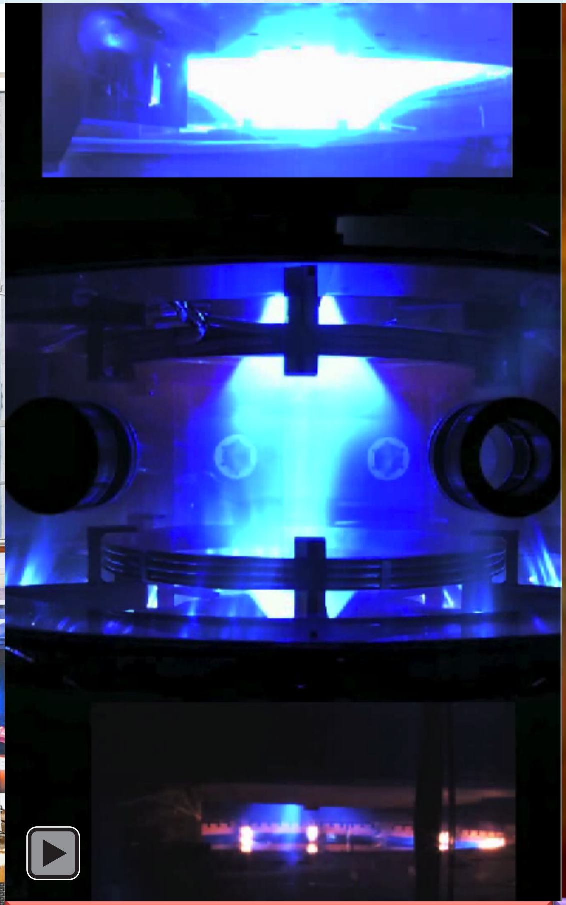
Present and future plans of PROTO-SPHERA

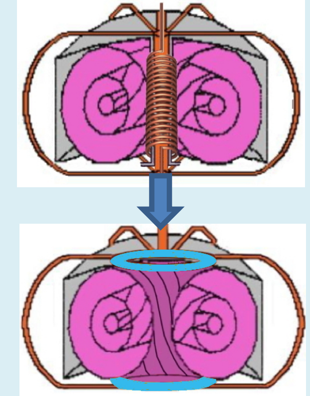
Franco Alladio & PROTO-SPHERA Group, CR-ENEA Frascati



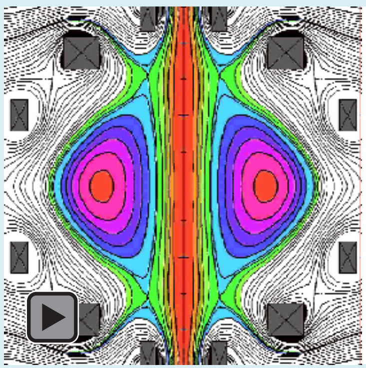
PROTO-SPHERA

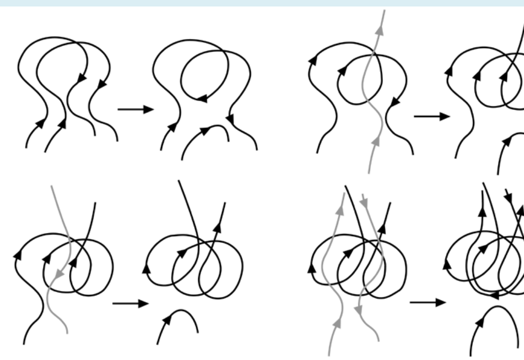
Crab Nebula remnant

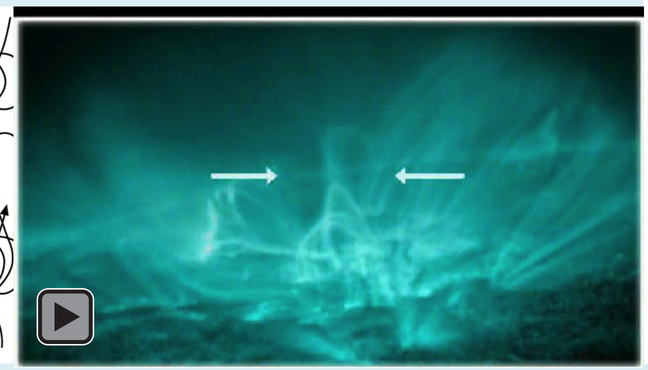
SUMMARY

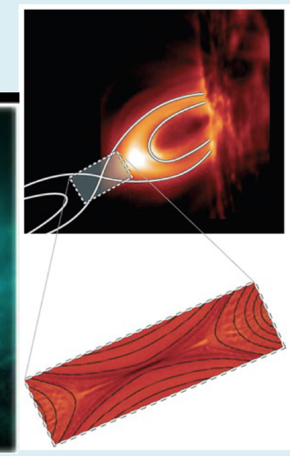


- PROTO-SPHERA replaces the two central metal conductors of Tokamaks by a Centerpost Discharge (helically wound B lines)
- Magnetic reconnection physics: at ordinary magnetic X-points, a «tear» is operated, followed by a different «mending»
- transferring magnetic flux & electric current
- converting magnetic field energy to plasma temperature



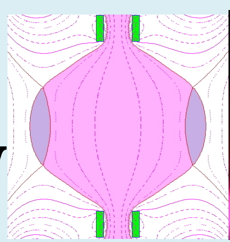


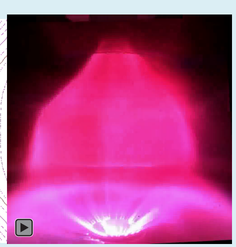




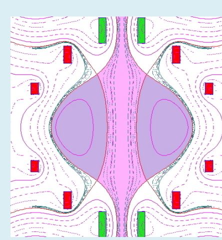
- In Phase-1 (2018) «thin tori», have filled 7% of the total plasma volume.
- In Phase-1.5 (2019, 2020) 6 new PF coils inside an insulating vacuum vessel, spherical tori are planned to fill 70% of the plasma volume.
- In Phase-2 the aim is to fill 95% of the plasma volume.

2018
2.5 MW

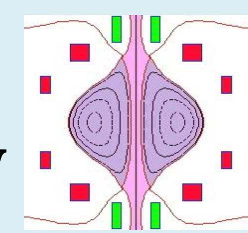




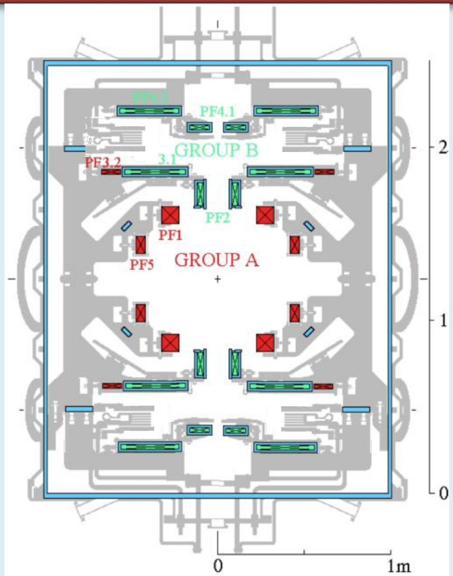
2019
3.5 MW

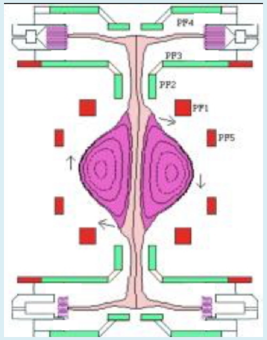


2021
20 MW

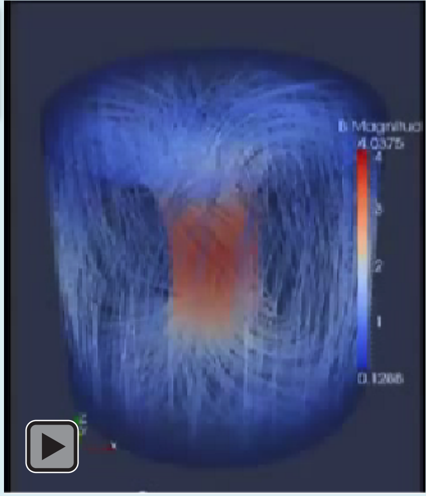


Ideal MHD stability of PROTO-SPHERA





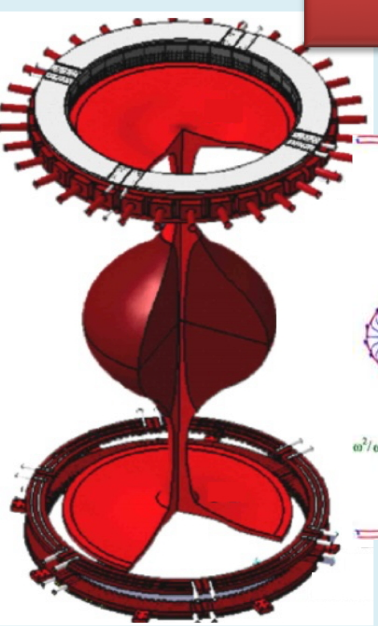
Tilt instability: toroidal dipole of vertical field overturns plasma current toroidal dipole

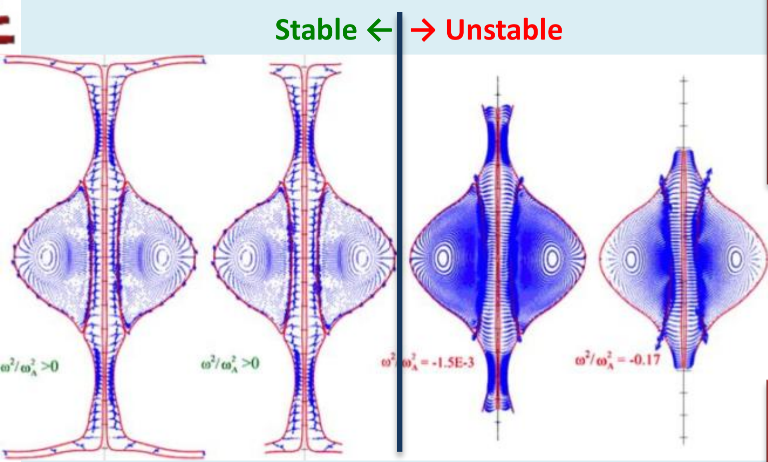


But PROTO-SPHERA dipoles:

"Group A" PF compression coils against Plasma dipole
"Group B" PF shaping coils aligned to Plasma dipole
Net result: rigid tilt instability is stabilized

Stability in terms of β = plasma beta = $\dfrac{\textit{kinetic plasma pressure}}{\textit{confining magnetic field pressure}}$





Ideal MHD stability calculations

ELECTRODE-FACING DISK-SHAPED PLASMA CENTERPOST PROVIDES IDEAL MHD STABILITY

(cutting shorter & shorter the Plasma Centerpost destabilizes the configuration)

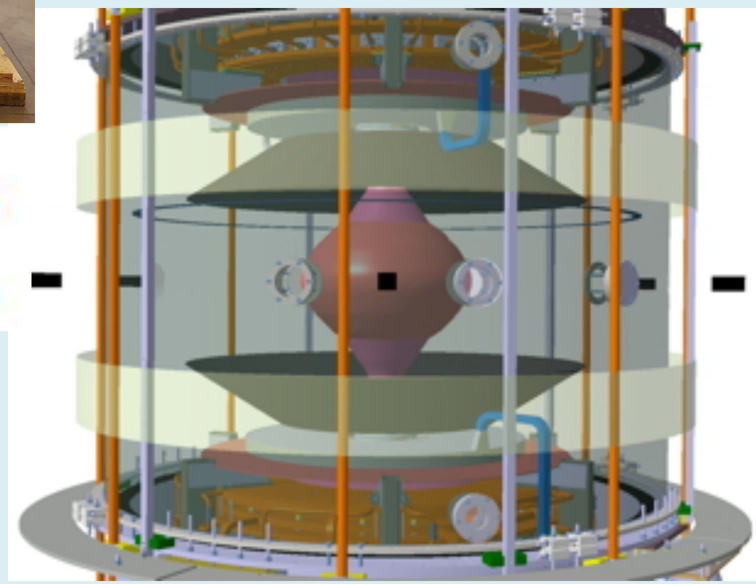
$\beta = 1$ is achievable
any metal vessel is unneeded

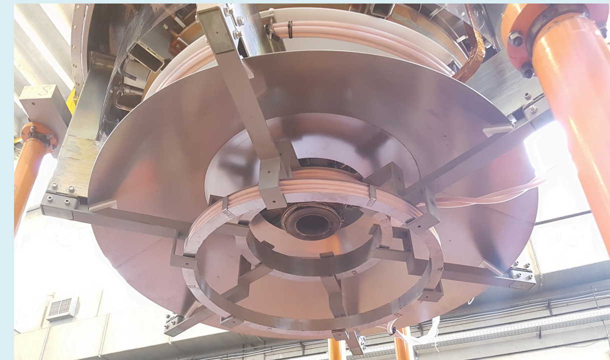
Phase 1.5 Autumn 2019: Tori sustained up to 1 s

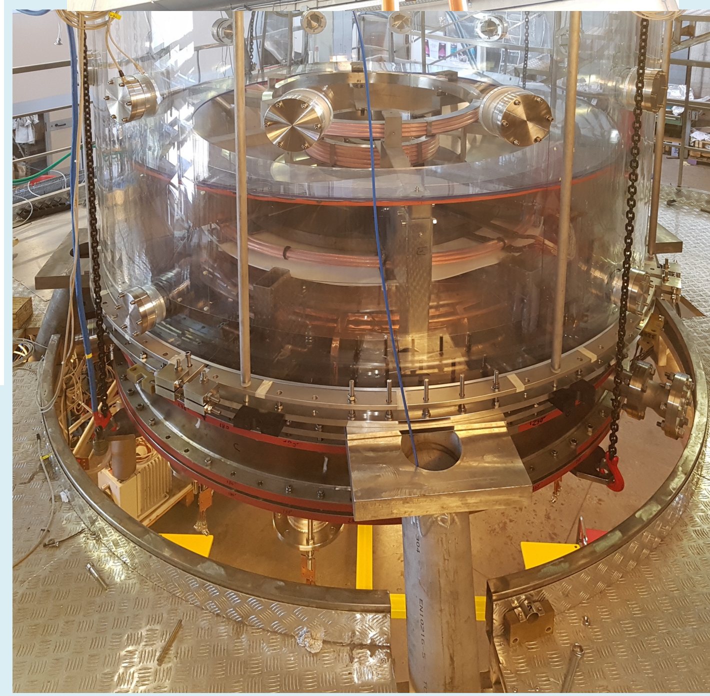
by new insulating PMMA Vessel (no skin effect: B immediate)

Reynolds
POLYMER TECHNOLOGY, INC.
Building the Impossible

Vacuum as good as with a metal vessel: $5{\bullet}10^{-5}$ mbar
Operation at > 10^{-2} mbar





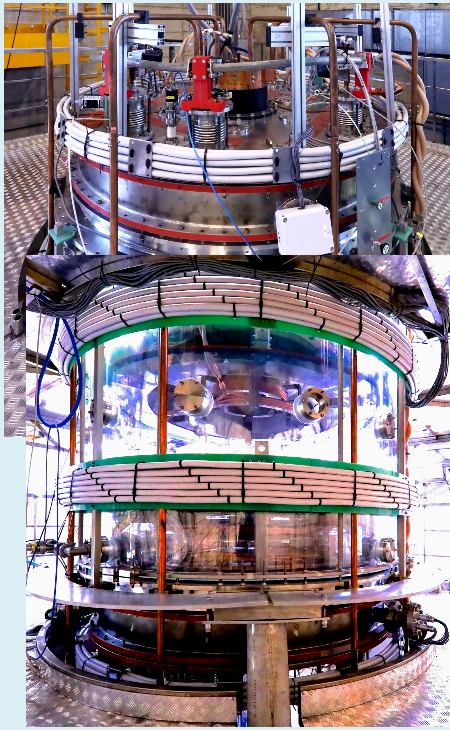


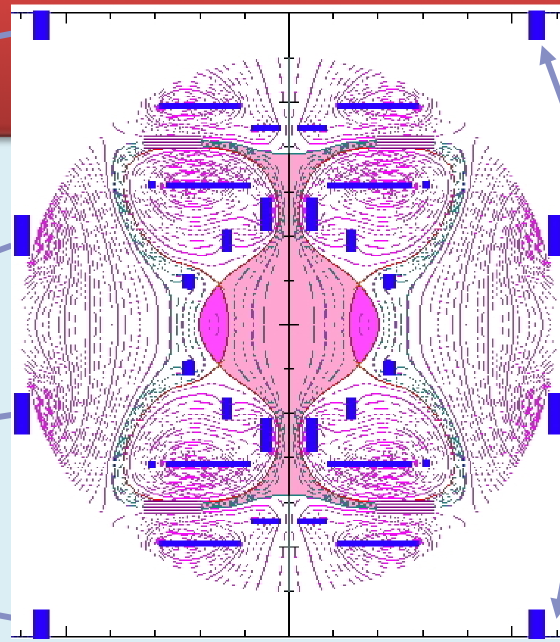
The presence of a gas blanket around the plasma cushions the inside of the 9 cm thick PMMA vessel

A further 2 mm thick polycarbonate liner inside the PMMA vessel protects it & screens UV light

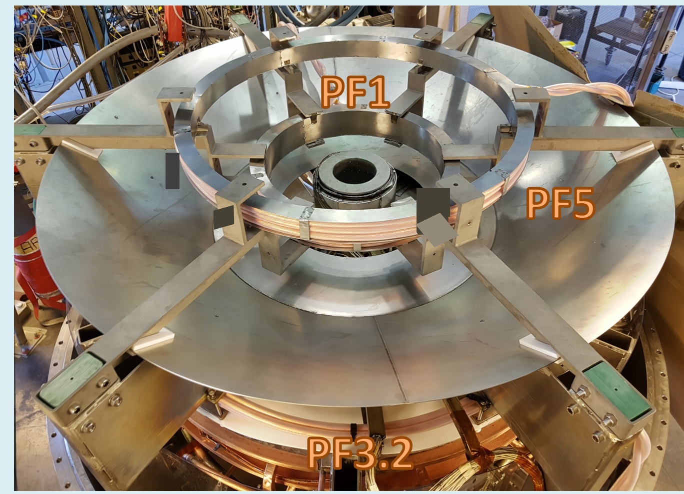
Confined plasma can be obtained without a nearby metal wall : the absence of any conducting shell distiguishes PROTO-SPHERA from any spheromak

Phase 1.5 Autumn 2019: 4 refurbished External PF & 6 new Compression (CPF): 18 PF coils, 2 power supplies

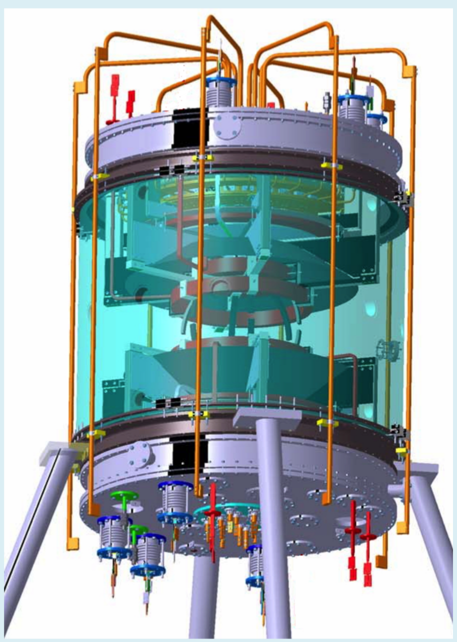


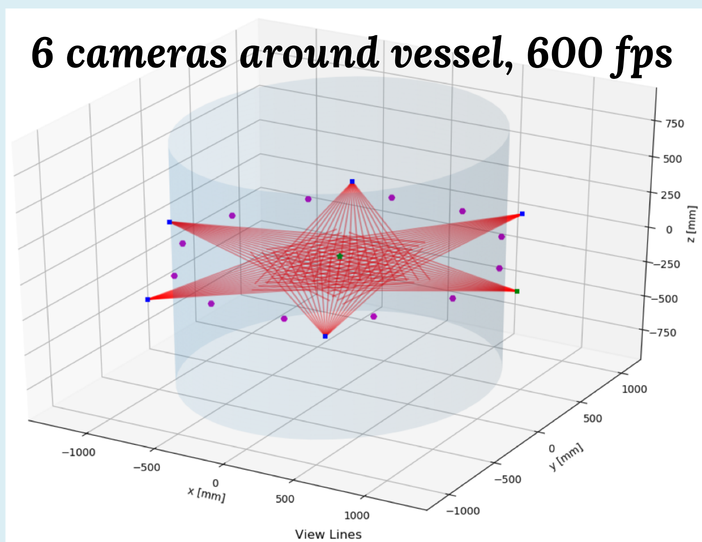


«Thin tori» are produced by External PF coils (PFExt) alone



The 6 compression CPF coils fed by a Supercapacitor bank



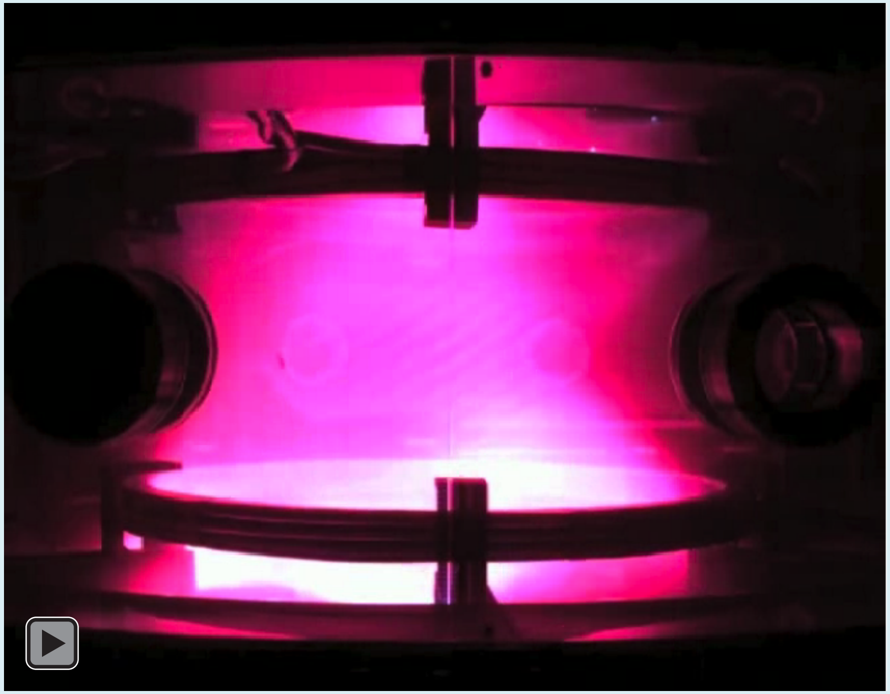


The transparent vessel allows for 3D plasma tomography in visible light

OCEM POWER ELECTRONICS

«Thin Tori» sustained without surrounding conducting shells

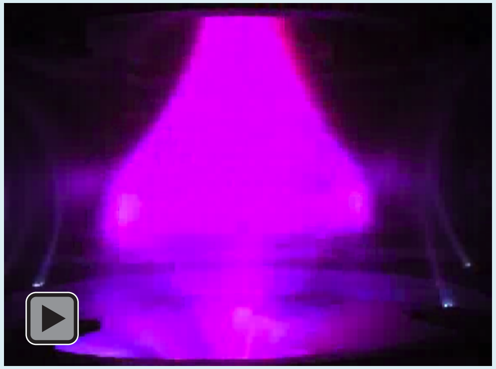
#1611



«Thin tori» (R/a=7, b/a=4) obtained in PMMA VV same as in 2018 Aluminium VV

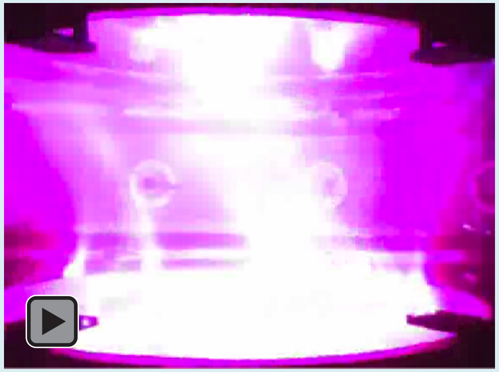
- *now sustained for 1 sec in static B field!*

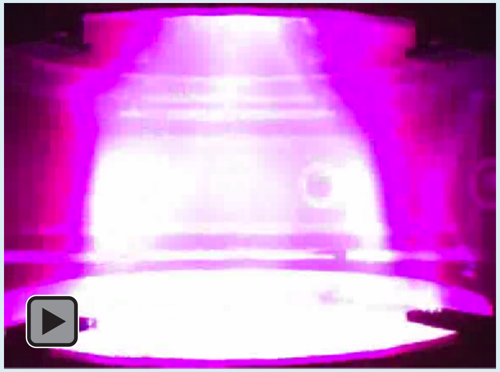
Vision from 6 cameras rotates to show 3D phenomena



Plasma breakdown & Plasma switch-off

Magnetic reconnections are 3D events around X-point circles:



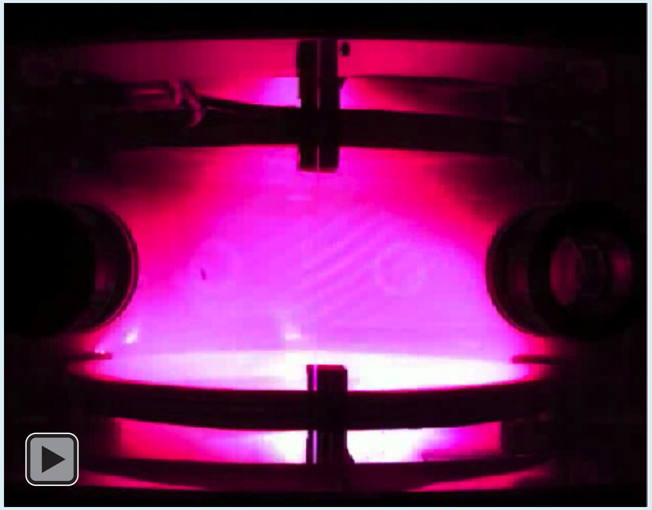


their intensity is the strongest & their repetition rate is the highest at torus formation then both decline during torus maintenance

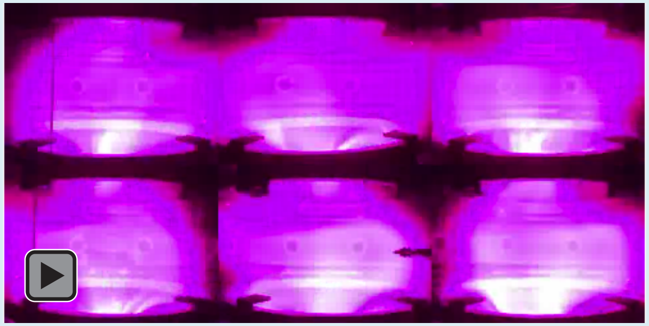
torus formation & torus maintenance

«Thin Tori» difficult to produce by pulsing PFExt coils

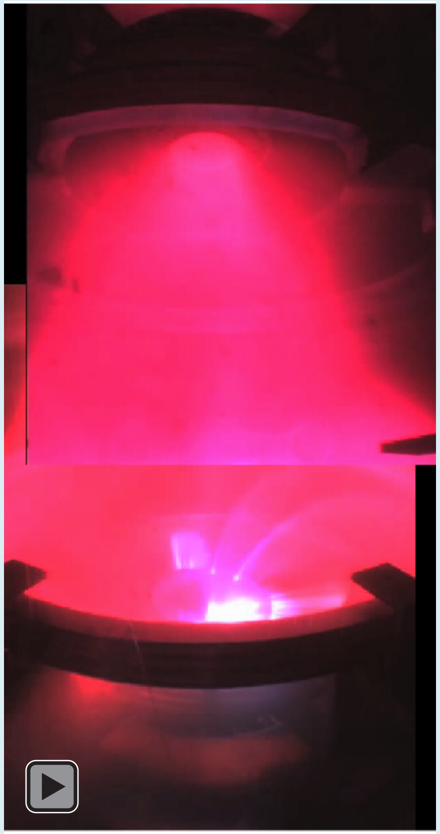
#1621



Visions from 6 cameras



Magnetic reconnections do not decline in their strength & rate



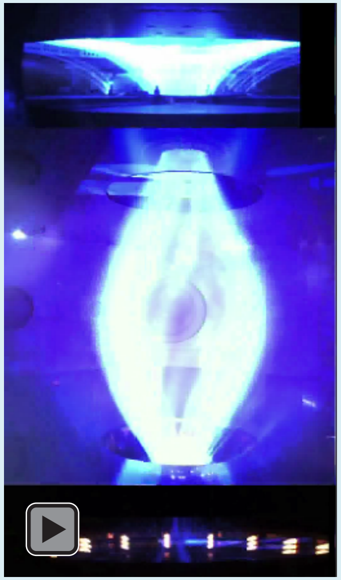
Supercap power supply pulsed PFExt coils with the right current (compression CPF inactive)

So «*Thin torus*» *formation was attempted on the pre-existing* Centerpost discharge: «Thin torus» did not stabilize!

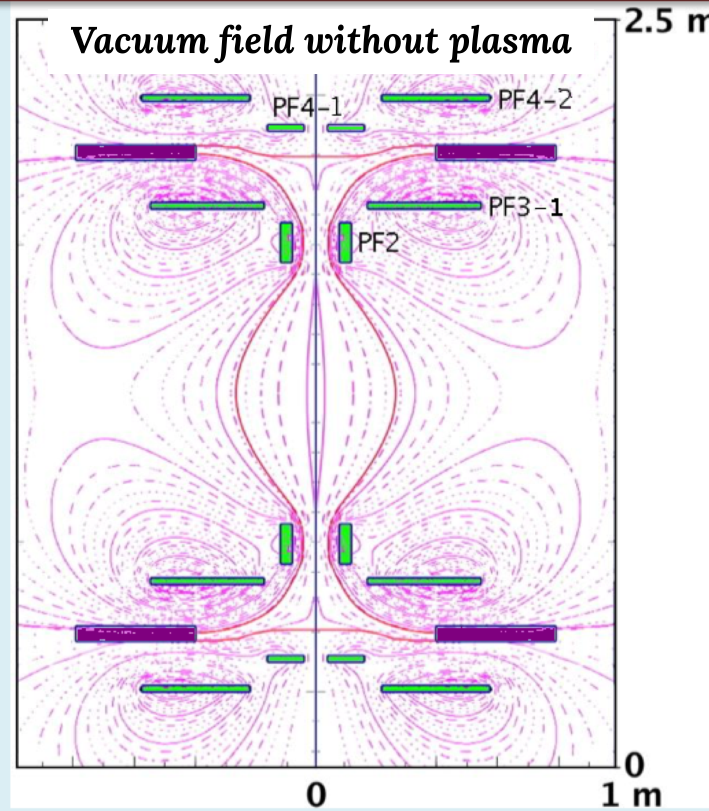
The absence of a toroidal magnet & the torus formation in a magnetostatic field suggest: ***magnetic confinement devices could be built*** *(in principle)* ***using axisymmetric permanent magnets surrounding a Plasma Arc Discharge***

Stray plasma current paths have been cured during the whole Phase-1

#614

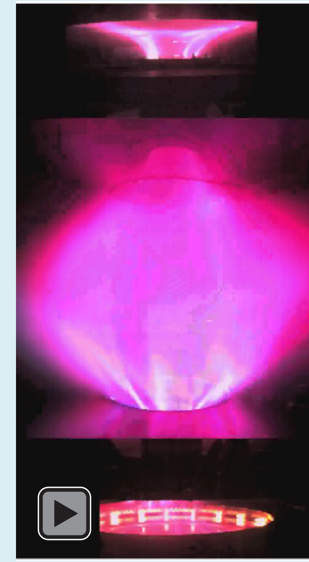


DC voltage



DC voltage

#977



#1555

Argon: currents disconnected from torus connect the electrodes' rear: **4 kA lost over 10!**

In Hydrogen sparks from lower PF2 coil surround the torus

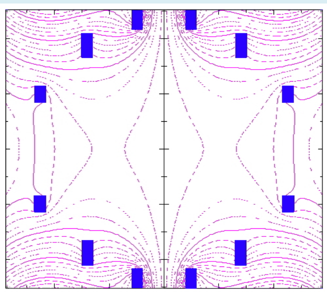
#1662

…but still in Phase-1.5 stray current paths are present around the tori … curtailing the efficiency of helicity injection!

Argon Tori by PFExt formation, then CPF (Compression coils) or directly in static field (PFExt+CPF together)

The CPF current feedthroughs at first acted as secondary electrodes

Vacuum field without plasma



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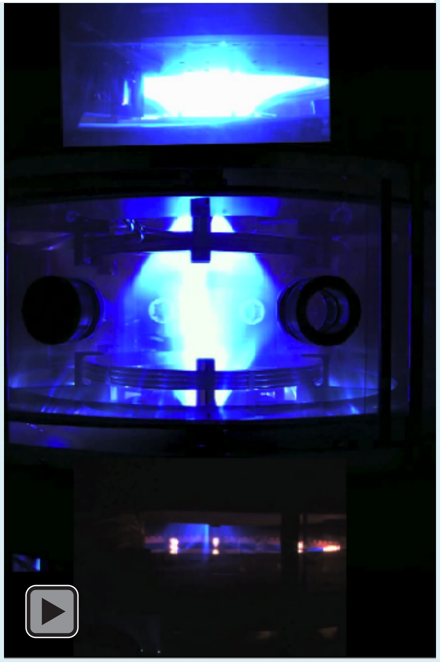
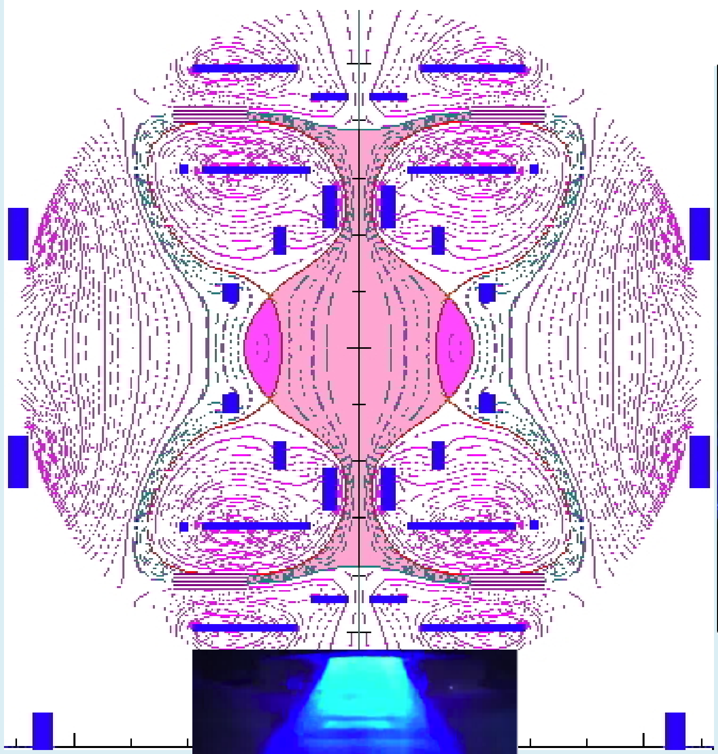


Magnetics $I_{torus}=I_{electrodes}=6$ kA



Feedthroughs fixed

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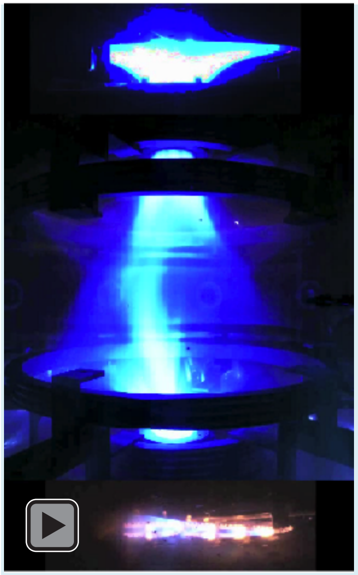
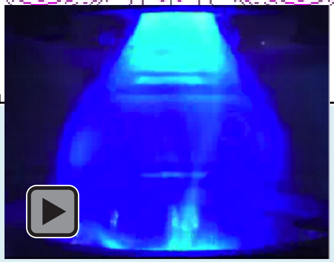
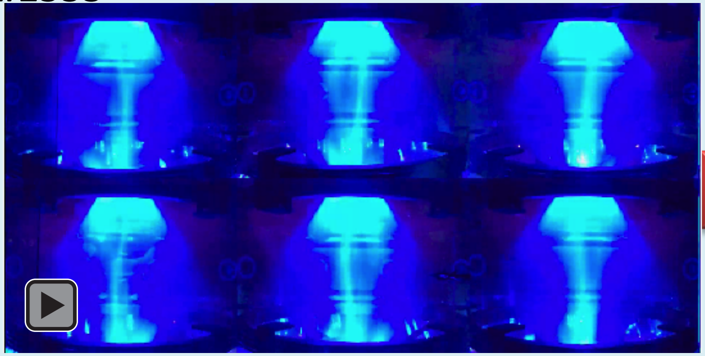


#1686



Vision from 6 cameras rotates to show 3D phenomena

#1555



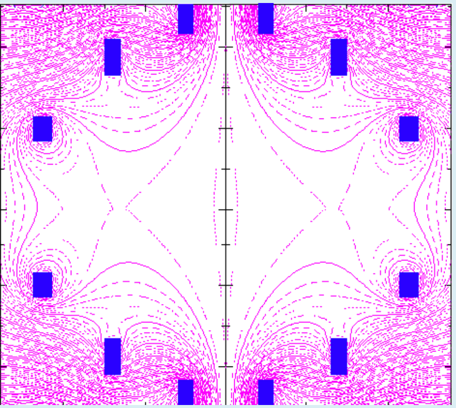
Reconnections with compressing CPF

You don't get what you see …you don't see what you get!

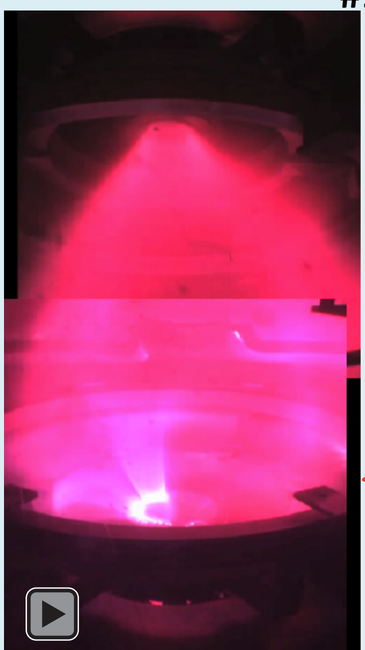
…not yet a spherical torus
Magnetics (currents in PFC & separatrix position) gives $I_{Torus}/I_{electrodes}$ = 6 kA/6 kA = 1

Hydrogen Tori by CPF (Compression coils) alone

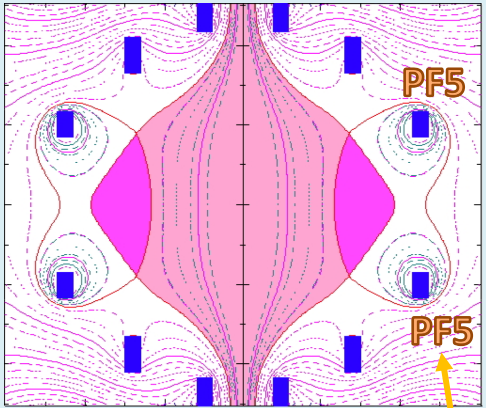
Vacuum field without plasma

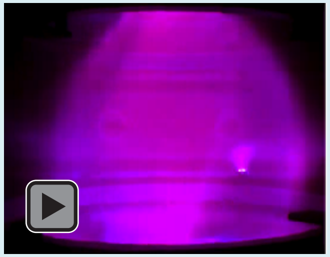


#1683



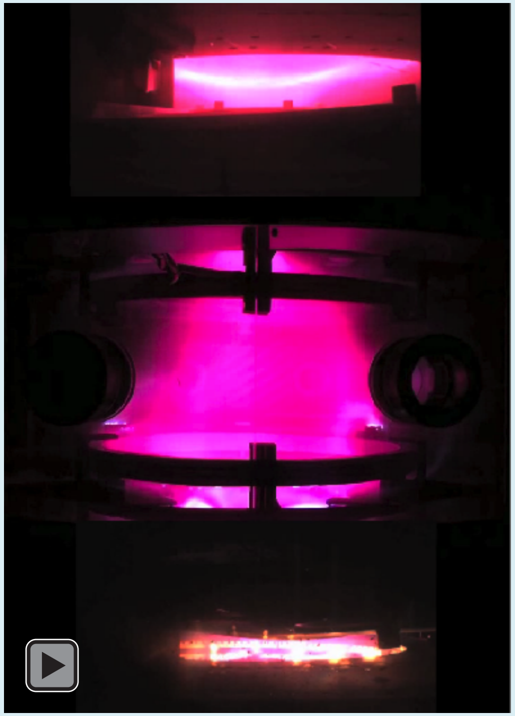
Magnetics I_{torus}= 3 kA
$I_{electrodes}$=10 kA





Vision from 6 cameras rotates to show 3D phenomena

#1662



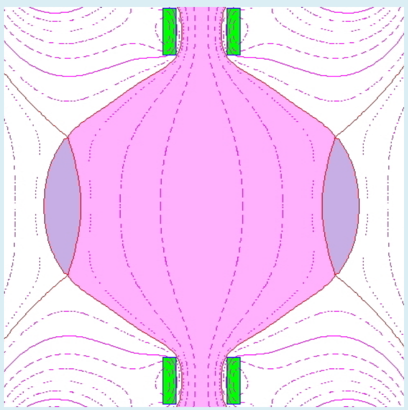
Plasma surrounds both PF5

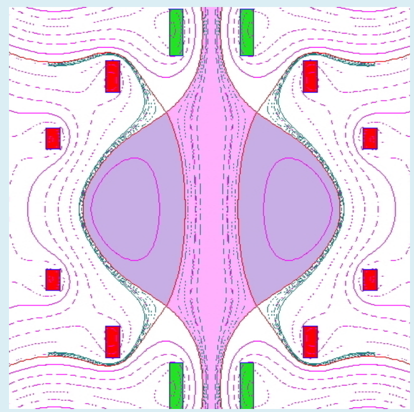
Sparks from PF2 flow around torus

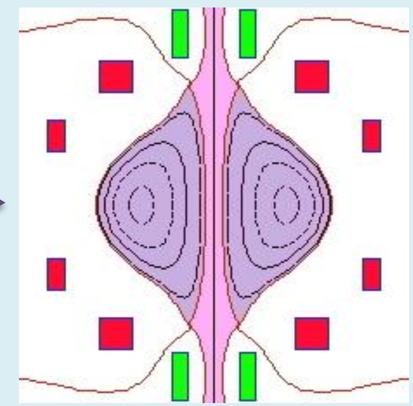
...far from a spherical torus
Magnetics (currents in PFC & separatrix position) gives $I_{Torus}/I_{electrodes}$ = 3 kA/10 kA = 1/3

Planned escalation of performances

2018-2019	2019-2020	end 2021
2.5 MW power to overall plasma	up to 3.5 MW overall	up to ~ 20 MW overall
From Phase-1	to Phase-1.5	to Phase-2
I_e = 10 kA	I_e = 10 kA	I_e = 70 kA
I_{ST} = 7 kA	20-40 kA	I_{ST} = 0.28 MA





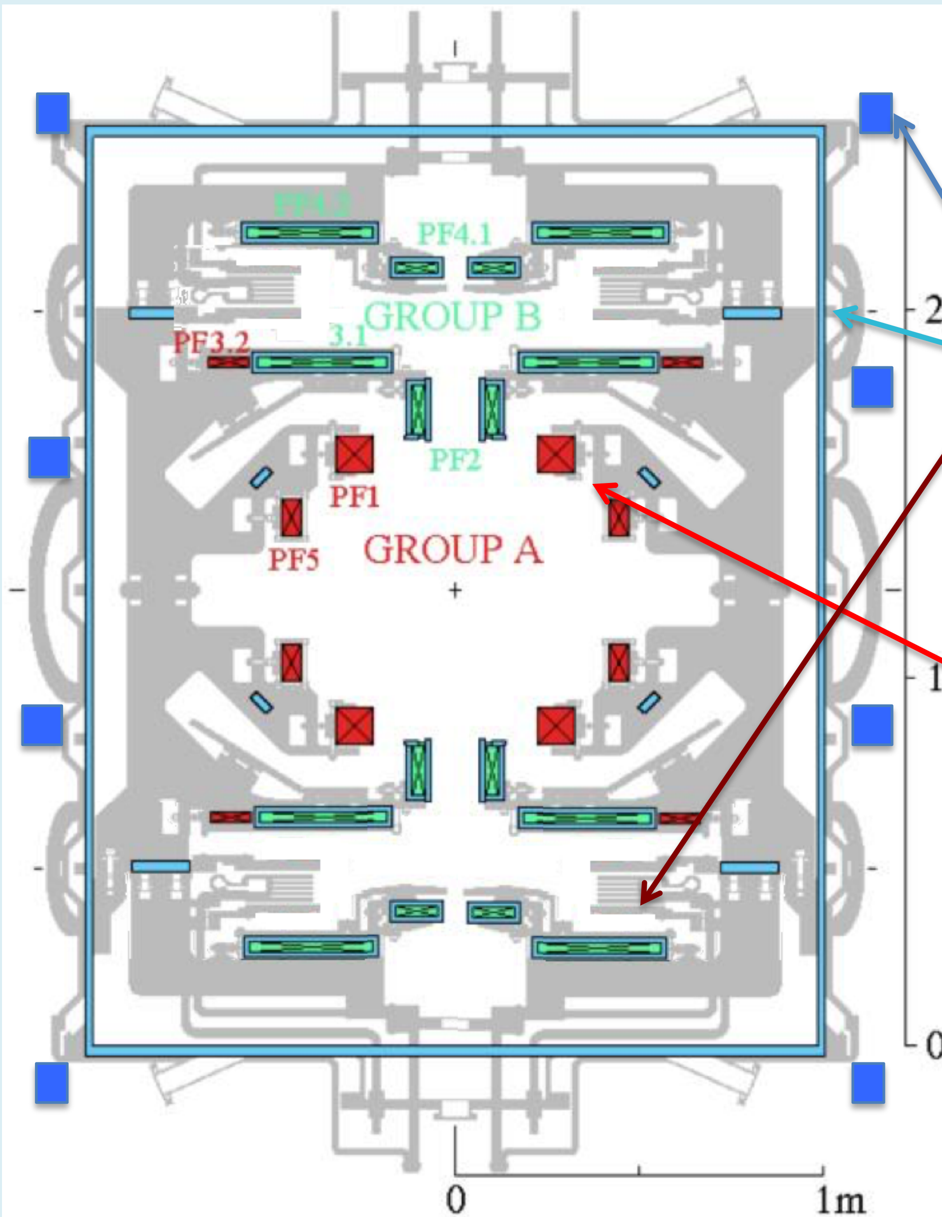


From 7% Torus/Sphere volume	to 70% Torus/Sphere volume	to 95% Torus/Sphere volume
7% of Power Input to Torus	? of Power Input to Torus	? of Power Input to Torus

No additional heating systems? (reconnection heating)

β~1 ⇒ cost is 1% of a Tokamak (β~1%), with same power input into plasma

To be built to achieve 1/3 MA Spherical Torus (Phase-2 2021)



Already built, for Phase 1.5, June 2019

PFExt 8+12+12+8, 240 mm^2

PMMA Vacuum vessel

W cathode Filaments(54→378) (still 54 now)

To be built, at the end of Phase 1.5

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

Electric power supplies based on *Super-Caps*

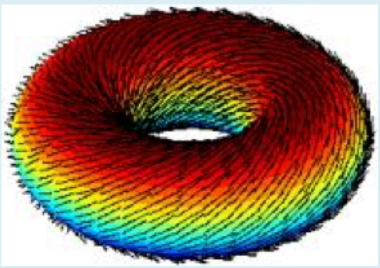
- **Compression Group A** (fit up to I_{ST}=0.5 MA)
- **Cathode (I_{cath} 10→70 kA)**
- **Centerpost** (I_e **10→70 kA**)

Cost incurred so far (2019)	~ 2.5 M€
Cost for completion (Phase-2)	~ 1.5 M€

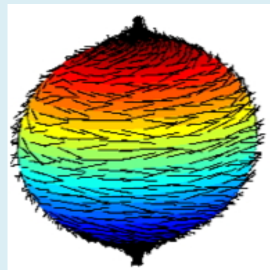
Last Confinement Surface spherical, but Tori inside

Poincare' "Hairy-ball theorem": no continuous field tangent to a sphere there is at least upon ***one point*** $\vec{B} = 0$ ***and*** $\vec{\nabla} p = 0$

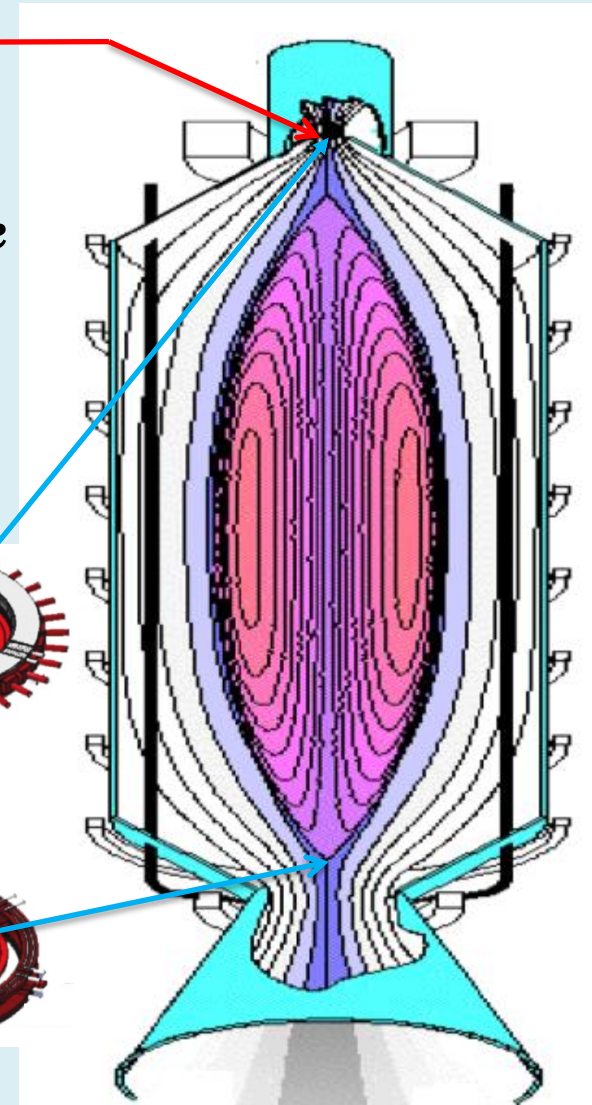
null or degenerate X-point



a hairy torus can be combed

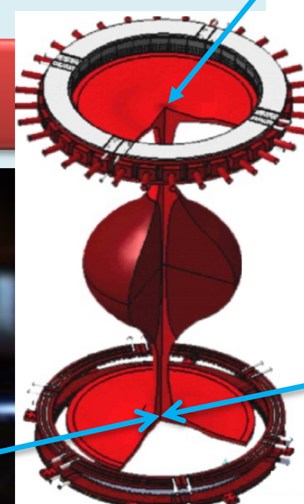


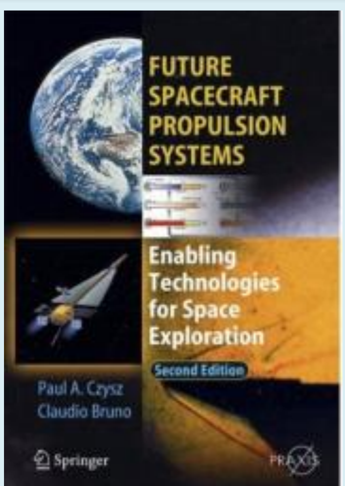
a hairy sphere cannot!



One of the "***tufts***" of the sphere is predominant **in expelling charged fusion products**

Space-thruster forerunner?





Magnetic nozzle observed in PROTO-SPHERA experiment (2015)

Remarks:

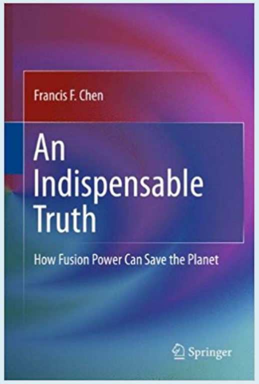
- **The machine** does not aim at refining previously achieved results, but to be **ground-breaking**
- Until now **the physics ideas seem sound**: **tori were sustained until $I_{Torus}/I_{electrodes} = 1$**
- **Technically** it can achieve Phase-2 **without design uncertainties, with limited corrections**
- Until now these **corrections have dealt with boundary conditions** (magnetic & electrostatic)
- The **progress of the machine** must follow a **step by step path**: no hazards, …single steps

…btw: complete successfully Phase-1.5 before moving to Phase-2 PF coils & Power Supplies

- **Successfull Phase-1.5 requires a spherical torus with $I_{Torus}/I_{electrodes} > 2$ in Hydrogen**
- Fusion might be a dream, but **magnetic reconnections studies must aim at excellence**

…& must accommodate ***experiments of astrophysical interest***

- But there's a dream: a **permanent magnets confined arc discharge** as ultimate fusion machine



Francis Chen: An Indispensable Truth, How Fusion Power Can Save the Planet - Springer Science & Business Media 2011
Part II - 10 **Fusion Concepts for the future** - **Ultimate Fusion** pag. 413 …the very end of the book

One hundred years from now, what will a fusion reactor look like?
They may look like those of the Chandrasekhar–Kendall–Furth force-free configuration shown in Fig. 10.56.
The exterior regions above and below the divertor necks can be expanded like those of an axisymmetric mirror.
High-energy alpha particles leaving the divertors can be channeled into direct converters to generate high-voltage DC directly. The central core can be slid up or down continuously to be refreshed without a shutdown.
This is a dream, but we can hope