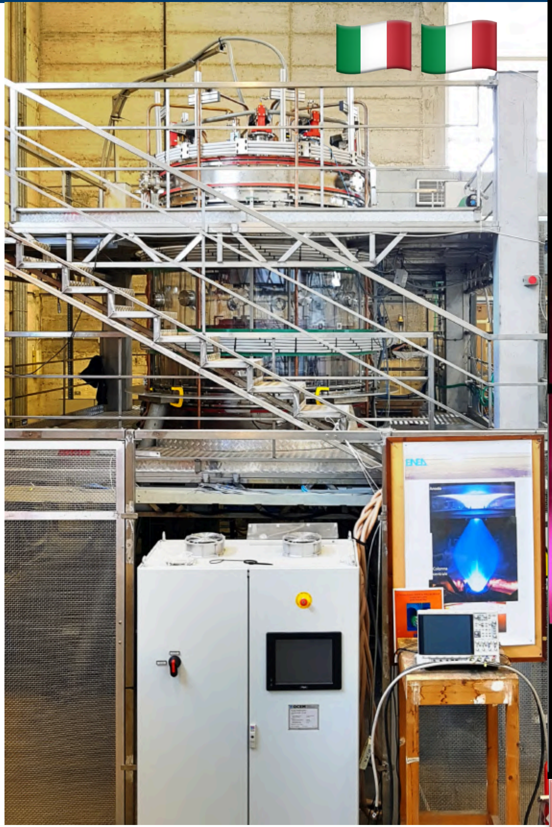
PROTO-SPHERA : an ”astrophysics” configuration

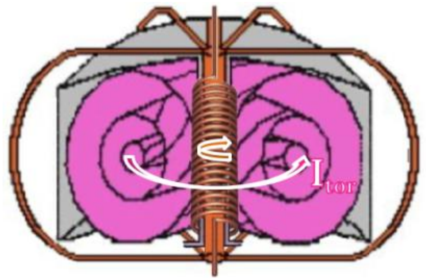
(more details in F. Alladio presentation)



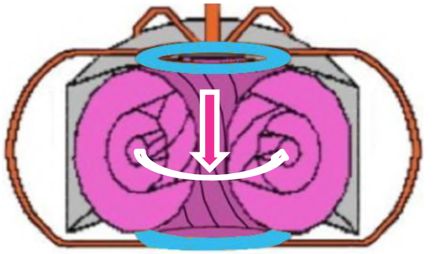
PROTO-SPHERA

Crab Nebula remnant

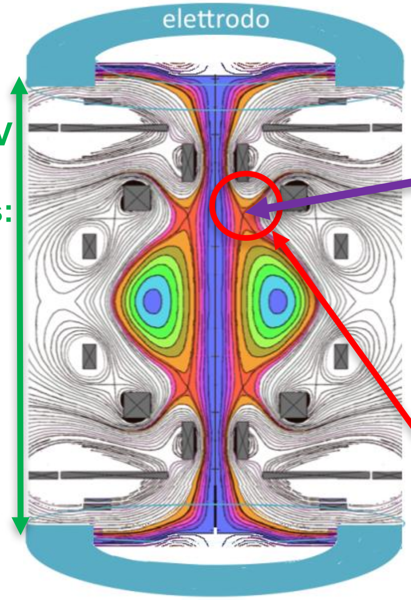
PROTO-SPHERA Vs Tokamak: the stationary state

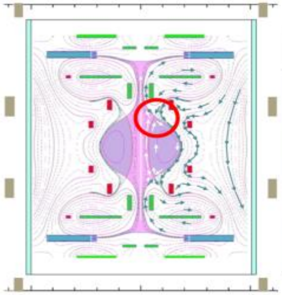


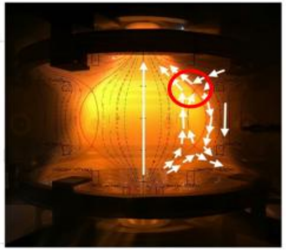
On Tokamaks the central solenoid induces the toroidal current
… but is not stationary



Constant V between electrodes: stationary

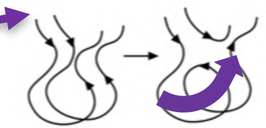






On the standard X-points reconnections are present: the Helicity Injection sustains the torus toroidal current

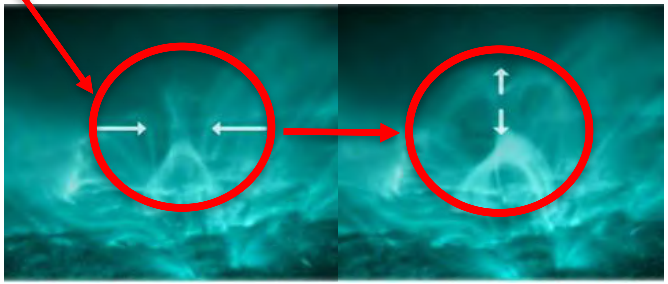
X-points



Which is the level of axisimmetry violations?

In the Sun probably the reconnections explain the coronal heating

Solar corona (milions ºC)

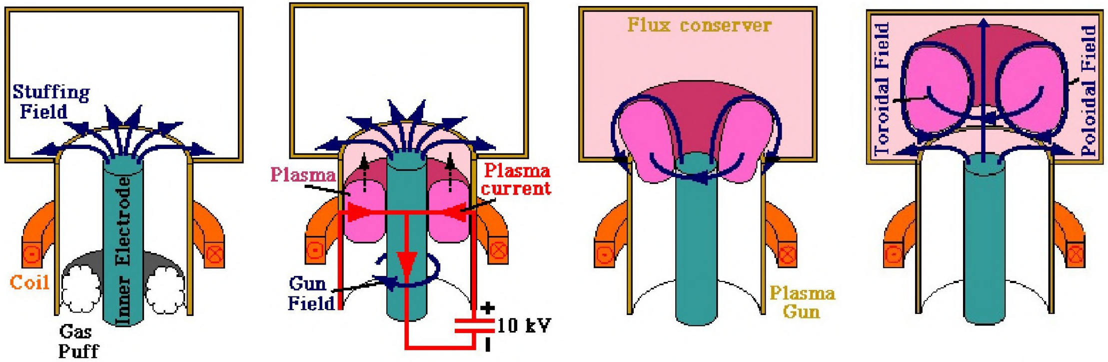


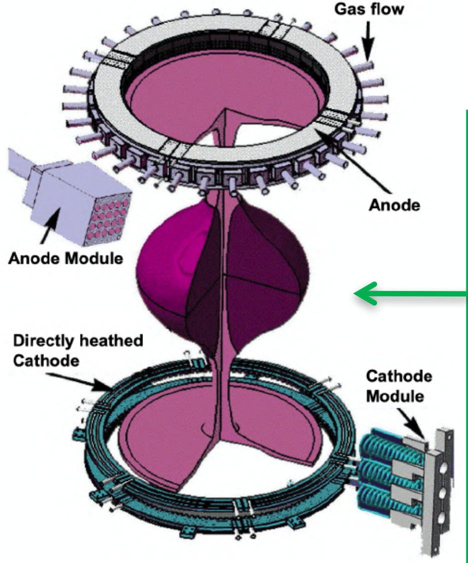
Solar photosphere (~6000 ºC)

ENEA

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)





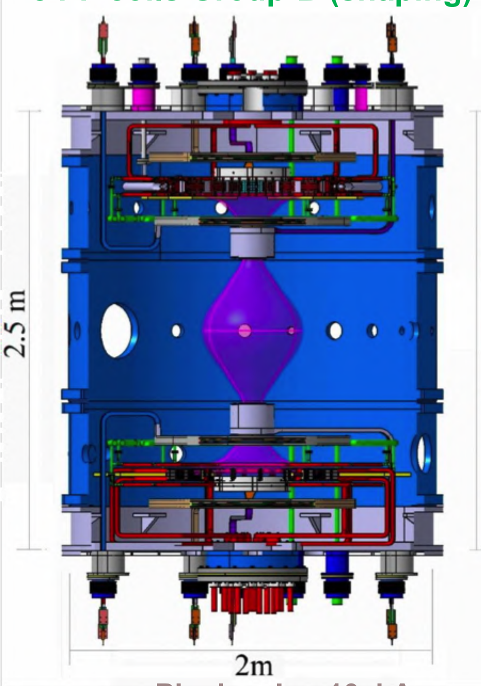
PROTO-SPHERA
- Formation: MHD instability of the Pinch
- Voltage ~100÷200 V between electrodes
- Tokamak-like gas filling (10^{-3}÷10^{-1} mbar)
- Confined by PF coils
  in absence of conducting walls close to the plasma

- Annular electrodes, disk shape of the Pinch on interface
  (fluxed hollow Anode, directly heated (AC) Cathode: W at 2900 ºC)
- Power density upon electrodes: P_e ~ 20÷30 MW/m^2
  (sustained for >1000 discharges,1 sec duration, on Proto-Pinch)

Proto-Pinch (2000)

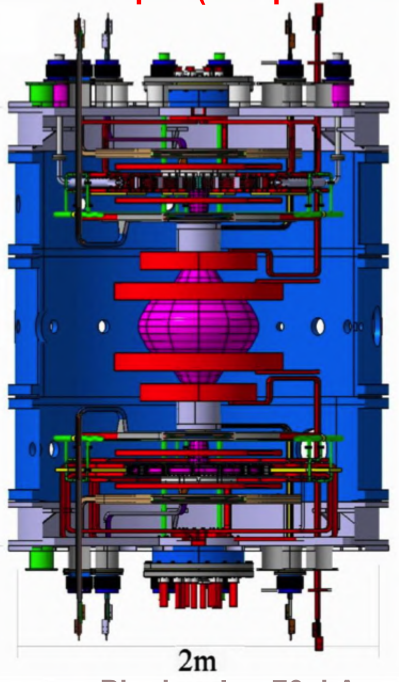
PROTO-SPHERA: the machine

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



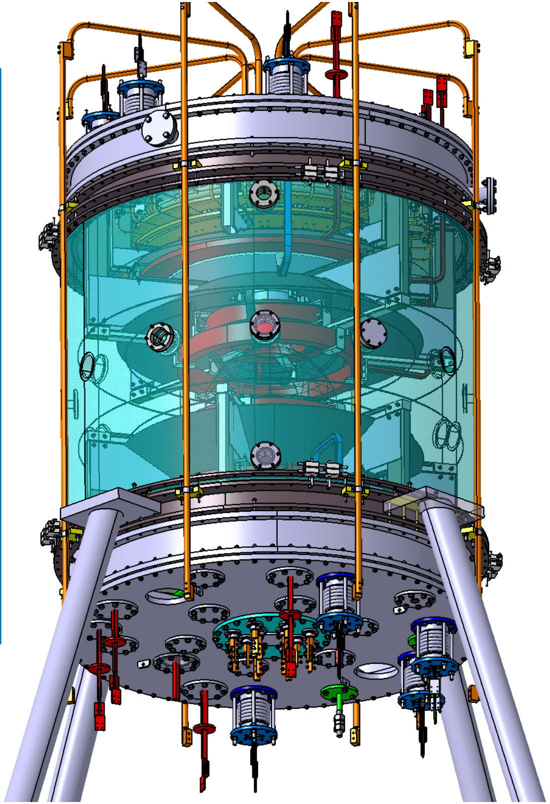
Pinch I_e = 10 kA
Spherical Torus I_{ST}= 7 kA…!

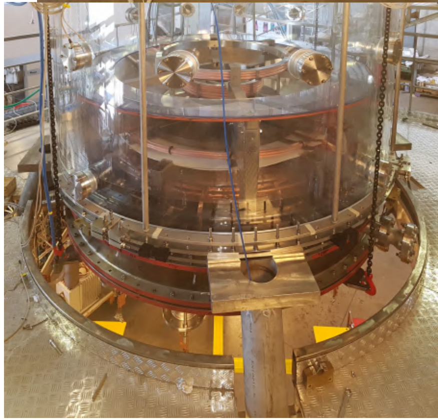
Phase-2: 8 PF coils + 6 PF
Group-A (compression)



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

Vacuum Vessel of START (Culham)

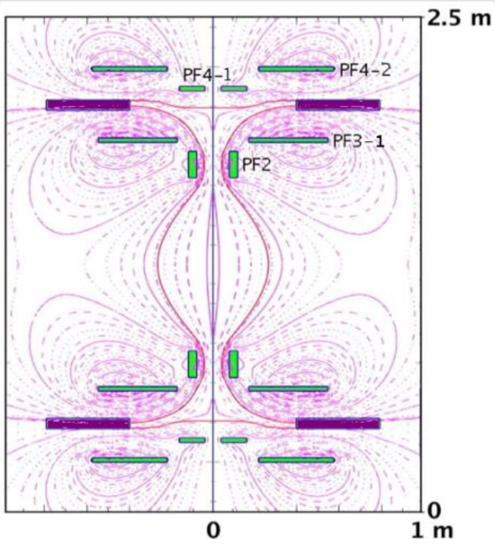




Insulating/transparent Vacuum Vessel in PMMA

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):
$\langle n_e \rangle \propto I_e$ $\langle n_e \rangle = 4 \cdot 10^{20}$ m^{-3} at I_e=10 kA

Plasma rotation ω ~ 2π (500) rad/sec
*(**E**$\wedge$**B** effect: no arc anchoring on the Anode)*

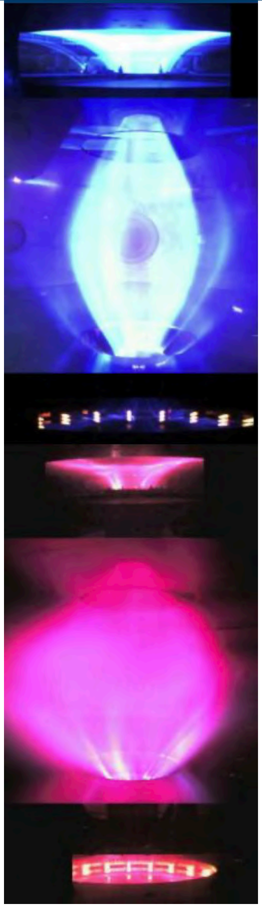
Anode-Cathode voltage:
~320 V at break-down, ~220 V at 10 kA flat-top

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

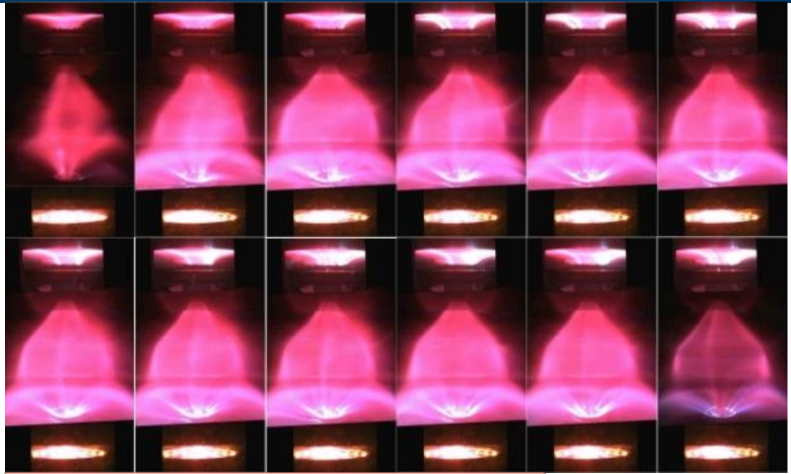
High field Tokamak densities!

DC Voltage

DC Voltage



PROTO-SPHERA: the Phase-1 toroids

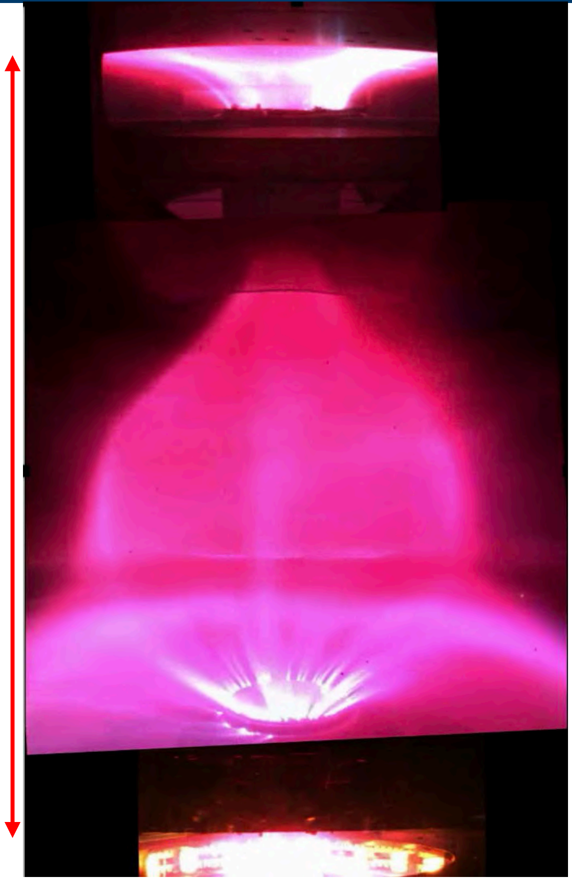


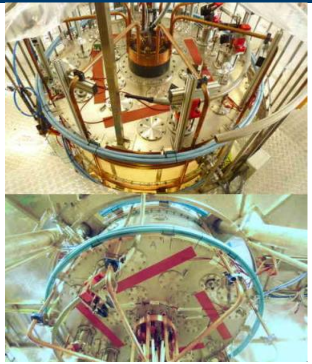
Static magnetic field!

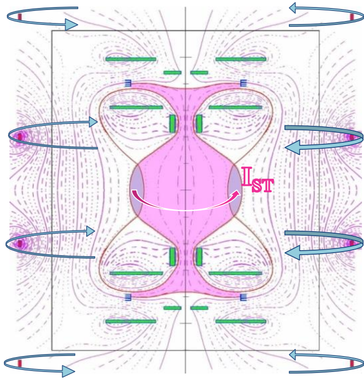
"Slim" tori aspect-ratio $A=R/a\sim7$
& elongation $b/a\sim3.5$
…impossibile in a Tokamak!
(I_e=10 kA ; I_{ST}~7 kA)

Hydrogen tori sustained for 0.25 sec *(Aluminium vessel)*
*(**but persist until the voltage is applied**)*

DC Voltage



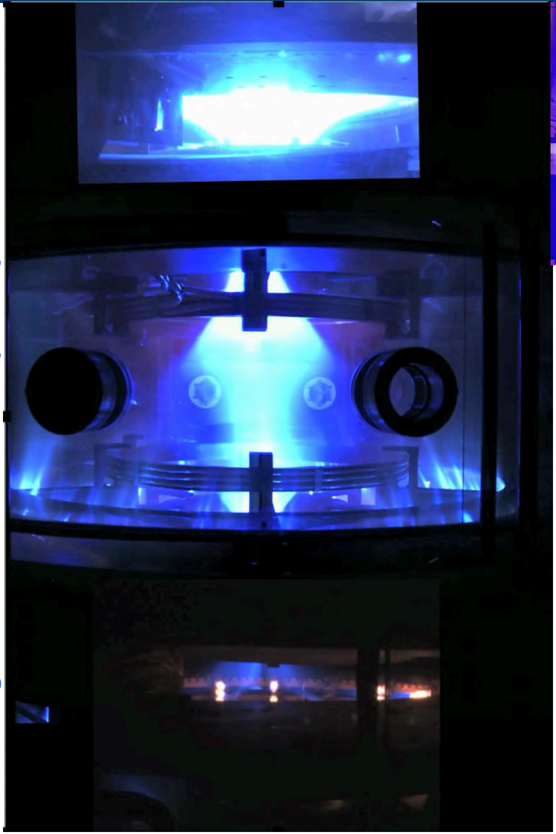


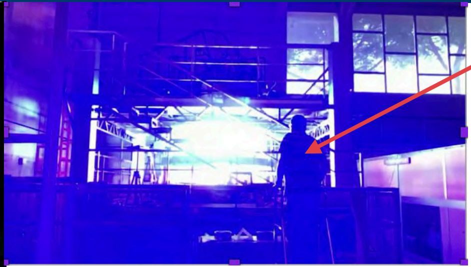


Compression PF coils external to the vessel

PROTO-SPHERA: Phase-1.5 (2019 campaign)

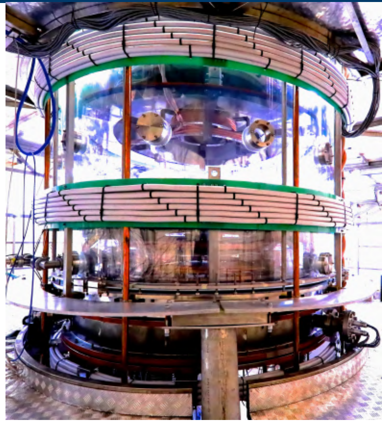
#1555, Argon, duration 0.5 sec: *"quasi-spherical" torus ?*



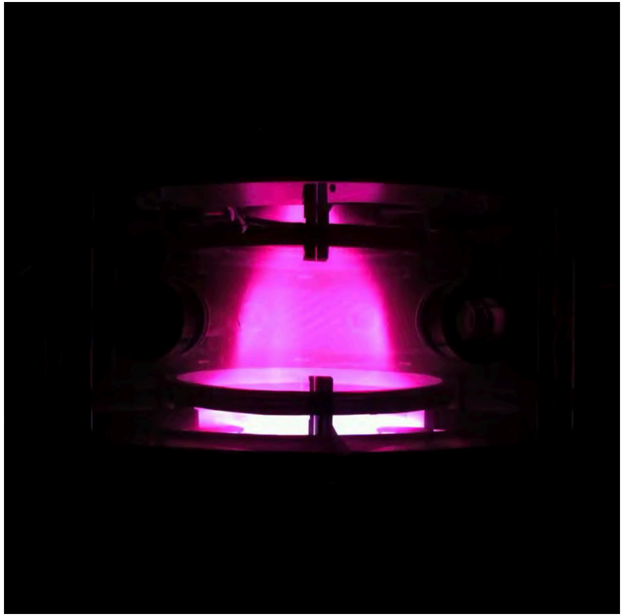


Franco Alladio! 😎

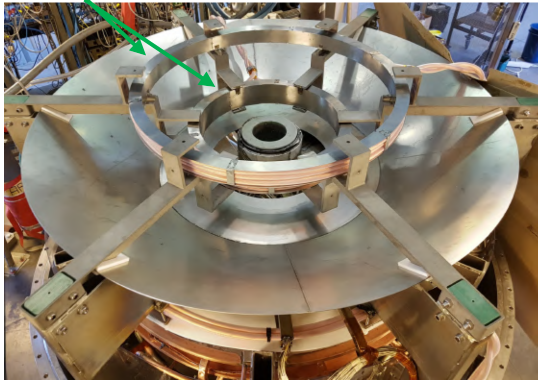
Transparent-insulating Vacuum Vessel and new "improved" PFext



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



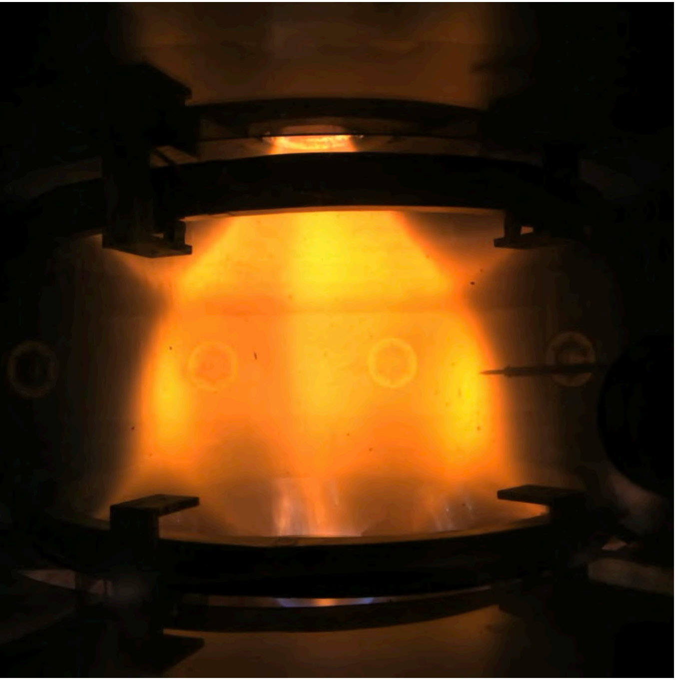
PF coils inside the VV for "compression"



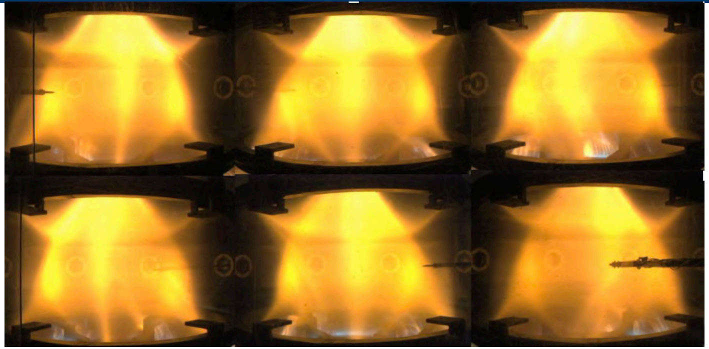
Powered with Super-Caps

PROTO-SPHERA: Phase-1.5 (2020, 2021… and ‘22)

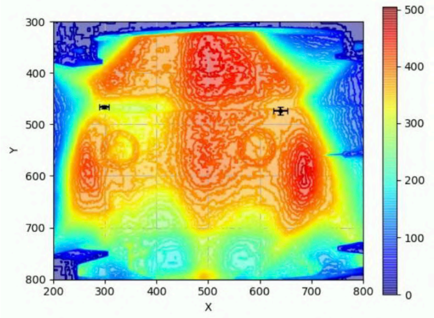
After insulation improvement: better tori
But impurities limit the discharges to 0.3 sec and problems of up/down asimmetry persist

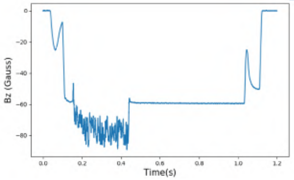


#2141 Helium: f.c. (3600 fps)



#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





Hall probes (Bv) show clear evidence of the toroid effect

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

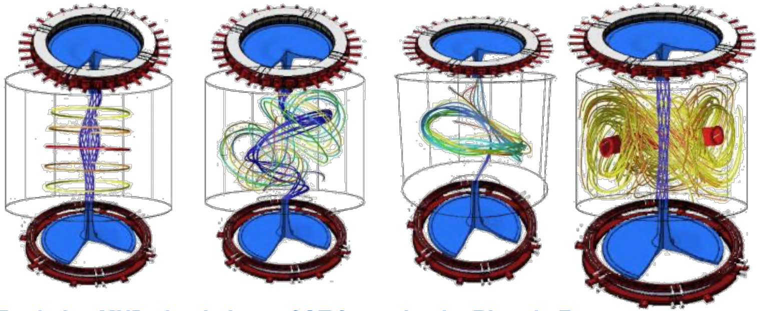
2022

Insulation in Teflon on up & down divertor

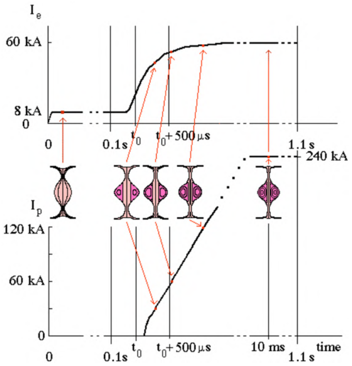
Gas injection also from cathode

PROTO-SPHERA: what we learn from Phase-1.5

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

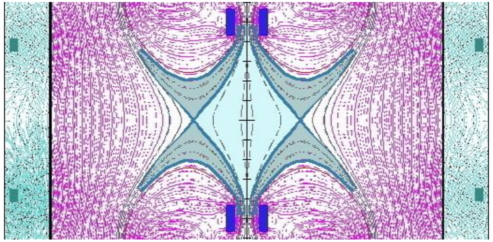


Resistive MHD simulations of ST formation by Ricardo Farengo
(ISTW2008-Frascati)



In origin (2001 Report) we planned to form the torus by destabilizing the Pinch (q_{pinch}<2)
with a fast rise (<1ms) 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 sustainement 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≤10kA. After destabilizing it "looks for" a stable configuration: the SP+ST one!



Vacuum field

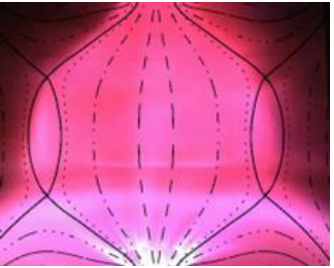
47.5 ms | 48.06 ms | 48.61 ms | 51.39 ms | 51.94 ms | 56.39 ms

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

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

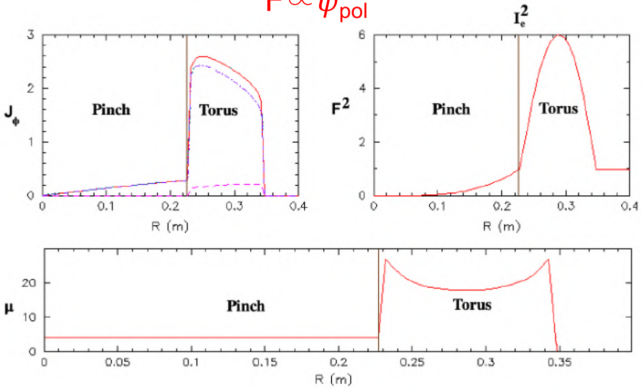
On Phase-1.5 any attempt to rise the I_{ST} by compressing the ST failed: $I_{ST} \approx$ 5-7 kA with $I_e \approx$ 10 kA is the limit

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



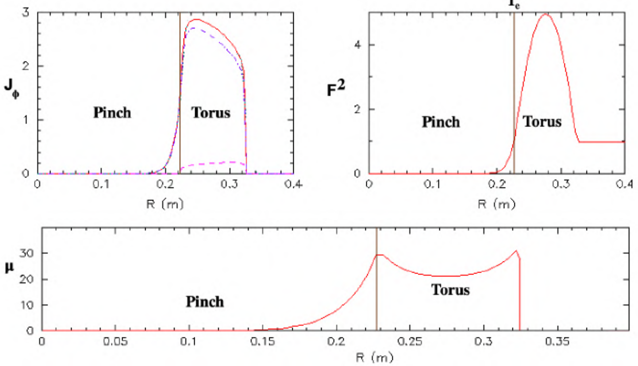
Equilibrium obtained trying to fit separatrices and external boundary (measured I_e & PF coil currents as input): I_e = 9.47 kA , $I_{ST} \approx$ 6 kA

$F \propto \psi_{pol}$



Wrong $\nabla(\mu)$

Peaked F



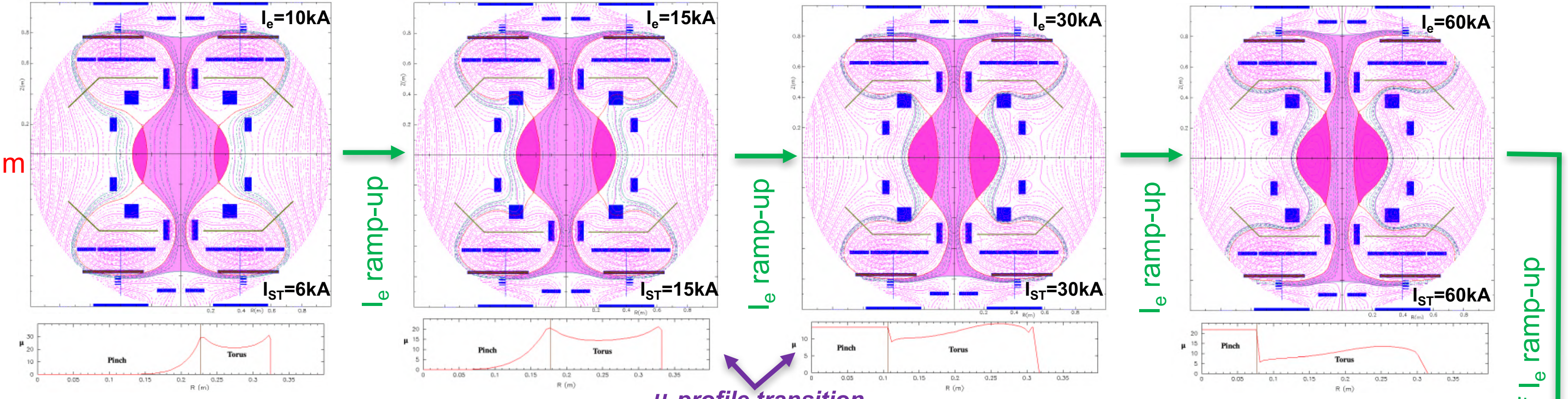
Marginally right $\nabla(\mu)$

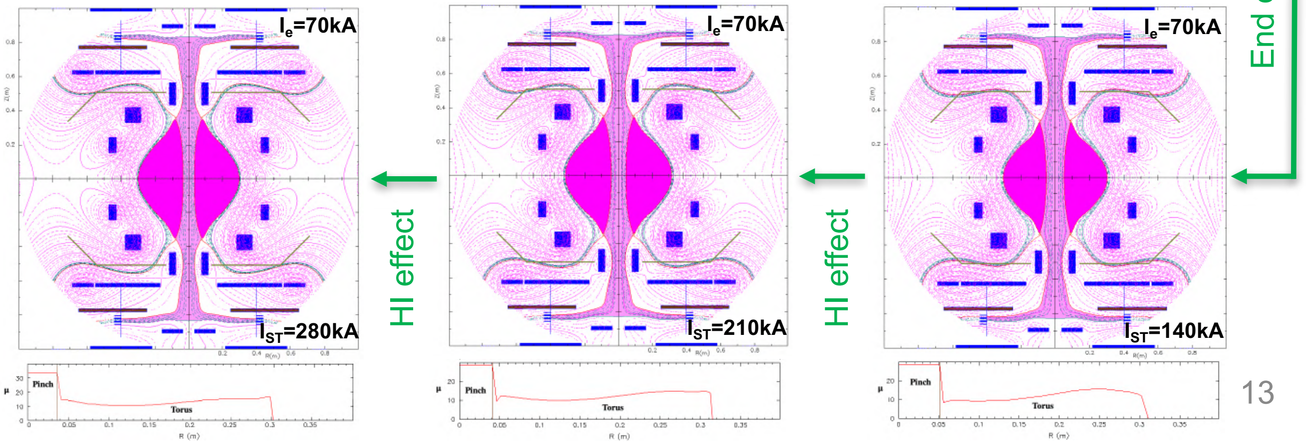
Therefore there are indications of a “skin current” inside the Pinch, and that the HI is marginal at low I_e
Probably the SP+ST equilibrium “rearranges” to maintain a stationary configuration

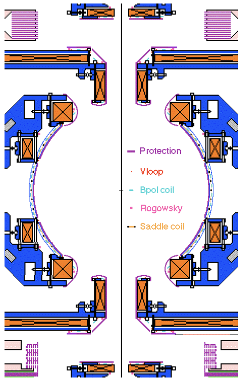
Some evidences from plasma diagnostics: in particular the line averaged density decreases of a factor of 3 when toroids are present

PROTO-SPHERA: Phase-2 scenarios

Present equilibrium

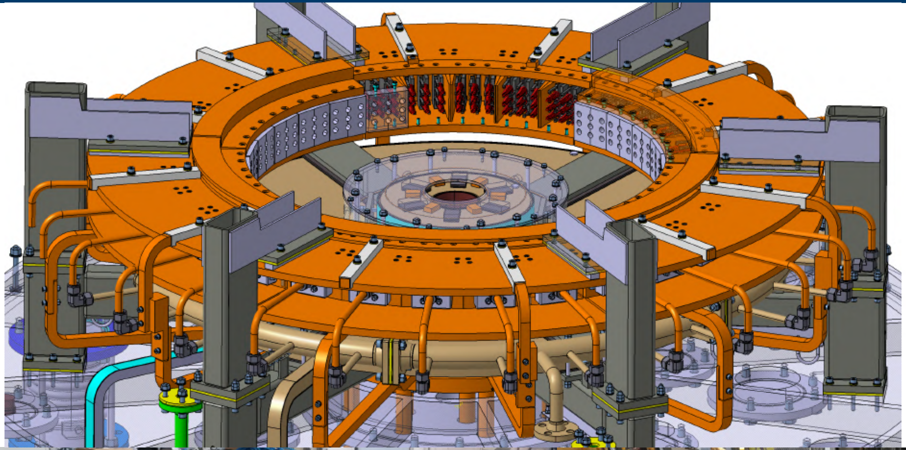


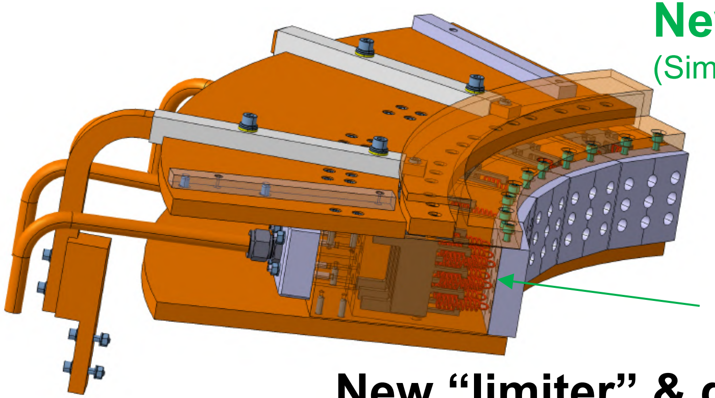




During the slow ramp-up of I_e & I_{ST} Group A PF coils are operated in feedback to fix the R_{ext} of toroid (R_{ext} position provided by magnetic probes)

PROTO-SPHERA: Phase-2 improvements



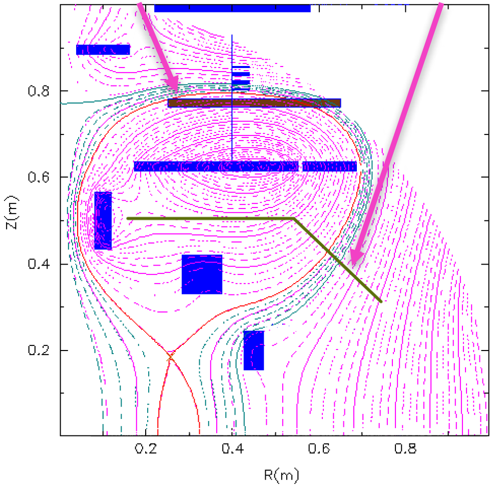


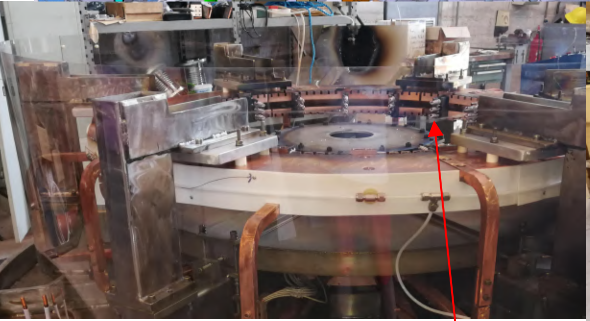
New Cathode

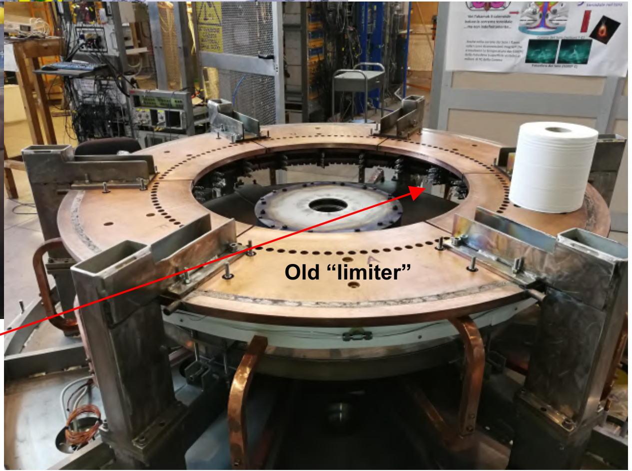
(Similar to the Anode)

Tungsten wires protected

New "limiter" & divertor







Actual Cathode

Tungsten wires too exposed

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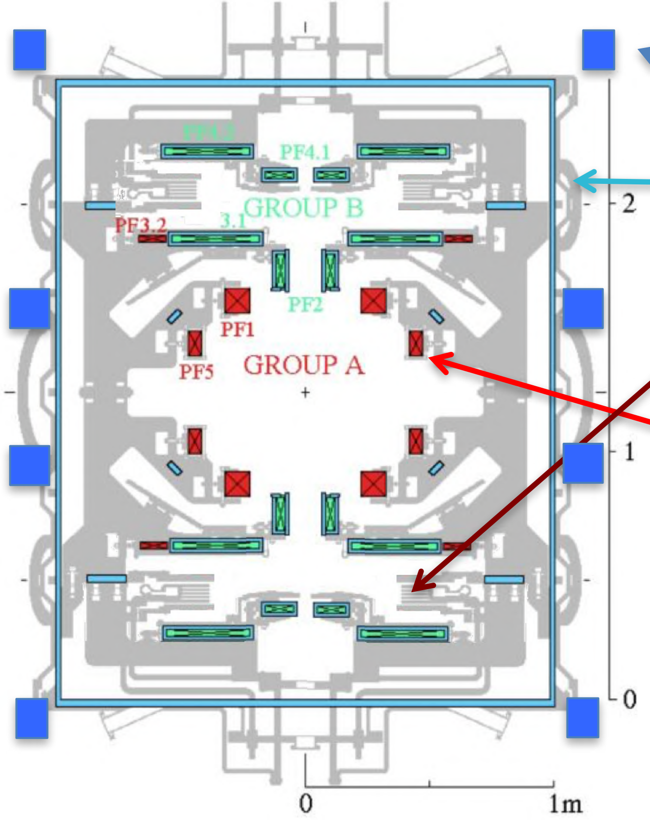
PROTO-SPHERA: towards Phase-2



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***