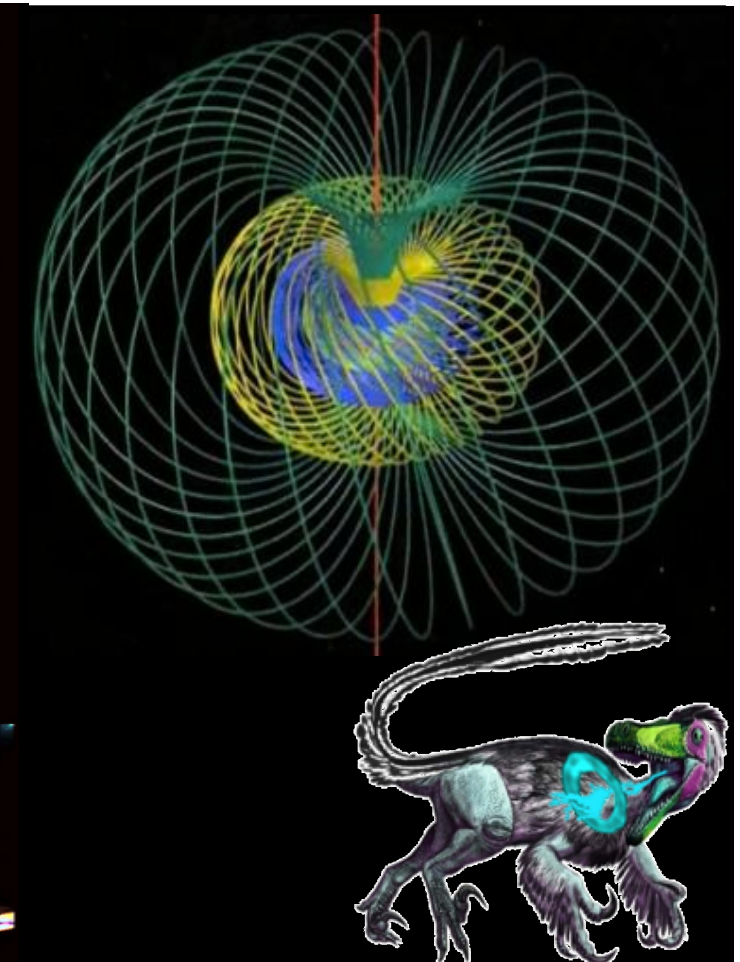
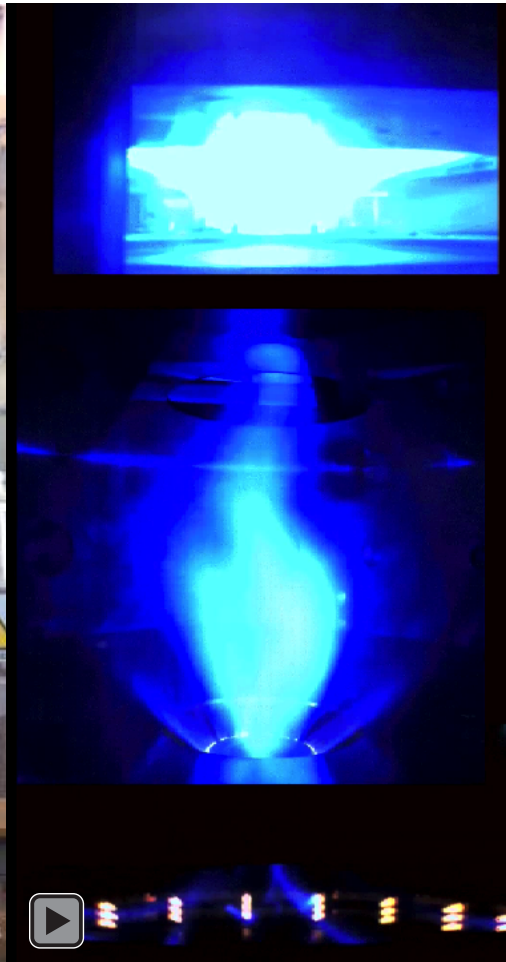


# Obtainment of the Phase1 full performances in PROTO-SPHERA and future perspectives of the experiment



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# PROTO-SPHERA concept

Substitute the Spherical Tokamak central rod with a Screw Pinch plasma ( $I_{TF} \rightarrow I_e$ )

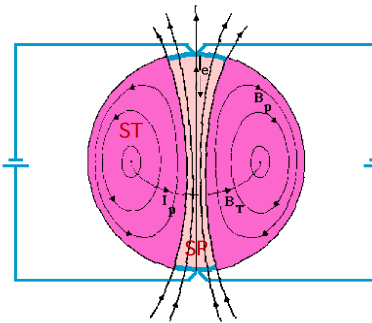
Potentially two conventional ST problems solved:

- Simply connected configuration (no conductors inside)
- $I_p$  driven by  $I_e$  (Helicity Injection from SP to ST)

## Flux Core Spheromak (FCS)

Theory: Taylor & Turner, Nucl. Fusion 29, 219 (1989)

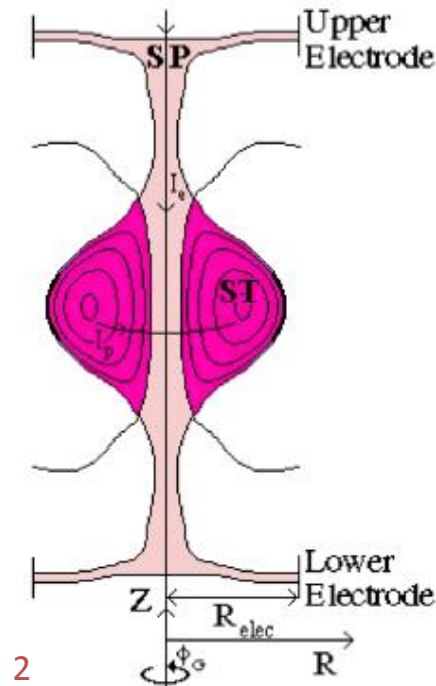
Experiment: TS-3; N. Amemiya, et al., JPSJ 63, 1552 (1993)



## But Flux Core Spheromaks are:

- injected by plasma guns
- formed by ~10 kV voltage on electrodes
- high pressure prefilled
- with ST safety factor  $q \leq 1$

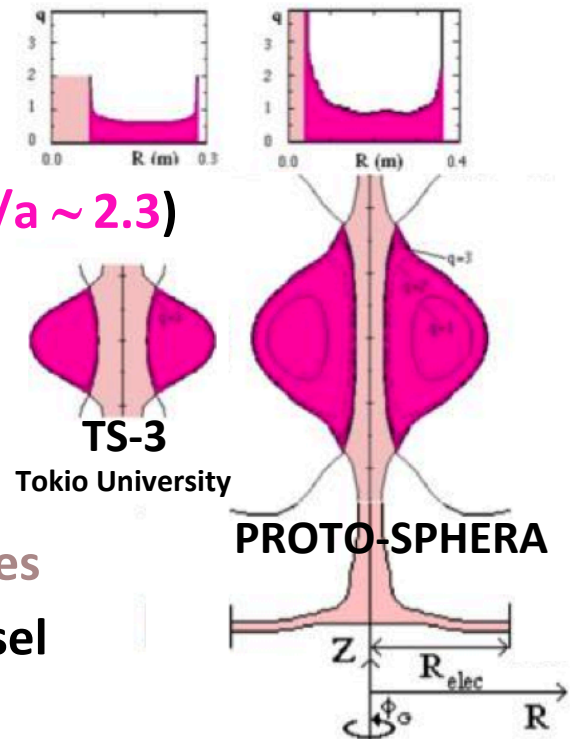
## PROTO-SPHERA key differences:



- Designed for a Tokamak-like field-line rotational transform ( $q_0 \geq 1$ ,  $q_{edge} \sim 3$ ) (aspect ratio  $A = R/a \geq 1.2$ , elong.  $k = b/a \sim 2.3$ )

- PROTO-SPHERA formed “slowly” as a prolated low aspect ratio Spherical Torus from the pre-existing plasma centerpost, mushroom-shaped in front of electrodes

- At low voltage (~100 V), inside big vessel





# PROTO-SPHERA

Centerpost current

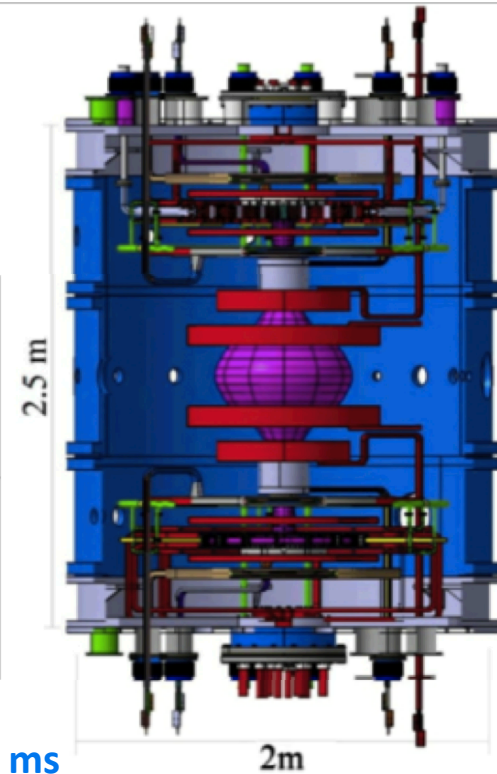
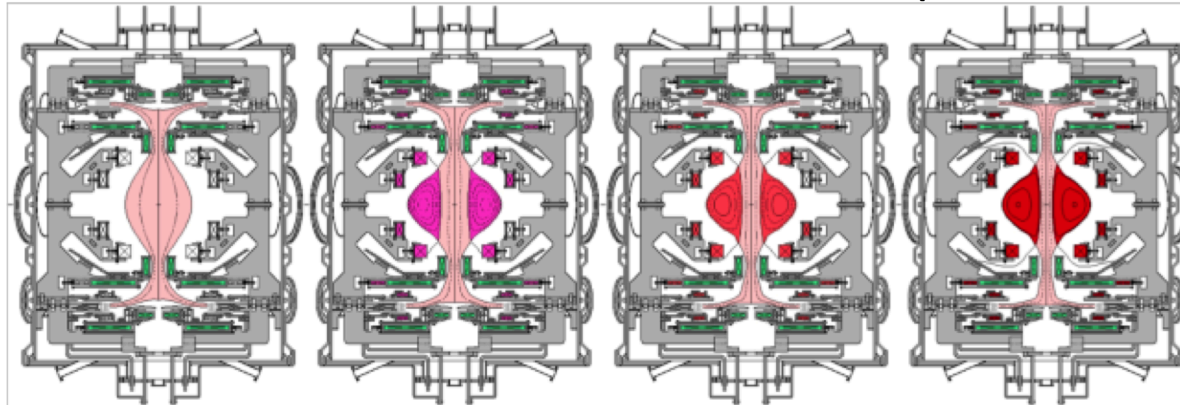
$I_e = 60 \text{ kA}$

ST toroidal current

$I_p = 120 \div 240 \text{ kA}$

ST diameter

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

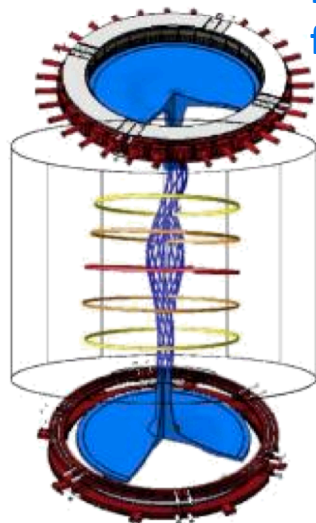


## Axisymmetric simulation of ST formation

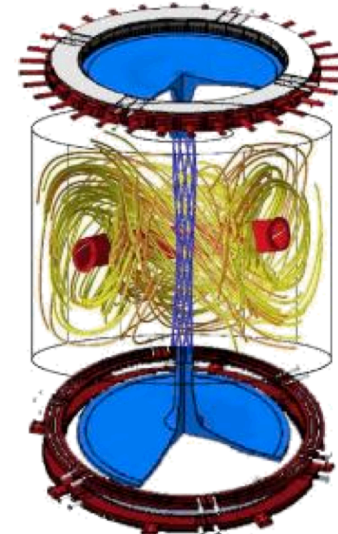
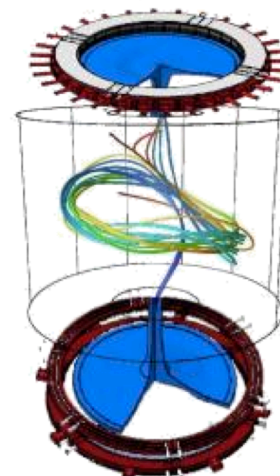
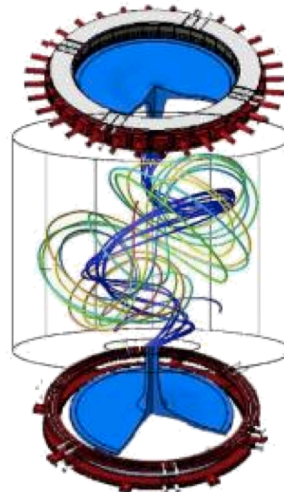
Formation time scale  $(\tau_{\text{Alfvén}} \cdot \tau_{\text{Resist}})^{1/2} \sim 0.6 \text{ ms}$

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

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



*Resistive MHD  
simulations of  
ST formation*



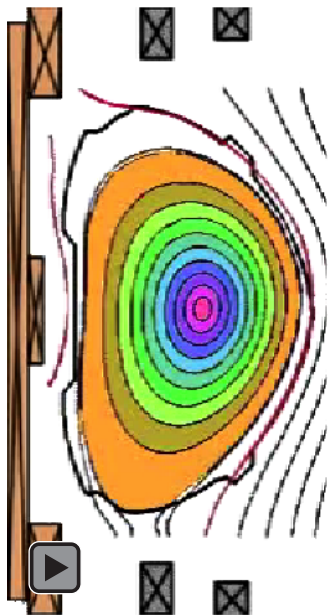
## Non-axisymmetric simulation of ST formation

Garcia-Farengo, PoP 16,112508 (2009)  
and  
Ricardo Farengo, ISTW2008 - Frascati

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# SUSTAIN THE CONFINING CURRENT: by DC voltage from anode to cathode

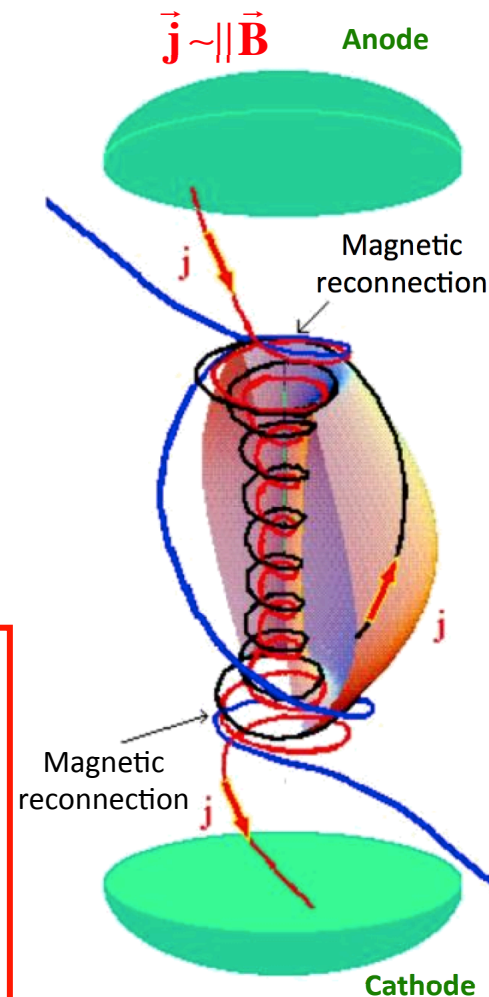
- In front of the electrodes:  
**open magnetic field lines,**
- Open magnetic field lines are wound  
in a circular direction
- Magnetic reconnections convert  
open  $\vec{B}$  lines  
into closed  $\vec{B}, \vec{j}$  lines  
**wrapped around the Spherical Torus**



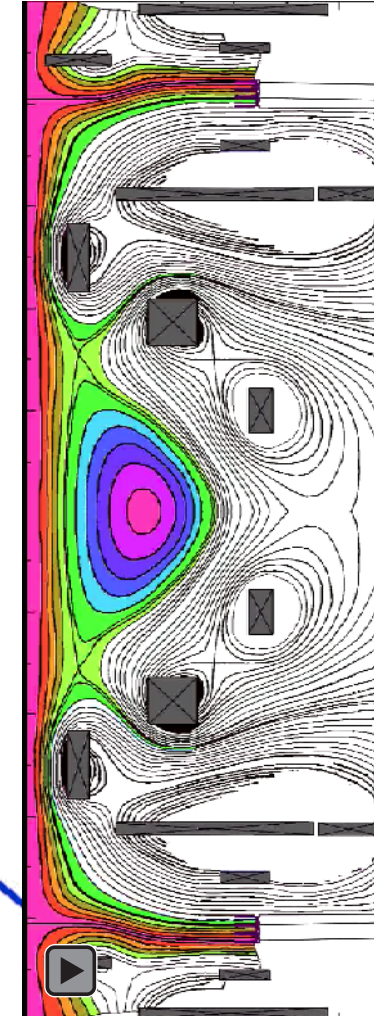
## Critical points of PROTO-SPHERA:

- $I_{ST} = 240$  kA ( $4 \times I_e$ ) really achievable?
- Can it be sustained by Helicity Injection  
for at least  $\tau_R \sim 70$  ms?  
(machine designed for 1 sec sustainment!)
- Resistive MHD stability & confinement?

$\vec{E}$  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**



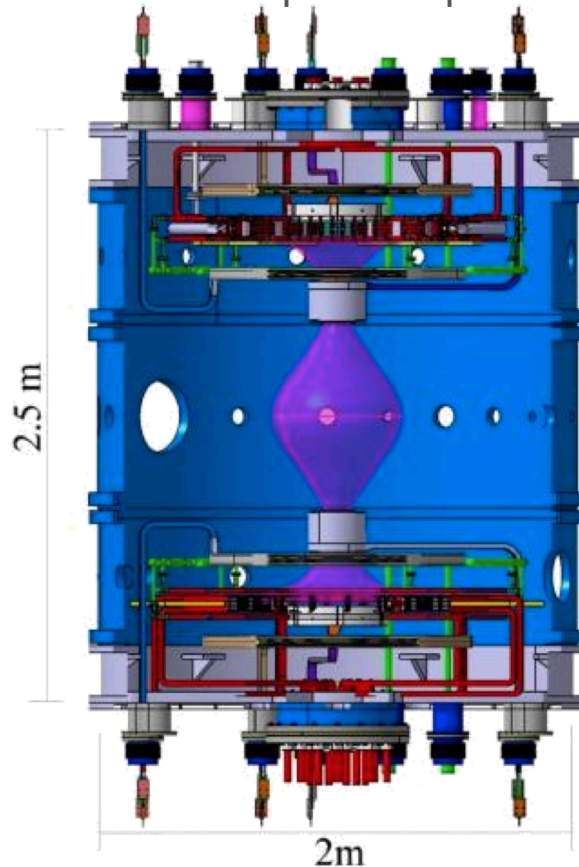
← HOW EFFICIENT THE SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS? →



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

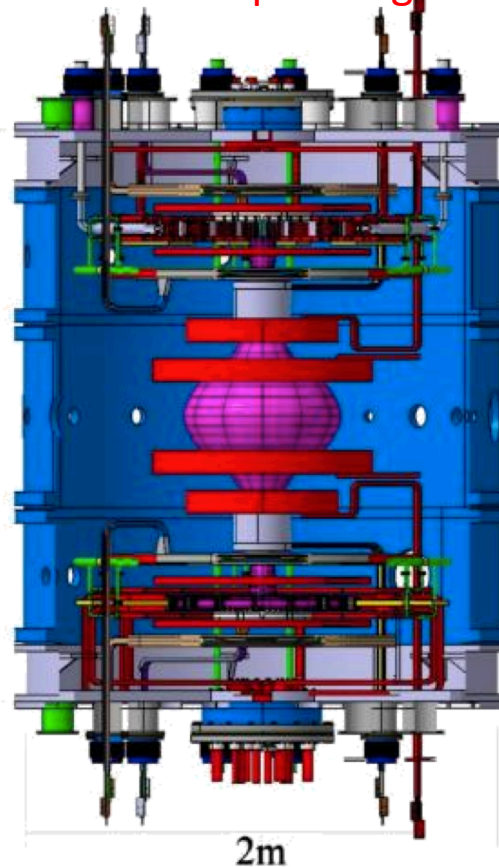
- **Phase 1:** demonstrate Plasma Centerpost's feasibility
- **Phase 2:** machine completed such as to produce the Spherical Torus

**Phase1:** 8 PF coils  
Centerpost shape



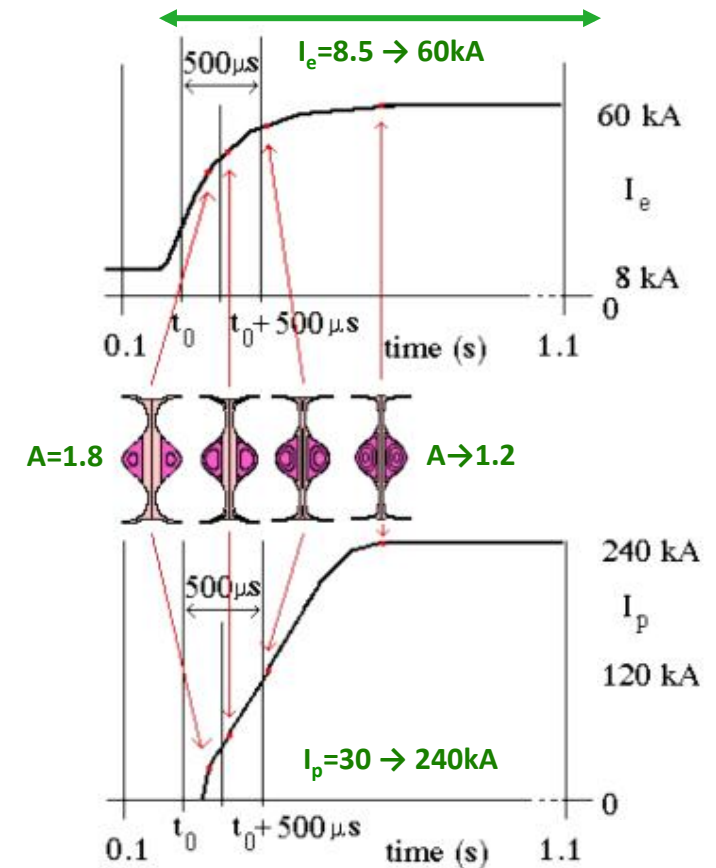
SP centerpost current  $I_e = 8.5$  kA  
No ST toroidal current

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



SP centerpost current  $I_e = 60$  kA  
ST toroidal current  $I_p = 120 \div 240$  kA

**ST compression**



Cylindrical vacuum vessel was START vacuum vessel, donated by Culham in 2004  
**from Culham the old vacuum vessel found its road to Frascati**



**PROTO-SPHERA was built (2006-2009) by ASG Superconductors of Genoa, cost 1 M€**



**Years 2004 - 2010:**

*...from ideas ...to detailed design*

*...to hard metal*

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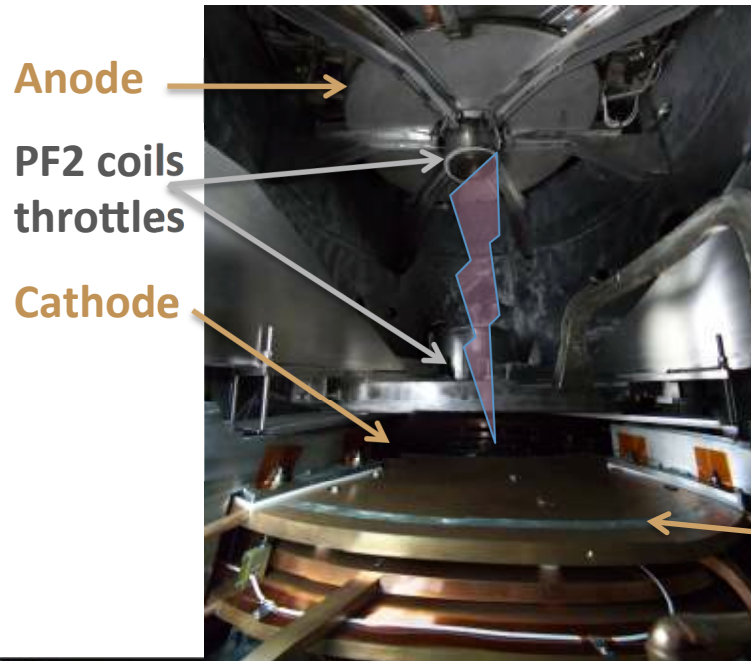


## PROTO-SPHERA POWER SUPPLY

To fire the **plasma centerpost (Phase1)**

**3 Power supplies** are required

- **Cathode heating** rotating 6-phase: 6 x(1.7 kA,25 V) rms (18 modulus i.e. 1/6 with respect to Phase2)
- **PF coils:** 2kA, 350 V DC current
- **Plasma centerpost:** 10 kA, 350 V DC current



**Cathode**



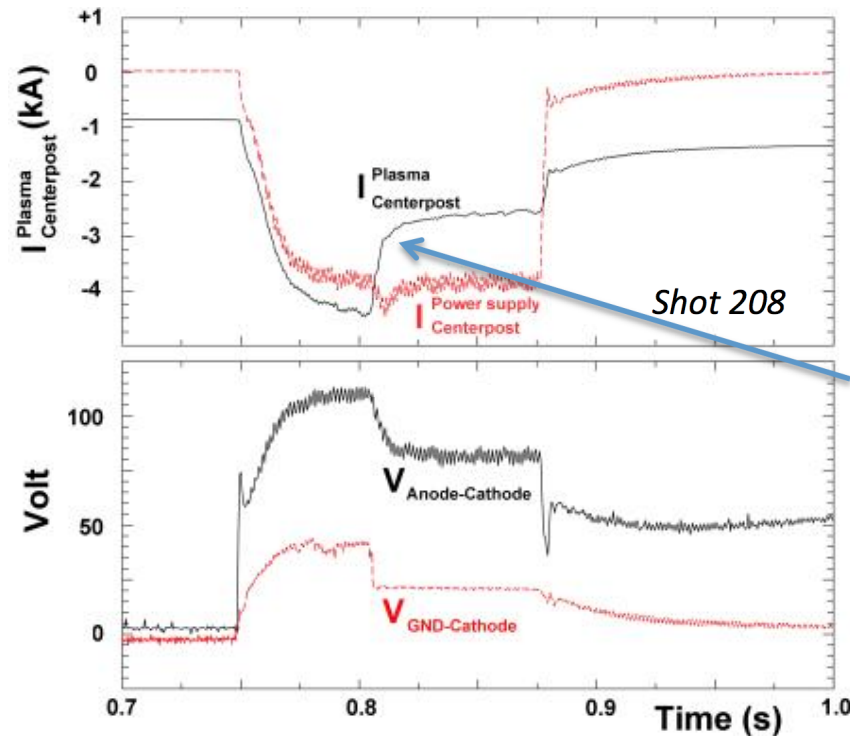
**Years 2011 - 2014:** 



October 2015 / January 2016  
experiments with external PF coils:

Status of art at EPR2016

Plasma current outer paths for  $I > 3.5$  kA



Argon plasma aiming to 4 kA reaches 3.5 kA

~ 1.5 kA lost from main plasma

in discharge from cathode down to lid\ vessel

plasma fired after 0.75 s of PF current  
(skin current time to remove X-point from inside vessel)

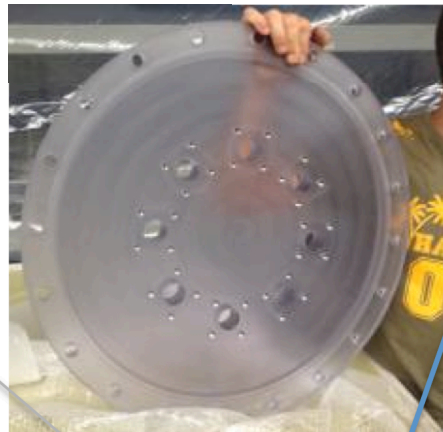
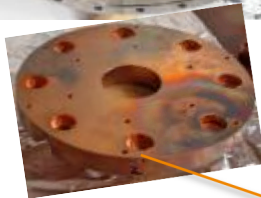
Also the Cathode emission lowers after 1.5 kA are lost





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

On the top (near anode) a SS flange, pierced by 8 bus-bars, such a flange substituted by a **4 cm thick Polycarbonate one**

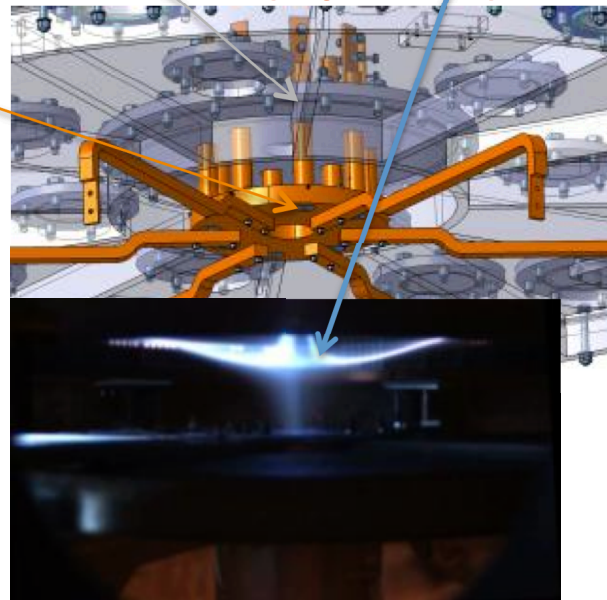
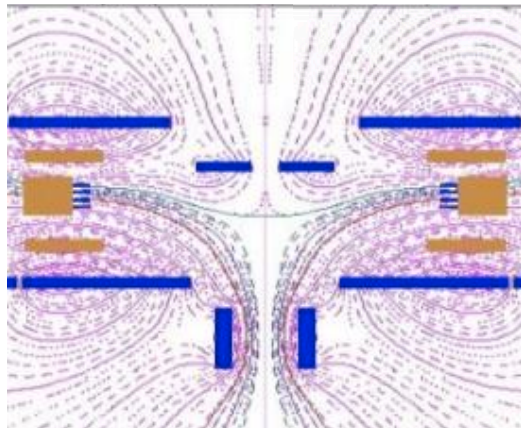


**Bus-bars (top-anode)**

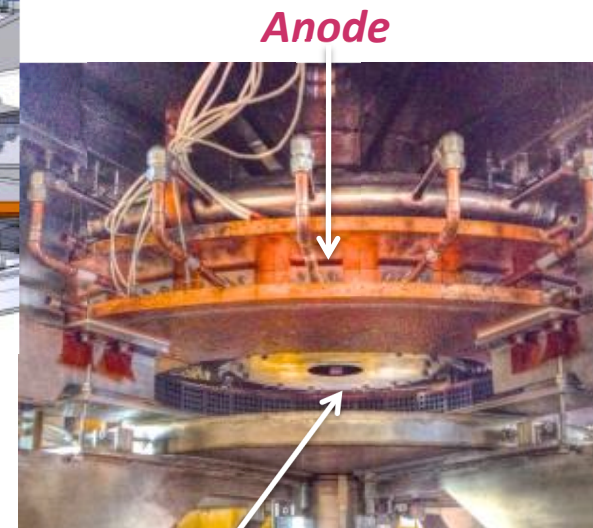


*Top flange view from plasma side*

*Geometry of magnetic nozzle*



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*Anode*

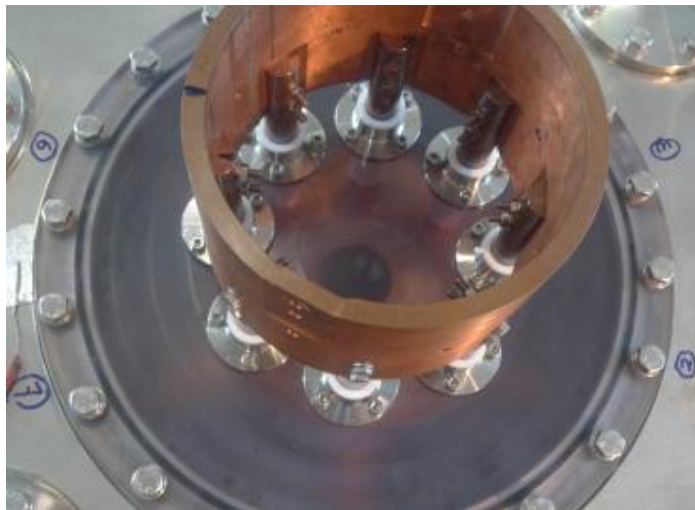
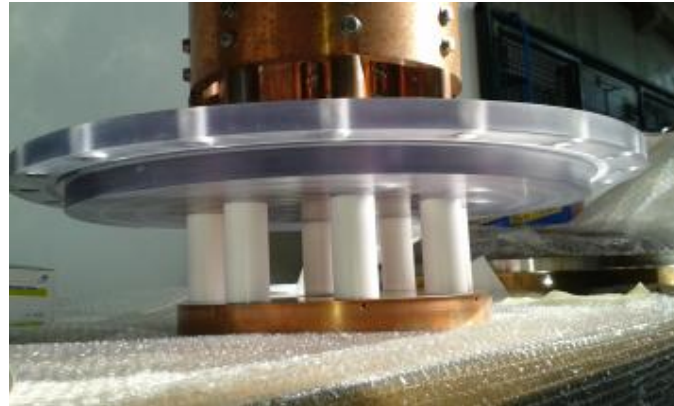
*Anode exit of*

**June 2016:** insertion of Polycarbonate (transparent) anode bus-bar flange on top of machine

*Heavily metallized*  
*top & bottom bus-bar flanges*

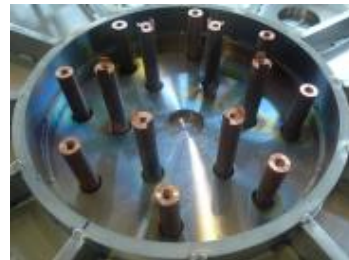


4 cm thick Polycarbonate  
(required by atmospheric pressure)





At the bottom (near cathode) a SS flange, pierced by 14 bus-bars, such a flange has been substituted by a **Polycarbonate** one



**July 2016: Polycarbonate flange on machine bottom**



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## Secondary discharges from electrodes hitting Al vacuum vessel wall (plenty of scars!)

October  
2016



Polycarbonate flanges got rid of all metallization from bus-bars:  
2mm thick Polycarbonate lining covers the Al vacuum vessel

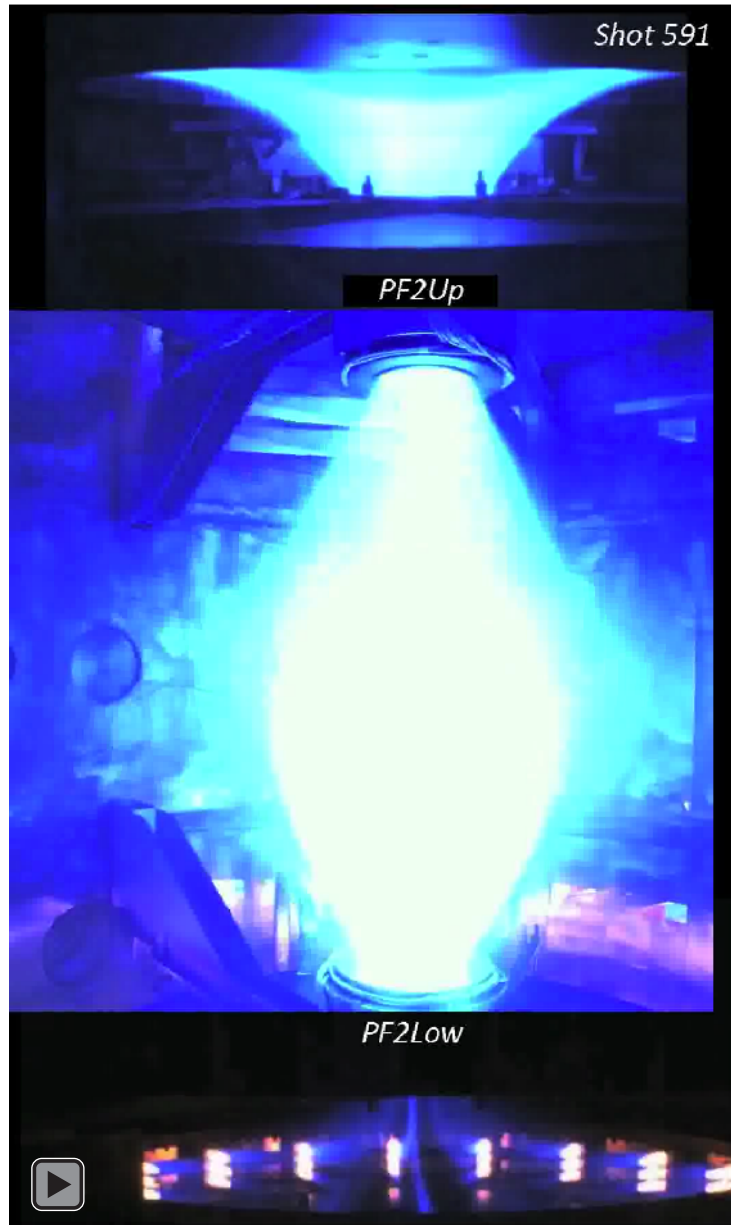


December  
2016



secondary  
2mm thick  
Polycarbonate  
screen  
surrounds  
rear of anode





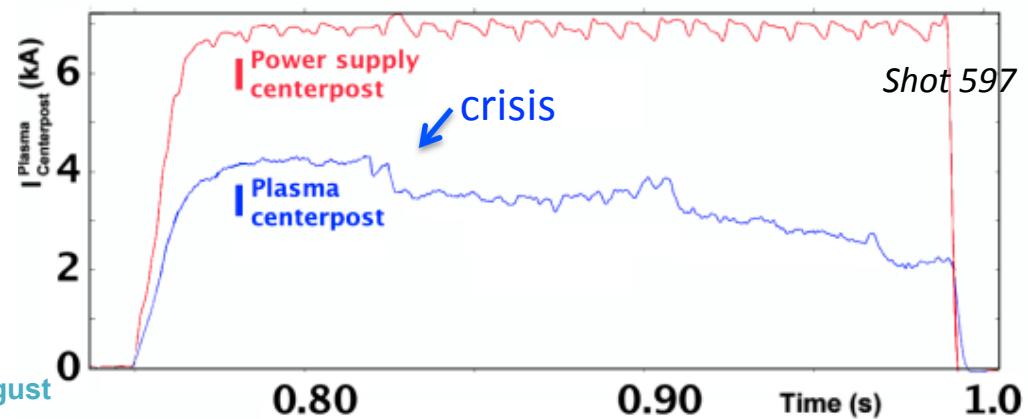
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Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but  
**1) Spurious plasma currents still flow outside the centerpost (albeit inside the vacuum vessel)**

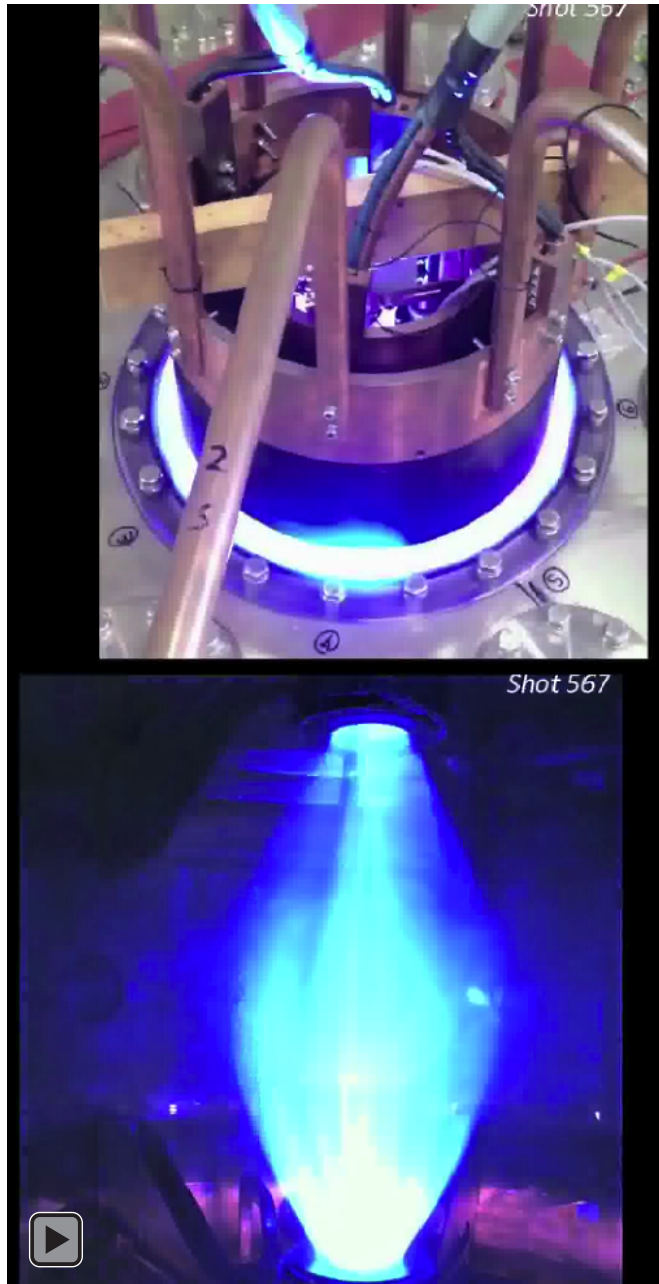
January 2017  
patterns of spurious  
currents are  
either diffused  
or filamentary



**Input 0.6 MW**  
**7 kA from power supply**  
**Centerpost drives 60%**

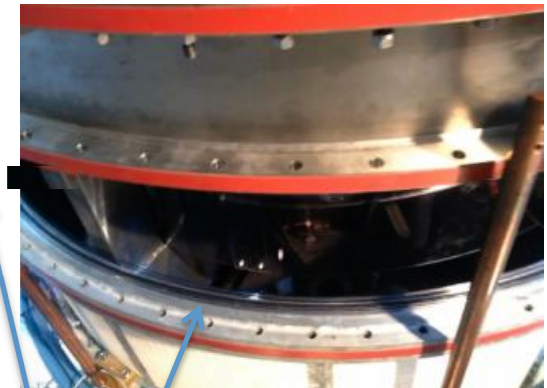
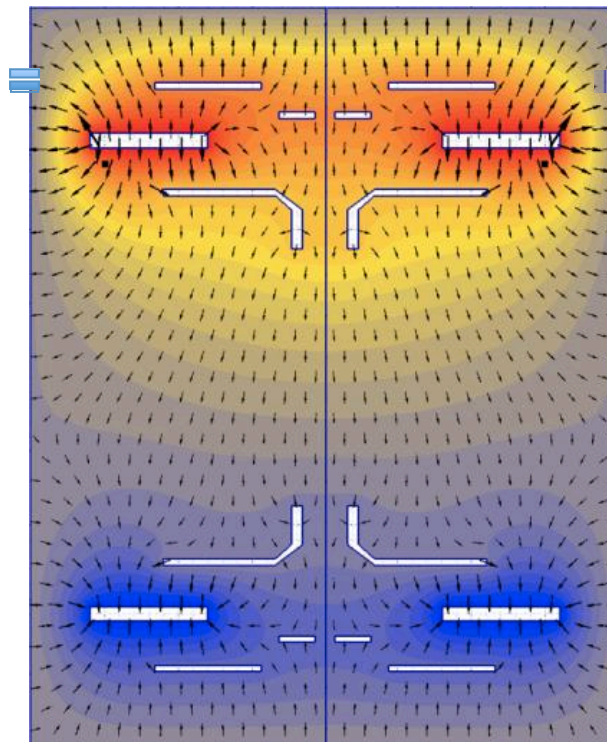


January 2017



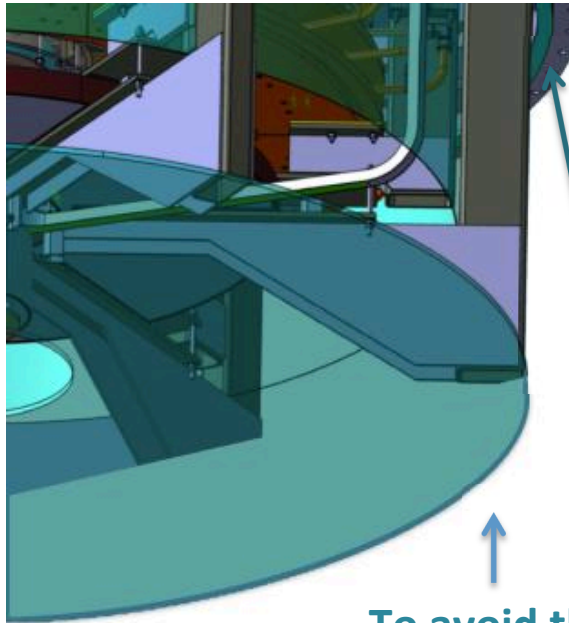
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but 2) in Hydrogen (250 V breakdown) there was still a problem of current through the vessel, this was triggered in Argon (80 V breakdown), connecting the common star potential of the six-phased cathode power supply to the machine GND

Most critical electric field is at contact between SS upper extension & Al vacuum vessel



A spacing insulating ring was inserted in May 2017





to avoid the bus-bar to vessel  
current flow an insulating  
spacer ring has been inserted

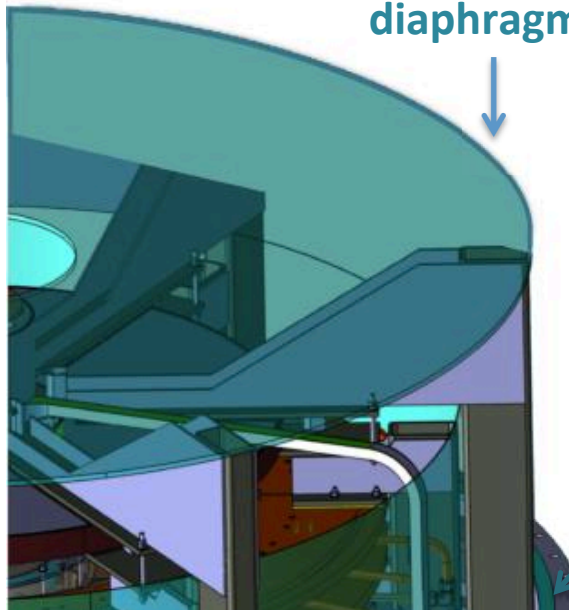


lower  
diaphragm

To avoid the flowing of plasma currents  
outside the desired path of the plasma  
centerpost two large insulating Polycarbonate  
diaphragm separators have been inserted



lower  
diaphragm



**May 2017:** Insertion of  
Polycarbonate lower diaphragm

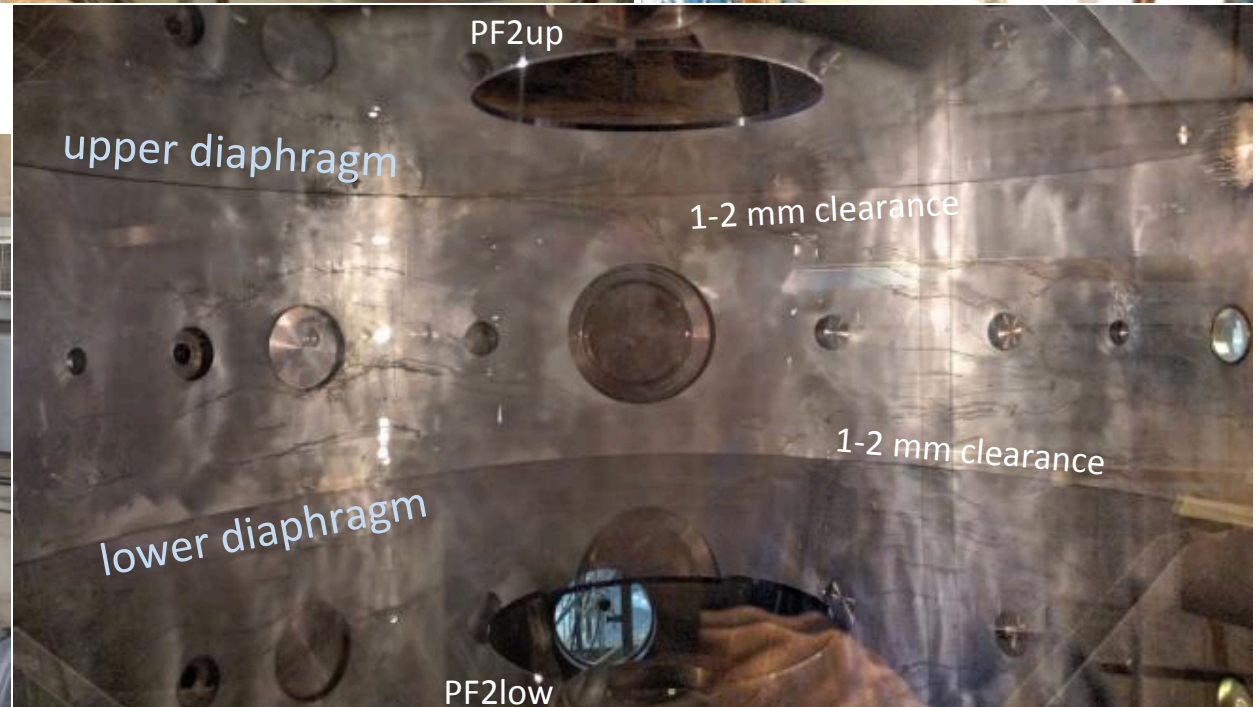
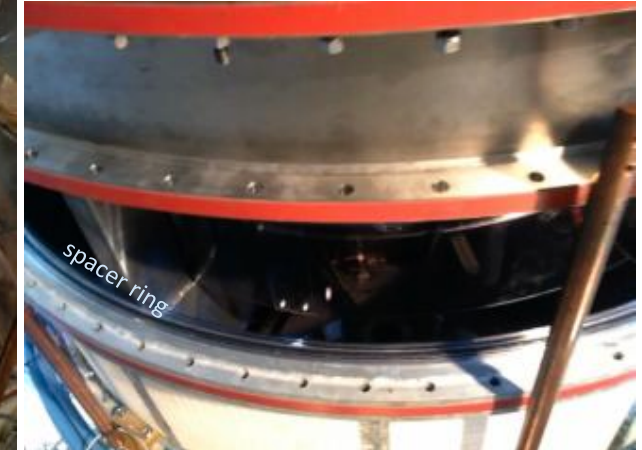
Lower spacer ring not yet inserted



lower  
diaphragm



**May 2017:** Insertion of  
Polycarbonate upper diaphragm  
& Polycarbonate spacer ring





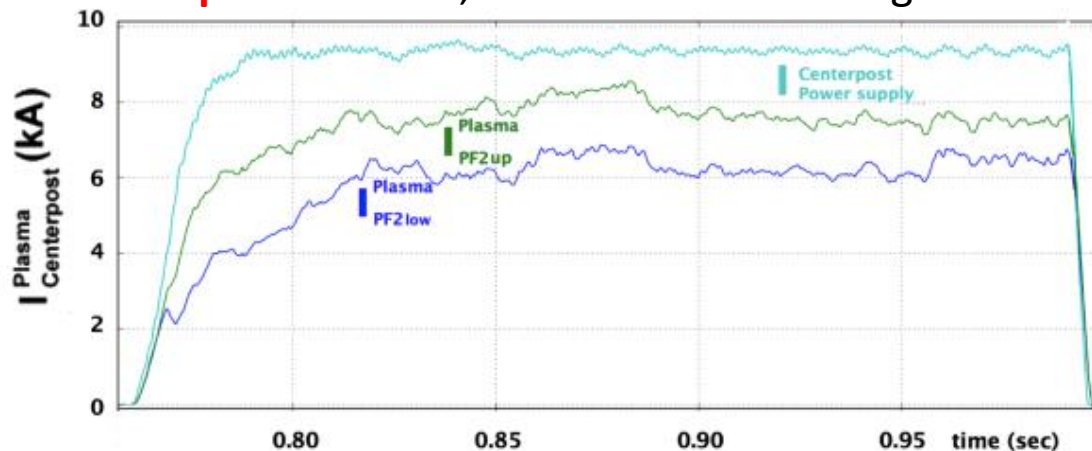
**June 2017** Plasma with Polycarbonate two diaphragms & upper Polycarbonate spacer ring

**High currents (8 kA), external PF coils are on**

*Some spurious and concentrated plasma current still sneaks through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm,*

**Plasma currents with 8.6 kA through PF2 are achieved**

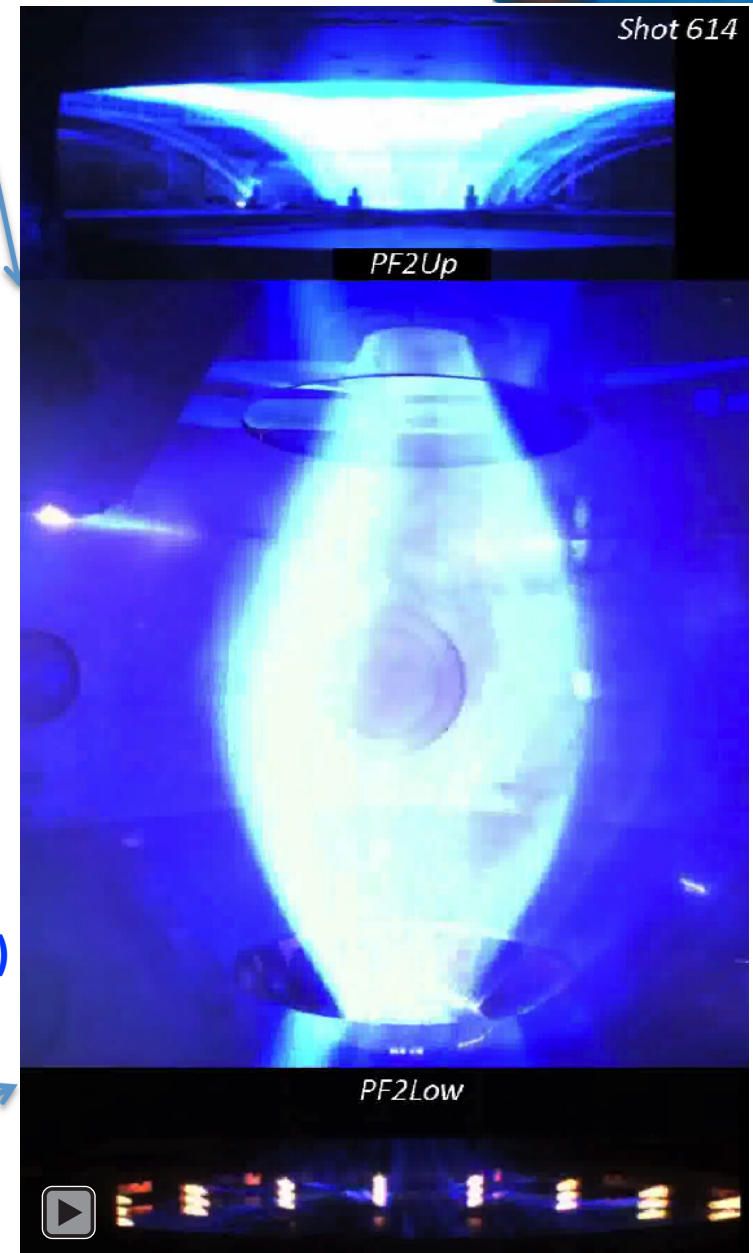
**Power input 1.65 MW**, Anode-cathode voltage 195 V



With currents through PF2 exceeding ~ 6kA the rotational transform of plasma centerpost ( $q \sim 2.5-3$ ) becomes clearly visible...

*The plasma centerpost seems to rotate azimuthally ( $\vec{E} \wedge \vec{B}$ ) in clockwise direction (looking from above) (...the six-phased cathodic rotation is switched off...)*

*The spurious plasma current closes on the outside of PF2low, producing bright filaments:*



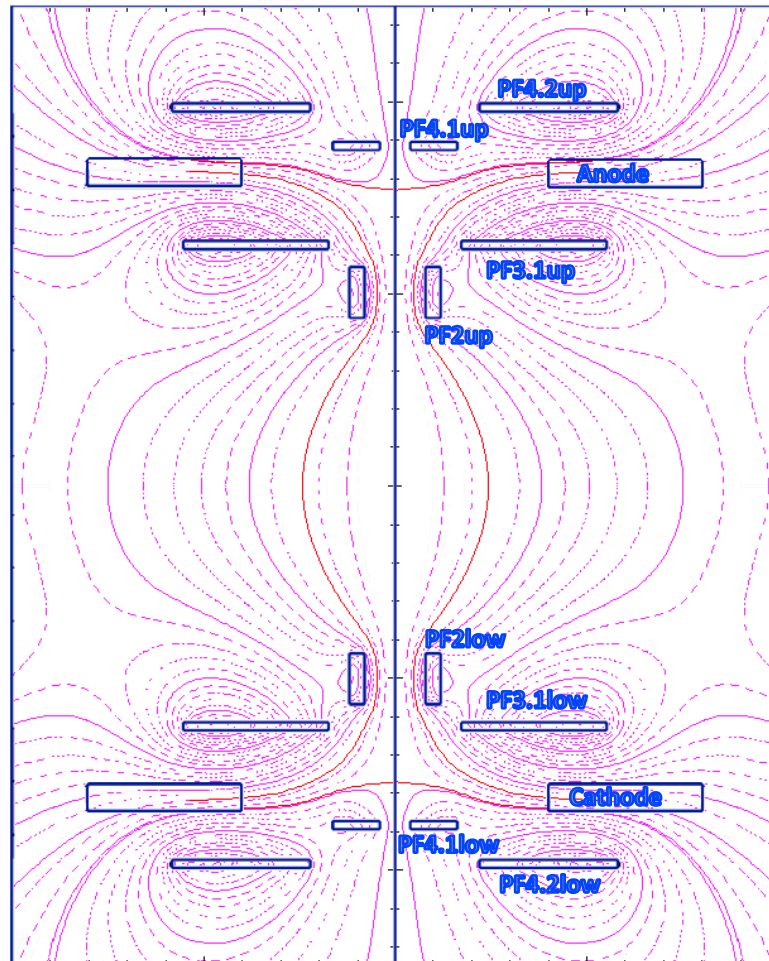
**High currents (8 kA), switching on the external PF coils:** PF coils casings built as floating  
 Electrostatic potential is dominated by the plasma; **PF coils casings better left floating!**  
 Upper lid & extension also better left floating!

**Strong toroidal rotation due to  $\vec{E} \wedge \vec{B}$  prevents any anchoring on Anode!**

through Polycarbonate spacer ring



**upper lid & extension float at 90 V**



$V_{PF4up} \sim 130 \text{ V}$

$V_{anode} \sim +150 \text{ V}$

$V_{PF2-3up} \sim +75 \text{ V}$

Ext.Coil up

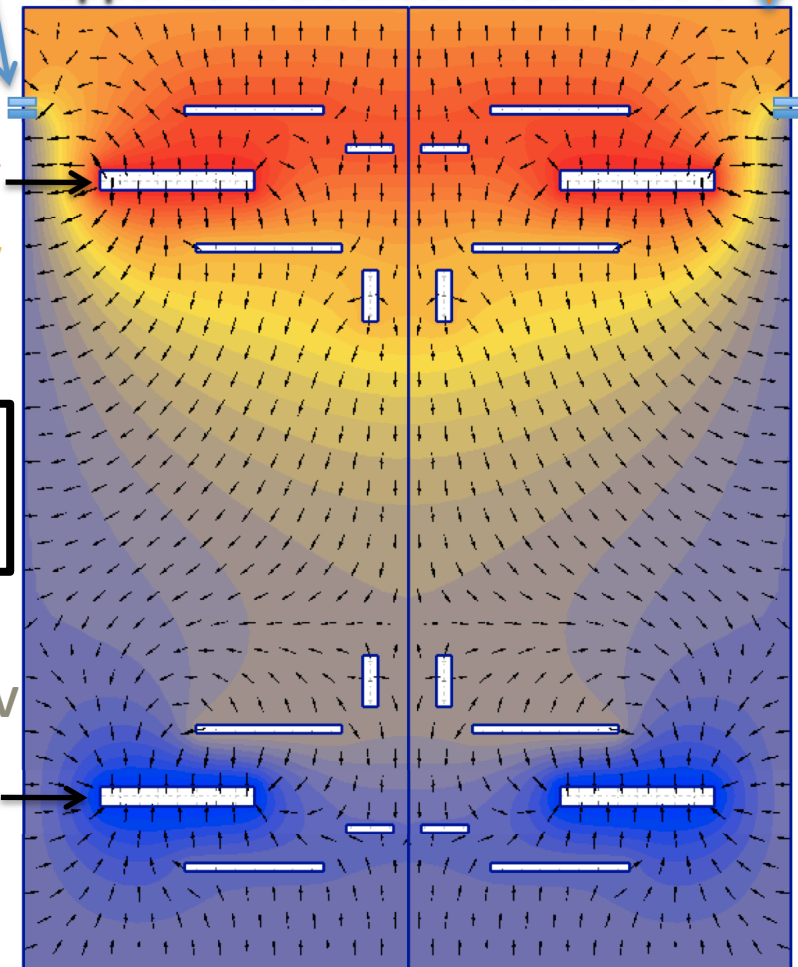
#614 8.6kA Argon  
 Plasma centerpost  
**June 2017**

Ext.Coil low

$V_{PF2-3low} \sim +20 \text{ V}$

$V_{cathode} \sim -45 \text{ V}$

$V_{PF4low} \sim -7 \text{ V}$



**vacuum vessel at GND (0 V)**

**Lines: magnetic field**

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

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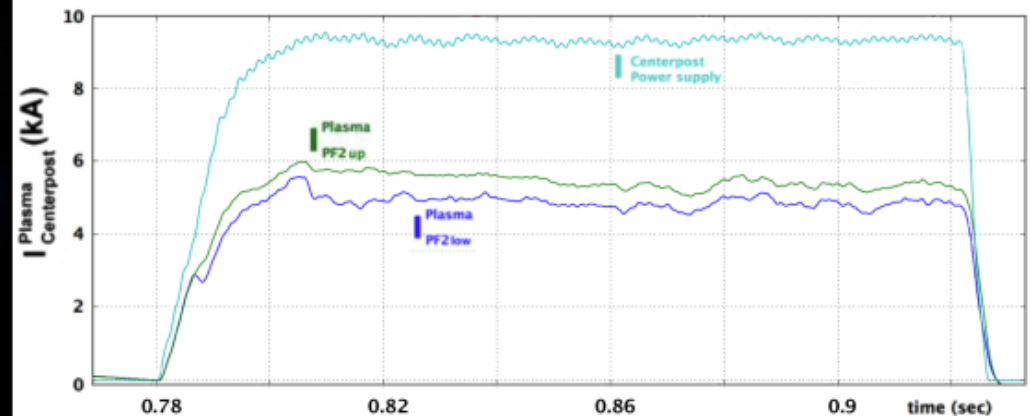


Shot 665

June 2017

**Switching off the external PF coils** it is possible to have a more uniform distribution of the spurious plasma current that sneaks through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm, however in this case the plasma currents through the PF2 coils reduces to  $\sim 6$  kA

It is quite evident that the to the plasma that sneaks through the upper narrow clearance corresponds to the bright filaments on the outside of PF2low, which diffuse towards the clearance



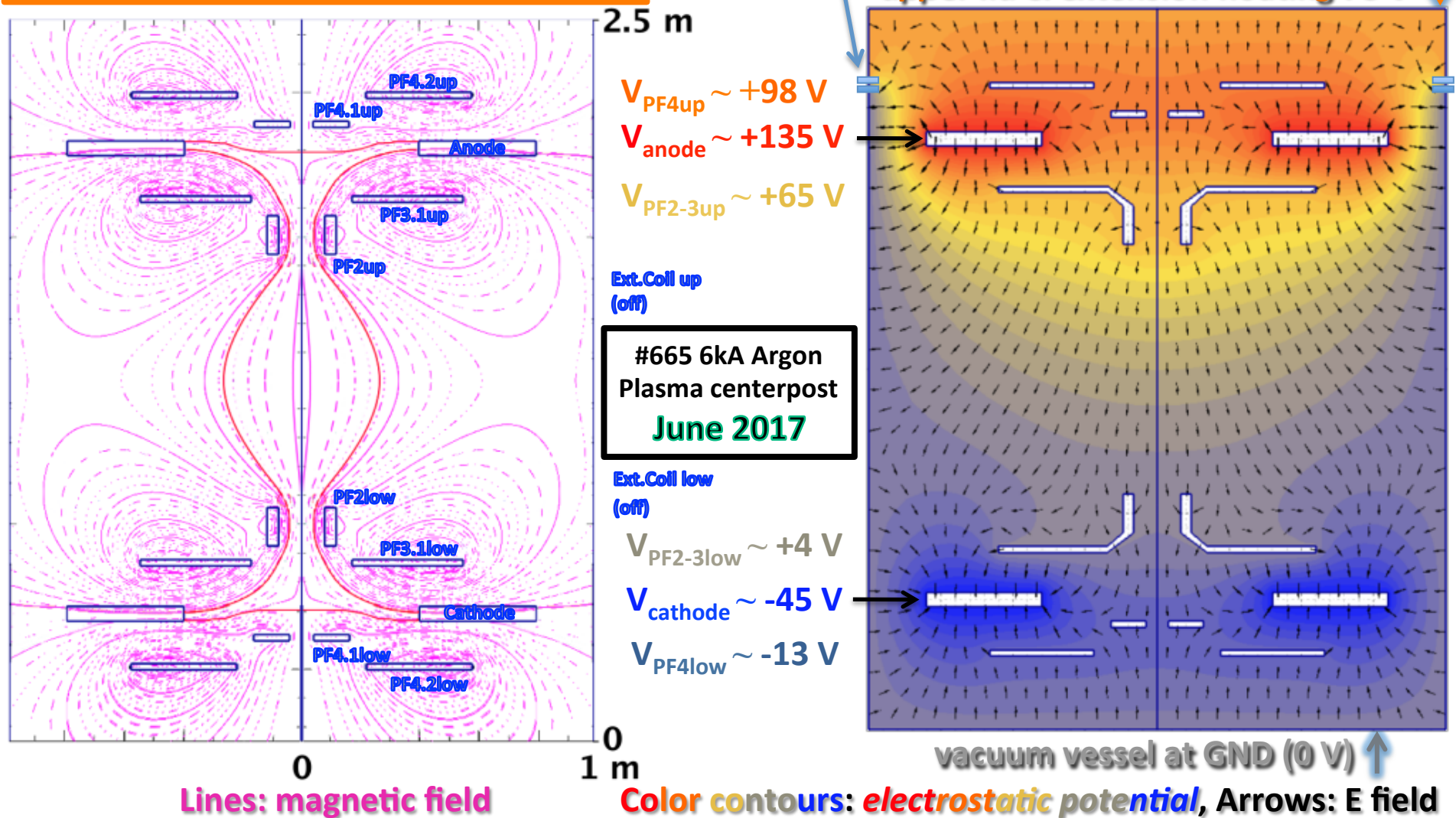
**Lower currents, switching off the external PF coils:** PF coils casings built as floating  
Electrostatic potential is dominated by the plasma; PF coils casings better left floating!

Upper lid & extension also better left floating!



**Strong toroidal rotation due to  $\vec{E} \wedge \vec{B}$  prevents any anchoring on Anode!**

through Polycarbonate spacer ring

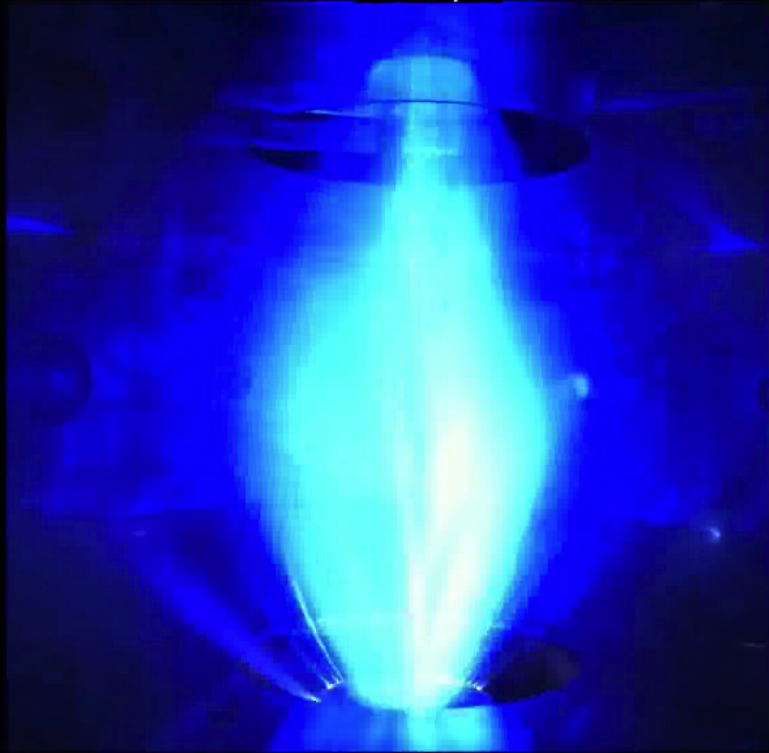




Shot 644



PF2Up



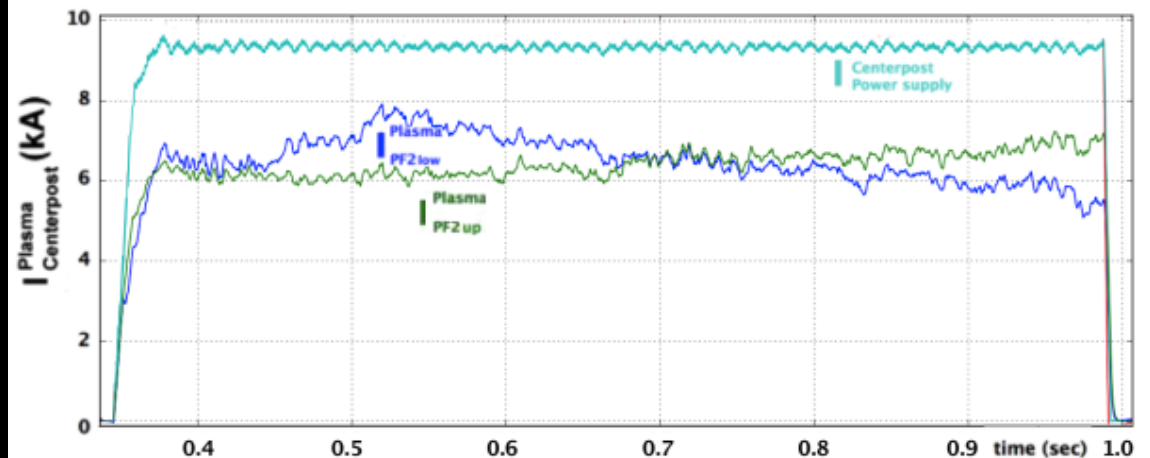
PF2Low



June 2017

**Lower currents, switching off the external PF coils  
0.7 s long discharge**

Switching off the external PF coils, long duration plasma centerposts have been obtained with plasma currents through the PF2 coils  $\sim 6 \text{ \AA } 7 \text{ kA}$



**This plasma centerpost discharge is quite near to the rotational transform value  $\iota \sim \frac{1}{2} \rightarrow (q_{\text{Pinch}} \sim 2)$**

Shot 645



PF2Up



PF2Low



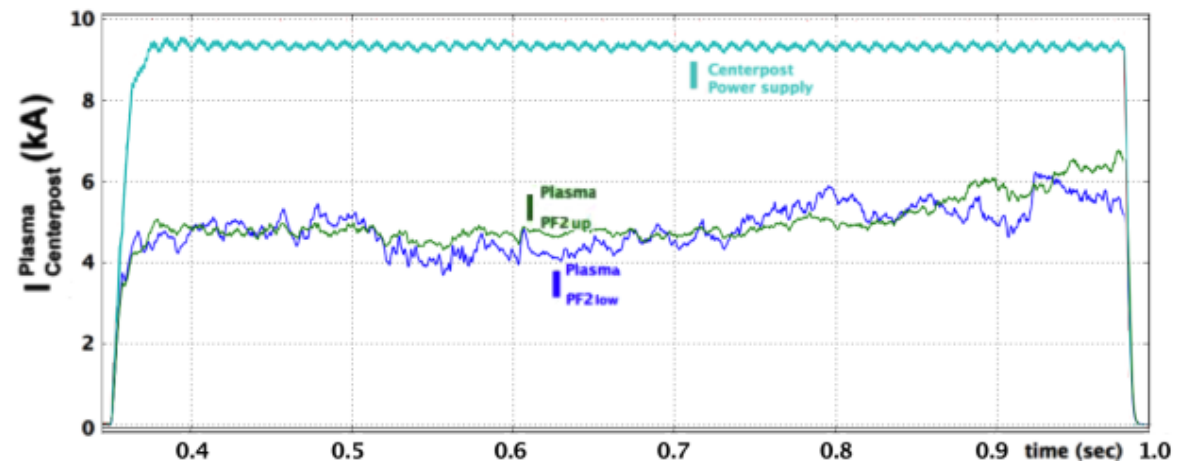
June 2017

## Kink destabilization maintained in 0.7s long discharge

← *The anode plasma wobbles gently*

Reducing by a factor of 4 the magnetic field of the internal PF coils, the plasma centerpost has been destabilized

A long duration kink-bended plasma centerpost has been obtained with plasma currents through the PF2 coils  $\sim 5 \setminus 6$  kA

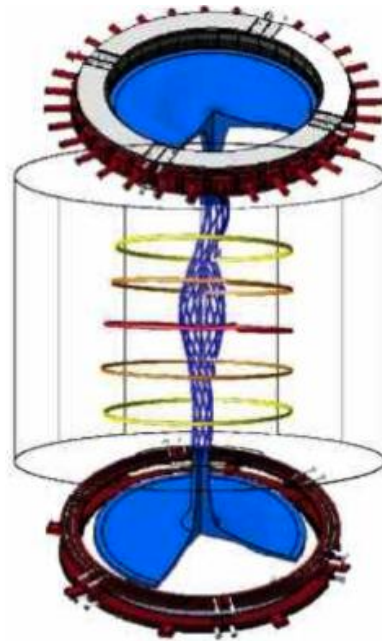


This plasma kink-bended centerpost discharge survives at a rotational transform value  $\iota \sim 1.66 \rightarrow (q_{\text{Pinch}} \sim 0.6)$

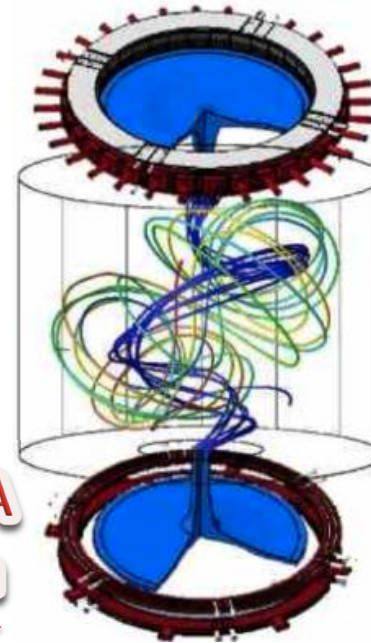
← *Cathode plasma wobbles more than centerpost, but the discharge survives till the DC voltage is applied!*



Physics Design  
1997-2008



PROTO-SPHERA  
destabilization  
←→

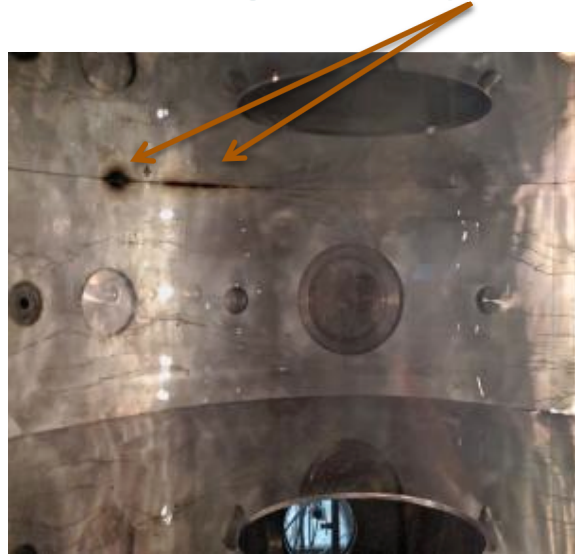


Experiment  
2017



The plasma current sneaking through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm induces damages

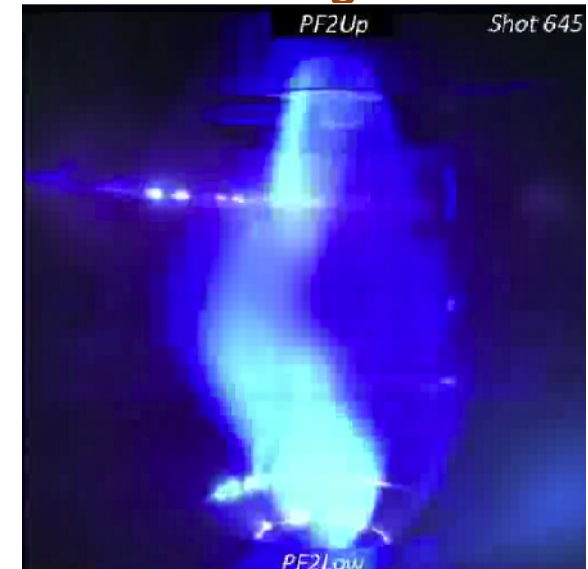
The narrow clearance has to be closed completely by a bonding material able to sustain the diaphragms weight



The port where the polycarbonate lining was cut, in order to allow for vacuum gauges measurements, has to be closed & the gauges moved elsewhere



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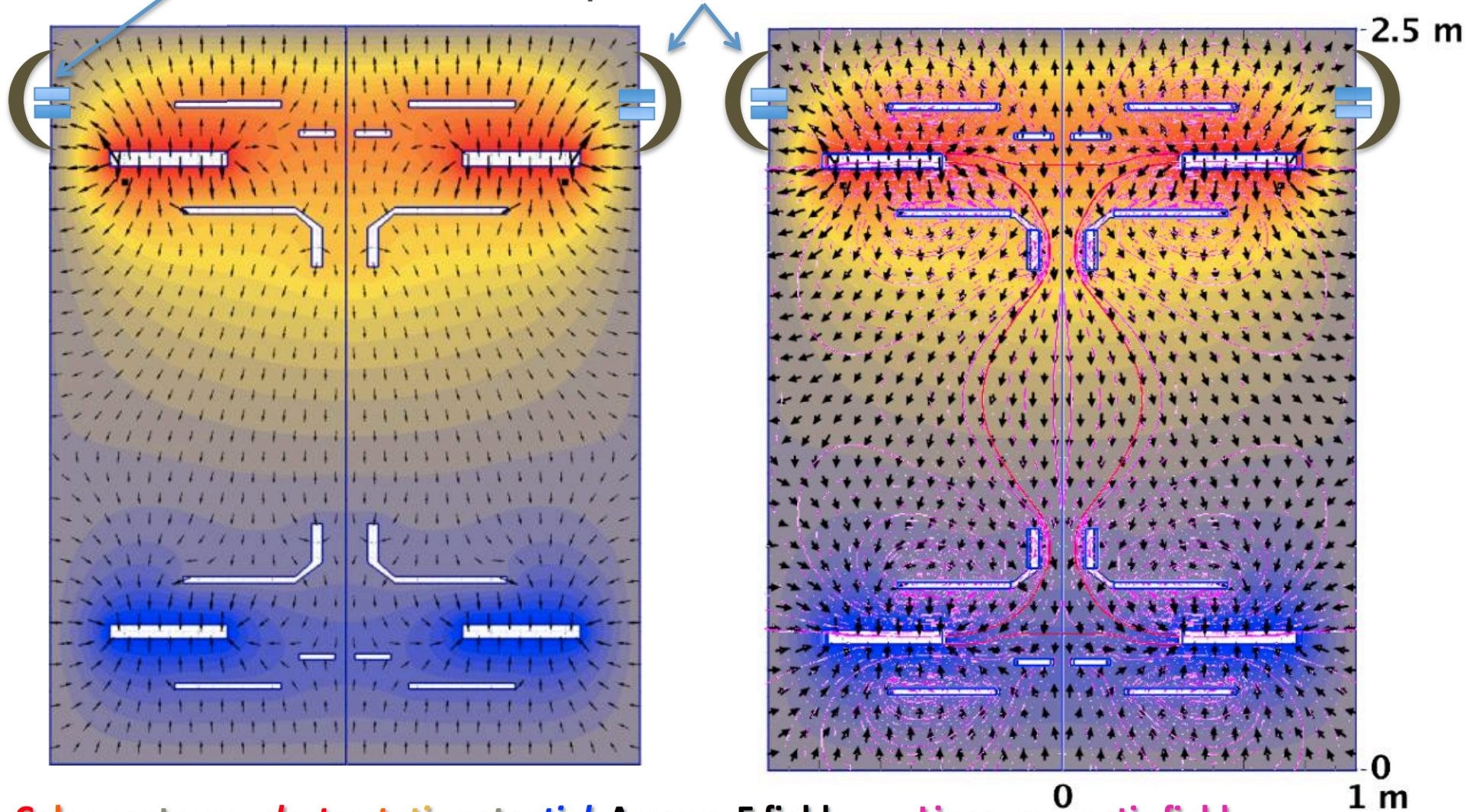




## Disaster if top lid & top extension are not floating!

#649 kA Argon Plasma centerpost (June 2017)

Polycarbonate spacer ring insulating top lid and top extension from vessel (GND)  
have been put back in contact with vessel



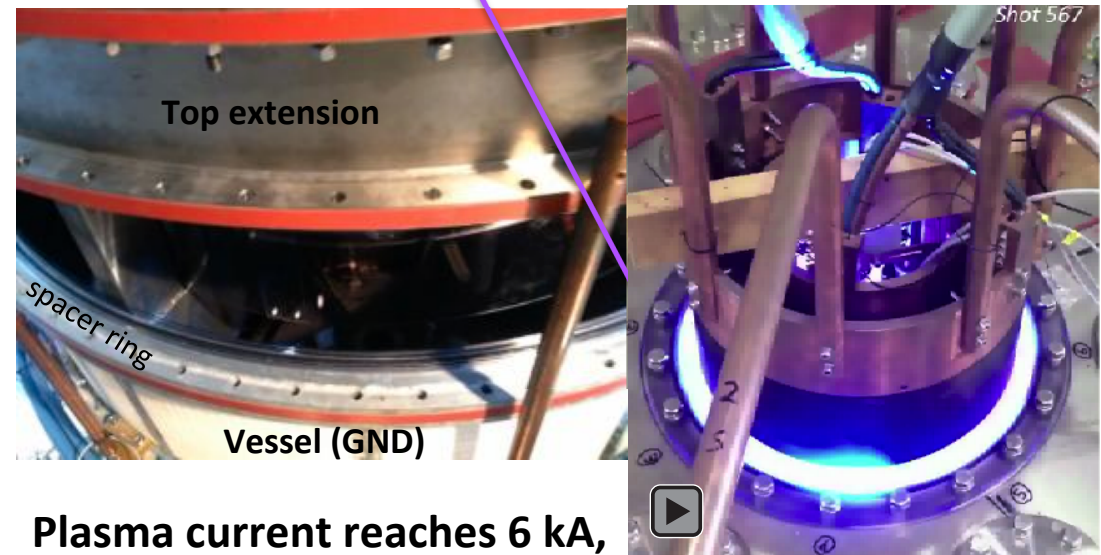
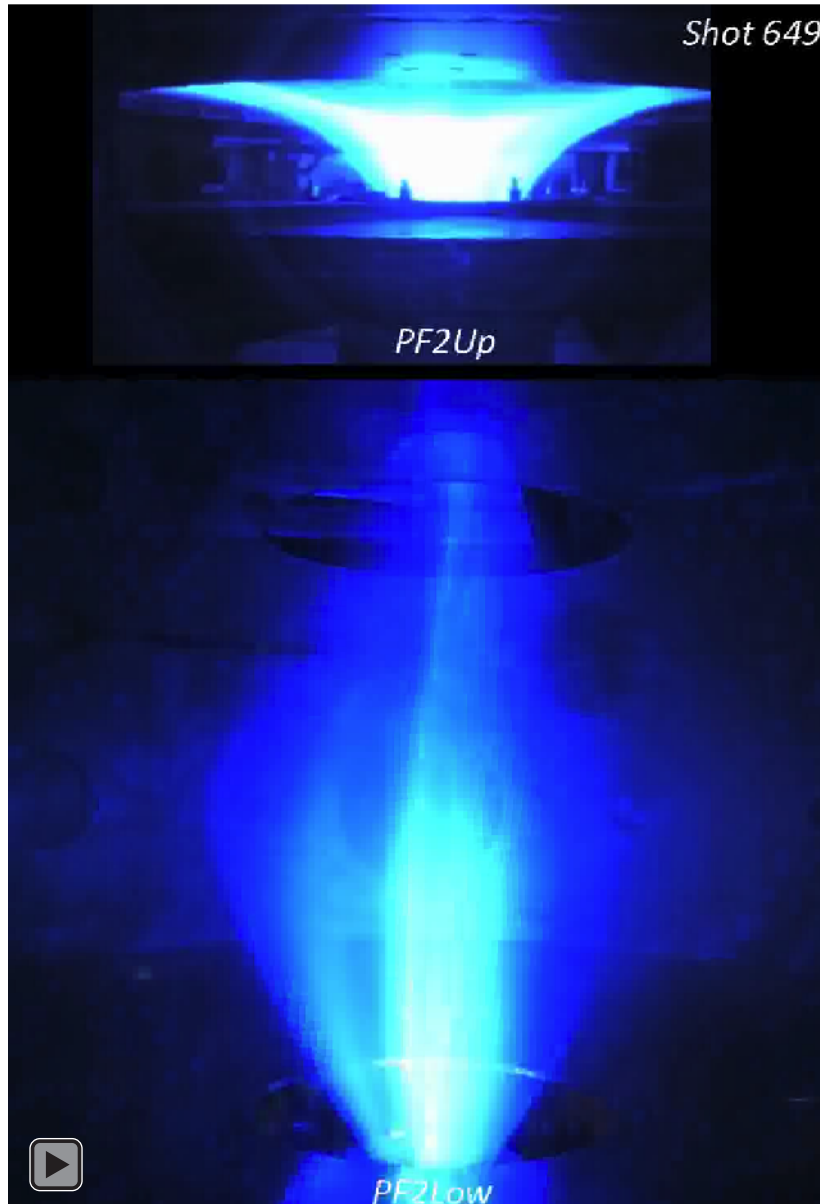
Color contours: *electrostatic potential*, Arrows: *E field* Lines: *magnetic field*

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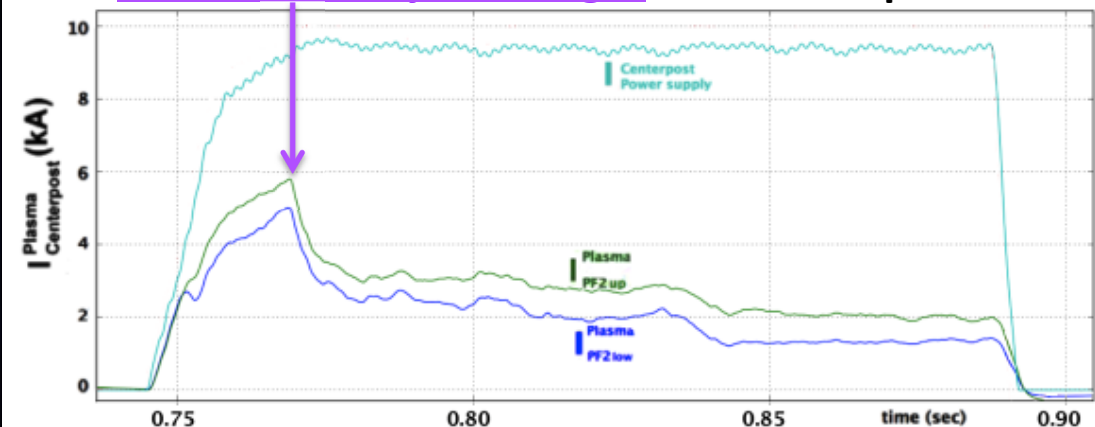


**June 2017:** Polycarbonate spacer ring insulates top lid and top extension from vessel (GND)  
if they are put back in contact with vessel, plasma centerpost current through PF2 is hampered

→ Large part of current flows into vacuum vessel → secondary discharges bus-bars → vessel



Plasma current reaches 6 kA,  
but after secondary discharges current drops to 3 kA

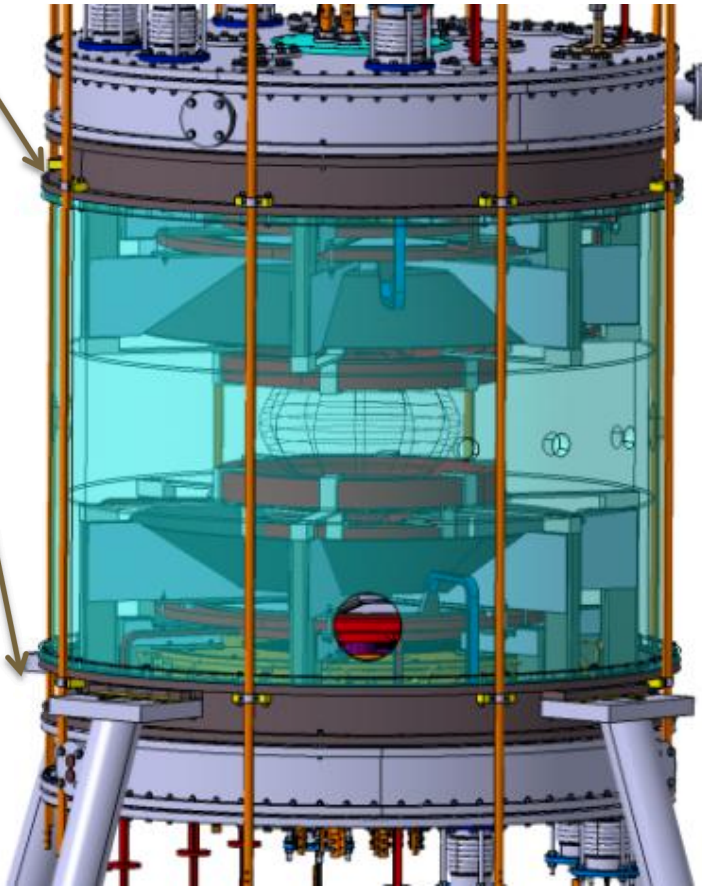


To achieve full centerpost current in **Hydrogen (250 V break-down)** needs a **new insulating vacuum vessel**

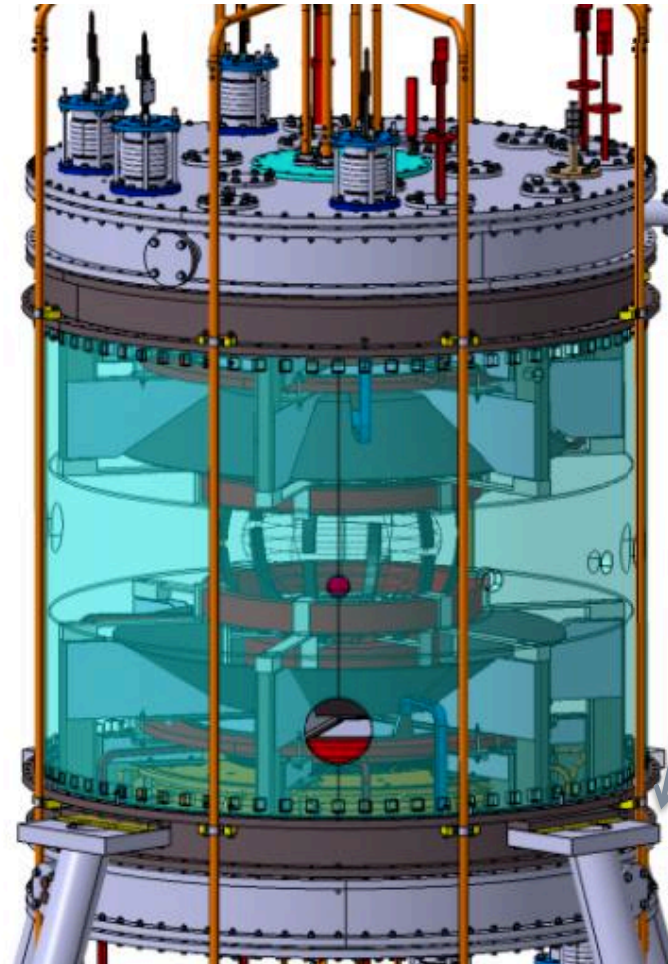


A new insulating & transparent vacuum vessel has to be built: will be Phase-2 ready  
If whole current of power supply (10 kA) is successfully driven in the Argon centerpost plasma  
it will be necessary to substitute the Al vacuum vessel with  
a Polymetacrylate (PPMA) transparent and insulating vessel (5 cm thick, 2m  $\varnothing$ , 1.6 m high)  
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  
then try Hydrogen plasma



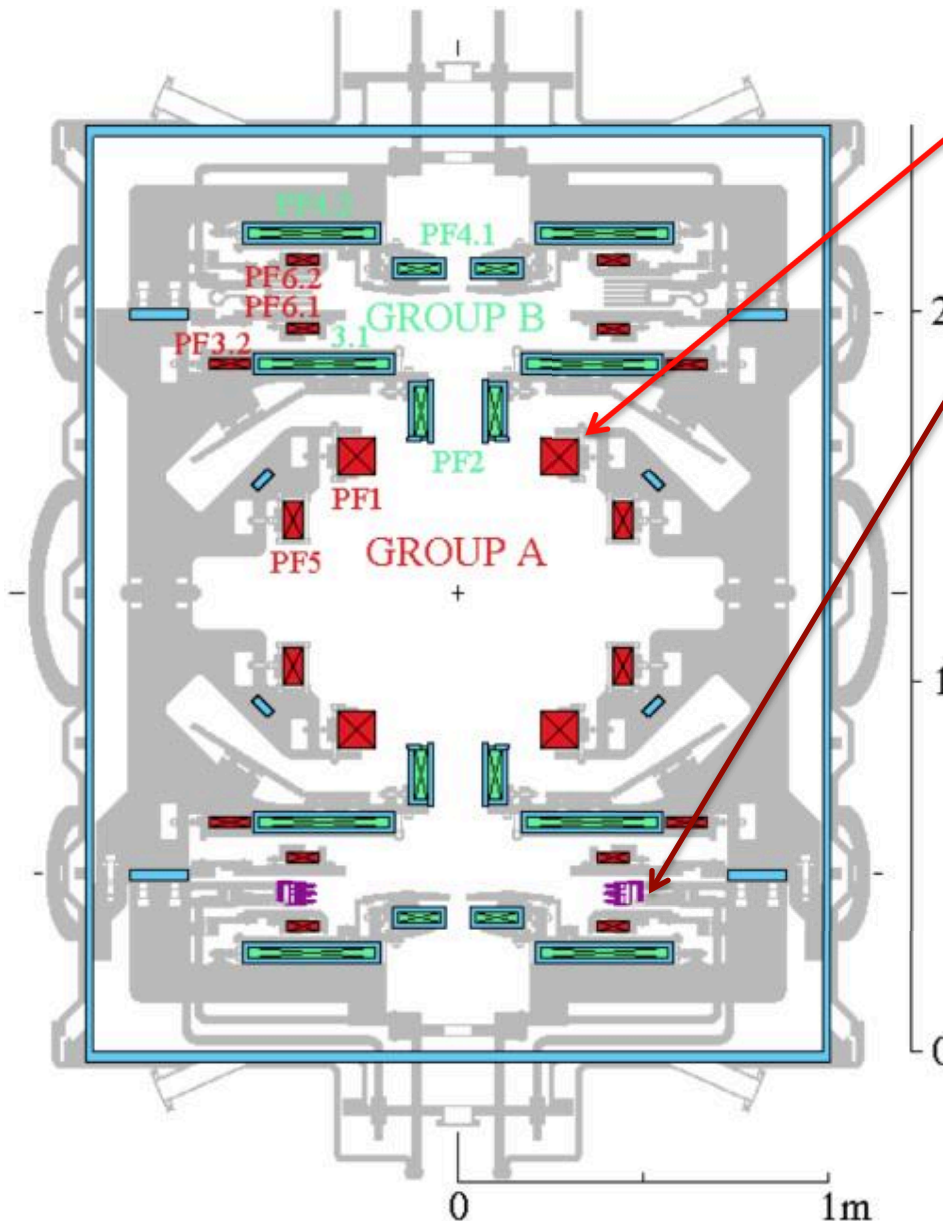
*flanged PPMA cylinder*



*carved PPMA cylinder*

EPR2017 | Vancouver, 1-4 August

To be build, after 10 kA plasma centerpost routinely achieved,  
full PROTO-SPHERA load assembly and power supplies



### Group A: ST compression coils (5+5 series)

*Not yet built, but inner vessel ready to host*

- high voltage ( $\sim 20$  kV) insulation
- thin Inconel casings cost  $\sim 0.5$  M€

**Tungsten filaments (54  $\rightarrow$  324)** cost  $\sim 0.2$  M€

### Final Power Supplies for:

- 1) Group A PF coils cost  $\sim 0.1$  M€
- 2) Cathode ( $I_{\text{cath}} 10 \rightarrow 60$  kA) cost  $\sim 0.2$  M€
- 3) Centerpost ( $I_e 10 \rightarrow 60$  kA) cost  $\sim 0.6$  M€

**SuperCapacitors will be used**

**Cost up to now**  $\sim 2.0$  M€

**Cost for final stage of experiment**  $\sim 1.6$  M€



## Status (June/July 2017)

- Hollow anode surprise, no anode arc attachment (electrostatic potential,  $E \times B$  plasma rotation)
- 8.6 kA achieved (10 kA available from power supply), 7 kA sustained 0.7 s in Argon plasma
- Preliminary measurements with Langmuir probes (in the anode zone):  $T_e \approx 8\text{--}10\text{ eV}$ ,  $n > 10^{19}\text{ m}^{-3}$
- After Argon centerpost is tamed (80 V break-down, 2 MW), build new insulating & transparent vessel, then tame Hydrogen centerpost (250 V break-down, 3MW?)
- If full current of plasma centerpost (10 kA) is achieved and sustained with 54 sparsely spaced emitting filaments, then full current (60 kA) will be even better achieved with 324 filaments

## Perspectives

***PROTO-SPHERA will assess a new magnetic confinement configuration, potentially stationary***

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

**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 zero, then ST plasma  $T = 10\text{ eV}$   
PROTO-SPHERA studies plasma-electrode interactions
- should it be 1 MW, then ST plasma  $T \sim 100\text{ eV}$   
PROTO-SPHERA studies magnetic reconnections at relevant magnetic Lundquist number,  $S \sim 10^5$
- should it be many MW, then ST plasma  $T \sim 1\text{ keV}$   
... $\beta \sim 1$  !  
...would do as a Tokamak, but at 1/100 of the cost



