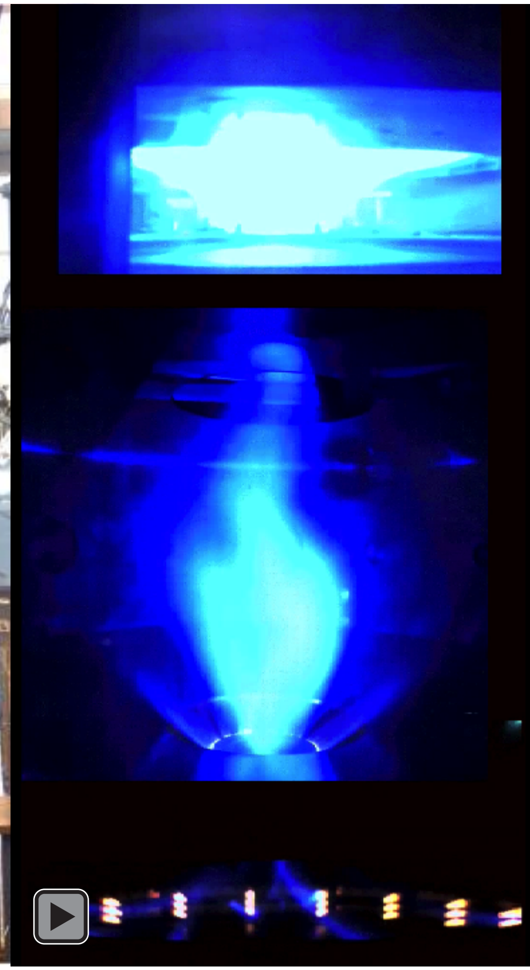
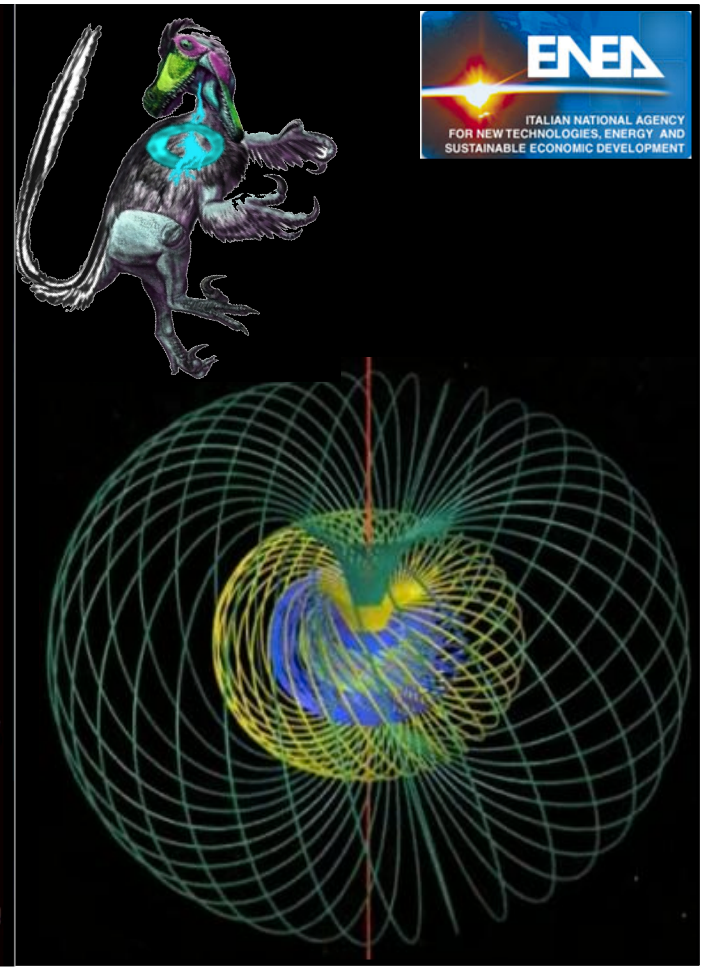
The PROTO-SPHERA experiment, an innovative confinement scheme for Fusion

Franco Alladio[1], P. Micozzi, 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

CR-ENEA Frascati, [1]franco.alladio@enea.it





19th International Spherical Torus Workshop (ISTW 2017), Seoul National University, 18-22 September 2017

Outline

A Spherical Torus whose Centerpost is a Plasma discharge

Why a new and different magnetic confinement device?

- **Possible unlimited sustainment of plasma current by DC voltage**
- **Natural examples of rings emitted by jets in fluids & plasmas**
- **High β value ~ 1 calculated for its ideal MHD stability**
- **If successful it could be the engine of a Fusion Space Thruster**

Present experiment produces only Plasma Centerpost

- **Modifications of boundary conditions:**
  - **- additional external PF coils**
  - **- insulating materials near the plasma,**

  have allowed achievement of full plasma current in Argon
- **Plasma configuration resilient to operation accidents**
- **Spontaneous rotation of Plasma Centerpost**
- **Mixed magnetic & electrostatic confinement**
- **A new vacuum vessel for Hydrogen discharges?**
- **Perspective**

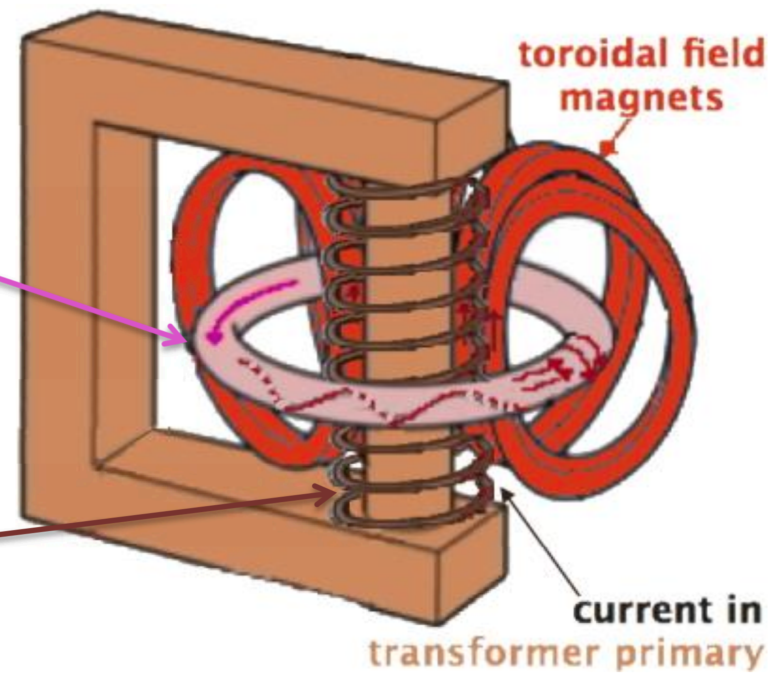
。。。二龙抢珠 èrlóng qiǎngzhū

Two Dragons are snapping at a pearl!

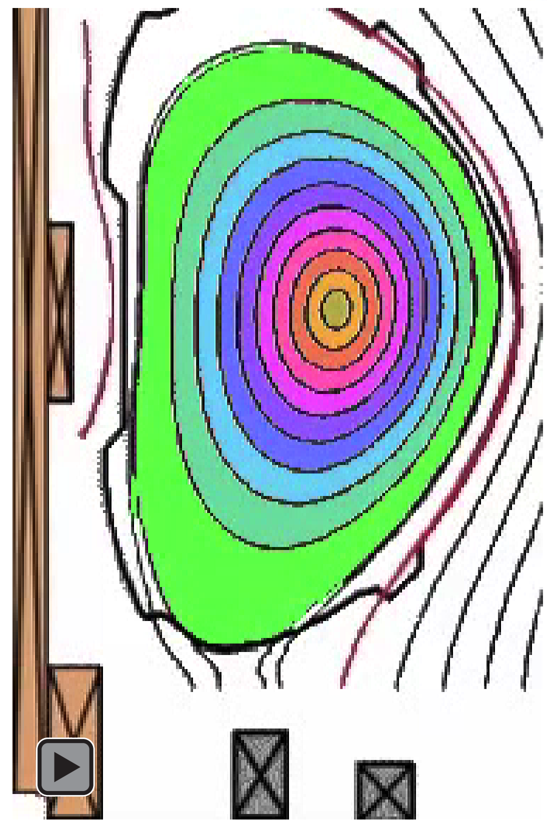
Therefore a **plasma confining current has to flow inside the Torus**:

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…

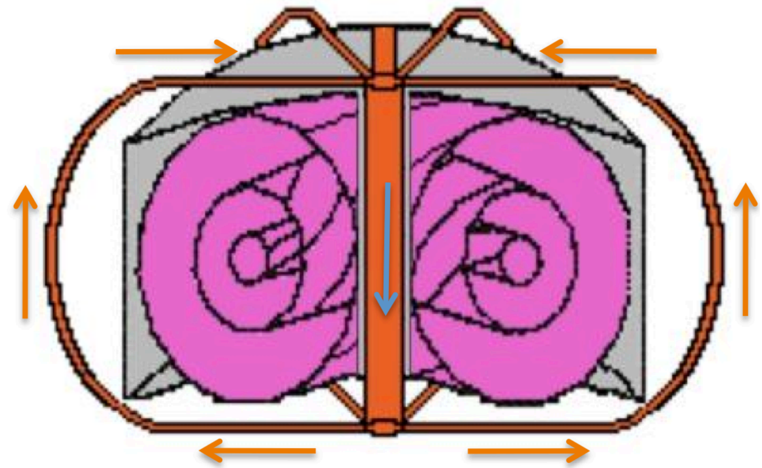


- **The plasma ohmic drive in a Tokamak can be seen as motion of closed flux surfaces, that from outside 'feed' the plasma, which dissipates them while they move toward the magnetic axis**
- **In tokamaks this process is due to the transformer current change:**
- **Tokamaks cannot have steady drive!**

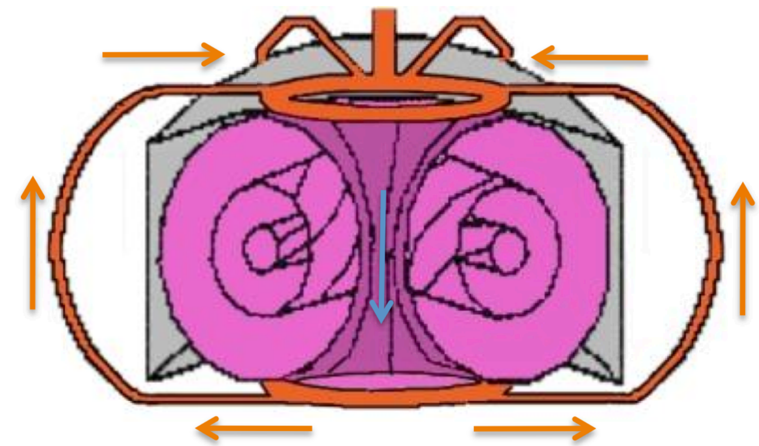


The main idea of PROTO-SPHERA

- "Conventional Tokamak": magnetic surfaces of toroidal plasma surround a "Metal Centerpost"
- *Vacuum vessel has toroidal geometry*



Electric current flow



- 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*

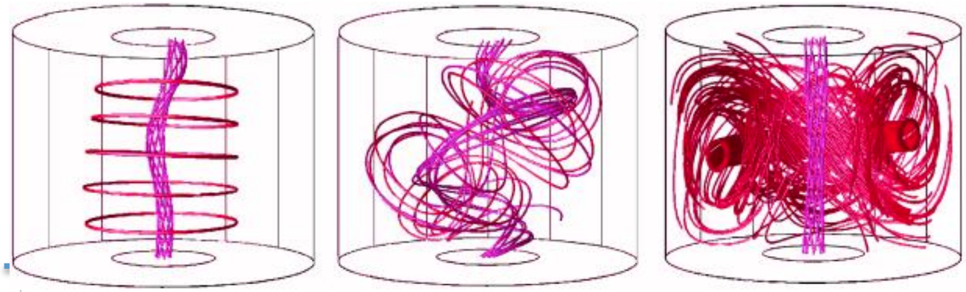
...but electrodes are required inside vacuum

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

→ easy of access & of repair...

PROTO-SPHERA Japanese precursor

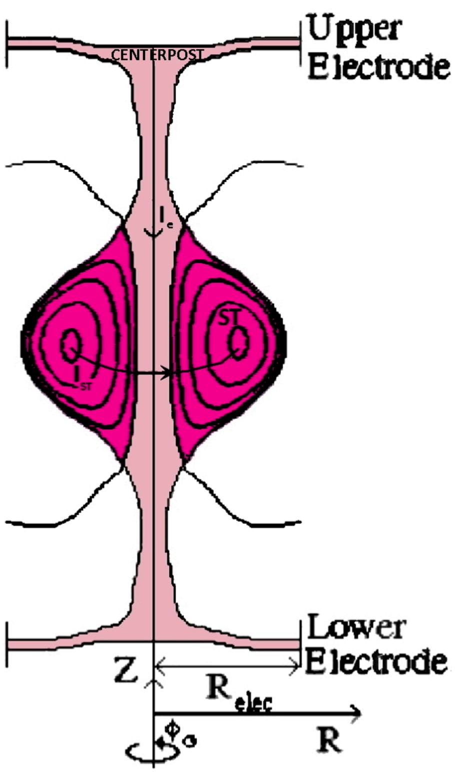
TS-3 (**Tokyo University**): **1993 removed the metal centerpost**, applied **1kV** between two plasma guns, produced a **I_e = 40 kA Plasma Centerpost, non-linear "kink" instability formed a Spherical Torus toroidal plasma current 50 kA < I_{ST} < 100 kA**



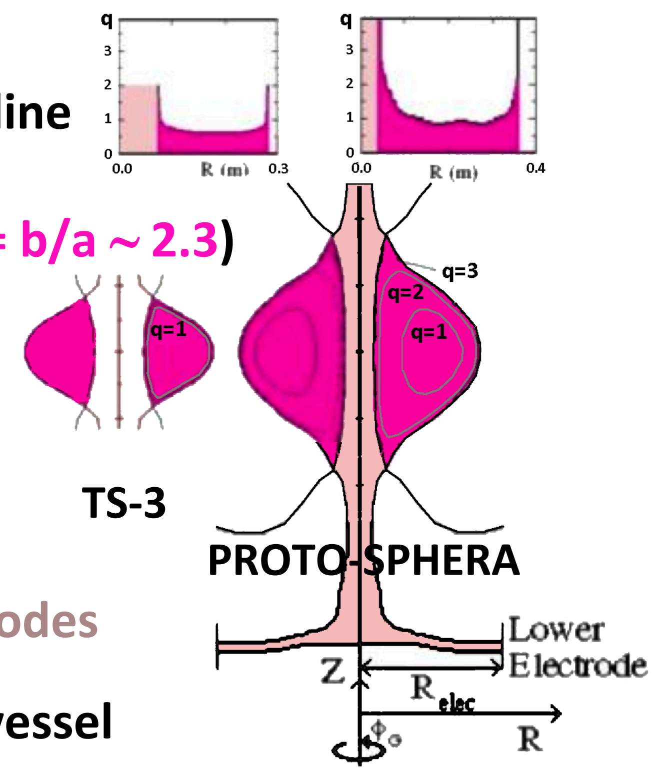
Stable Plasma Centerpost | Instability & Magnetic Reconnection | Plasma Centerpost & Torus

60 µs formation
20 µs sustainment
total duration **80 µs ~ 100 $\tau_{Alfvén}$**
(short but significant…)

PROTO-SPHERA key differences

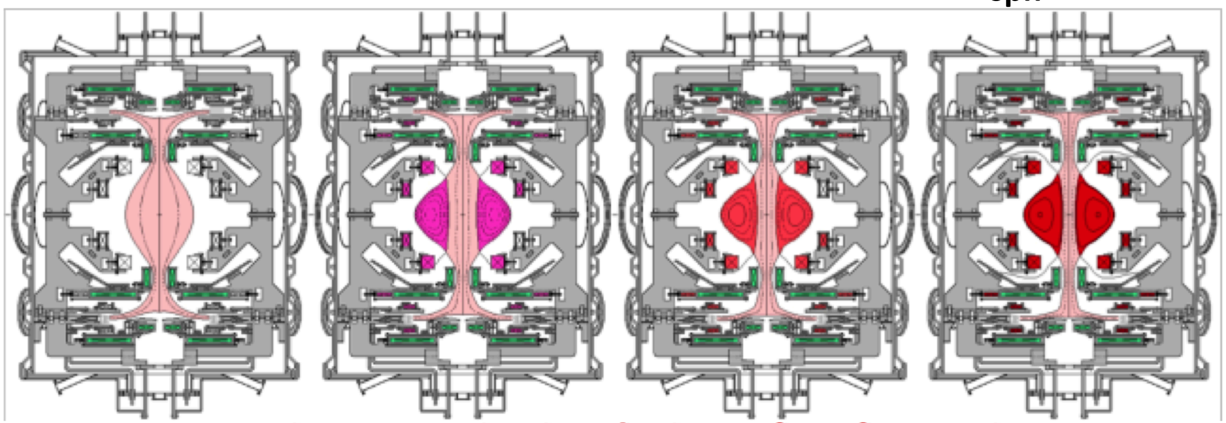


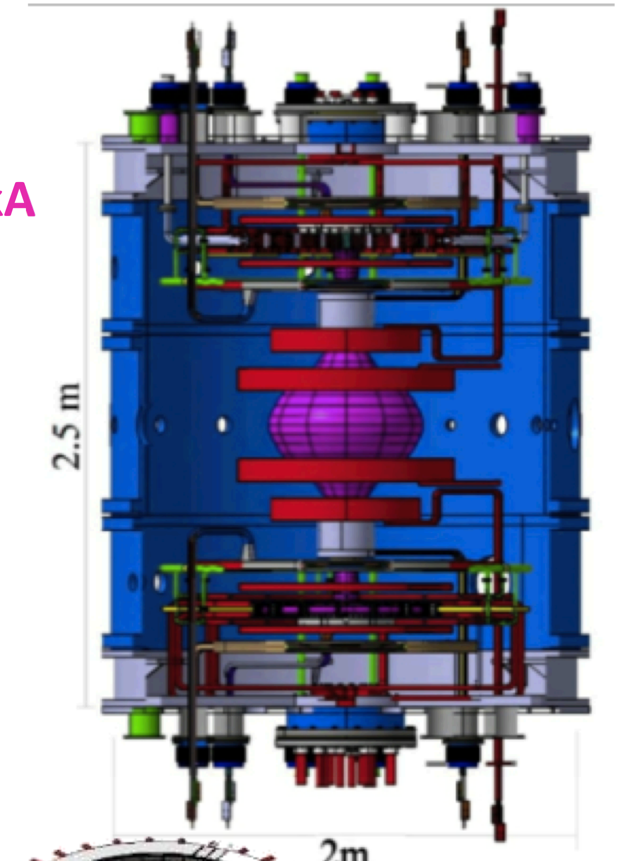
- **Designed for a Tokamak-like field-line rotational trasform ($q_0 \geq 1$, $q_{edge} \sim 3$) (aspect ratio A = R/a ≥ 1.2, elong. k = b/a ~ 2.3)**
- **PROTO-SPHERA formed "slowly" as a prolated low aspect ratio Spherical Torus from the pre-existing plasma centerpost, mushroom-shaped in front of electrodes**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



PROTO-SPHERA main design parameters:

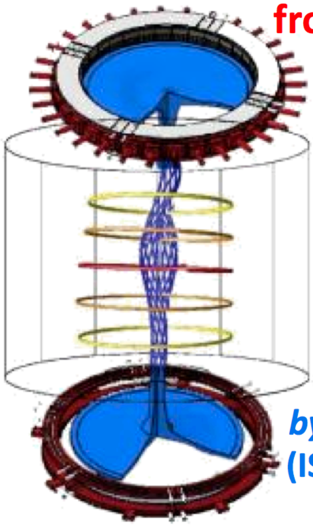
Centerpost current	I_e= 60 kA
ST toroidal current	I_{ST}= 120÷240 kA
ST diameter	$2R_{sph}$= 0.7 m





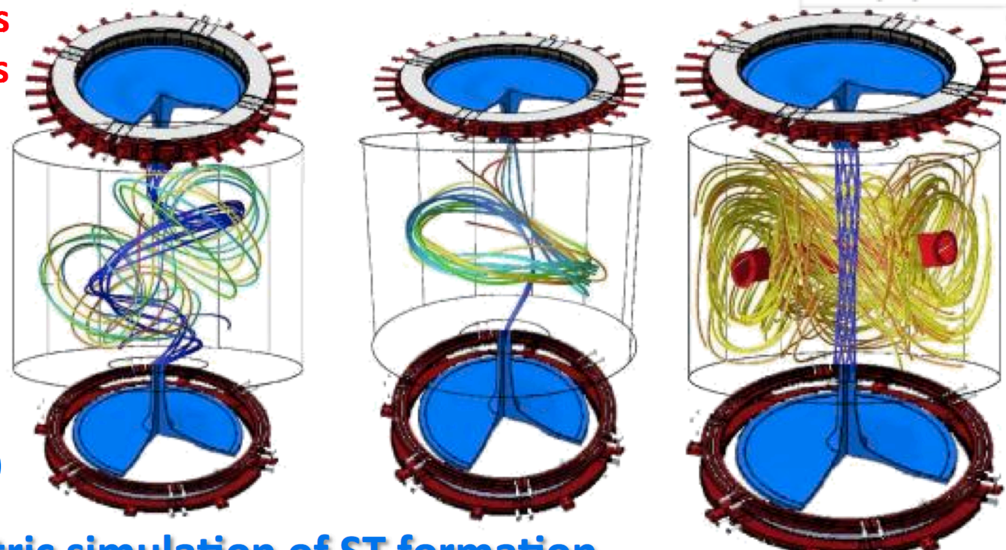
Axisymmetric simulation of ST formation

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

by Ricardo Farengo (ISTW2008-Frascati)

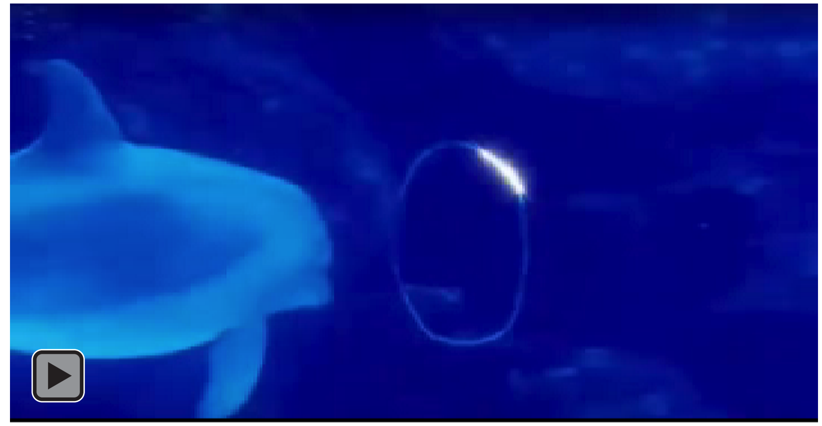


Non-axisymmetric simulation of ST formation

Garcia-Farengo, PoP **16**,112508 (2009)

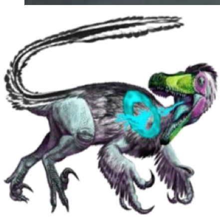
Formation & sustainment of Rings from Jets is a common occurrence in Nature!

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

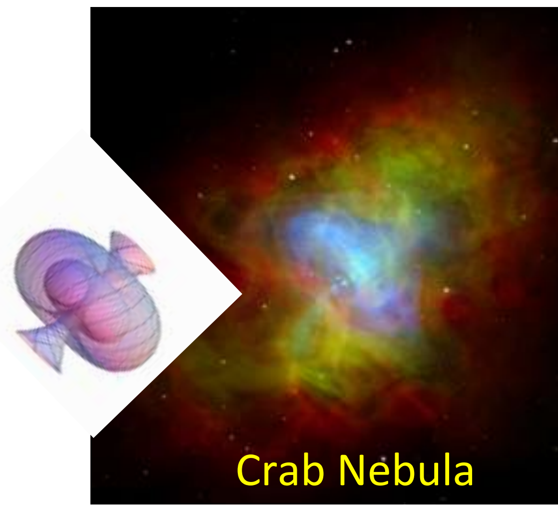


Fluid dynamics examples

William Irvine-University of Chicago



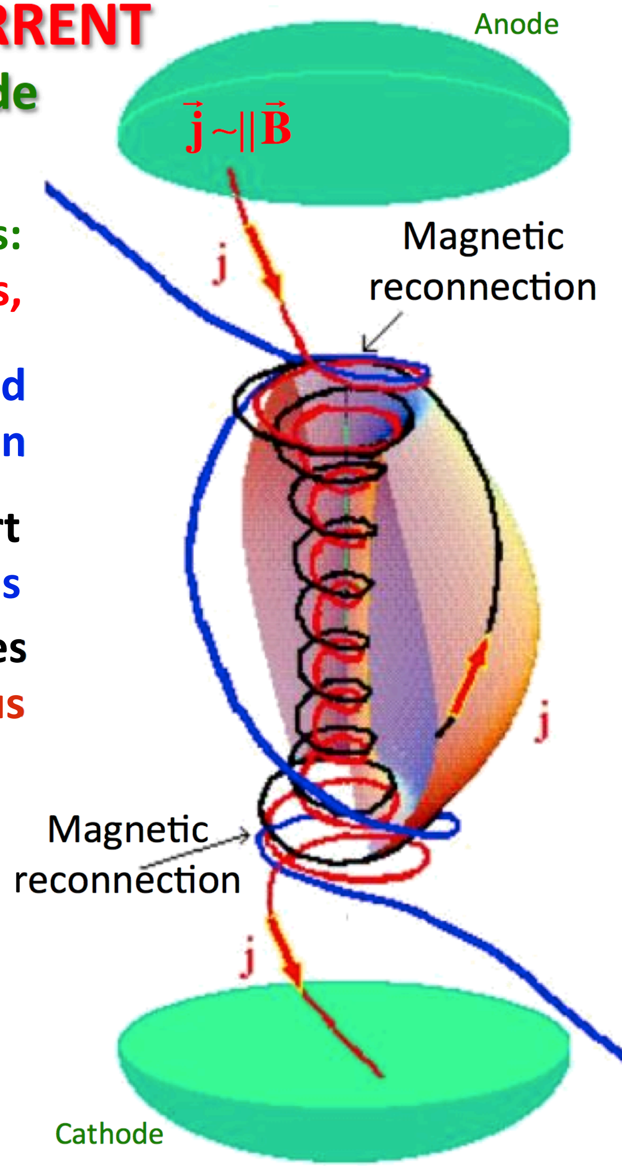
Plasma dynamics example

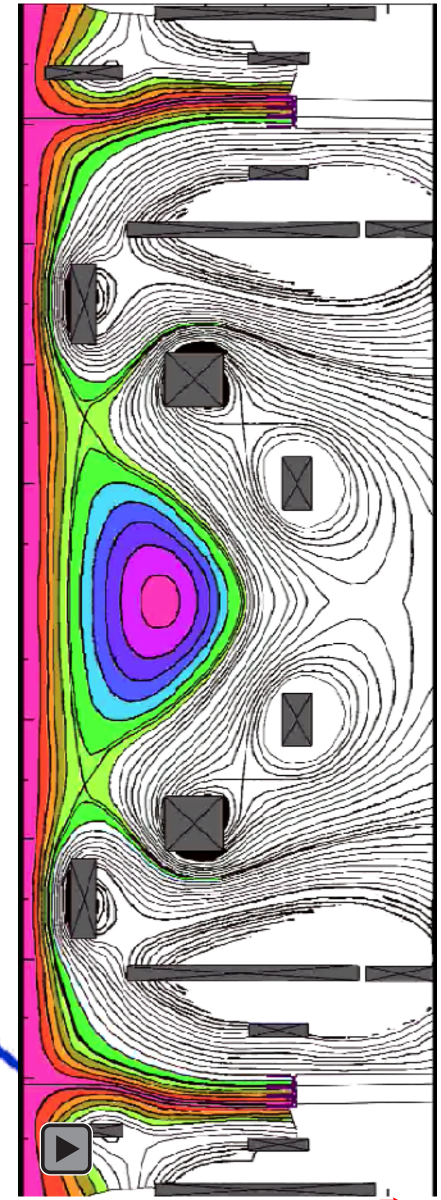


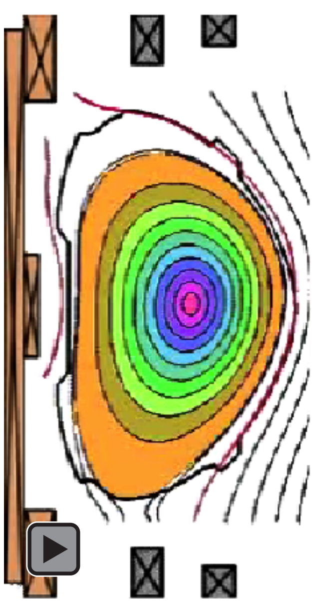
SUSTAIN THE CONFINING CURRENT

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

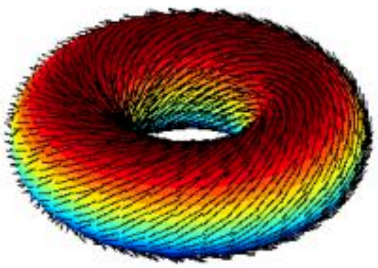
HOW EFFICIENT THE SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS?

Space Thruster?

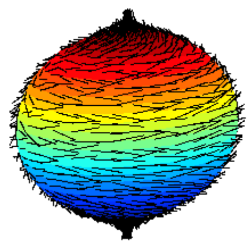
abandon vacuum vessel toroidal geometry, move to cylindrical one

… → natural expulsion of charged fusion products (Space Thruster)

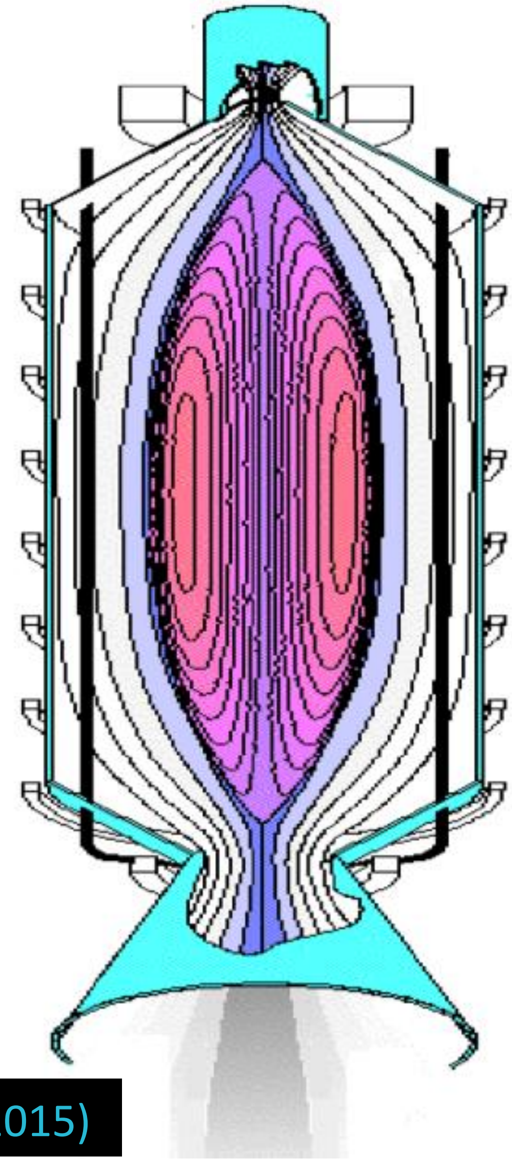
Due to filamentary nature of B field
a fundamental mathematical difference appears:



a hairy torus can be combed

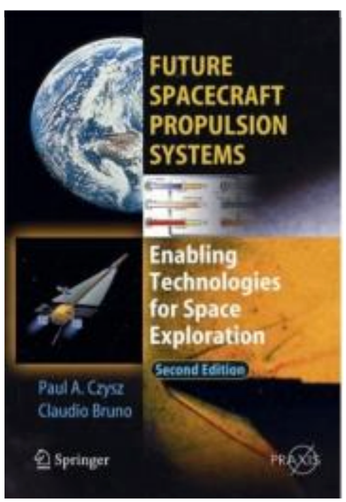


a hairy sphere cannot!



From one of the "***tufts***" of the sphere (…not combed)
very high velocity (~ MeV) charged fusion products emerge

Possible future application as a Space Fusion Thruster…

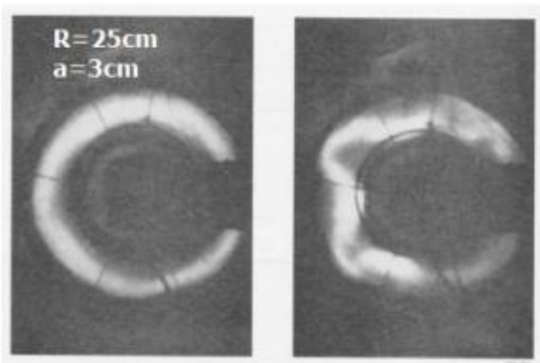


Nozzle observed in PROTO-SPHERA experiment (2015)

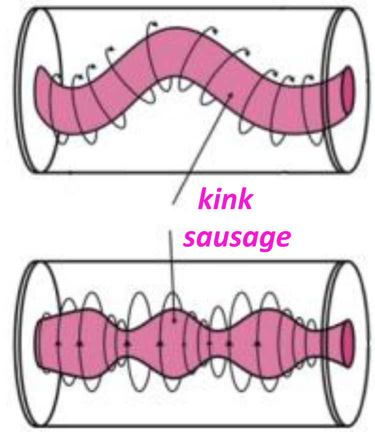
Why a new and different magnetic confinement device? one reason is ..."disruption"

Alan Ware & Thomson Imperial College 1947.

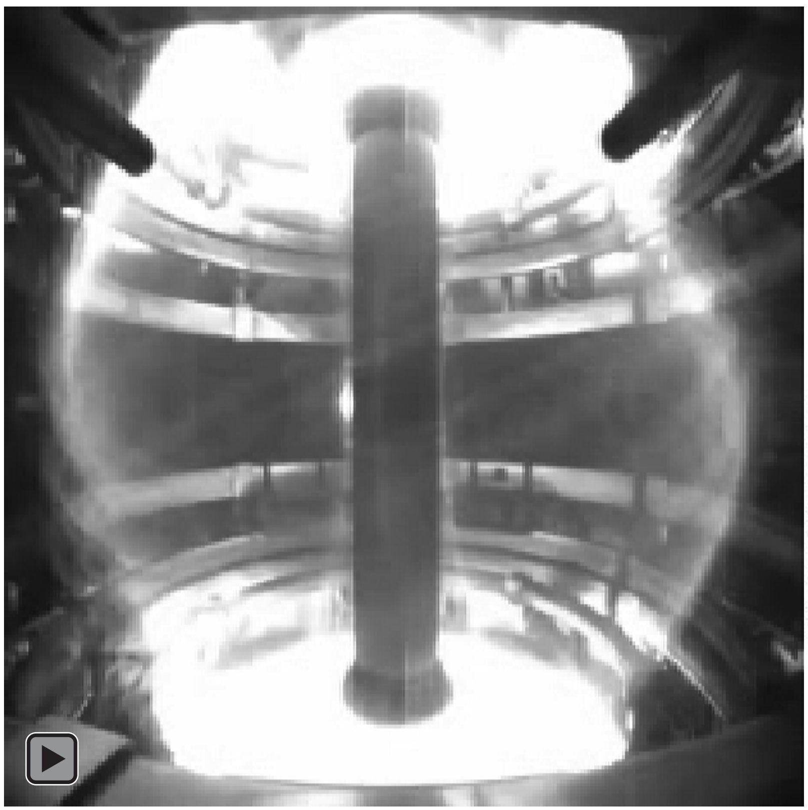
... Even if the muttered mantra is that Tokamak physics is perfectly known ...



MHD instabilities appeared since the earliest toroidal magnetic confinement devices

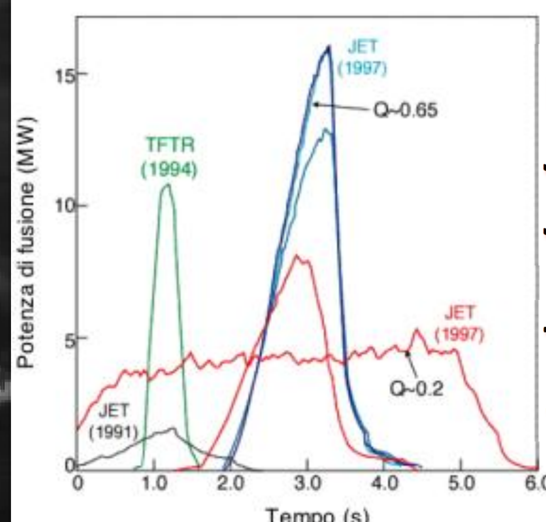


Mast 2004



...the problem of disruption has not yet been solved

... Only Stellarator configurations (no net toroidal current!) avoid this inconvenience

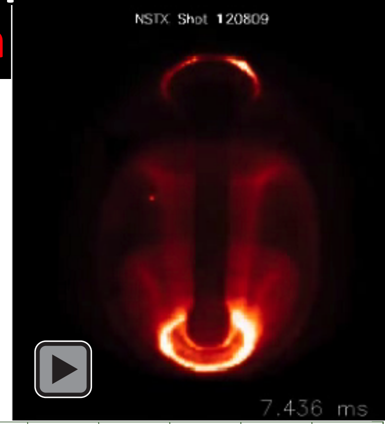


In D - T experiments:
JET 1991- TFTR 1994
JET 1997

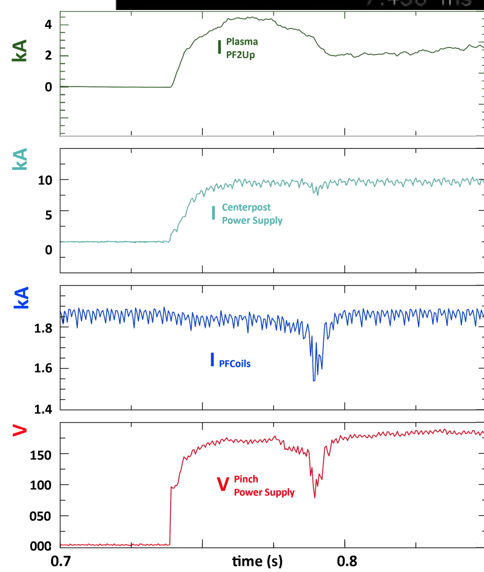
The highest neutron yield ...terminates in a disruption

- **Disruptions …toroidal plasma vanishes → damages, very long plasma restart, …**

DC helicity injection in NSTX Spherical Tokamak (with metal centerpost)
plasmoids are born & reborn



PROTO-SPHERA shot #364 (2016)
Plasma started without B field
Centerpost forms when B field is on



shot #734 (2017)
Langmuir probe
accident

In case of disappearance of toroidal current the configuration can reappear

Why a new and different magnetic confinement device?
another reason is ... "β limit"

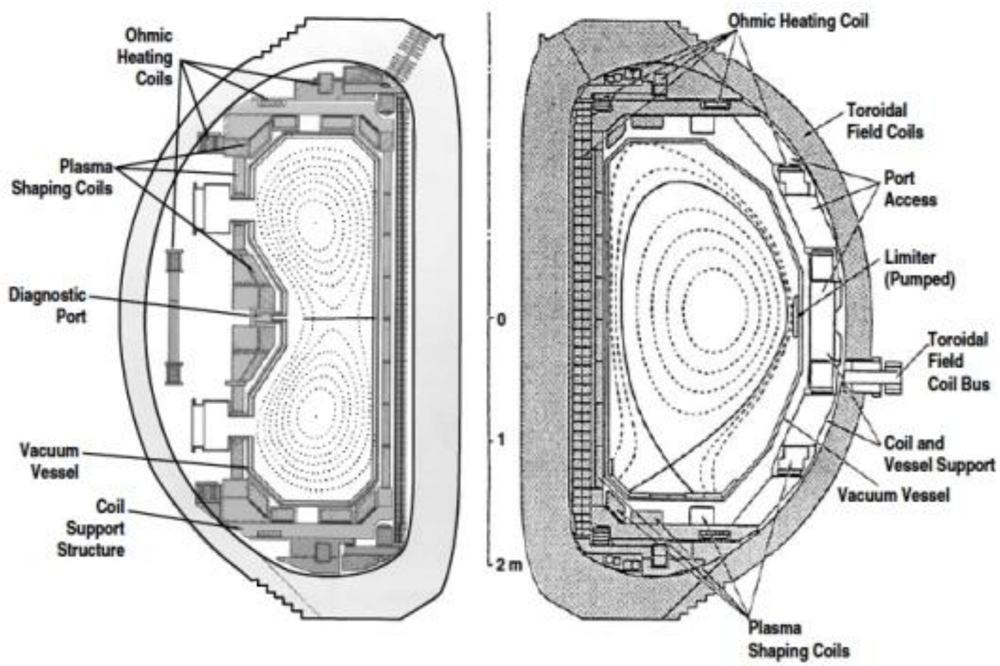
... Even if the muttered mantra is that tokamak physics is perfectly known ...

$$\boldsymbol{\beta} \text{ = plasma beta = } \frac{\textit{kinetic plasma pressure}}{\textit{confining magnetic field pressure}}$$

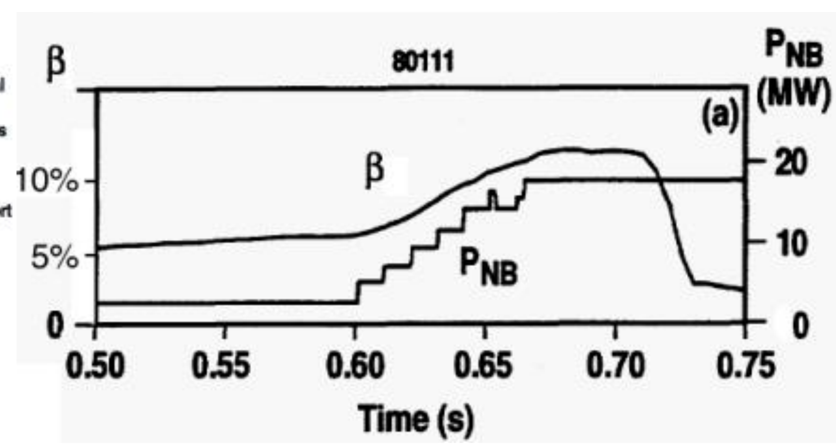
$\beta = 2\mu_0 \int p\, dV \Big/ \int B^2\, dV$ but in tokamak experimental data one often uses β_{T0}

$\beta_{T0} = 2\mu_0 \int p\, dV \Big/ B_{T0}^2\, V$ where B_{T0} is the vacuum field on the axis of the plasma

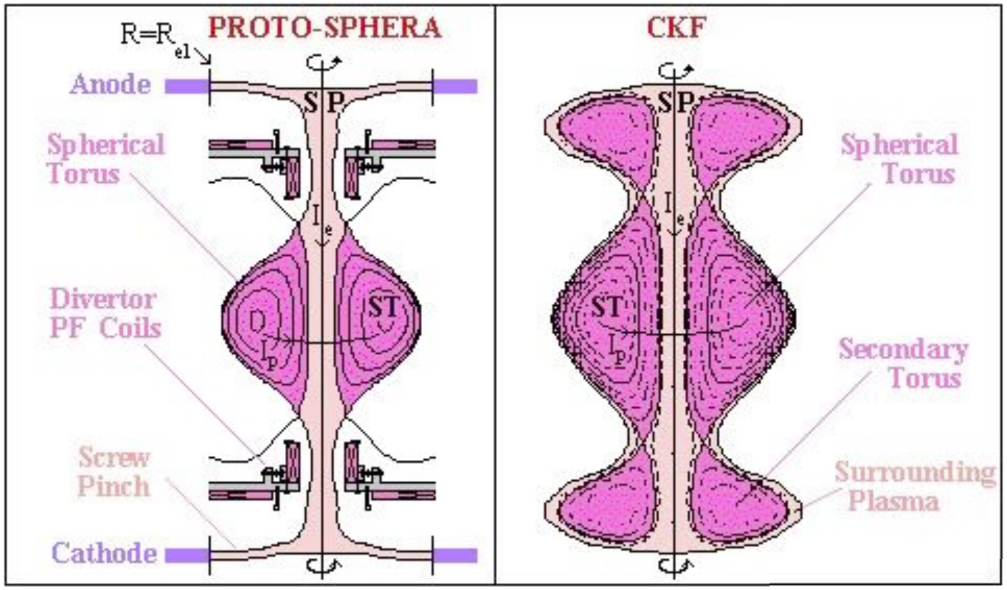
DIII-D in 1994 reached the highest value of β in conventional Tokamaks



DIII-D reached β_{T0} = 12.5%, but…the plasma "disrupted" vanished in ~ 1 msec !



• **Beta …plasma pressure few % of magnetic pressure → cost, size, …**



Chandrasekhar-Kendall-Furth configuration
CKF an extrapolation of PROTO-SPHERA:

• ***internal PF coils** replaced by* ***secondary Tori of Plasma***

• ***Centerpost hitting electrodes** replaced by* ***Surrounding Plasma***

CKF are ideally MHD stable up to β =1
but also PROTO-SPHERA can approach β =1

For low toroidal numbers n=1, 2 & 3
ideal MHD stability obtained

expressed with $\beta = 2\mu_0 \int p\, dV \big/ B^2 dV$

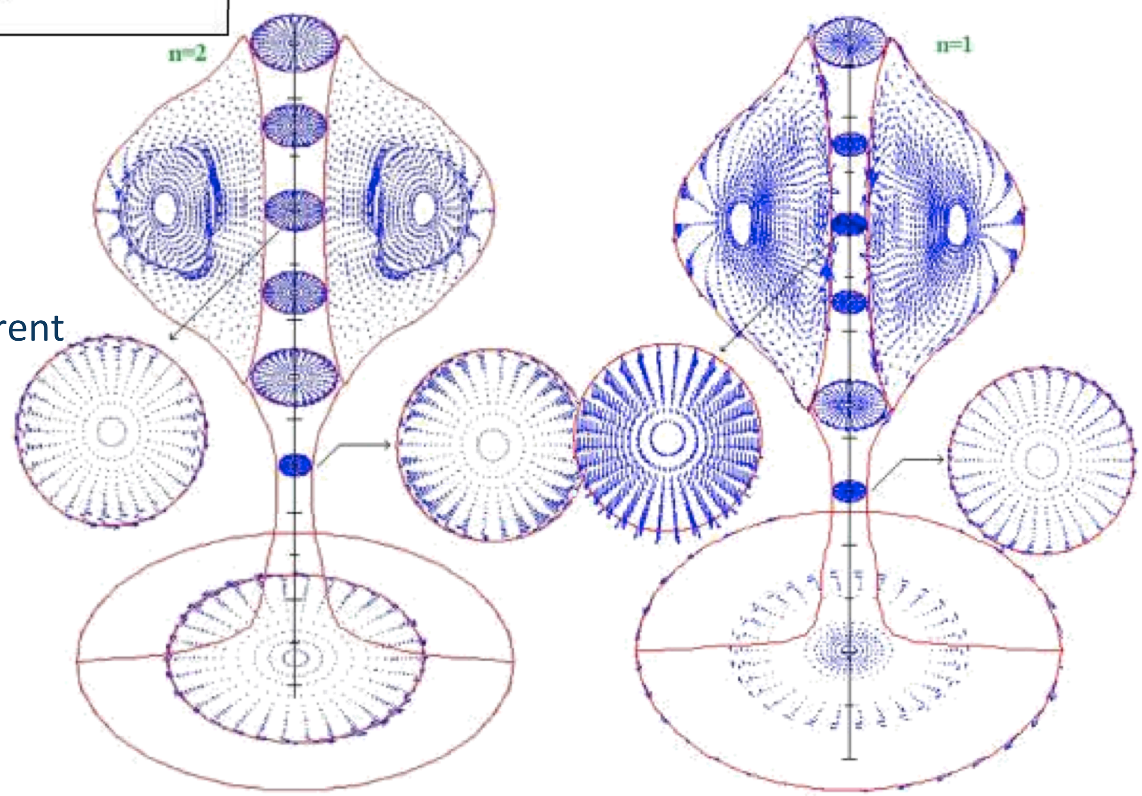
ratio of the two plasma currents

I_{ST}/I_e = toroidal ST current/centerpost current

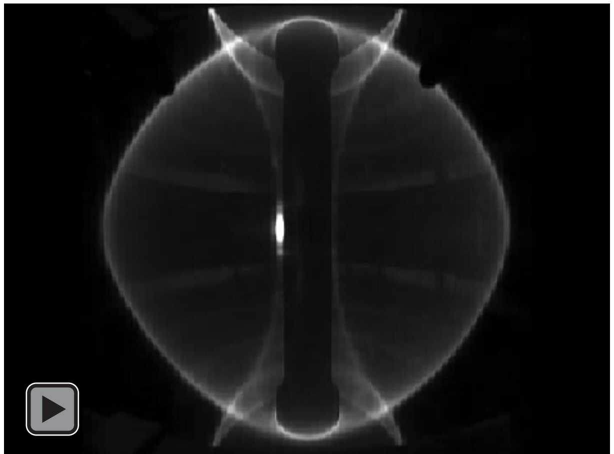
- up to β = 21÷26% , I_{ST}/I_e = 0.5 - 1
- up to β = 14÷15% , I_{ST}/I_e = 2-4

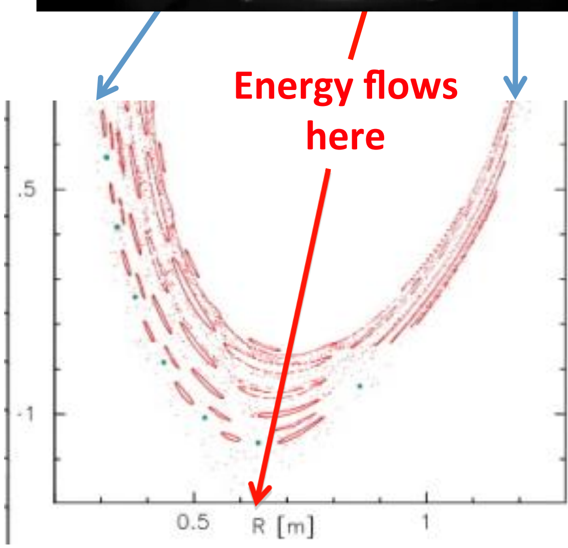
expressed with $\beta_{To} = 2\mu_0 \int p\, dV \big/ B_{T0}^2 V$

- up to β_{T0} =28÷29% , I_{ST}/I_e = 0.5 - 1
- up to **β_{T0} =72÷84% , I_{ST}/I_e = 2-4**

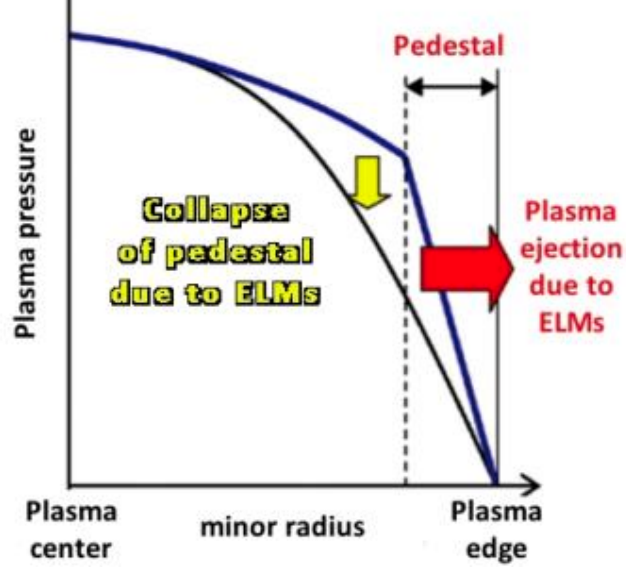


Why a new and different magnetic confinement device? still other reason are... "ELMs" (unstable edge localized modes)

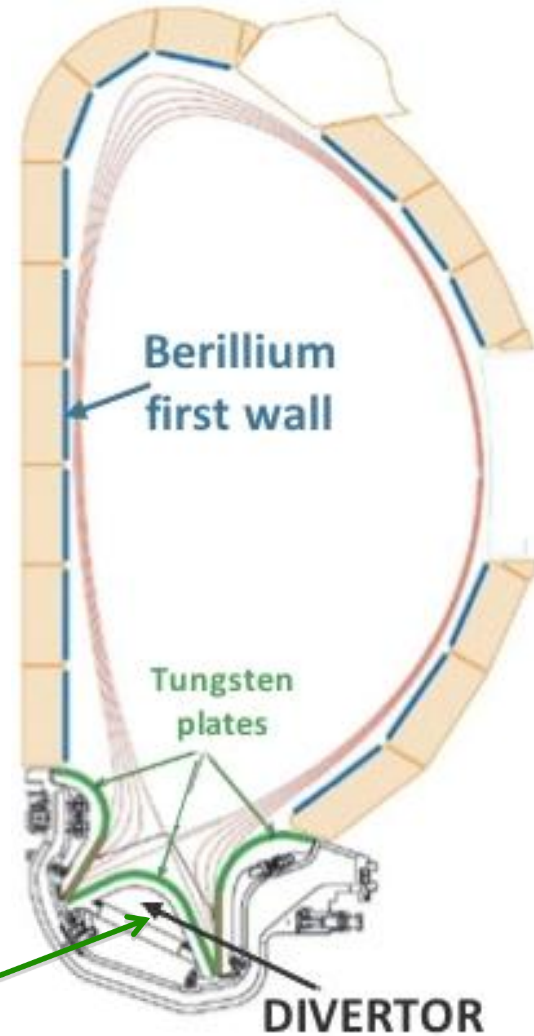




"**ELM**" mode throw upon the divertor a sizeable portion (~ **20%**) of the **energy in the pressure pedestal**



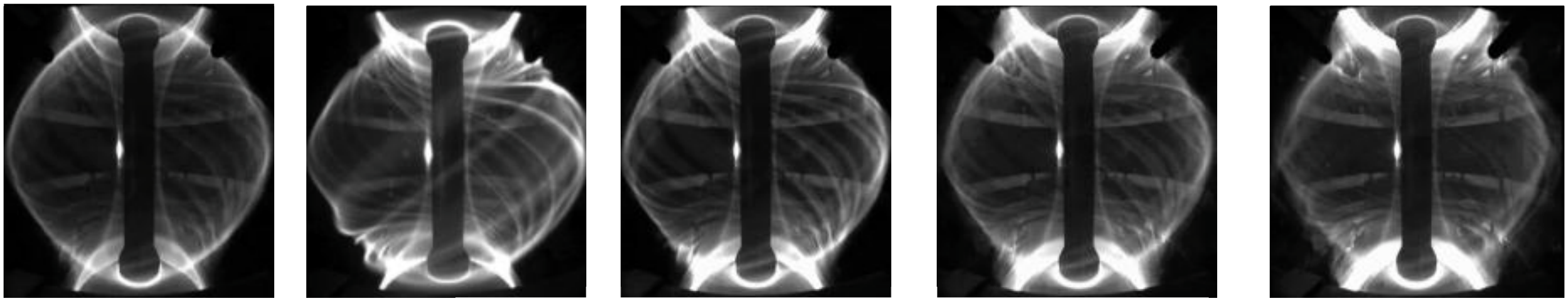
This happens in a **very short time (250 μs)** as the **plasma edge becomes ergodic** (**ELM** filaments carry current)



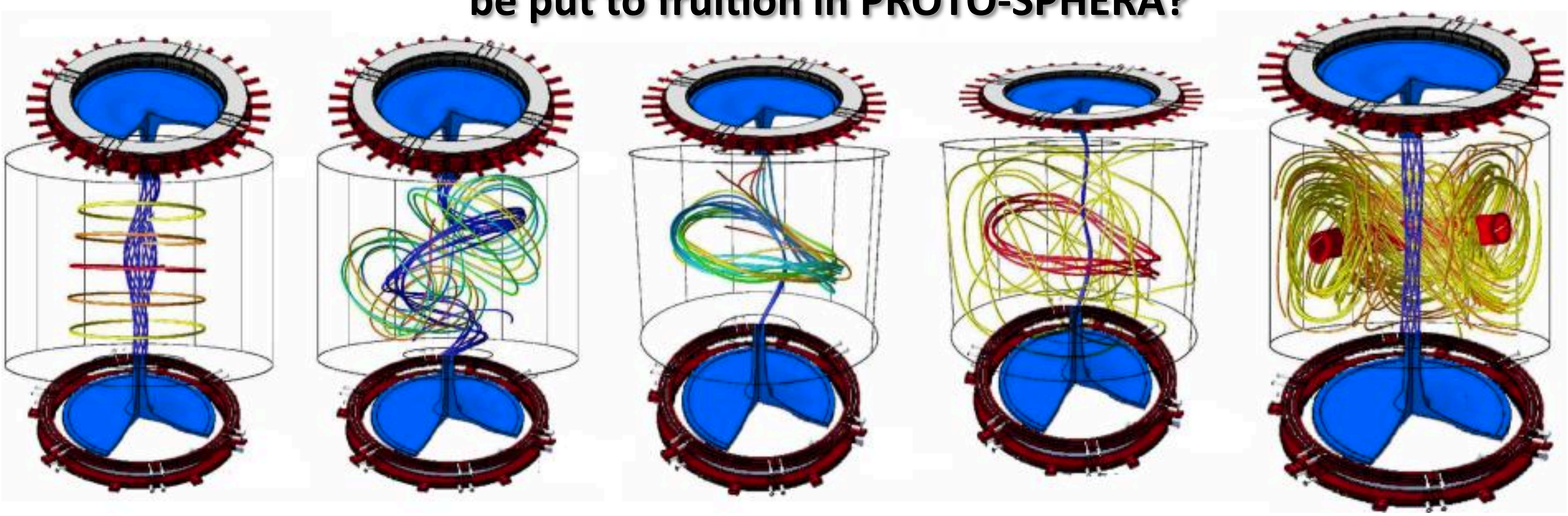
On **ITER** an **ELMs carrying > 3% of pedestal energy** can even **melt or sublimate** the **Tungsten of the Divertor plates**

"ELMs" (unstable edge localized modes):

can these spontaneous filamentations (which in Tokamaks are only dangerous)



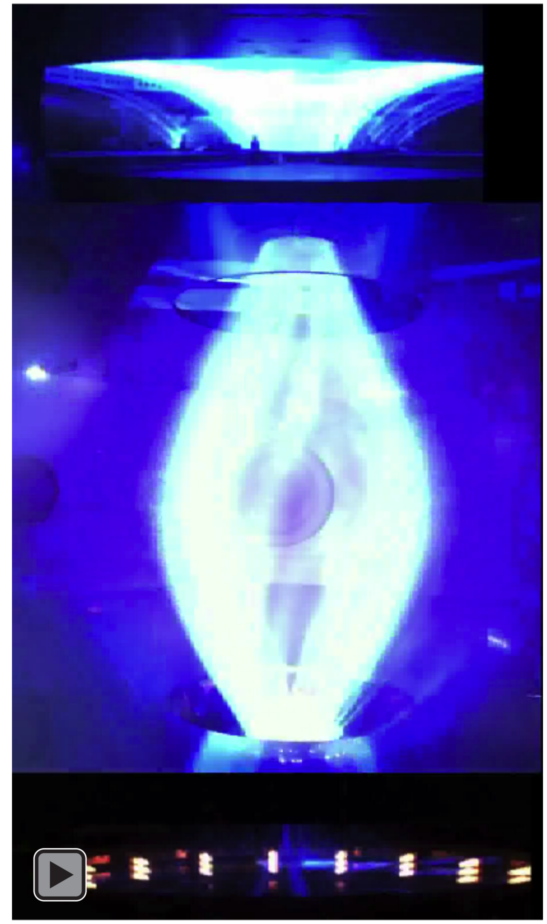
be put to fruition in PROTO-SPHERA?



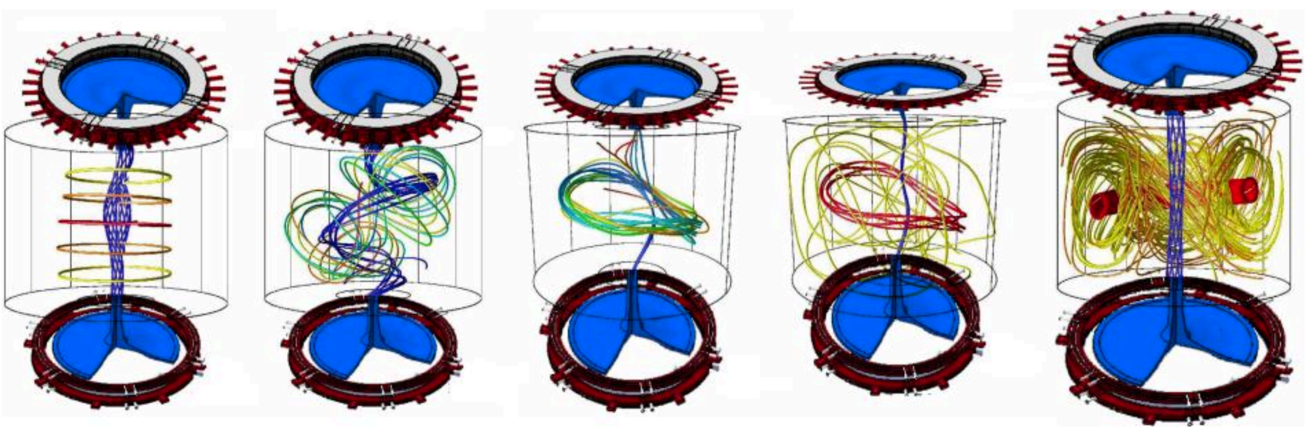
Plasma rotation in Tokamaks is extremely advantageous, as it stabilizes the torus

Plasma rotation induced by additional heatings (Neutral Beam Injection, NBI), becomes more & more difficult on larger tokamak experiments

Plasma Centerpost of PROTO-SPHERA rotates!



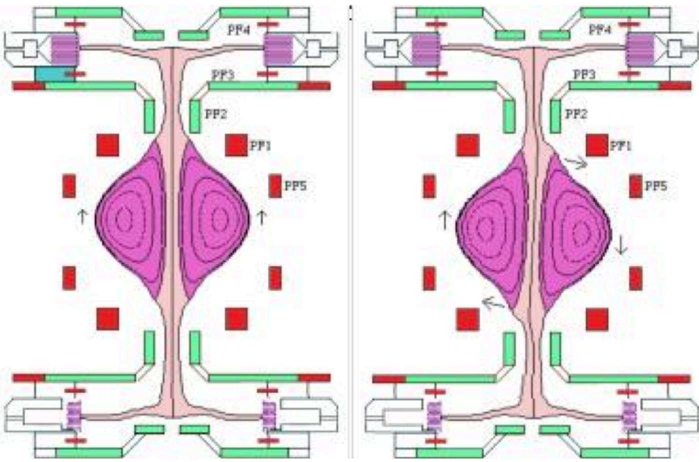
Operational experience in Tokamaks shows that the **best way of puffing fuel is from the high field side**



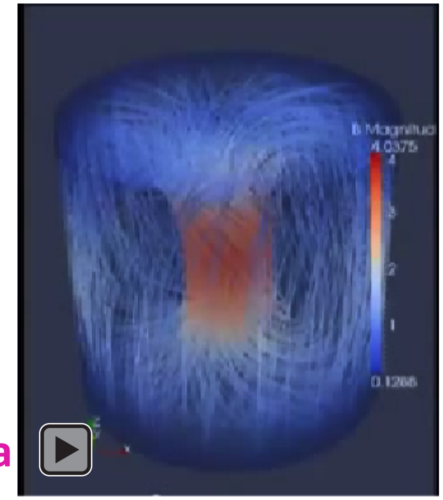
Gas puffed hollow anode

IDEAL MHD STABILITY of PROTO-SPHERA

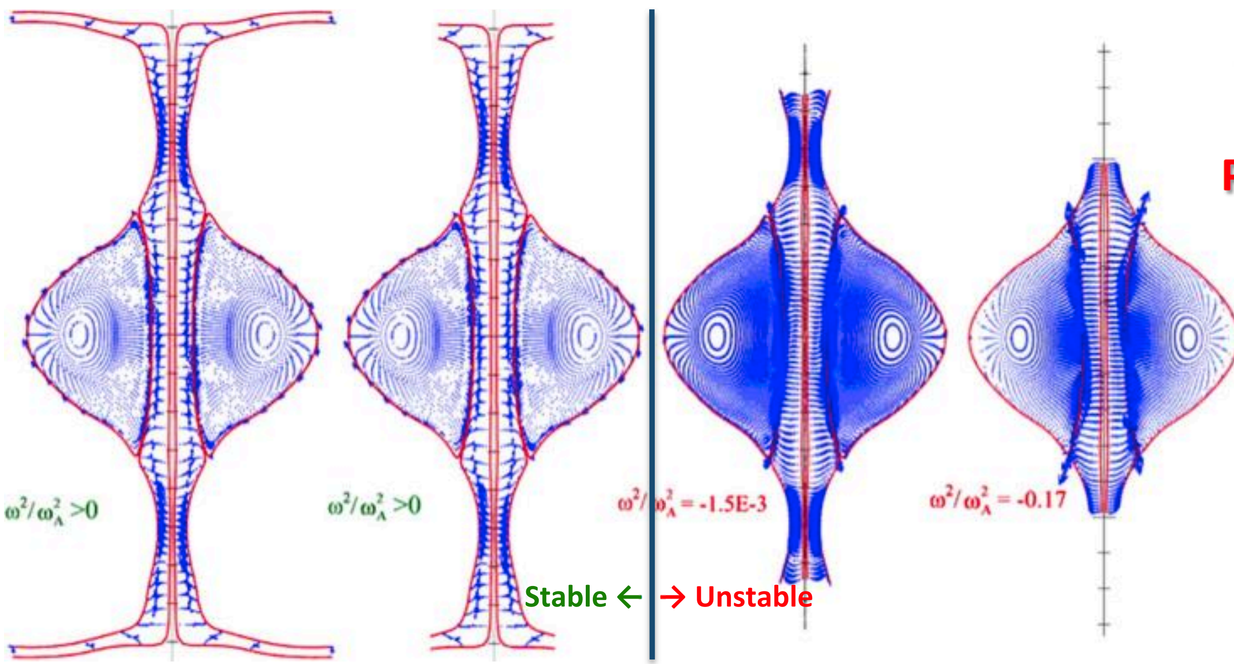
Spheromak tilt instability is due to
dipole of containing field opposite to toroidal plasma current dipole



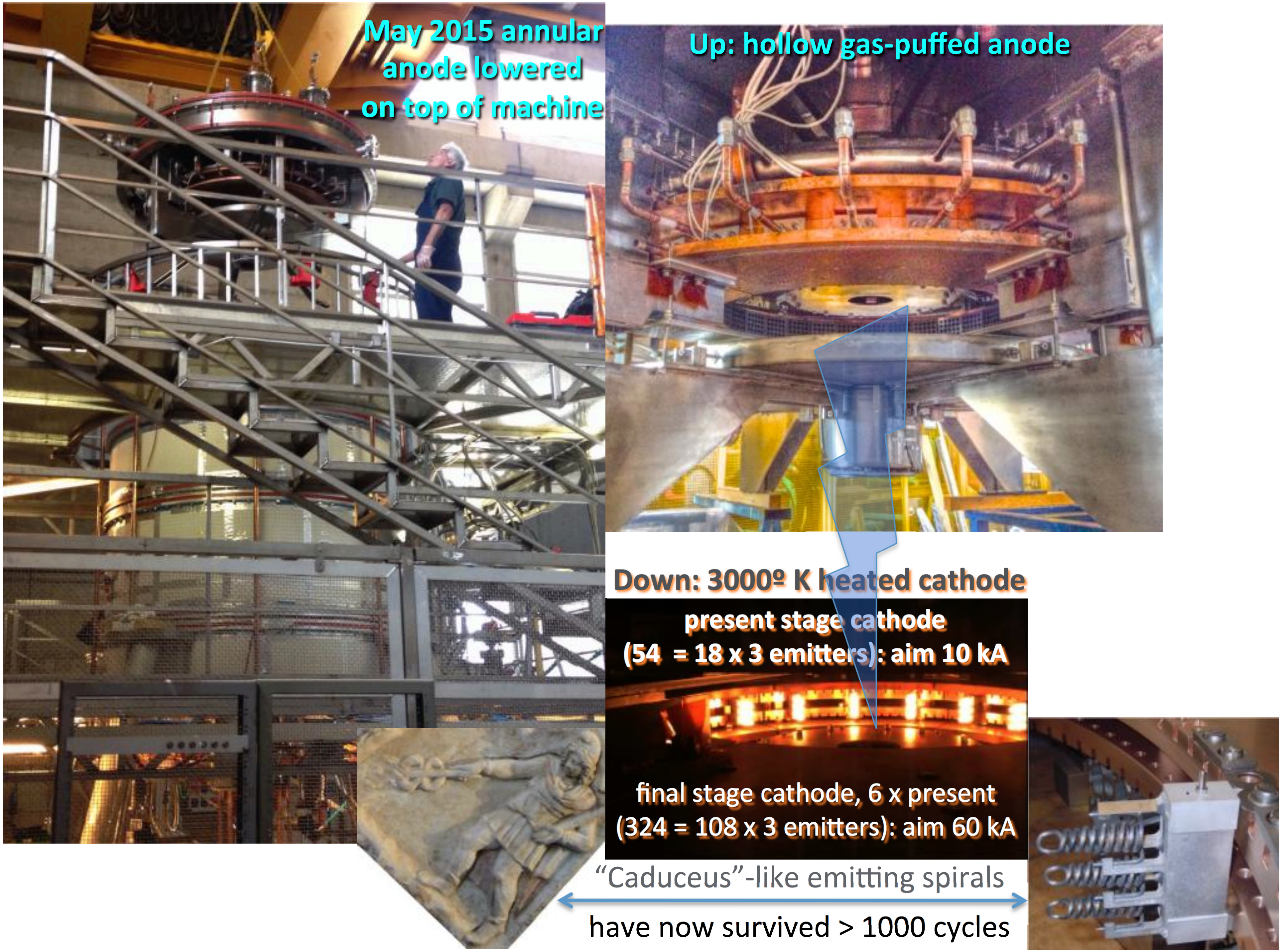
"Group A" PF coils (compression coils)
has dipole moment opposite to Plasma
but "Group B" PF coils (shaping coils)
has dipole moment aligned to Plasma



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



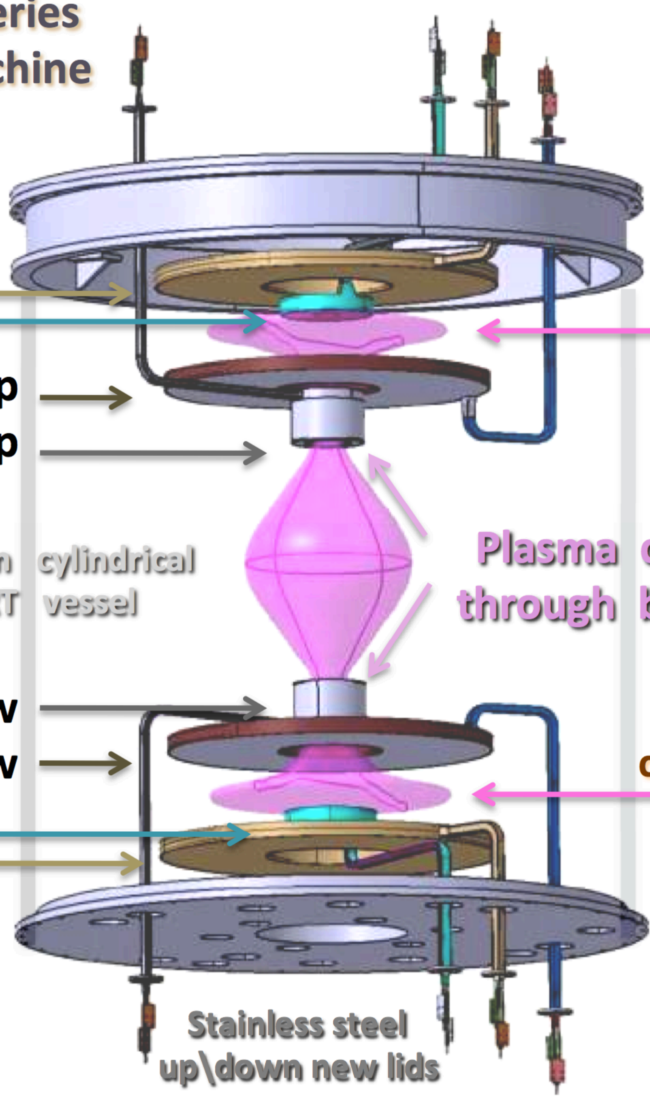
Cutting shorter & shorter
the plasma centerpost
PROTO-SPHERA at 120 kA
gets destabilized

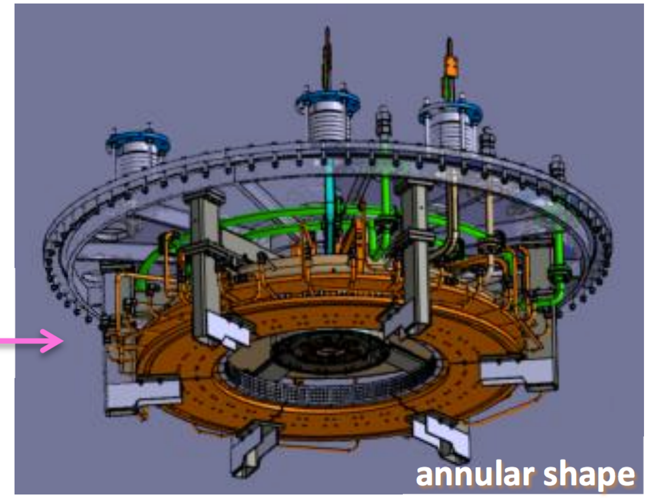

May 2015 annular
anode lowered
on top of machine
Up: hollow gas-puffed anode
Down: 3000º K heated cathode
present stage cathode
(54 = 18 x 3 emitters): aim 10 kA
final stage cathode, 6 x present
(324 = 108 x 3 emitters): aim 60 kA
"Caduceus"-like emitting spirals
have now survived > 1000 cycles

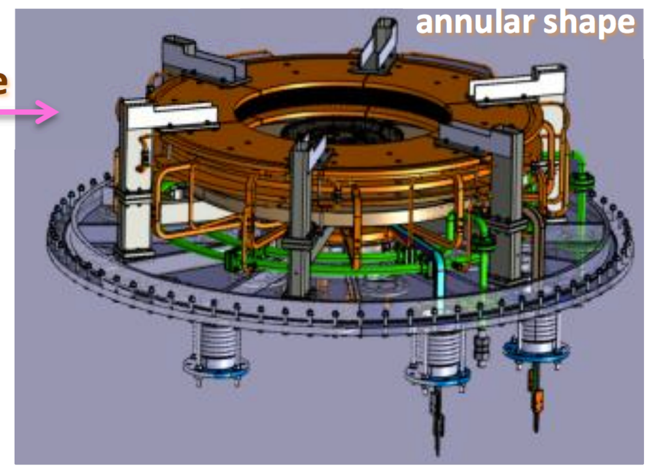
INSULATIONS

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

8 PF coils in series inside the machine





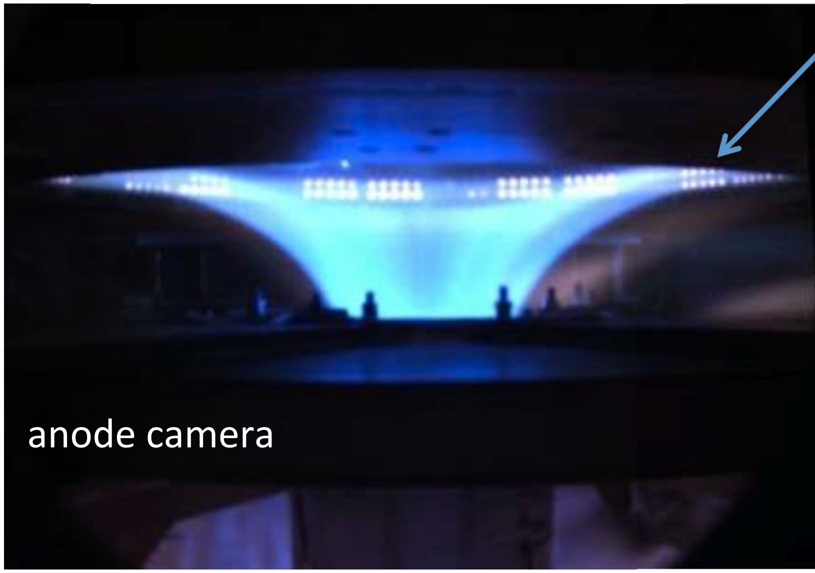


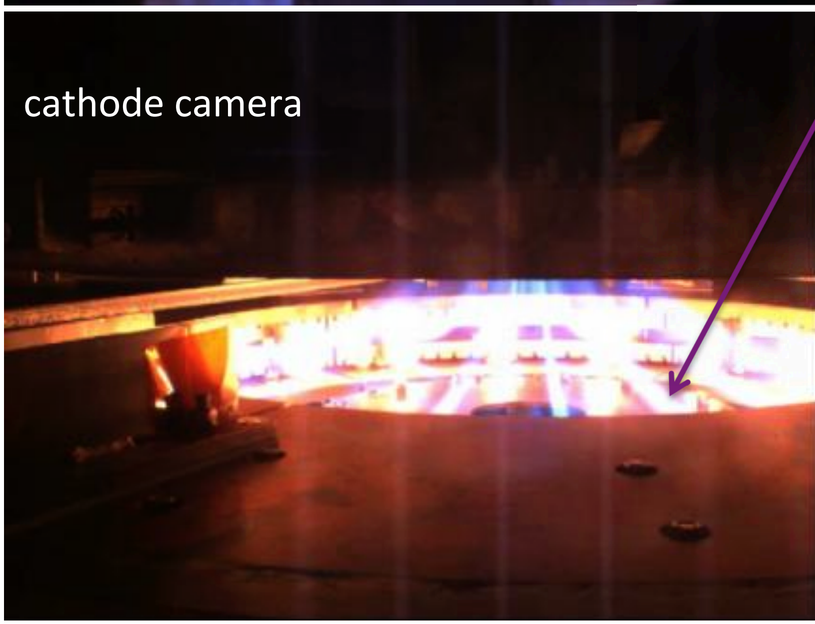
vacuum vessel is GND potential

PF coils casings built as floating, can be connected to potentials: anode +, cathode -, vessel 0

No Anode Arc Attachment!

Argon plasma: break-down 80 V

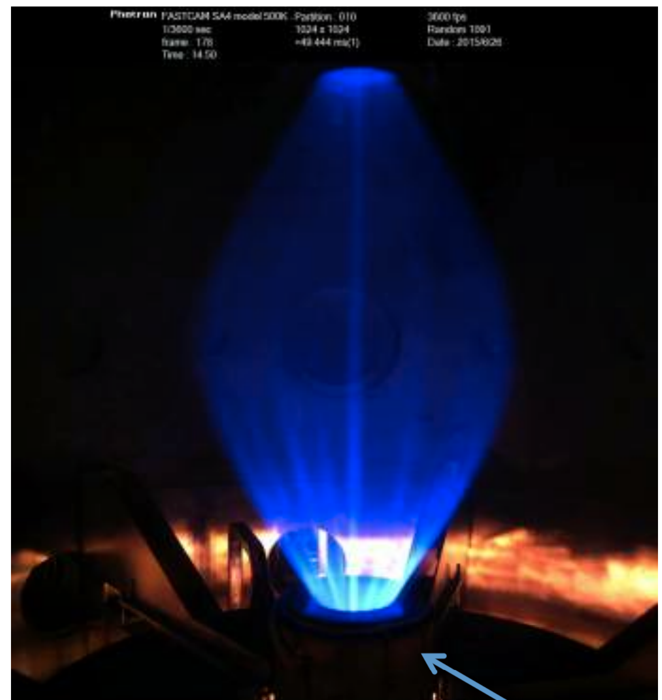




Hollow annular anode performs

- plasma goes through both PF2 throttles
- plasma enters anode gas-puffing holes
- no sign (I_e < **8.6 kA**) of anode attachment
- filling pressure **10^{-3} - 10^{-2} mbar**

annular anode plasma is never filamented whereas annular catode plasma is filamented (due to sparse emitters)



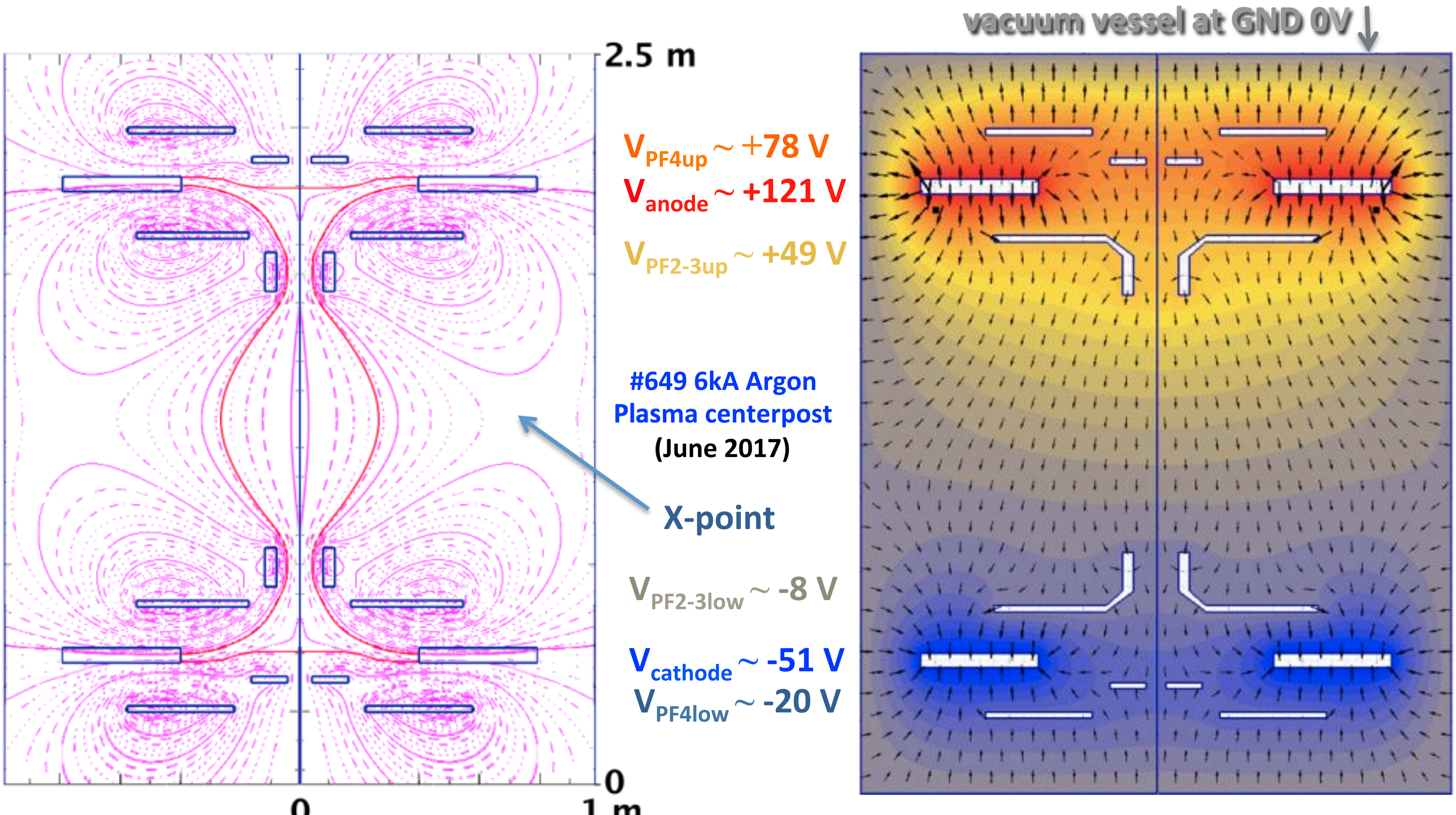
even plasma centerpost is in part filamented
(...cathode switched off before the plasma...)

No Anode Arc Attachment: Electrostatic plasma effects!

PF coils casings built as floating, can be connected to: anode +, cathode -, vessel 0

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

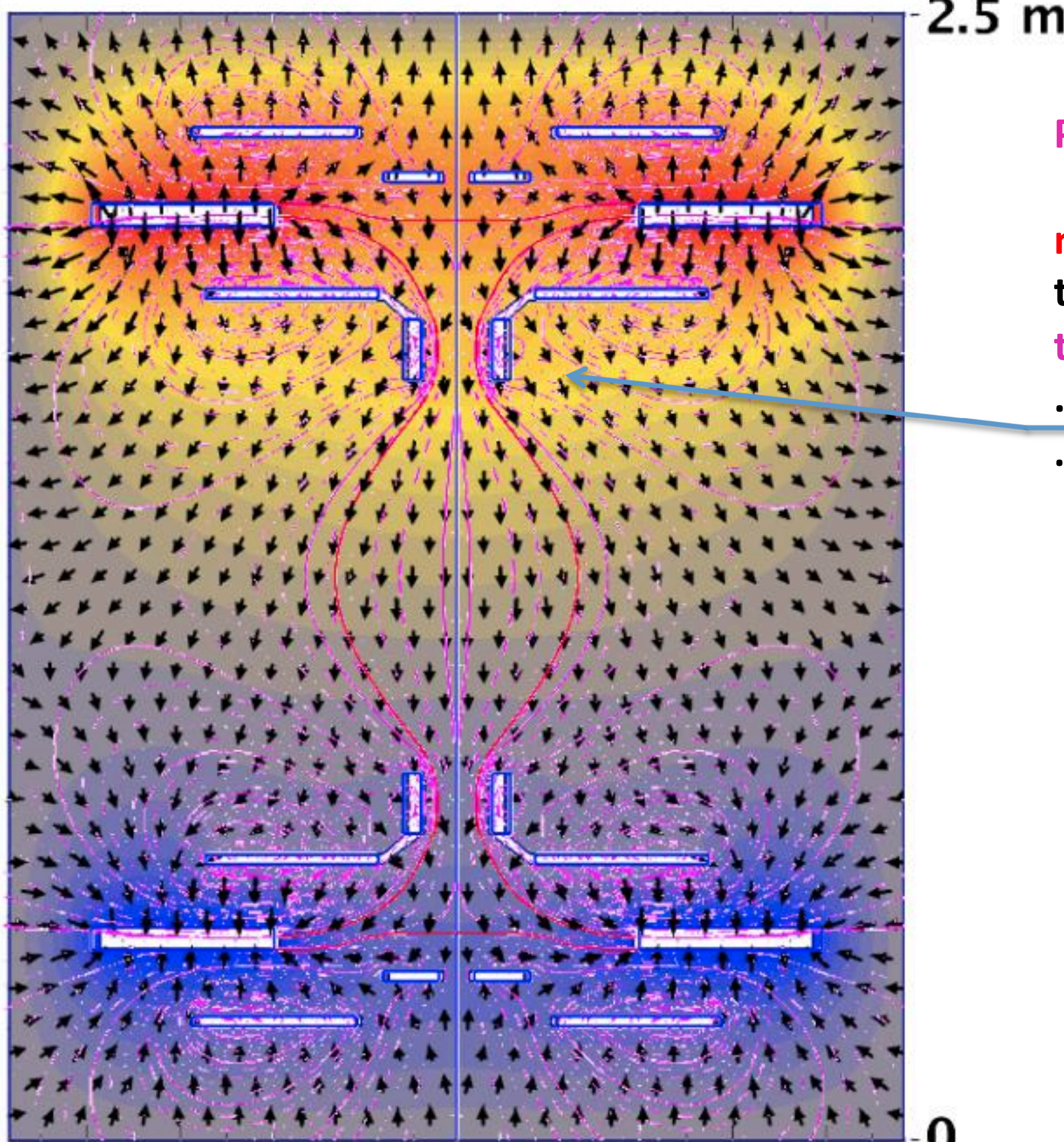
the magnetic field is up\down symmetric but electrostatic field not up\down symmetric



Line contours: magnetic field

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

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



#649, 6 kA Argon

Line contours: 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

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

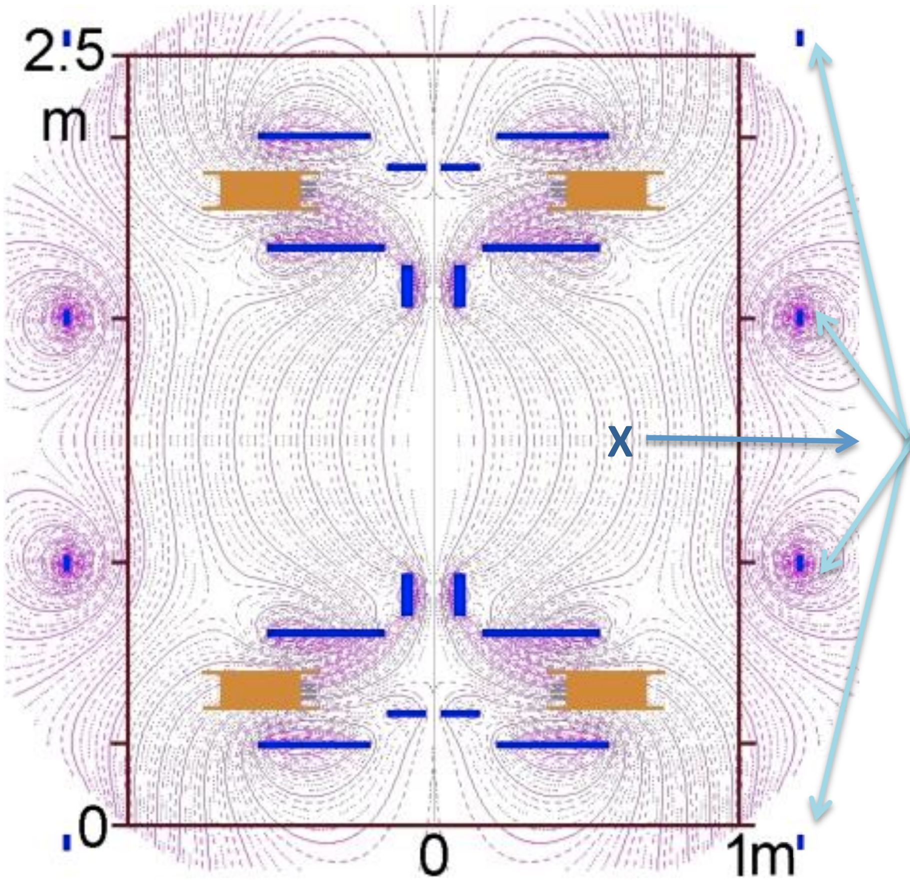
near the annular cathode
the E field is ~ parallel to B field
… less $\vec{E} \wedge \vec{B}$ **plasma rotation**

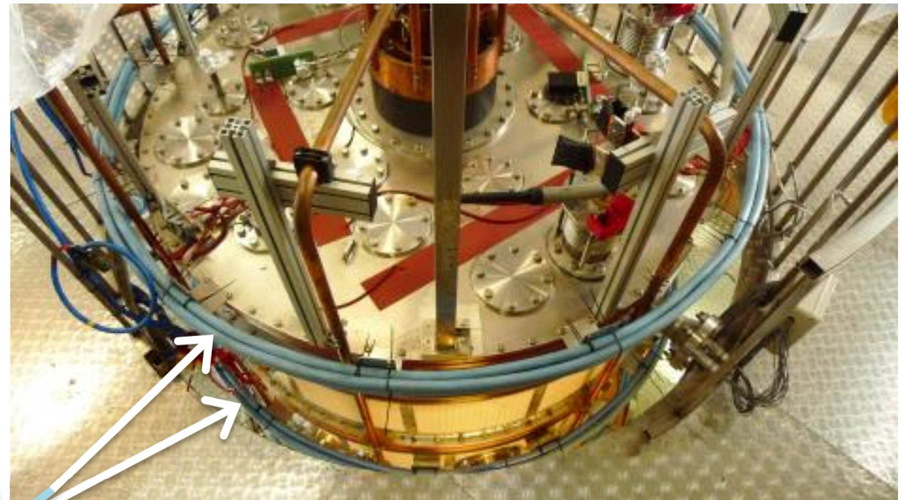
Self-organization at work inside annular electrodes plasma

The equatorial X –point has been removed from inside the vessel

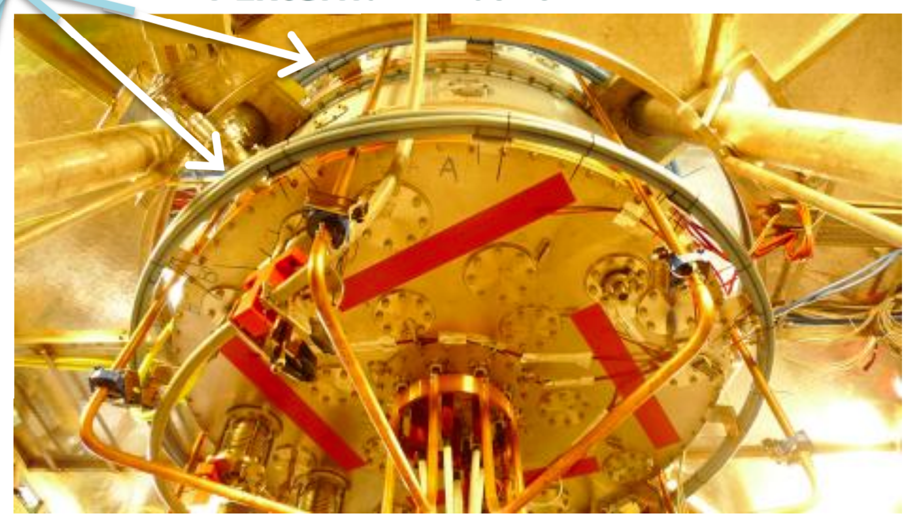
4 External PF coils have been added (**home-made from** spare connection cables)

…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

Within 2017 a new Super-capacitor based Power Supply for External PF coils should operate!

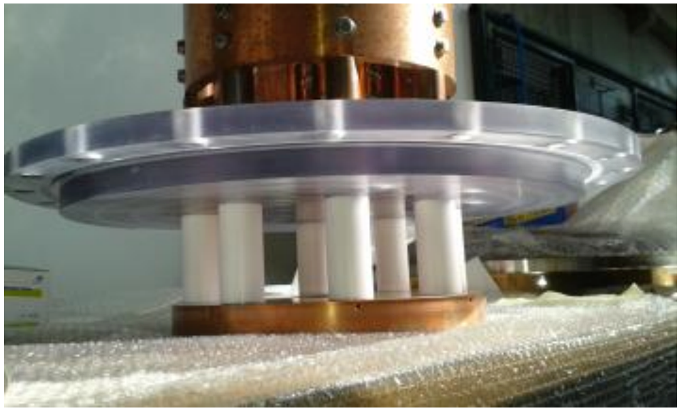
2015/16 experiments produced a heavy metallization on top (anode) & bottom (cathode) bus-bar vacuum entrance flanges,

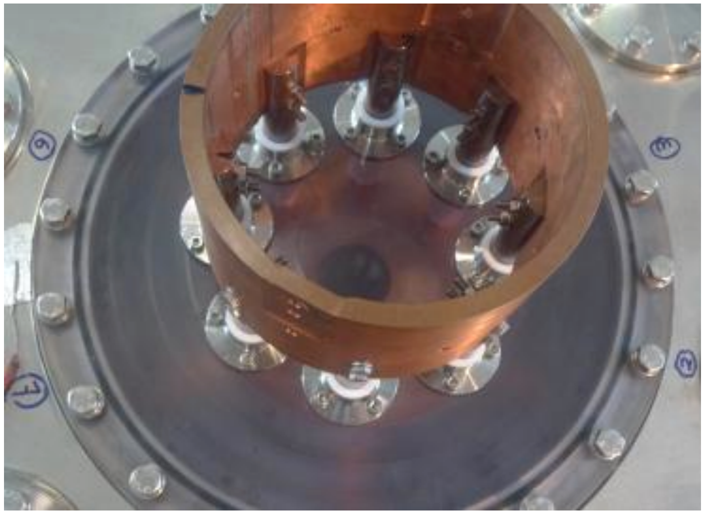
associated with magnetic "nozzles"

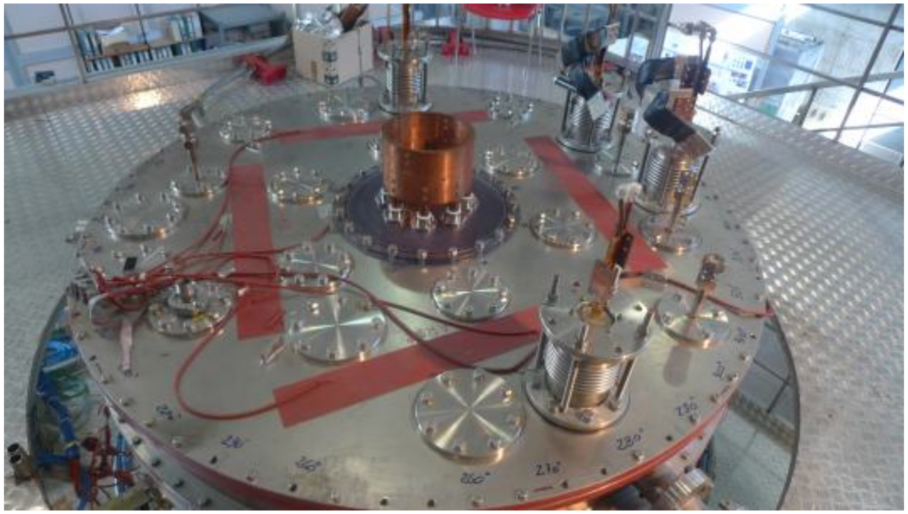
June 2016: insertion of Polycarbonate (transparent) anode bus-bar flange on top of machine

Heavily metallized
top & bottom bus-bar flanges

4 cm thick Polycarbonate
(required by atmospheric pressure)

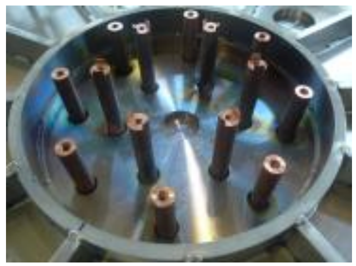






At the bottom (near cathode) a SS flange, pierced by 14 bus-bars, such a flange has been substituted by a Polycarbonate one



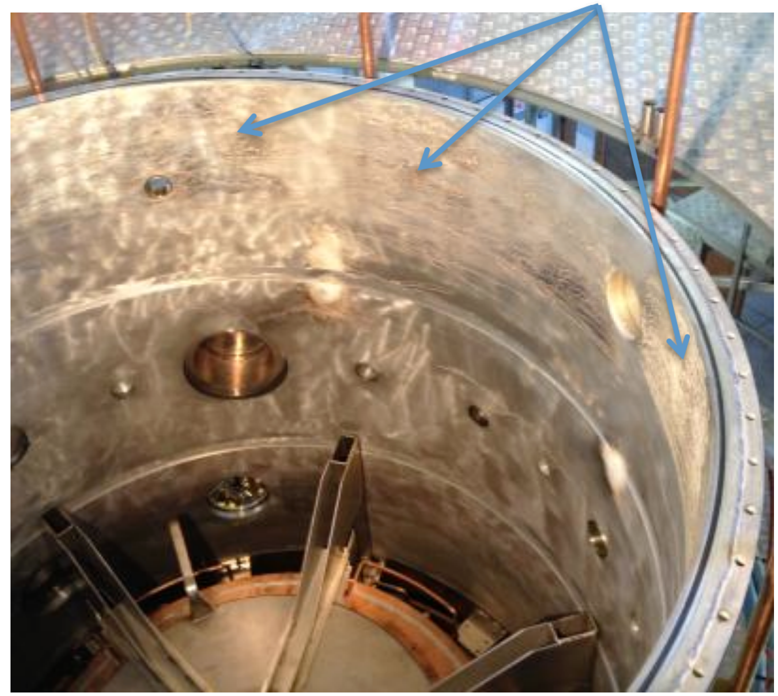



July 2016: Polycarbonate flange on machine bottom



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

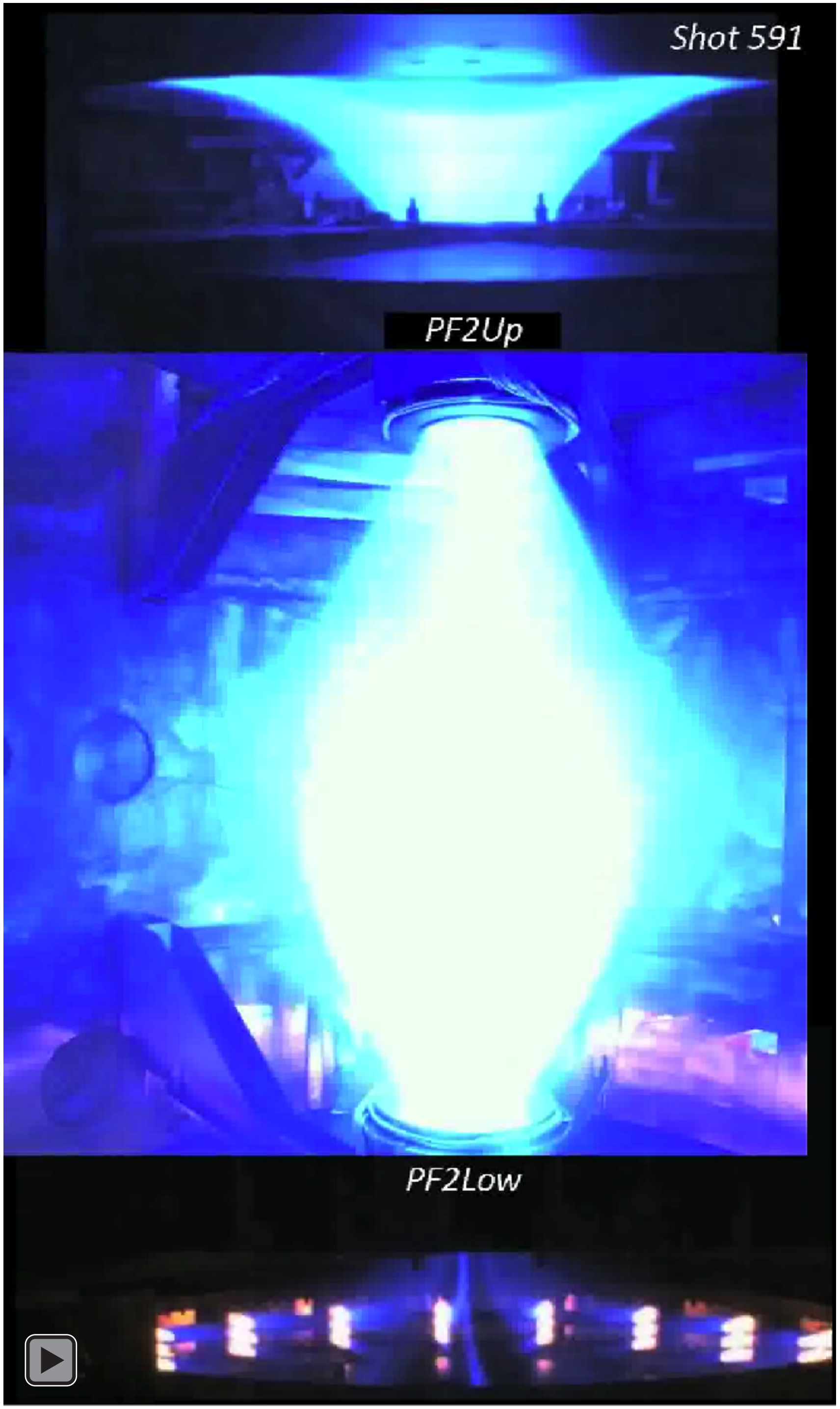
I_e= 2.7 kA



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

December 2016

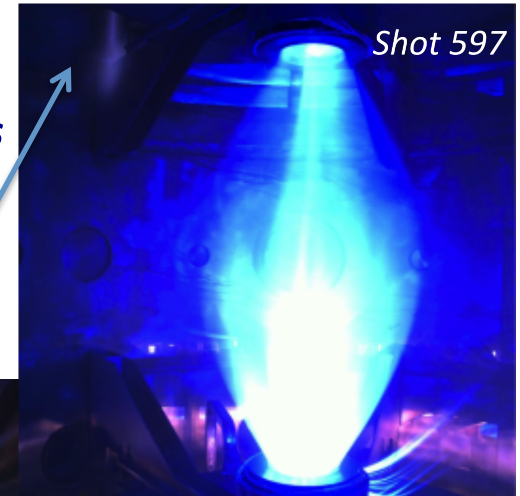
secondary 2mm thick Polycarbonate screen surrounds rear of anode



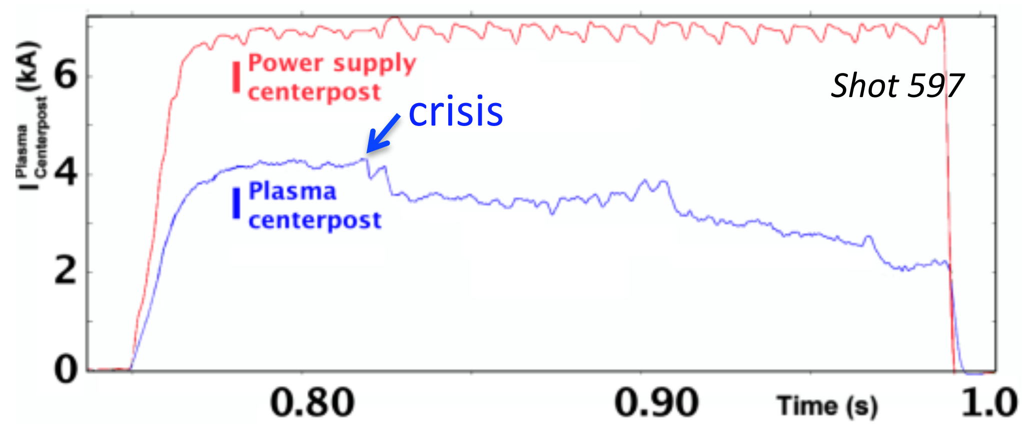
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but Spurious plasma currents still flow outside the centerpost (albeit inside the vacuum vessel)

January 2017

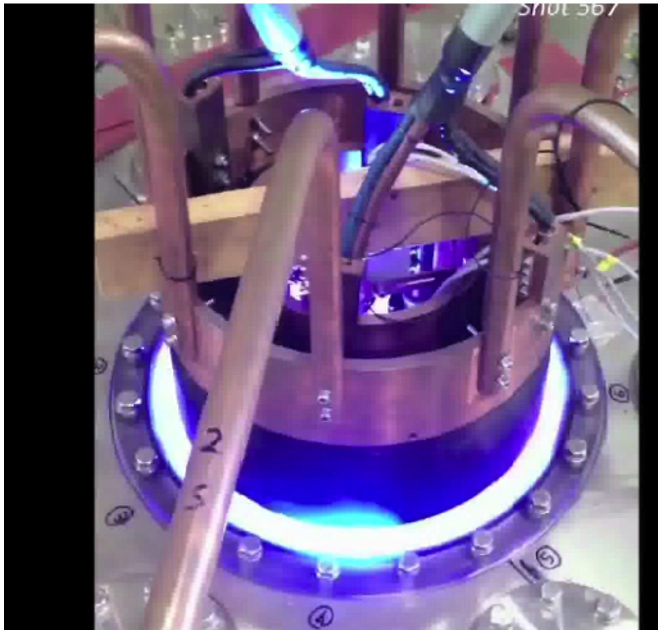
patterns of spurious currents are either diffused or filamentary



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

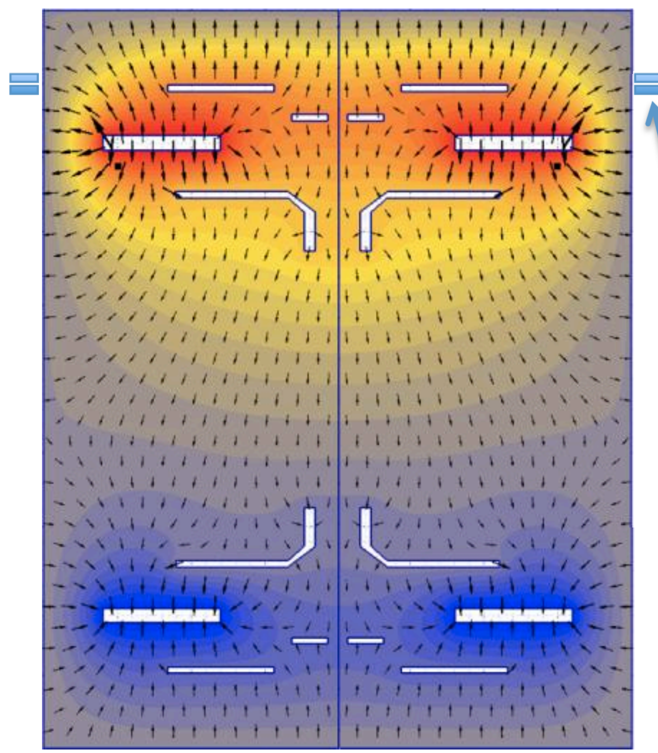


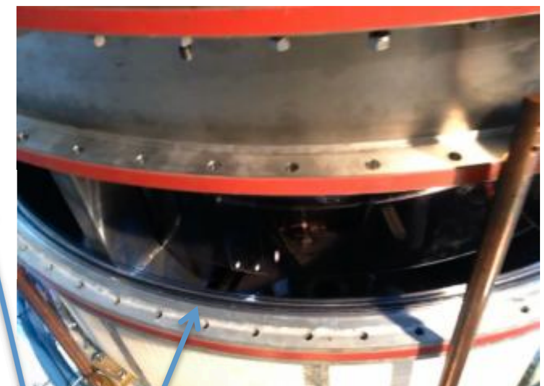
January 2017



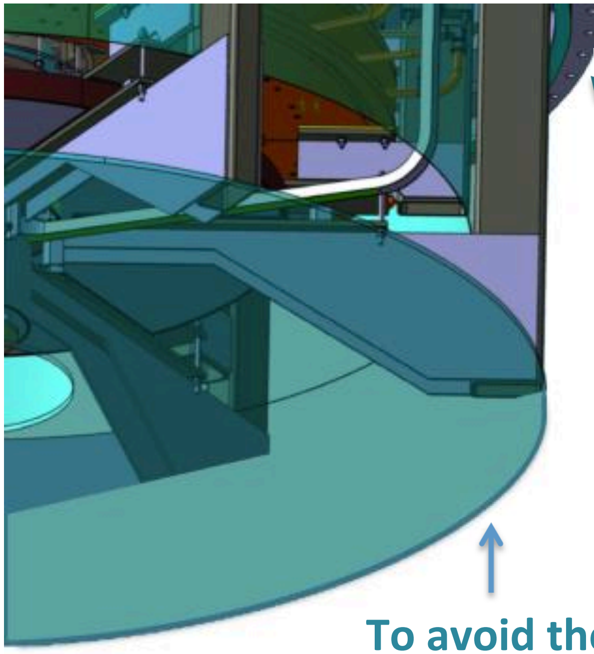
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but
In Hydrogen (250 V breakdown) there was still a problem of current through the vessel,
this was triggered in Argon (80 V breakdown),
connecting the common star potential of the six-phased cathode power supply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

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



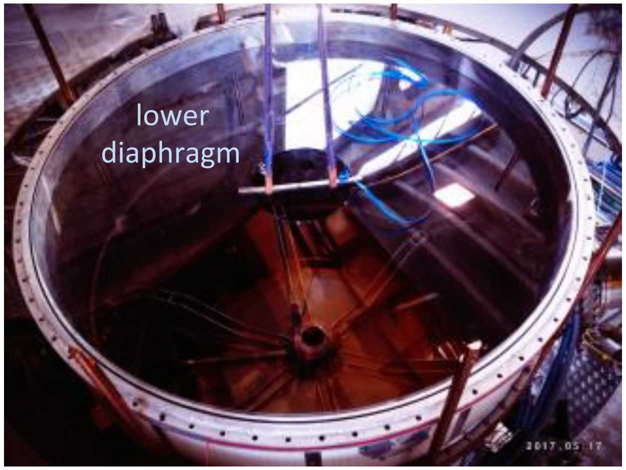


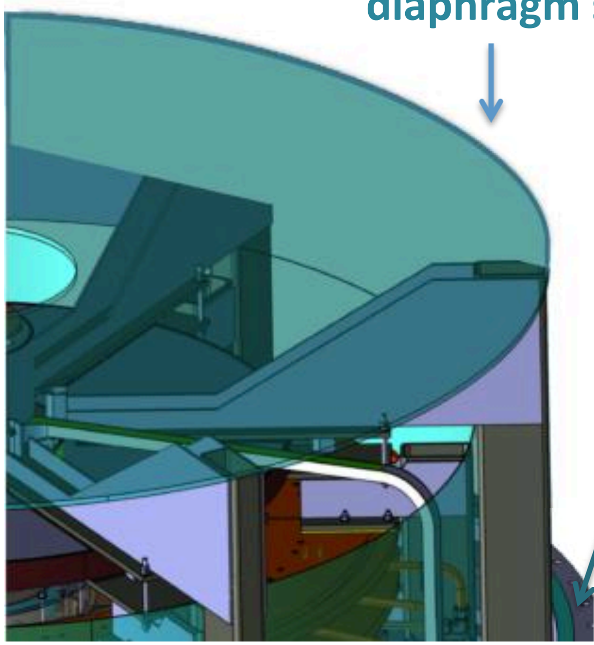
A spacing insulating ring was inserted in **May 2017**



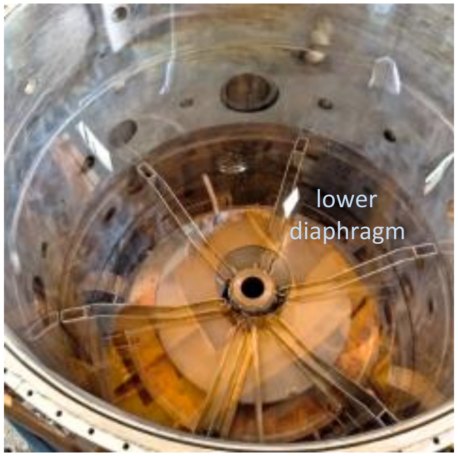
to avoid the bus-bar to vessel current flow an insulating spacer ring has been inserted

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



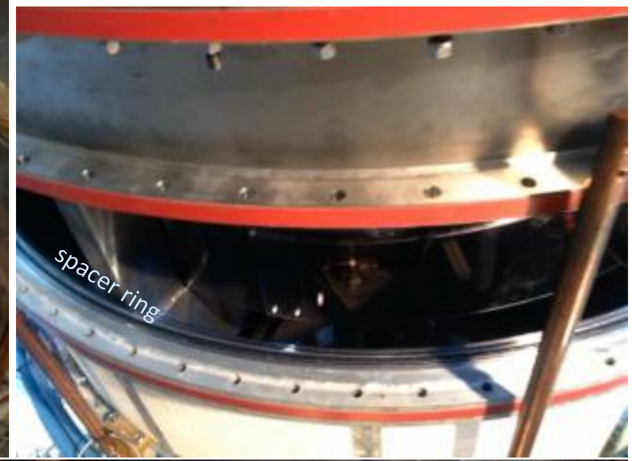


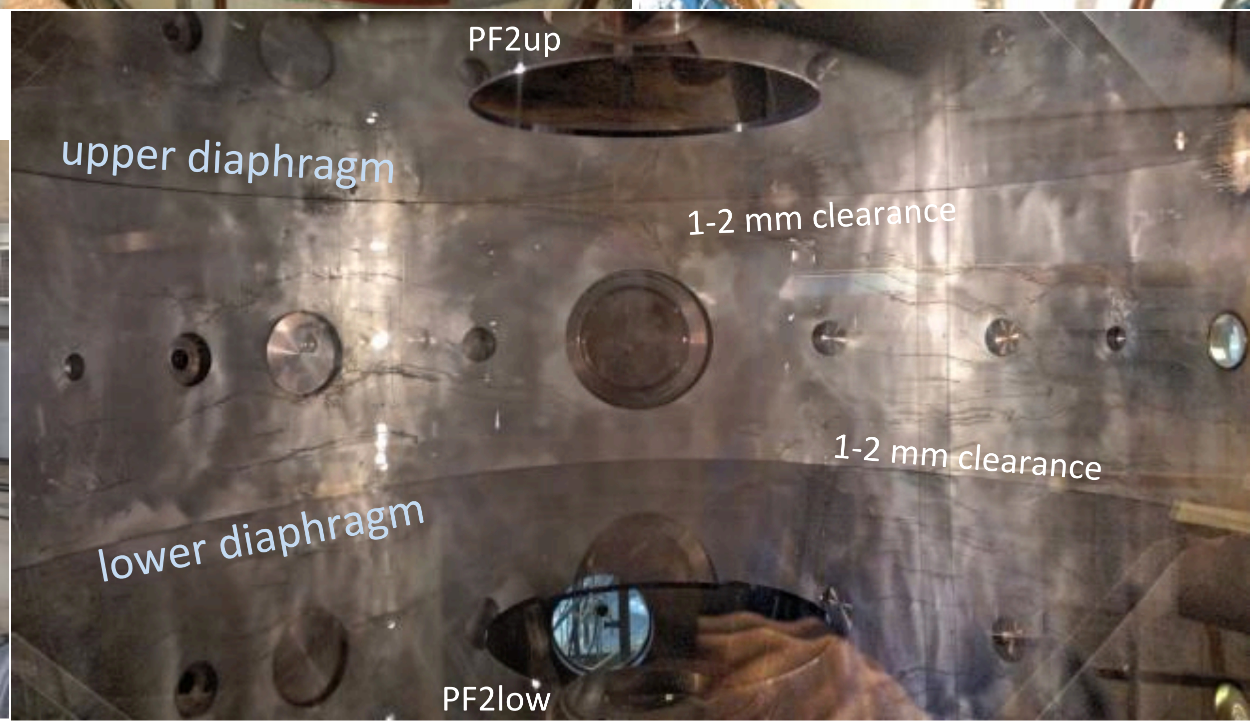
May 2017: Insertion of
Polycarbonate lower diaphragm



Lower spacer ring not yet inserted

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

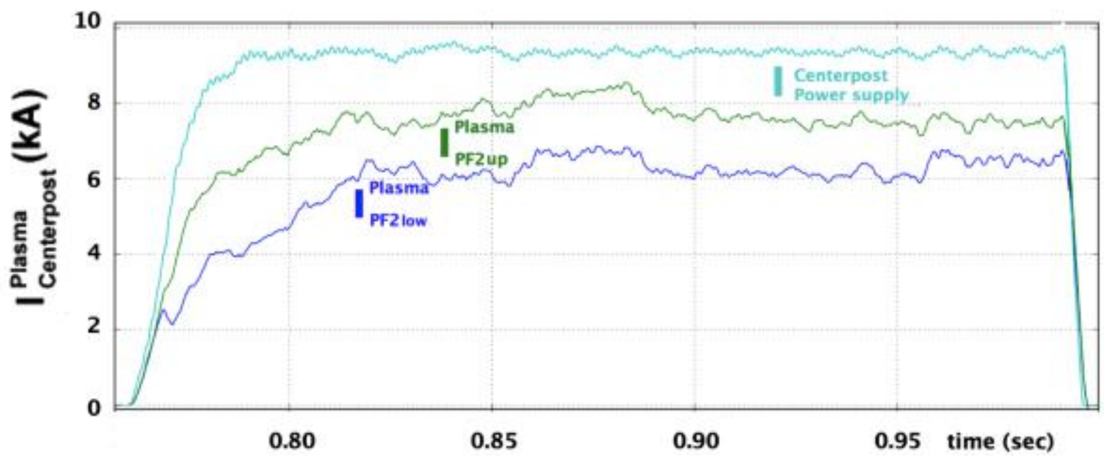




June 2017: Plasma with Polycarbonate two diaphragms & upper Polycarbonate spacer ring

High currents, external PF coils are on

Some spurious and concentrated plasma current still sneaks through the narrow clearance (1-2 mm) bet'wn 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 ($q_{Centerpost}$ ~ 2) becomes clearly visible

The plasma centerpost seems to rotate azimuthally in clockwise direction (looking from above)

the spurious plasma current closes on the ouside of PF2low, producing bright filaments

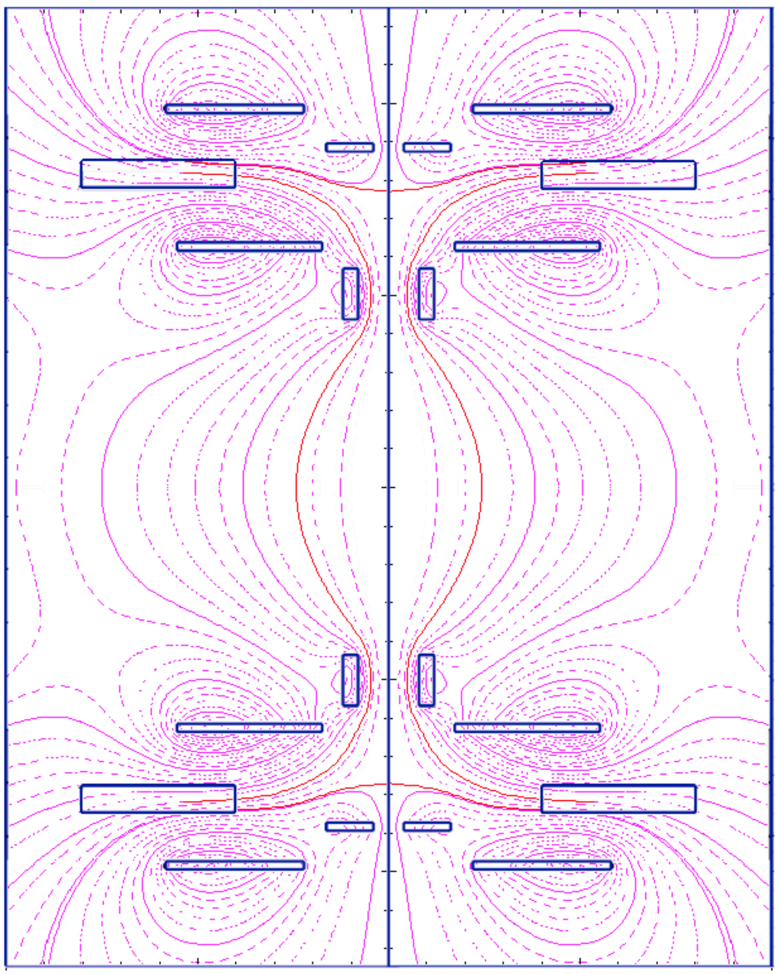
High currents (8 kA), switching on the external PF coils: PF coils casings built as floating

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

SS upper lid & upper extension also better left floating!

through Polycarbonate spacer ring

upper lid & extension float at 90 V



V_{PF4up} ~ 130 V

V_{anode} ~ +150 V

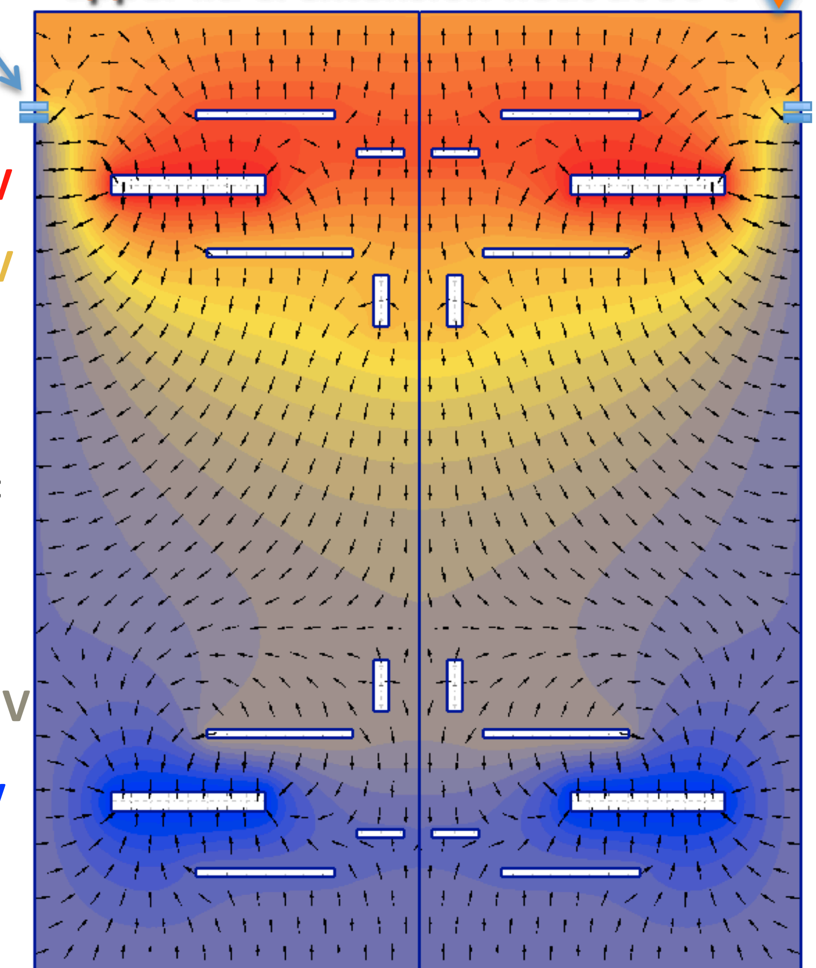
$V_{PF2\text{-}3up}$ ~ +75 V

#614, 8kA Argon
Plasma centerpost
June 2017

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

$V_{cathode}$ ~ -45 V

V_{PF4low} ~ -7 V



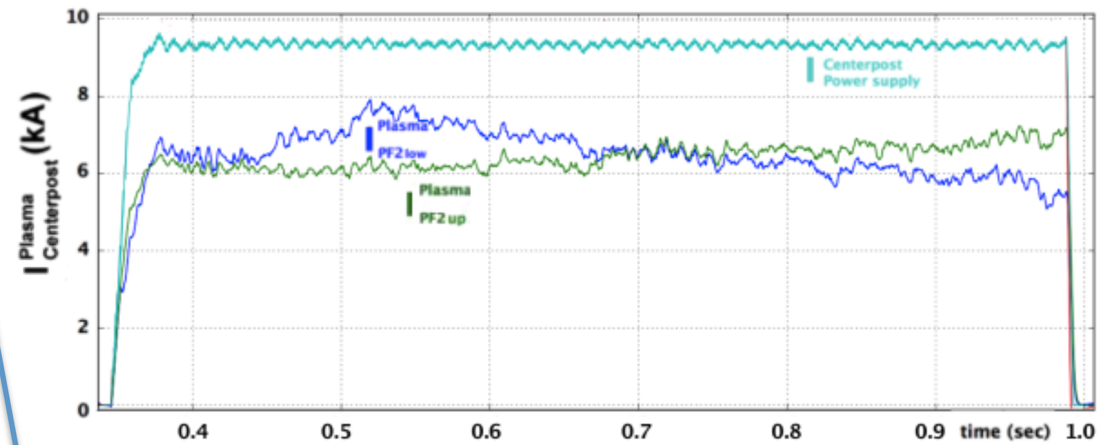
vacuum vessel at GND (0 V)

Line contours: magnetic field

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

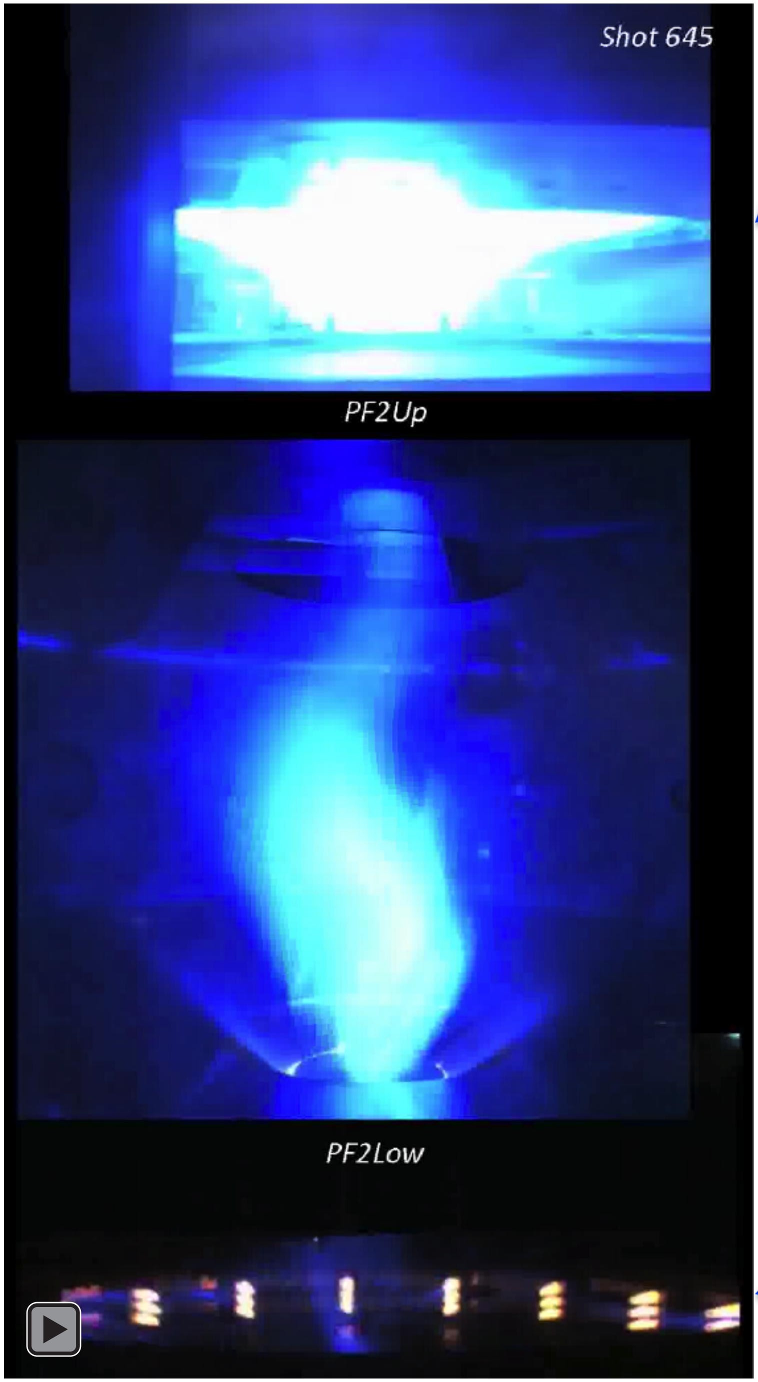
External PF coils are off, lower currents, 0.7 s persisting discharge

Switching off the external PF coils, long duration plasma centerposts have been obtained with plasma currents through the PF2 coils ~ 6÷7 kA



The plasma centerpost discharge is quite near to the rotational trasform value $\iota \sim \frac{1}{2}$ ➔ ($q_{Centerpost} \sim 2$)

Autumn 2017: the narrow clearances will be closed completely by a bonding material (able to sustain the diaphragms' weight)

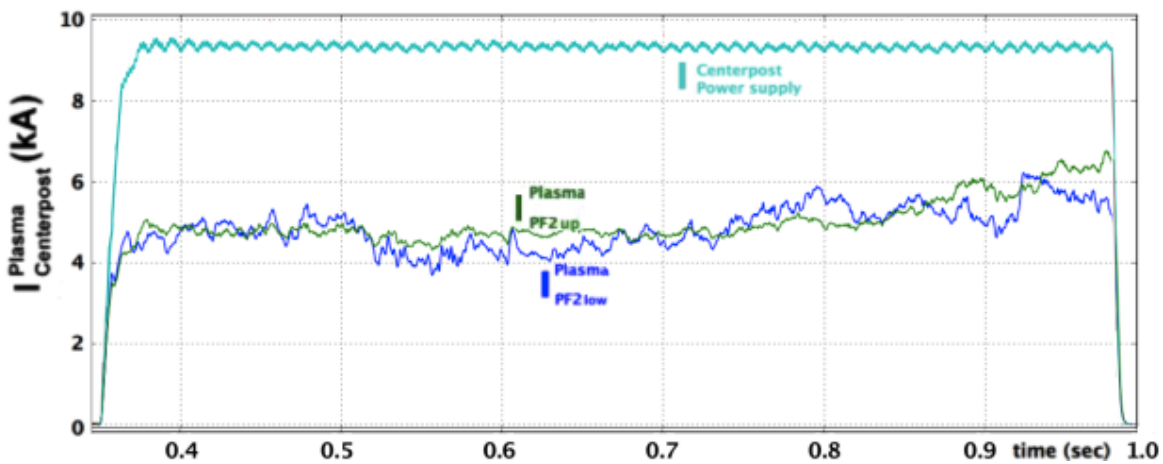


Kink destabilization persists for 0.7 s

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**

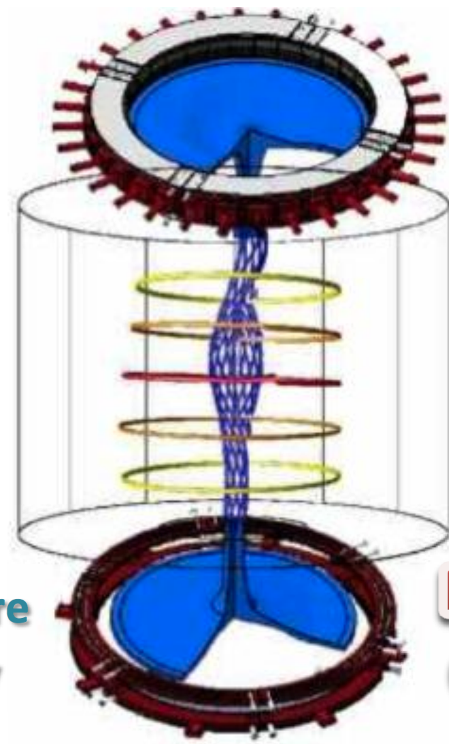
A long duration kink-bended plasma centerpost has been obtained with plasma currents through the PF2 coils ~ 5÷6 kA

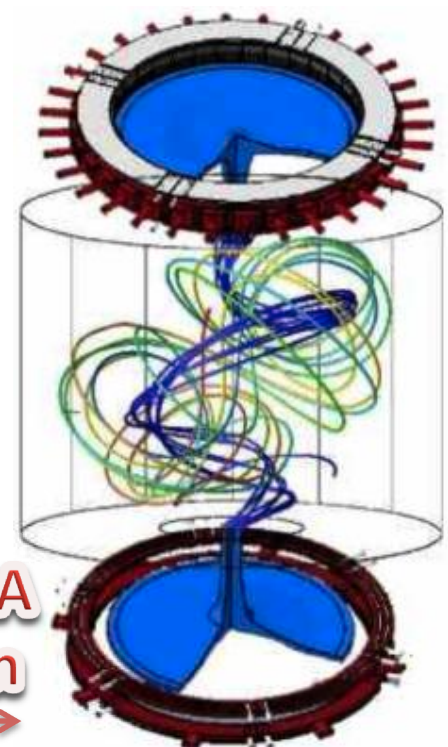


This plasma kink-bended centerpost discharge survives at a rotational trasform value $\iota \sim 1.66$ ➔ $(q_{Centerposth} \sim 0.6)$

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

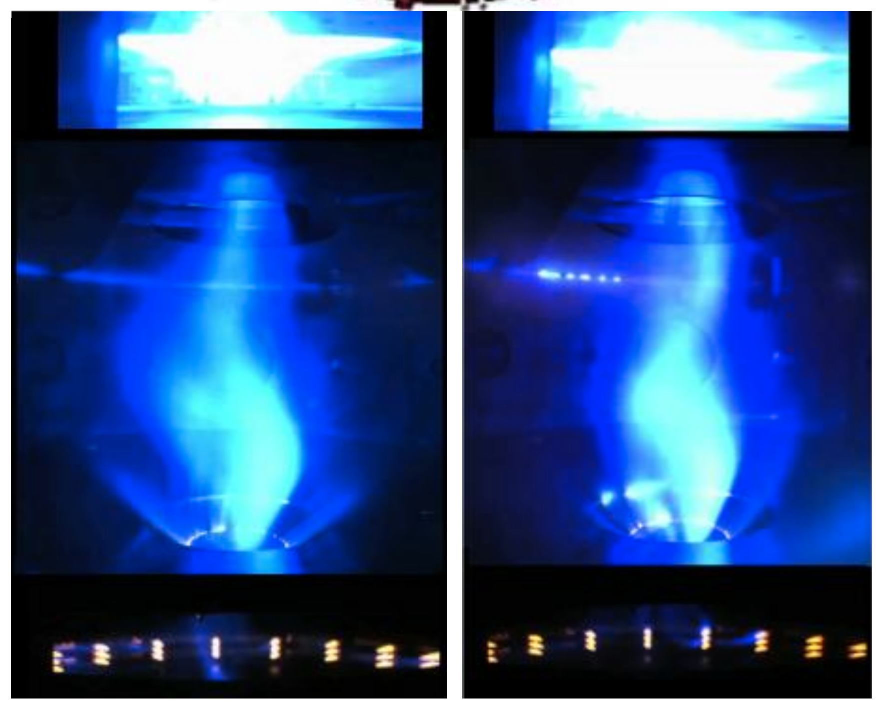
Physics Design
1997-2008





PROTO-SPHERA
destabilization

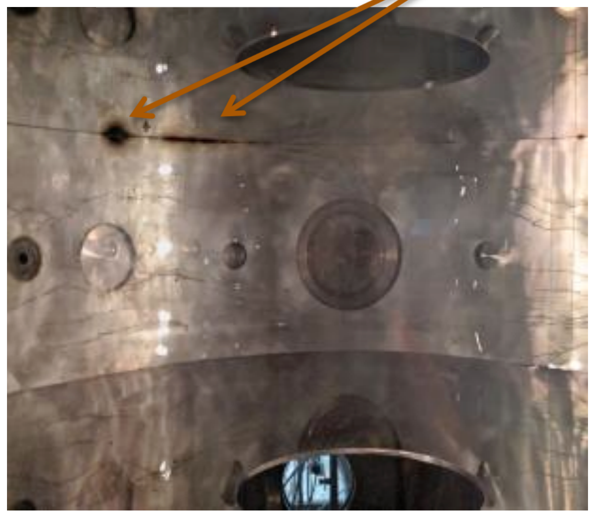
Langmuir probe measurements give
10÷3 eV temperature
$2\div5\cdot10^{19}$ m^{-3} density
at edge of anodic plasma mushroom

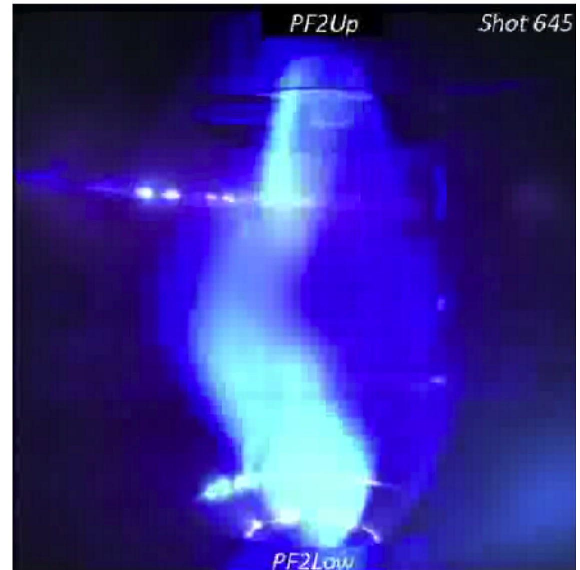


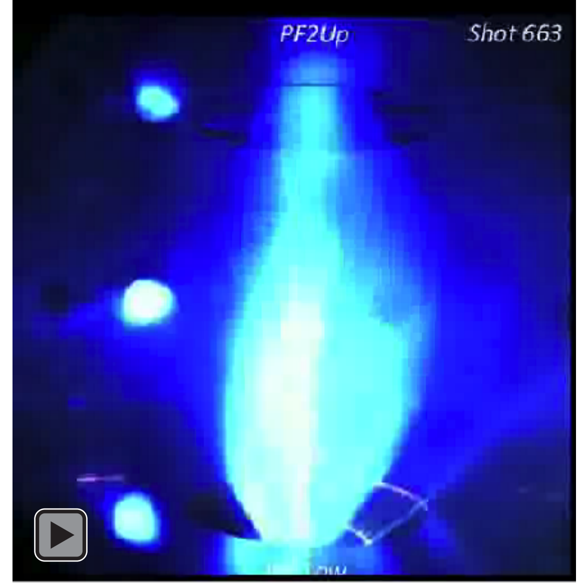
Experiment
2017

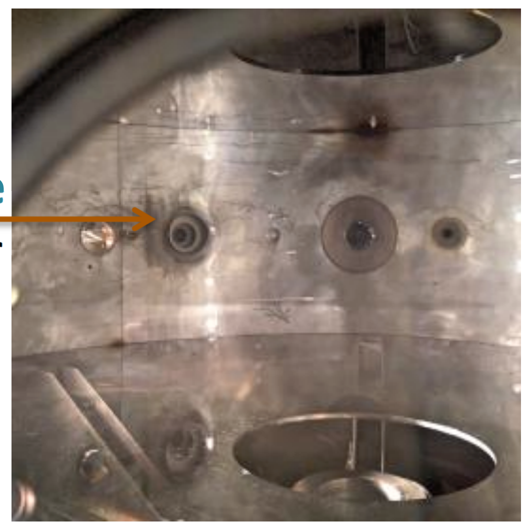
The plasma current sneaking through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm induces damages

The narrow clearance has <u>to be closed completely by a bonding material</u> (able to sustain the diaphragms weight)





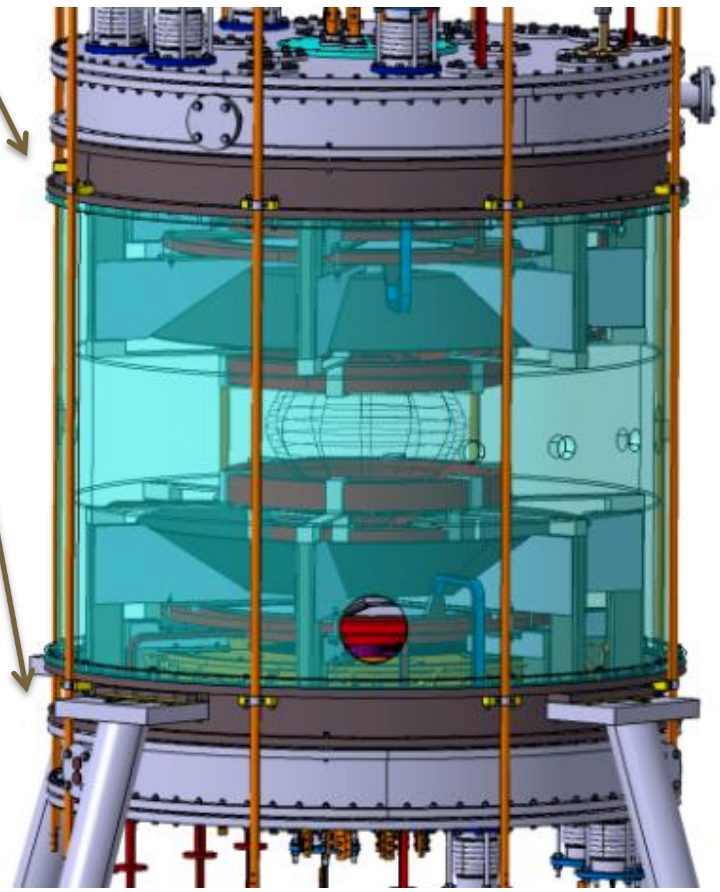


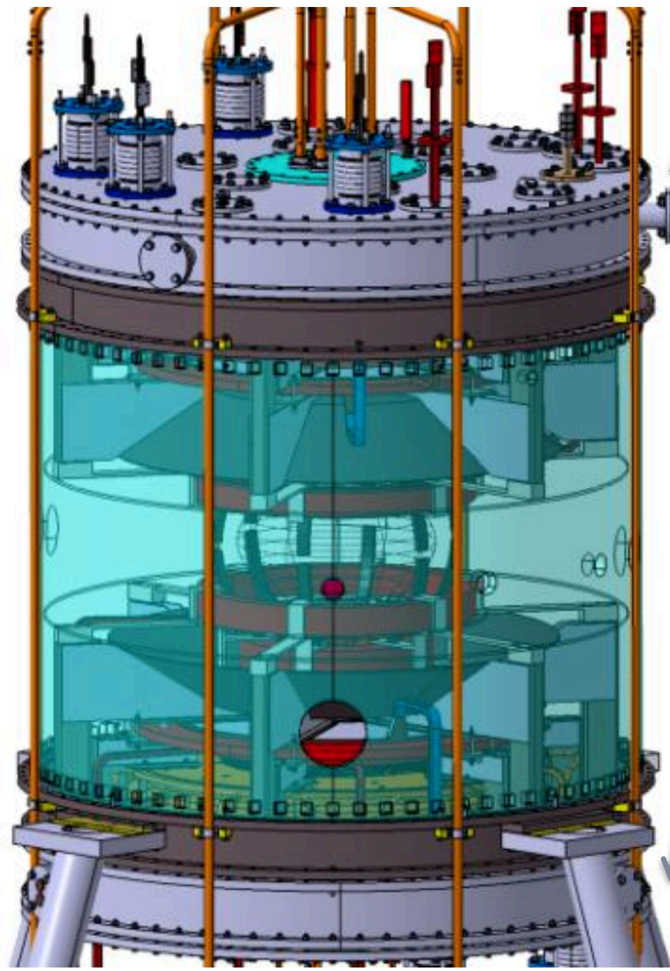


The port where the polycarbonate lining was cut, in order to allow for vacuum gauges measurements, **has to be closed**
& the gauges moved elsewhere

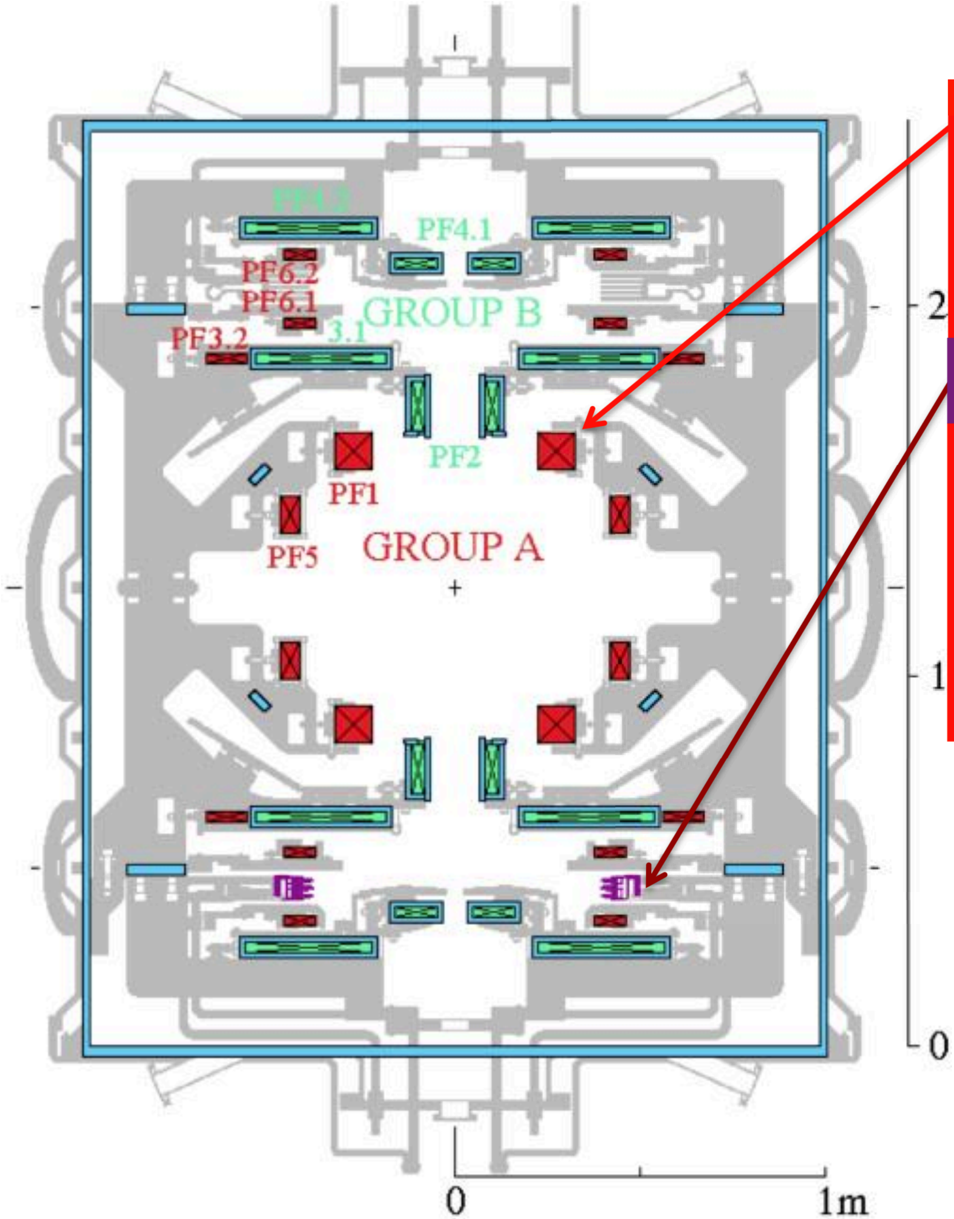
A new insulating & transparent vacuum vessel has to be built: will be Phase-II ready

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
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€

No additional heatings for PROTO-SPHERA?

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

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?

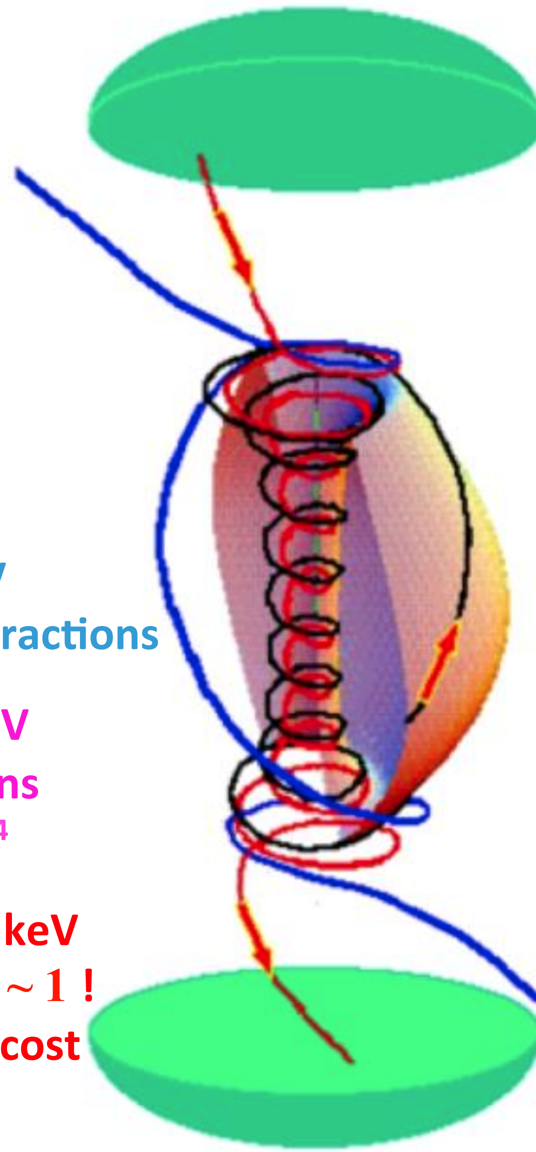
No one is able to predict:

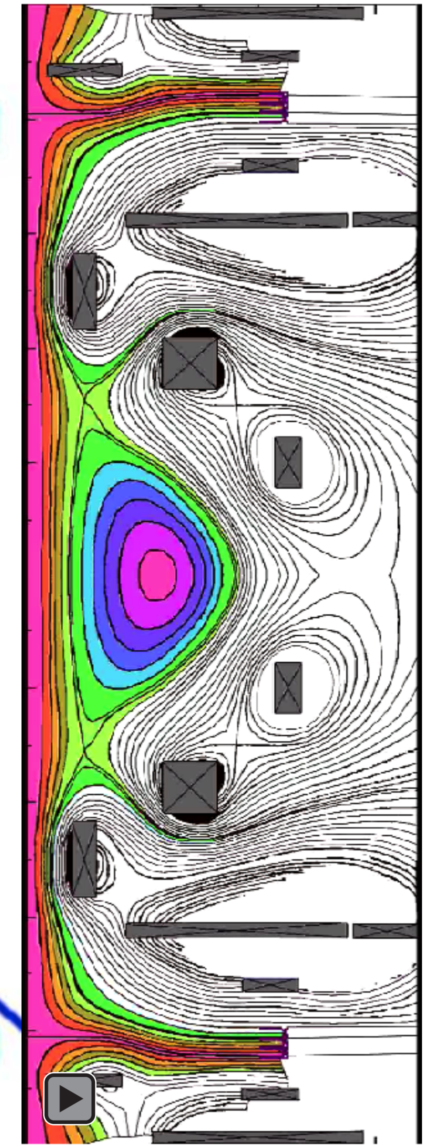
• should it be ~ zero, then ST plasma T = 10 eV
PROTO-SPHERA studies plasma-electrode interactions

• should it be 1 MW, then ST plasma T = 100 eV
PROTO-SPHERA studies magnetic reconnections
at relevant magnetic Lundquist number, $S=10^4$

• shoud it be many MW, then ST plasma T = 1 keV
…$\beta \sim 1$!

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





Perspective

。。。放龙如海! fànglóng rùhăi
...set free the Dragon into the sea!

Proto-Sphera will assess a new magnetic confinement configuration

- simply connected (easier construction & maintenance)
- sustained (indefinitely?) by helicity injection, through magnetic reconnections
- mixed magnetic & electrostatic confinement, major role of plasma velocity?
- (if magnetic reconnection efficient) high plasma beta? (minimal geometrical size)

Proto-Sphera can develop this program:
at very modest costs (~ 1.6 M€); in a flexible way (new components can be easily added)

PROTO-SPHERA Phase2 will be much more demanding in manpower and effort than the present Phase1 of PROTO-SPHERA with Centerpost plasma only

Will be an experiment as much challenging for Frascati as START was for Culham
- ***with sophisticated control requests (very fast rise of currents for Torus formation)***
- ***with demanding diagnostic requests***
- ***challenging physicists, engineers and technologists creativity with its adaptability***
- ***easily modifiable and therefore an ideal ground for student and PhD theses***

Fasten seatbelts: surprises along the road!


+ Other
authors