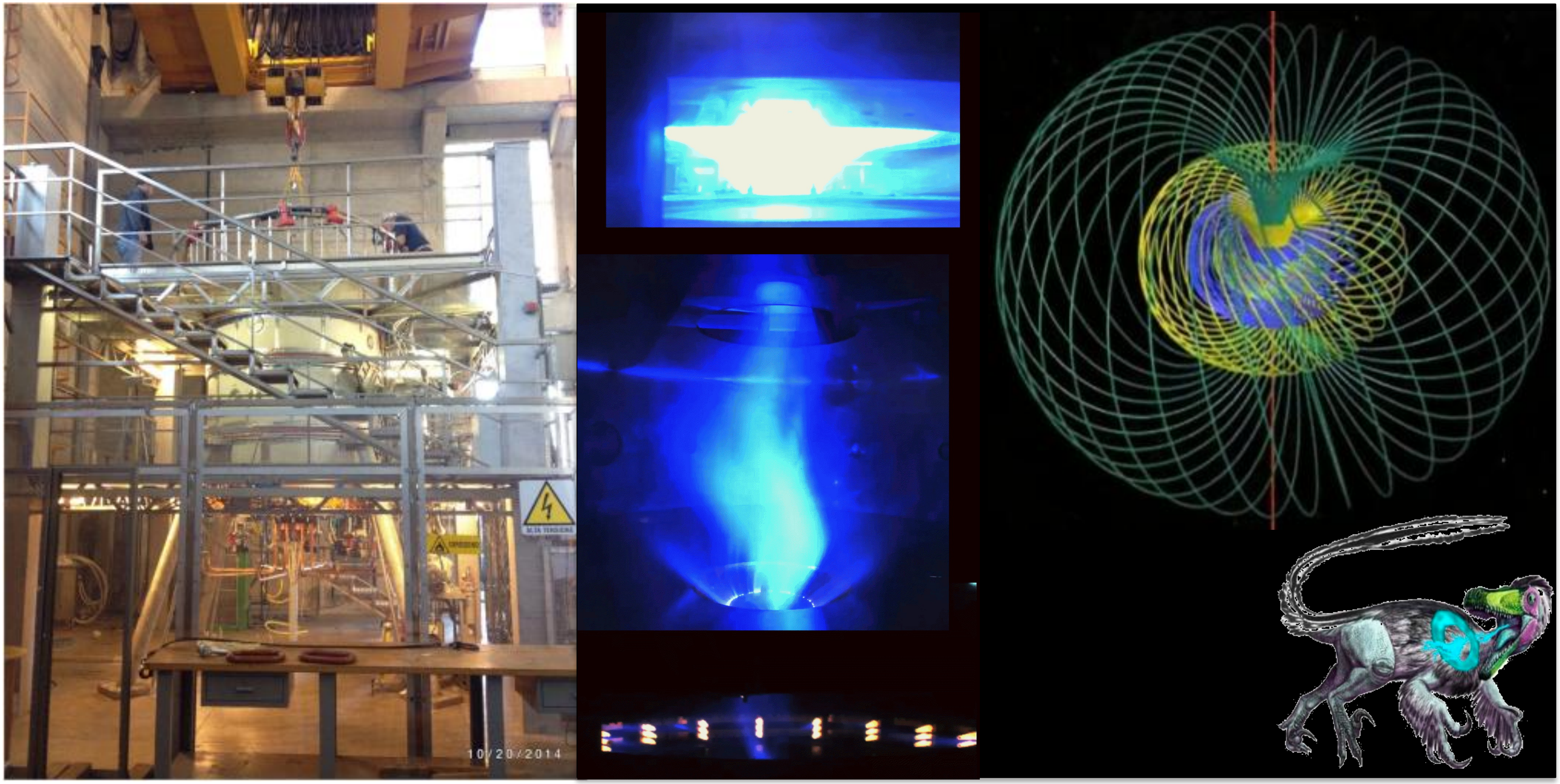
Obtainment of the Phase1 full performances in PROTO-SPHERA and future perspectives of the experiment

P. Micozzi[1], F. Alladio, G. Apruzzese, L. Boncagni, O. D'Arcangelo, E. Giovannozzi, A. Grosso, M. Iafrati, A. Lampasi, G. Maffia, A. Mancuso, V. Piergotti, G. Rocchi, A. Sibio, B. Tilia, O. Tudisco, V. Zanza

Centro Ricerche ENEA, Frascati C.P. 65, Rome, Italy [1]*e-mail: paolo.micozzi@enea.it*



EPR2017 | Vancouver, 1-4 August

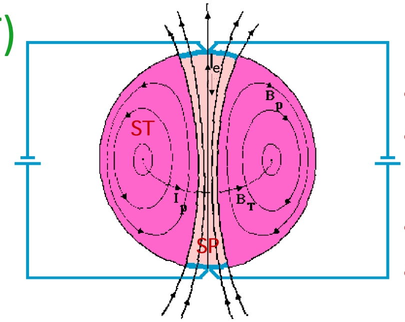
PROTO-SPHERA concept

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)

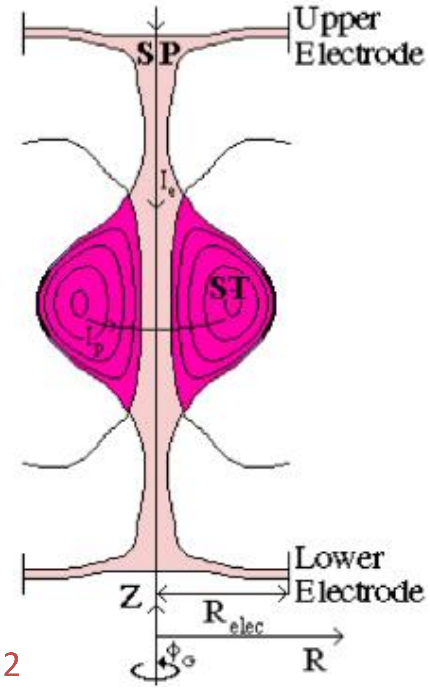


Theory: Taylor & Turner, Nucl. Fusion 29, 219 (1989)
Experiment: TS-3; N. Amemiya, et al., JPSJ 63, 1552 (1993)

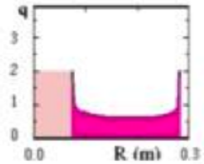
But Flux Core Spheromaks are:

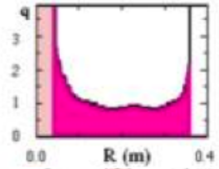
- injected by plasma guns
- formed by ~10 kV voltage on electrodes
- high pressure prefilled
- with ST safety factor q≤1

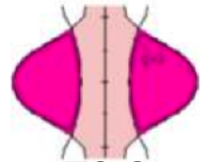
PROTO-SPHERA key differences:



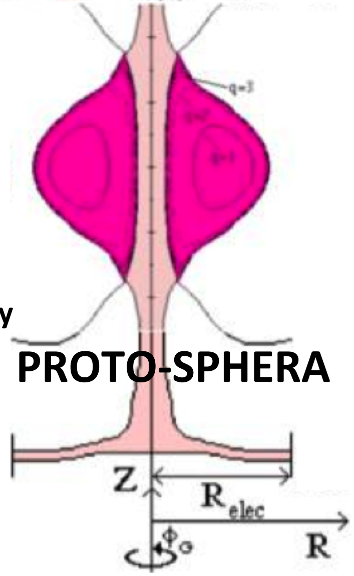
- **Designed for a Tokamak-like field-line rotational trasform ($q_0 \geq 1$, $q_{edge} \sim 3$) (aspect ratio $A = R/a \geq 1.2$, elong. $k = b/a \sim 2.3$)**
- **PROTO-SPHERA formed "slowly" as a prolated low aspect ratio Spherical Torus from the pre-existing plasma centerpost, mushroom-shaped in front of electrodes**
- **At low voltage (~100 V), inside big vessel**







TS-3
Tokio University



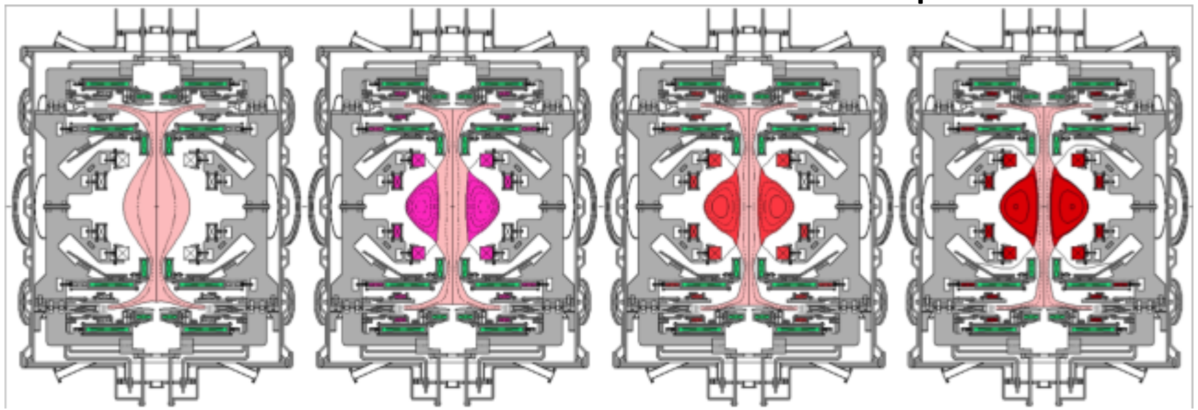
PROTO-SPHERA

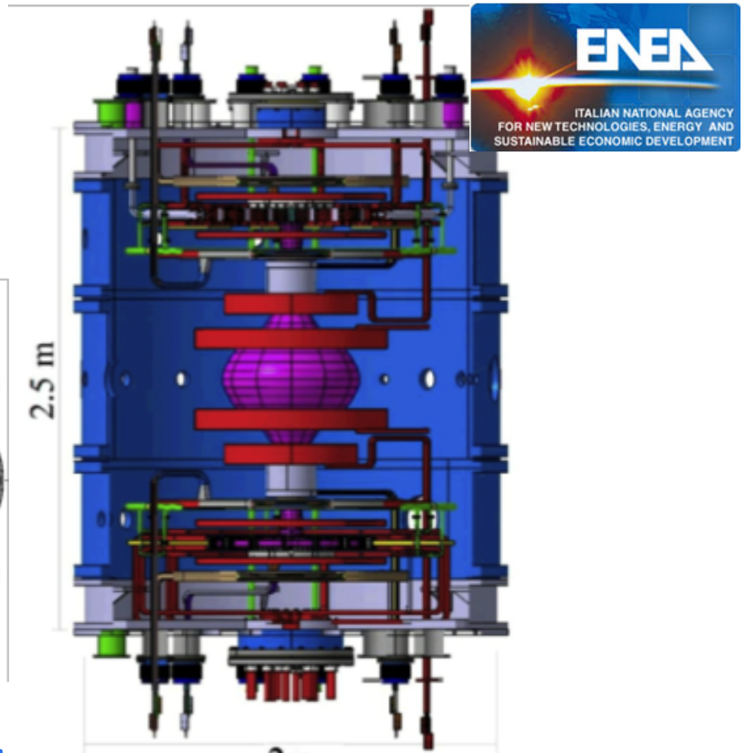
PROTO-SPHERA

Centerpost current I_e= 60 kA

ST toroidal current I_p= 120÷240 kA

ST diameter $2R_{sph}$= 0.7 m



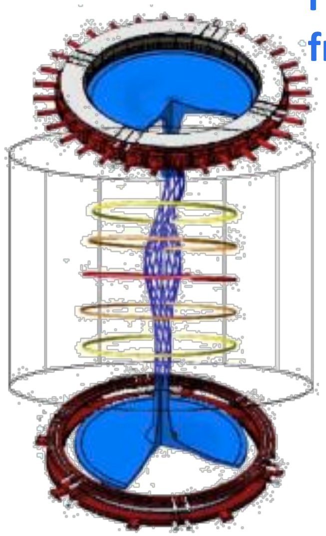


Axisymmetric simulation of ST formation

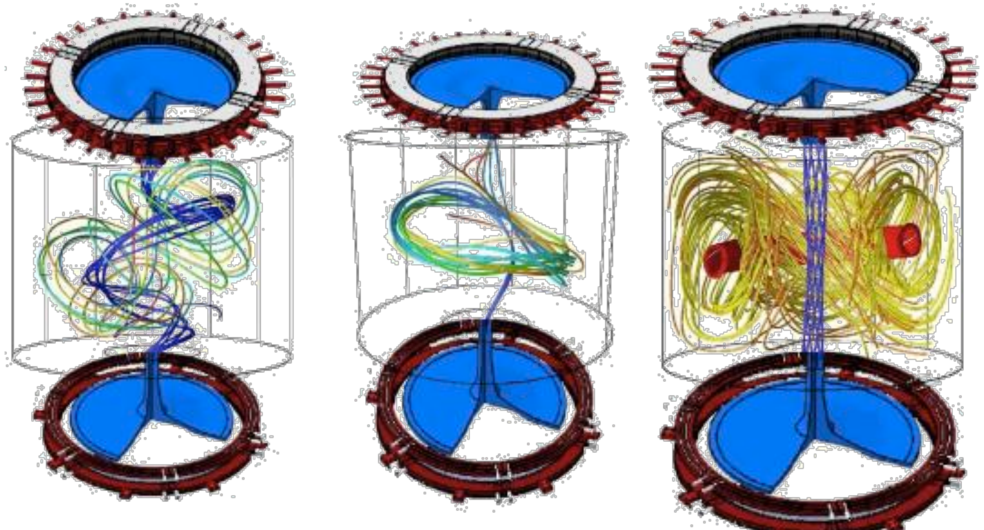
Formation time scale $(\tau_{Alfvén} \cdot \tau_{Resist})^{1/2} \sim$ 0.6 ms

from $\tau_{Alfvén} \sim$ 0.5 μs

$\tau_{Resist} \sim$ 70 ms



Resistive MHD simulations of ST formation



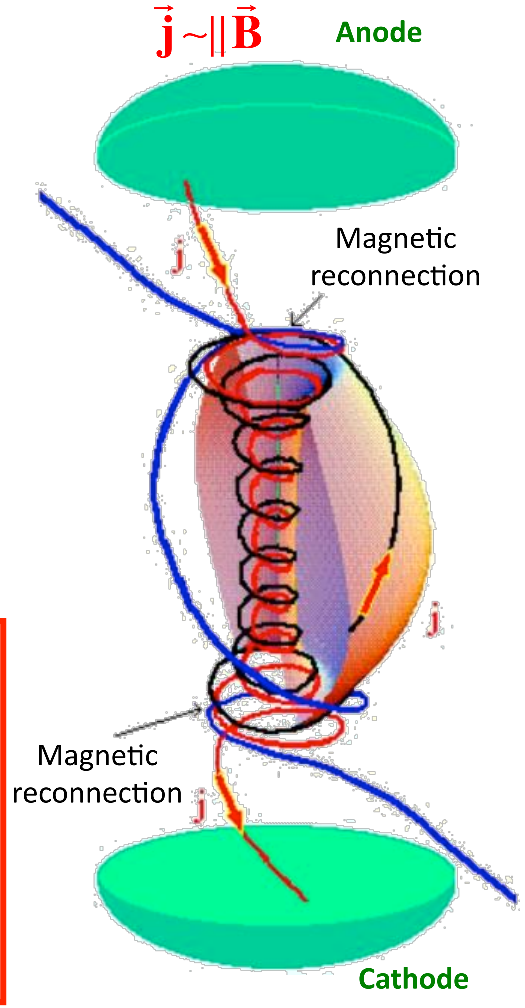
Garcia-Farengo, PoP **16**,112508 (2009)
and
Ricardo Farengo, ISTW2008 - Frascati

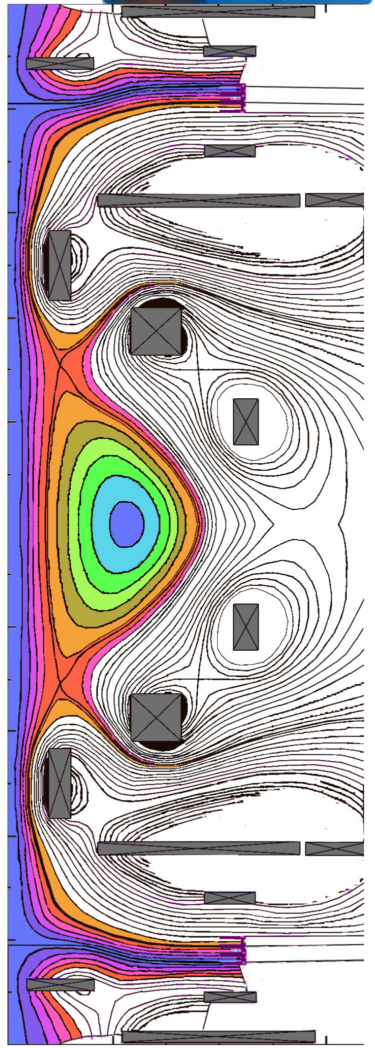
Non-axisymmetric simulation of ST formation

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 ($4xI_e$) really achievable?
- Can it be sustained by Helicity Injection for at least τ_R~ 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

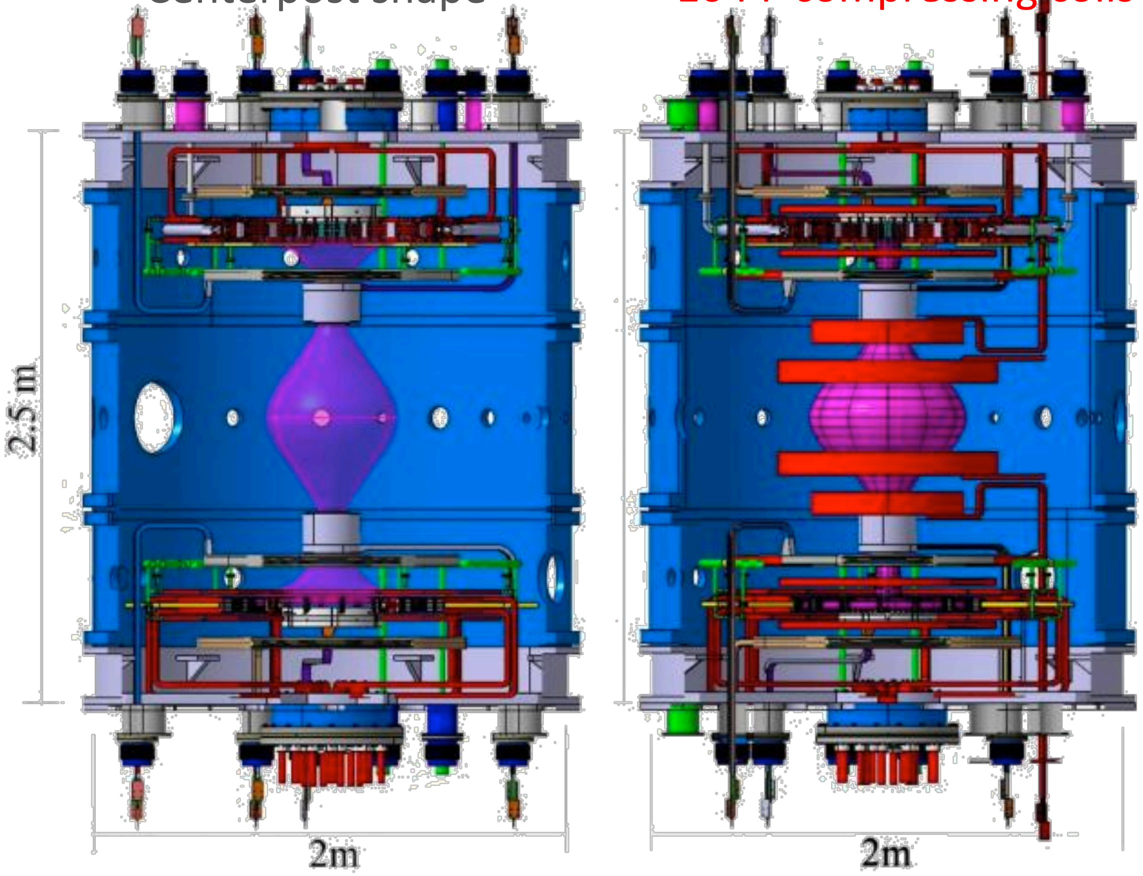
HOW EFFICIENT THE SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS?

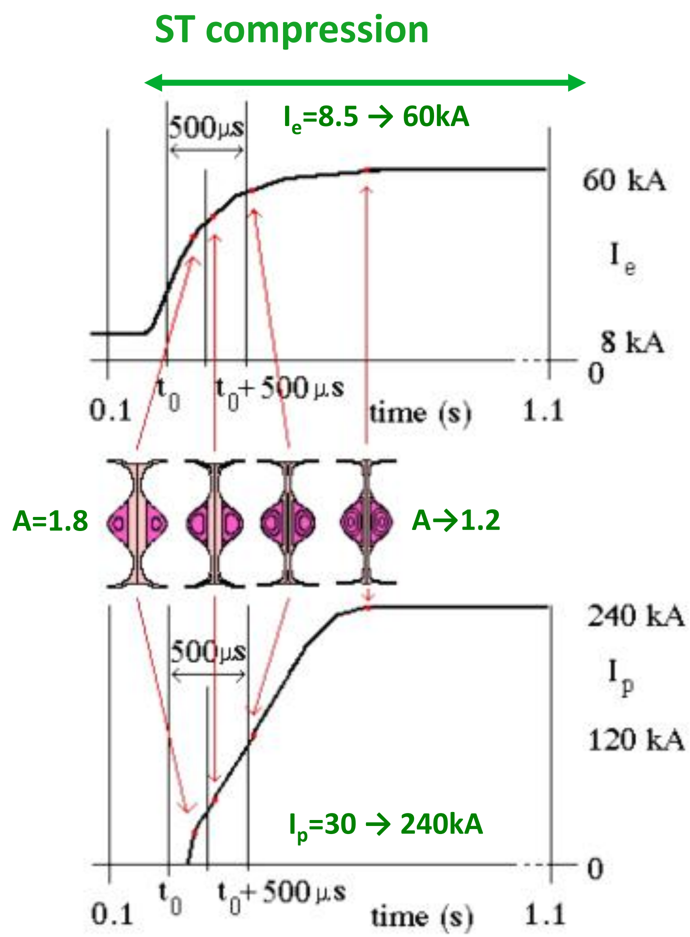
In **2002** at Frascati an **International Workshop** advised to build the machine in 2 steps:

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

Phase1: 8 PF coils
Centerpost shape

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



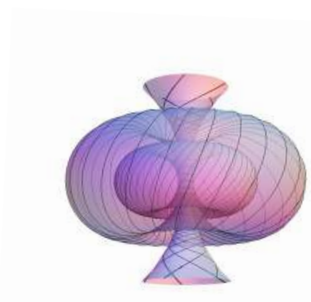


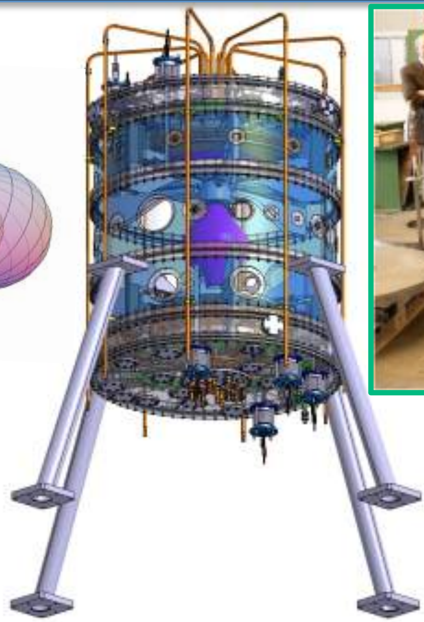
SP centerpost current I_e= 8.5 kA
No ST toroidal current

SP centerpost current I_e= 60 kA
ST toroidal current I_p= 120÷240 kA

Cylindrical vacuum vessel was START vacuum vessel, donated by Culham in 2004

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*

PROTO-SPHERA POWER SUPPLY

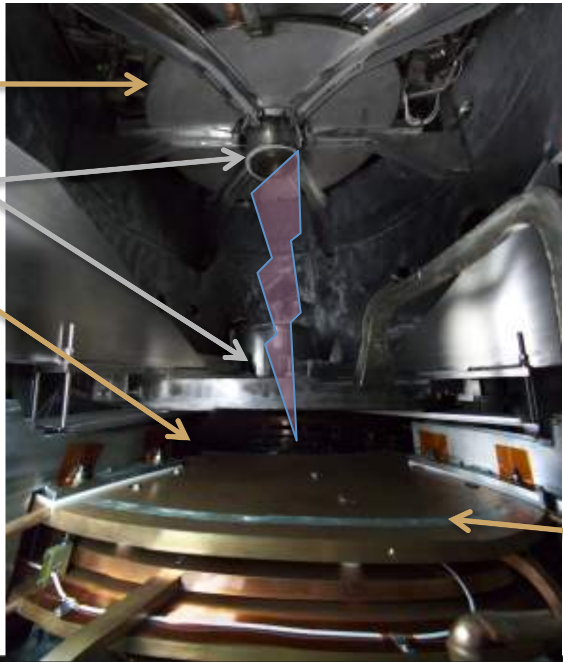
To fire the **plasma centerpost (Phase1)**
3 Power supplies are required

- **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

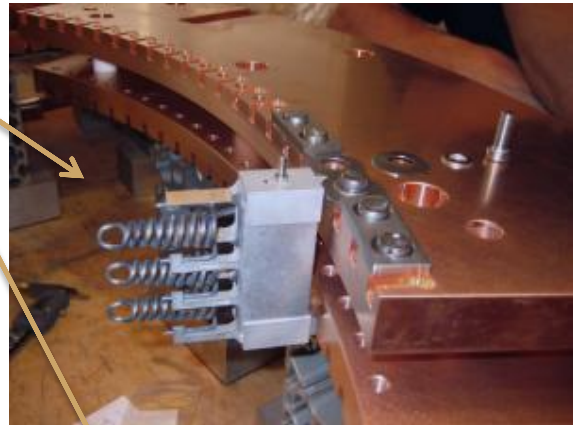
Anode

PF2 coils throttles

Cathode



Cathode

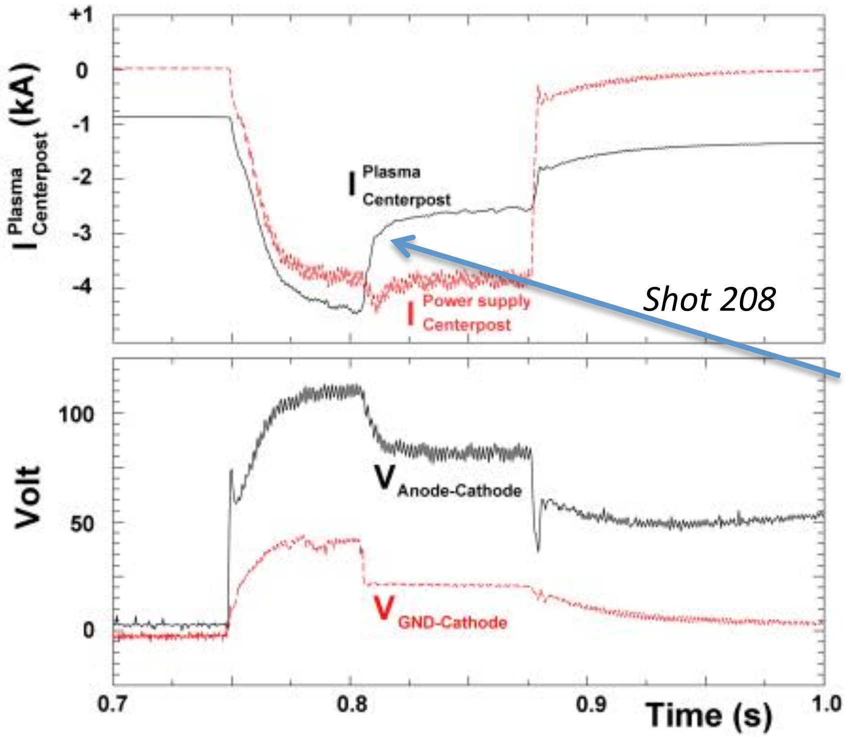


Electrical power supplies built by EEI of Vicenza, cost 0.7 M€

Years 2011 - 2014:

October 2015 / January 2016
experiments with external PF coils:
Plasma current outer paths for I > 3.5 kA

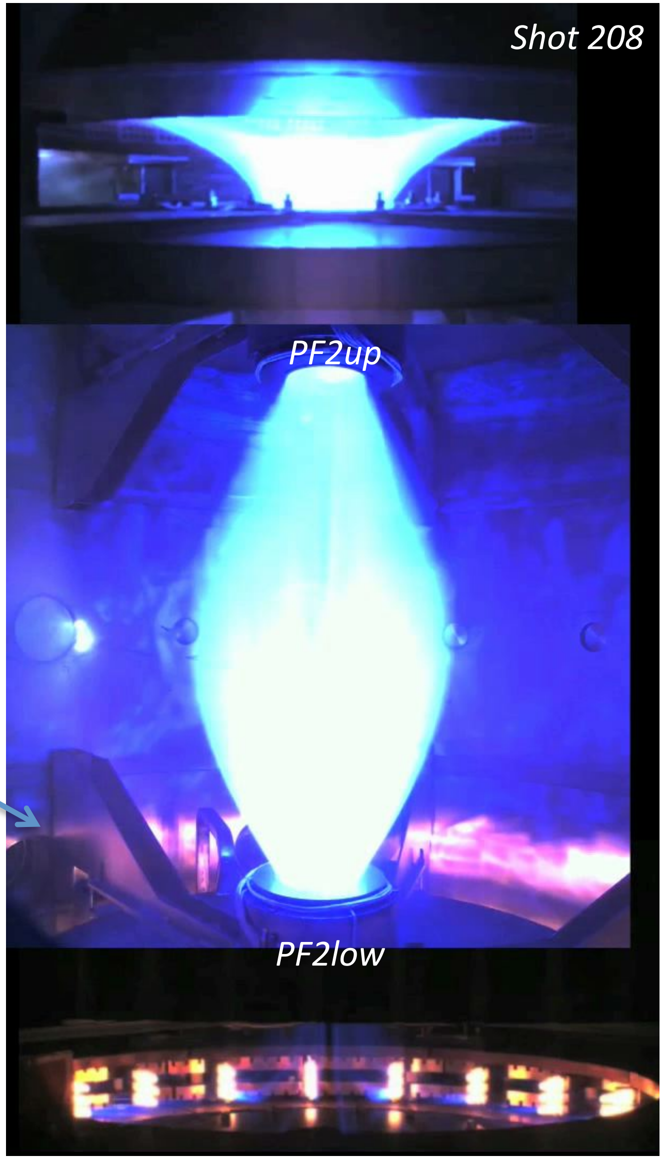
Status of art at EPR2016



Argon plasma aiming to 4 kA reaches 3.5 kA

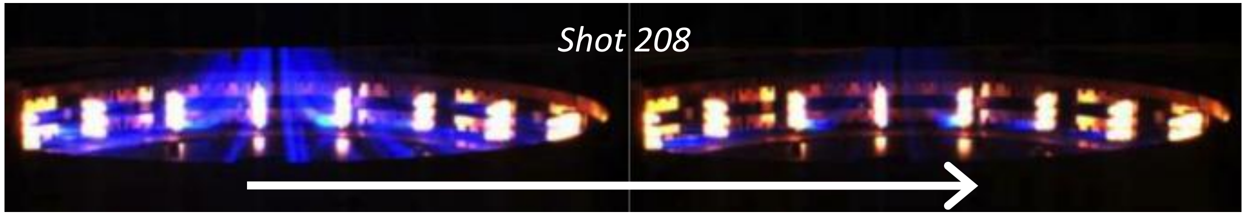
~ 1.5 kA lost from main plasma

in discharge from cathode down to lid\vessel



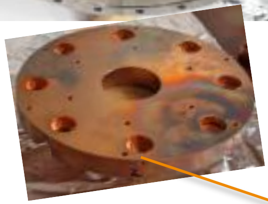
plasma fired after 0.75 s of PF current
(skin current time to remove X-point from inside vessel)

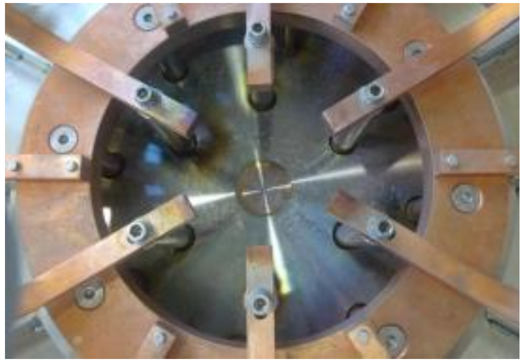
Also the Cathode emission lowers after 1.5 kA are lost



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

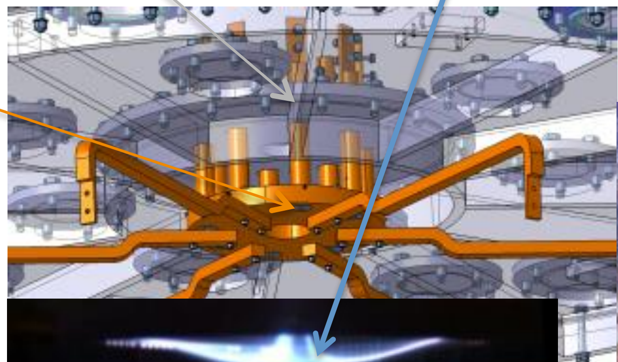
On the top (near anode) a SS flange, pierced by 8 bus-bars, such a flange substituted by a 4 cm thick Polycarbonate one



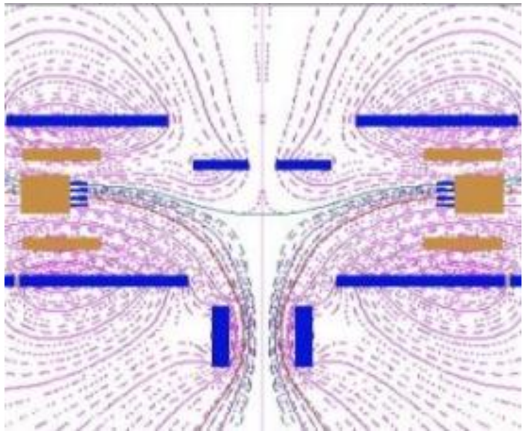


Top flange view from plasma side

Bus-bars (top-anode)



Geometry of magnetic nozzle



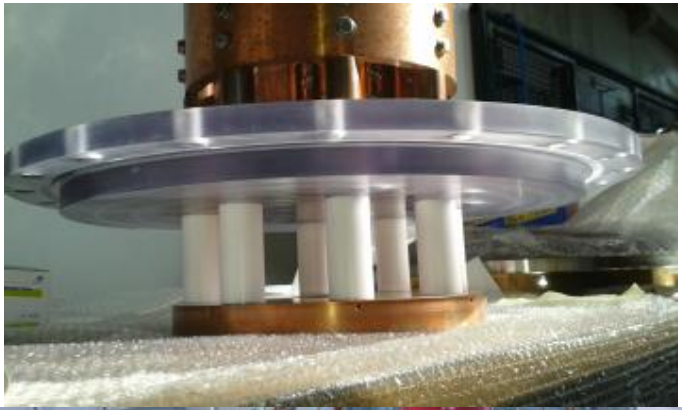
Anode

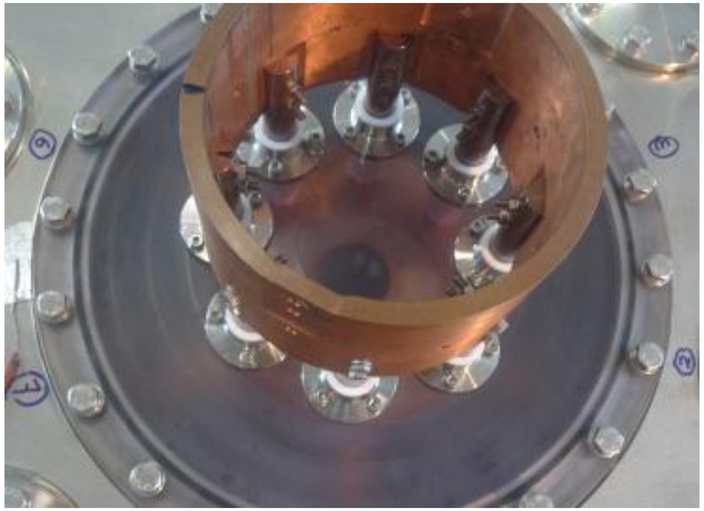
Anode exit of nozzle

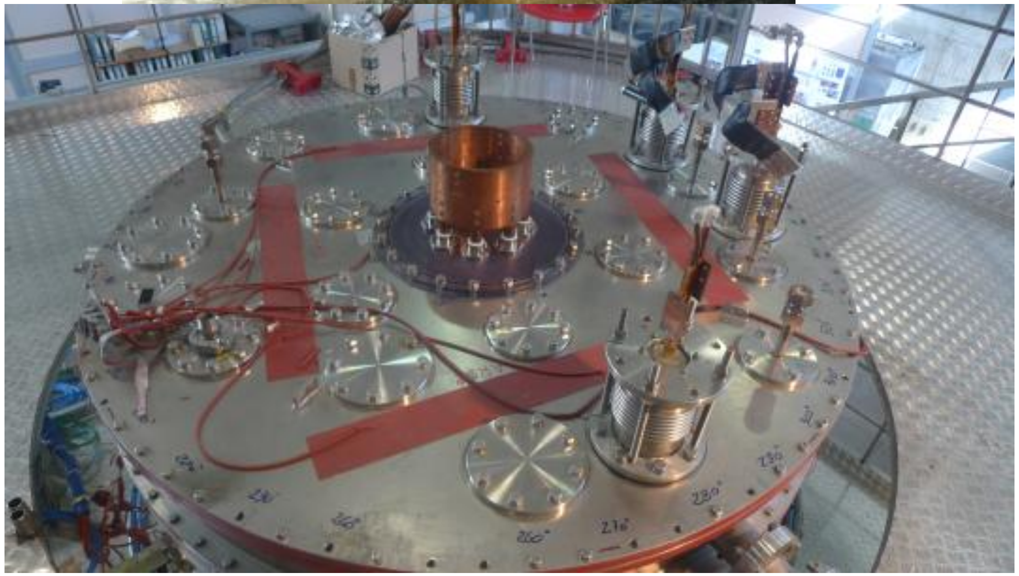
June 2016: insertion of Polycarbonate (transparent) anode bus-bar flange on top of machine

Heavily metallized
top & bottom bus-bar flanges

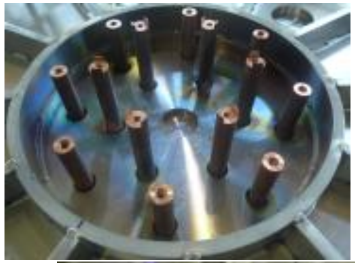
4 cm thick Polycarbonate
(required by atmospheric pressure)







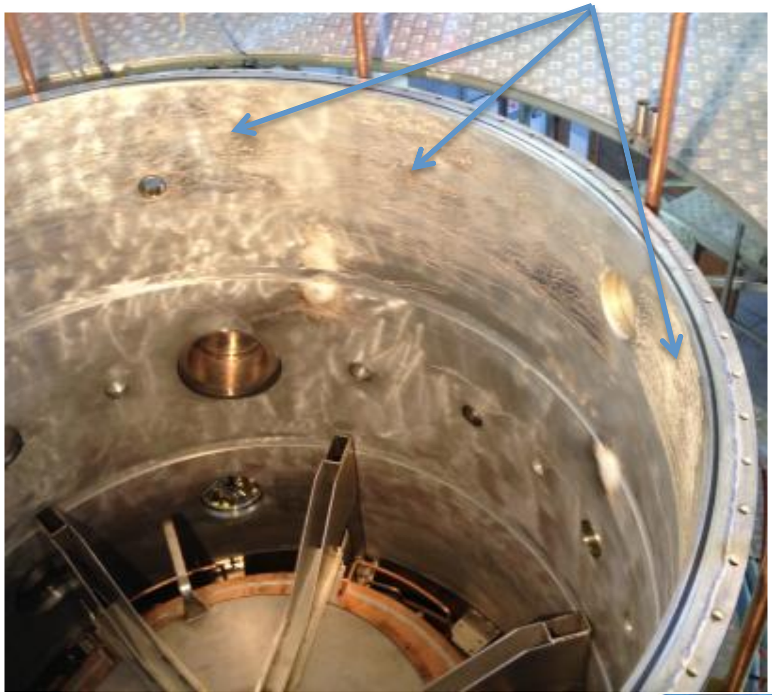
At the bottom (near cathode) a SS flange, pierced by 14 bus-bars, such a flange has been substituted by a Polycarbonate one



July 2016: Polycarbonate flange on machine bottom

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

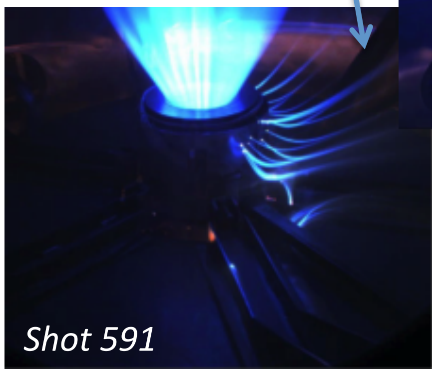
secondary 2mm thick Polycarbonate screen surrounds rear of anode

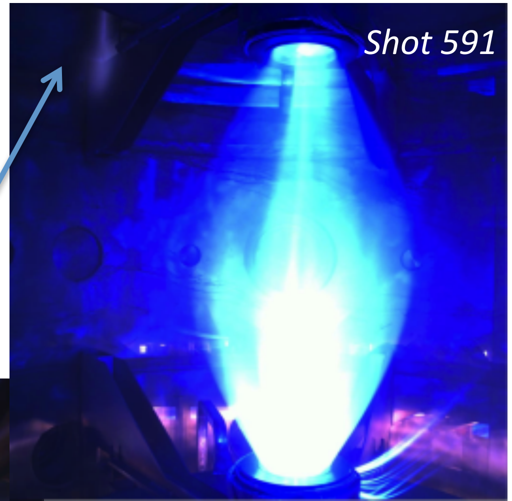
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but

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

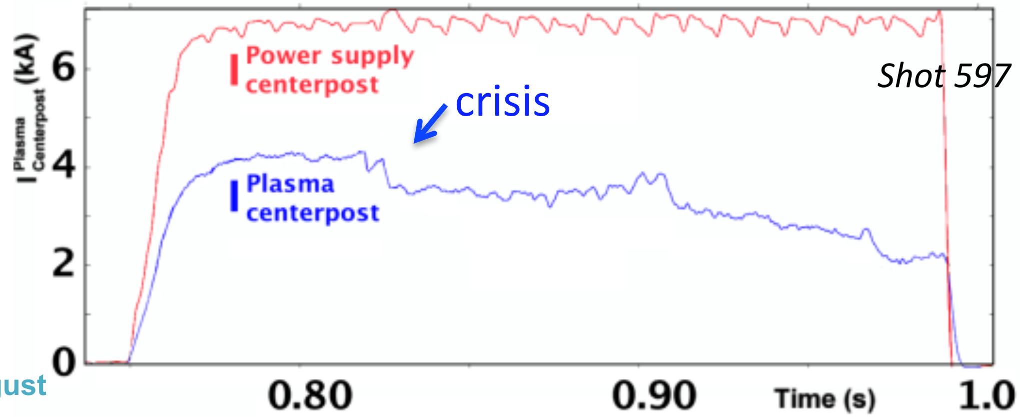




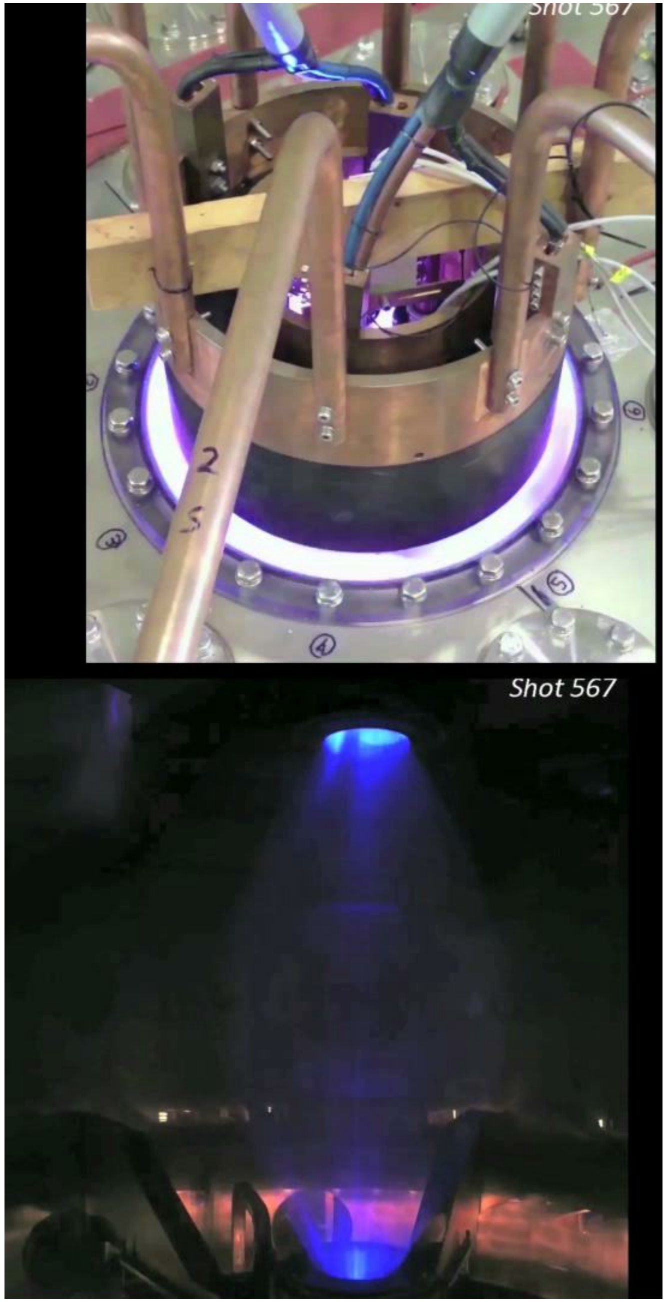
Input 0.6 MW

7 kA from power supply

Centerpost drives 60%



January 2017

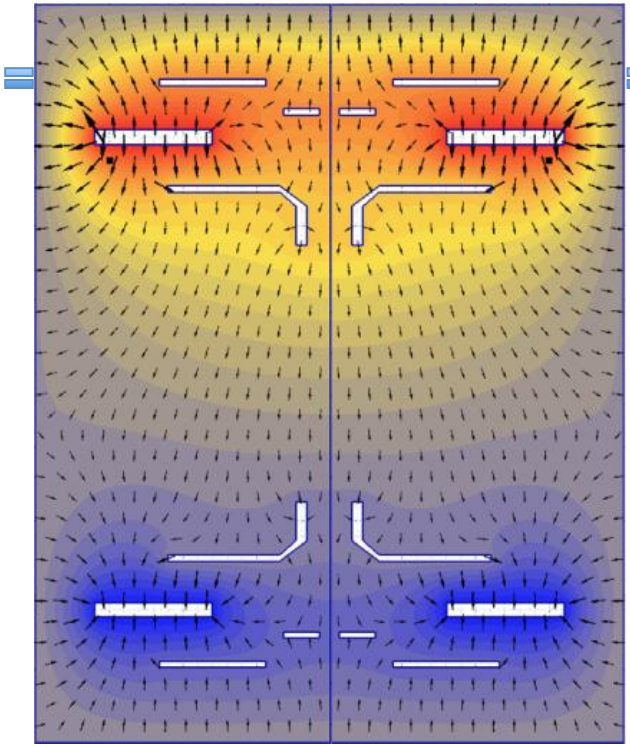


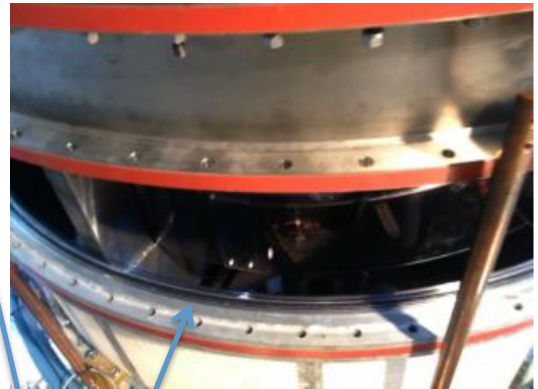
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but

2) in Hydrogen (250 V breakdown) there was still a problem of current through the vessel,

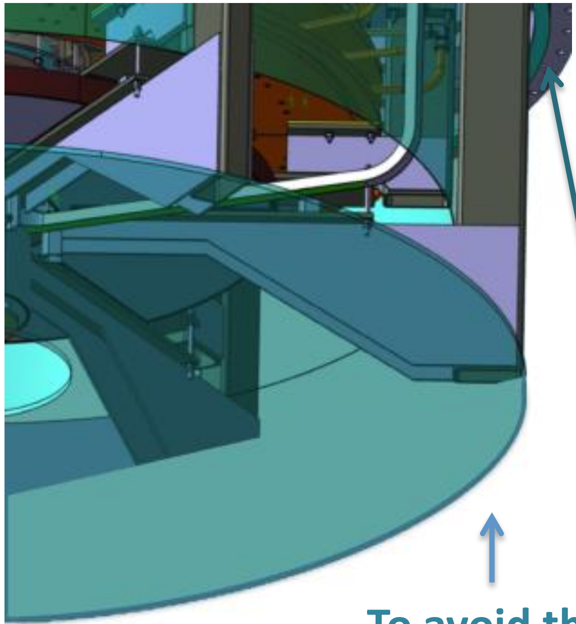
this was triggered in Argon (80 V breakdown), connecting the common star potential of the six-phased cathode power supply to the machine GND

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



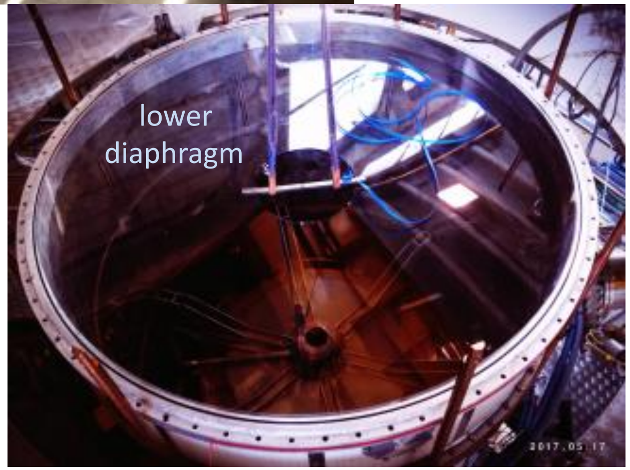


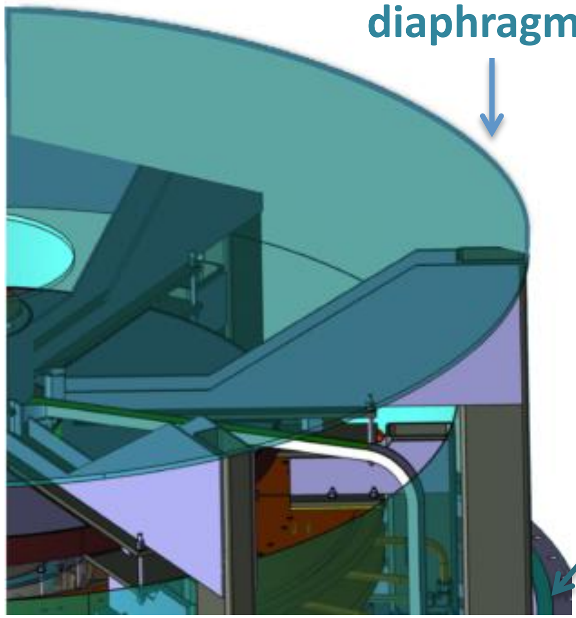
A spacing insulating ring was inserted in **May 2017**



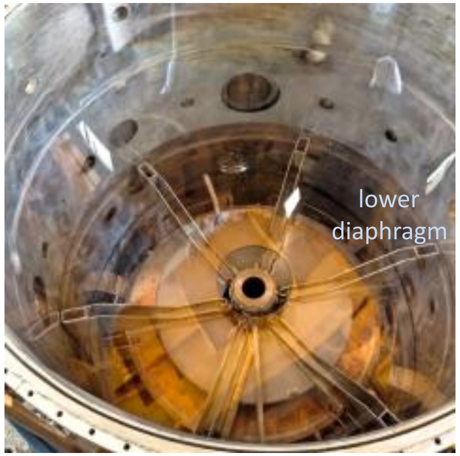
to avoid the bus-bar to vessel current flow an insulating spacer ring has been inserted

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



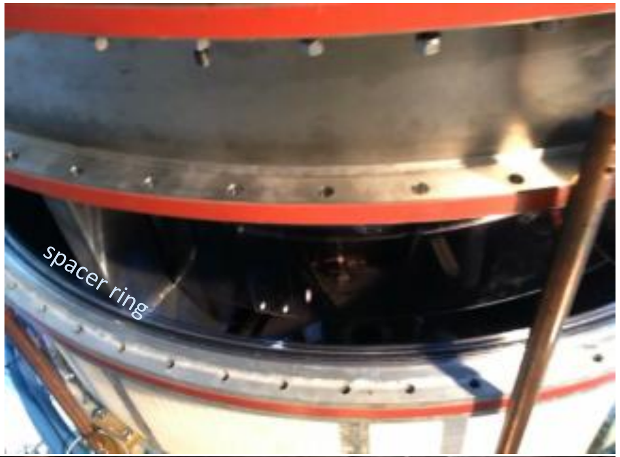


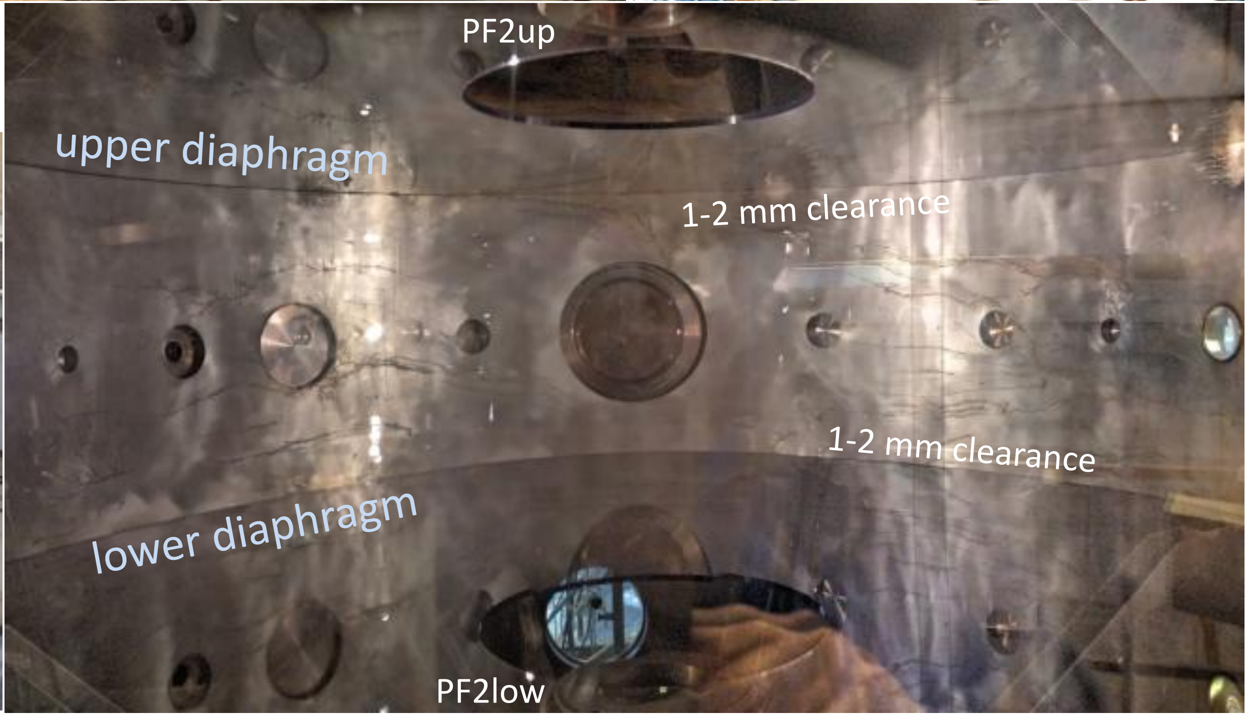
May 2017: Insertion of Polycarbonate lower diaphragm



Lower spacer ring <u>not yet</u> inserted

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





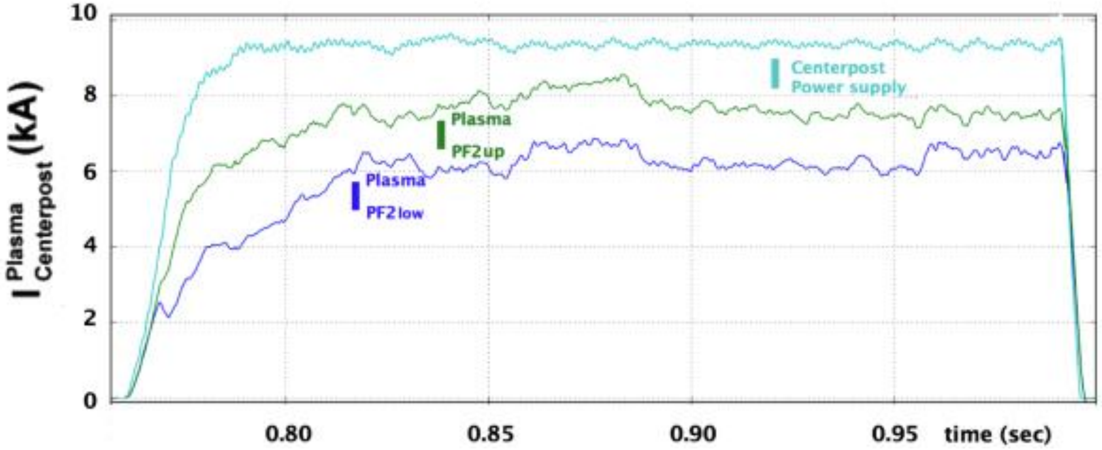
June 2017 Plasma with Polycarbonate two diaphragms & upper Polycarbonate spacer ring

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

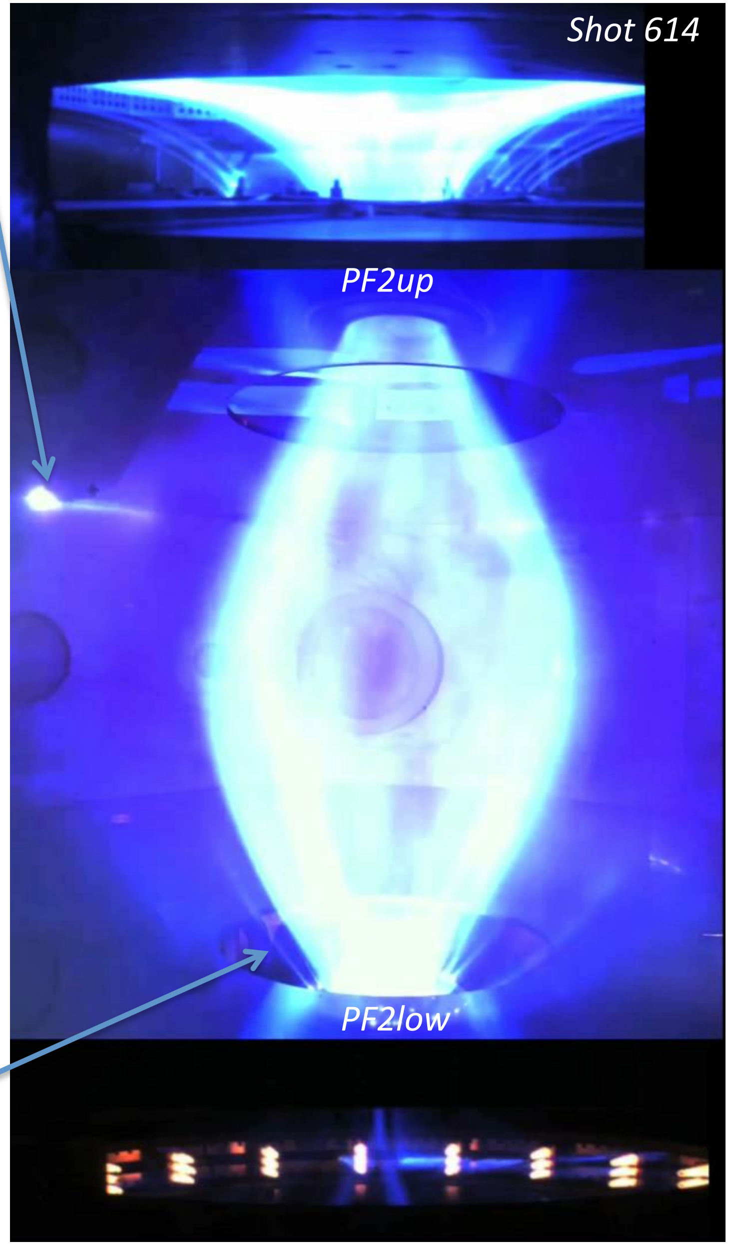


With currents through PF2 exceeding ~ 6kA the rotational transform of plasma centerpost (q ~ 2.5-3) becomes clearly visible…

The plasma centerpost seems to rotate azimuthally $(\vec{\mathrm{E}} \wedge \vec{\mathrm{B}})$ ***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!

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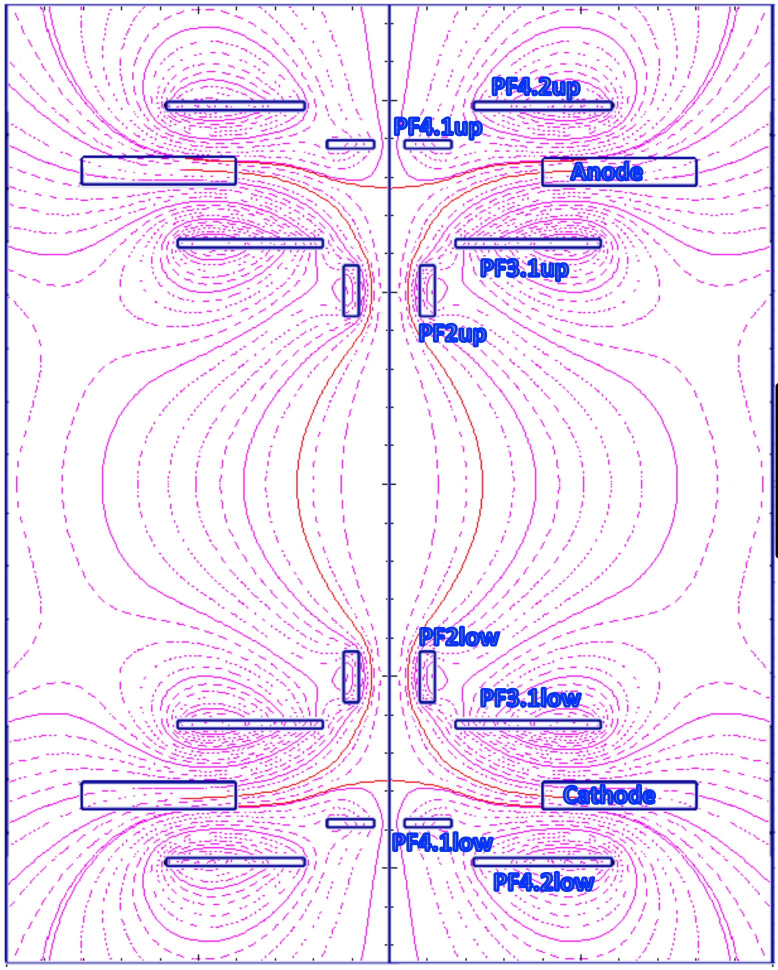
Strong toroidal rotation due to $\vec{E} \wedge \vec{B}$ prevents any anchoring on Anode!

through Polycarbonate spacer ring

upper lid & extension float at 90 V



$V_{PF4up} \sim 130$ V

$V_{anode} \sim +150$ V

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

Ext.Coil up

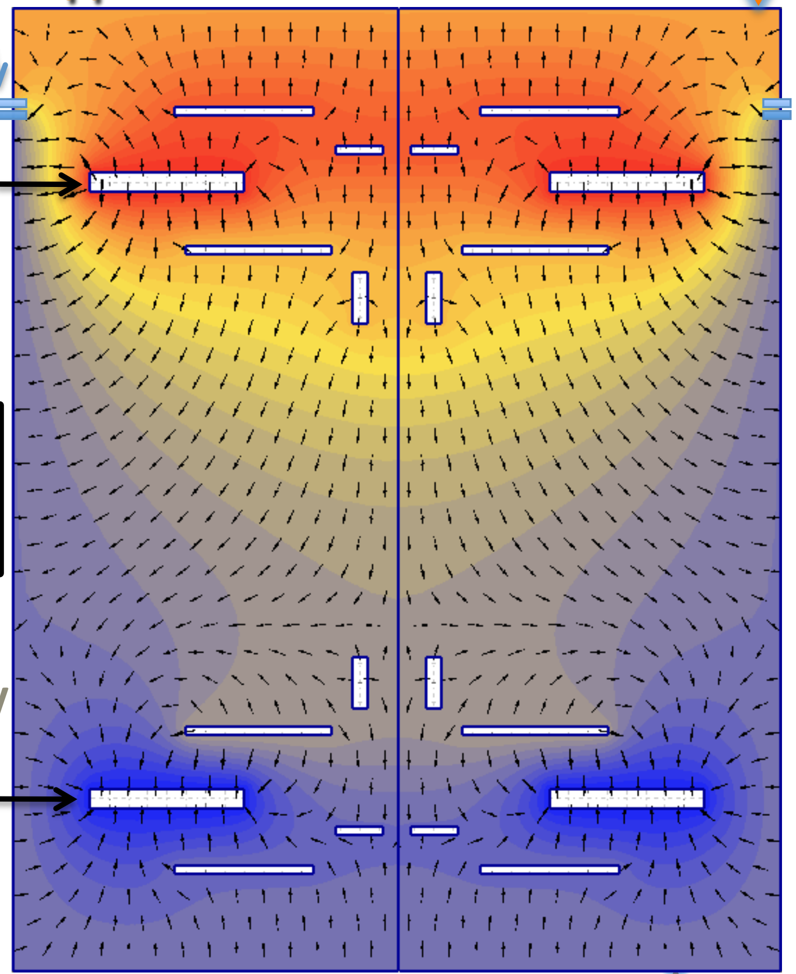
#614 8.6kA Argon
Plasma centerpost
June 2017

Ext.Coil low

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

$V_{cathode} \sim -45$ V

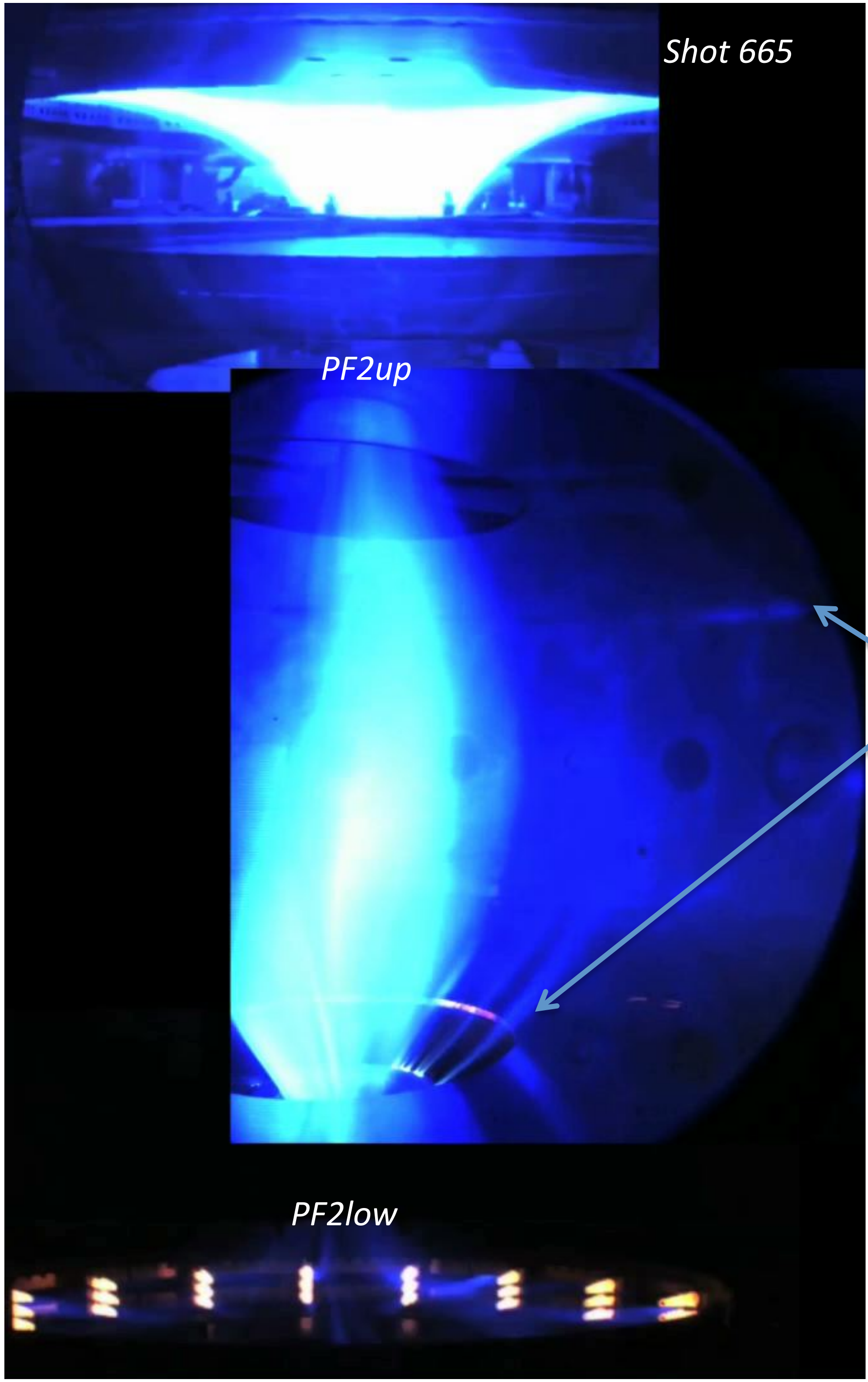
$V_{PF4low} \sim -7$ V



vacuum vessel at GND (0 V)

Lines: magnetic field

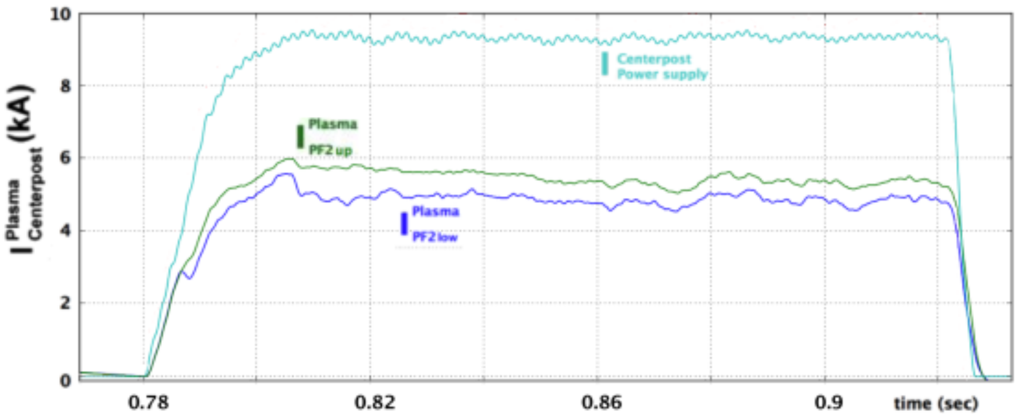
Color contours: *electrostatic potential*, Arrows: E field



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 ~ 6kA

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

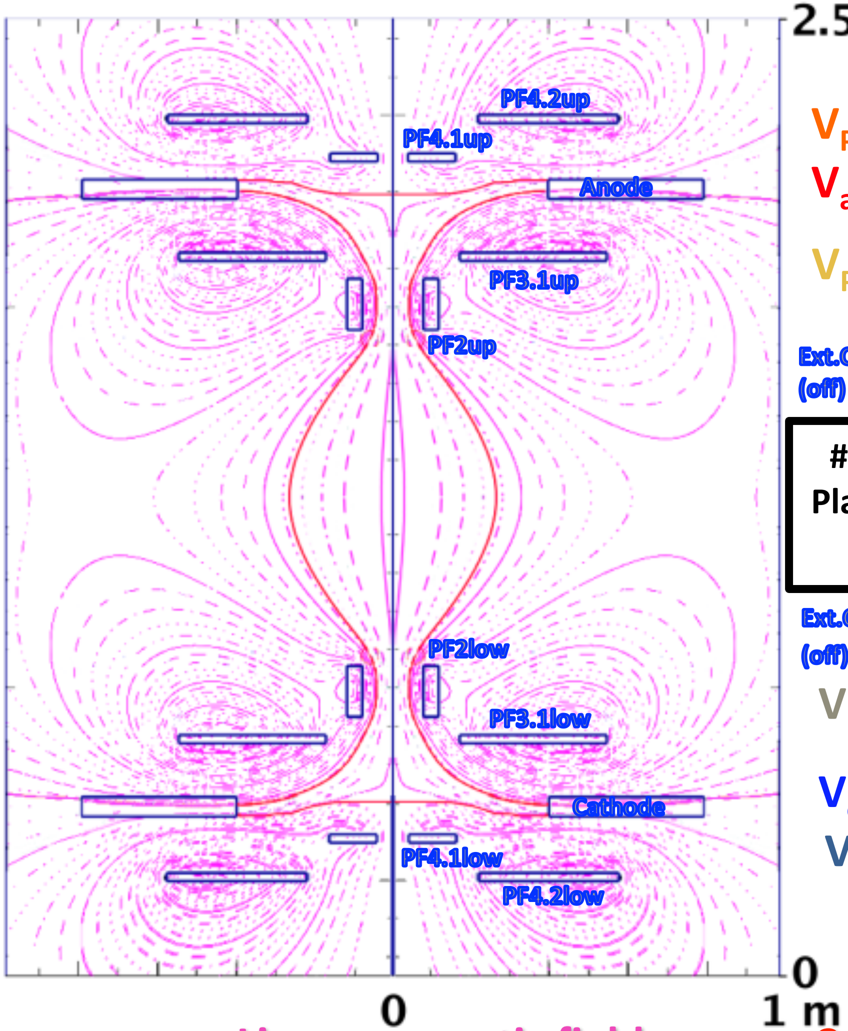


Lower currents, switching off the external PF coils: PF coils casings built as floating

Electrostatic potential is dominated by the plasma; PF coils casings better left floating!

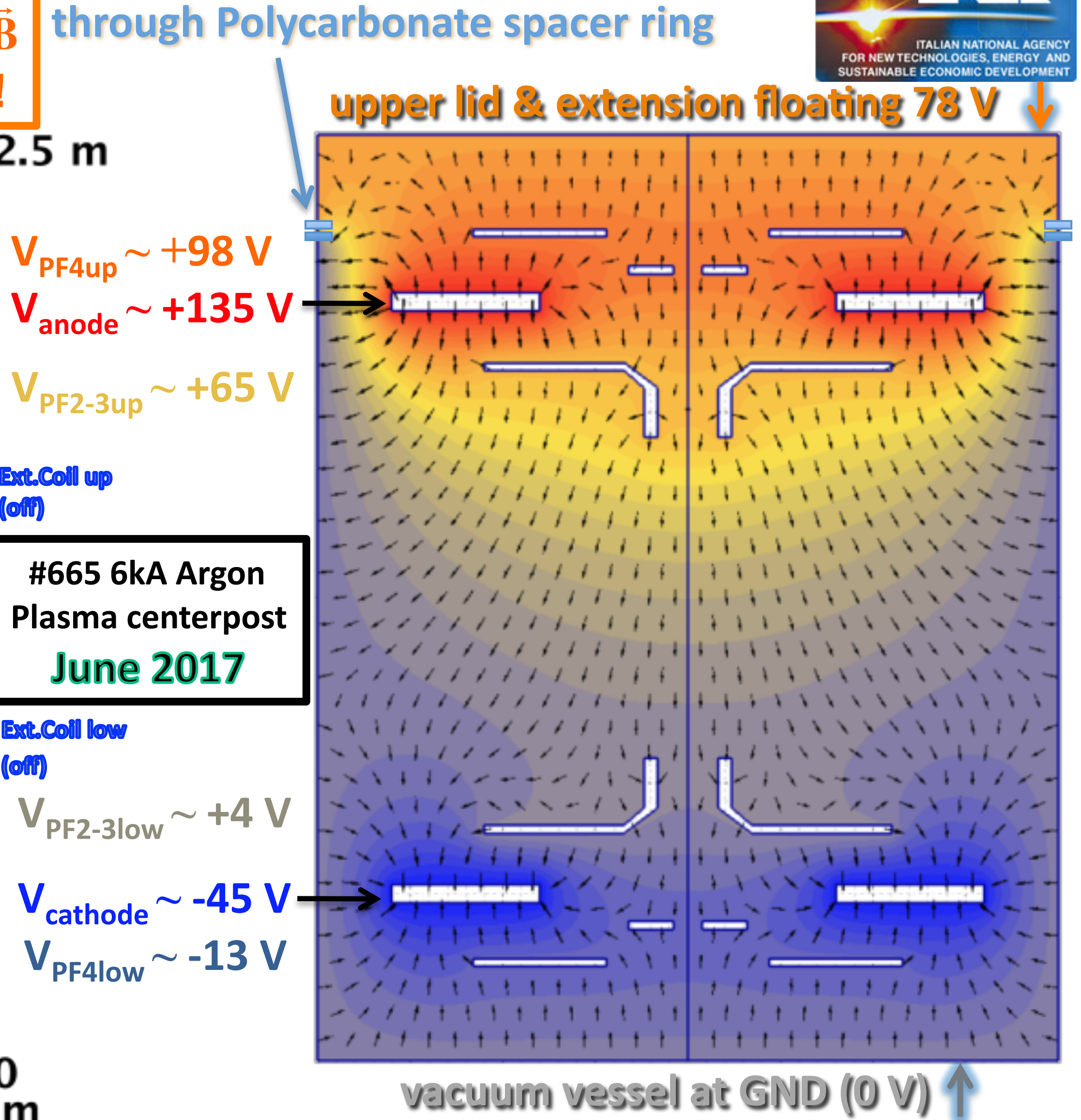
Upper lid & extension also better left floating!

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

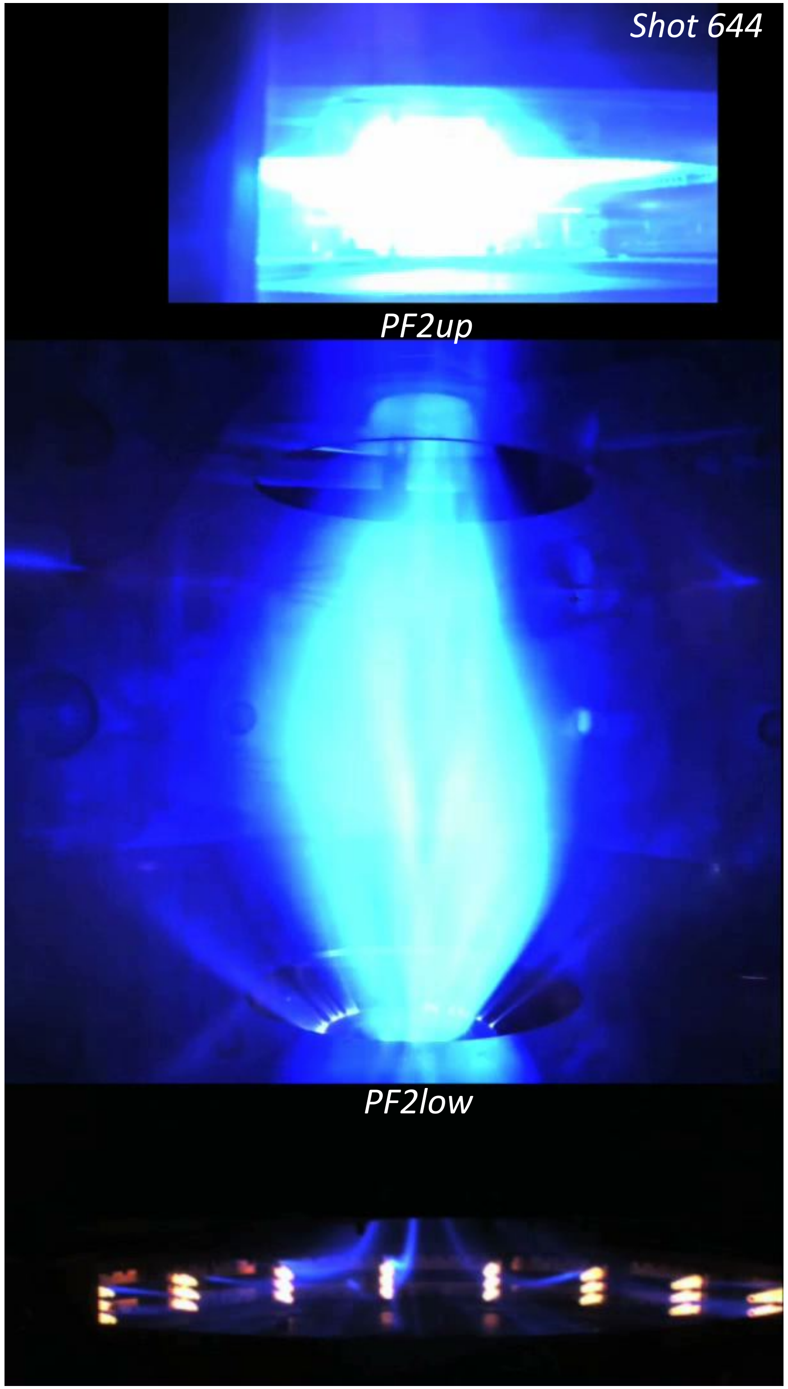


Lines: magnetic field

#665 6kA Argon Plasma centerpost June 2017



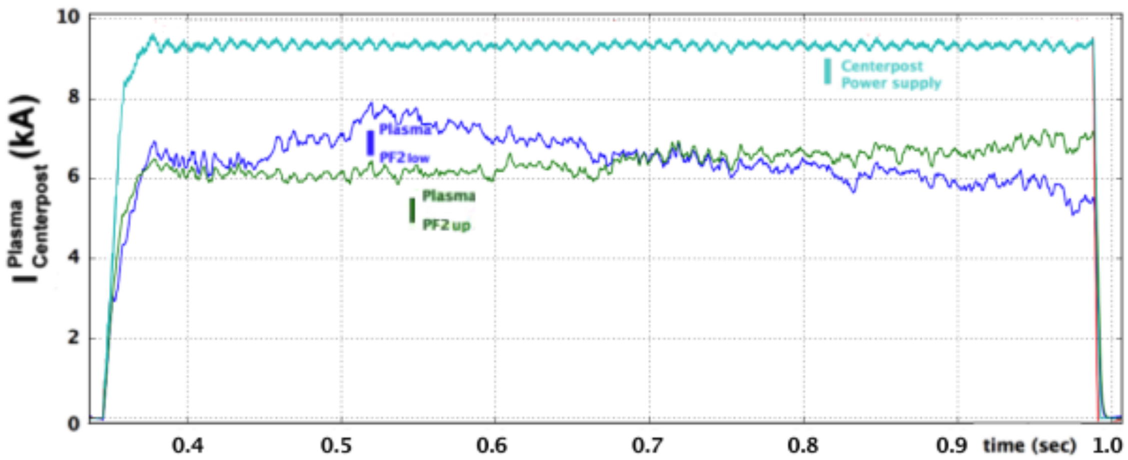
Color contours: *electrostatic potential*, Arrows: E field



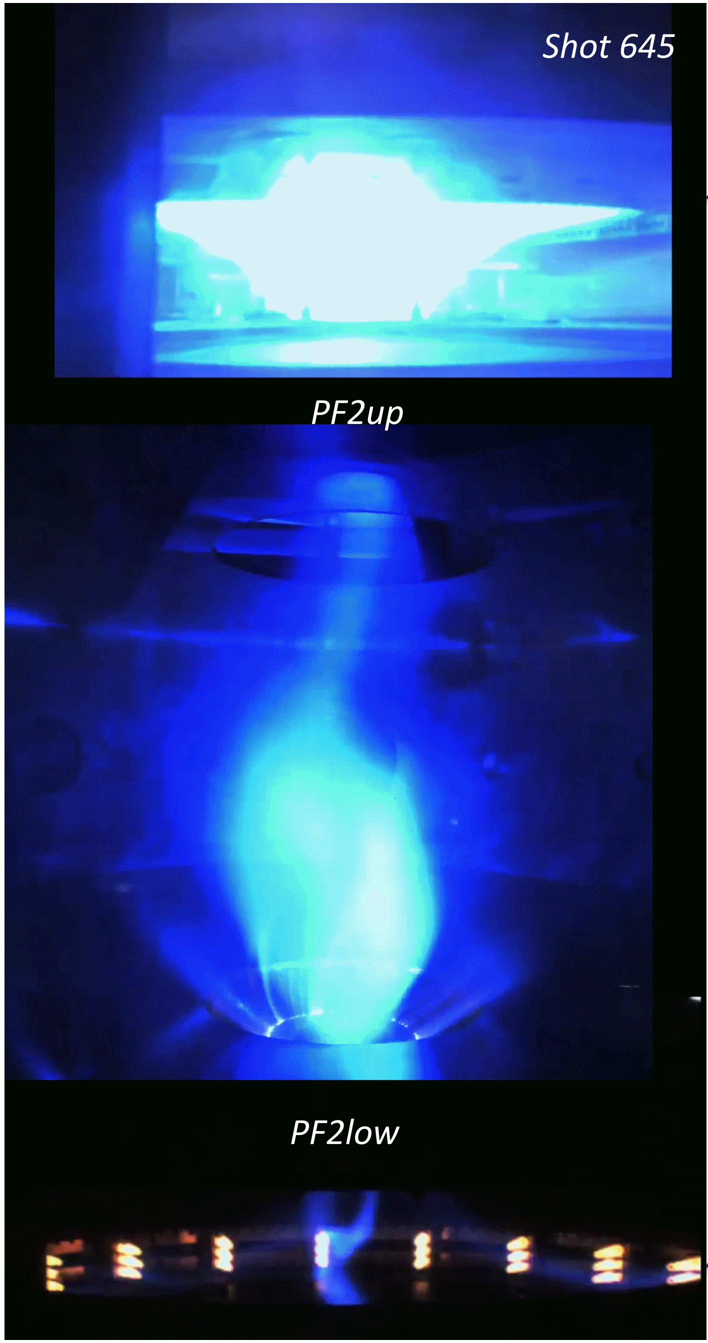
June 2017

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 ~ 6 \ 7 kA



This plasma centerpost discharge is quite near to the rotational trasform value ι ~ ½ ➔ (q_{Pinch} ~ 2)



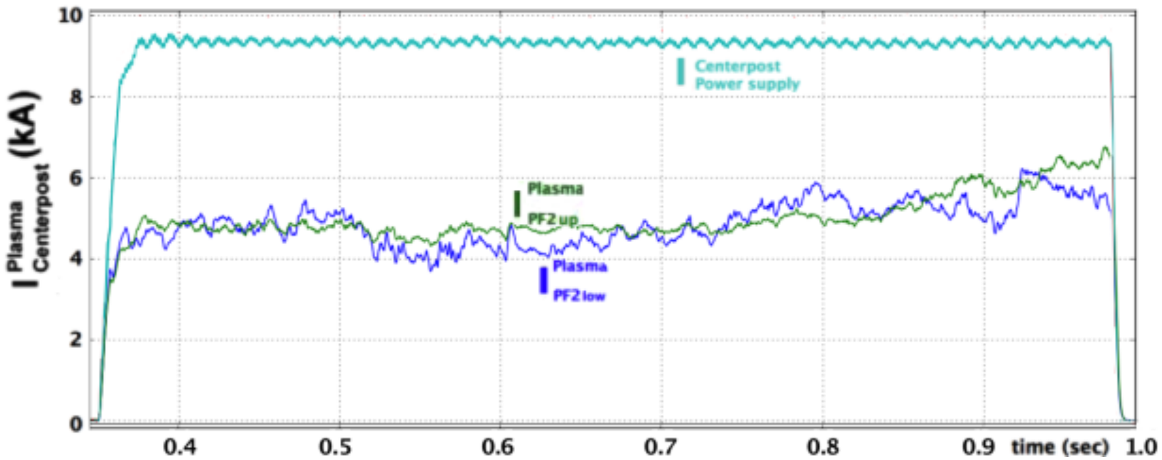
June 2017

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**

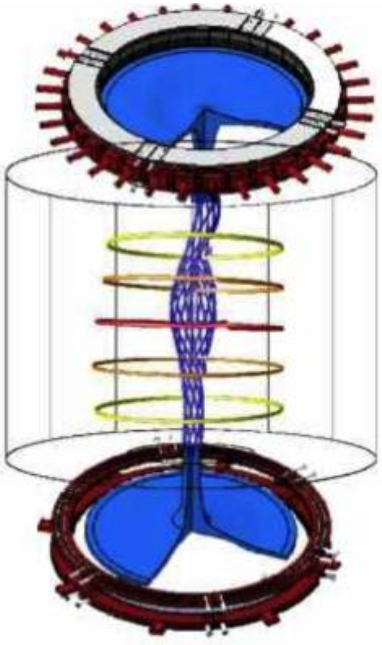
A long duration kink-bended plasma centerpost has been obtained with plasma currents through the PF2 coils ~ 5 \ 6 kA



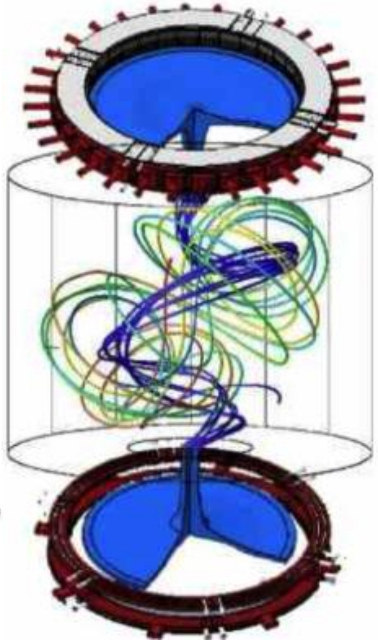
This plasma kink-bended centerpost discharge survives at a rotational trasform value ι ~ 1.66 ➔ (q_{Pinch} ~ 0.6)

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

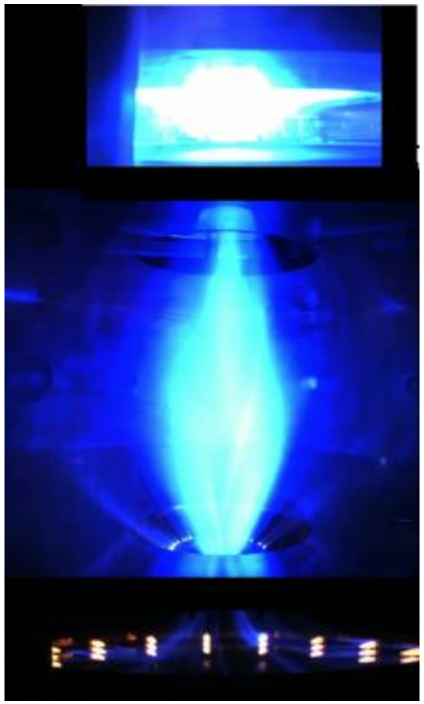
Physics Design
1997-2008

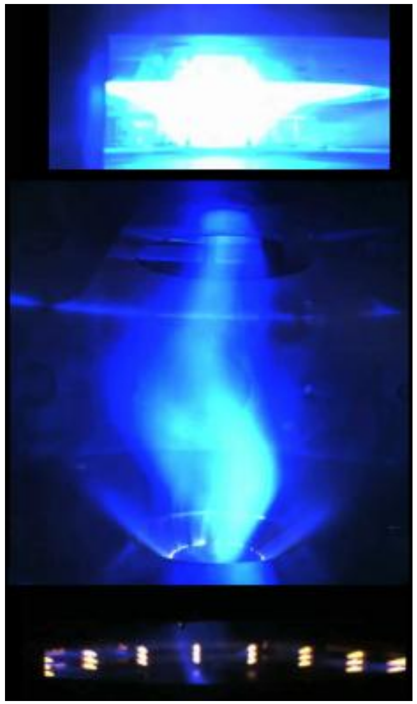


PROTO-SPHERA
destabilization



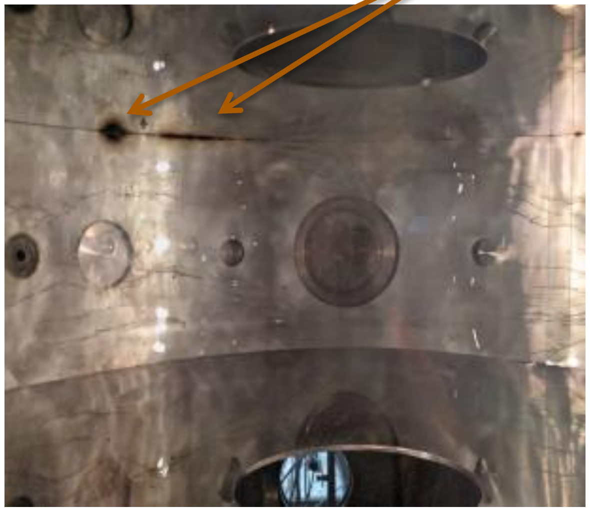
Experiment
2017

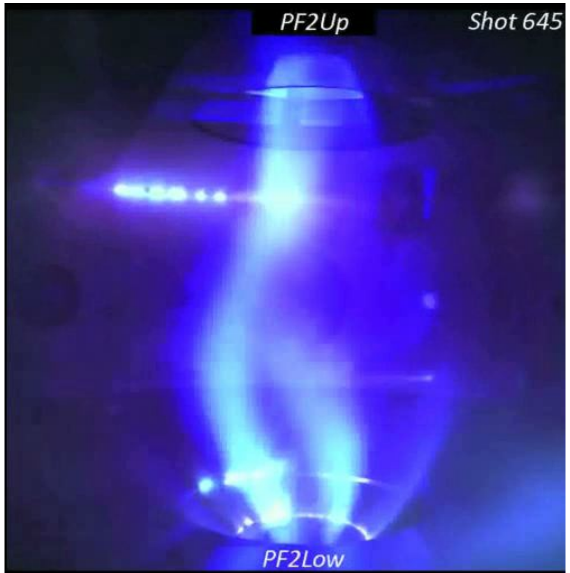




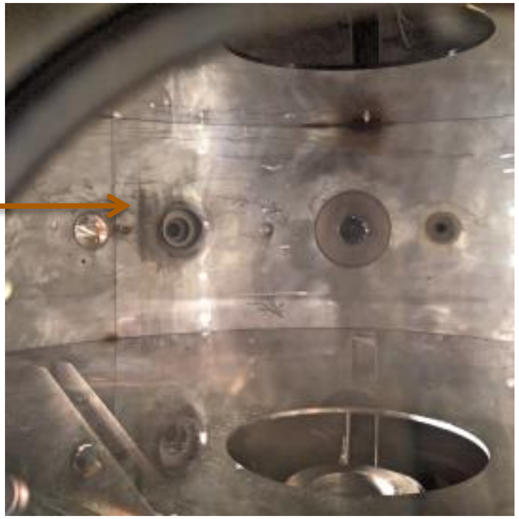
The plasma current sneaking through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm induces damages

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





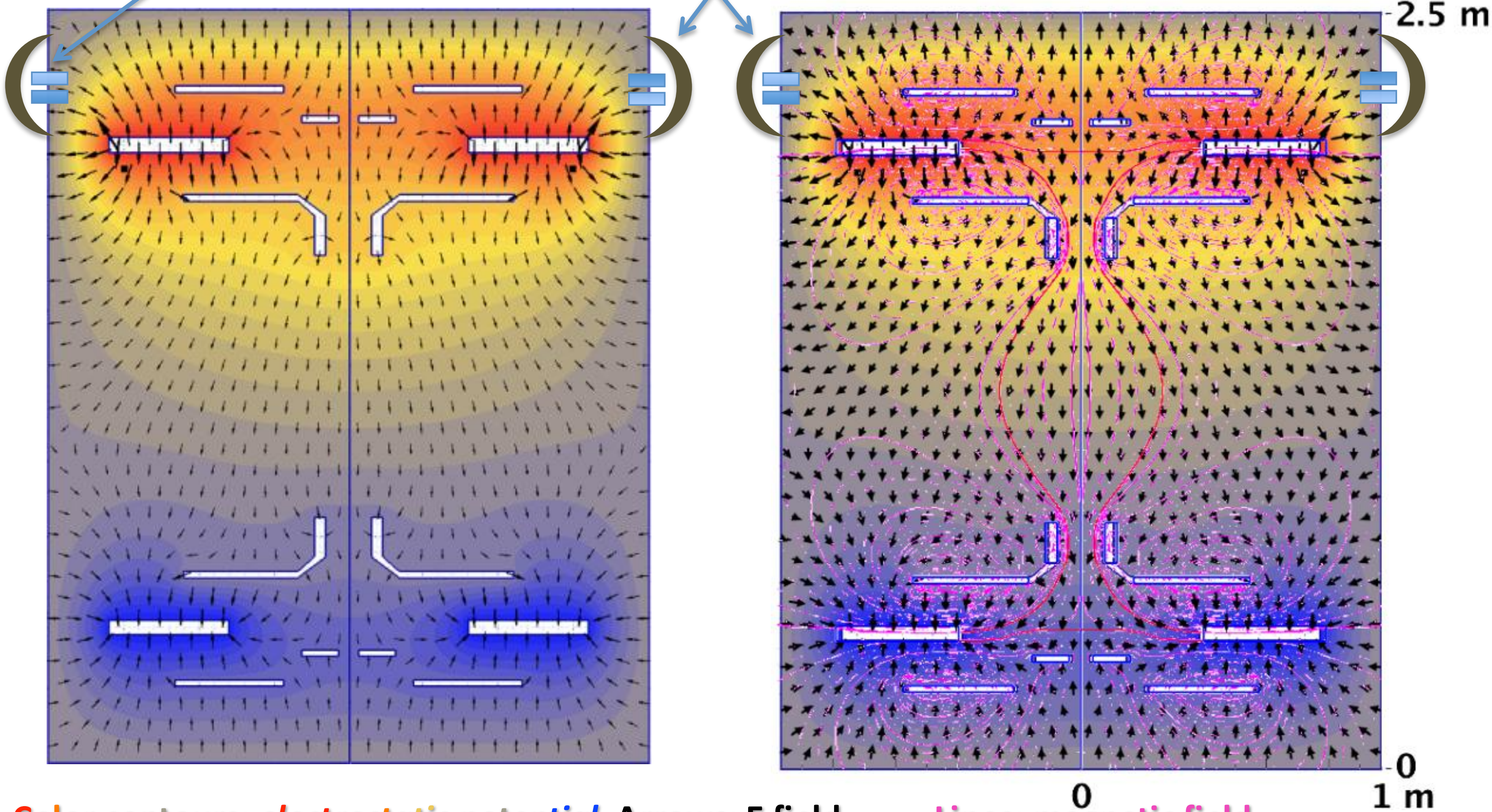
The port where the polycarbonate lining was cut, in order to allow for vacuum gauges measurements, **has to be closed**
& the gauges moved elsewhere



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**

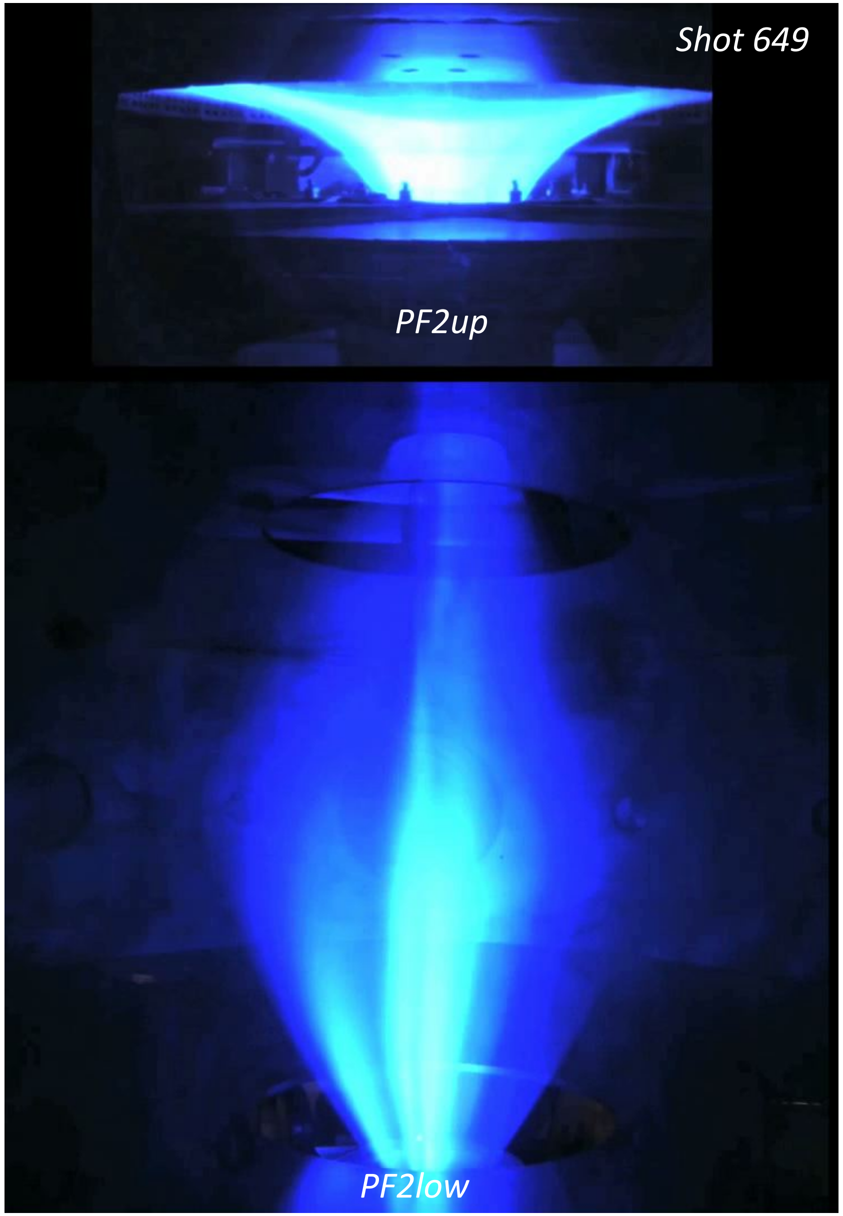


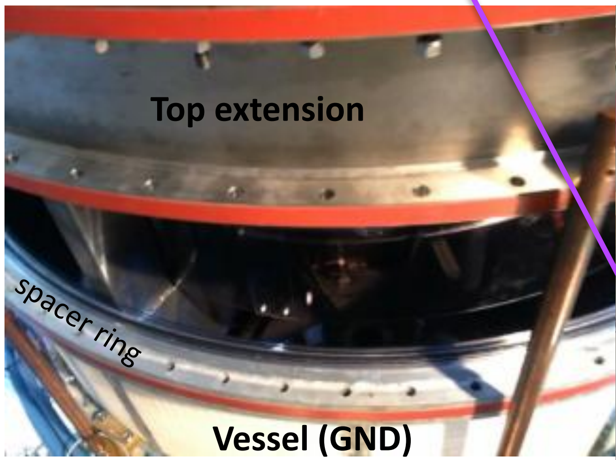
Color contours: *electrostatic potential*, Arrows: E field **Lines: magnetic field**

June 2017: **Polycarbonate spacer ring** **insulates top lid and top extension from vessel (GND)**

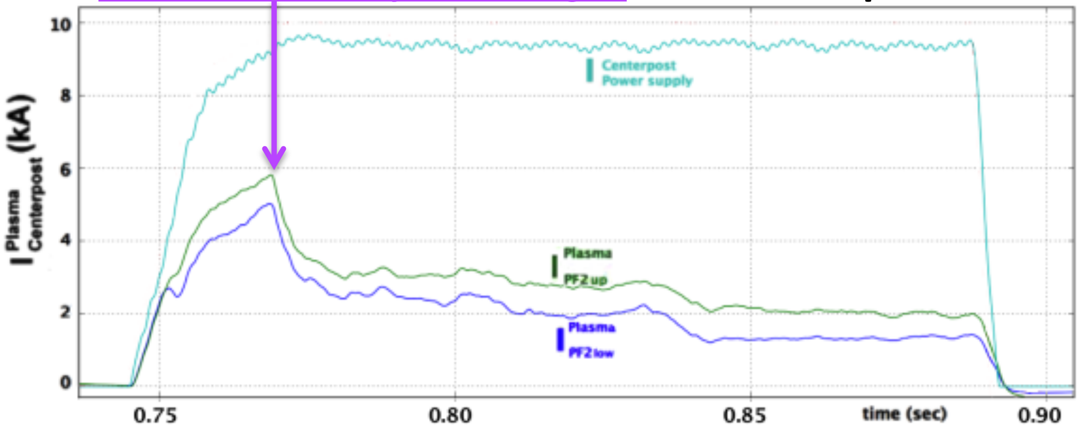
if they are put back in contact with vessel, plasma centerpost current through PF2 is hampered

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





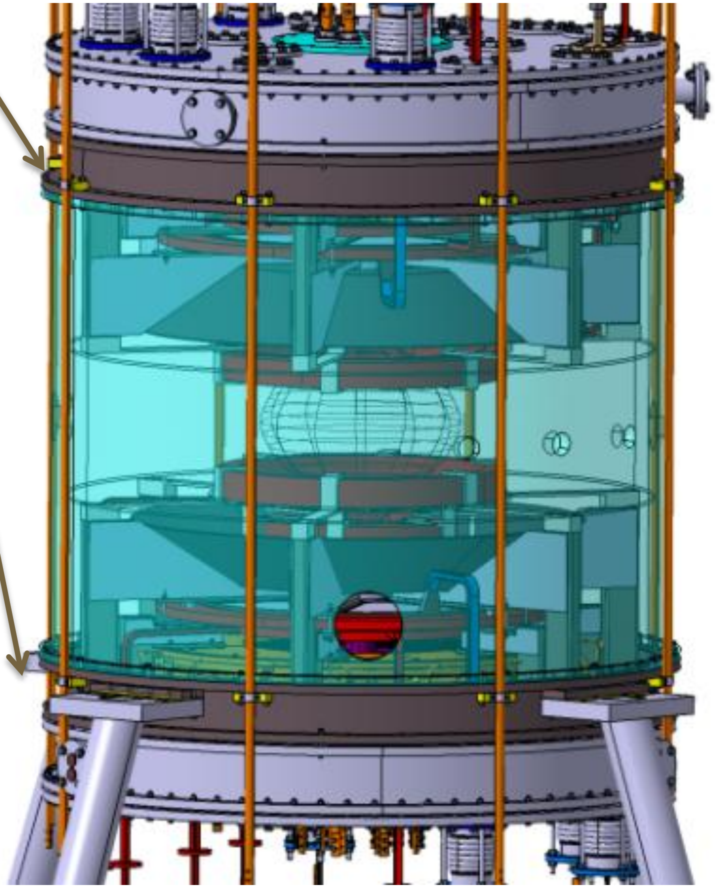
Plasma current reaches 6 kA, but after secondary discharges current drops to 3 kA



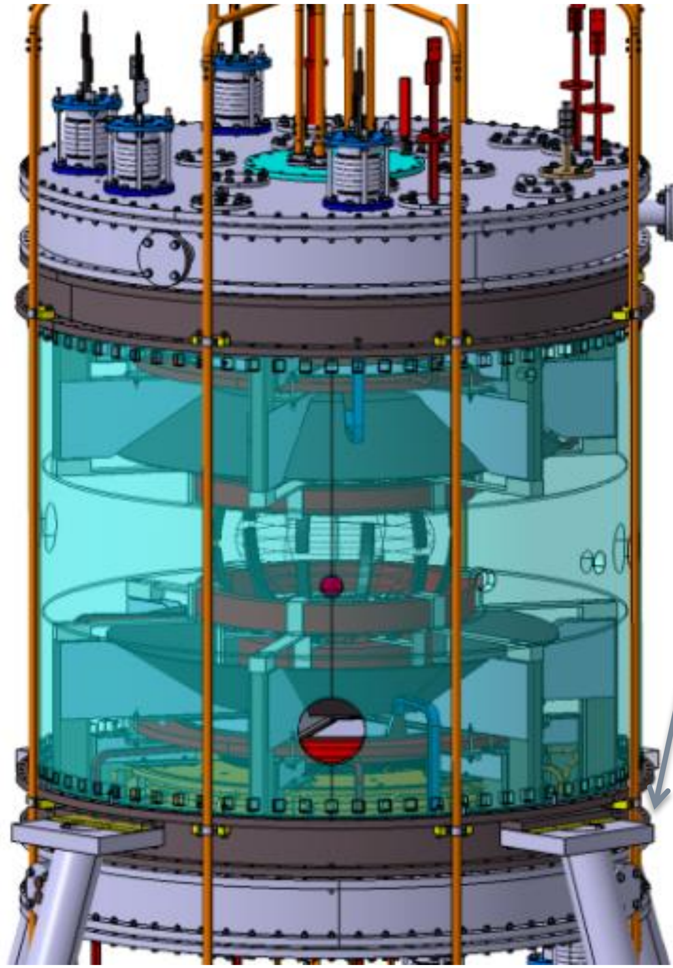
To achieve full centerpost current in Hydrogen (250 V break-down) needs a new insulating vacuum vessel

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 ⃠, 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

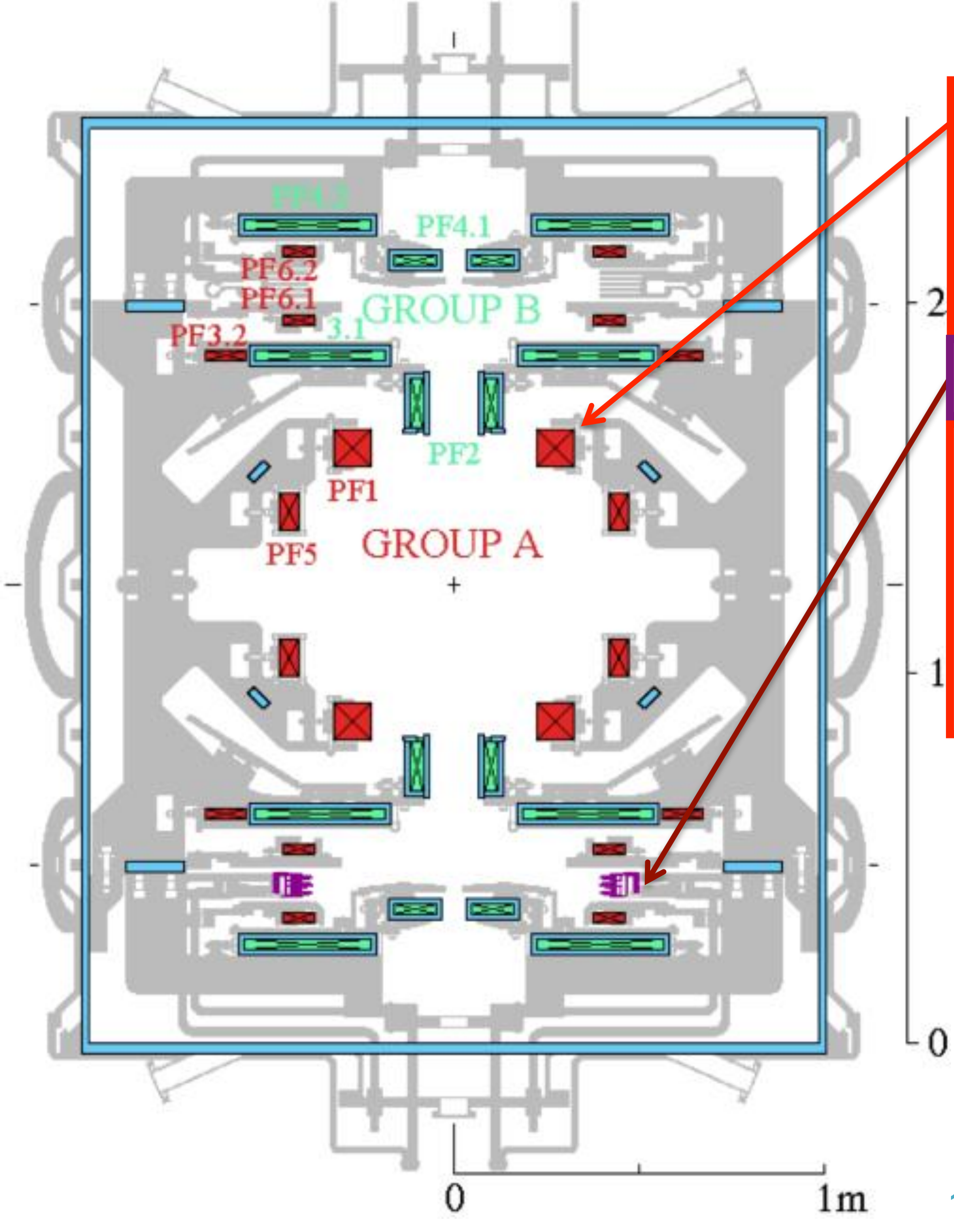


flanged PPMA cylinder



carved PPMA cylinder

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 (~ **20 kV**) insulation
- thin Inconel casings cost ~ 0.5M€

Tungsten filaments (**54 → 324**) cost ~ 0.2M€

Final Power Supplies for:

1) Group A PF coils cost ~ 0.1M€
2) Cathode (**I_{cath} 10 → 60 kA**) cost ~ 0.2M€
3) Centerpost (**I_e 10 → 60 kA**) cost ~ 0.6M€

SuperCapacitors will be used

Cost up to now ~ 2.0 M€

Cost for final stage of experiment ~ 1.6 M€

Status (June/July 2017)

- Hollow anode surprise, no anode arc attachment (electrostatic potential, E x 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): Te≈8-10 eV, n > 10^{19} 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

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

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

Power injected into the centerpost should be > 250 V • 60 kA = 15 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 eV PROTO-SPHERA studies plasma-electrode interactions
- **should it be 1 MW, then ST plasma T ~ 100 eV PROTO-SPHERA studies magnetic reconnections at relevant magnetic Lundquist number, S~10^5**
- **should it be many MW, then ST plasma T ~ 1 keV …β ~ 1 !**

…would do as a Tokamak, but at 1/100 of the cost

+ Other authors