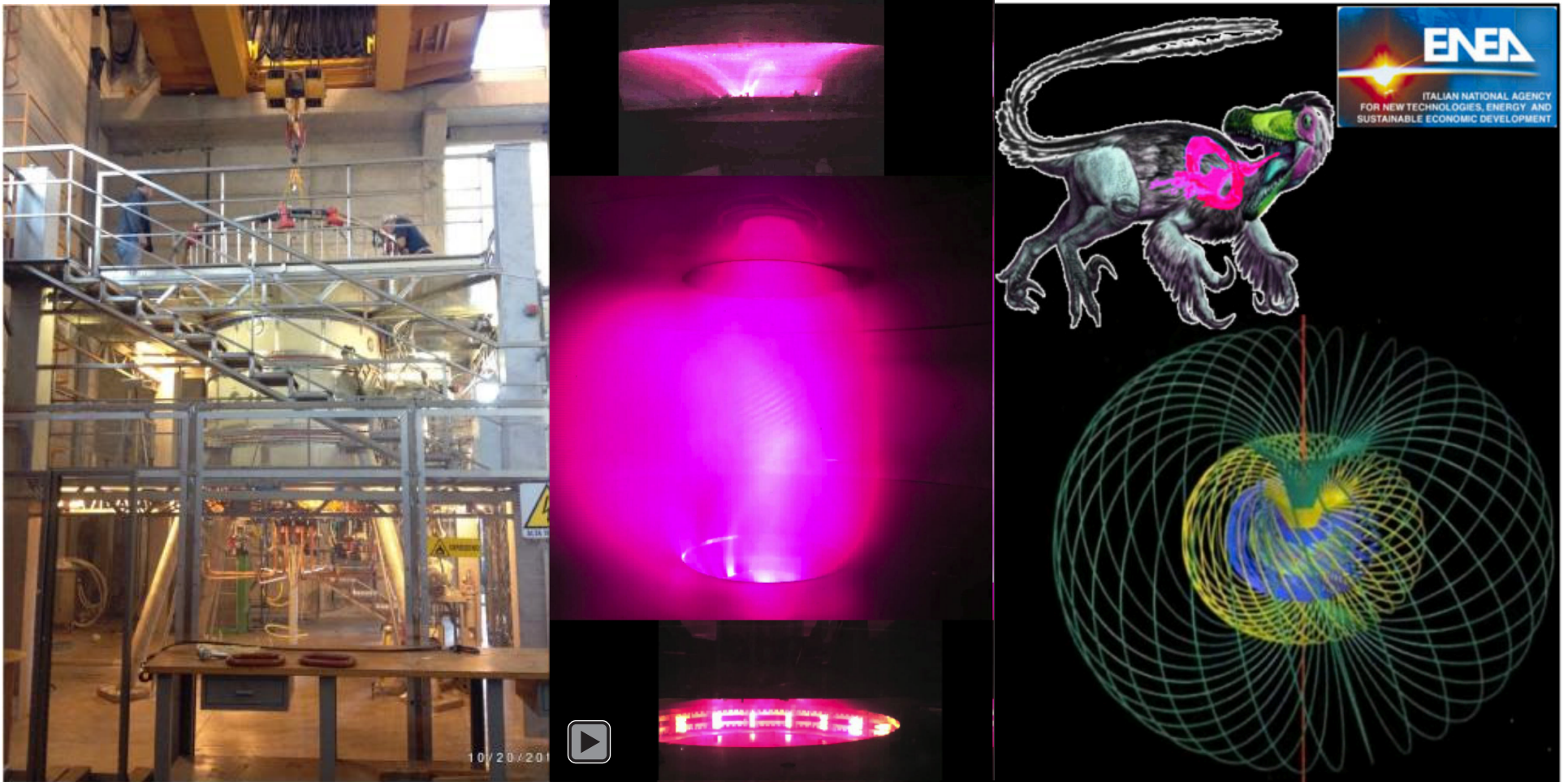


PROTO-SPHERA - Phase 1

10 kA Hydrogen plasma

Franco Alladio, CR-ENEA Frascati



February 2018, Frascati

A Spherical Torus whose Centerpost is a Plasma discharge

Natural examples of rings emitted by jets in fluids & plasmas

A priori advantages...

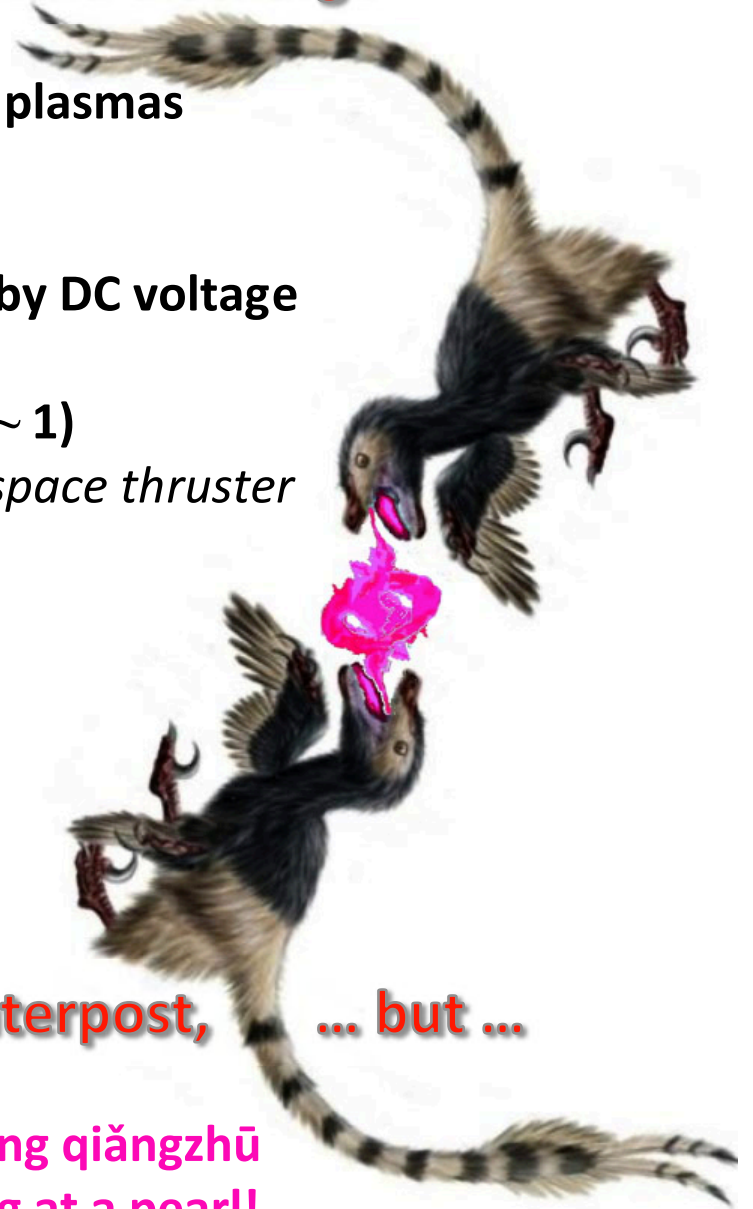
- Unlimited sustainment of toroidal plasma current by DC voltage
- Resilient to disruptions
- High β value (plasma pressure \magnetic pressure ~ 1)
- *If successful it could become the engine of a fusion space thruster*

A posteriori advantages... from experimental results

- Spontaneous rotation of Plasma Centerpost
- Mixed magnetic & electrostatic confinement

Now experiment produces only Plasma Centerpost, ... but ...

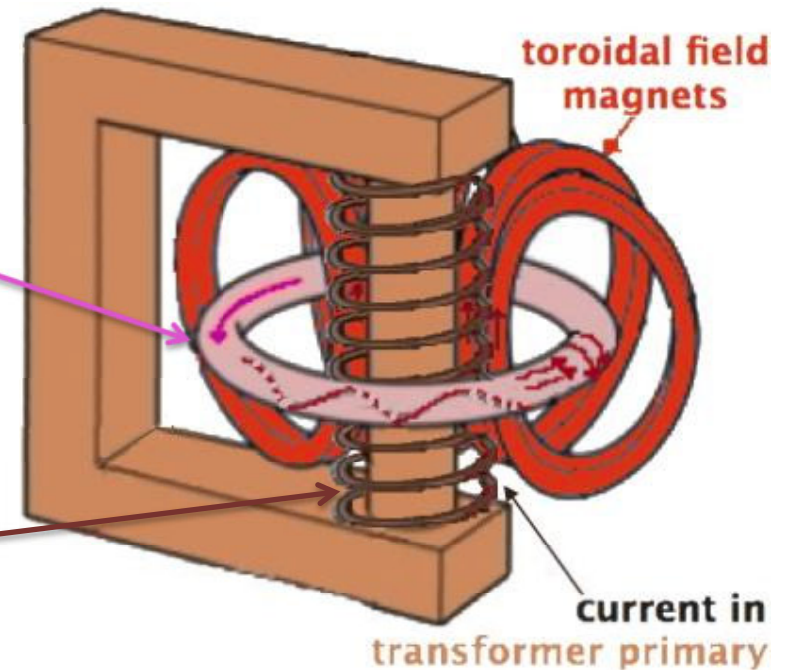
。。。二龙抢珠 èrlóng qiǎngzhū
Two Dragons are snapping at a pearl!



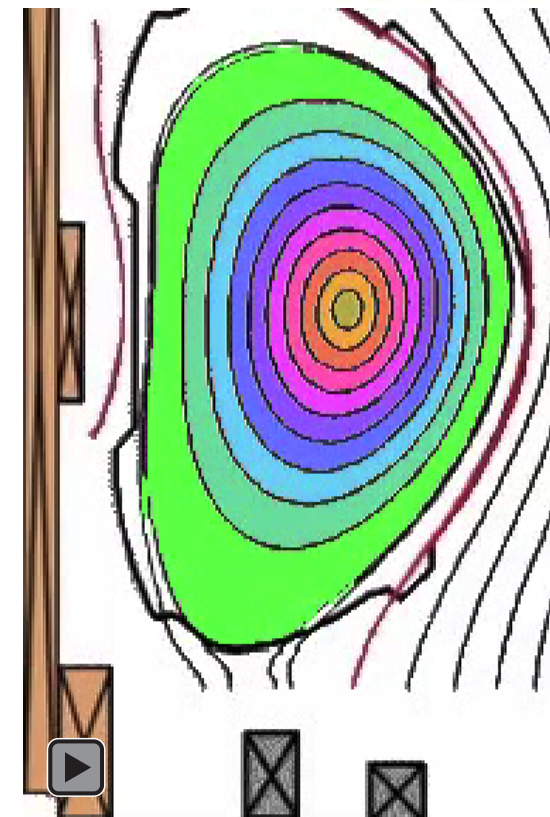
In Tokamaks **a plasma confining current has to flow inside the Torus:**

such a current has to be **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 can be seen as **motion of closed flux surfaces**, that from outside 'feed' the plasma, which dissipates them while they move toward the magnetic axis
- In tokamaks this process is due **to the transformer current change:**
- **Tokamaks cannot have steady drive!**

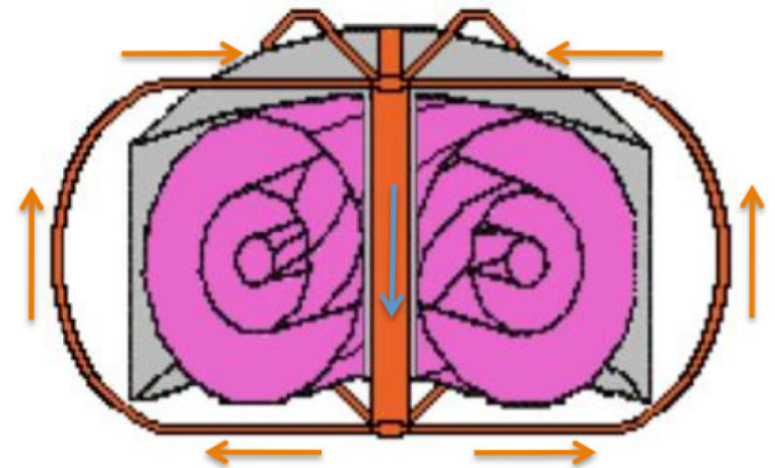


The main idea of PROTO-SPHERA

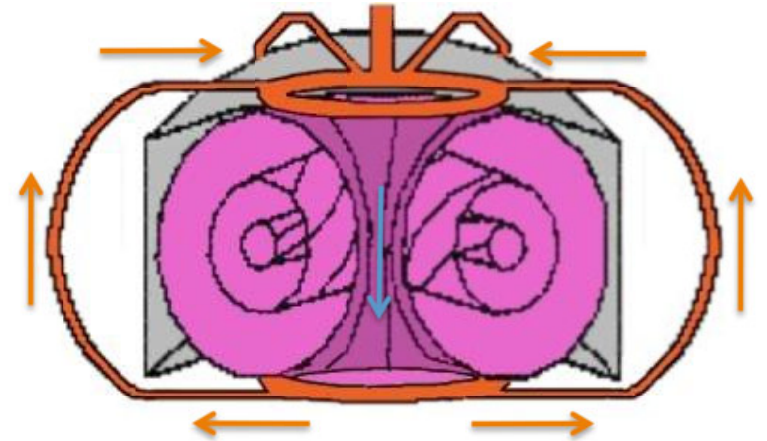
- “Conventional Tokamak”: **magnetic surfaces of toroidal plasma** surround a “**Metal Centerpost**”
- *Vacuum vessel has toroidal geometry*
- **PROTO-SPHERA: magnetic surfaces of toroidal plasma** surround a “**Plasma Centerpost**”; **only current return external legs are made of metal**
- *Vacuum vessel has cylindrical geometry*
...but electrodes are required inside vacuum

Abandon vacuum vessel complicated geometry,
move to a cylindrical vacuum vessel!

→ easy of access & of repair...

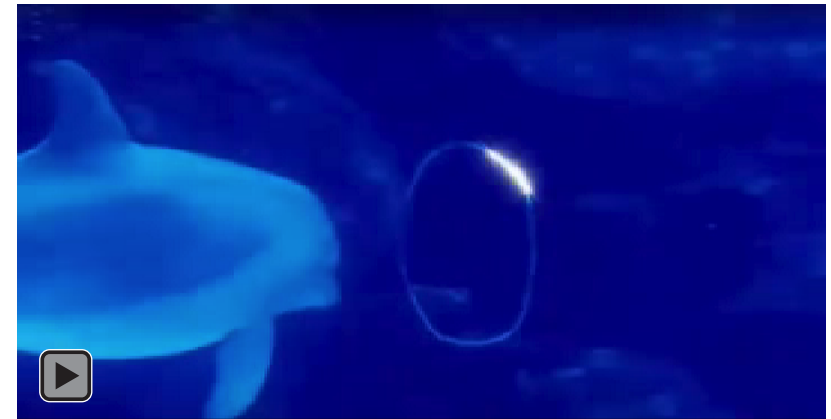


Electric current flow



Formation & sustainment of Rings from Jets is a common occurrence in Nature!

Aim is to sustain the Plasma Torus
for at least 1 resistive timescale: $\tau_{\text{Resist}} \sim 70 \text{ ms}$
...but *PROTO-SPHERA* designed for 1 sec sustainment!

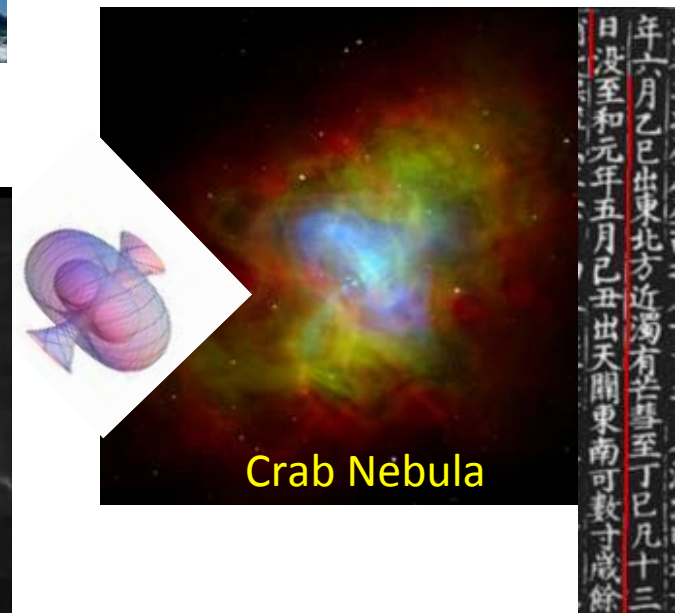


William Irvine-University of Chicago



Fluid dynamics examples

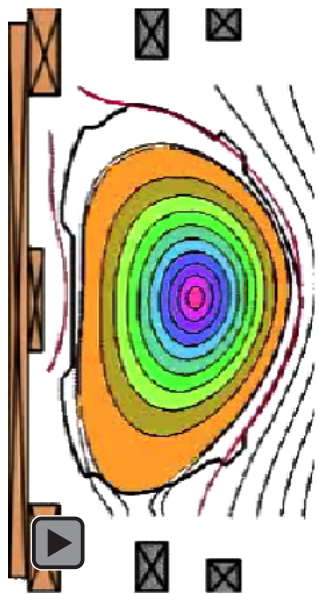
Plasma dynamics example



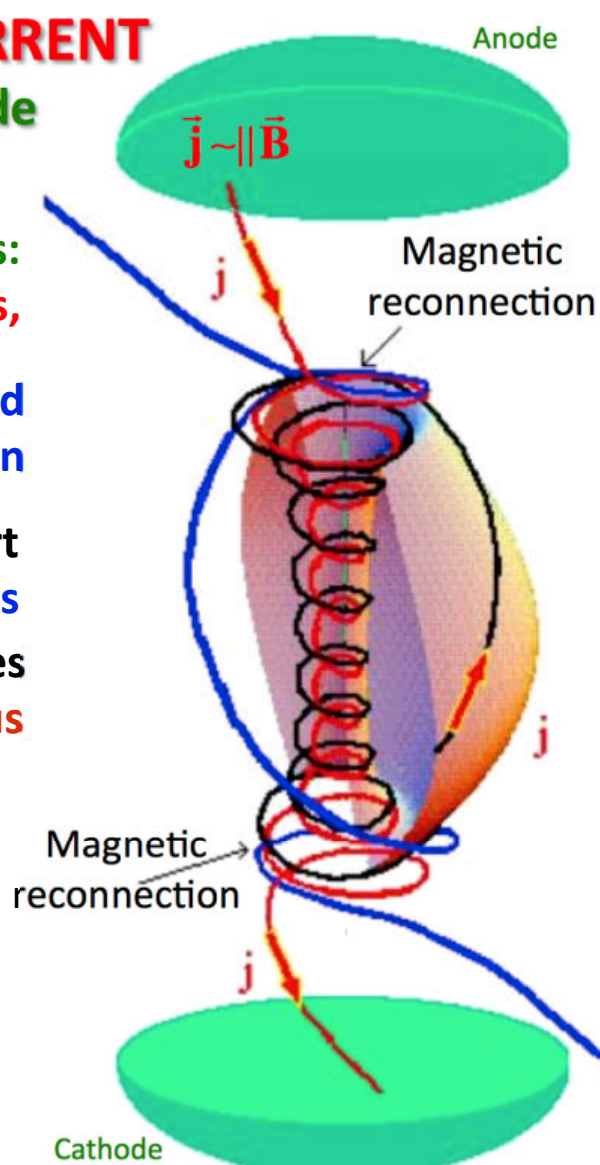
SUSTAIN THE CONFINING CURRENT

by DC voltage from anode to cathode

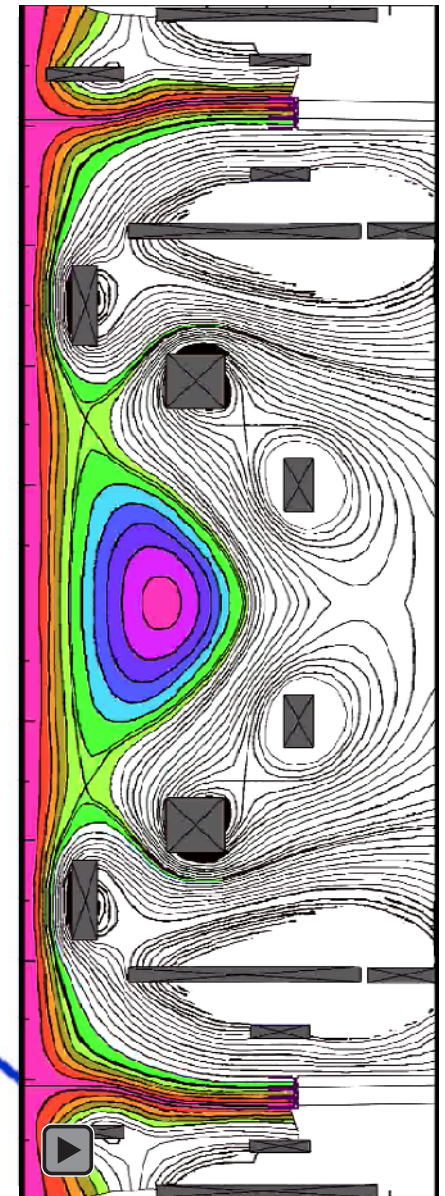
- In front of the electrodes: open magnetic field lines,
- Open magnetic field lines are wound in a circular direction
- Magnetic reconnections convert open $\vec{B}$ lines into closed $\vec{B}, \vec{j}$ lines wrapped around the spherical torus



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



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

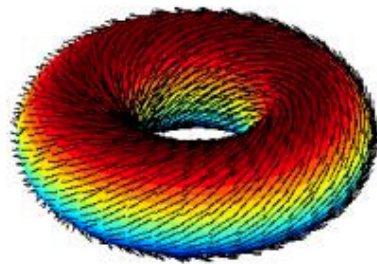


HOW EFFICIENT THE SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS?

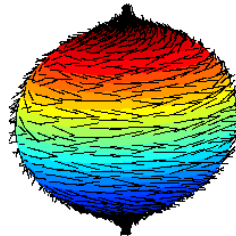
Space Thruster?

abandon vacuum vessel toroidal geometry, move to cylindrical one
... → **natural expulsion of charged fusion products (Space Thruster)**

*Due to filamentary nature of B field
a fundamental mathematical difference appears:*



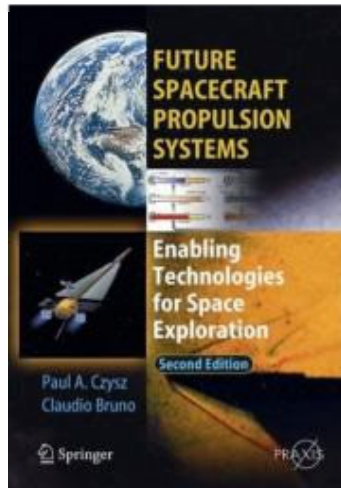
*a hairy torus
can be combed*



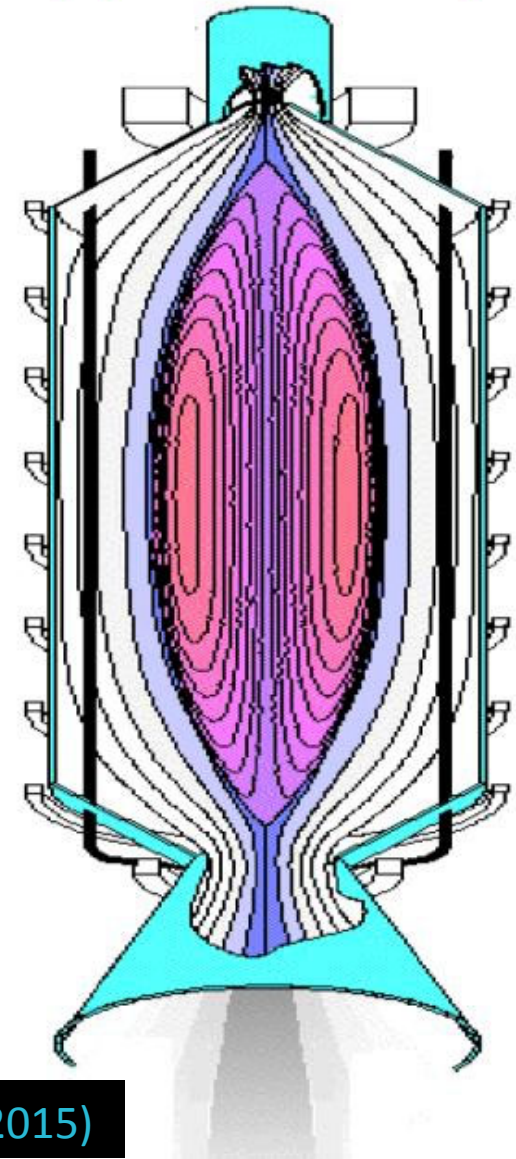
*a hairy sphere
cannot!*

From one of the “**tufts**” of the sphere (...not combed)
very high velocity ($\sim$ MeV) charged fusion products emerge

Possible far future application as a Space Fusion Thruster...



Nozzle observed in PROTO-SPHERA experiment (2015)



PROTO-SPHERA main design parameters:

Centerpost current

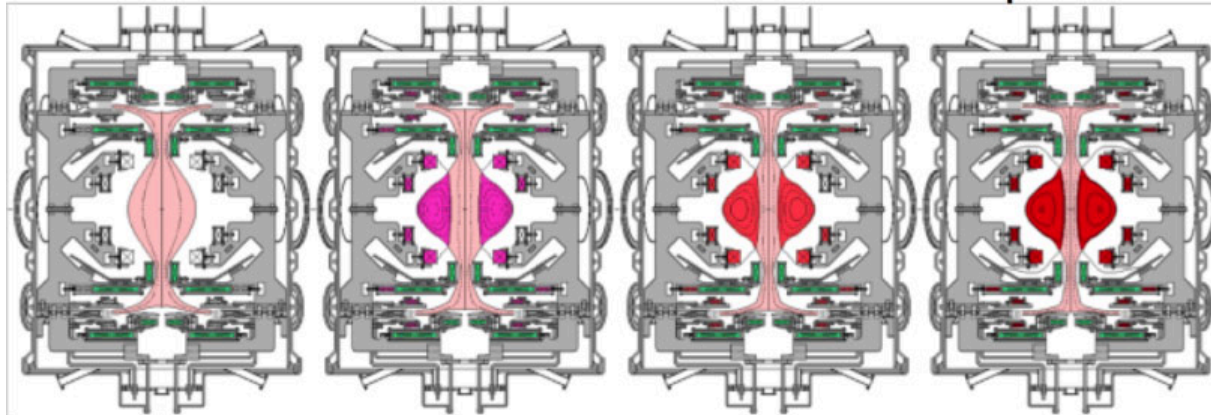
$I_e = 60 \text{ kA}$

ST toroidal current

$I_{ST} = 120 \div 240 \text{ kA}$

ST diameter

$2R_{sph} = 0.7 \text{ m}$

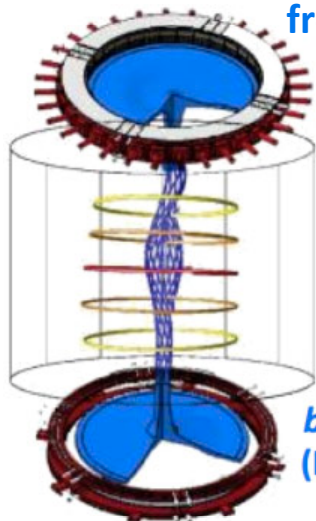


Axisymmetric simulation of ST formation

Formation time scale $(\tau_{\text{Alfvén}} \cdot \tau_{\text{Resist}})^{1/2} \sim 0.6 \text{ ms}$

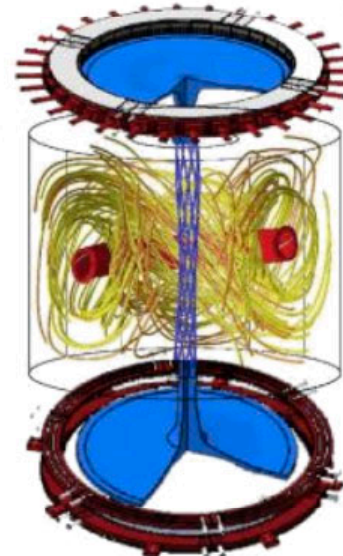
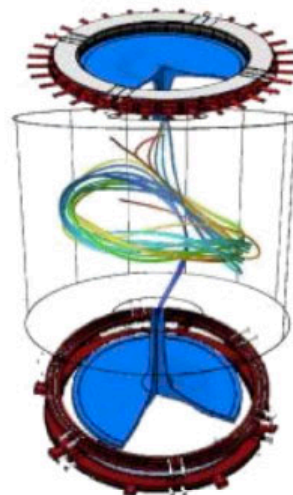
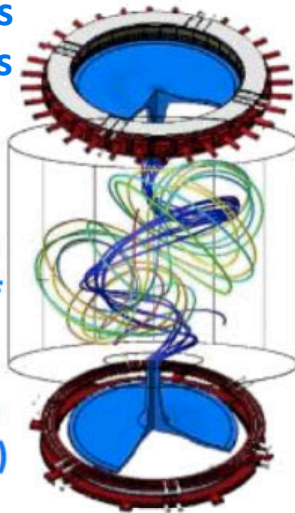
from $\tau_{\text{Alfvén}} \sim 0.5 \mu\text{s}$

$\tau_{\text{Resist}} \sim 70 \text{ ms}$

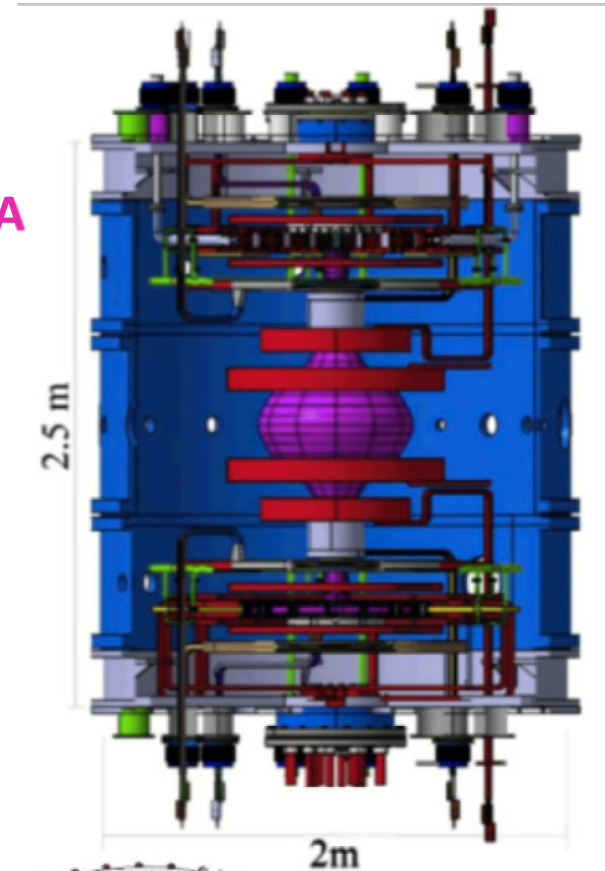


*Resistive MHD
simulations of
ST formation*

*by Ricardo Farengo
(ISTW2008-Frascati)*



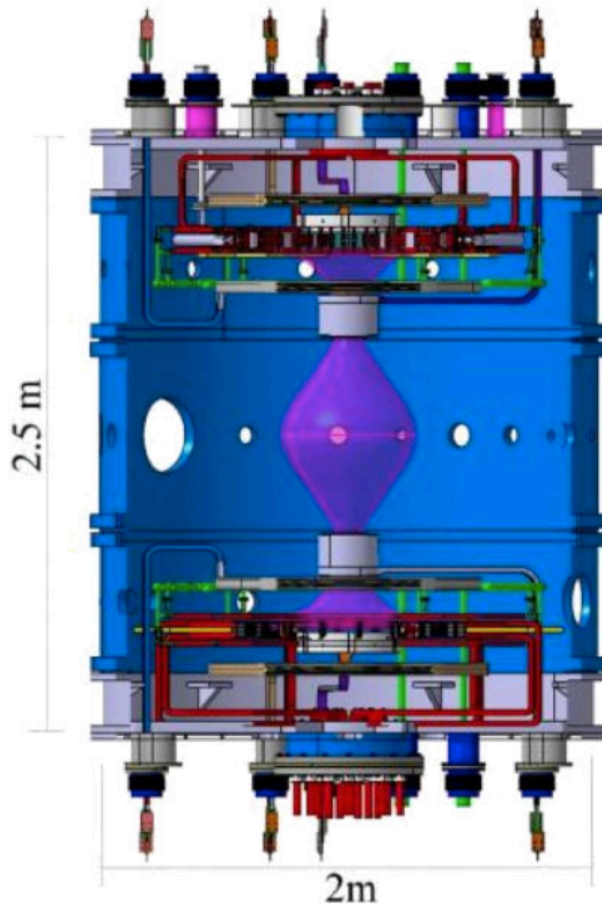
Non-axisymmetric simulation of ST formation



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

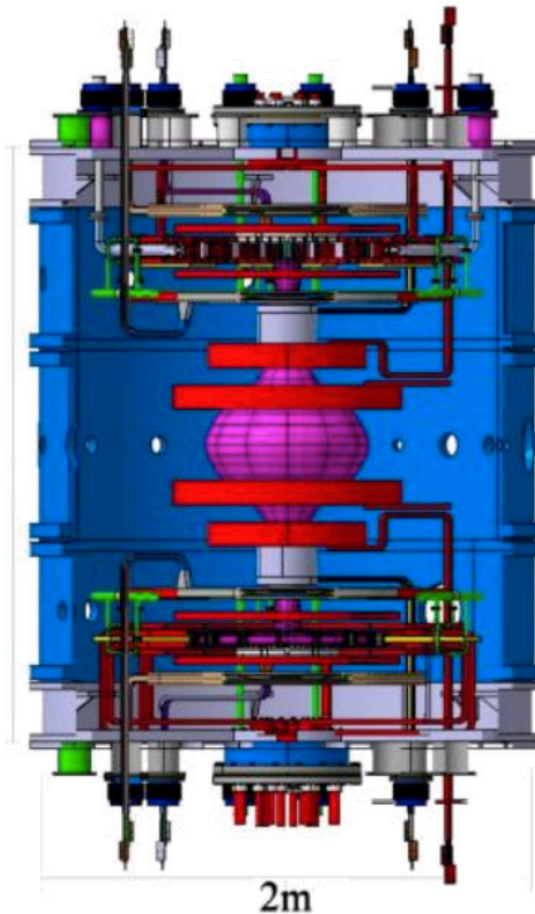
- Phase 1: demonstrate Plasma Centerpost's feasibility
- Phase 2: machine completed such as to produce the Spherical Torus

Phase1: 8 PFcoils
Centerpost shape



Centerpost current $I_e = 10 \text{ kA}$
No ST toroidal current ?

Phase 2: 8 PF shaping coils
+ 10 PF compressing coils



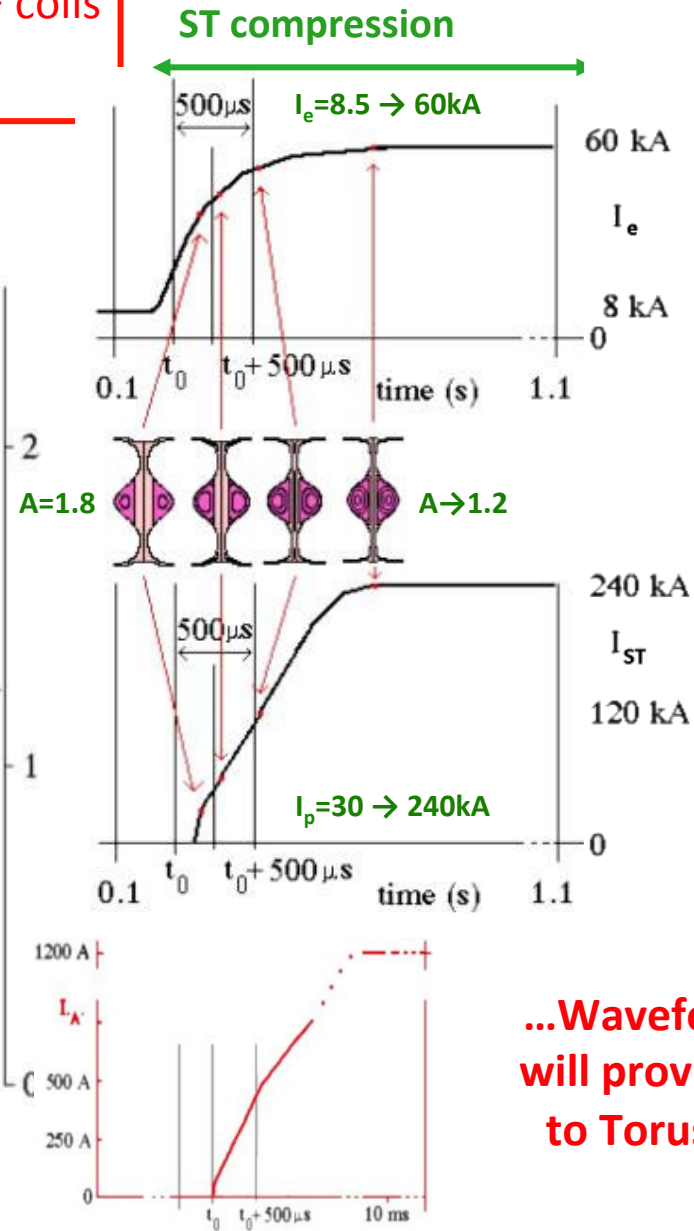
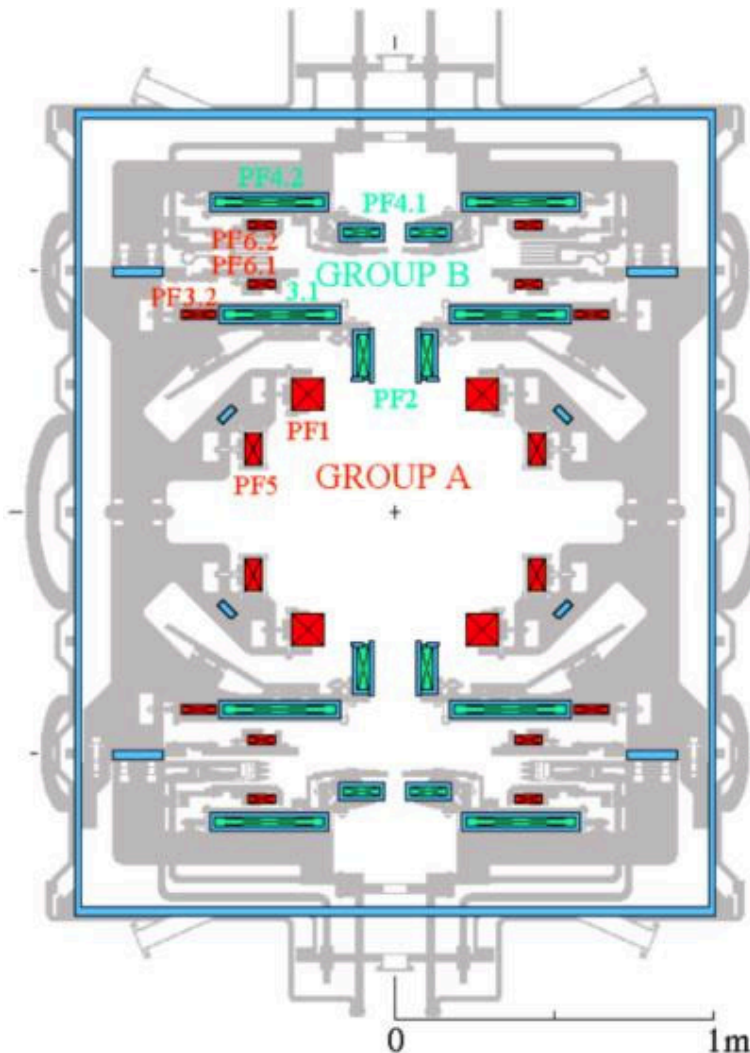
Centerpost current $I_e = 60 \text{ kA}$
ST toroidal current $I_{ST} = 120 \div 240 \text{ kA}$

The PF coils have been designed as two sets, each connected in series

Group B (4+4 coils): Centerpost shaping PF coils, *now inside machine*

Group A (5+5 coils): ST compression PF coils

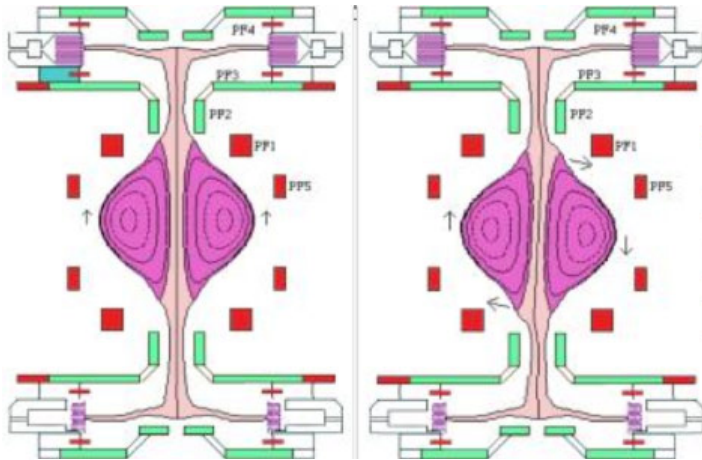
Not yet built ... fast increase: **0.5 ms**



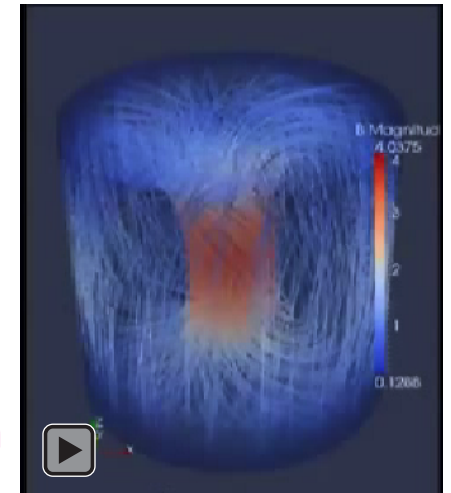
...Waveform of Group A will provide ohmic drive to Torus up to **120 kA**

IDEAL MHD STABILITY of PROTO-SPHERA

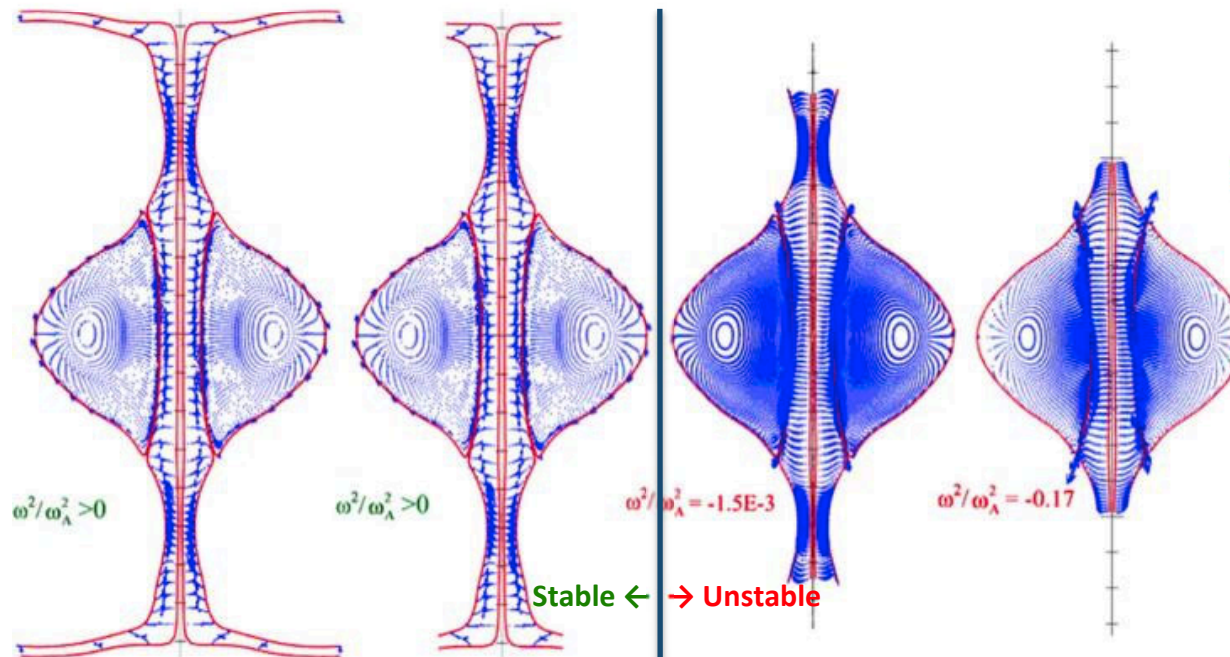
Spheromak tilt instability is due to
dipole of containing field opposite to toroidal plasma current dipole



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



DISK-SHAPED CENTERPOST PLASMA: IMPORTANT FOR THE IDEAL MHD STABILITY



Cutting shorter & shorter
the plasma centerpost
PROTO-SPHERA at 120 kA
gets destabilized

INSULATIONS

Only the PF coils necessary for setting up the plasma centerpost have been built

8 PF coils in series inside the machine

up\down extensions
Stainless steel
(floating)

PF4up

PF3up

PF2up

Aluminium cylindrical
START vessel

PF2low

PF3low

PF4low

insulator

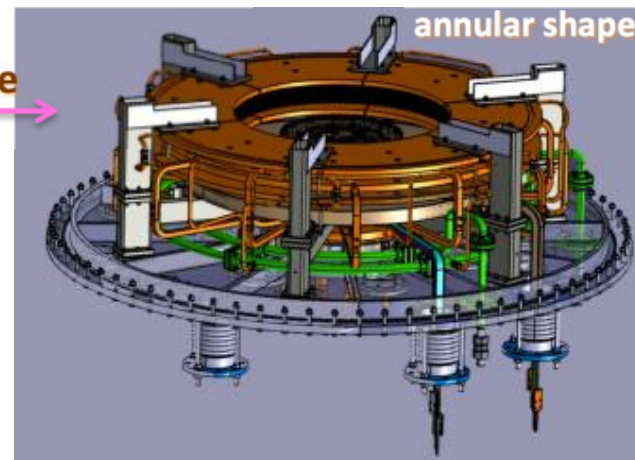
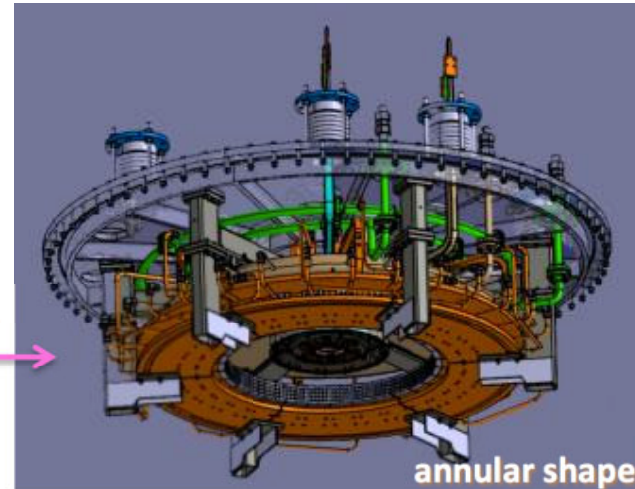
Stainless steel
up\down floating lids

insulator

anode

Plasma current runs
through both PF2 throttles

cathode



vacuum vessel is at GND potential

can be connected to potentials: **anode +**, **cathode -**, vessel 0

PF coils casings built as floating,

No Anode Arc Attachment!

Annular anode plasma never filamented

Argon plasma since June 2015...

In Argon break-down at ~ 80 V

Hollow annular anode performs...

- plasma goes through both PF2 throttles
- plasma enters anode gas-puffing holes
- no sign (up to $I_e = 10$ kA) of anode attachment
- filling pressure $10^{-3} - 10^{-2}$ mbar

January 2018 – line averaged electron density measured in Argon plasma

(Pisa University & its PlasmaTech spin-off):

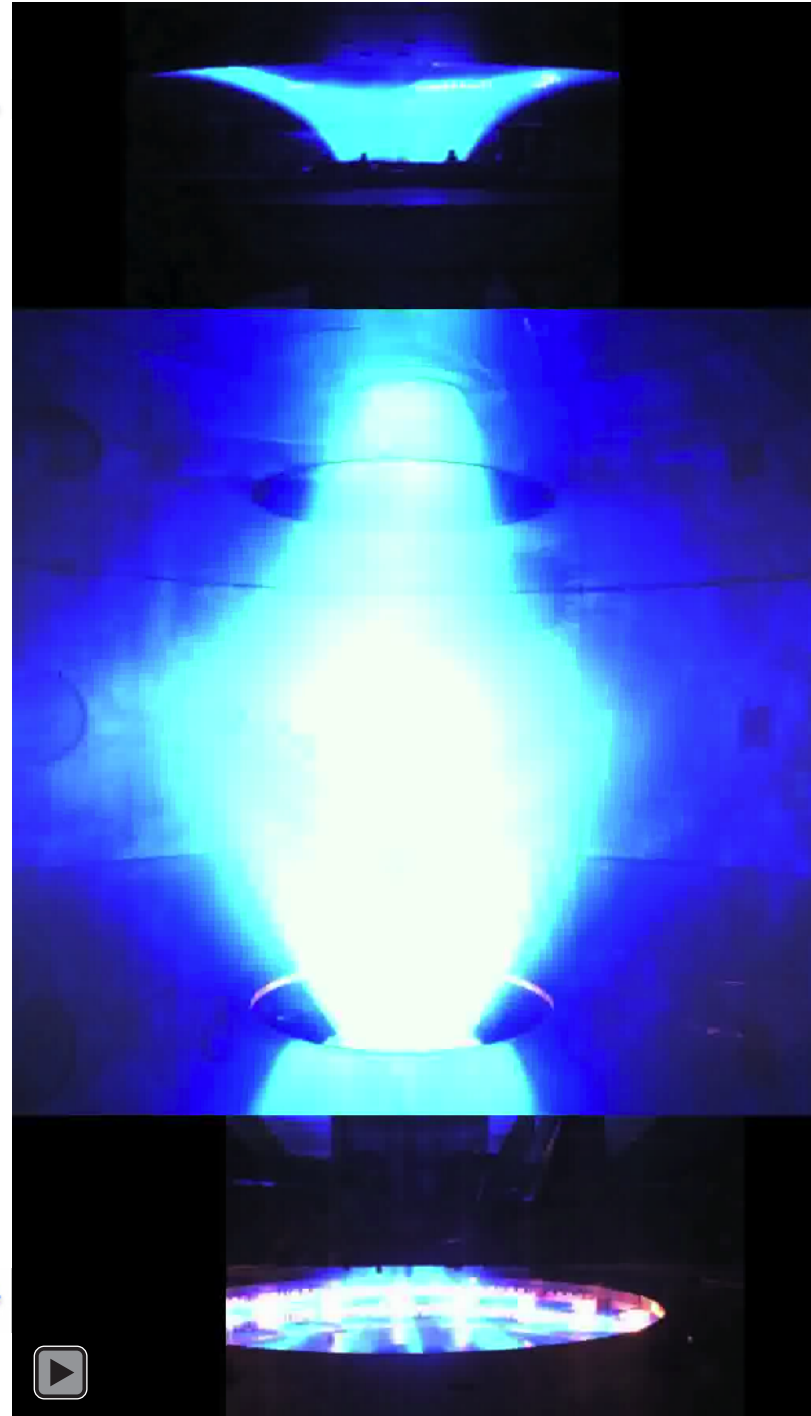
$\langle n_e \rangle \sim$ linear with I_e ,

at $I_e = 10$ kA, $\langle n_e \rangle \sim 4 \cdot 10^{20} \text{ m}^{-3}$



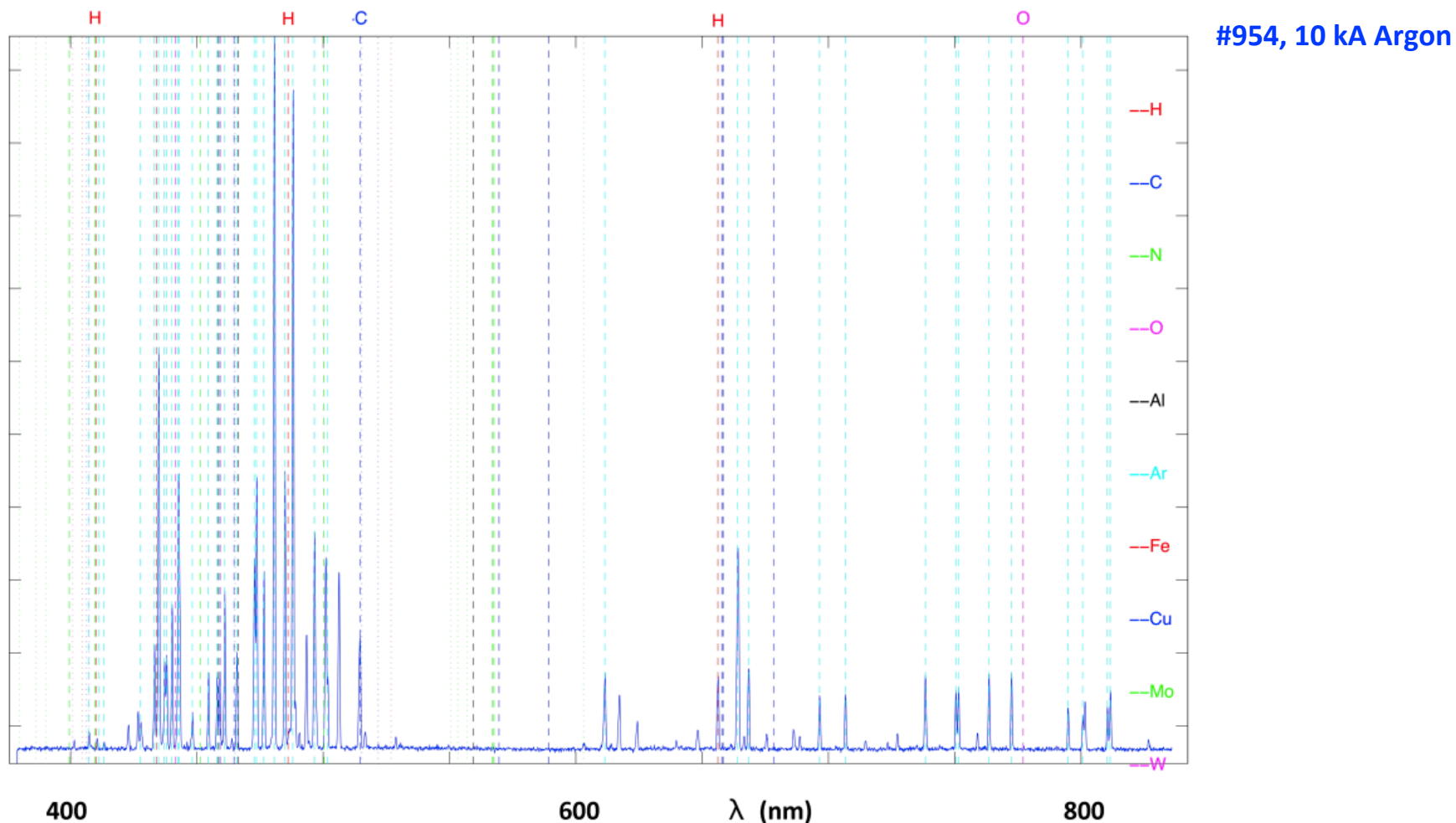
whereas annular cathode plasma is filamented (due to sparse emitters)

#954, 10 kA Argon



Preliminary spectrum of Argon Plasma Centerpost, low-res Vis Spectrometer :

In the Visible Spectrum **a forest of many Argon lines**,
but no Copper, no Tungsten, no Iron, no Molybdenum (Anode and Cathode materials)
and a slight presence of **Carbon**, **Hydrogen** and **Oxygen**, from Polycarbonate linings?



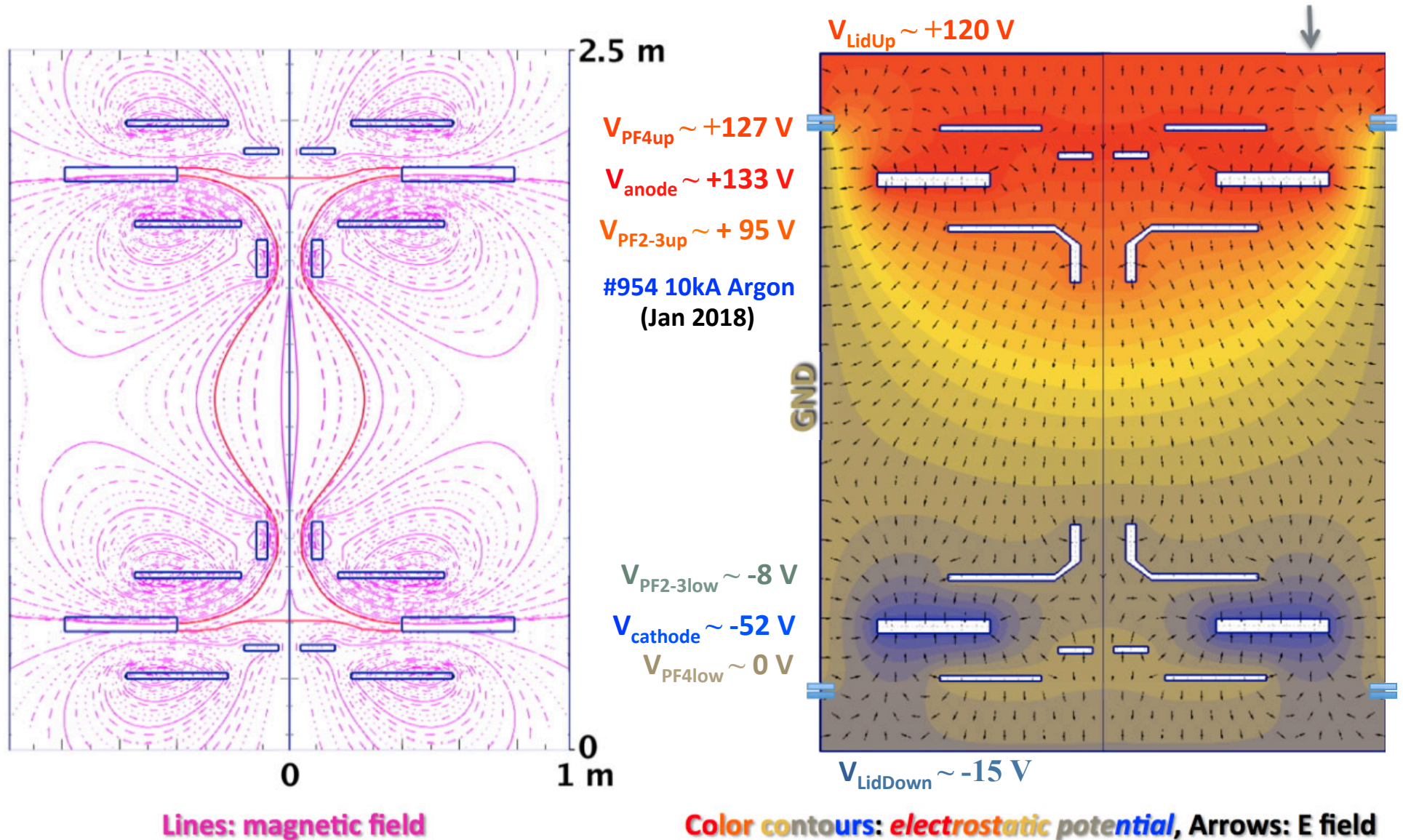
No Anode Arc Attachment: Electrostatic plasma effects!

PF coils casings left floating!

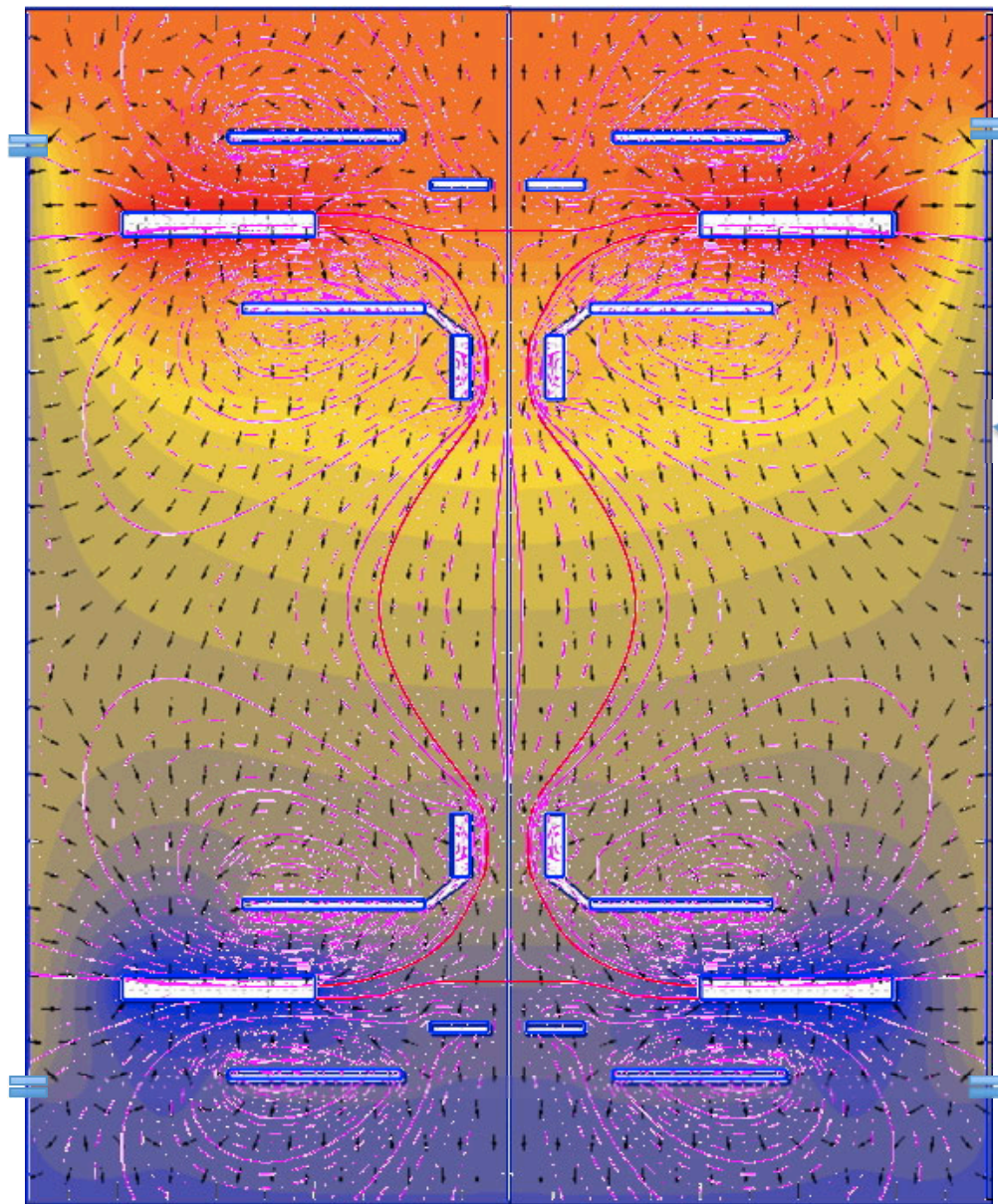
magnetic field is up\down symmetric

but

electrostatic field not up\down symmetric



Color contours: *electrostatic potential*, Arrows: E field



#977 10 kA Hydrogen

Lines: magnetic field

Plasma-induced electric potential:

near the annular anode

the E field is in part perpendicular to the B field

... $\vec{E} \wedge \vec{B}$ azimuthal plasma rotation

... starting from PF2up throttle

$$v_{\text{ExB}} = (E/B) \sim 10^2 - 10^3 \text{ m/s}$$

near the annular cathode

the E field is $\sim$ parallel to B field

... less $\vec{E} \wedge \vec{B}$ plasma rotation

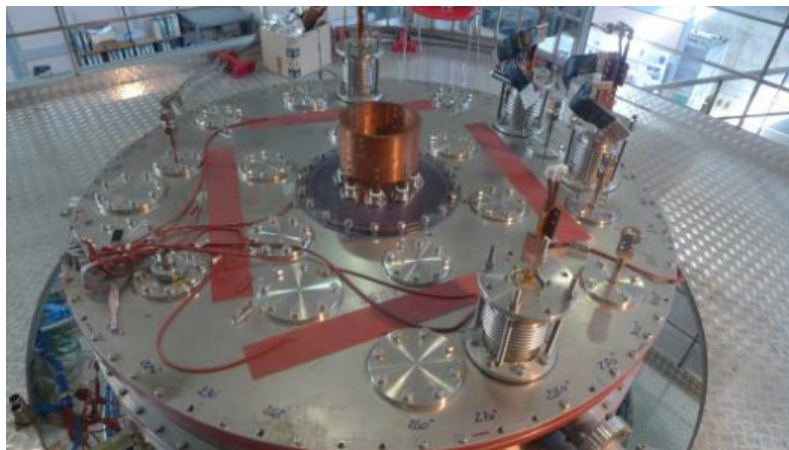
Self-organization at work inside annular electrodes plasma

Electrostatic plasma effects: caring for boundary conditions

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



Polycarbonate (transparent) anode bus-bar flange on top & bottom of machine inserted in December 2016



Electrostatic plasma effects: caring for boundary conditions

2mm thick
Polycarbonate
lining covers Al
vacuum vessel

inserted in
December 2016

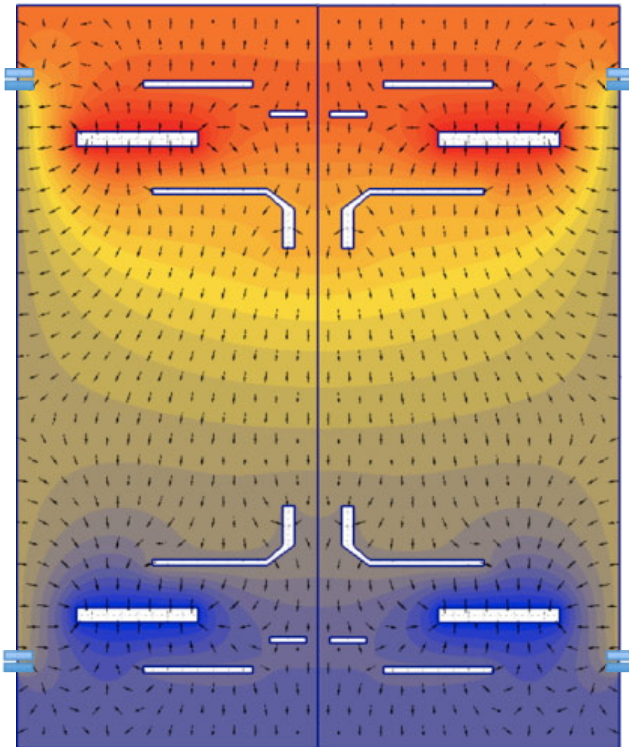


2mm thick
Polycarbonate
screens
surround
rear of
anode

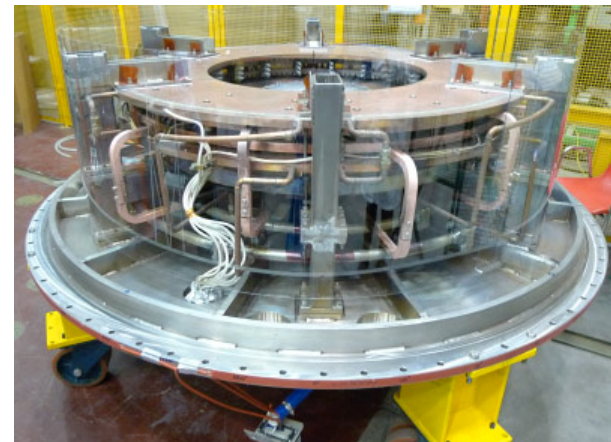
&

rear of
cathode

#985, 10 kA Hydrogen, destabilized



upper insulating ring
inserted in **May 2017**

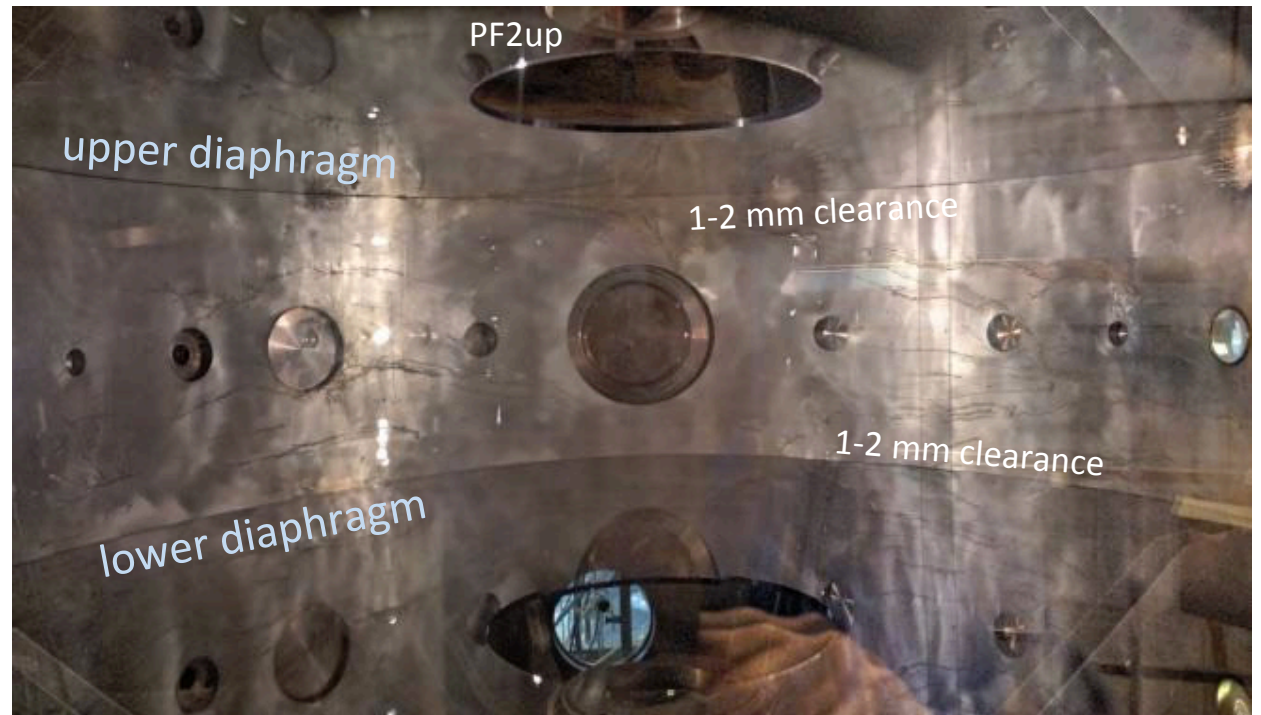


lower insulating ring

inserted in **December 2017**

**Electrostatic plasma effects:
caring for boundary conditions**

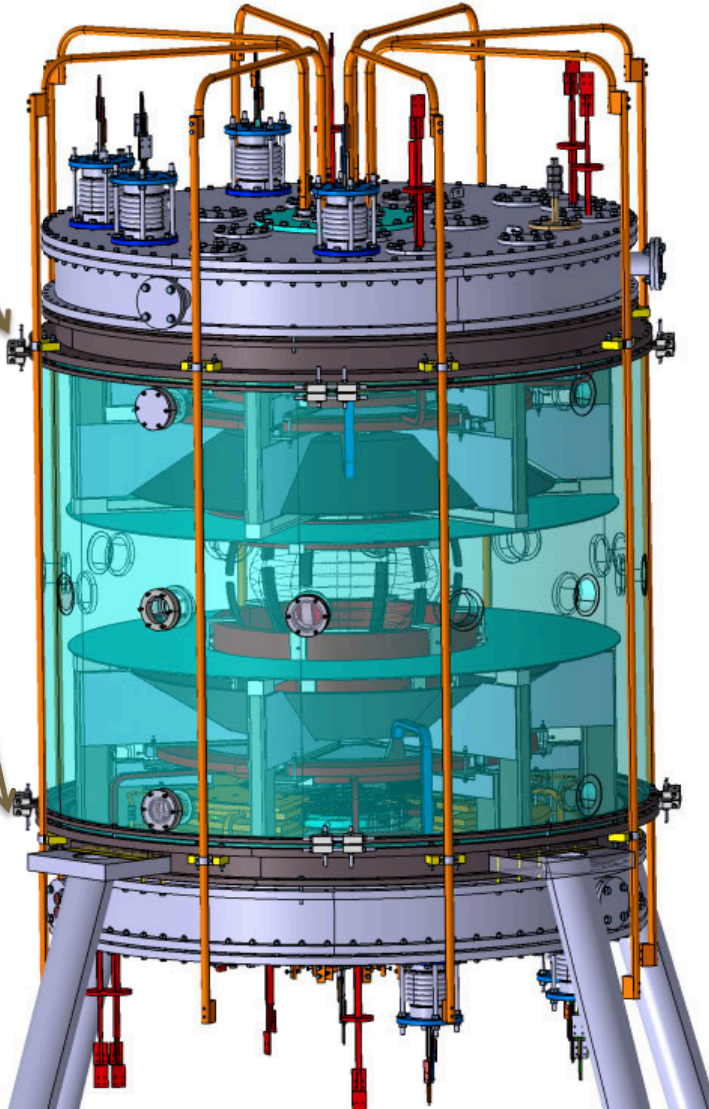
To avoid the flowing of
plasma currents outside the
plasma centerpost two large
insulating polycarbonate
diaphragms were inserted
May 2017



November 2017: the narrow
clearance **has been closed by**
a bonding material sustaining
the diaphragms weight
November 2017



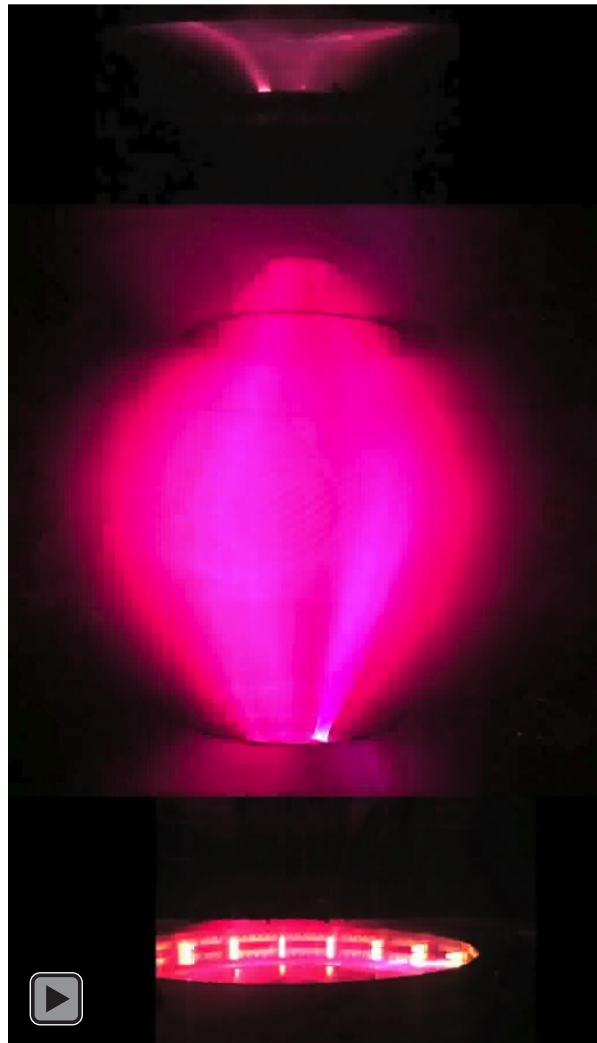
A new insulating & transparent vacuum vessel will be built: Phase-II ready
will substitute the Al (START) vacuum vessel with a Polymetacrylate (PMMA)
transparent and insulating vessel (9.5 cm thick, 2m $\varnothing$, 1.7 m high), endowed with 20 ports
adding 2 further SS rings on top & bottom of the experiment,
keeping all internal components attached to the existing SS upper\lower lid and extension



Reynolds
POLYMER TECHNOLOGY, INC.
Building the Impossible



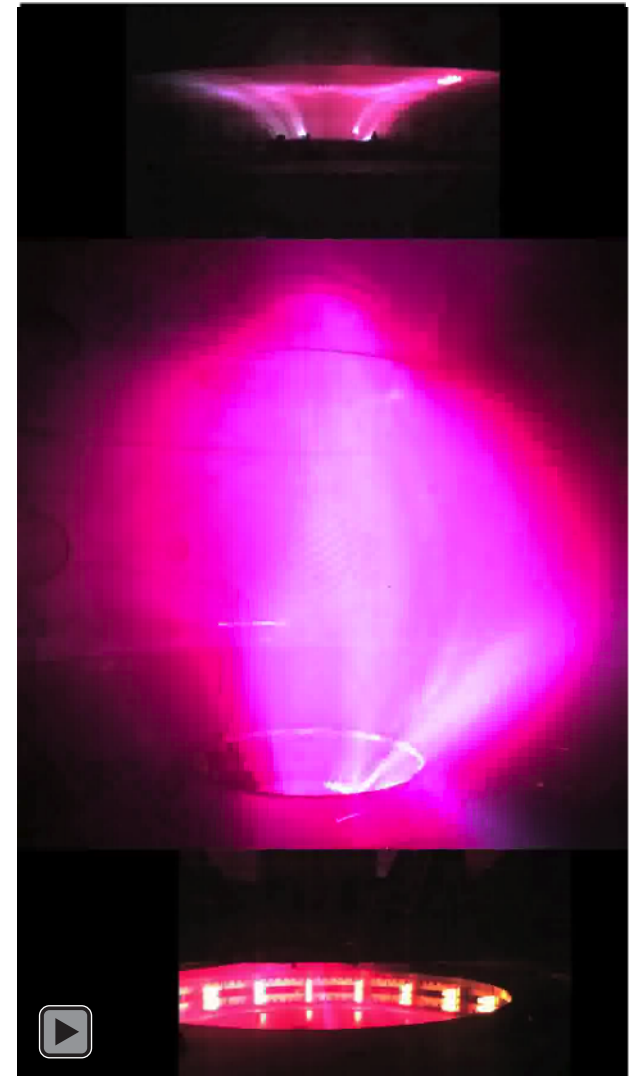
In Hydrogen break-down at ~ 300 V - January 2018



#966, 3 kA Hydrogen



#967, 5 kA Hydrogen



#969, 8 kA Hydrogen

$\sim$ MHD destabilization



**Hydrogen at full current 10 kA,
already beyond MHD destabilization**

January 2018 – line averaged electron
density $\langle n_e \rangle$ measured in Argon plasma
(*Pisa University & PlasmaTech spin-off*):
at $I_e = 10$ kA, $\langle n_e \rangle \sim 1.5 \cdot 10^{20} \text{ m}^{-3}$

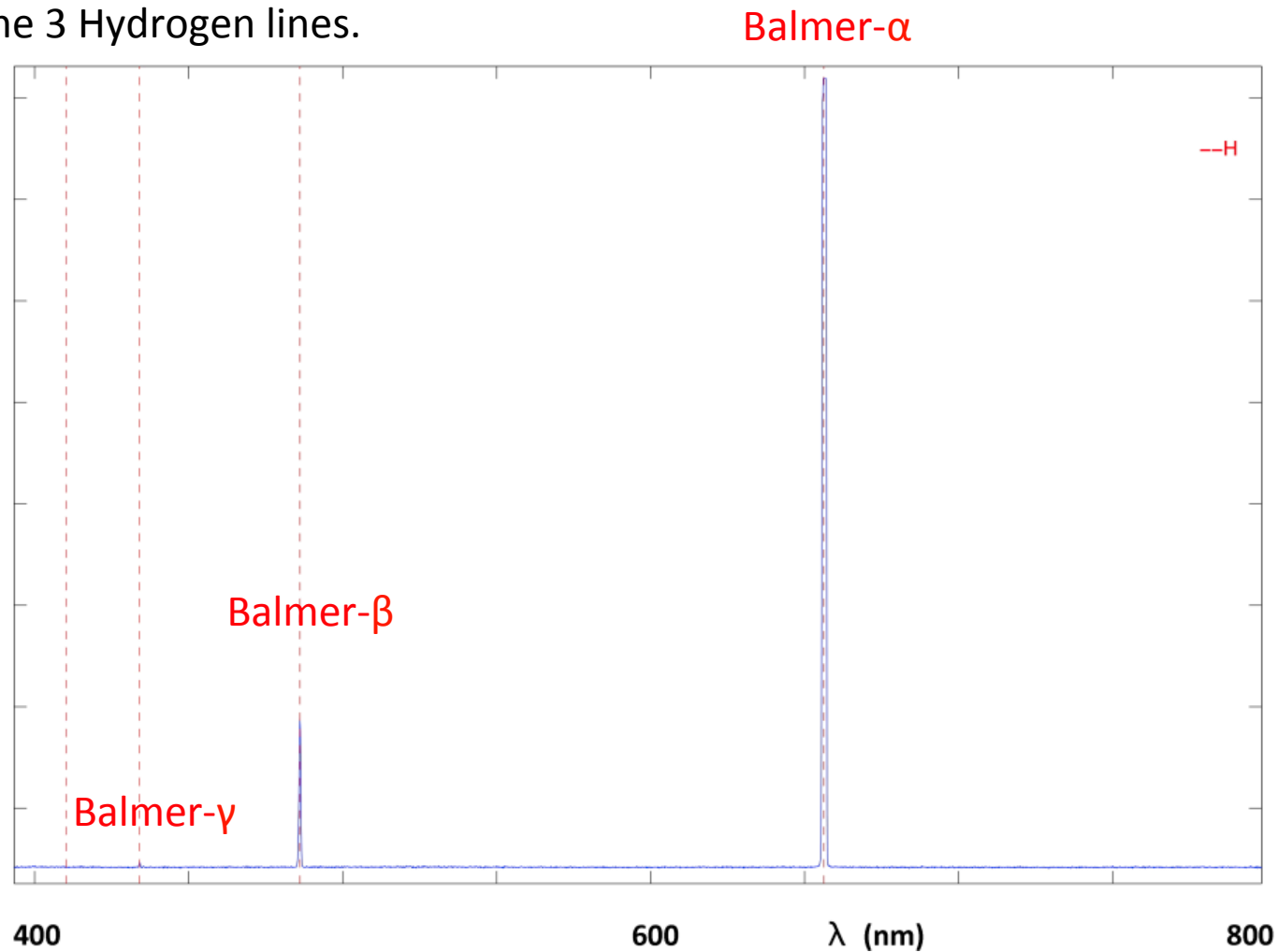
PROTO-SPHERA Phase 2 at 60 kA predicts
 $\langle n_e \rangle \sim 1 \cdot 10^{21} \text{ m}^{-3}$ for the Hydrogen
Centerpost Plasma:
a high-field-Tokamak like density
(several 10^{20} m^{-3}) for the Spherical Torus?

#983, 10 kA Hydrogen



Preliminary spectrum of Hydrogen Plasma Centerpost:

In the Visible Spectrum nothing but the 3 lines of **Balmer-alpha**, **beta** and **gamma**.
No impurities whatsoever, at least on a vertical scale that does not lead to saturation of the 3 Hydrogen lines.

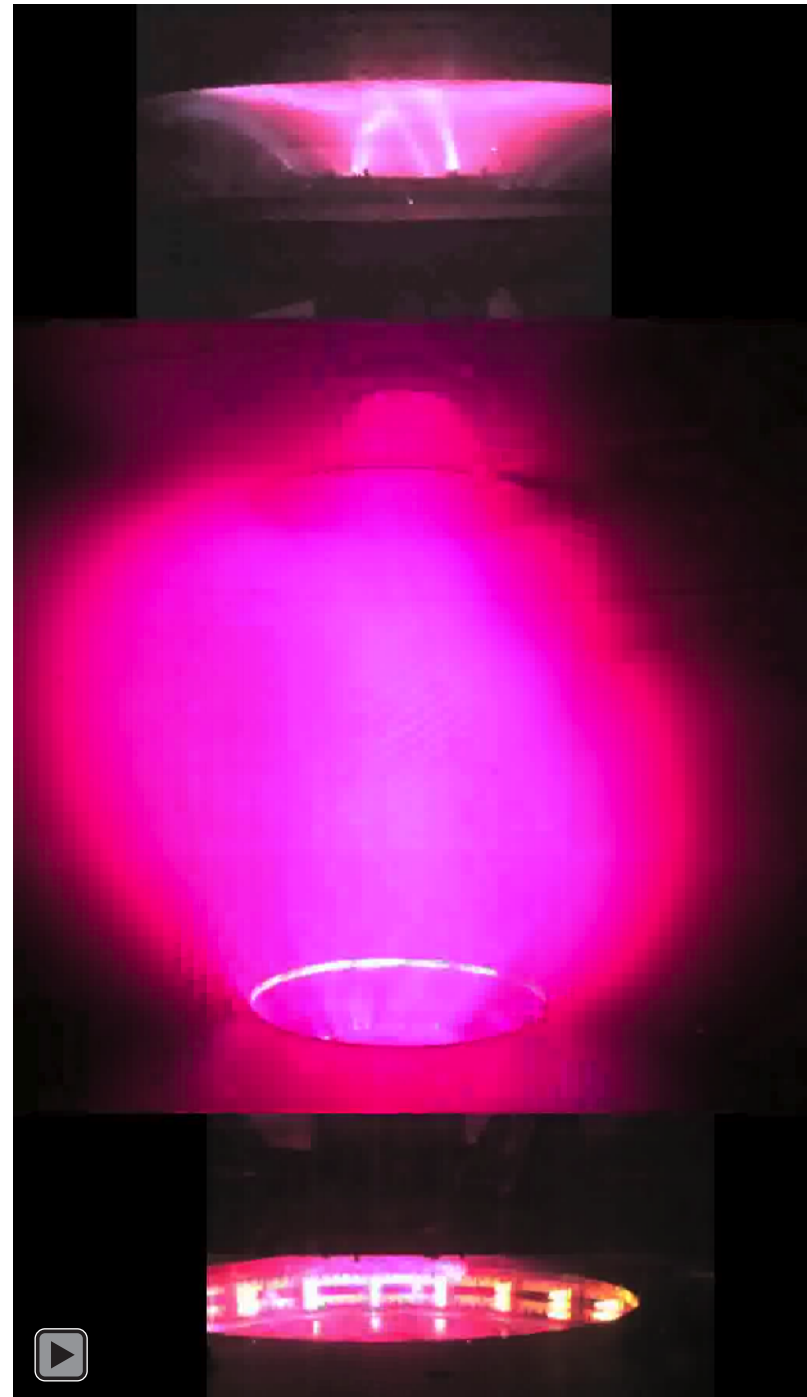


Hydrogen at full current 10 kA,
but with shaping magnetic field
reduced to $\frac{1}{4}$ of full value,
MHD destabilized

Discharge seems willing to
eject a Spherical Torus
...but a vertical field is missing...

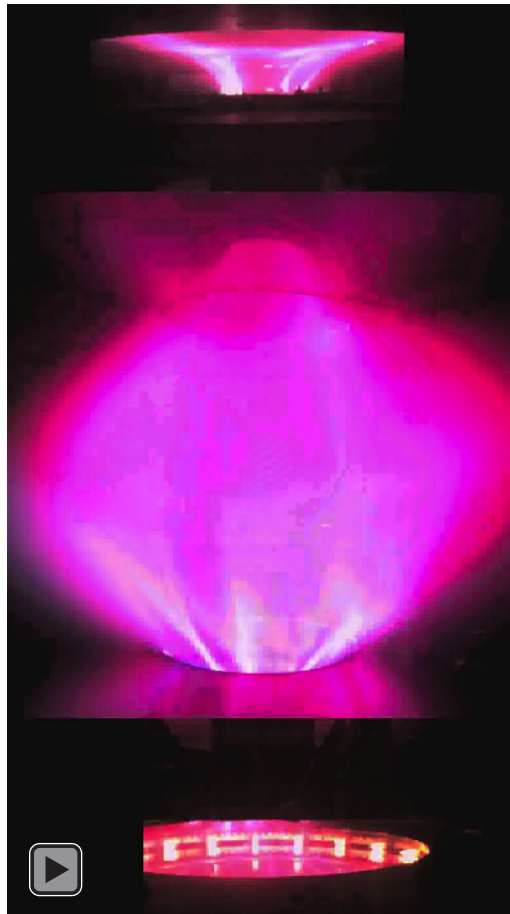


#985, 10 kA Hydrogen
 $\frac{1}{4}$ poloidal B field

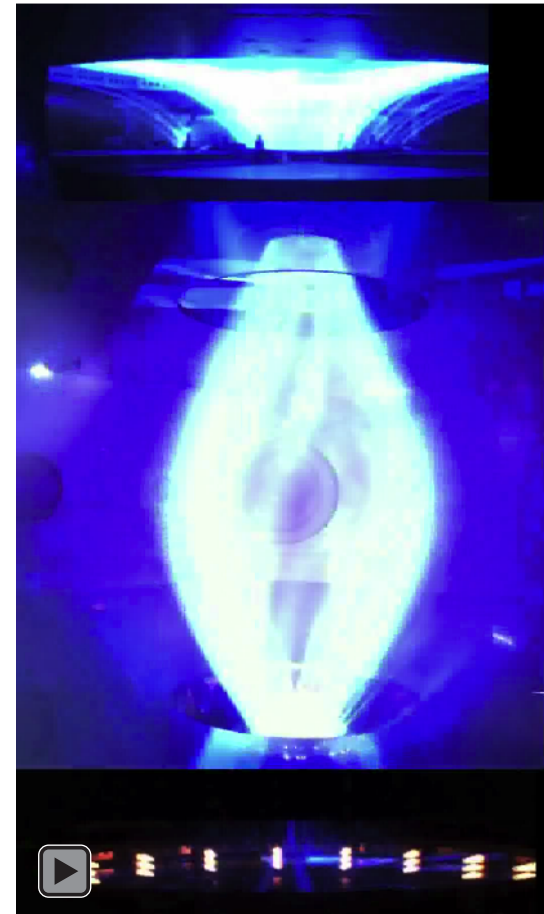


Plasma rotation in Tokamaks extremely advantageous, as it stabilizes the torus

Plasma Centerpost of PROTO-SPHERA rotates!



#977, 10 kA Hydrogen



#614, 8.5 kA Argon

Operational experience in Tokamaks shows that the **best way of injecting fuel is from inboard (high field side)**

No additional heatings for PROTO-SPHERA?

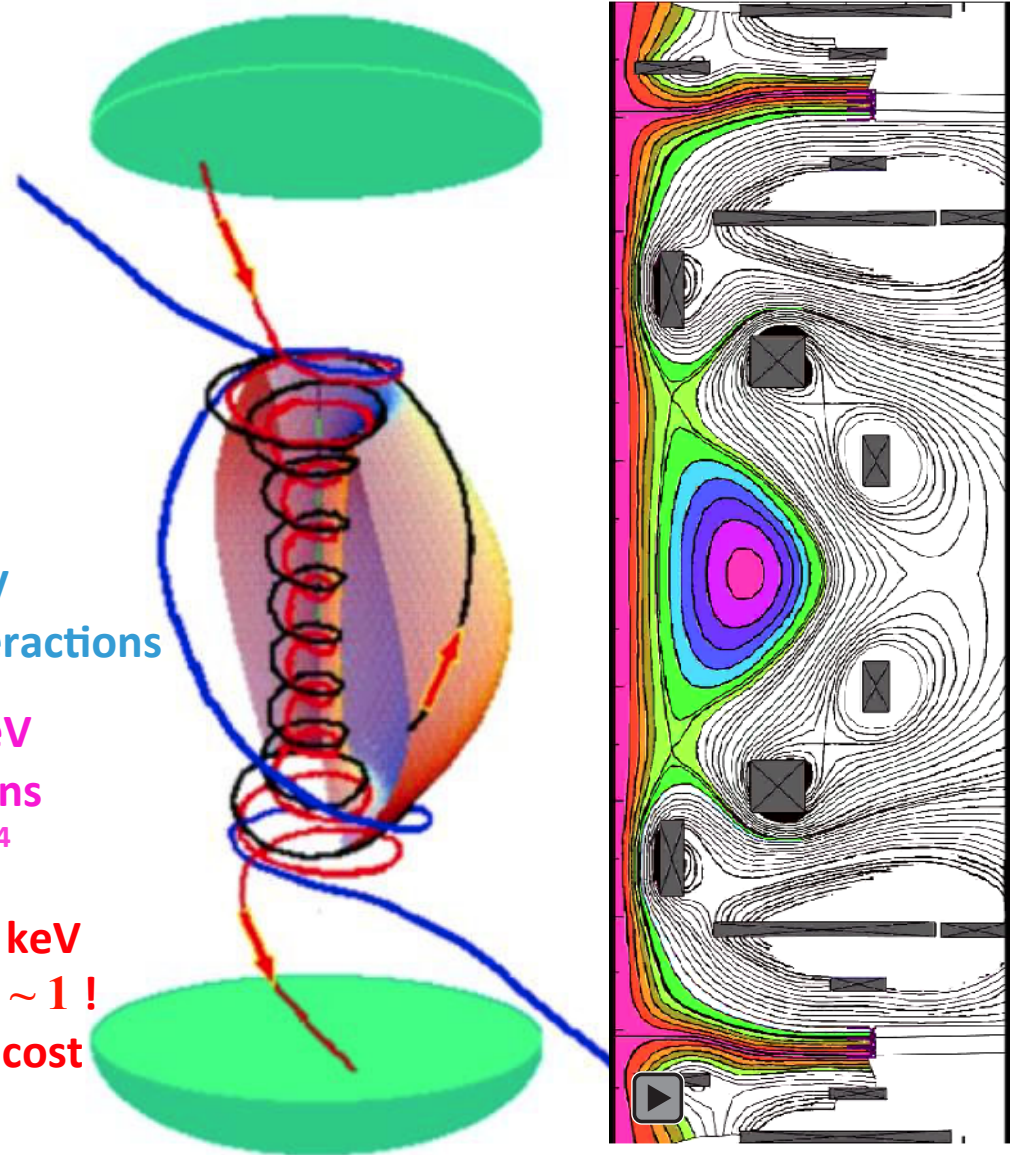
...magnetic reconnections quite efficient in heating up the Solar Corona!

Power injected into the centerpost
should be $> 250 \text{ V} \cdot 60 \text{ kA} = 15 \text{ MW}$...

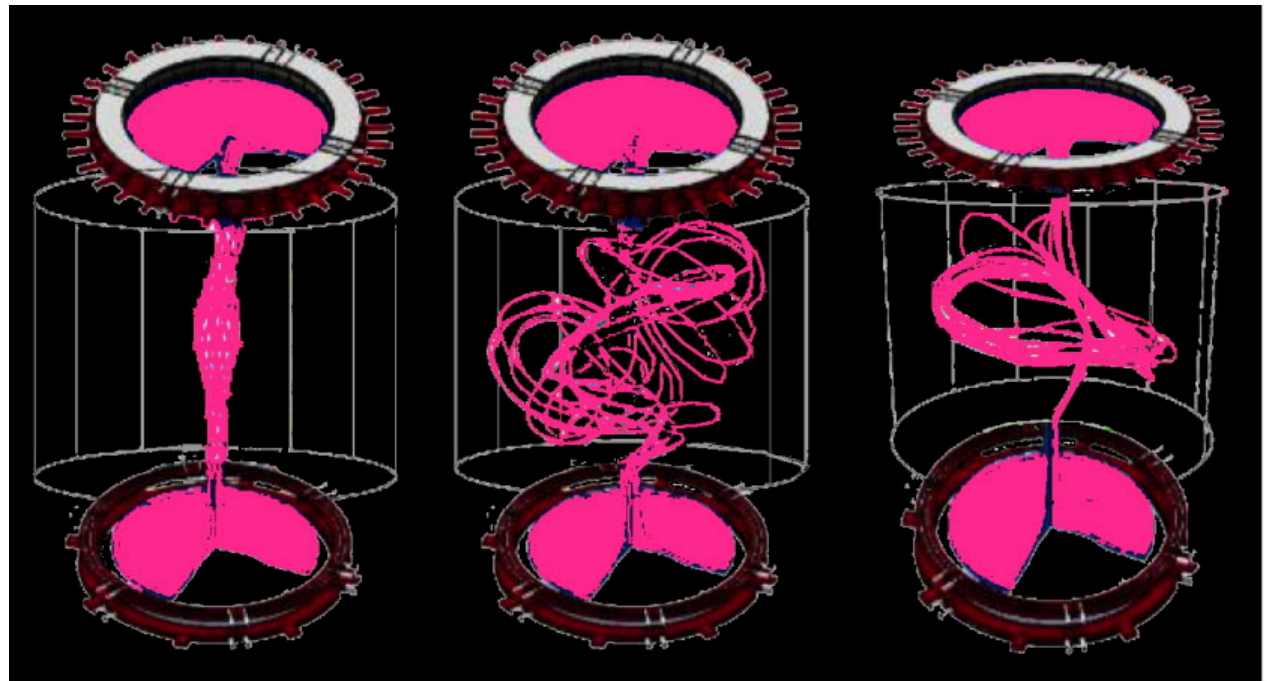
It is a huge power into such a small plasma
...however how much will go into
the confining Spherical Torus,
through magnetic reconnections?

No one is able to predict:

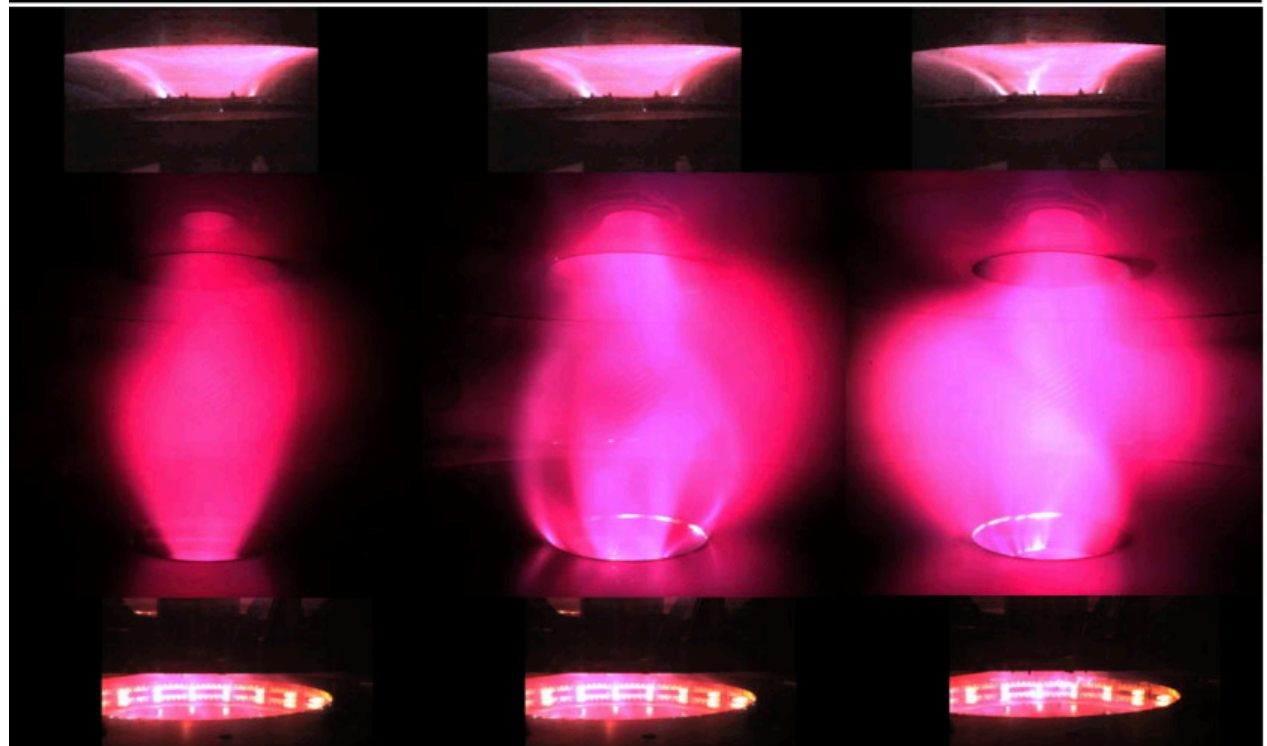
- should it be $\sim$ zero, then ST plasma $T = 10 \text{ eV}$
PROTO-SPHERA studies plasma-electrode interactions
- should it be 1 MW, then ST plasma $T = 100 \text{ eV}$
PROTO-SPHERA studies magnetic reconnections
at relevant magnetic Lundquist number, $S=10^4$
- should it be many MW, then ST plasma $T = 1 \text{ keV}$
... $\beta \sim 1$!
...would do as a Tokamak, but at 1/100 of the cost



Physics Design 1997-2008



Experiment 2018



#985, 10 kA Hydrogen

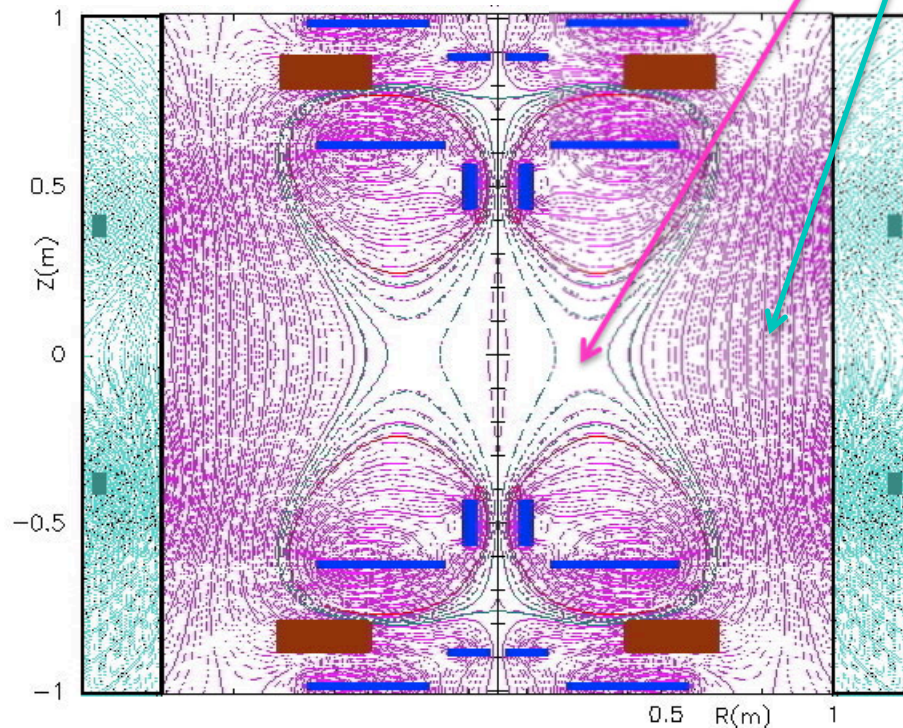
Discharge seems willing to eject a Spherical Torus
...and willing to do that at ease (on a timescale of ~ 10 ms)

Why not help it?

Providing:

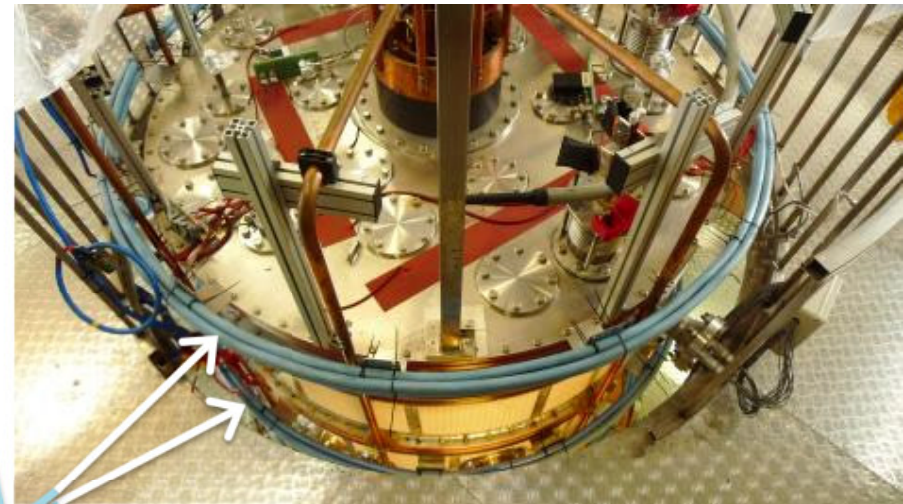
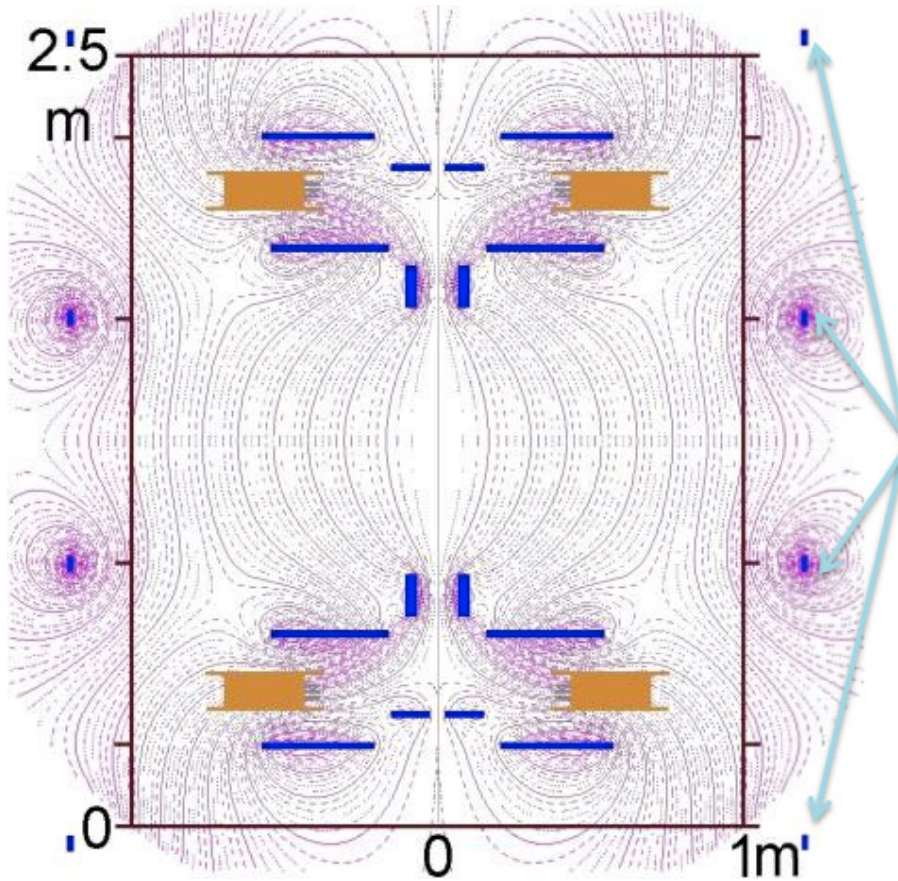
- in proximity of the Centerpost
an X point trap?
- a vertical field to close the trap?

#985, 10 kA Hydrogen
 $\frac{1}{4}$ poloidal B field



Impromptu External PF coils

4 external impromptu PF coils were added (home-made from spare connection cables)
...and fed in series with the internal PF coils (PF coils power supply has sufficient margin)



4 external PF coils

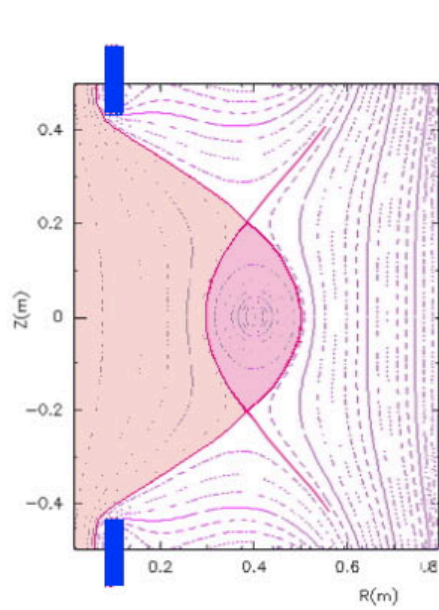
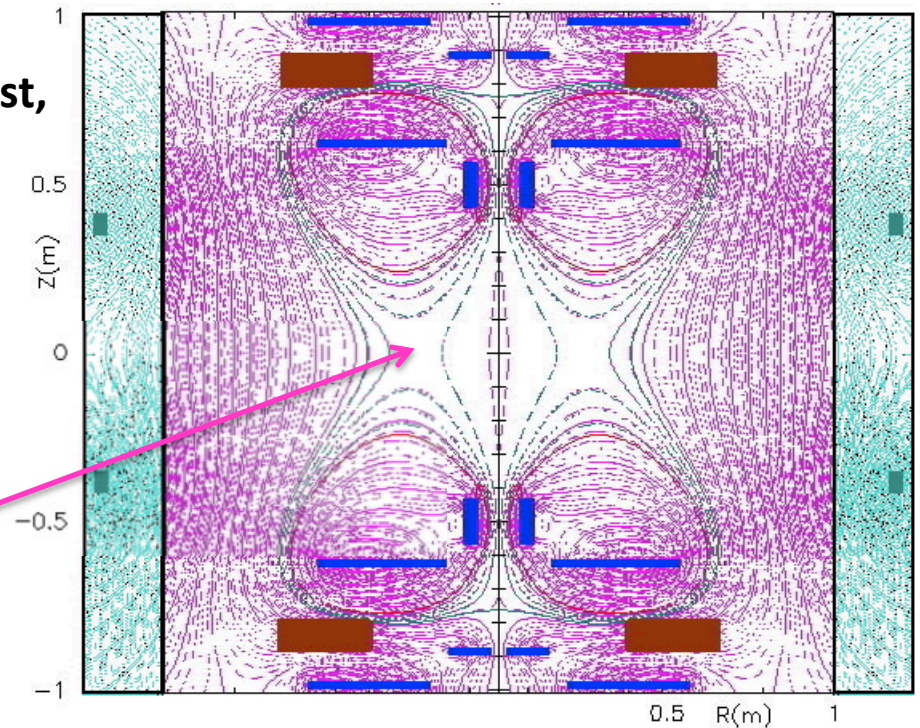


Plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids
A new Super-capacitor Power Supply for the impromptu External coils is now available!

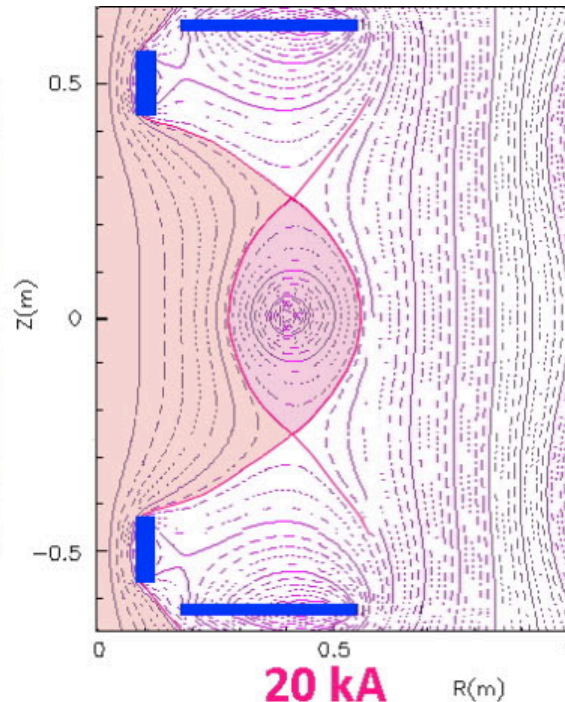
We shall try and destabilize the Plasma Centerpost, with 10 kA plasma current and $\frac{1}{4}$ poloidal B field: in order to produce a Plasma Torus, we shall use the 2 the impromptu external PF coils nearer to the equatorial plane, 8 turns each, fed in series with the internal PF coils.

We shall have to wait for $\sim 0,7$ s to exhaust the skin effect in the Aluminum vacuum vessel.

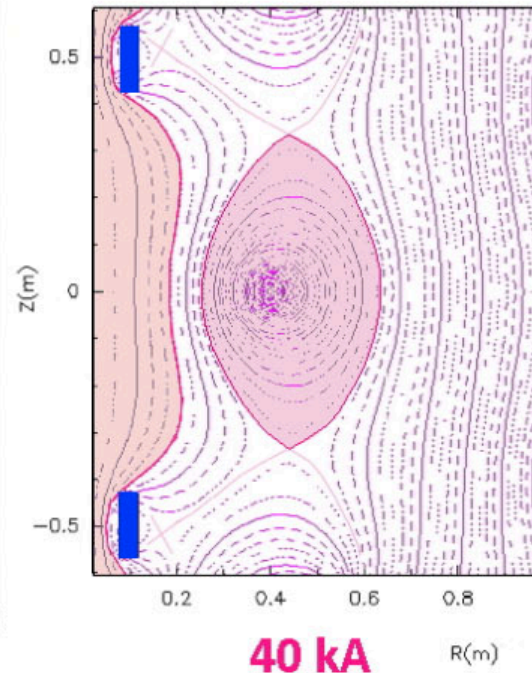
Will the plasma slowly fall into the trap?
With some luck a 20 kA toroidal current could be obtained in an aspect ratio $A=3$ torus...



10 kA

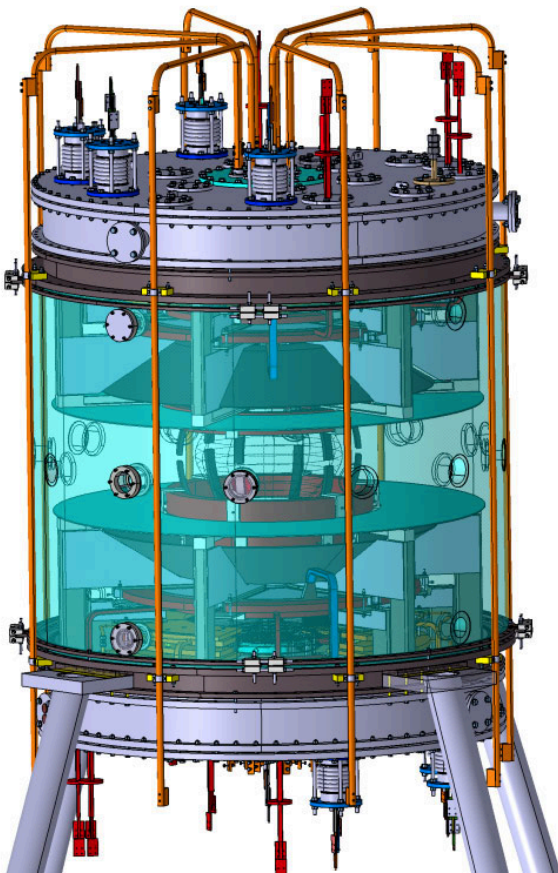


20 kA



40 kA

When the **new PMMA vacuum vessel** will be part of the machine (end of 2018) no skin current will be present and the torus formation will be attempted by feeding **the 2 the impromptu external PF coils nearer to the equatorial plane** by the **new (December 2017) Super-Capacitor power supply**



Phase 1 of PROTO-SPHERA has achieved its aim of driving the full current of the power supply (10 kA) in a Hydrogen Plasma Centerpost

ENEA has inserted PROTO-SPHERA in its 3-years plan (2018-2020):

In **2018** the new **PMMA vacuum vessel** will be built and will be inserted

In **2018** the full **Phase 2 cathode materials (Mo clamps and W filaments)** will be built (increasing x 6 their actual number, to provide $I_e = 60$ kA)

In **2019 and 2020** the existing **cathode heating power supply will be upgraded** to care for **the full Phase 2 cathode**

In **2019 and 2020** the **Group A PF coils** (vertical field) will be built

In **2019 and 2020** the **new Super-Capacitor power supply** will be upgraded to feed the **Group A PF coils**

In **2019 and 2020** a new **Super-Capacitor power supply** able to feed 60 kA to the Phase 2 Plasma Centerpost will be built

In the meantime we shall measure profiles of electron density, temperatures and plasma motions by spectroscopy, validate the modelling of the actual Plasma Centerpost ...and even try to produce the first Torus