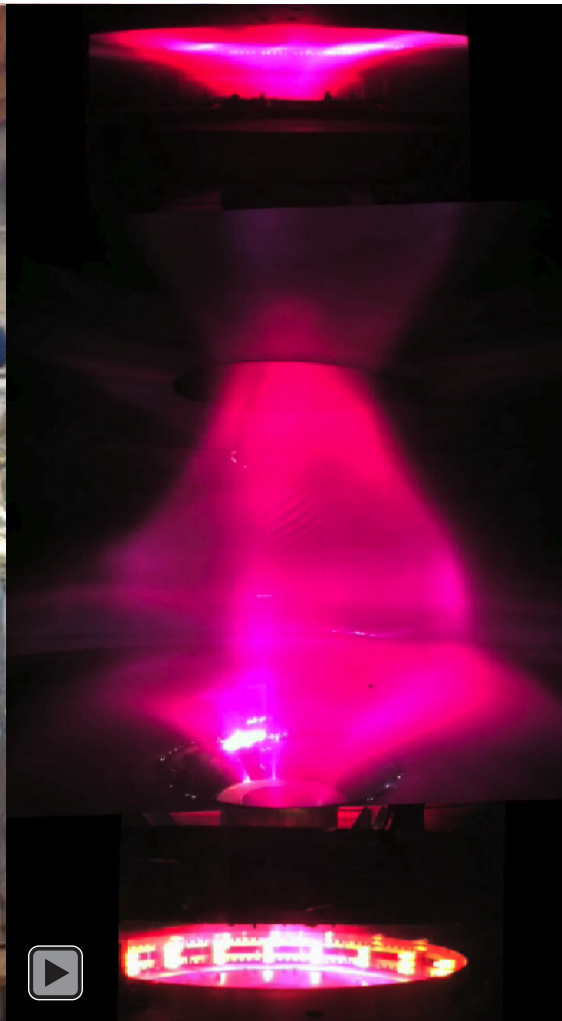


Plasma Torus ejection from the PROTO-SPHERA Centerpost Plasma

*Franco Alladio, CR-ENEA Frascati, *e-mail: franco.alladio@enea.it*



Crab Nebula



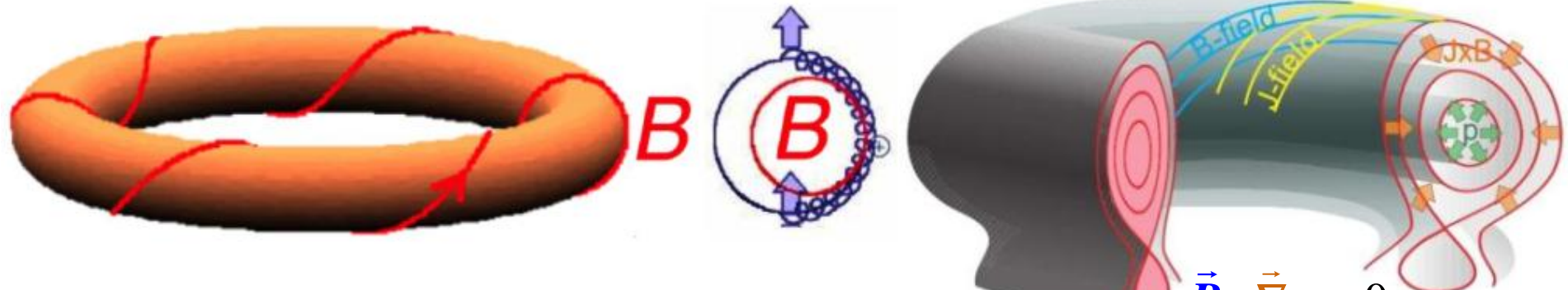
19th International Congress on Plasma Physics
Vancouver, June 4th-8th 2018

Outline

- PROTO-SPHERA has achieved the full Phase-1 current (10 kA) of Plasma Centerpost
- Surprise: Current carrying plasma Toroids (5-7 kA) formed & sustained routinely in Ar & H
- Surprise: Toroids formed & sustained in external magnetostatic B_{ext} field ($\vec{\nabla} \wedge \vec{B}_{ext} = 0$)
- DC voltage on Centerpost electrodes drives Toroidal Current (magnetic reconnections)
- How the experiment boundary conditions were modified to obtain such results
- In PROTO-SPHERA a Torus means a Divertor: this entails new modifications
- In 2019 an intermediate Phase-1½ for moving to Phase-2 on sound bases
- End of 2021: Phase-2 experiment ready to produce plasma?

Magnetic Confinement basics

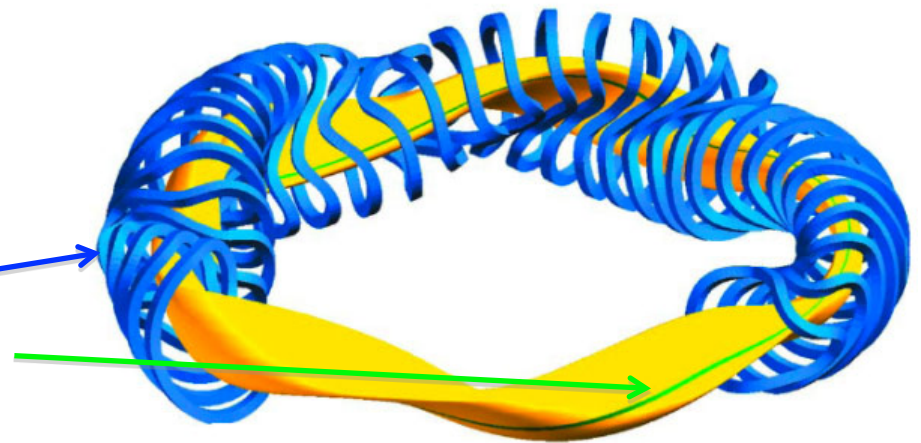
A poloidal $B_{\perp}$ magnetic field is required to contrast particle drifts
→ toroidal current has to flow in an axisymmetric plasma



(magneto-hydrostatic equilibrium) $\vec{\nabla} p = \vec{j} \wedge \vec{B}$
flux (...also p & j) surfaces must be Tori

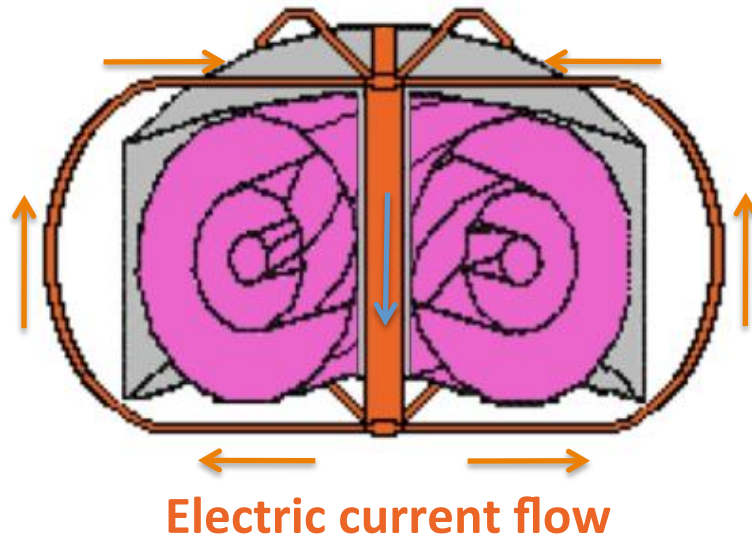
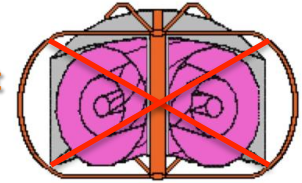
$$\vec{B} \cdot \vec{\nabla} p = 0$$
$$\vec{j} \cdot \vec{\nabla} p = 0$$

Stellarators avoid toroidal currents:
non axisymmetric magnetic coils
engender a 'poloidally wound' field
but a price has to be paid is:
the breaking of a symmetry



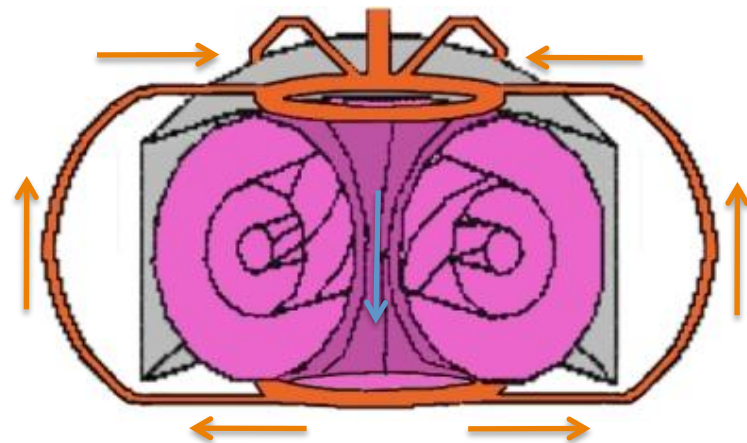
Main idea of PROTO-SPHERA

No Metal Centerpost
No Toroidal Vessel



- “Conventional Tokamak”: **magnetic surfaces of toroidal plasma** surround a “**Metal Centerpost**”

Toroidal geometry of Vacuum vessel



- **PROTO-SPHERA**: **magnetic surfaces of toroidal plasma** surround a “**Plasma Centerpost**”; slim **metal external legs** return the current

Cylindrical geometry of Vacuum vessel

...but electrodes required inside vessel

Cylindrical vacuum vessel geometry has obvious advantages!

← **easy to access & and to repair...**

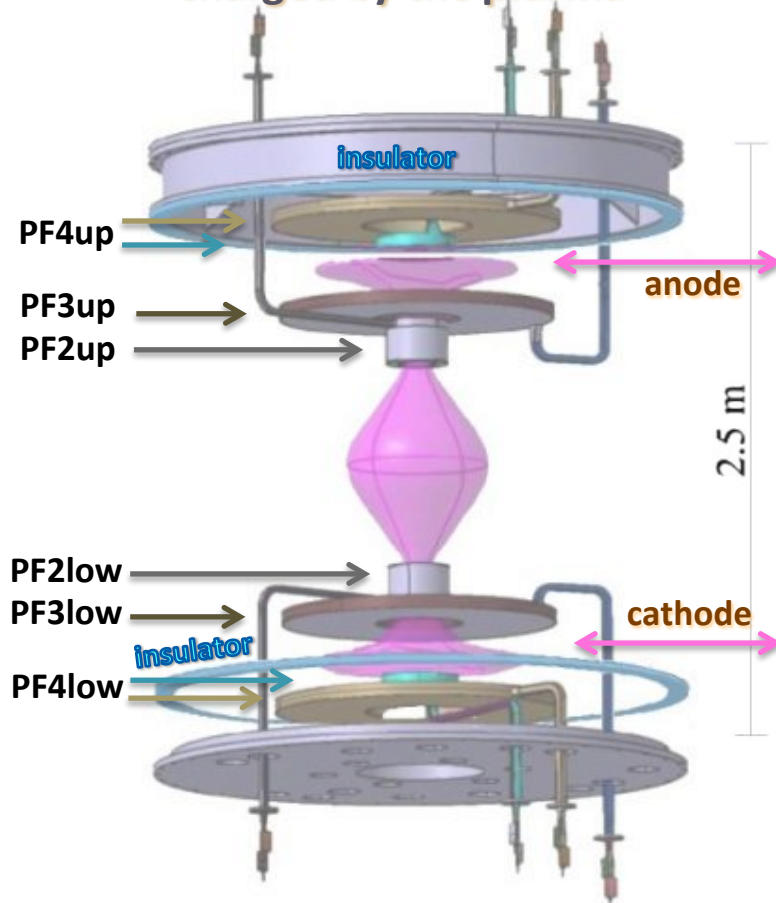


The two Phases of PROTO-SPHERA

In **2002** at Frascati an **International Workshop** advised to build the machine in 2 steps:

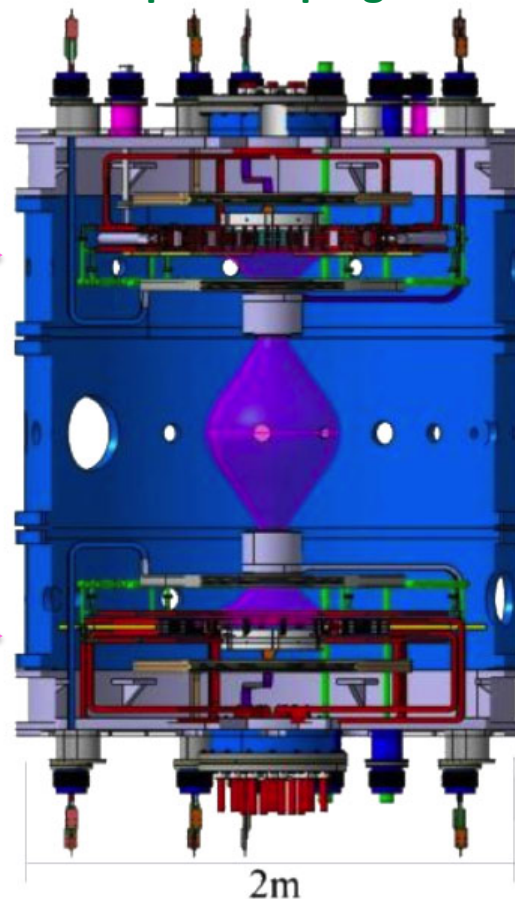
- Phase-1: demonstrate Plasma Centerpost's (fear of anode arc anchoring...)
- Phase-2: machine completed such as to produce the Spherical Torus

PF coils casings built as floating,
charged by the plasma



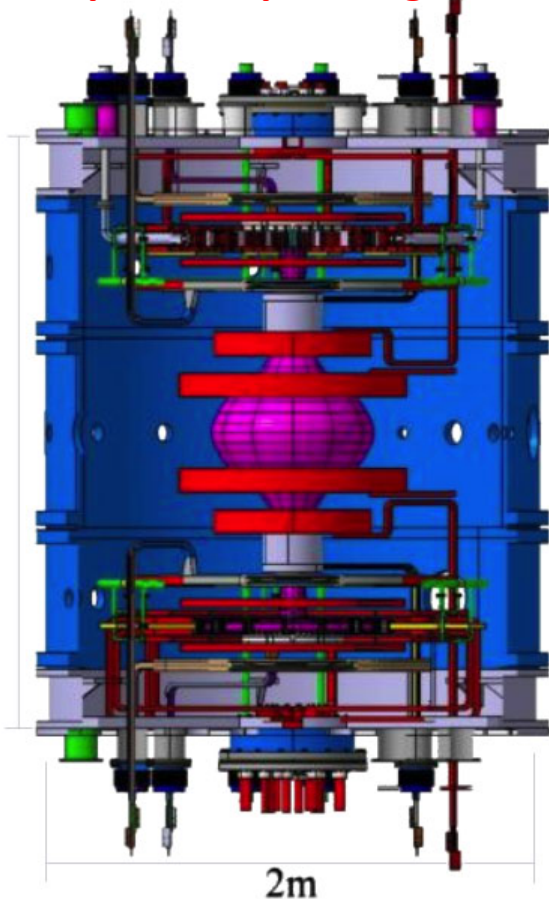
Also upper\lower extensions
& lids are floating

Phase-1: 8 PFcoils
'Group B' shaping coils



Centerpost $I_e = 10$ kA
...2018 Torus $I_{ST} = 5$ kA...!

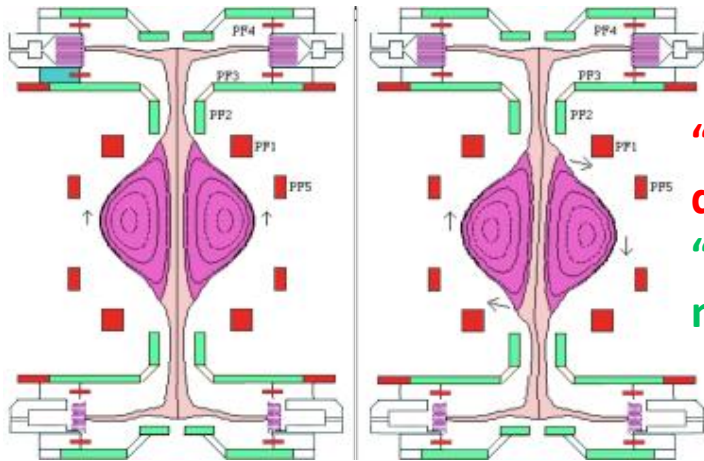
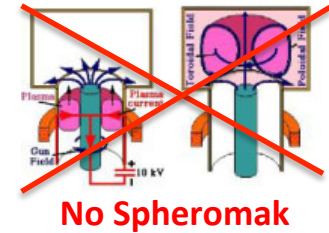
Phase-2: 8 PF coils + 10 PF
'Group A' compressing coils



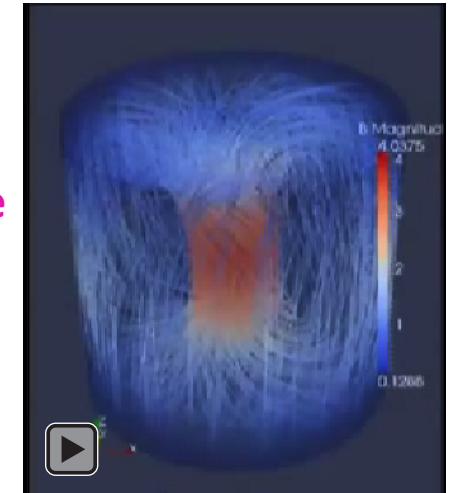
Centerpost $I_e = 60$ kA
ST current $I_{ST} = 240$ kA

Ideal MHD stability of PROTO-SPHERA

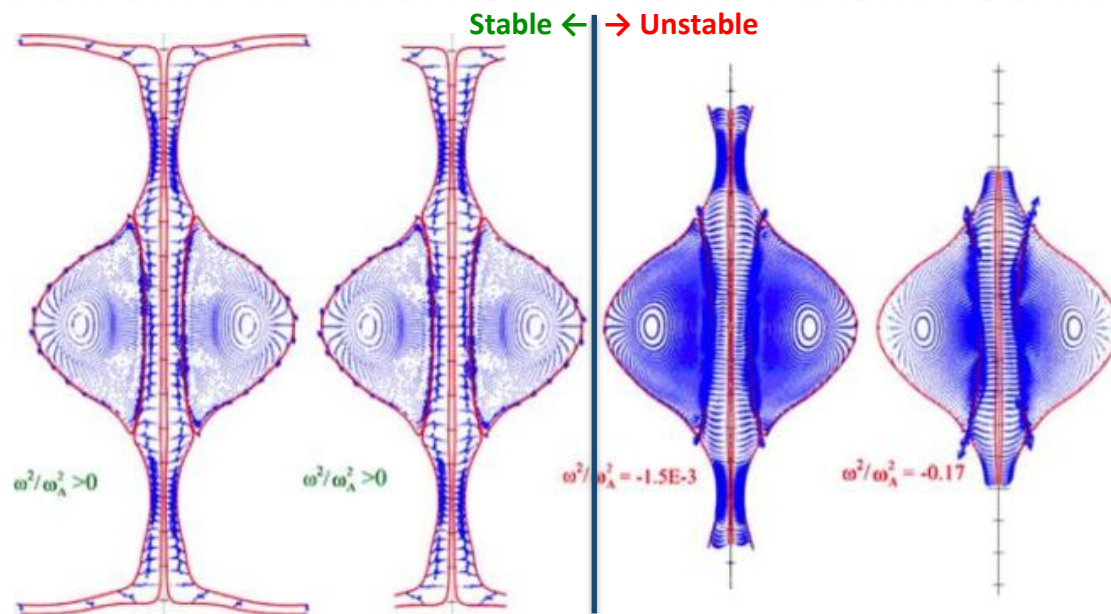
Spheromak tilt instability is due to
dipole of containing field opposite to toroidal plasma current dipole



“Group A” PF coils (compression)
dipole moment opposes Plasma dipole
“Group B” PF coils (shaping) dipole
moment aligned to Plasma dipole



DISK-SHAPED ELECTRODE-FACING PLASMA GUARANTEES IDEAL MHD STABILITY



Cutting shorter & shorter
the Plasma Centerpost
PROTO-SPHERA at current
of 120 kA inside Torus
gets destabilized;
in absence of any cutting
its stability extends to current
of 240 kA inside Torus

PROTO-SPHERA Electrodes



May 2015 annular anode lowered on top of machine

Low voltage (100-350 V)
between electrodes

at high-field tokamak
plasma density $\sim \text{few} \bullet 10^{20} \text{ m}^{-3}$



Up: hollow gas-puffed anode

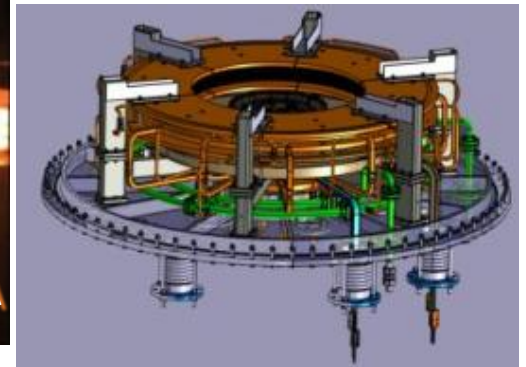
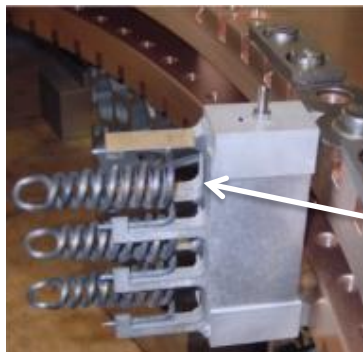


Down: 3000° K heated cathode

Phase-1 (present) cathode
(54 = 18 x 3 W emitters): aim 10 kA

Phase-2 cathode, 6 x Phase-1
(324 = 108 x 3 W emitters): aim 60 kA

“Caduceus”-like W emitting spirals
have now survived > 1500 cycles

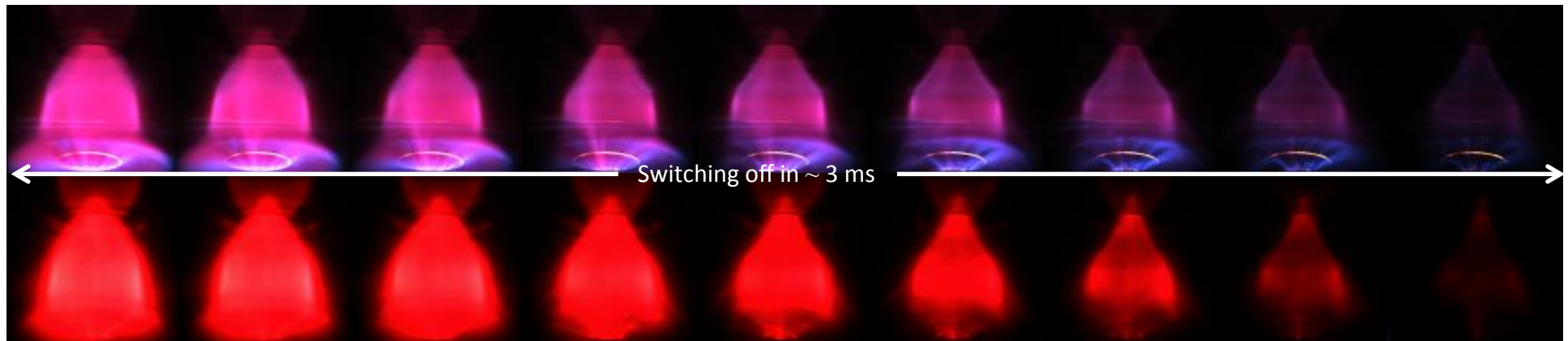
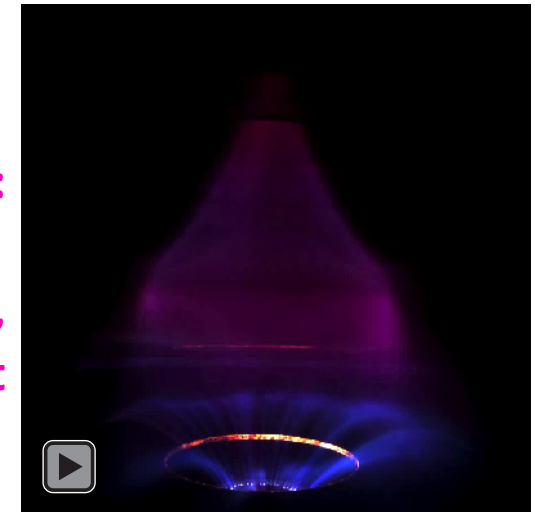


Magnetic Confinement basics at work

Switch-off of PROTO-SPHERA discharges containing a torus:

the brightness of the torus is the last to vanish,
both in the full spectrum of visible light

#1224, 10 kA Hydrogen



#1219, 10 kA Hydrogen, H α filter

as well as observed through a Balmer-alpha filter

Current in the Plasma Centerpost vanishes in about 3-4 ms
The energy in the Torus decays at a slower rate...



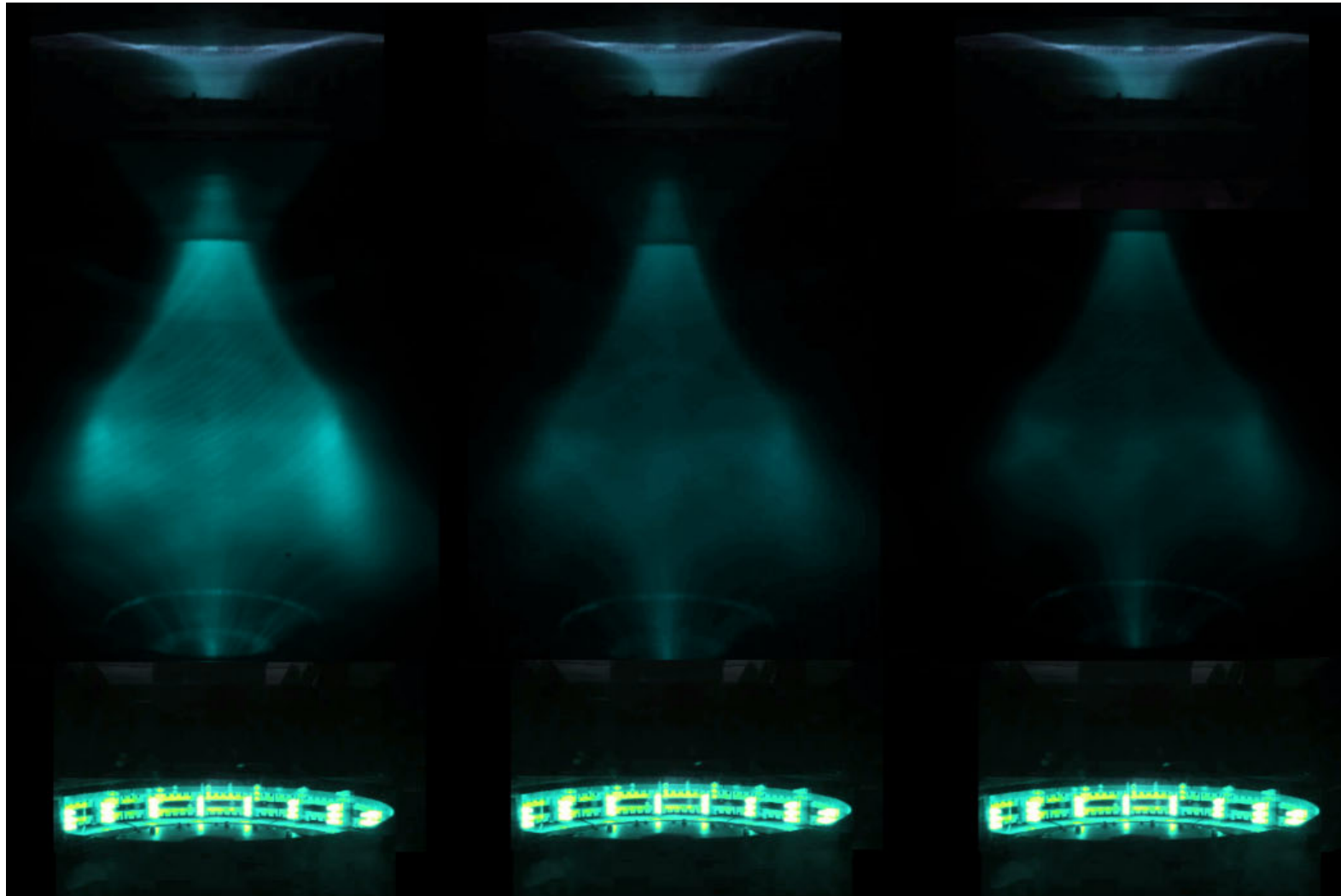
Confining toroidal current is quite resilient

During plasma switch-off the Torus current decays at a slower rate than the Centepost current: in last ms Torus becomes unstable & kinks

*anode
plasma*

*Plasma
Centerpost
& Torus*

*cathode
plasma*



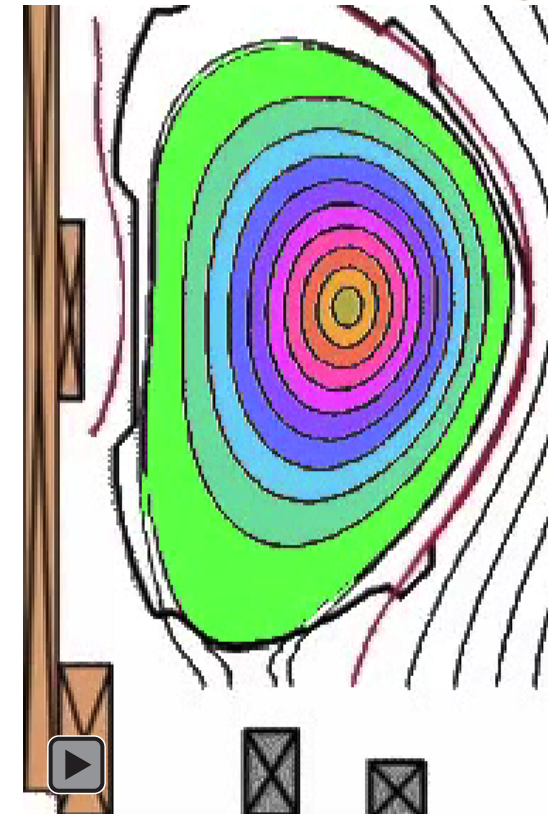
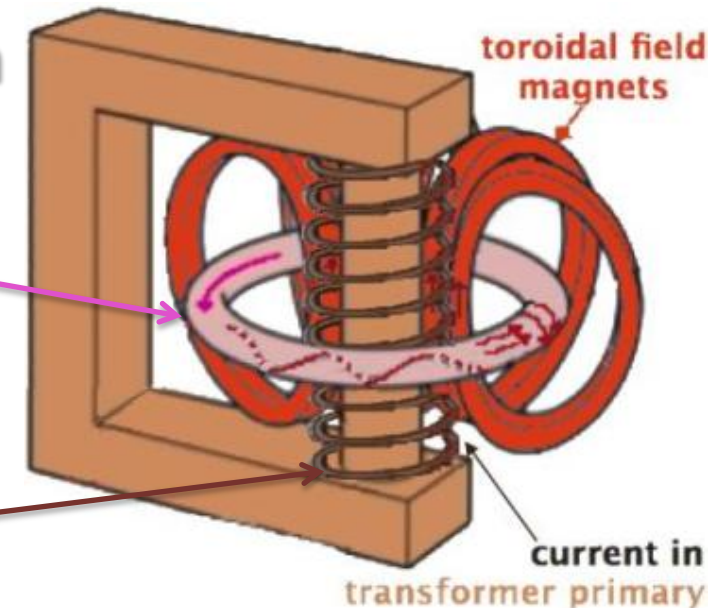
(false colors)

#1219, 10 kA Hydrogen, H α filter

Tokamak drive: AC currents, induction

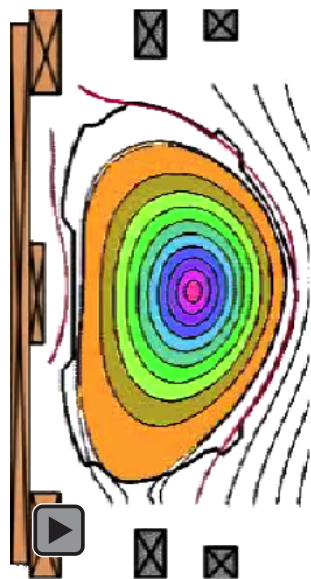
Plasma confining current inside Torus:
induced and sustained by a transformer
whose current varies in time ...but there
are limits: the transformer will break
beyond a given current limit...

- The plasma ohmic drive in a Tokamak: **moving closed flux surfaces**, “feeding” the plasma from outside, they are dissipated while they move toward the magnetic axis
- In tokamaks this process is due to the transformer current change:
- **Tokamaks cannot have steady drive** ...unless additional Current Drive (RF,NBI)...

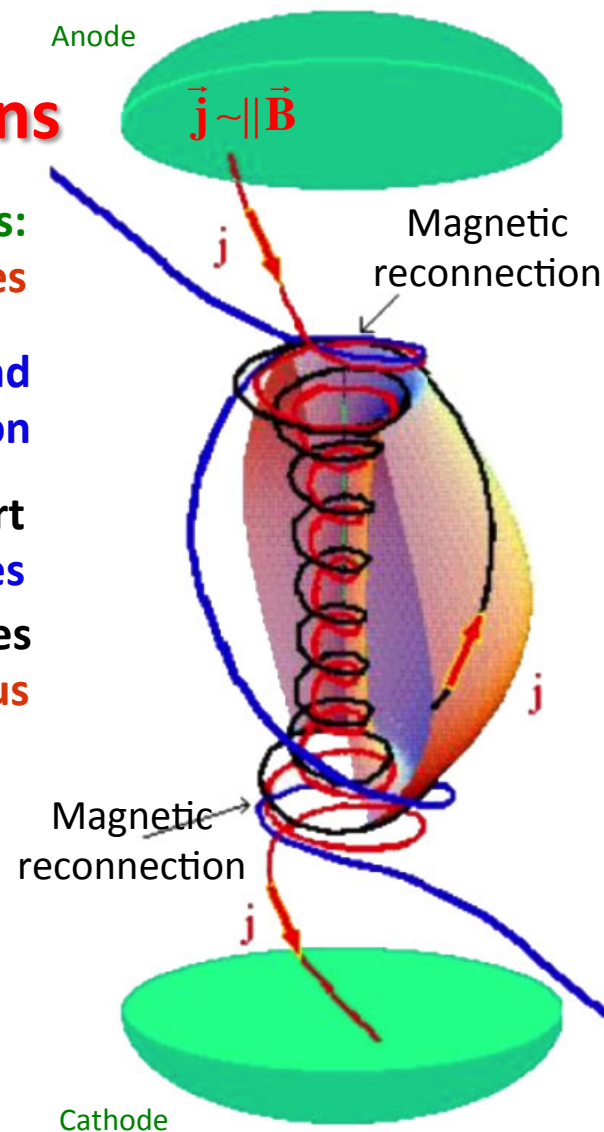


PROTO-SPHERA drive: DC currents, reconnections

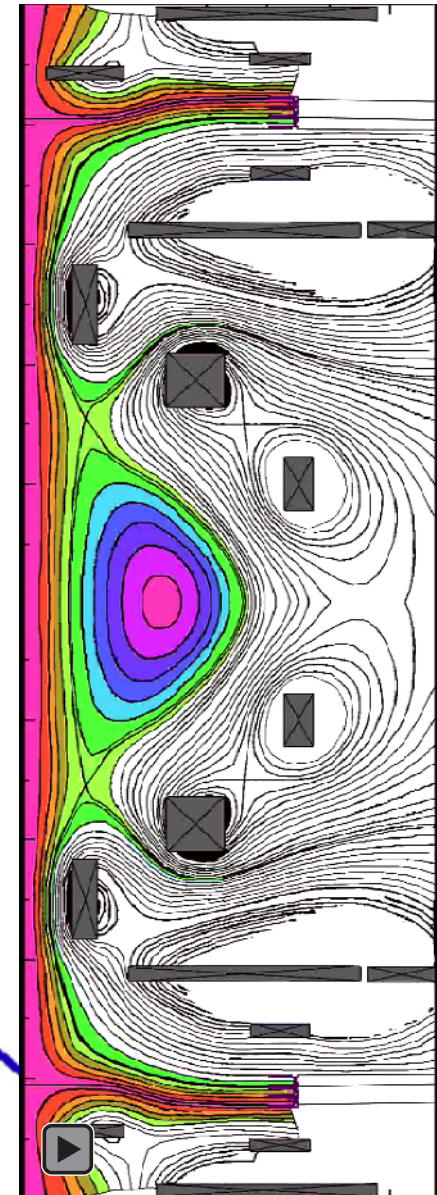
- In front of the electrodes:
open magnetic field lines
- Open magnetic field lines are wound
in a circular direction
- Magnetic reconnections convert
open $\vec{B}$ lines
into closed $\vec{B}, \vec{j}$ lines
wrapped around the spherical torus



$\vec{E}$ of Tokamaks relies on **induction**
efficient but **it is not forever...**



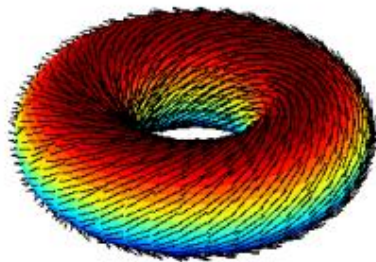
$\vec{E}$ of PROTO-SPHERA relies on $\vec{v} \wedge \vec{B}$
associated with **magnetic reconnections**



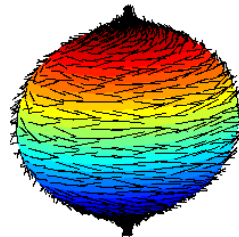
SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS OBTAINED in 2018 & IS FOREVER!

Last Confinement surface can be a sphere, but contains Tori

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



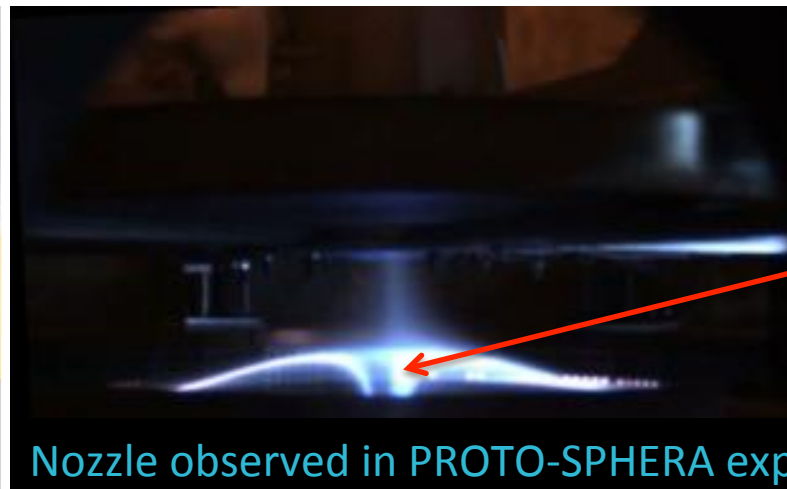
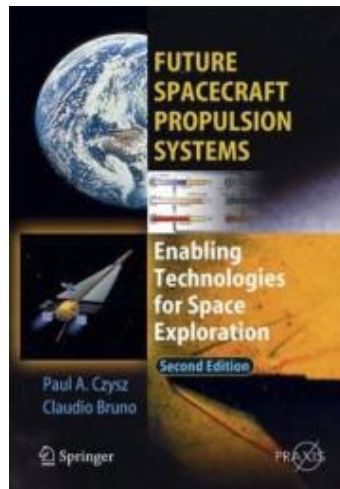
*a hairy torus
can be combed*



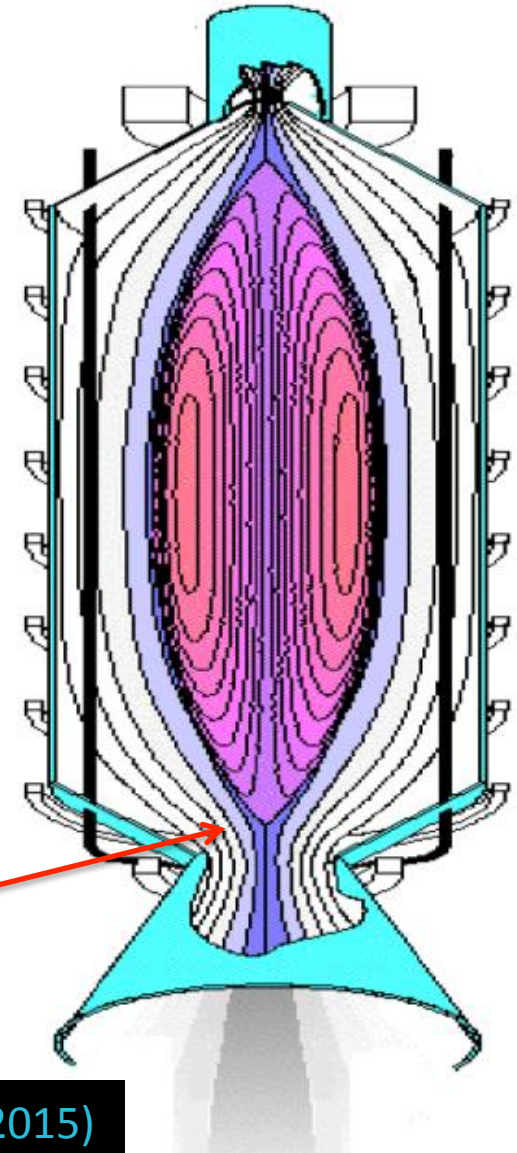
*a hairy sphere
cannot!*

Predominantly one of the “*tufts*” of the sphere:
expels charged fusion products

A SPACE-THRUSTER forerunner?



Nozzle observed in PROTO-SPHERA experiment (2015)



Electrostatic plasma effects: taking care of boundary conditions

2015/16 experiments produced a metallization on top (anode) & bottom (cathode) bus-bar vacuum entrance flanges, i.e. magnetic “nozzles”



Polycarbonate (transparent) cathode bus-bar flanges on top & bottom
Argon plasma



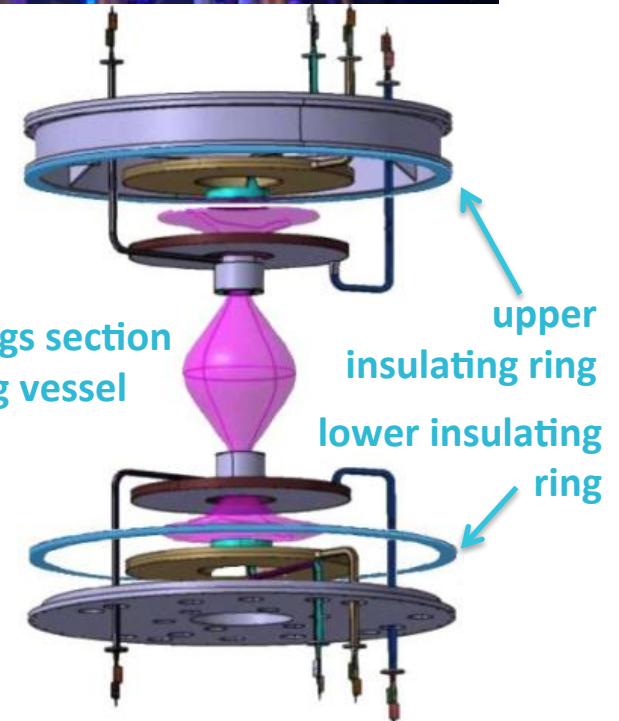
2mm thick Polycarbonate linings for:
internal Al vessel,
rear of anode,
rear of cathode



2 Polycarbonate diaphragms glued

2 insulating rings section the conducting vessel

upper insulating ring
lower insulating ring

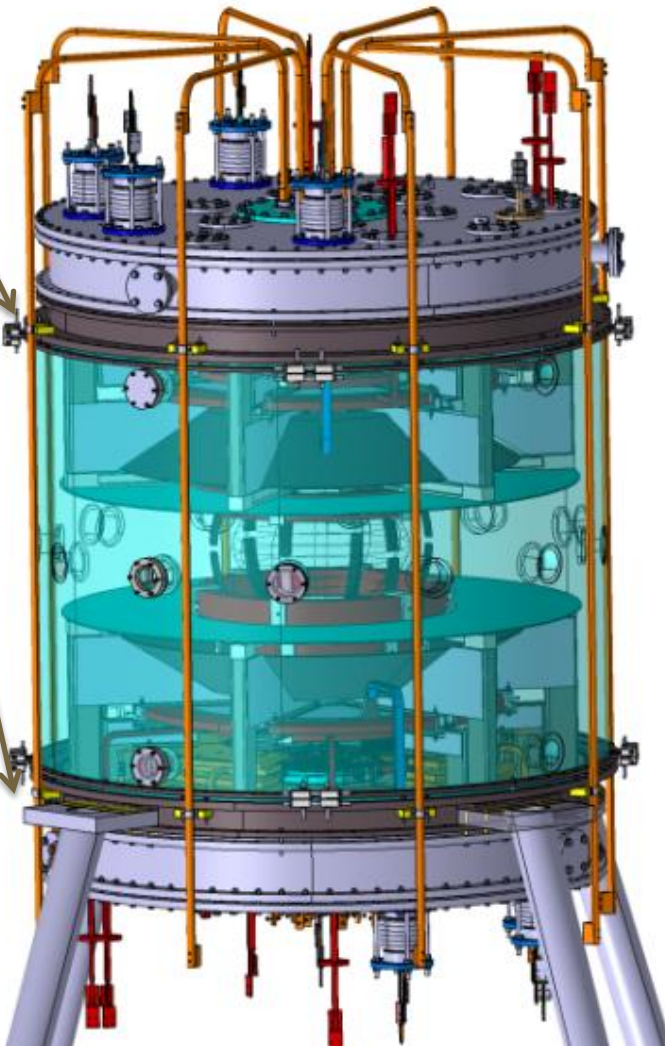


January 2018:

all these cures allowed to obtain Hydrogen plasmas

Insulating & transparent new vessel being built for Phase-2

will substitute the Aluminum vacuum vessel with a Poly methyl methacrylate (PMMA) transparent and insulating vessel (9.5 cm thick, 2m $\varnothing$, 1.7 m high), endowed with 20 ports adding 2 further SS rings on top & bottom of the experiment, keeping all internal components attached to the existing SS upper/lower lid and extension



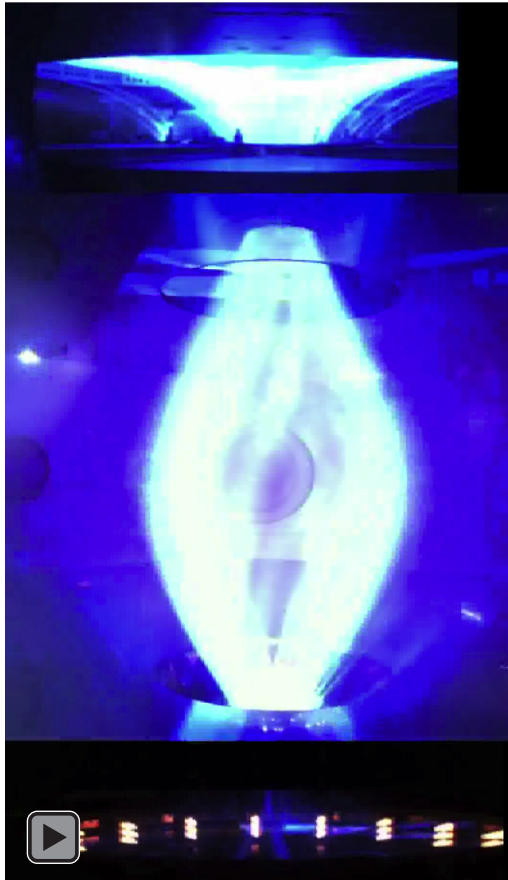
Reynolds
POLYMER TECHNOLOGY, INC.
Building the Impossible



PROTO-SPHERA Plasma Centerpost rotates & therefore avoids anode arc-anchoring



Anode arc-anchoring means
that a plasma arc discharge
is localized on an anode spot



#614, 8.5 kA Argon
break-down $V_e \sim 90$ V, steady $V_e \sim 200$ V



#977, 10 kA Hydrogen
break-down $V_e \sim 320$ V, steady $V_e \sim 220$ V

Plasma rotation in Tokamaks
always stabilizes the plasma

best way of injecting fuel is
from inboard (high field side)

(Pisa University & its PlasmaTech spin-off) line-averaged electron density on plasma equator:
in Argon Centerpost $\langle n_e \rangle \sim I_e$
at $I_e = 10$ kA, $\langle n_e \rangle \sim 4 \cdot 10^{20} \text{ m}^{-3}$
in Hydrogen Centerpost
at $I_e = 10$ kA, $\langle n_e \rangle \sim 1.5 \cdot 10^{20} \text{ m}^{-3}$

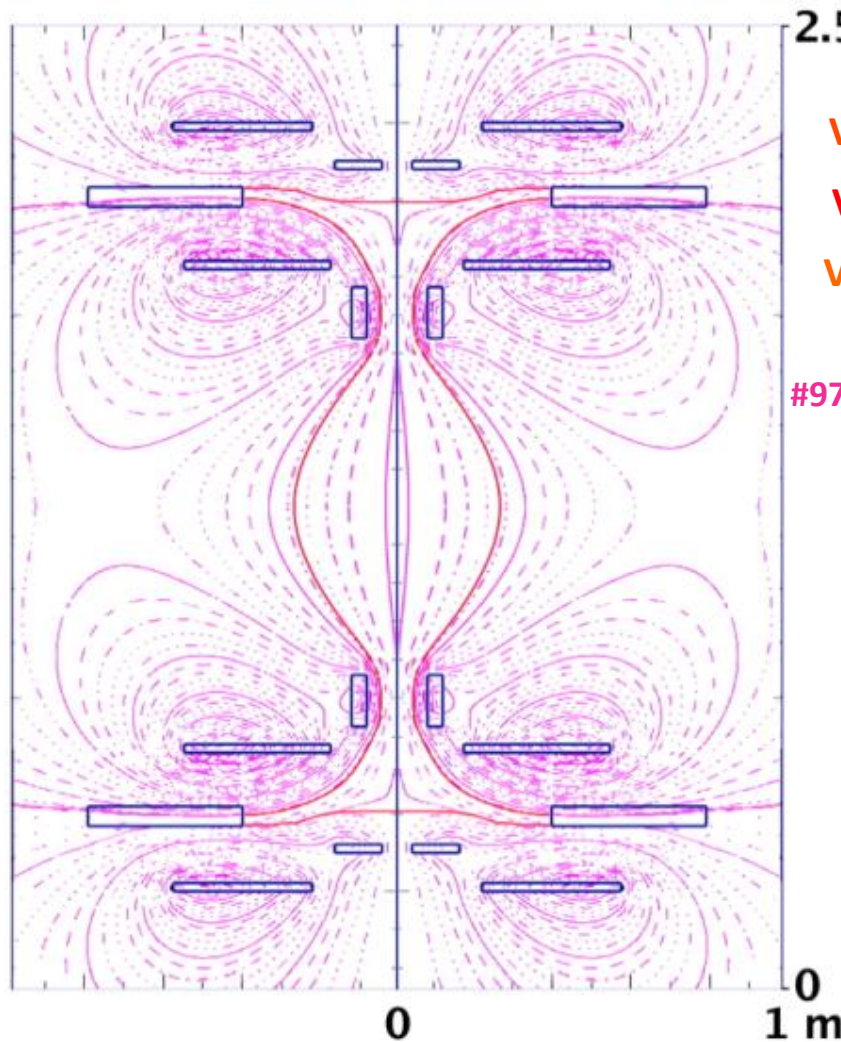
No Anode-Arc Anchoring: Electrostatic plasma effects!

$\vec{E} \wedge \vec{B}$ plasma rotation does the trick!

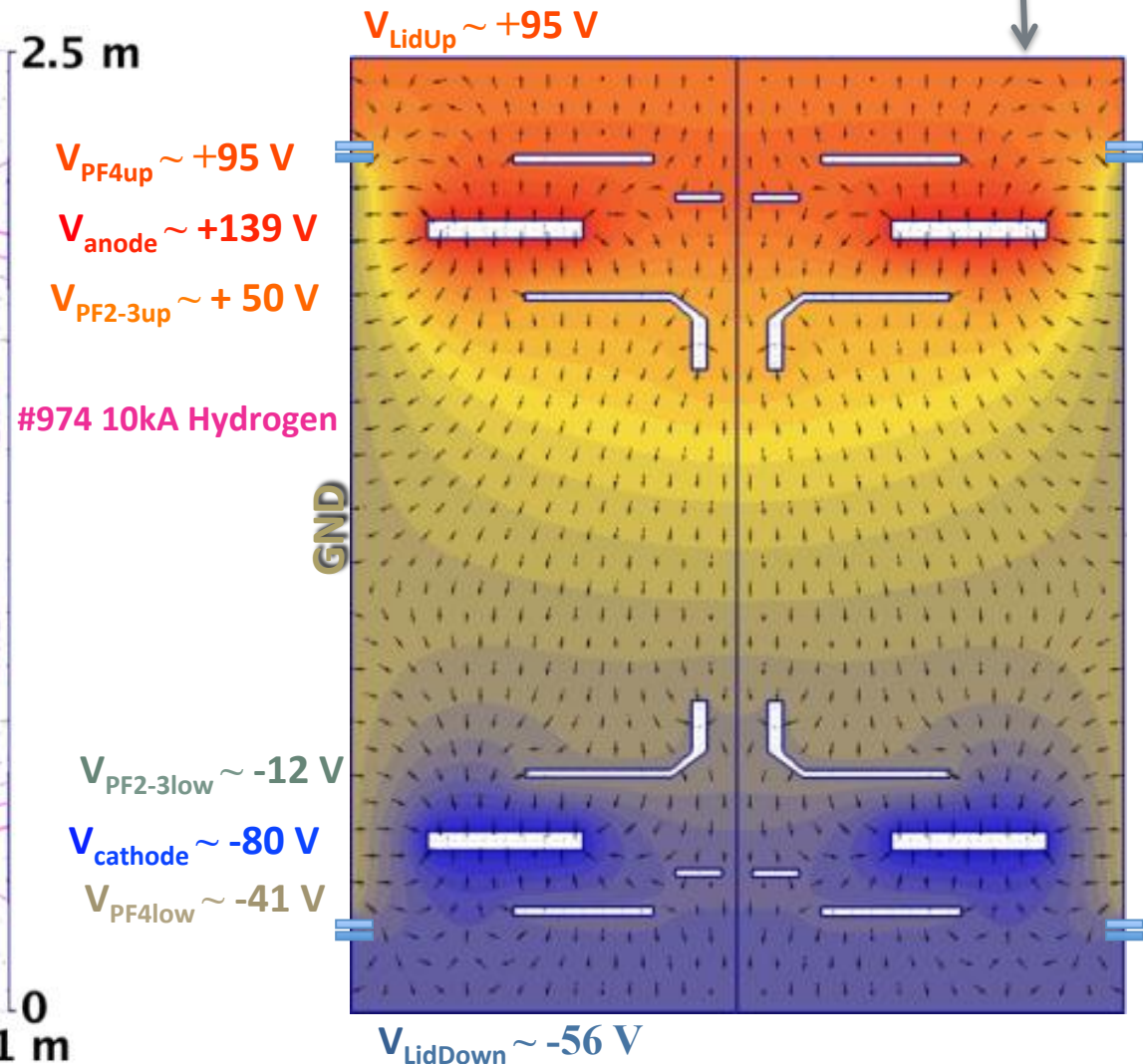
magnetic field is up\down symmetric

but

electrostatic field not up\down symmetric



Lines: magnetic field



Color contours: electrostatic potential, Arrows: E field

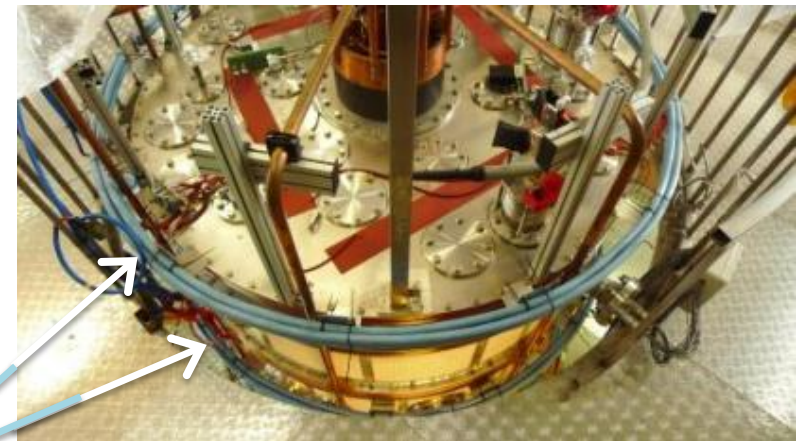
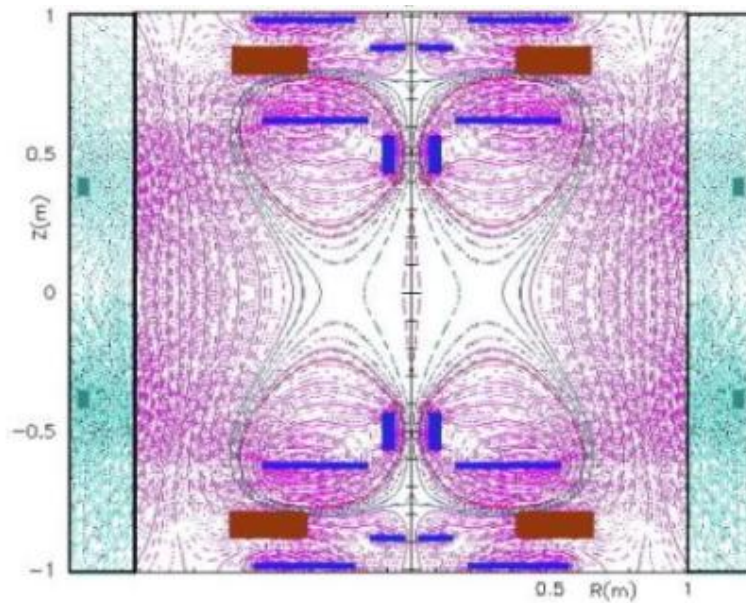
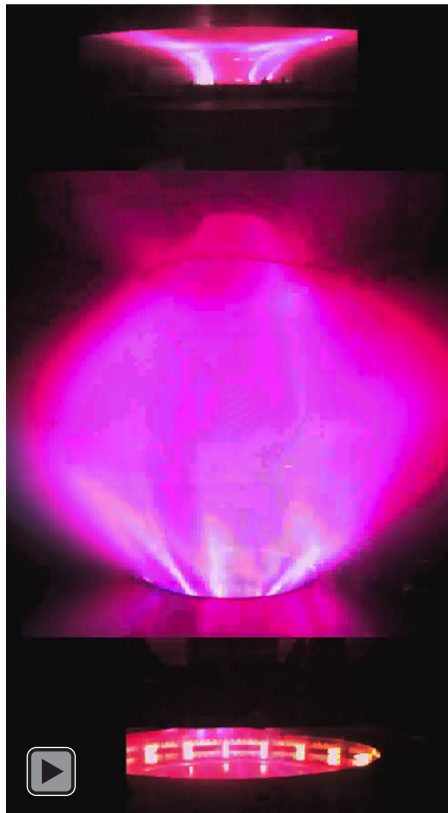
“Magnetic Boundary Conditions” changed

4 external PF coils added ...fed in series with the internal PFInt coils,
from April 2018 a further Super-Capacitor power
supply feeds some of the PFExt coils

Hydrogen Centerpost
at full current =10 kA
seemed quite inclined
to eject a Torus
...an added vertical field
...was used as midwife!

#983, 10 kA Hydrogen

Plasma fired after 0.75 s of PF current
to allow for skin current diffusion in Al vessel

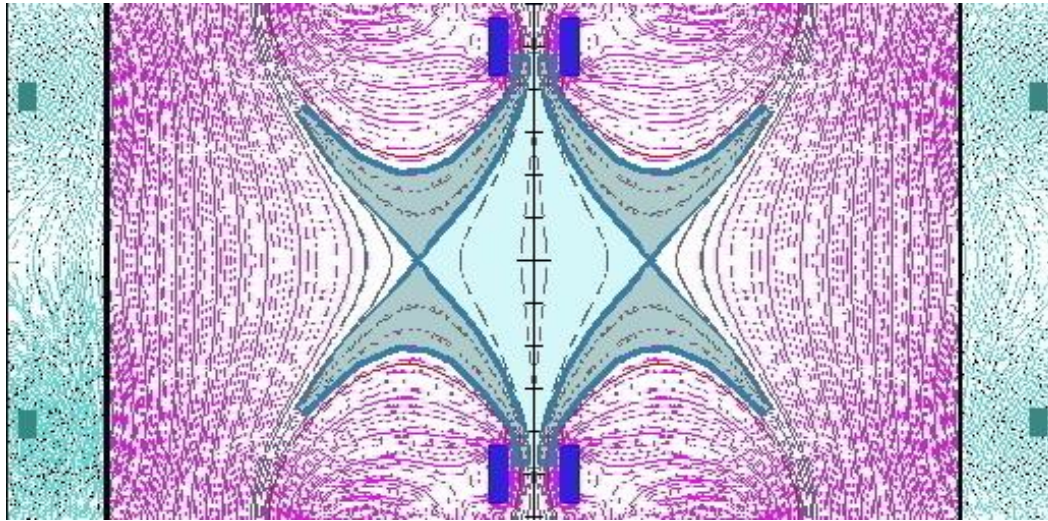


4 external PFExt (each 16 wires 25 mm²)



March 2018 Torus formed in Argon plasmas

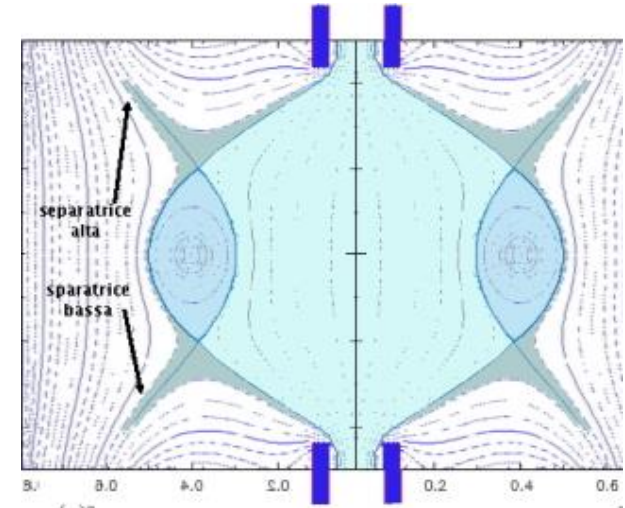
In absence of Torus formation



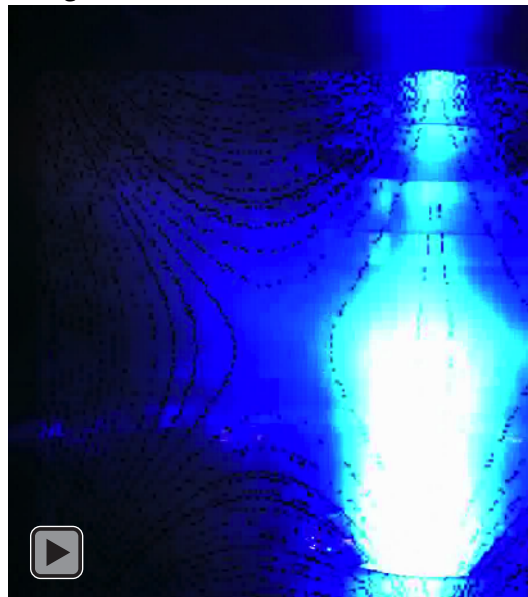
$I_e = 3$ kA

$I_e = 5$ kA

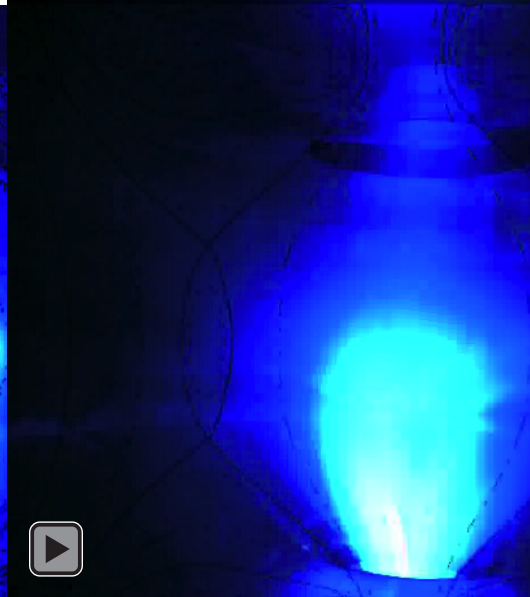
With Torus formation



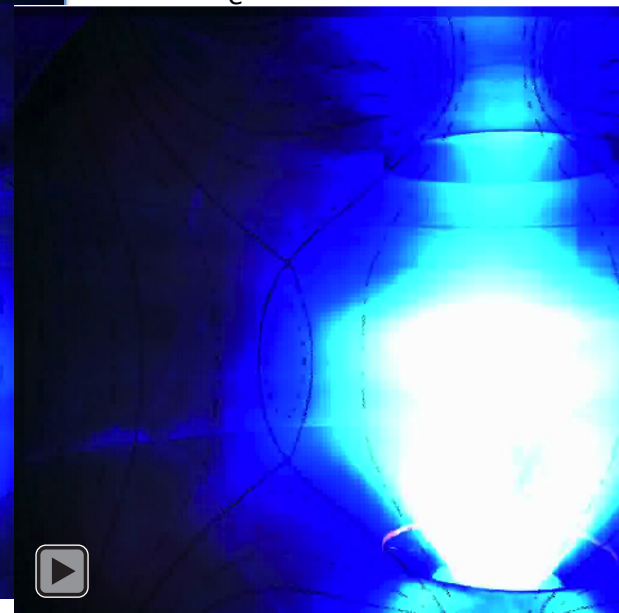
$I_e = 10$ kA



#1098, Argon



#1096, Argon

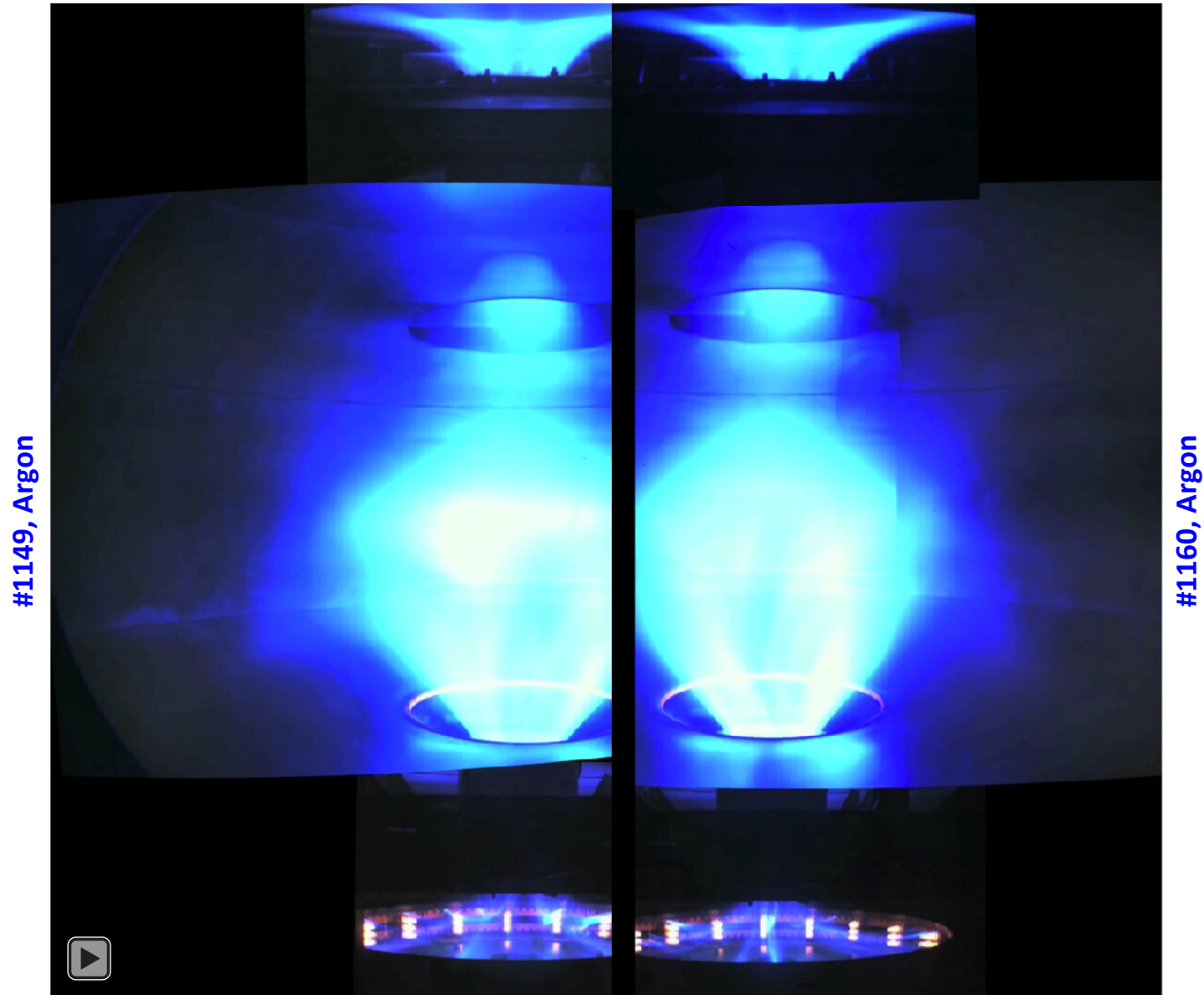


#1091, Argon

Torus forms at the expected current: $I_e \sim 8$ kA

$I_{\text{Torus}} = 5$ kA

The “gentle Divertor” of the (barely visible) Argon Torus

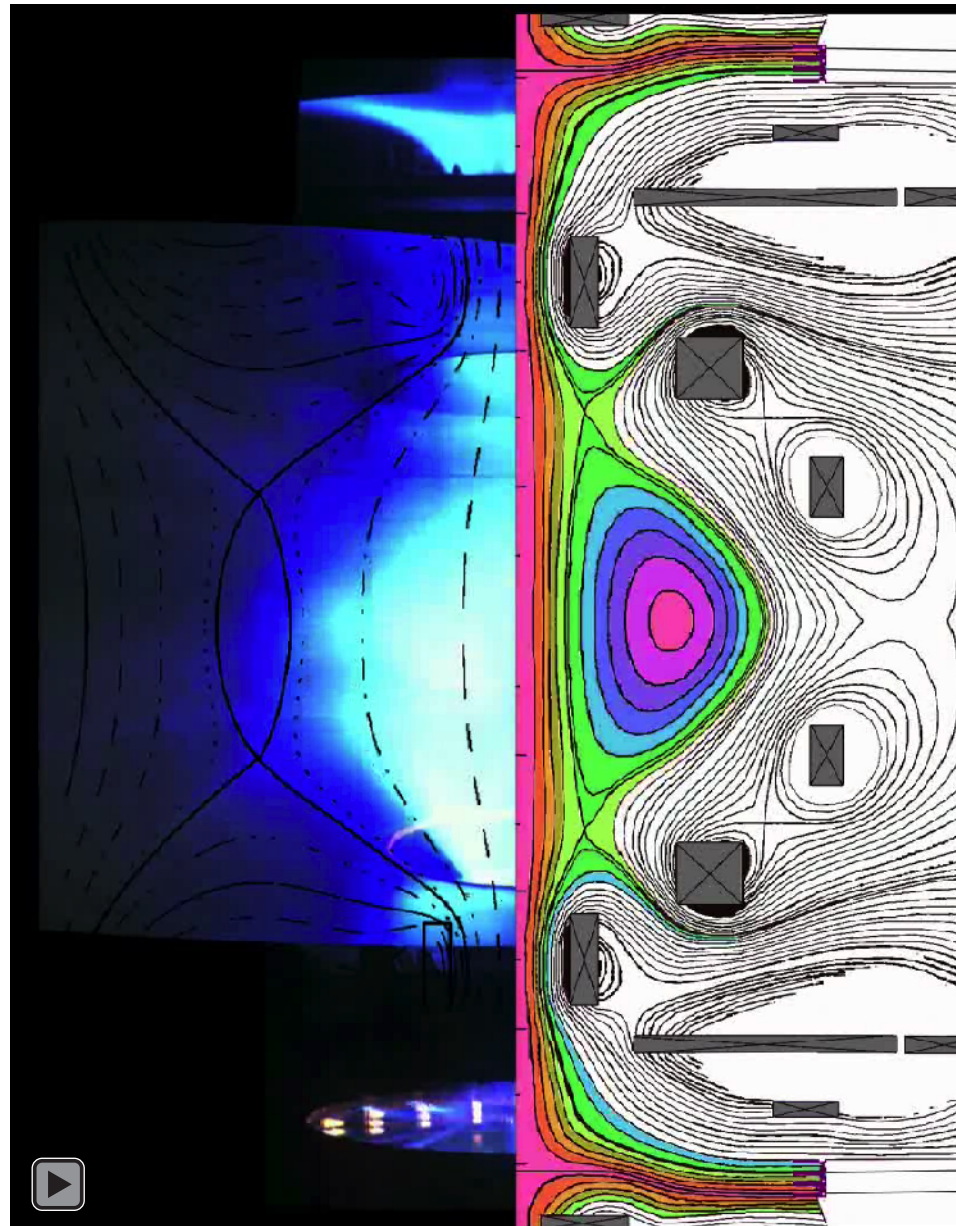


lower Divertor fan is dominant & slightly shifts down the Torus

The Argon Torus has been sustained for up to ½ sec

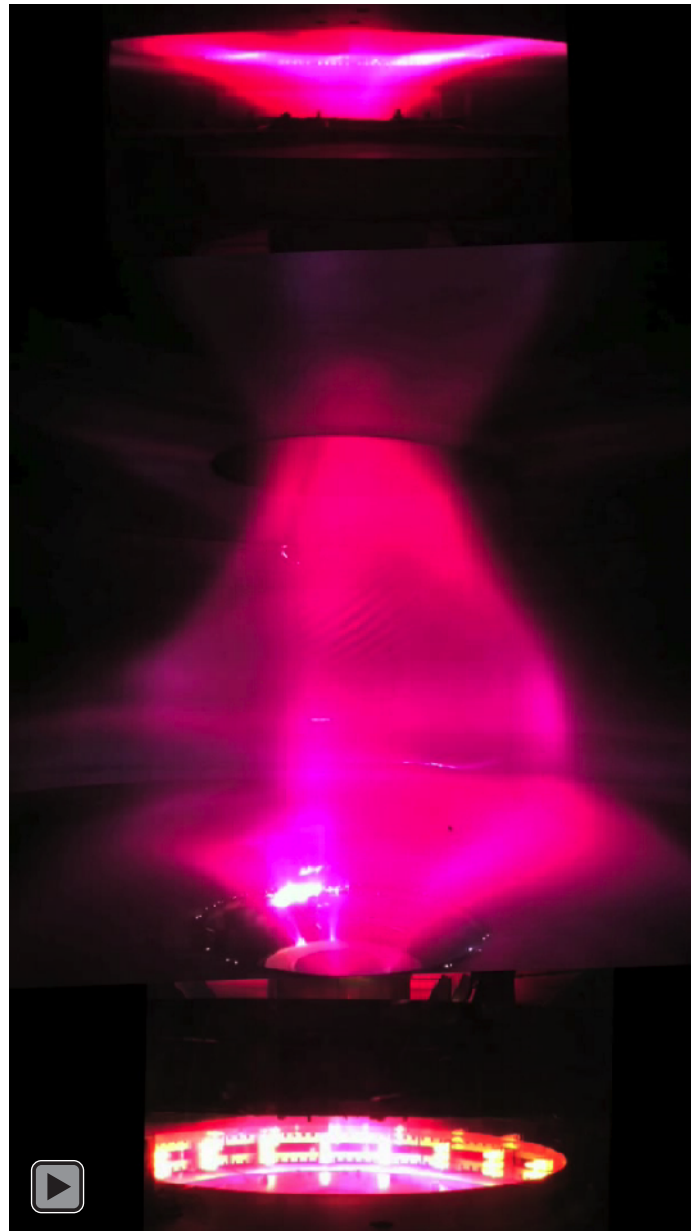


Argon Torus
break-down $V_e \sim 200$ V
steady $V_e \sim 220$ V



#1160, Argon, X-points fit $I_{ST}=5$ kA

April 2018 Torus formed in Hydrogen Plasma



evident at plasma breakdown



Hydrogen Torus
break-down
 $V_e \sim 360 \text{ V}$
steady $V_e \sim 320 \text{ V}$

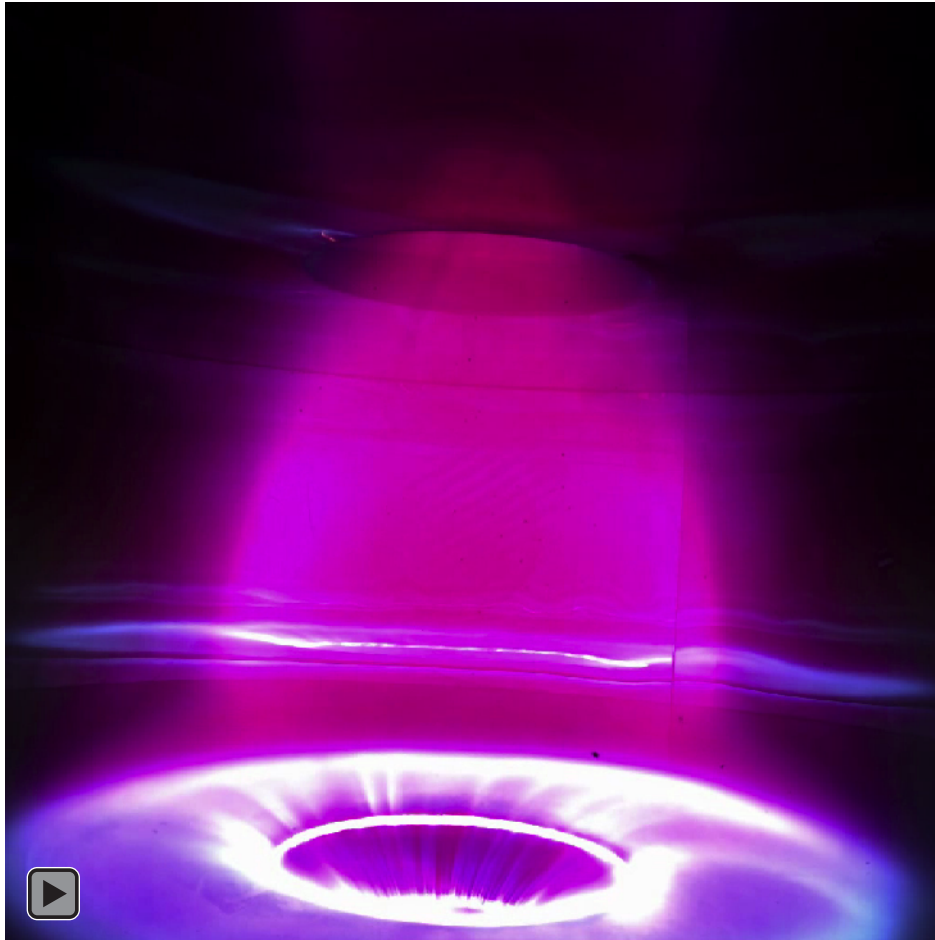
#1202, Hydrogen

& ...after ¼ sec

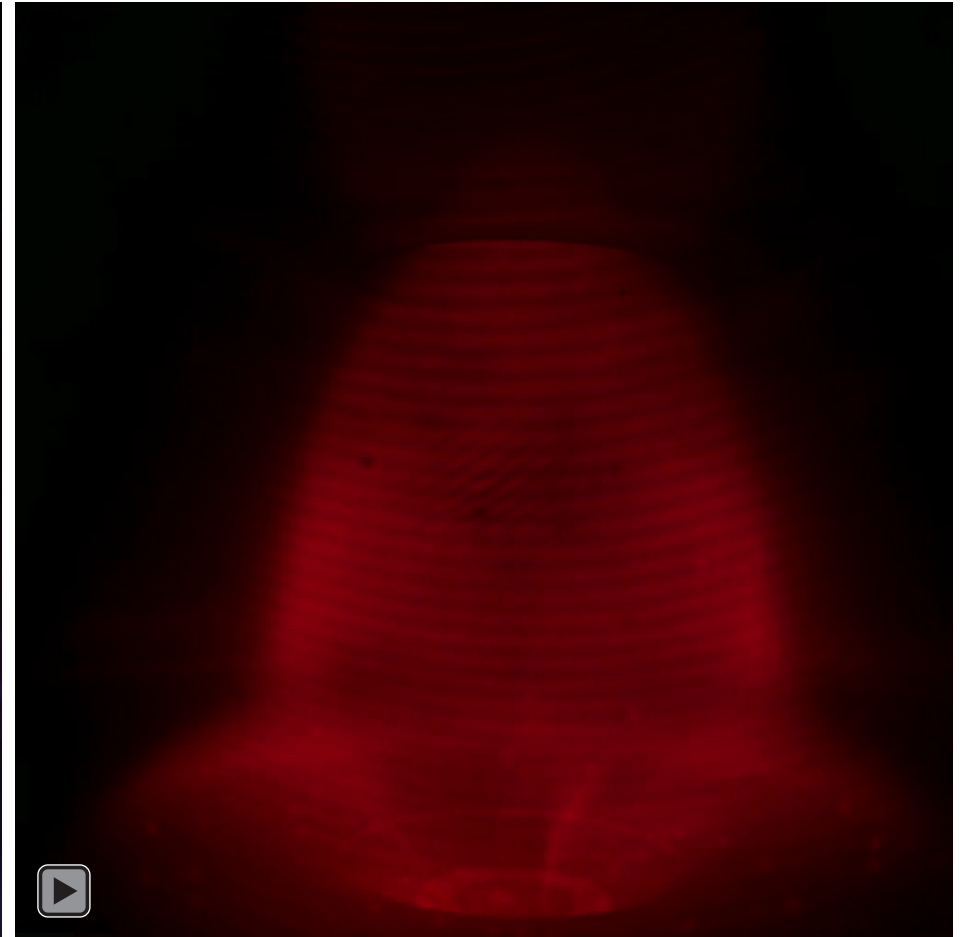


at plasma switch-off

Confining toroidal current injected in pulses every 2-3 ms



#1195, Hydrogen, ~22 ms long movie



#1221, Hydrogen, H α filter, ~22 ms long movie

Identified as magnetic reconnections: every pulse ejects plasma along the Divertor fans
Argon plasma Torus much less visible, but ejection along fans every 2-3 ms very evident



The “uncouth Divertor” of the Hydrogen Torus: lower divertor fan strongly dominant spurious current path below diaphragm

The present divertor plate is the lower polycarbonate diaphragm: an unsuitable choice of material!

But when we put it inside PROTO-SPHERA we did not expect to be able to form a Torus!

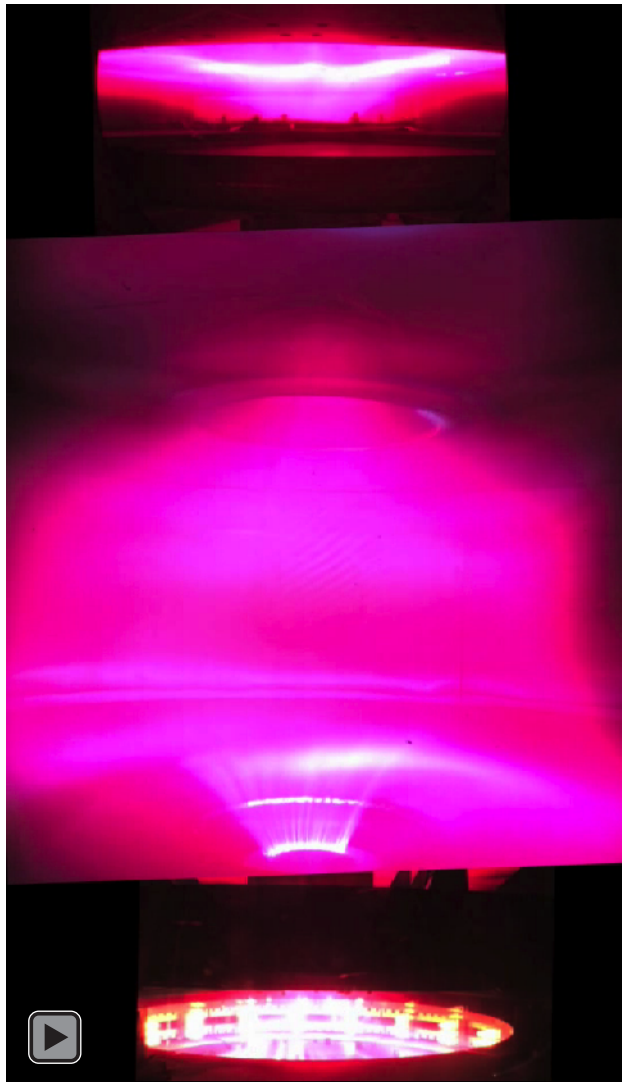
A new lower metal diaphragm being built now;
in 2019 PROTO-SPHERA will have 2 suitable plates

#1202, Hydrogen. $\frac{1}{4}$ s full movie

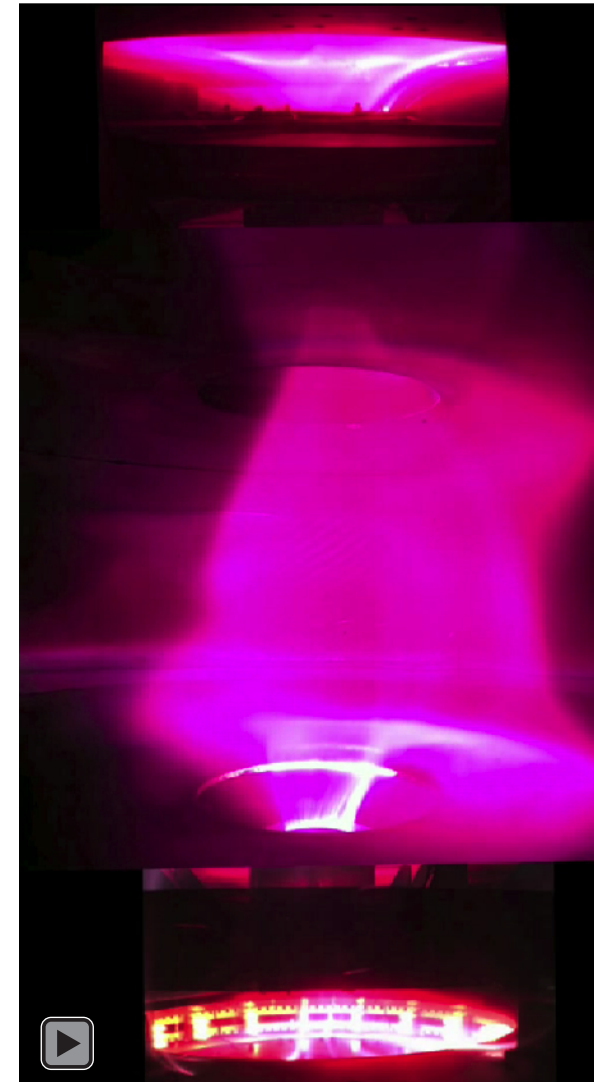


Reconnections, Helical States & Double Tori

#1211
Hydrogen



#1225
Hydrogen



Vertical field in excess? ...Double Torus!

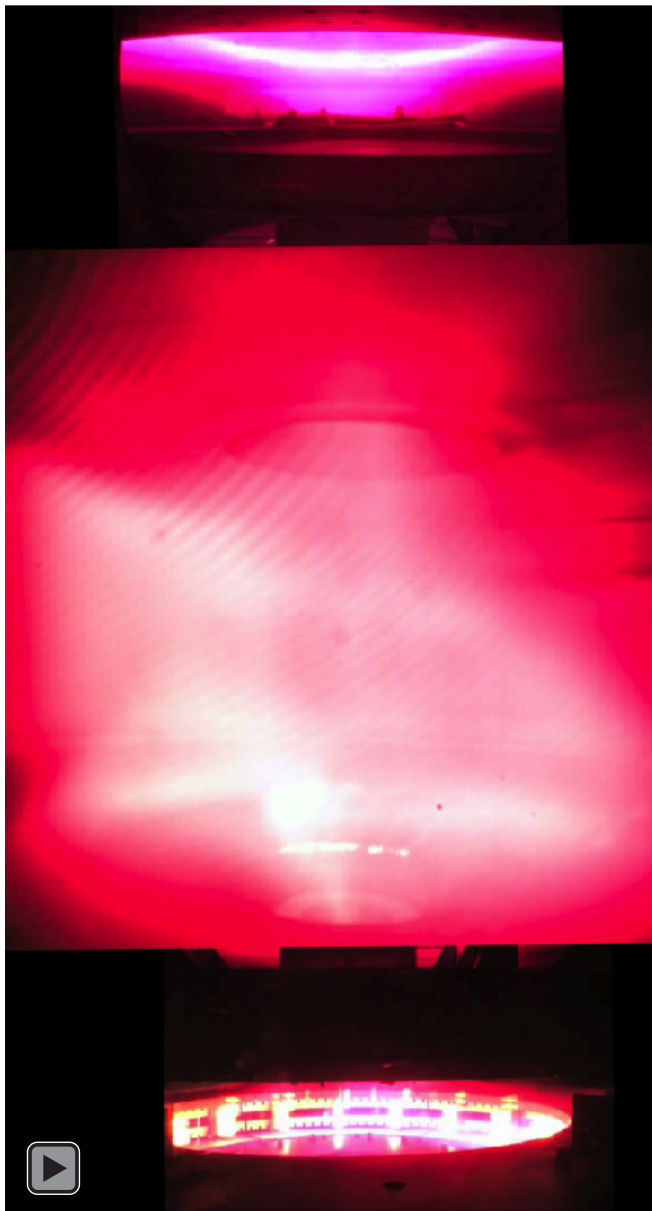
...or Helical States ...or lop-sided Tori!

The only occurrence you should never ever consider is plasma disruption: gone for good!

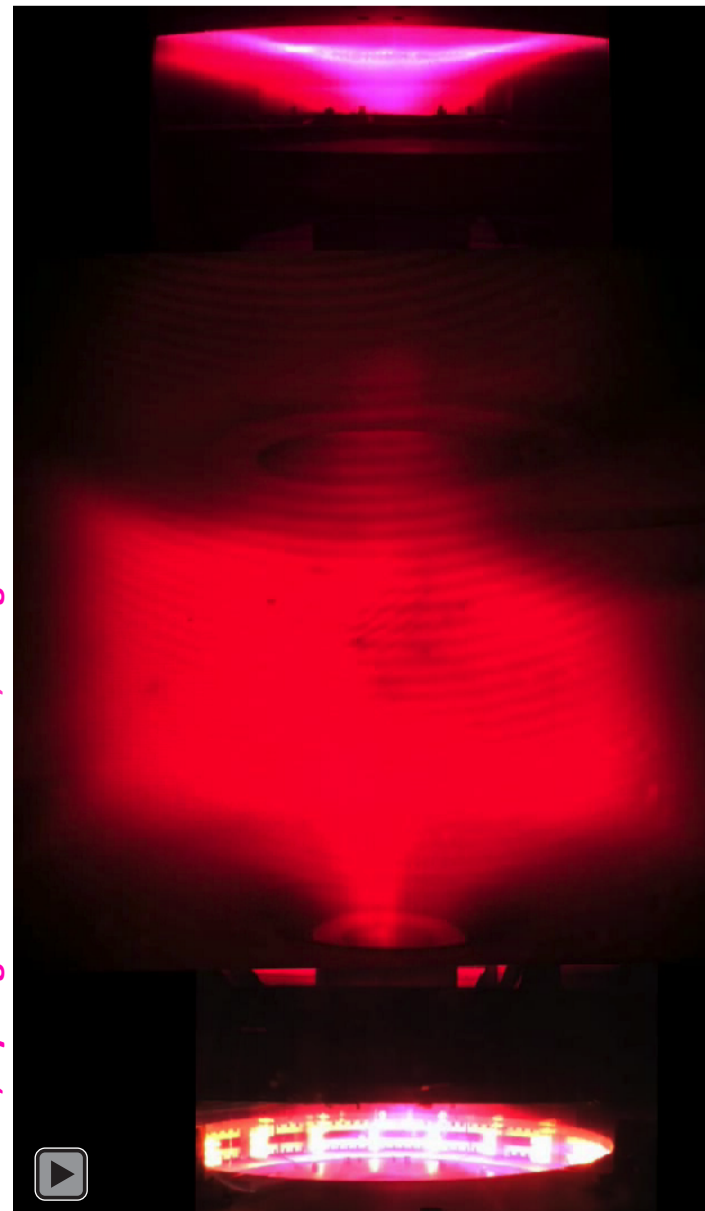
Disruptions gone for good!

Disruptions do not exist, even if plasma does crazy movements, it never vanishes
It can well recover from Multiple Tori, Helical States, Lop-sided Tori

#1219, Hydrogen. $\frac{1}{4}$ s full movie, H α light saturates



#1221, Hydrogen. $\frac{1}{4}$ s full movie, H α light



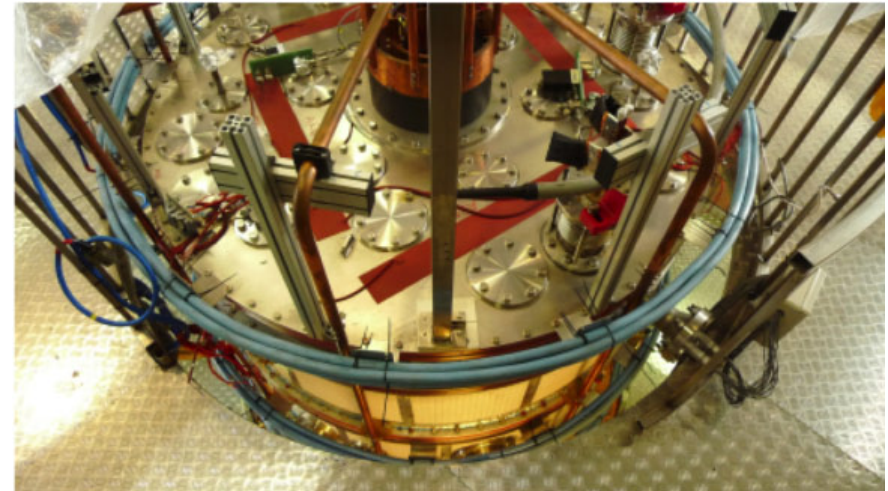
The new Super-Capacitor power supply (90 V, 2 kA, many sec) has been essential for Hydrogen Tori: the Internal PF power supply was already delivering its maximal Voltage & Current, an additional +25% Amperes•turns were fed by Super-Capacitor



The production of Argon Tori was obtained fine tuning by -12.5% the maximum Ampere•turns of the Internal PF power supply:
Ar Tori ~ 5 kA, H Tori ~ 7 kA

up/down dissymmetric PFExt contrasts divertor dissymmetry

upper PFExt 8 turns•1.9 kA in series PFInt



upEquator PFExt 8 turns•1.9 kA in series PFInt

PFExt 4 turns•1 kA SuperCap

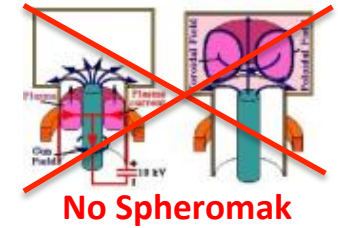
downEquator PFExt 4 turns•1 kA SuperCap

PFExt 8 turns•1.9 kA in series PFInt

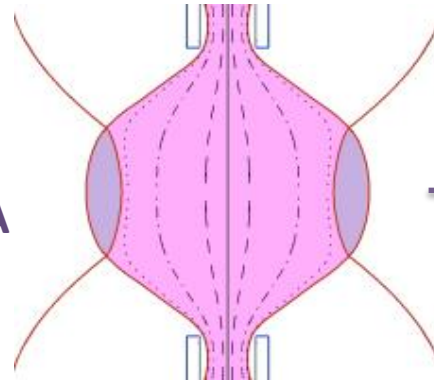


lowest PFExt 4 turns•1.9 kA in series PFInt

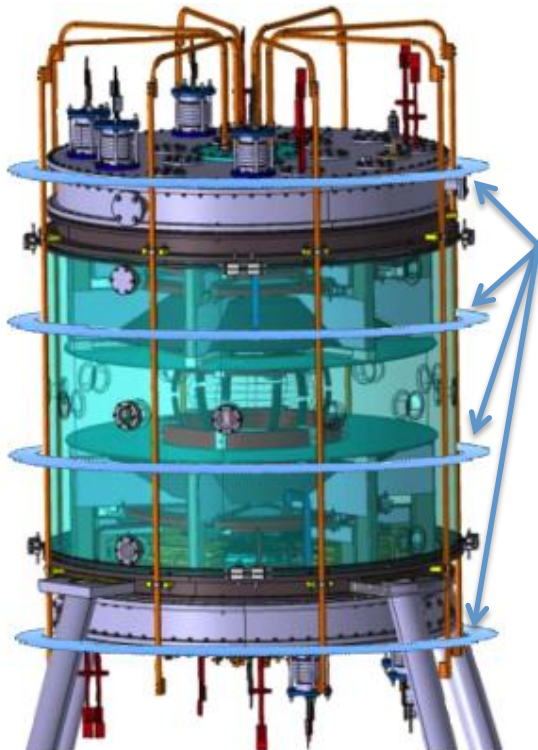
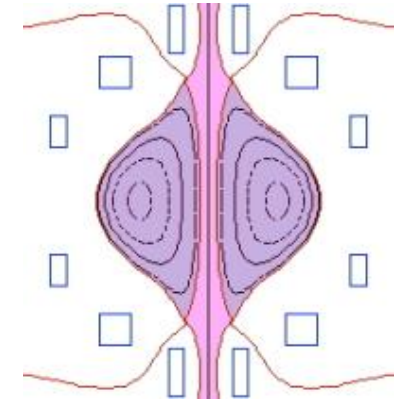
Major surprise: Current carrying Torus is formed and sustained in an external irrotational magnetostatic B^*
Slow rise of currents will ease Phase-2 operations,
which will produce Spherical Tori with $I_{ST} = \frac{1}{4}$ MA



from now
 $I_{ST} = 5-7$ kA



to Phase-2
 $I_{ST} = \frac{1}{4}$ MA

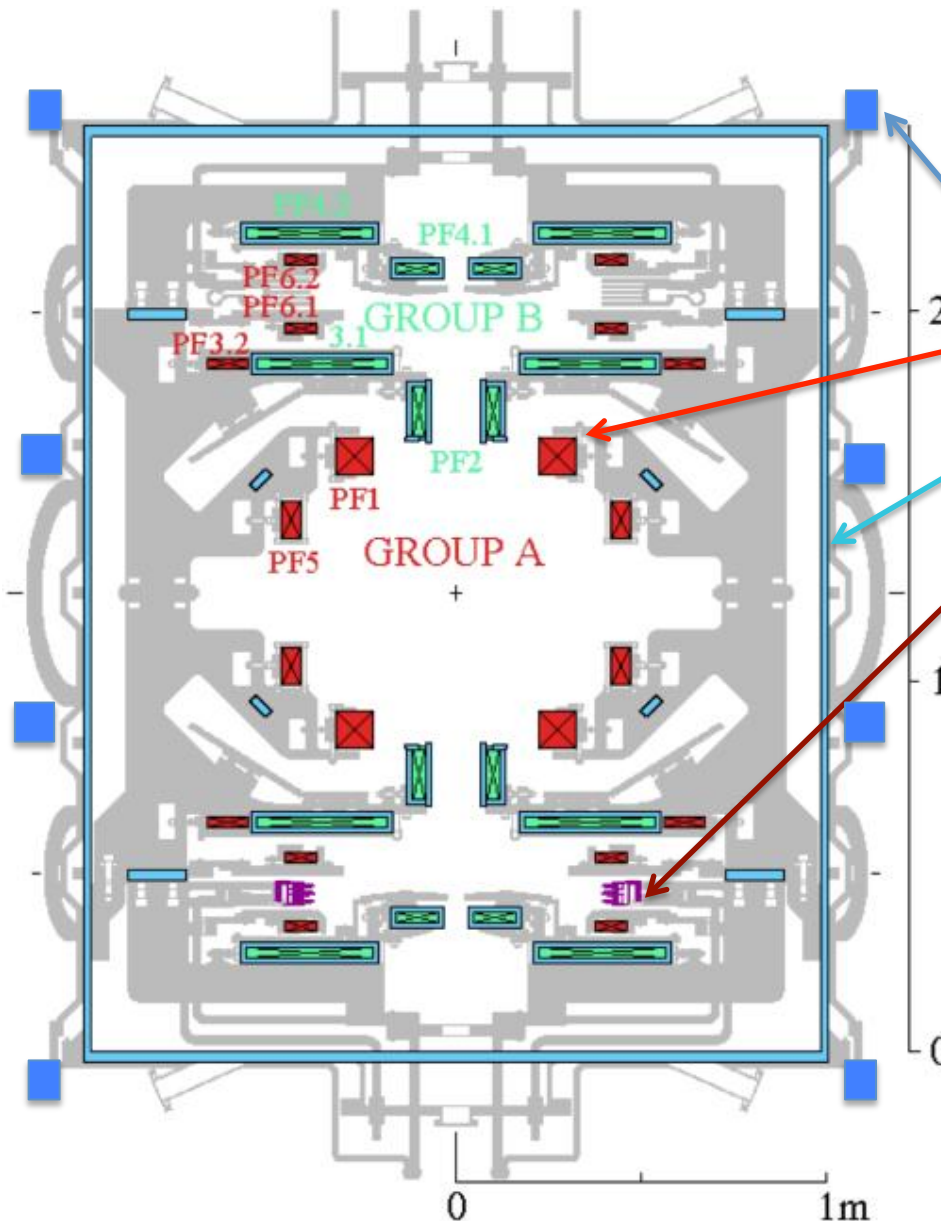


In 2019, Phase-1½ (new insulating PMMA Vessel)
 substitute present impromptu PFExt coils
 with larger cross-section (240 mm^2) flexible cables
 8+12+12+8 turns (top to bottom, flexible turn number)
 fed at 2 kA by existing Super-Capacitor power supply

- will allow to form from preexisting Plasma Centerpost Hydrogen Tori with 20 ms rise time, try and assess differences between static and 20 ms Torus formation

*** A Magnetic Confinement scheme sustainable by permanent magnets?**

What remains to be built to achieve a ¼ MA Spherical Torus (2021?):



PFExt* 8+12+12+8, 240 mm² each cost ~ 40 k€

Group A: compression coils (5+5 in series)

cost ~ 0.5 M€

PMMA Vacuum vessel¹

including vacuum components, divertor plates

W cathode Filaments¹(54→324) cost ~ 0.1 M€

Electric power supplies:

1) Group A cost ~ 0.1 M€

2) Cathode (I_{cath} 10→60 kA) cost ~ 0.2 M€

3) Centerpost. (I_e 10→60 kA) cost ~ 0.6 M€

Super-Capacitors will be used

Cost incurred so far ~ 2.0 M€

Cost for completion ~ 2.0 M€

^{1, 1} Under construction, * to be built before 2019



PROTO-SPHERA will not need additional heating...? ...magnetic reconnections heat the Solar Corona!

Phase-2 power injected into plasma $> 250 \text{ V} \bullet 60 \text{ kA} = 15 \text{ MW}$...how much into Torus?

~ 0 MW, $T = 10 \text{ eV}$
“cold” plasma:
divertor studies

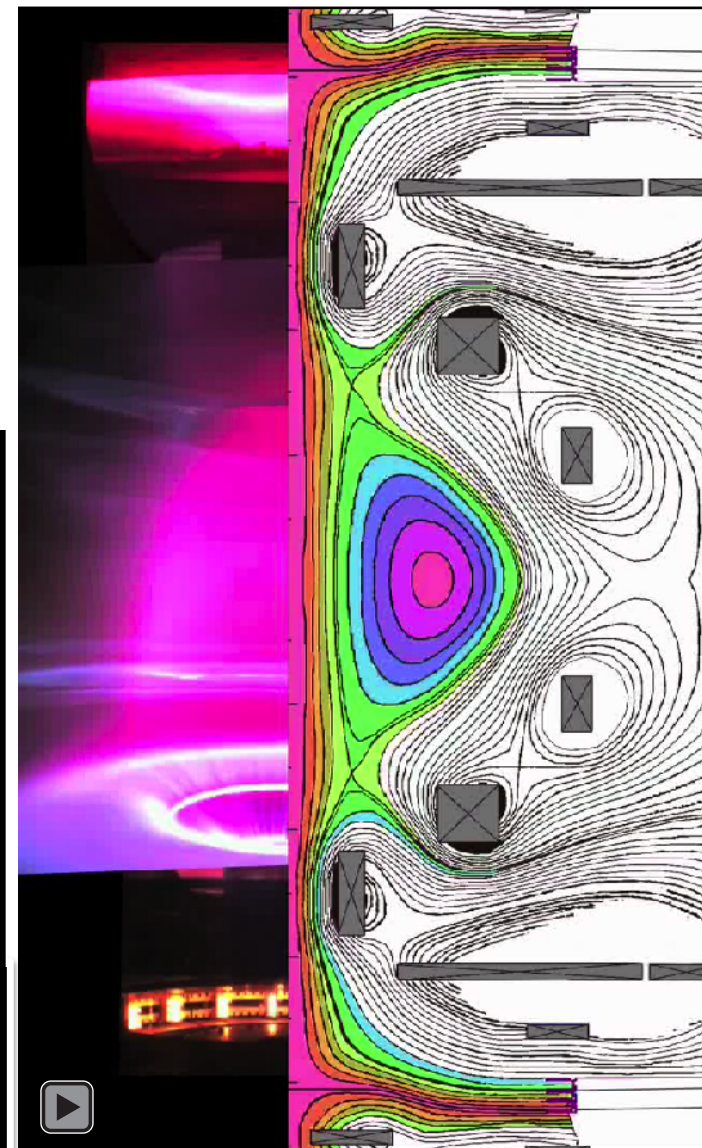


$< 1 \text{ MW}$, $T = 100 \text{ eV}$
“lukewarm” plasma:
magnetic reconnection
studies at $S \sim 10^4$

Fritz Lang's Metropolis (1926)

Metropolis

a few MW, $T = 1 \text{ keV}$, “hot” plasma at $\beta \sim 1$, no disruptions
no additional heating & no current drive required,
same T as a Tokamak, but 1/100 of the cost!



Perspectives

。。。放龙如海! fànglóng rùhǎi!
...let the Dragon swim in open sea!



PROTO-SPHERA will assess a new magnetic confinement configuration:

- simply connected (easy to build, maintain & modify)
- sustained (indefinitely) by magnetic reconnections induced by DC voltage
- mixed magnetic & electrostatic confinement, plasma flow being paramount
- could provide laboratory examples and insight into cosmic reconnection phenomena

Furthermore:

- a permanent magnet machine able to form and to sustain magnetic confinement?
- (if high T from magnetic reconnections) plasma $\beta \sim 1$: small size future Fusion reactor?
- a forerunner for a (far future) Fusion Space Thruster?

**Proto-Sphera can pursue such an aggressive program:
with limited costs (~ 2.0 M€); with flexibility (new components easy to accommodate)**



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