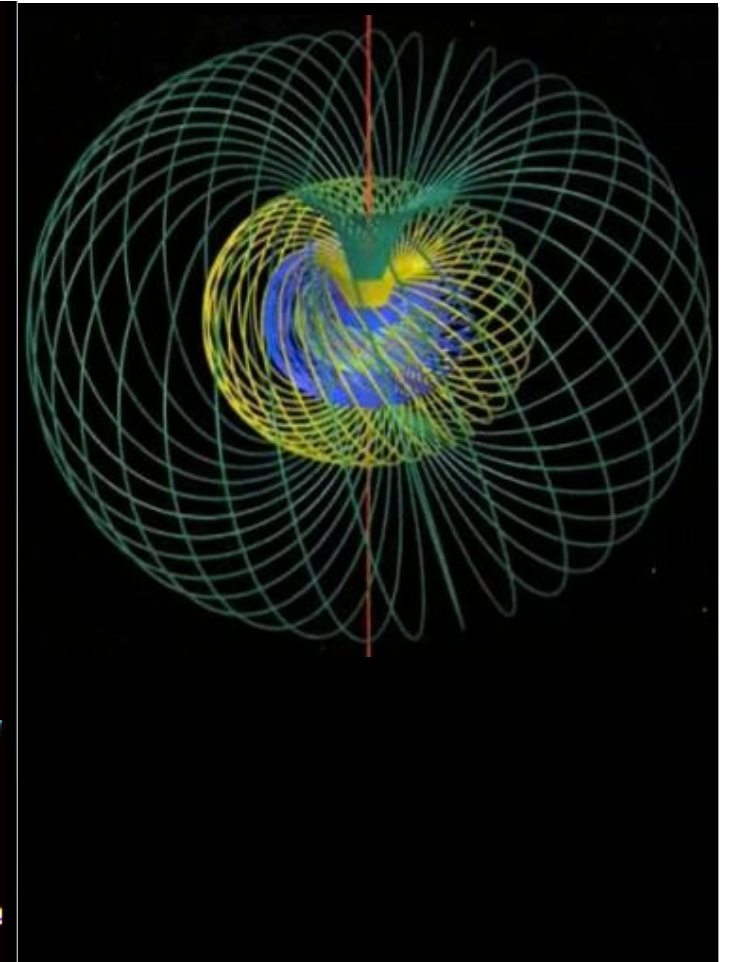
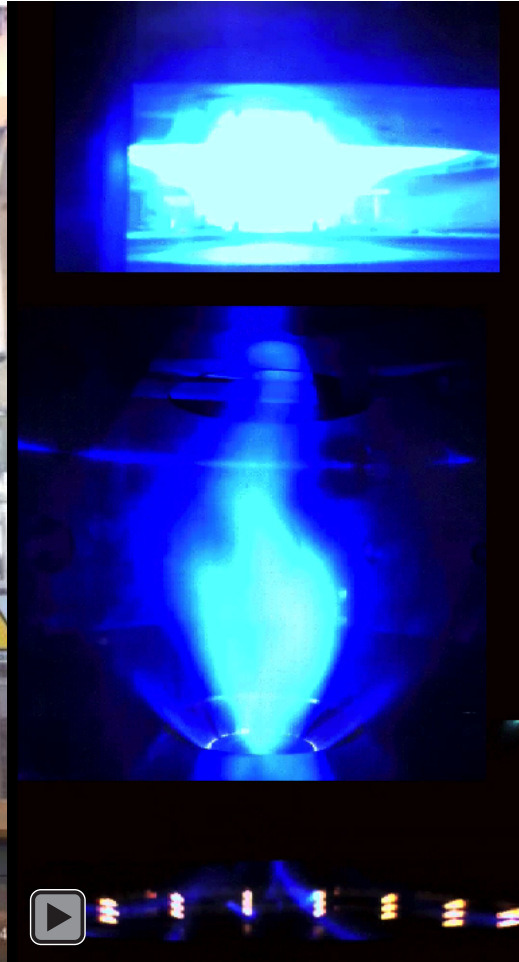


The PROTO-SPHERA experiment, an innovative magnetic confinement scheme

Franco Alladio

CR-ENEA Frascati, July 5 2017



OUTLINE

Why a new and different magnetic confinement device?

- Natural examples in fluids & plasmas
- Unlimited sustainment of plasma by DC voltage
- High β value

How to form a Spherical Torus around a Plasma Centerpost: 1994-1997

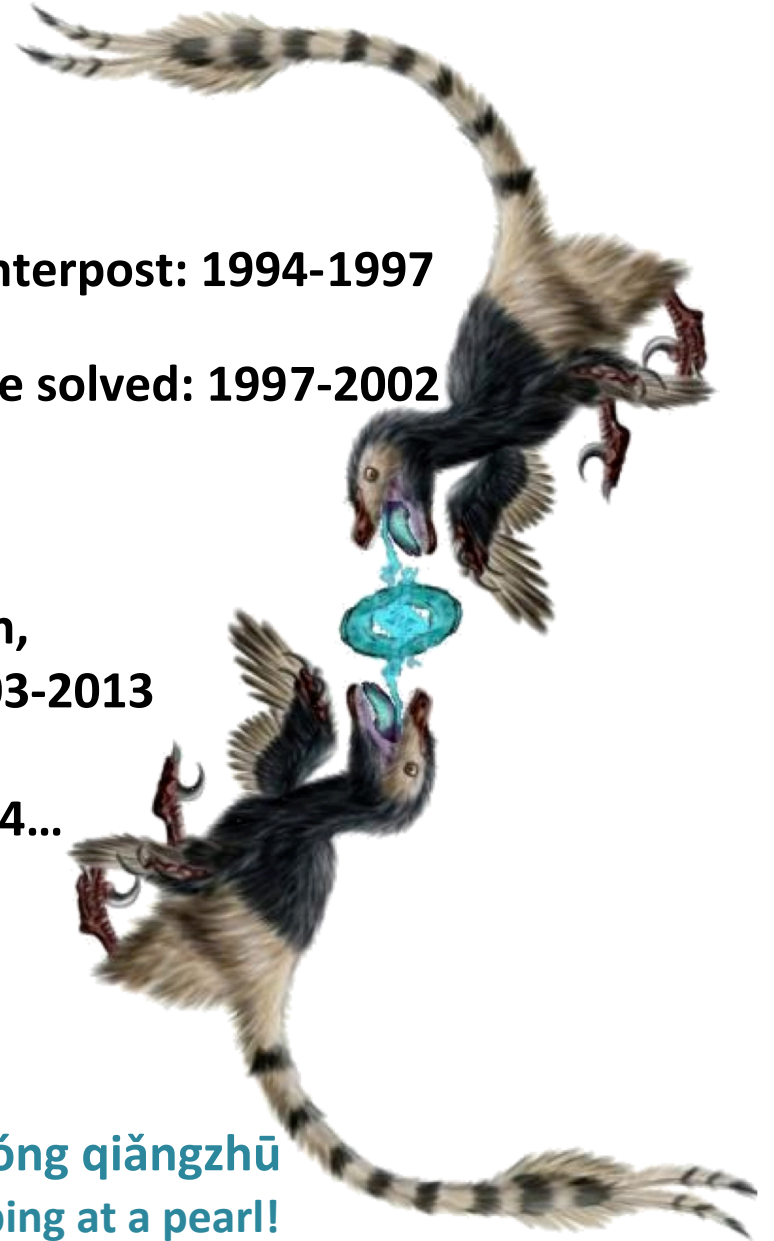
Before building the experiment two issues had to be solved: 1997-2002

- reliability of electrodes
- ideal MHD stability of the magnetic configuration

**An old vacuum chamber, as a gift from Great Britain,
started the construction of the experiment: 2003-2013**

- PROTO-SPHERA produces plasma centerpost: 2014...

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

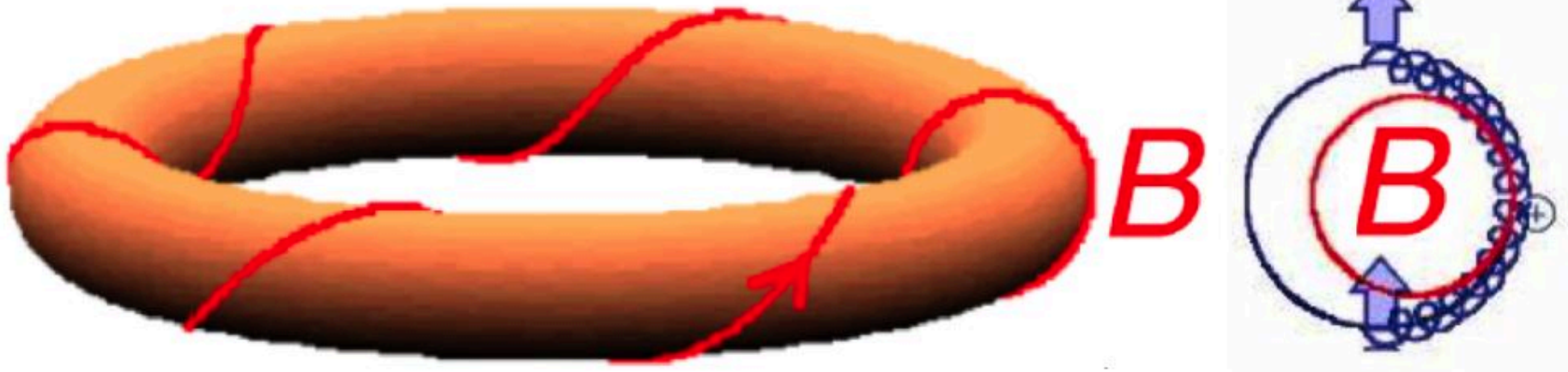


Magnetic Fusion Basics:

Particle drifts & current density $\perp$ to B constrained by a $B_{\perp}$ (poloidal) component:

→ toroidal current flowing in axisymmetric plasma (Tokamak)

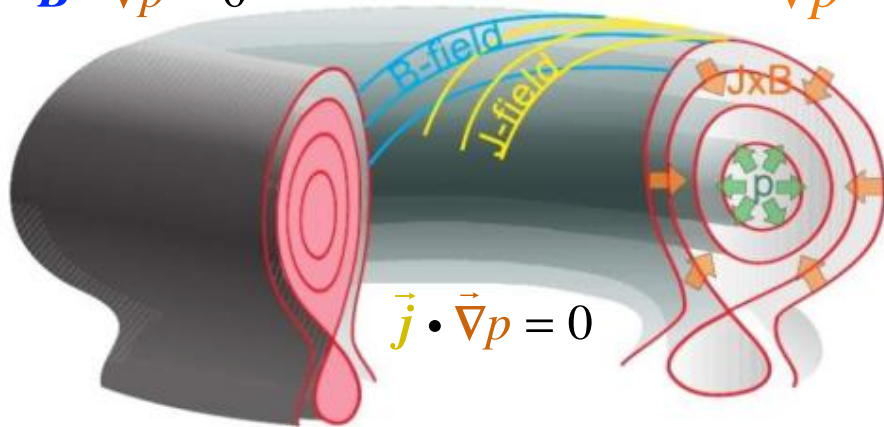
→ or non-axisymmetric configuration (Stellarator)



To avoid plasma ejection requires **2D flux** & **pressure surfaces**, not 1D lines

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

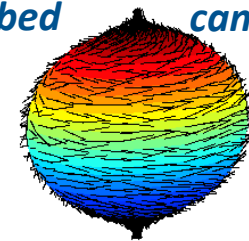
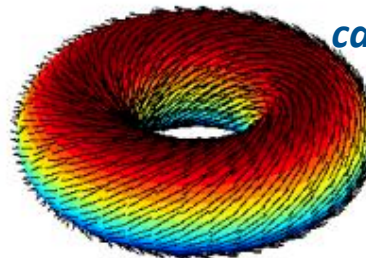
$$\vec{\nabla} p = \vec{j} \wedge \vec{B} \quad (\text{magneto-hydrostatic equilibrium})$$



flux surfaces must be **Tori**:

*a hairy torus
can be combed*

*a hairy sphere
cannot!*

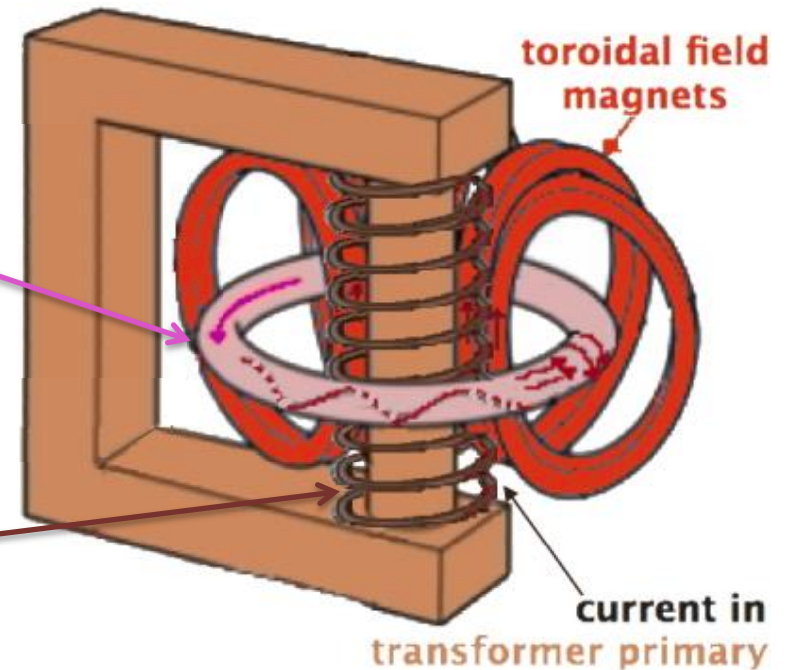


*"Hairy ball theorem": no continuous field tangent to a sphere
unless there is at least upon one point $\vec{B} = 0$ and $\vec{\nabla} p = 0$*

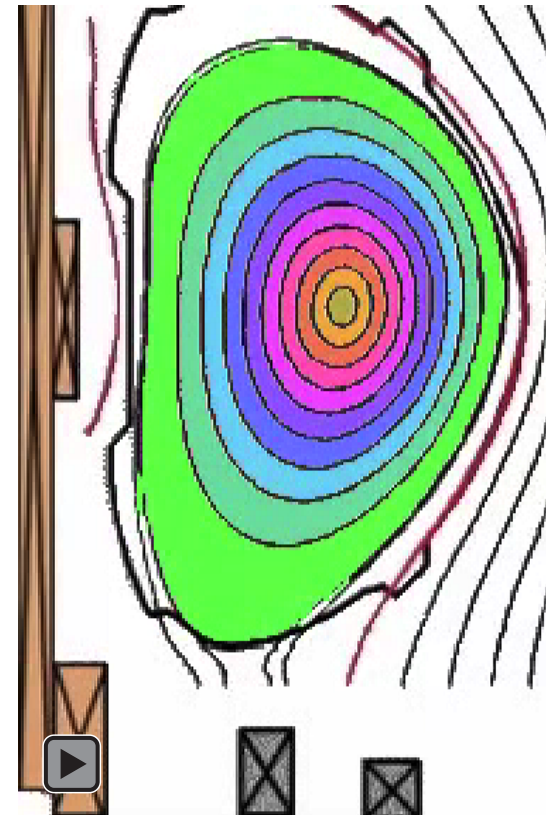
Therefore a **plasma confining current has to flow inside the Torus:**

such a current has to be **induced and sustained by a transformer**

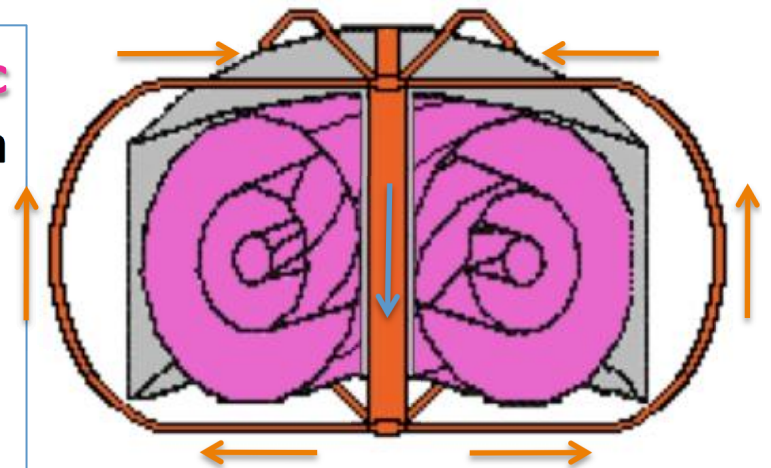
whose current varies in time ...but there are limits: the transformer will break beyond a given current limit...



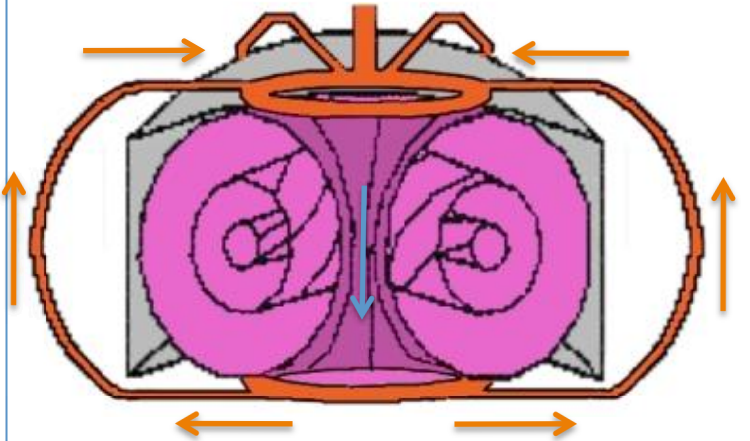
- The plasma ohmic drive in a Tokamak can be seen as motion **of closed flux surfaces**, that from outside 'feed' the plasma, which dissipates them while they move toward the magnetic axis
- In tokamaks this process is due **to the transformer current change:**
- **Tokamaks cannot have steady drive!**



- “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



Electric current flow



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

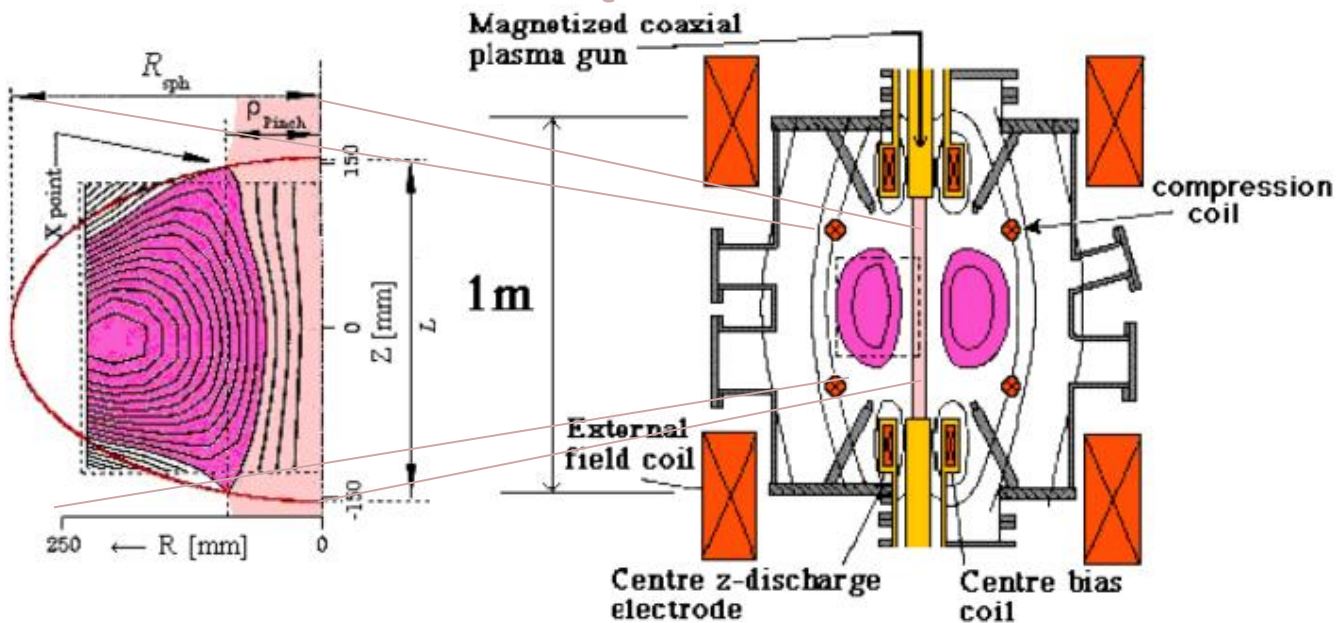
→ easy of access & of repair...



PROTO-SPHERA Japanese precursor:

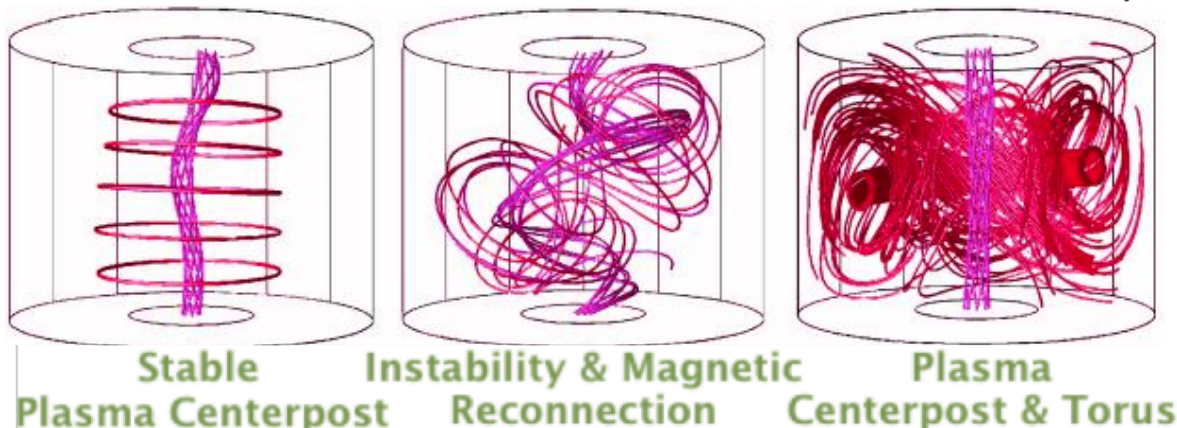
TS-3 (Tokyo University): **plasma toroids** magnetic reconnection around a **metal centerpost**

In 1993 TS-3 **removed the metal centerpost**, applied 1kV between two plasma guns, produced a $I_e = 40 \text{ kA}$ **Plasma Centerpost**



non-linear “kink” instability formed a **Spherical Torus**

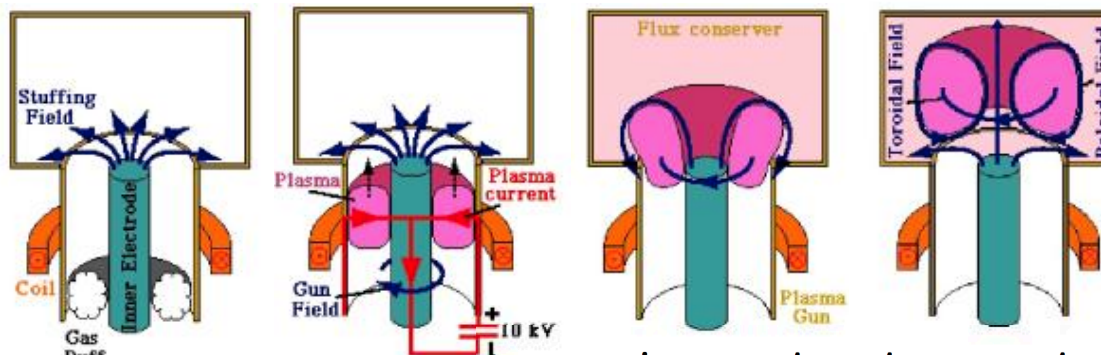
toroidal plasma current $50 \text{ kA} < I_{ST} < 100 \text{ kA}$



60 μs formation
20 μs sustainment
total duration 80 $\mu\text{s} \sim 100 \tau_{\text{Alfvén}}$
(short but significant...)

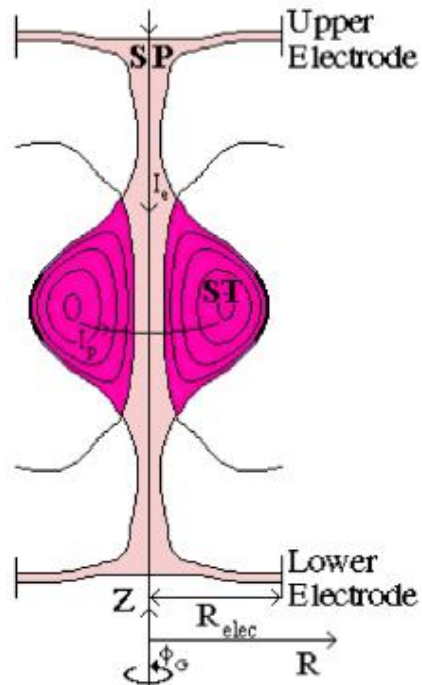
Other precursors of PROTO-SPHERA: GUN INJECTED FLUX-CORE-SPHEROMAKS

Breakdown in small spaces, with extremely high filling pressures and 10 kV voltages
Neutrals and impurities are released from the gun



After the formation, the Spheromak is accelerated and expanded into a flux conserver field errors already present in the gun are amplified

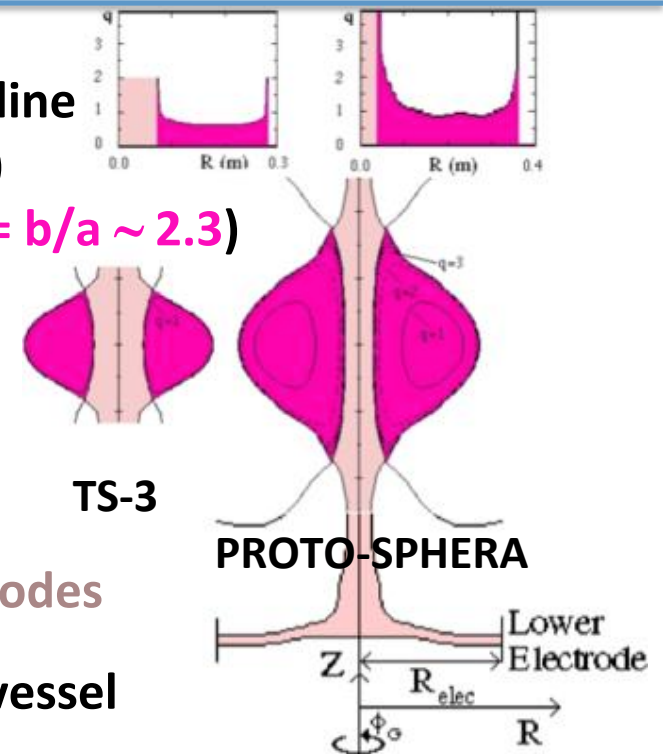
PROTO-SPHERA key differences:



- Designed for a Tokamak-like field-line rotational transform ($q_0 \geq 1$, $q_{\text{edge}} \sim 3$) (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

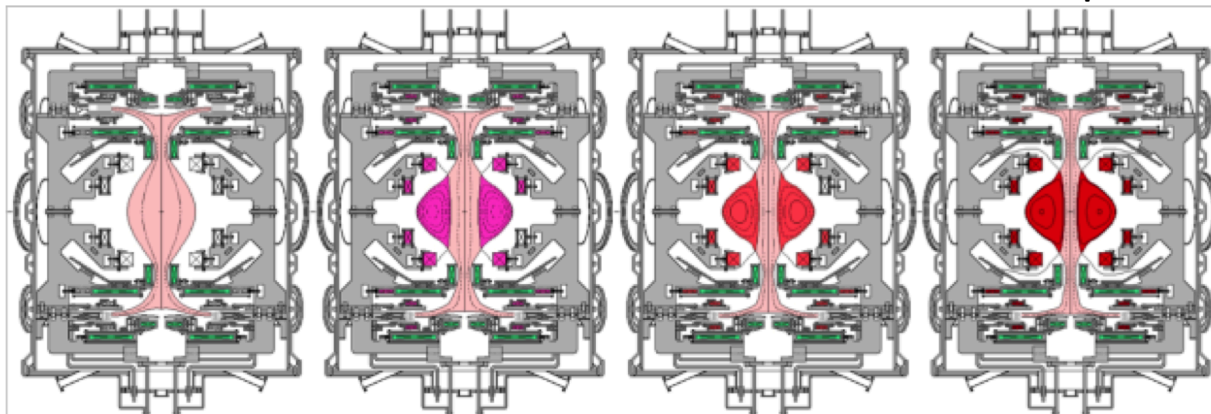
ST toroidal current

ST diameter

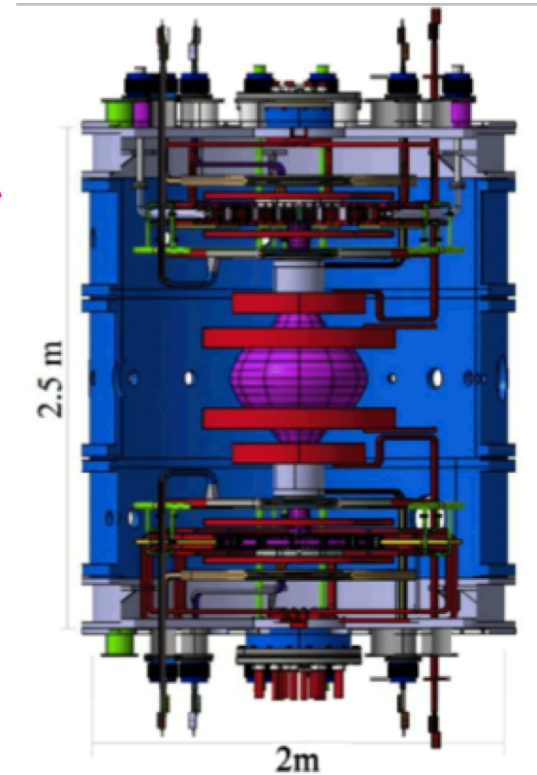
$I_e = 60 \text{ kA}$

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

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



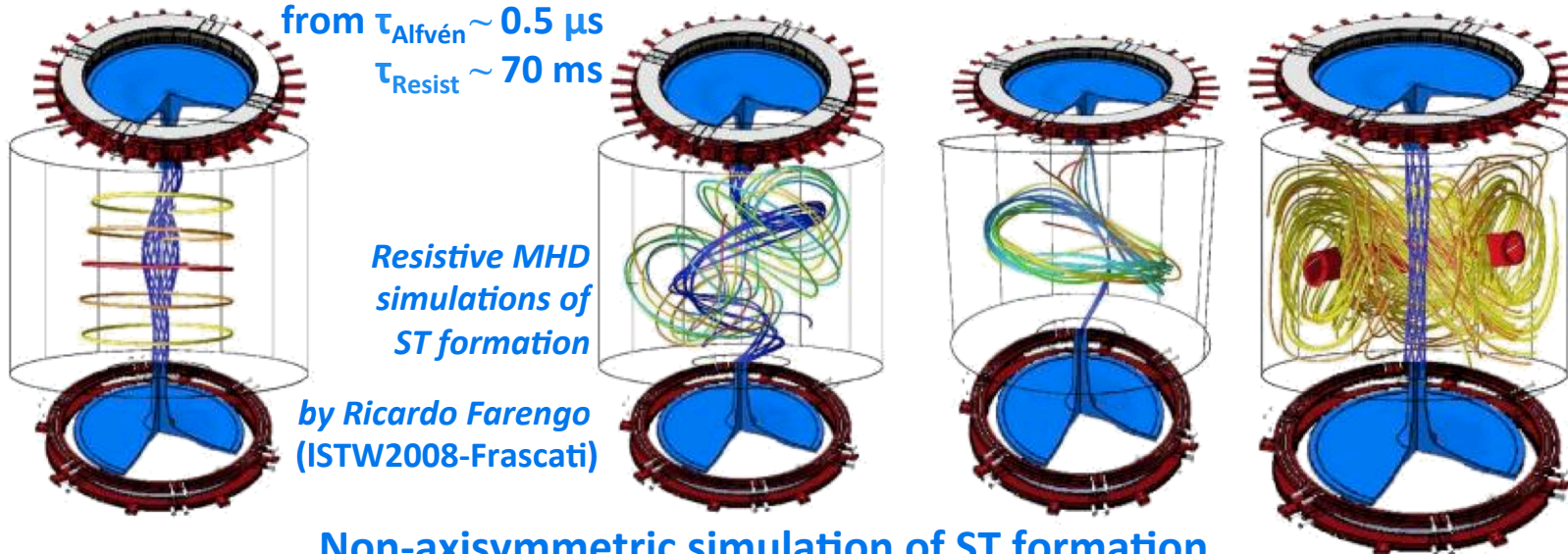
Axisymmetric simulation of ST formation



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

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

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



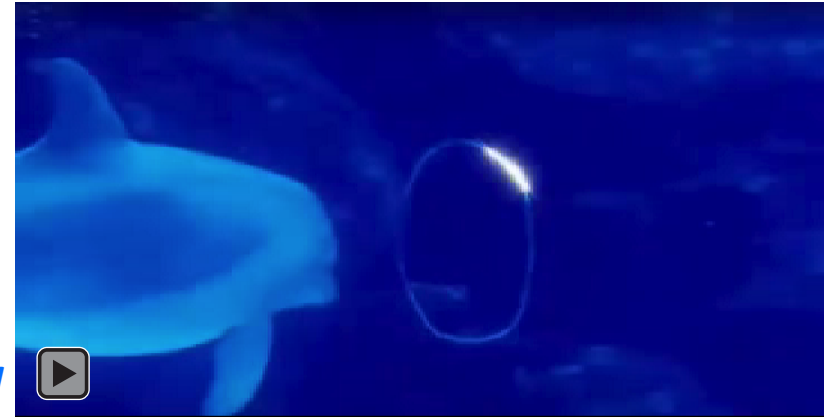
Resistive MHD
simulations of
ST formation

by Ricardo Farengo
(ISTW2008-Frascati)

Non-axisymmetric simulation of ST formation

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!

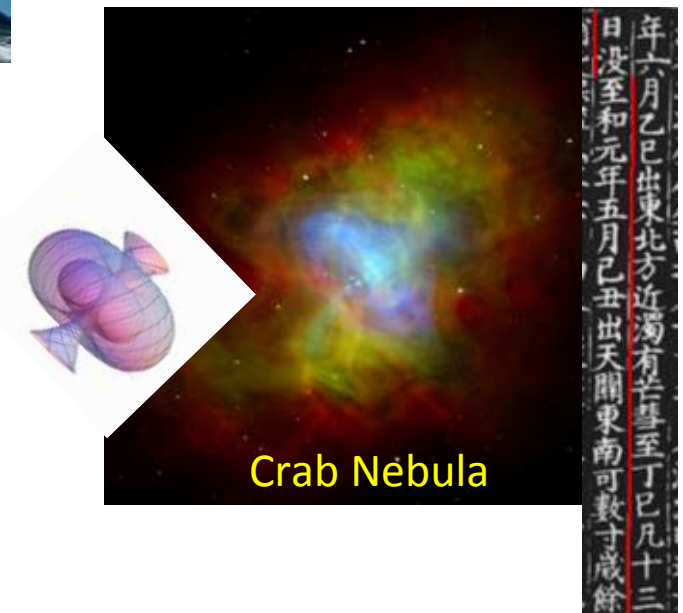


William Irvine-University of Chicago



Fluid dynamics examples

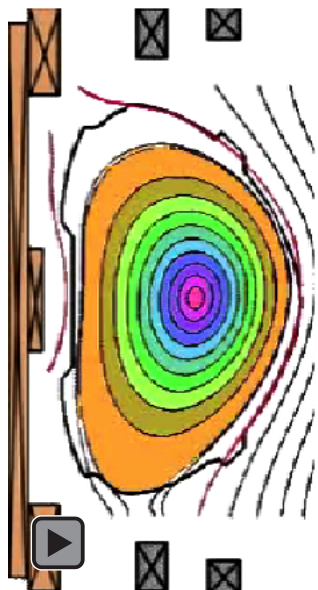
Plasma dynamics example



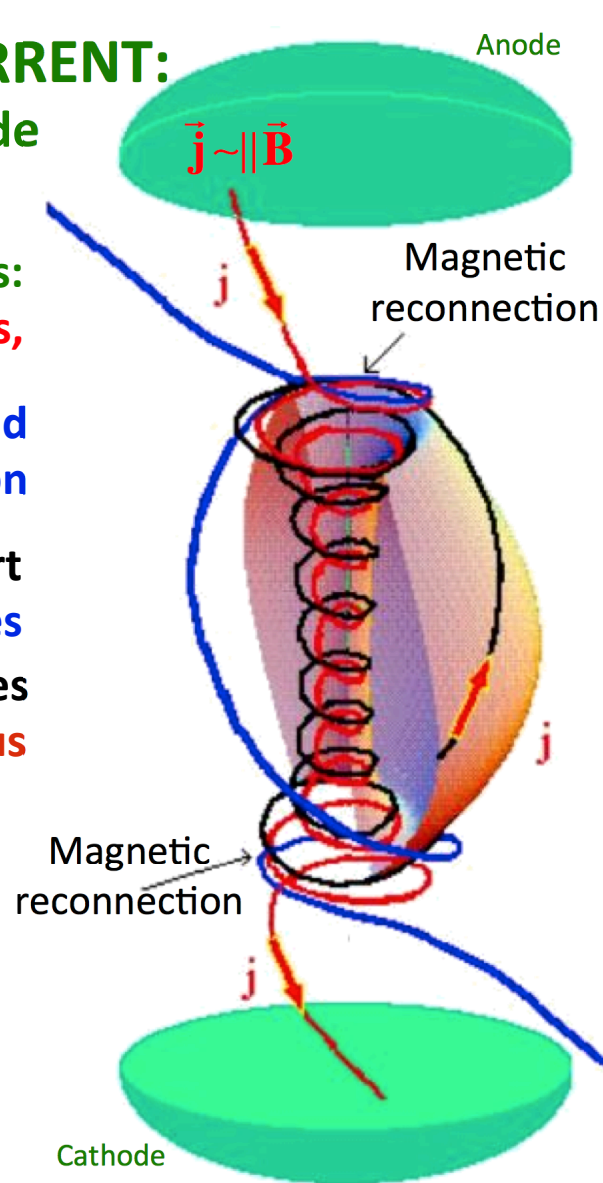
SUSTAIN THE CONFINING CURRENT:

by DC voltage from anode to cathode

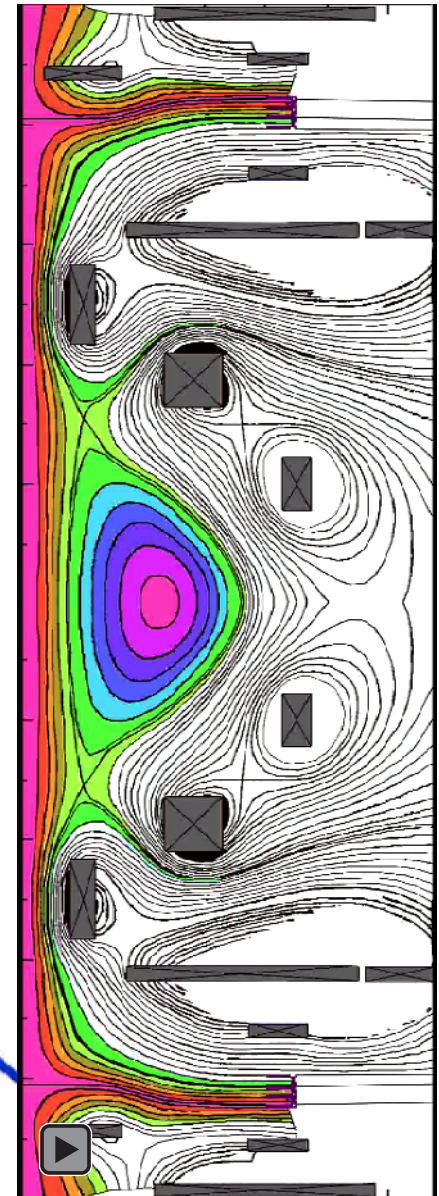
- In front of the electrodes:
open magnetic field lines,
- Open magnetic field lines are wound
in a circular direction
- Magnetic reconnections convert
open $\vec{B}$ lines
into closed $\vec{B}, \vec{j}$ lines
wrapped around the spherical torus



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**

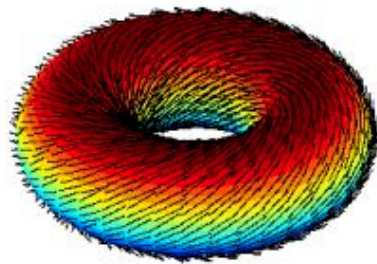


HOW EFFICIENT THE SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS?

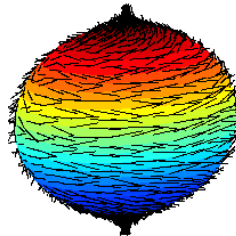
Space Thruster?

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:*



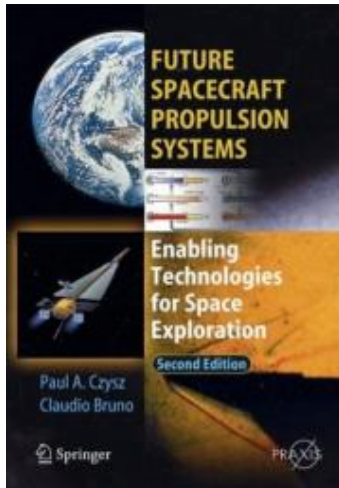
*a hairy torus
can be combed*



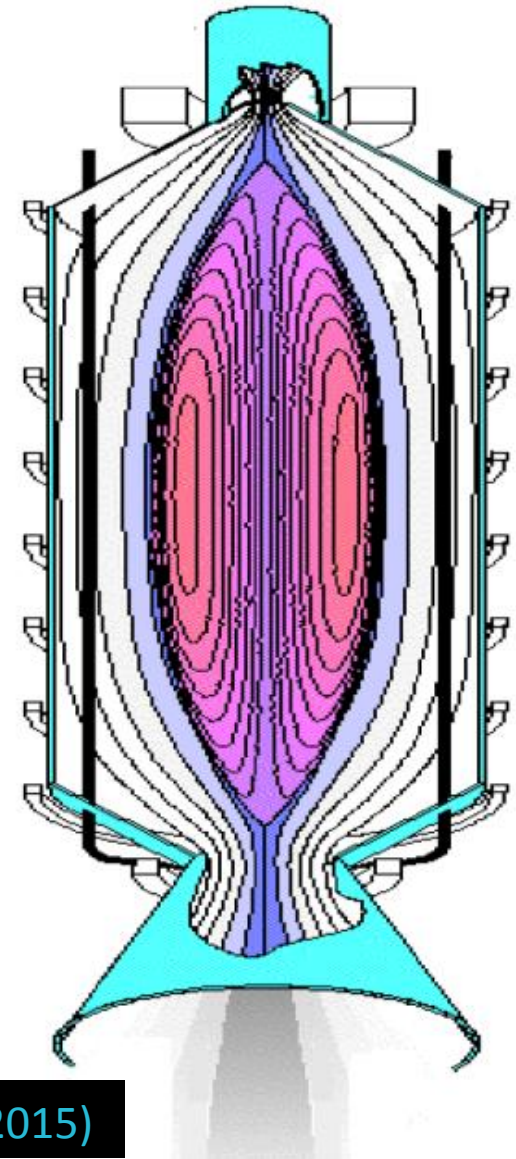
*a hairy sphere
cannot!*

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

Possible future application as a Space Fusion Thruster...



Nozzle observed in PROTO-SPHERA experiment (2015)



SPHERICAL TOKAMAKS

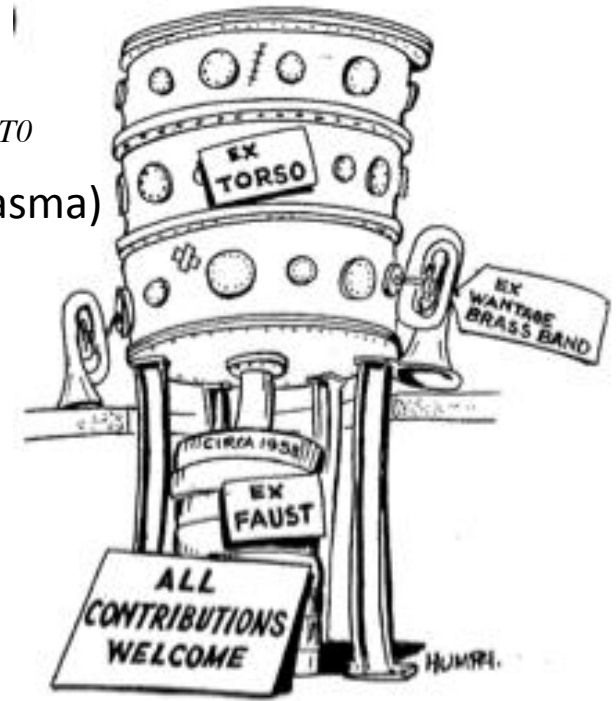
$$\beta = \text{plasma beta} = \frac{\text{kinetic plasma pressure}}{\text{confining magnetic field pressure}}$$

$$\beta = 2\mu_0 \int p dV / \int B^2 dV \quad , \text{ but in tokamak data one often uses } \beta_{T0}$$

$$\beta_{T0} = 2\mu_0 \int p dV / B_{T0}^2 V \quad (B_{T0} \text{ vacuum field on the axis of the plasma})$$

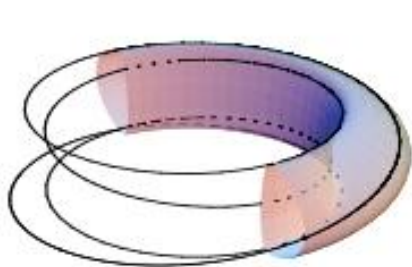
to increase its β the Tokamak needs a spherical shape

1991: Culham (UK) built the START Spherical Tokamak

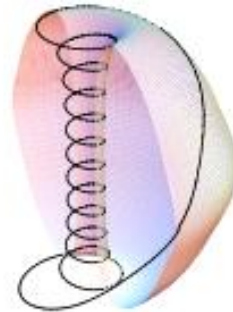


...revamping an *old vacuum vessel*

endowed with NBI heating START reached $\beta_{T0} \sim 40\%$ (3 x DIII-D)

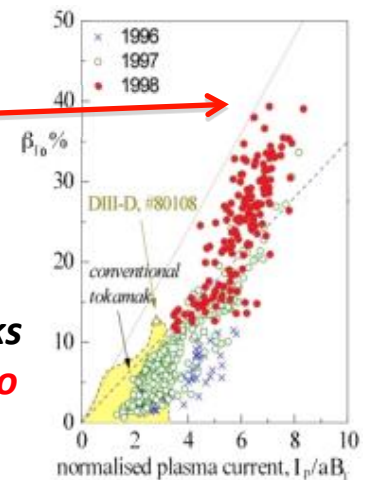


Conventional Tokamak

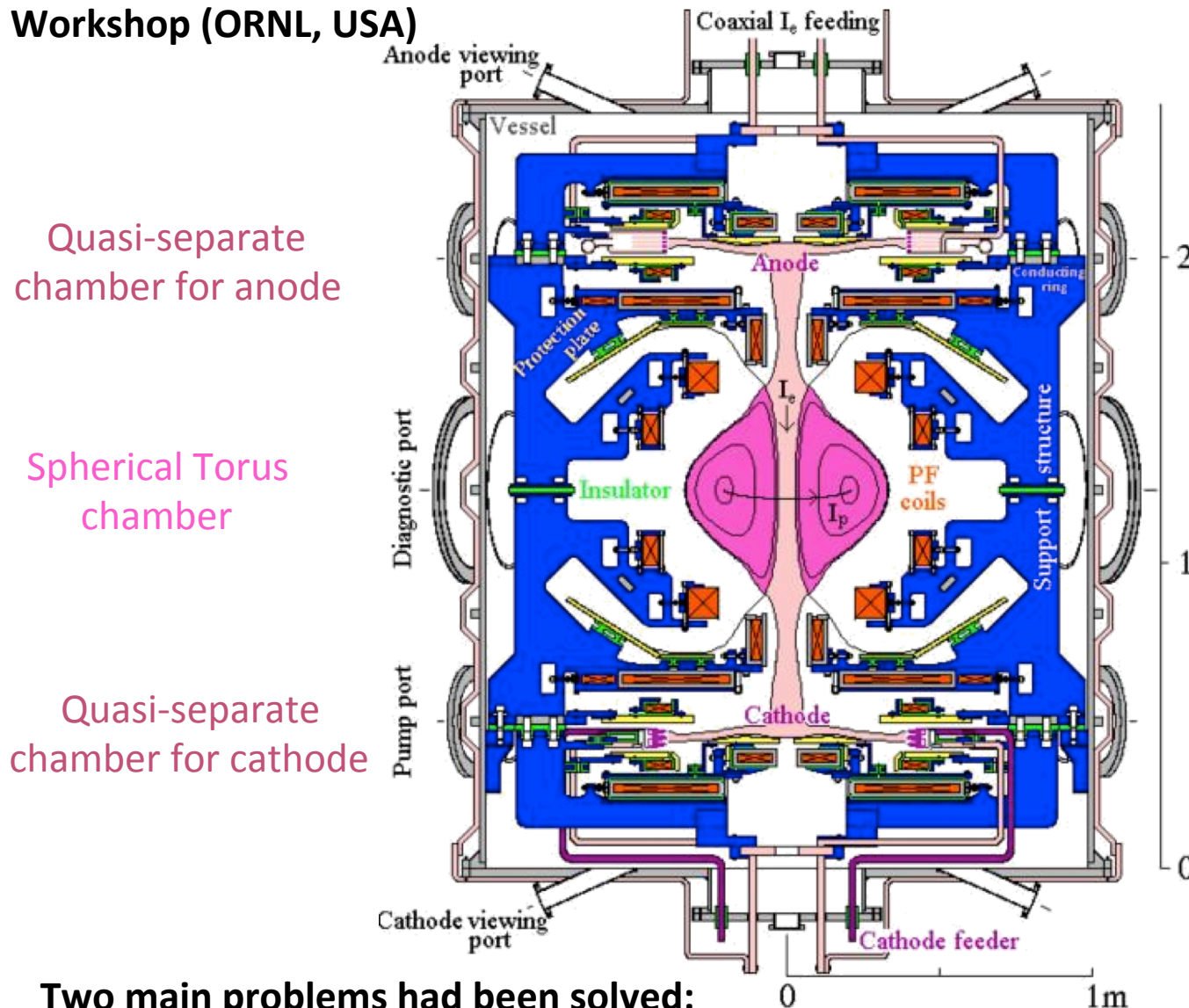


Spherical Tokamak

Favourable properties of Spherical Tokamaks are due to *lines of force that are very near to the geodesic lines of the magnetic surfaces*



PROTO-SPHERA was born (as idea) → 2001 final design report
in 1994 at the first Spherical Torus
Workshop (ORNL, USA)

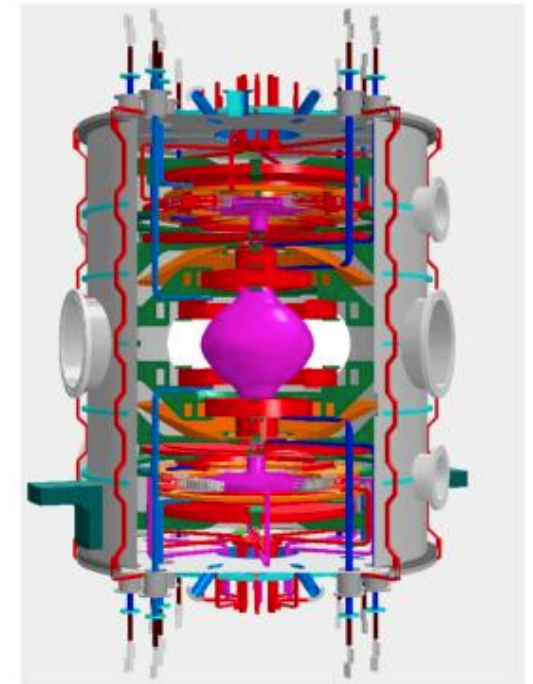


Quasi-separate
chamber for anode

Spherical Torus
chamber

Quasi-separate
chamber for cathode

PROTO-SPHERA



CR-ENEA Frascati, July 2001

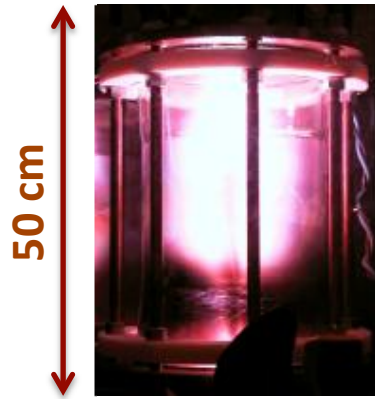
Electrode plasmas quasi
separated from main
plasma

Large number (18) of PF
(poloidal field) coils

Two main problems had been solved:

- building durable electrodes
- restrictions imposed by the ideal MHD stability

PROTO-PINCH testbench (1998-2000) developed the electrodes for PROTO-SPHERA
at a current and power density that is relevant for a **Biased Divertor of a Reactor-Grade Plasma**



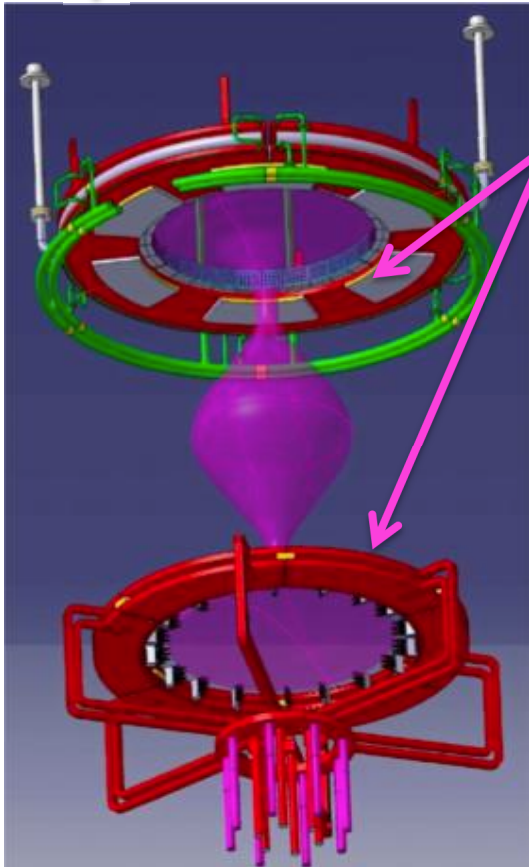
- @ low (100-200 V) voltage on electrodes
- @ Tokamak-like density

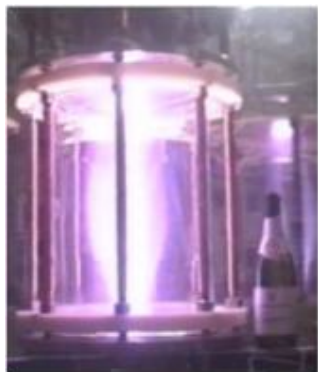
Modular annular electrodes:
Gas puffed hollow anode



Plasma centerpost at electrode
interfaces mushroom-shaped

Plasma current density $j_e = 1 \text{ MA/m}^2$
Power density $P_e = 20 \div 30 \text{ MW/m}^2$
W directly heated filament cathode



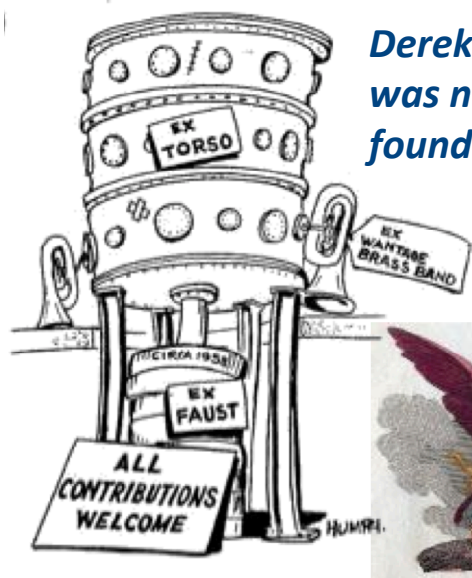


PROTO-PINCH

Derek Robinson
1941-2002

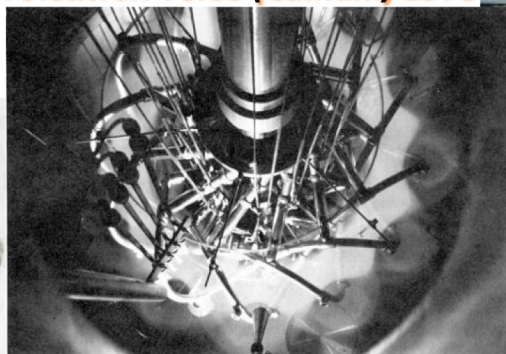


Derek Robinson (director of Culham from 1991) was very interested in the “**Champagne bottle**” **experiment**: in 1999 he proposed to build at Culham PROTO-SPHERA, inside the START vessel

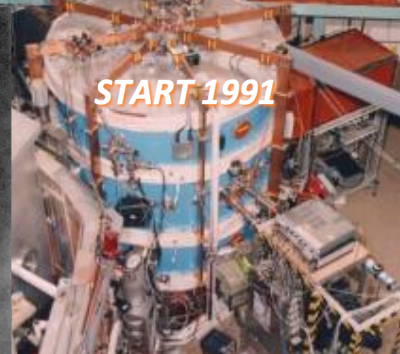


Derek Robinson’s proposal unfortunately was not accepted... but the “Old Vessel” found anyway its road ...to Rome!

Torsatron Torso (Culham) 1975



START 1991



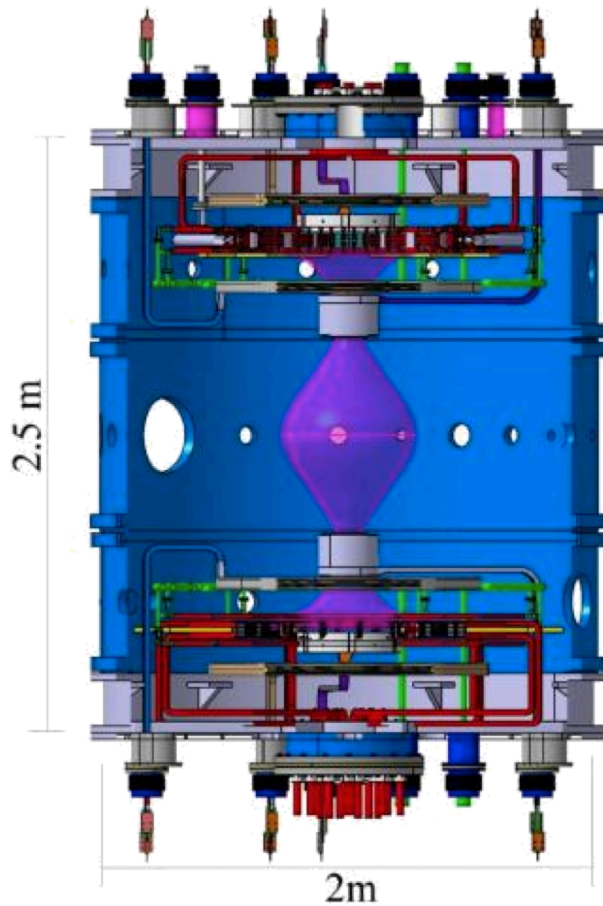
PROTO-SPHERA 2010



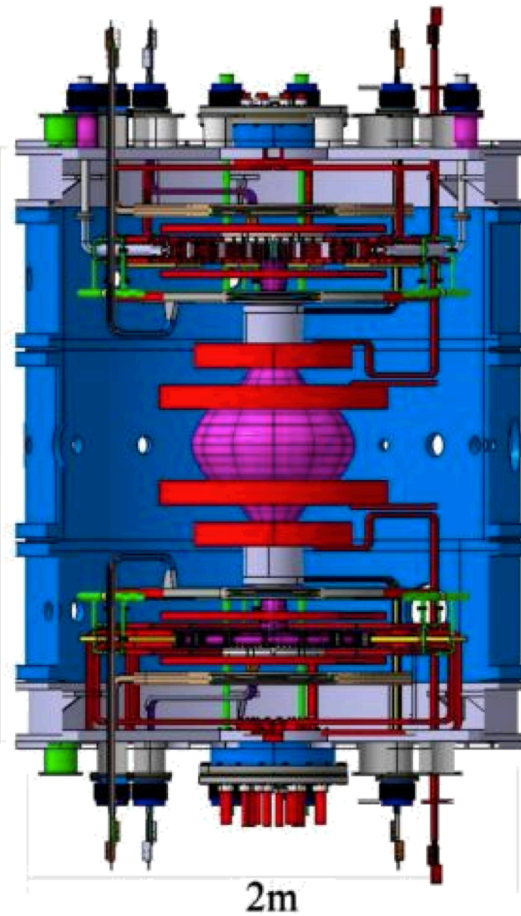
In **2002** at Frascati an **International Workshop** advised to build the machine in 2 steps:

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

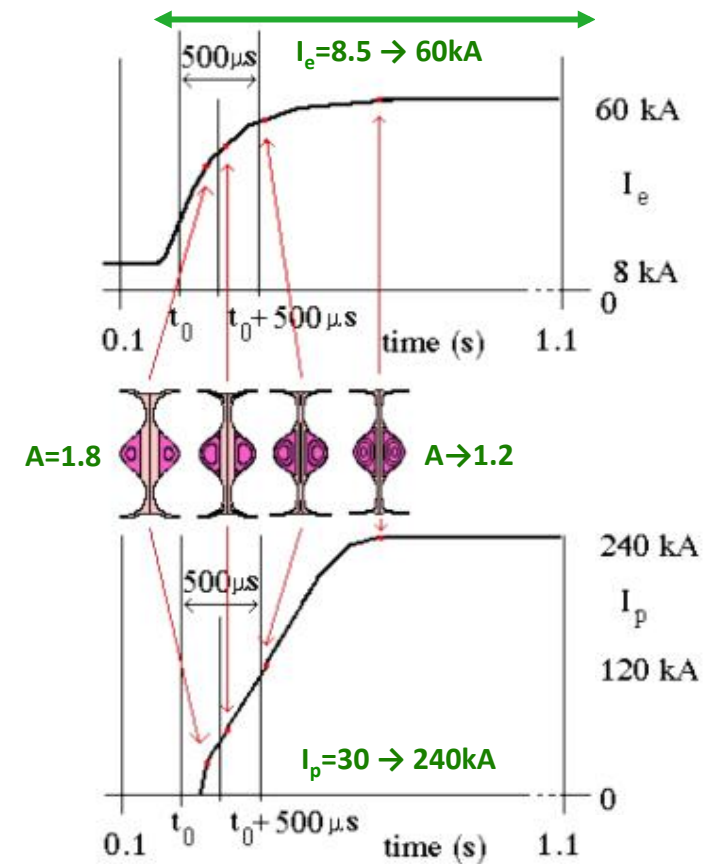
Phase1: 8 PFcoils
Centerpost shape



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



ST compression

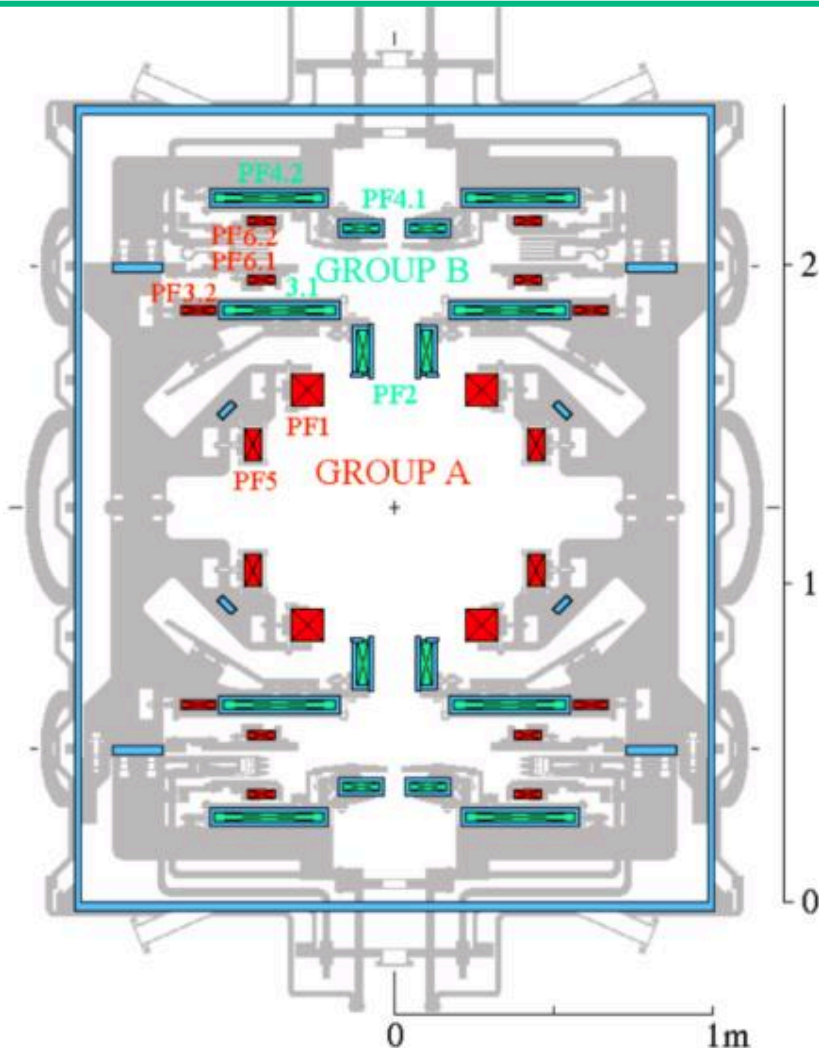


SP centerpost current $I_e = 10$ kA
No ST toroidal current

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

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

Group B (4+4 coils): Centerpost shaping PF coils ...*thick AISI casings ($\tau \sim 2\text{ms}$), now inside machine*



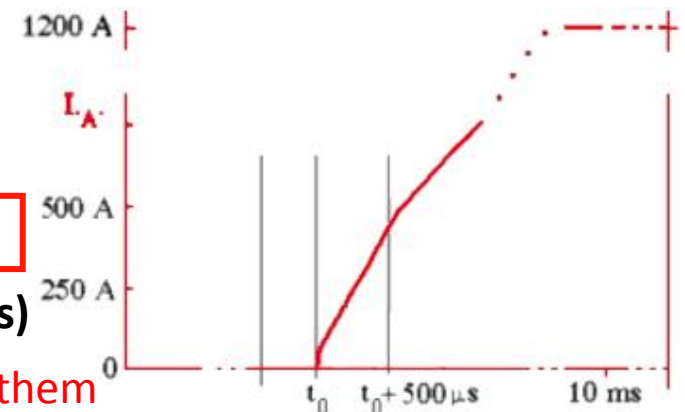
...waveform of **Group A** will provide ohmic drive to Torus up to 120 kA

Paradigm reversal:
ohmic drive followed by Helicity Injection

Group A (5+5 coils): ST compression PF coils ...*not yet built*

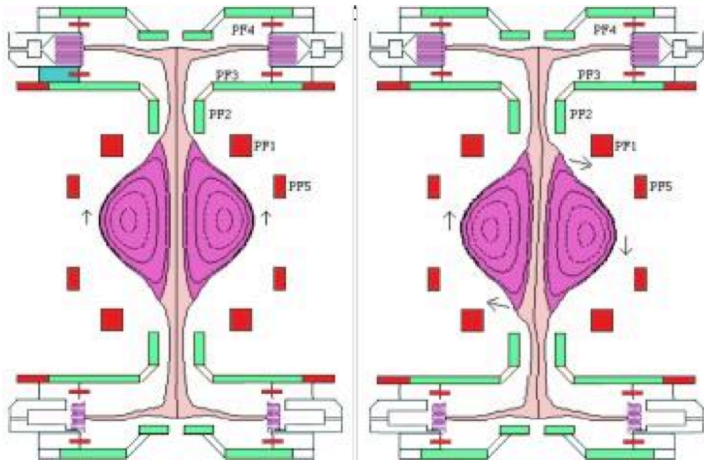
high voltage ($\sim 20\text{ kV}$) insulation: **fast current increase (0.5 ms)**

thin Inconel casings allow for B diffusion in $\tau \sim 200\text{ }\mu\text{s}$ across them

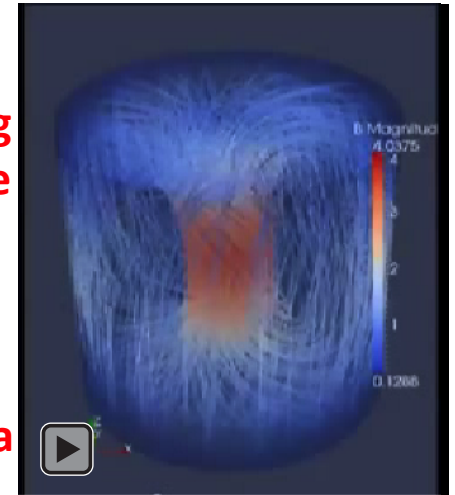


IDEAL MHD STABILITY of PROTO-SPHERA

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



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

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

ratio of the two plasma currents

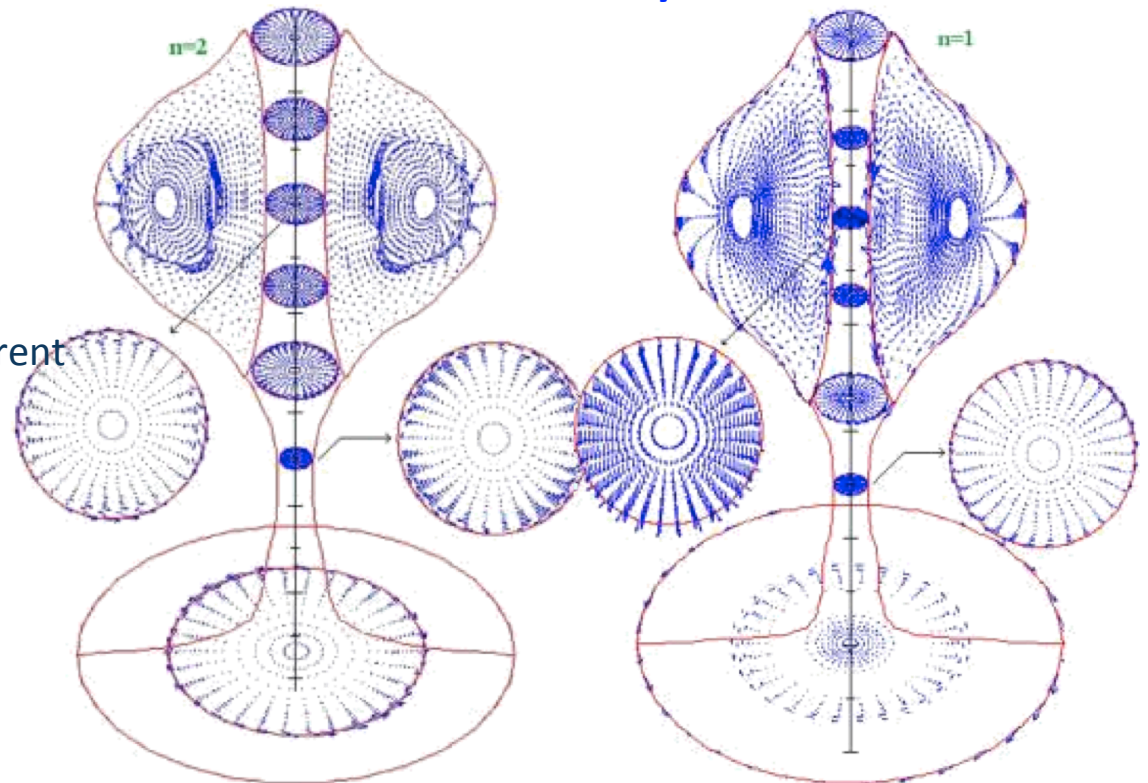
I_{ST}/I_e = toroidal ST current/centerpost current

- up to $\beta = 21\div 26\%$, $I_{ST}/I_e = 0.5 - 1$
- up to $\beta = 14\div 15\%$, $I_{ST}/I_e = 2-4$

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

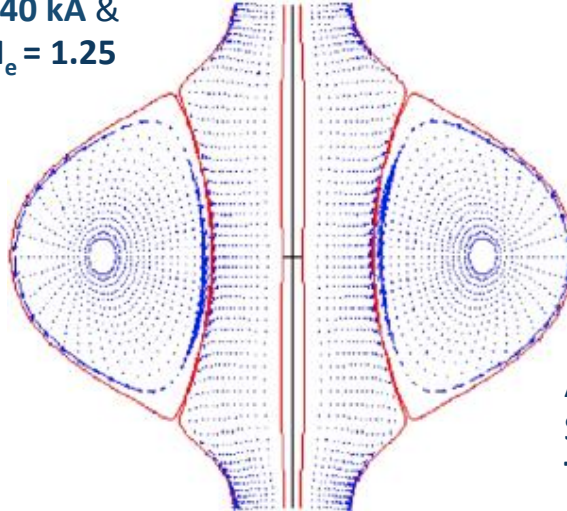
- up to $\beta_{T0} = 28\div 29\%$, $I_{ST}/I_e = 0.5 - 1$
- up to $\beta_{T0} = 72\div 84\%$, $I_{ST}/I_e = 2-4$

Full ideal MHD stability calculations

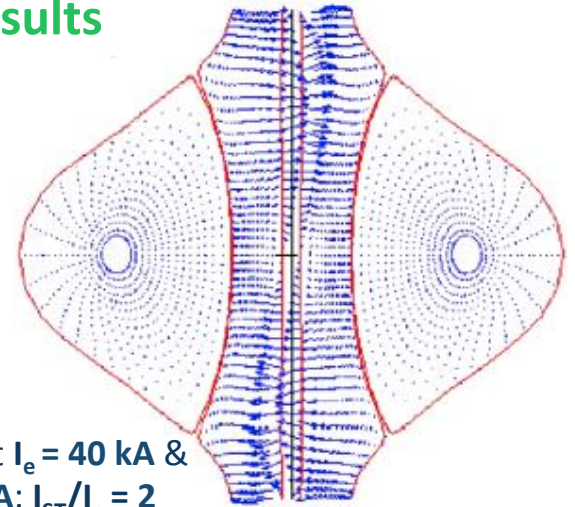


Comparison with TS-3 experimental results

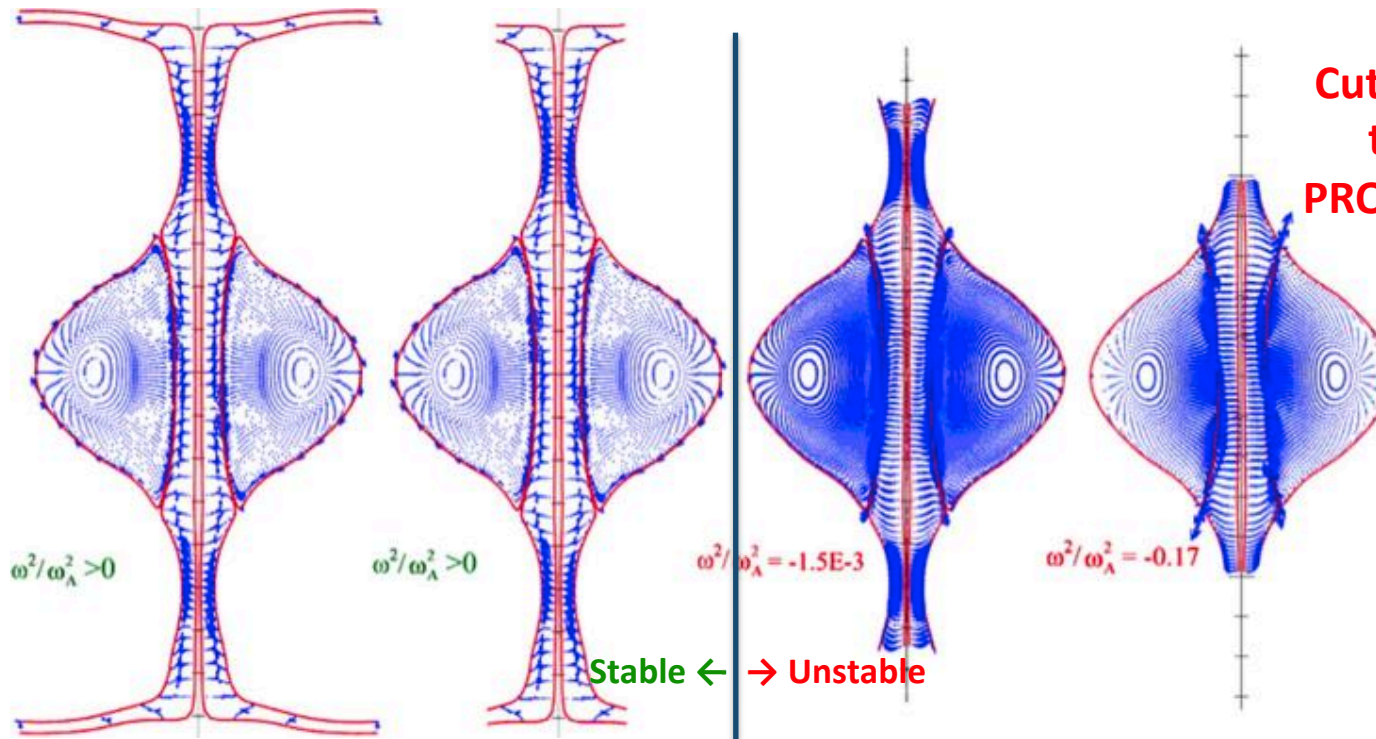
At centerpost current $I_e = 40$ kA &
ST current $I_{ST} = 50$ kA: $I_{ST}/I_e = 1.25$
TS-3 is **ideal MHD stable**



At centerpost current $I_e = 40$ kA &
ST current $I_{ST} = 100$ kA: $I_{ST}/I_e = 2$
TS-3 is **ideal MHD unstable: tilt of SP**



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



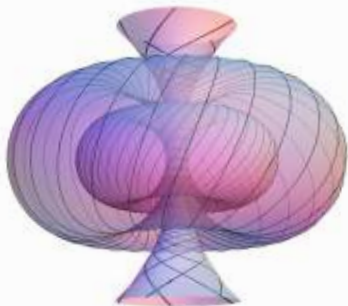
**Cutting shorter & shorter
the plasma centerpost
PROTO-SPHERA at 120 kA
gets destabilized**

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€



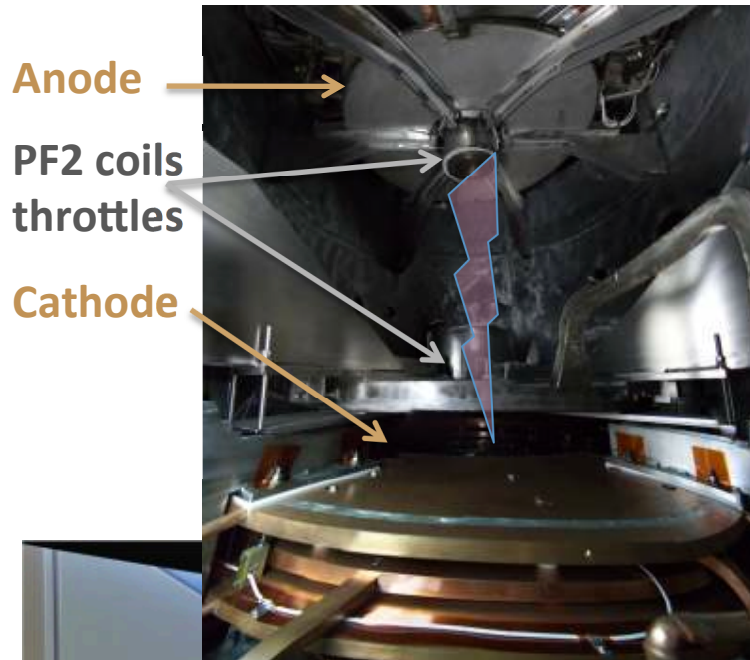
Years 2004 - 2010:

...from ideas

...to detailed design

...to hard metal

PROTO-SPHERA POWER SUPPLY



To fire the **plasma centerpost**
3 Power supplies are required

- **Cathode heating** rotating 6-phase: 6 x(1.7 kA,25 V) rms
- **PF coils:** 2kA, 350 V DC current
- **Plasma centerpost:** 10 kA, 350 V DC current



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

Years 2011 - 2014:



Cylindrical anode

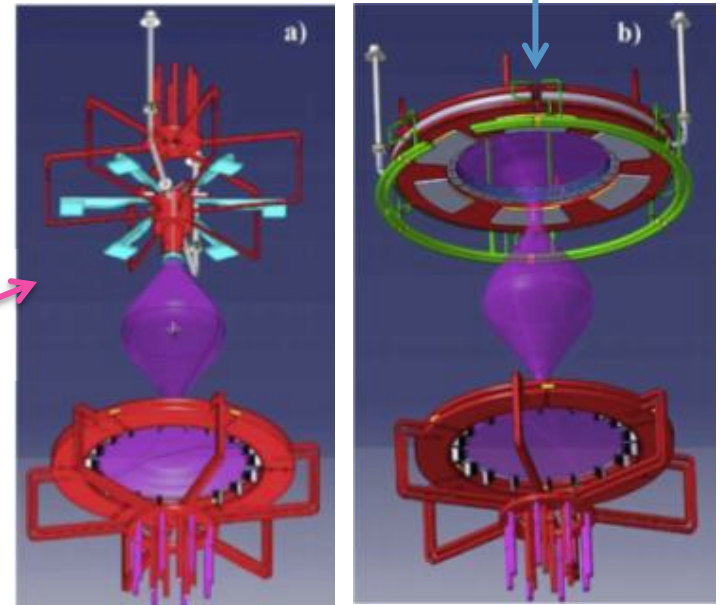
2014 cylindrical anode 2015 annular anode



*Being afraid of Anode Arc Attachment,
often observed in arc discharges
(arc welding, plasma torches)*

the first rounds of experiments
had a simple cylindrical anode

break-down was easily achieved,
apart from this ...the cylindrical anode
was just a source of troubles!



Cylindrical cathode results

Hydrogen plasma

break-down 170 V +10 ms, 500 A +20 ms, 1.5 kA

anode camera



April 2015
Annular Anode
installed





May 2015 annular
anode lowered
on top of machine



Up: hollow gas-puffed anode

Down: 3000° 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

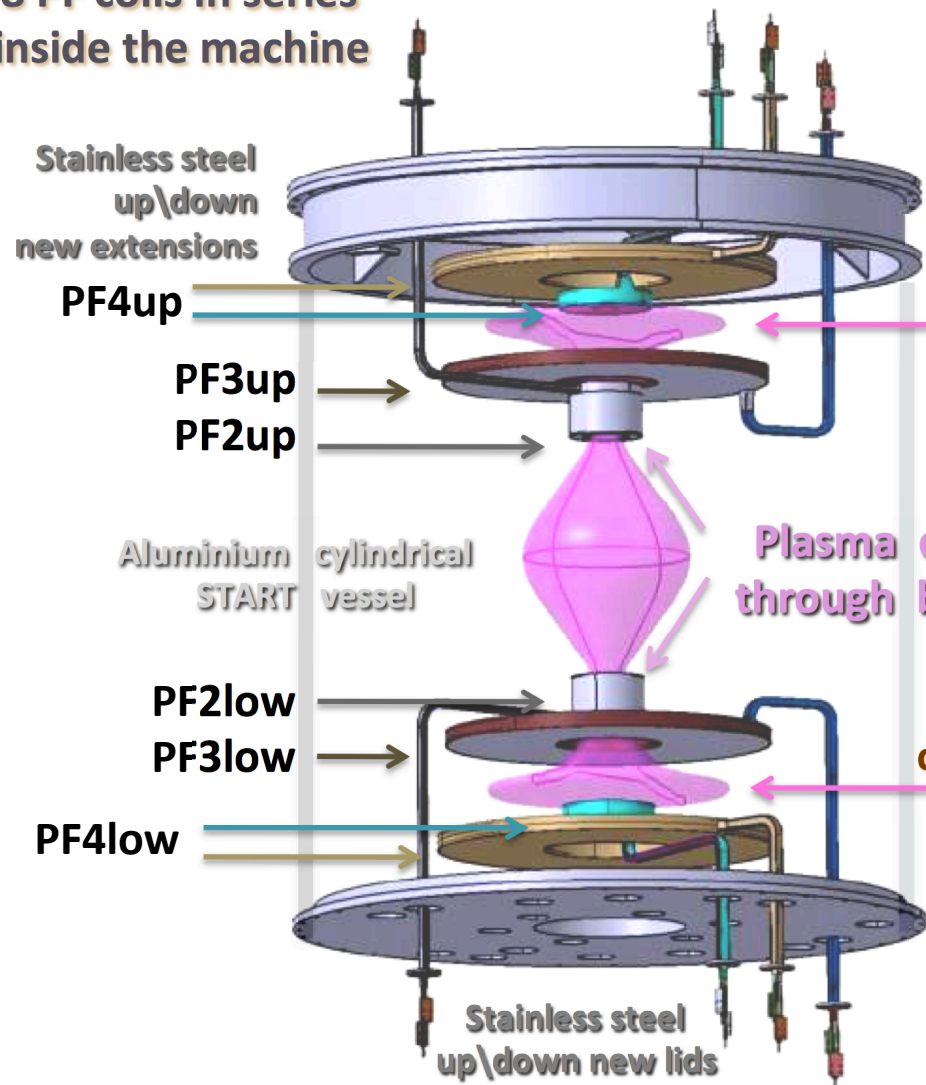
“Caduceus”-like emitting spirals
have now survived > 1000 cycles



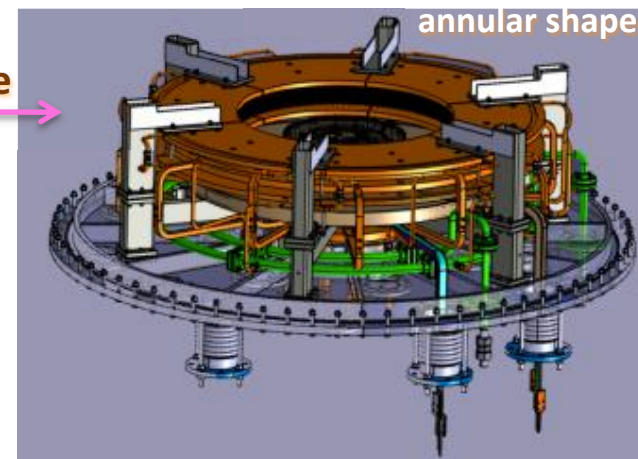
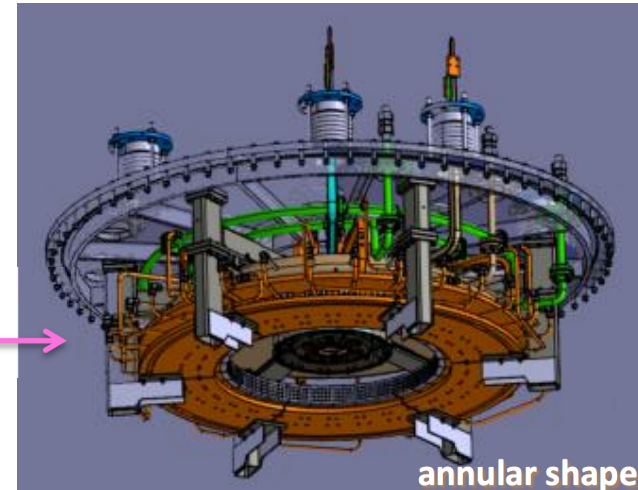
INSULATIONS

8 PF coils in series
inside the machine

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



Plasma current must run
through both PF2 throttles



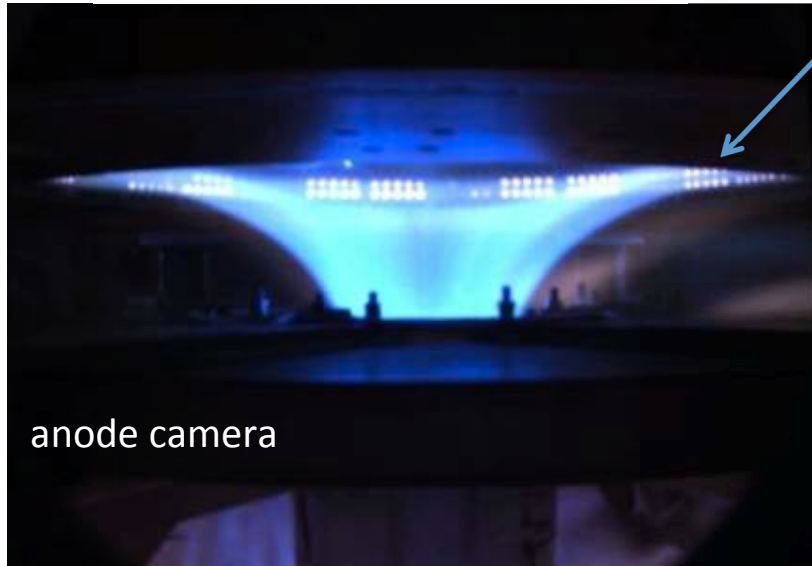
vacuum vessel is GND potential

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

PF coils casings built as floating,

No Anode Arc Attachment!

Argon plasma: break-down 80 V



anode camera



cathode camera

Hollow annular anode performs

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

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



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

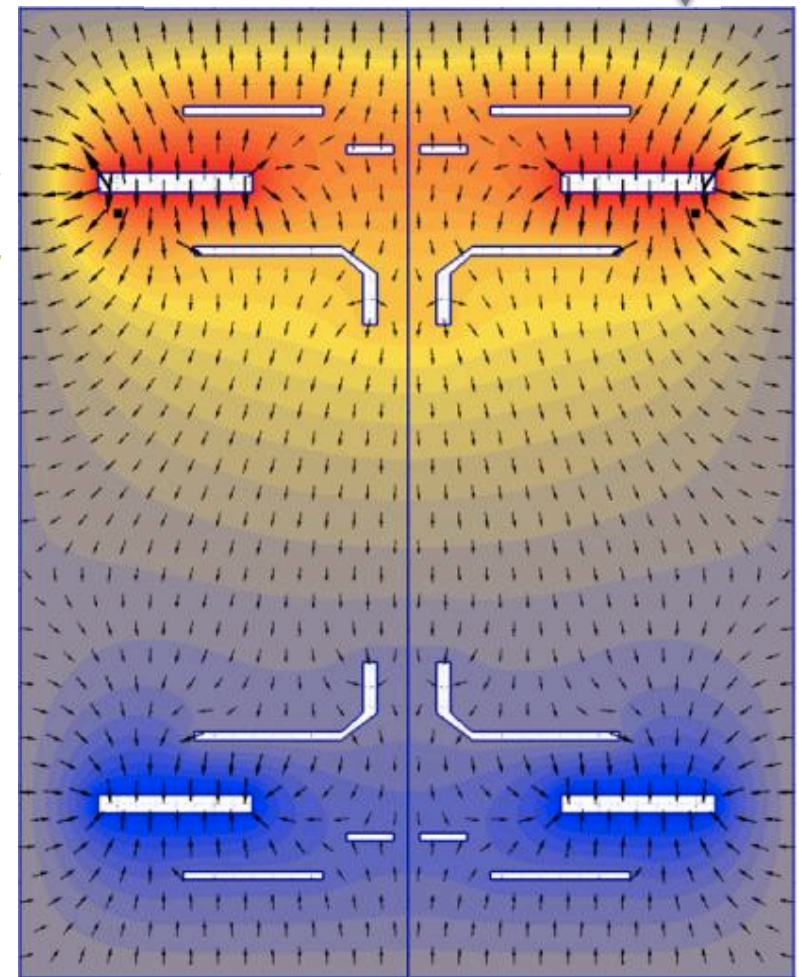
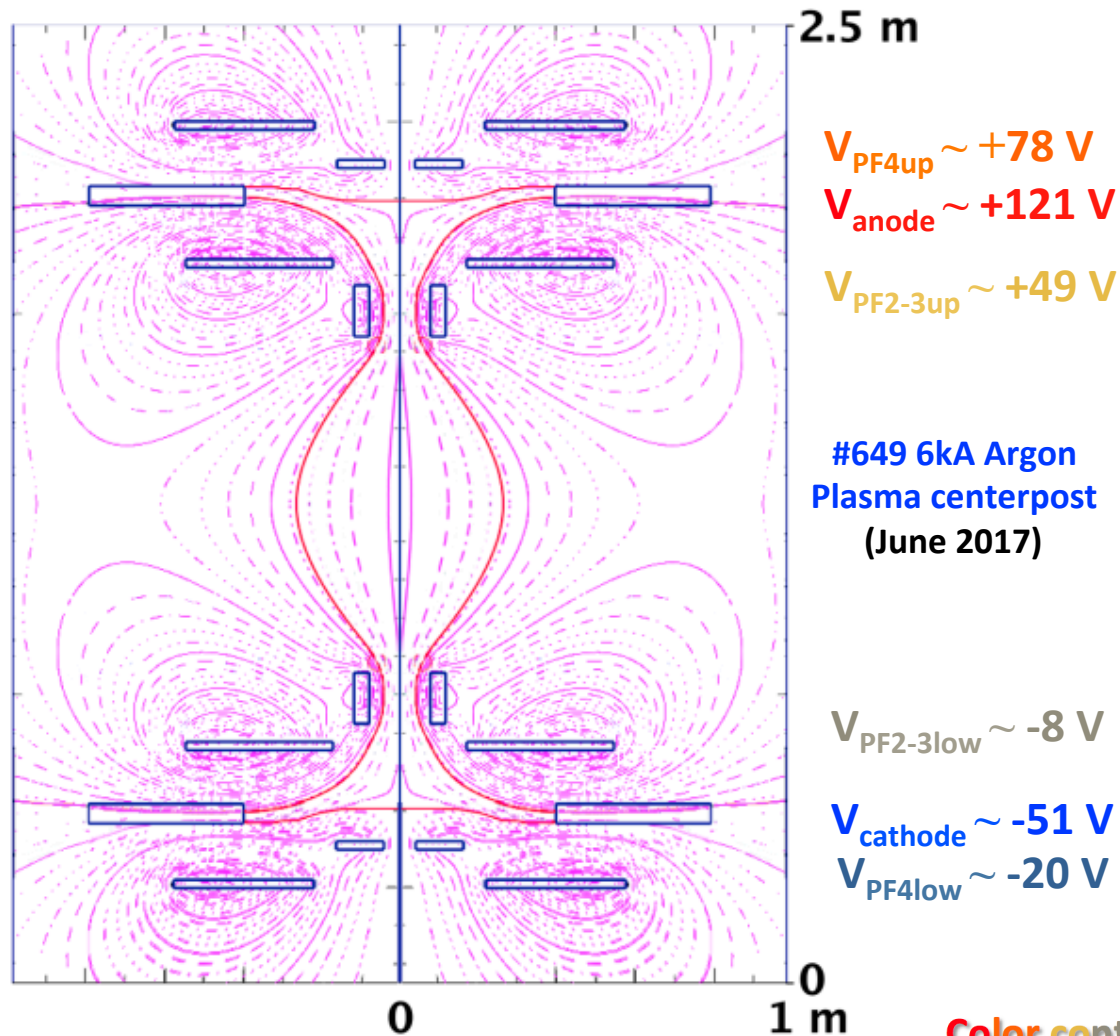
No Anode Arc Attachment: Electrostatic plasma effects!

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!**

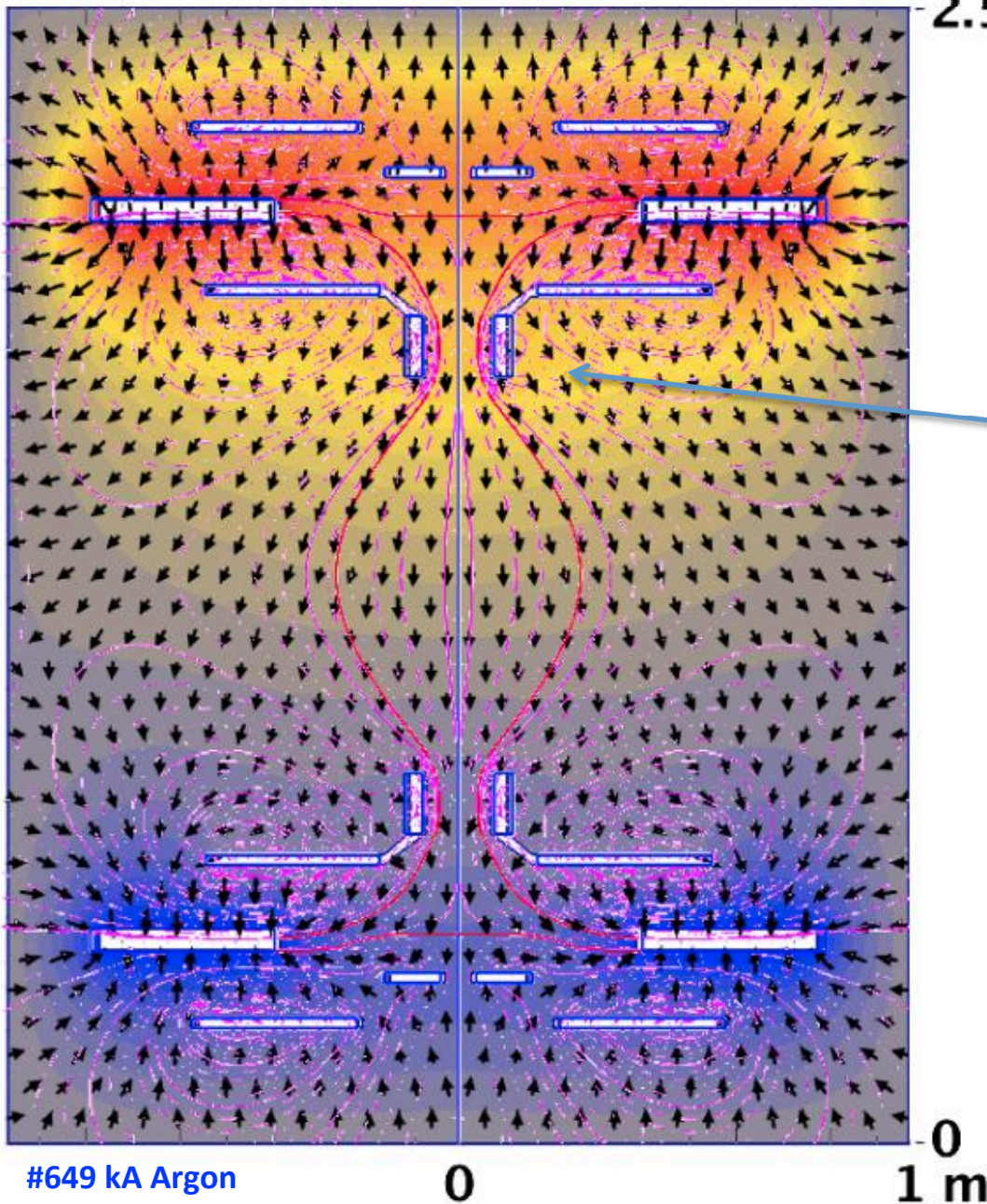
the magnetic field is up\down symmetric but **electrostatic field not up\down symmetric**

vacuum vessel at GND 0V ↓



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

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



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**

#649 kA Argon

Lines: magnetic field

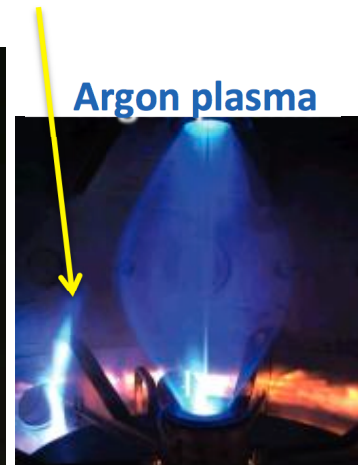
May 2015 **Hydrogen** & **Argon** plasma centerpost
half of the plasma current: (1 kA\2 kA)

was going around the required path due the

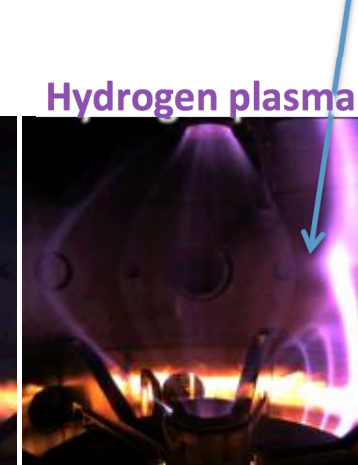
Equatorial X-point inside the vessel



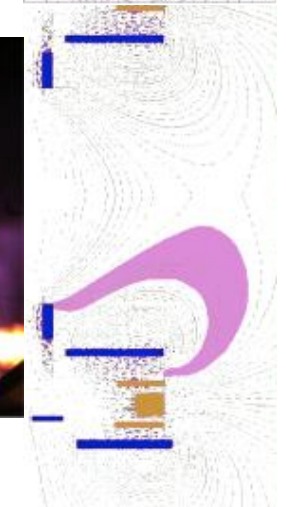
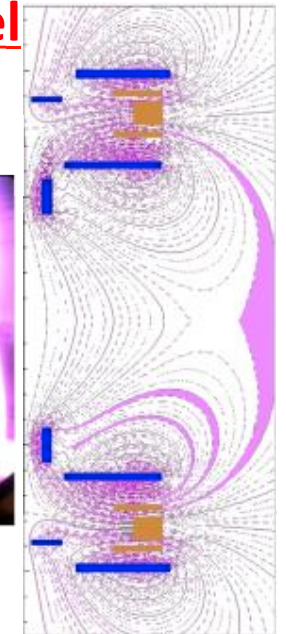
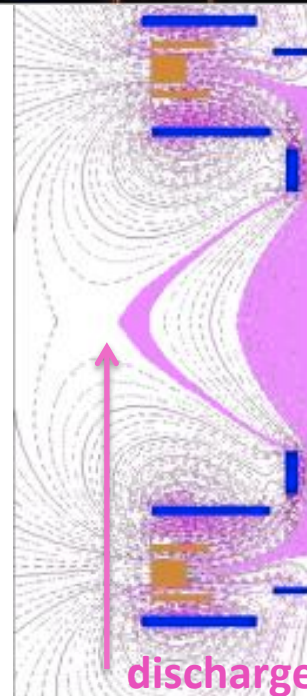
Shot 78



Argon plasma



Hydrogen plasma

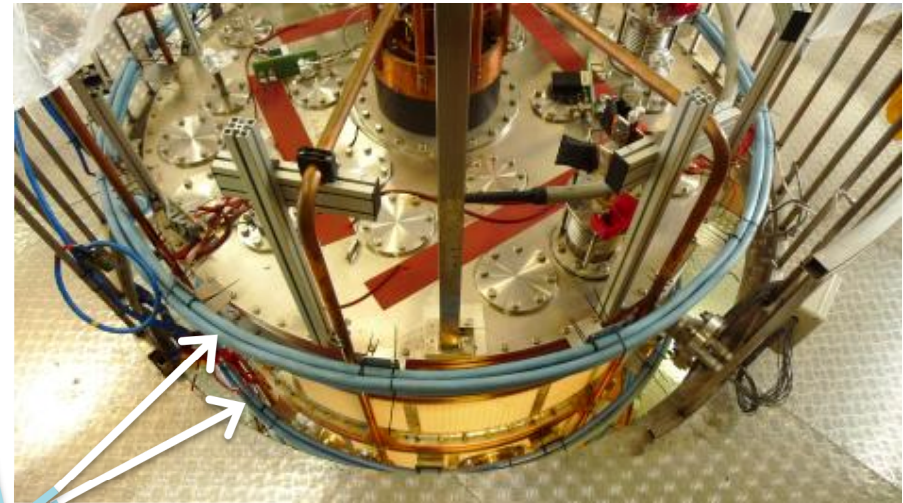
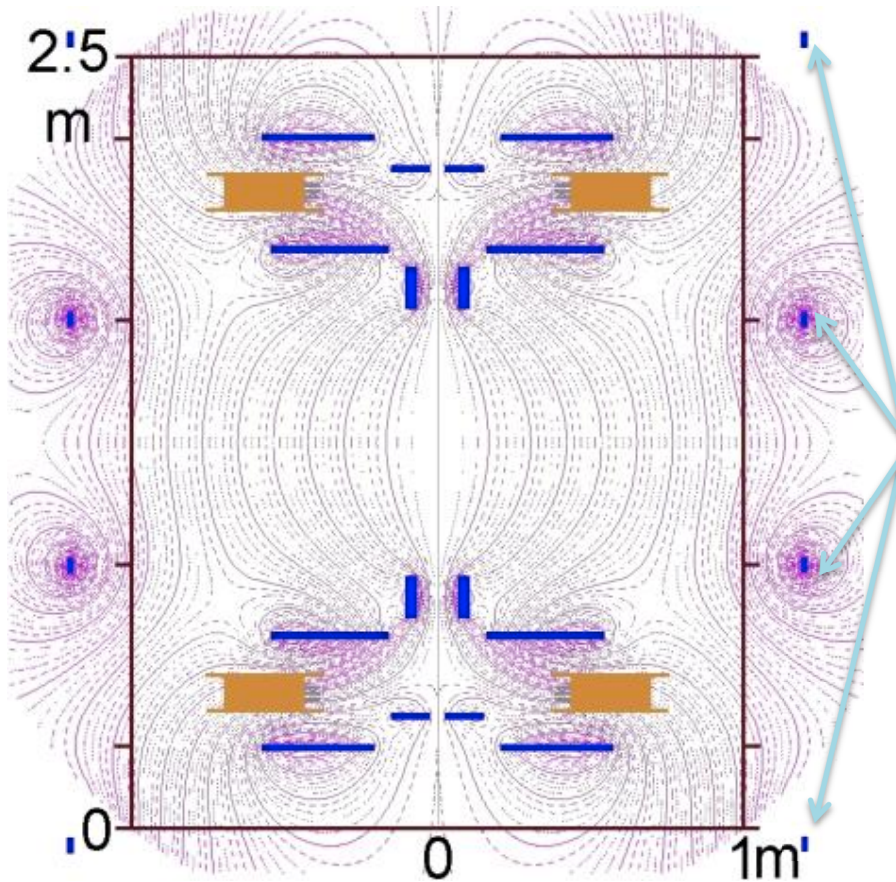


discharges along field lines near X-point

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)

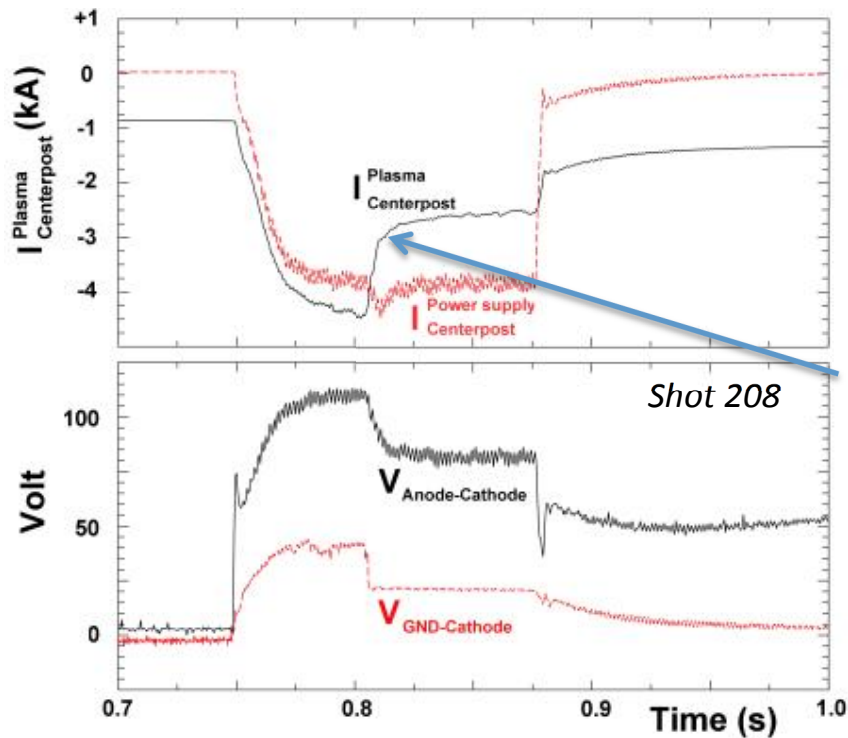


4 external PF coils



plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids

Plasma current outer paths for $I > 3.5$ kA



Argon discharge
aiming to 4 kA
reaches 3.5 kA

~ 1.5 kA lost
from main plasma

in discharge from
cathode down to
lid\vessel

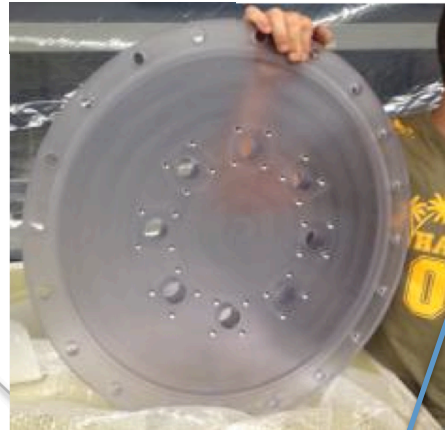
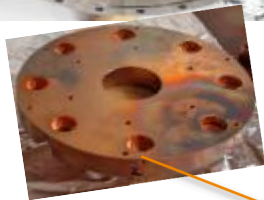
plasma fired after 0.75 s of PF current
(skin current time to remove X-point from inside vessel)

Also the Cathode emission lowers after 1.5 kA are lost

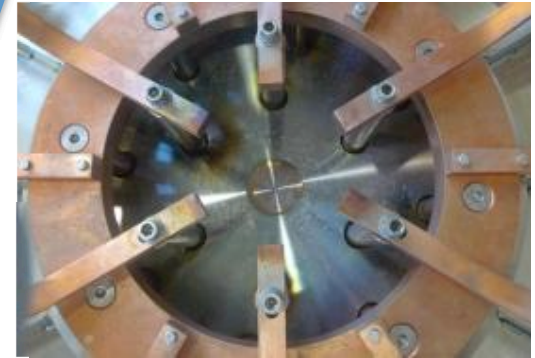


2015 experiments produced a heavy metallization on the top (anode) & bottom (cathode) bus-bar vacuum entrance flanges, **associated with magnetic “nozzles”**

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

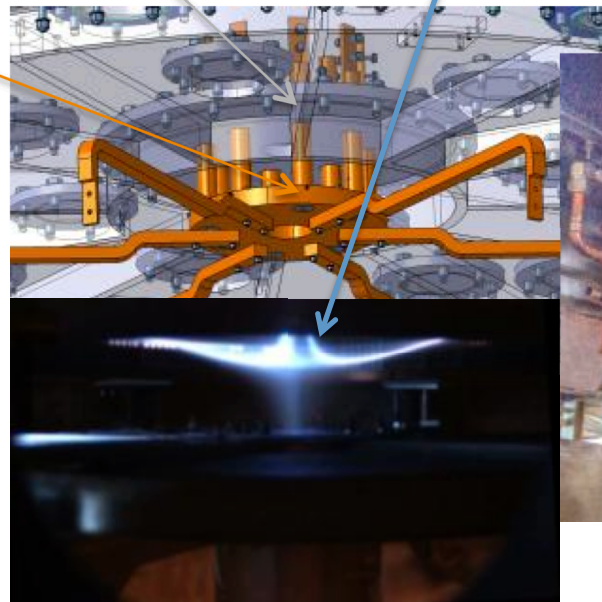
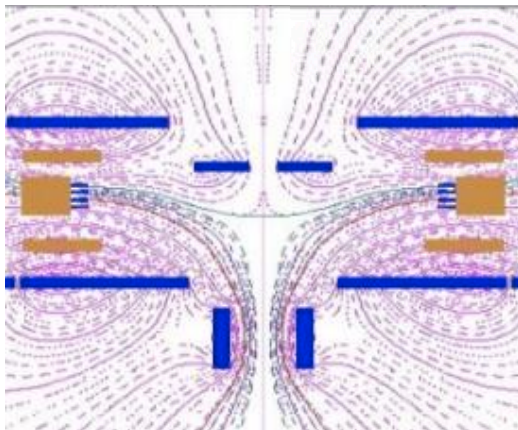


Bus-bars (top-anode)



Top flange view from plasma side

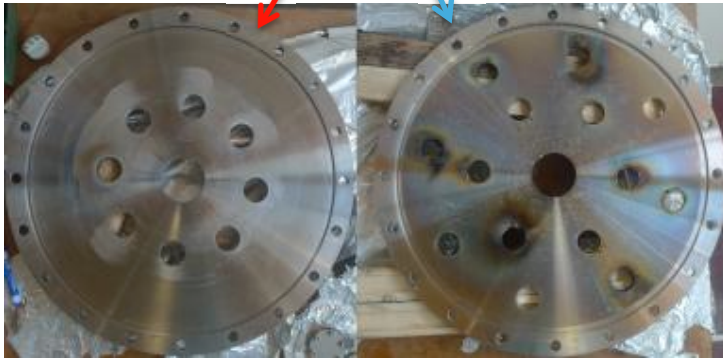
Geometry of magnetic nozzle



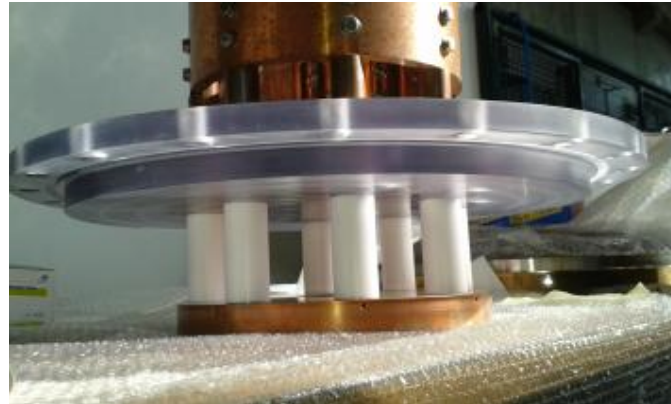
Anode exit of nozzle

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

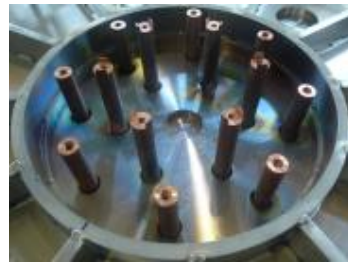
Heavily metallized
top & bottom bus-bar flanges



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!**)



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

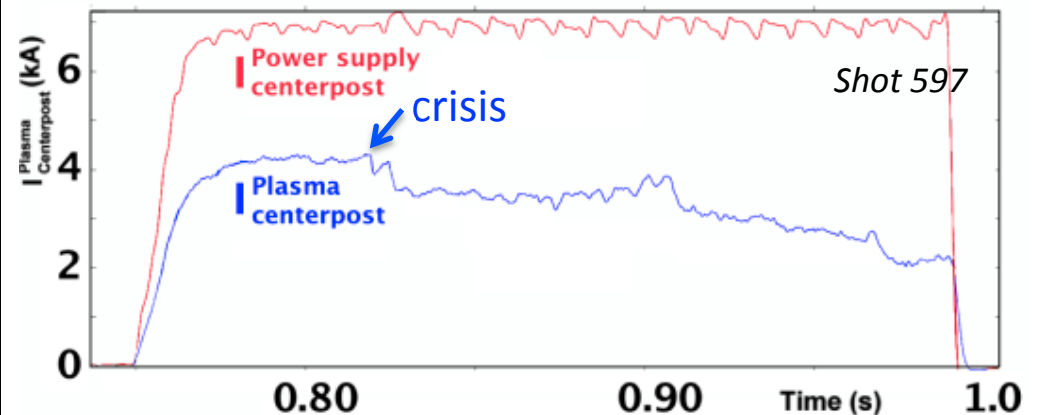


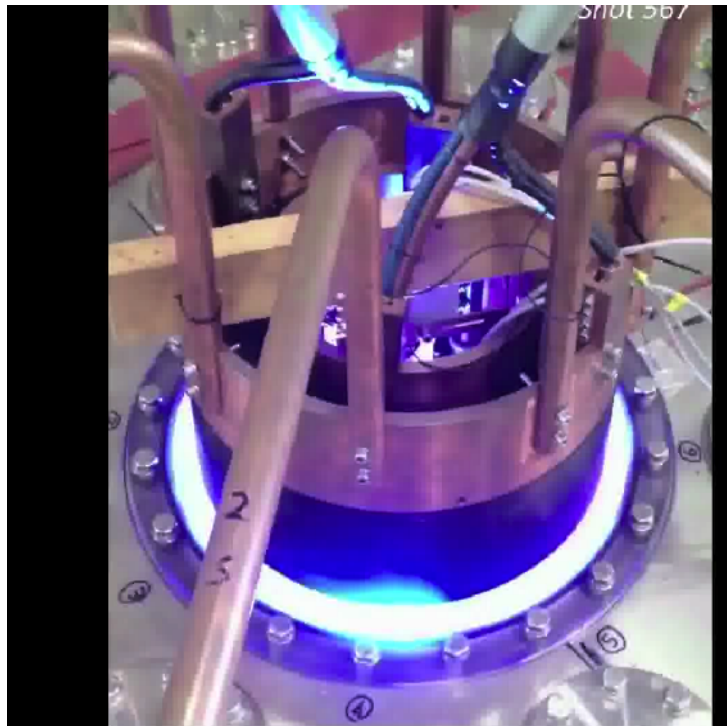
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but
1) Spurious plasma currents still flow outside the centerpost (albeit inside the vacuum vessel)

January 2017
*patterns of spurious
 currents are
 either diffused
 or filamentary*



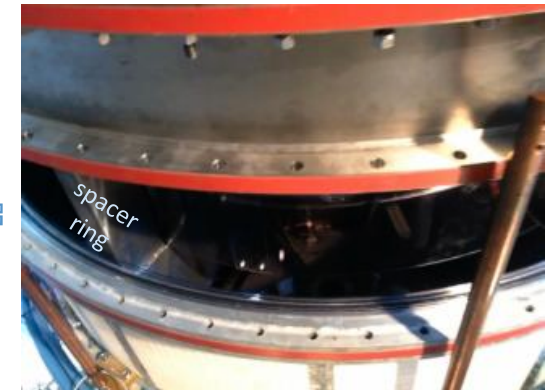
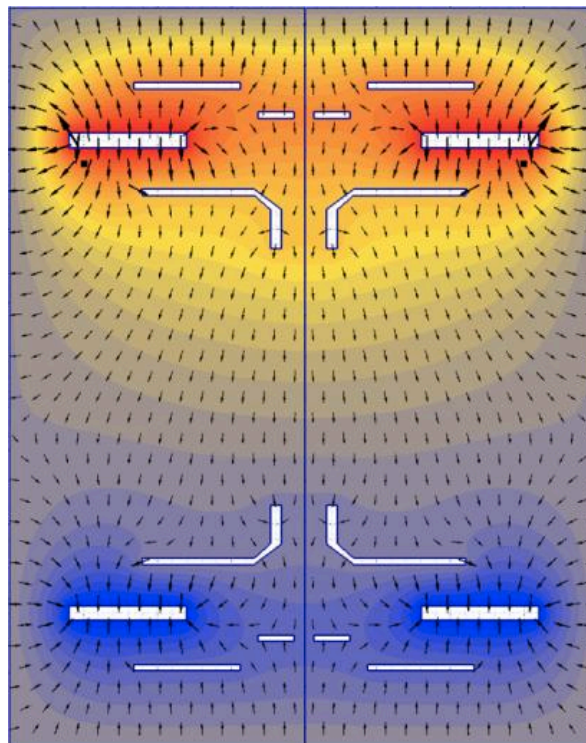
Input 0.6 MW
7 kA from power supply
Centerpost drives 60%



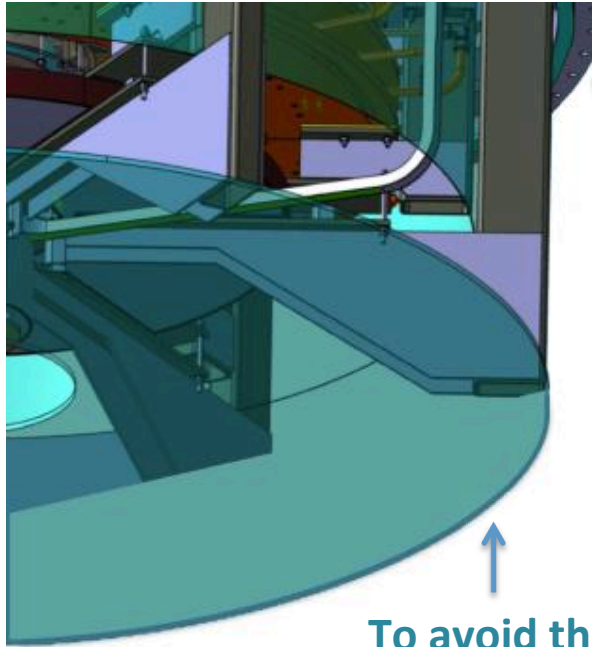


Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but in Hydrogen (250 V breakdown) there was still a problem of current through the vessel, this was triggered in Argon (80 V breakdown), connecting the common star potential of the six-phased cathode power supply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

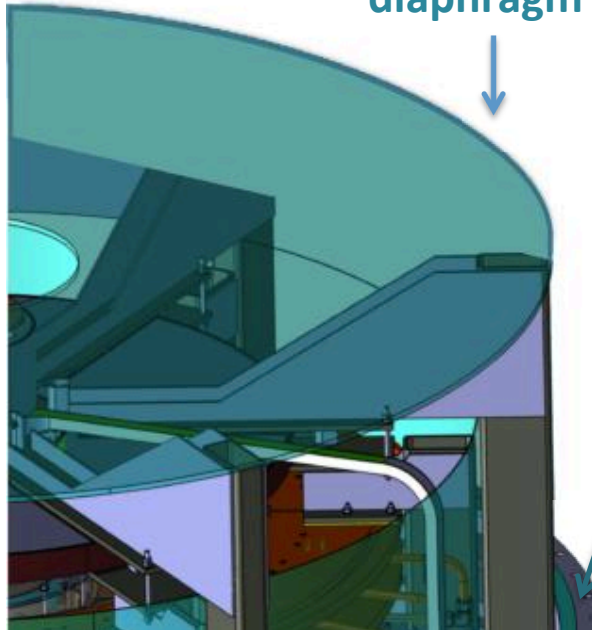
Most critical electric field is at contact between SS upper extension & Al vacuum vessel



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



Lower spacer ring not yet 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



lower diaphragm



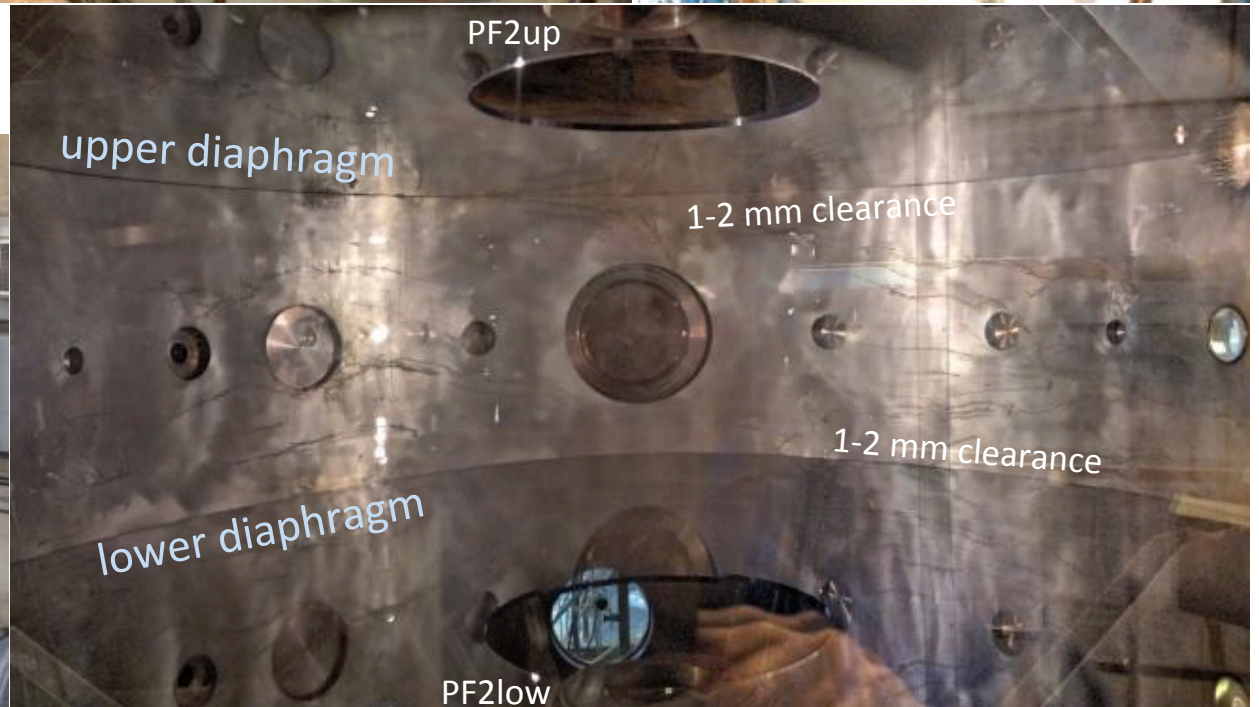
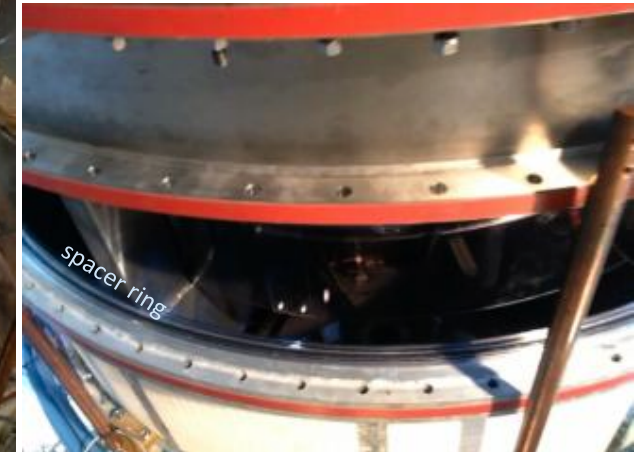
lower diaphragm

May 2017: Insertion of Polycarbonate lower diaphragm



lower diaphragm

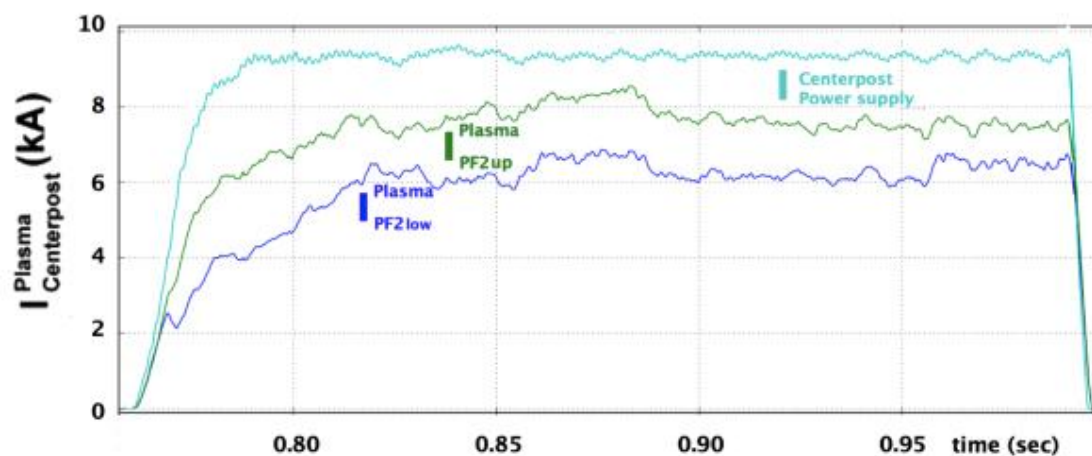
**May 2017: Insertion of
Polycarbonate upper diaphragm
& Polycarbonate spacer ring**



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

High currents, external PF coils are on

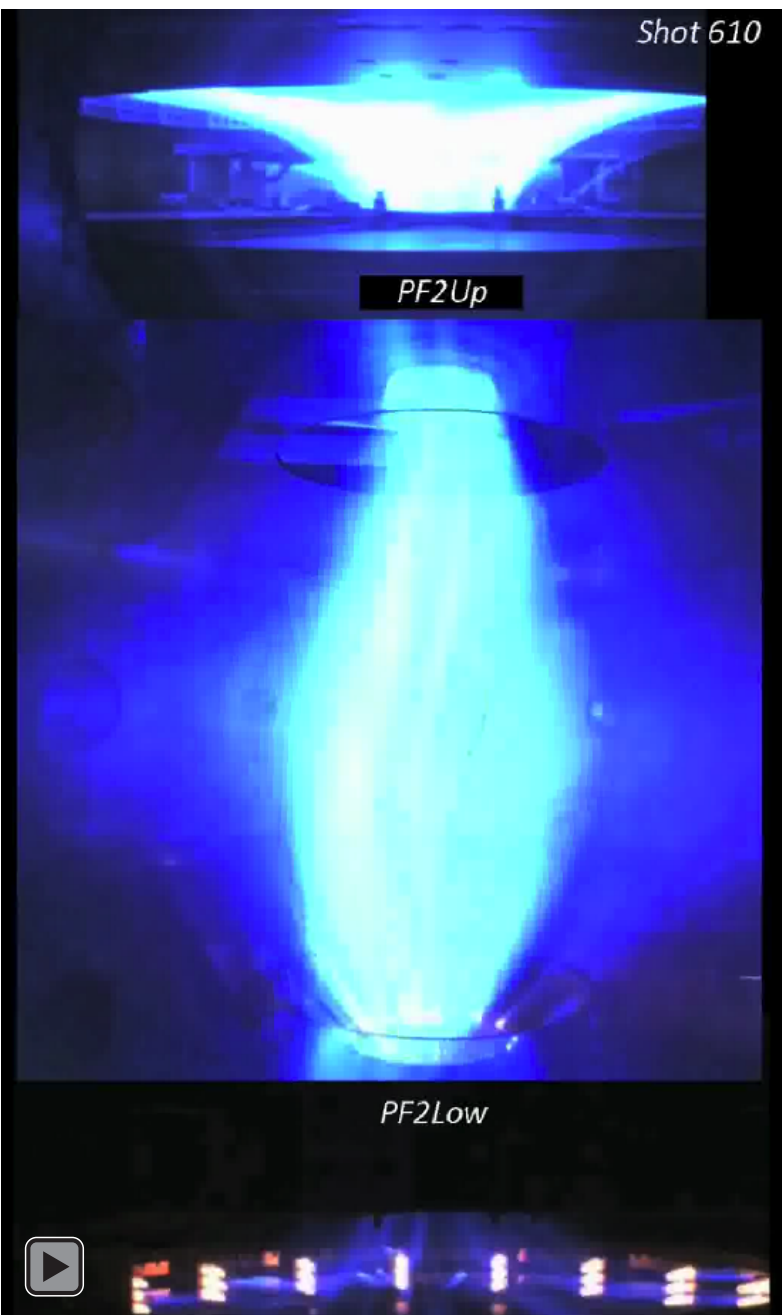
Some spurious and concentrated plasma current still sneaks through the narrow clearance (1-2 mm) bet'wn polycarbonate cylindrical lining and diaphragm, plasma currents with 8.6 kA through PF2 are achieved
Power input 1.65 MW, Anode-cathode voltage 195 V



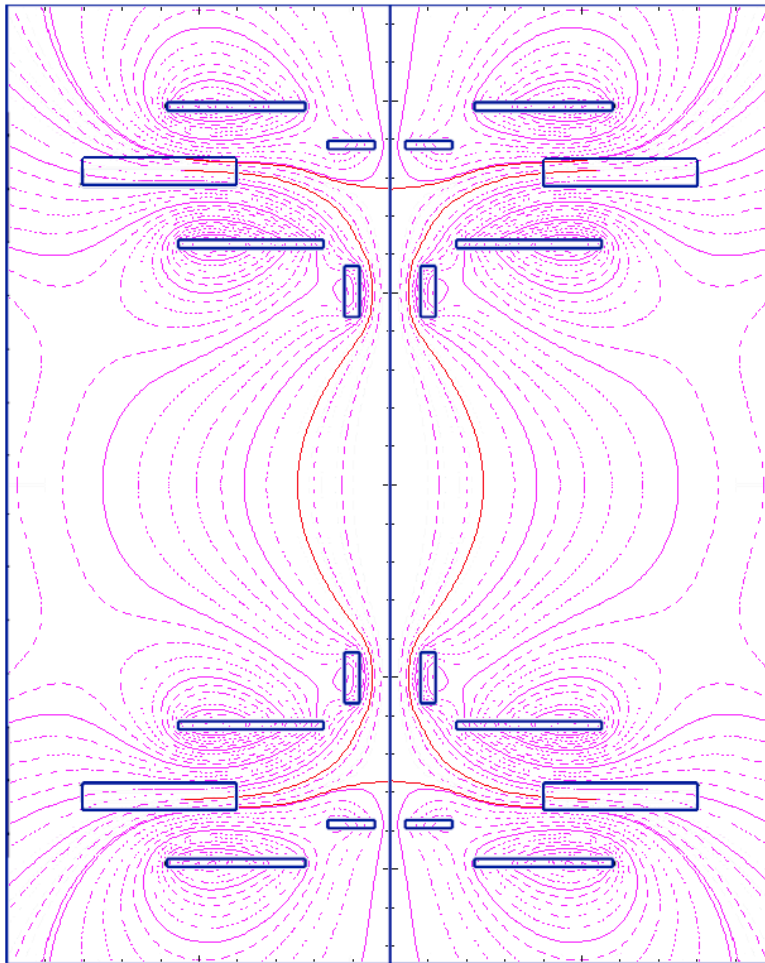
With currents through PF2 exceeding ~ 6 kA the rotational transform of plasma centerpost ($q \sim 2$) becomes clearly visible

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

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!
 through Polycarbonate spacer ring



Lines: magnetic field

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

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

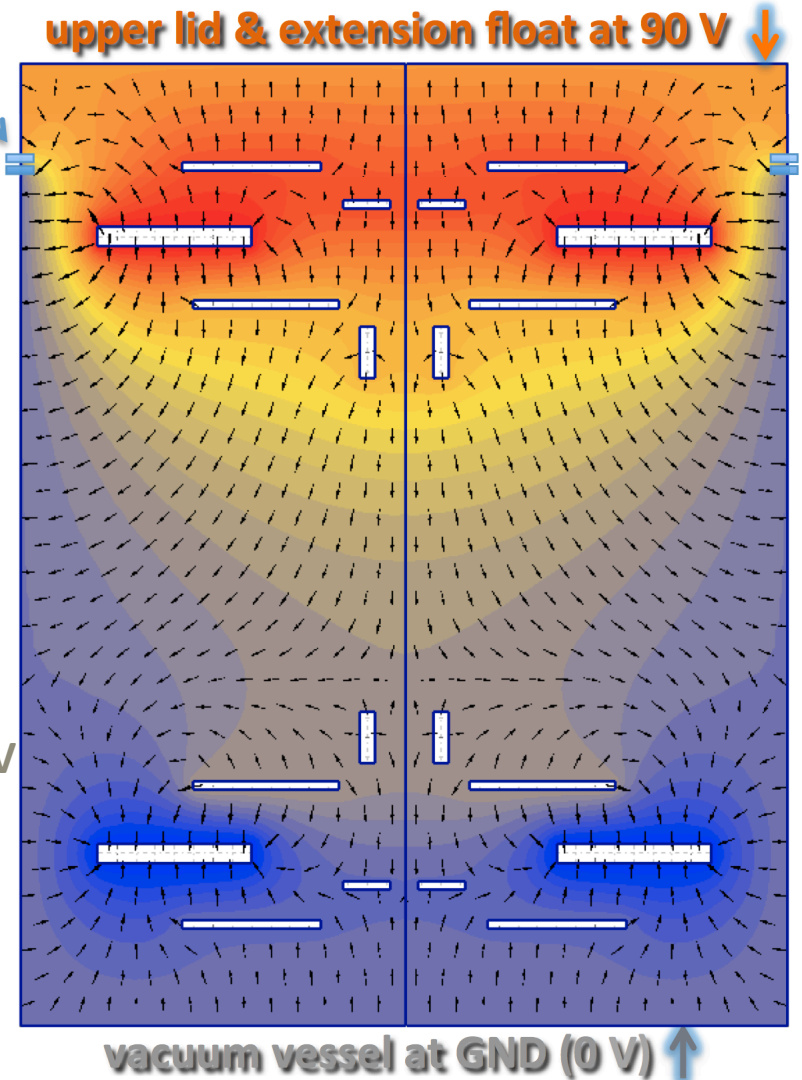
$V_{PF2-3up} \sim +75 \text{ V}$

#614 8kA Argon
 Plasma centerpost
 June 2017

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

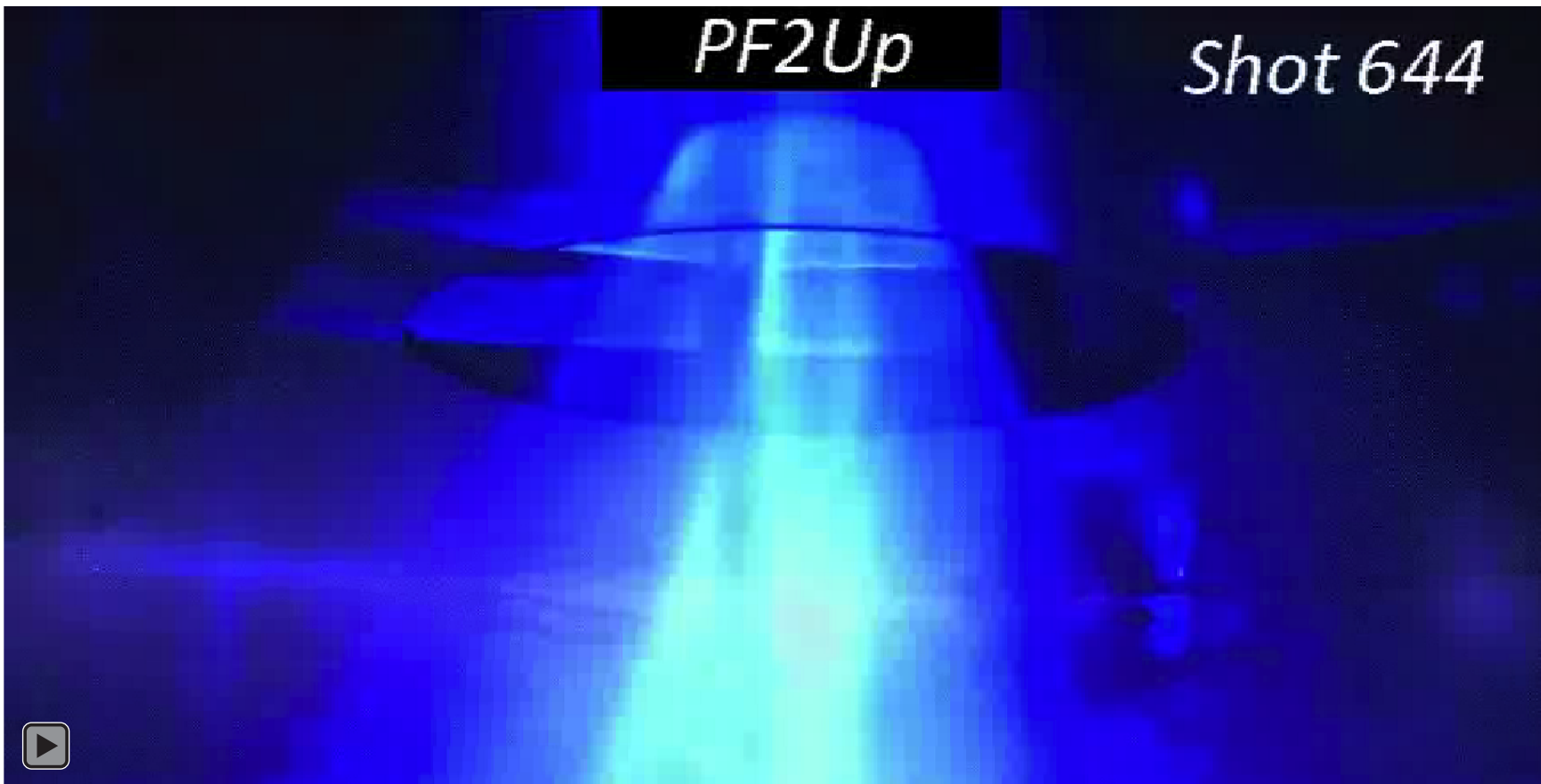
$V_{cathode} \sim -45 \text{ V}$

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



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

Is rotation due to $\vec{E} \wedge \vec{B}$ also outside the plasma centerpost?



velocity of 'black spot' = 70 m/s in rough agreement with
 $v_{\text{ExB}} = (E/B) \sim 10^2 - 10^3$ m/s near the PF2up, inside the plasma
(...Compatible with a plasma flux **$\mathbf{pv}$** component parallel to **$\mathbf{B}$**)

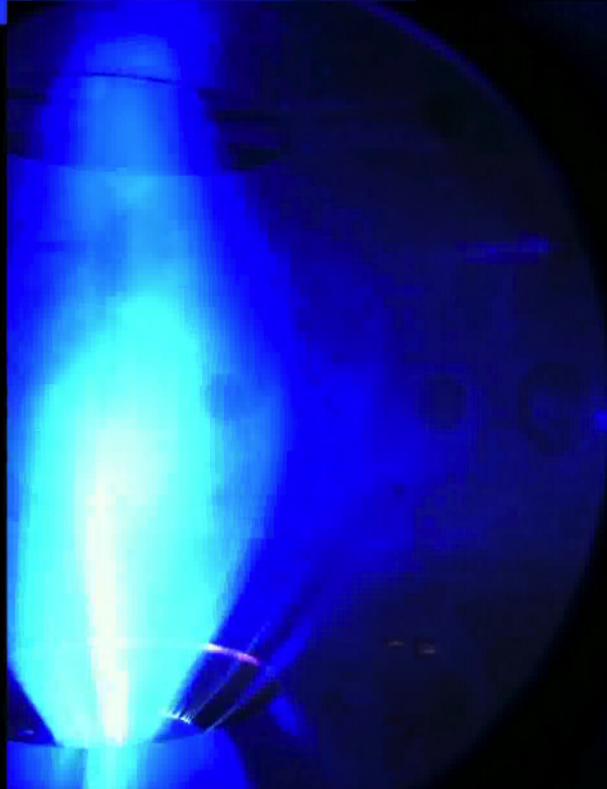
PROTO-SPHERA Plasma needs diagnostics & understanding

Urgent need of diagnostic data: **density** (Langmuir probes, interferometer, Mach-Zender)

temperature & impurities, flow velocity (spectroscopy)

First round of modelling (Buratti & Tirozzi)

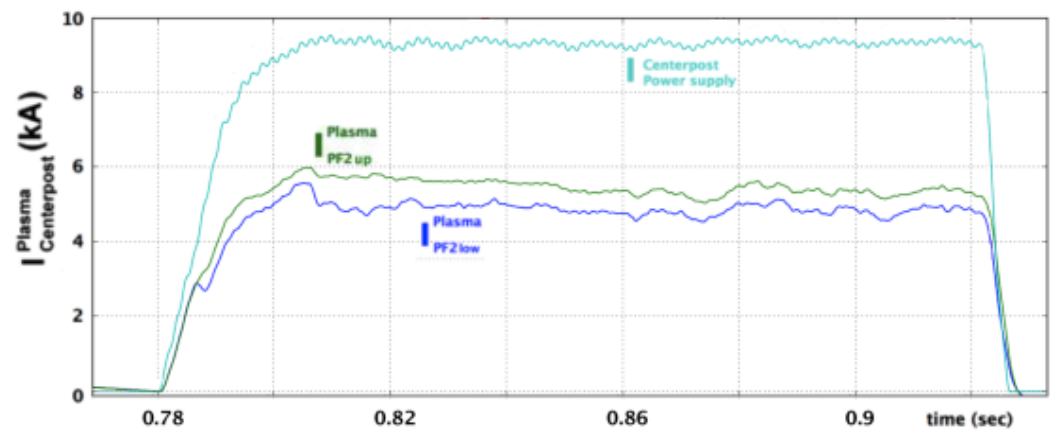
Shot 665



PF2Low

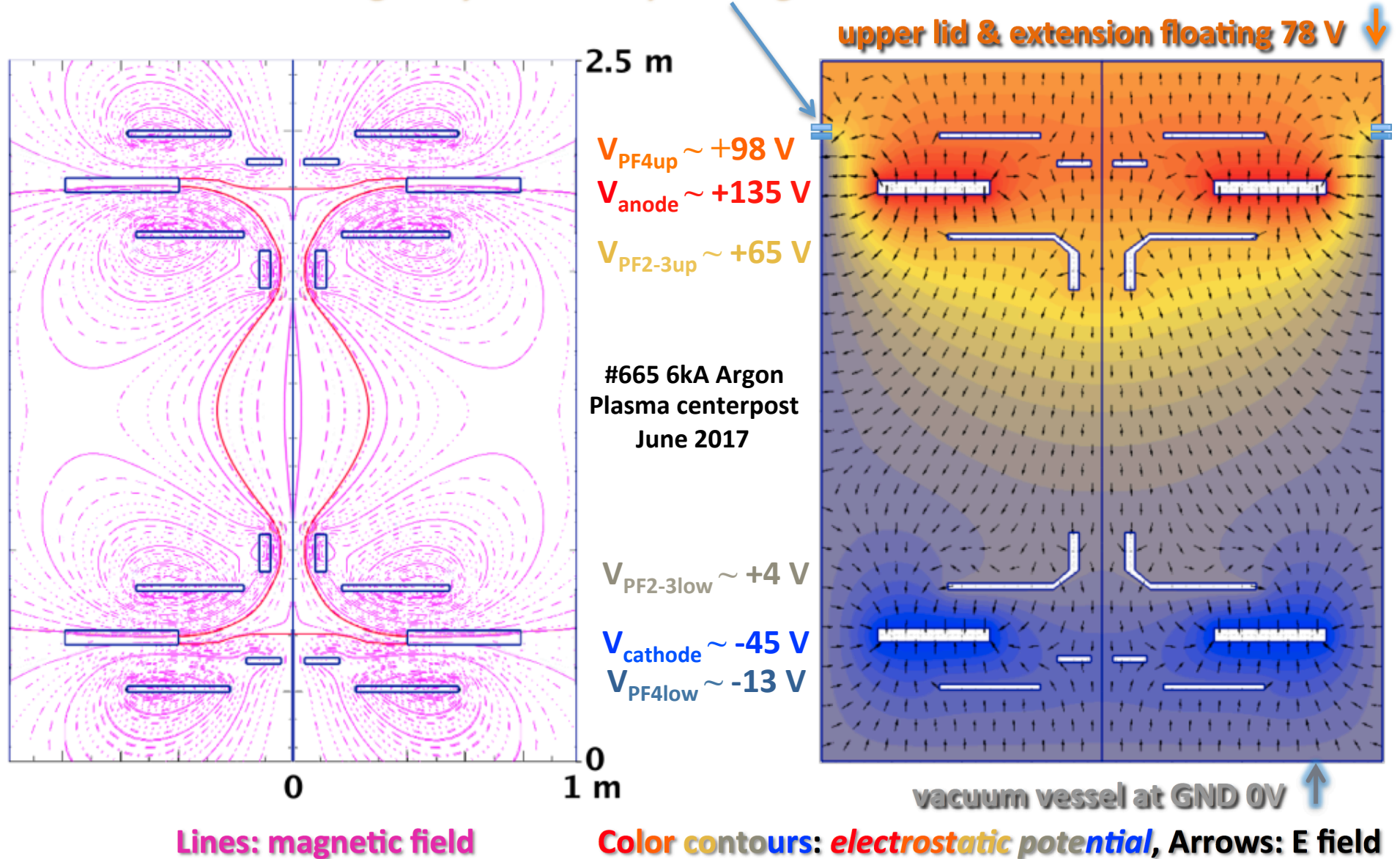
Switching off the external PF coils it is possible to have a more uniform distribution of the spurious plasma current that sneaks through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm, however in this case the plasma currents through the PF2 coils reduces to ~ 6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



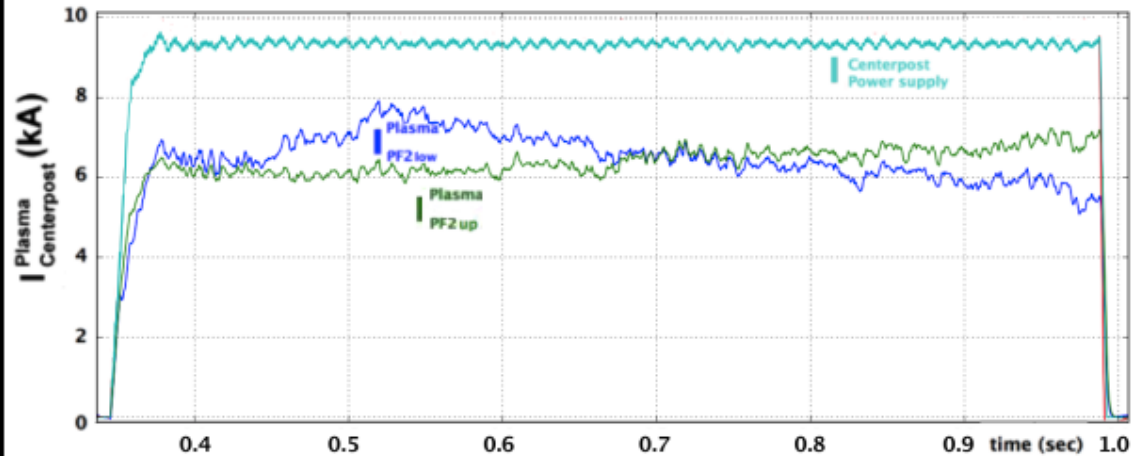
Shot 644



PF2Up

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 $\iota \sim \frac{1}{2} \rightarrow (q_{\text{pinch}} \sim 2)$

PF2Low



Kink destabilization maintained in 0.7s long discharge

Shot 645



PF2Up



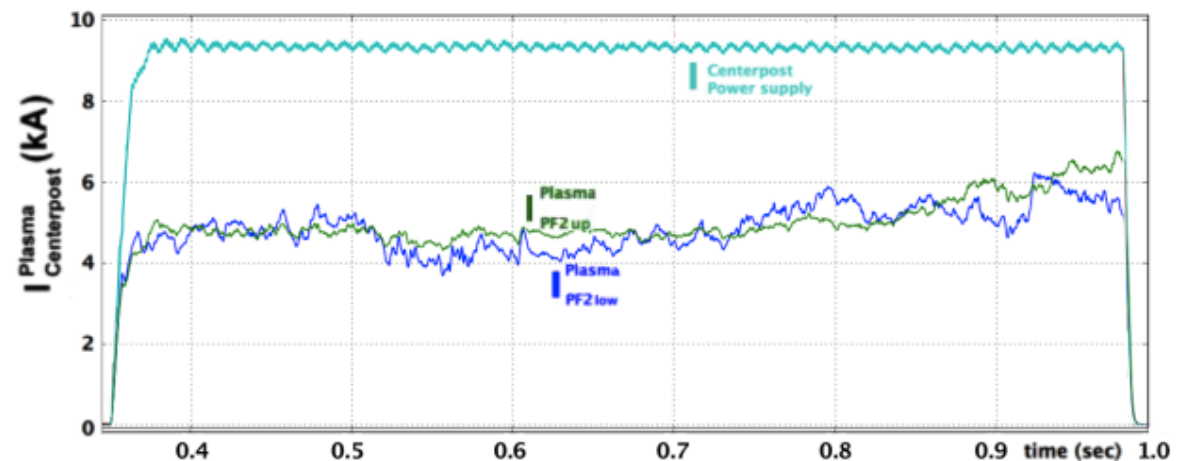
PF2Low

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

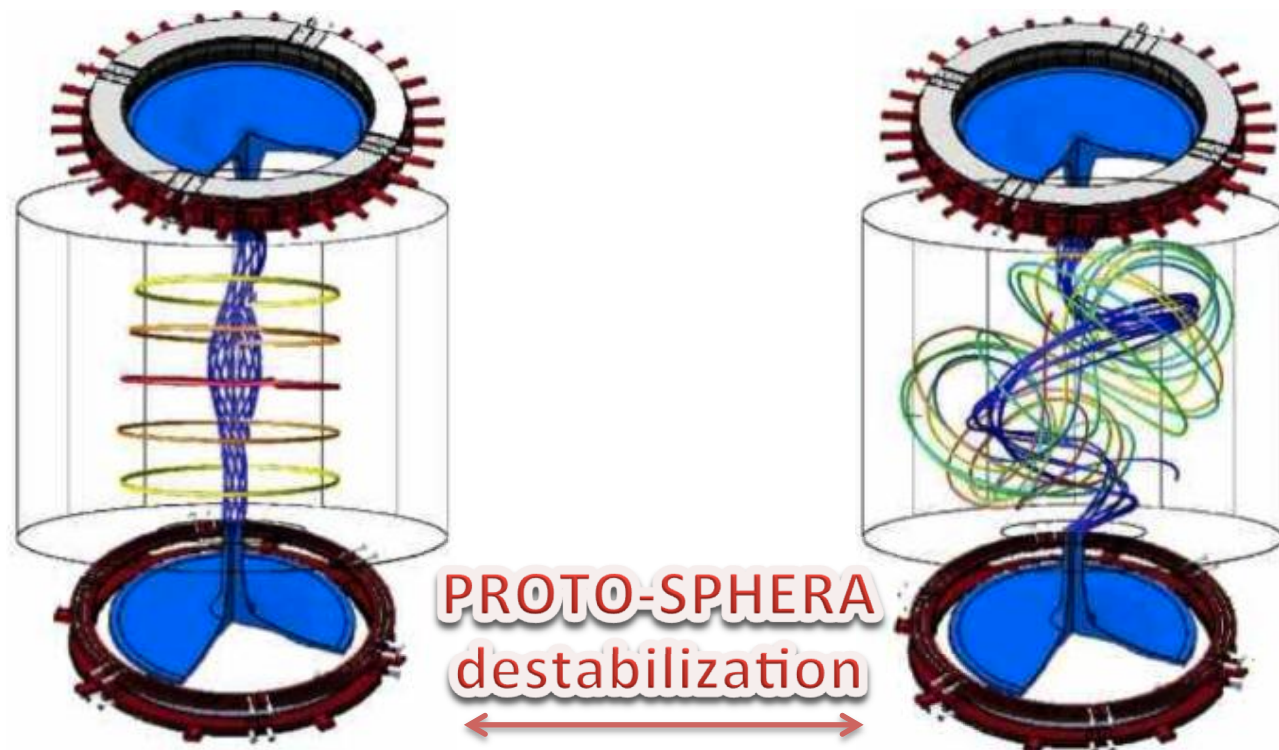
has been obtained with plasma currents through the PF2 coils $\sim 5 \text{ \AA } 6 \text{ kA}$



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

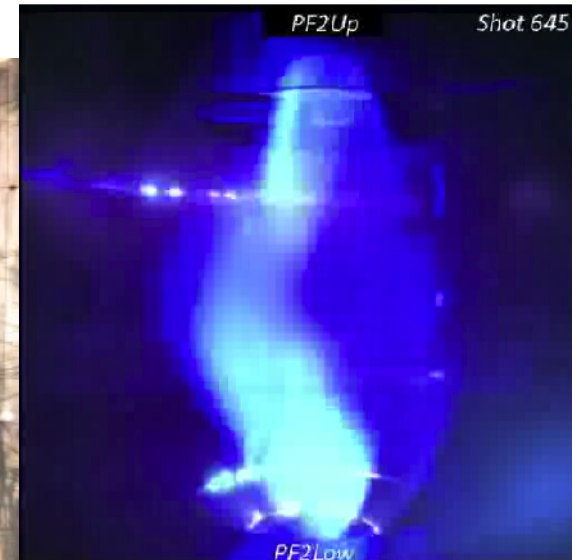
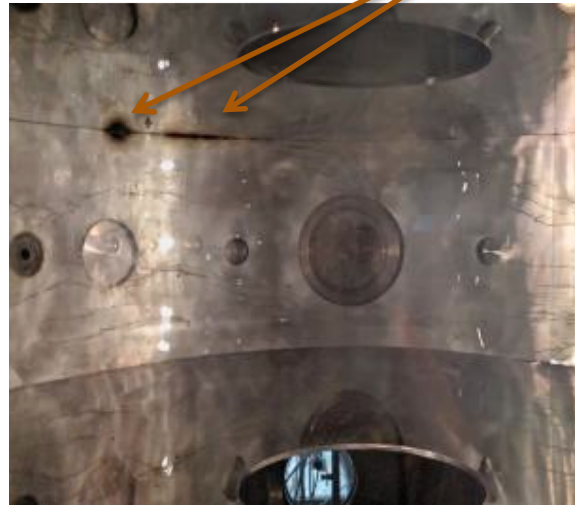


Experiment
2017

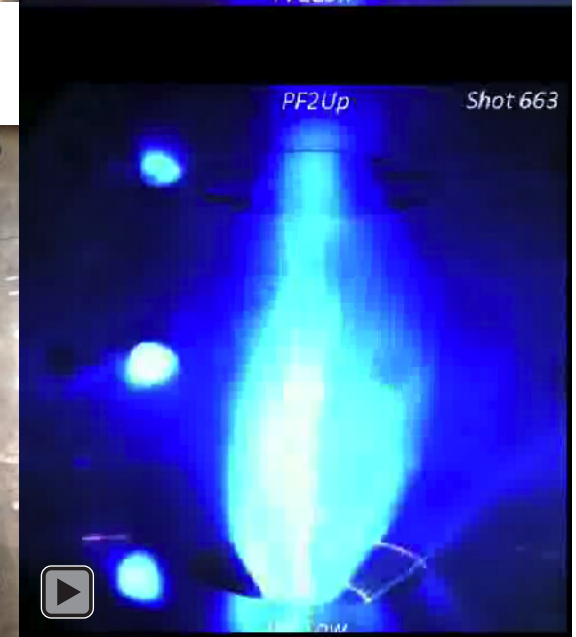


The plasma current sneaking through the narrow clearance (1-2 mm) between polycarbonate cylindrical lining and diaphragm induces damages

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



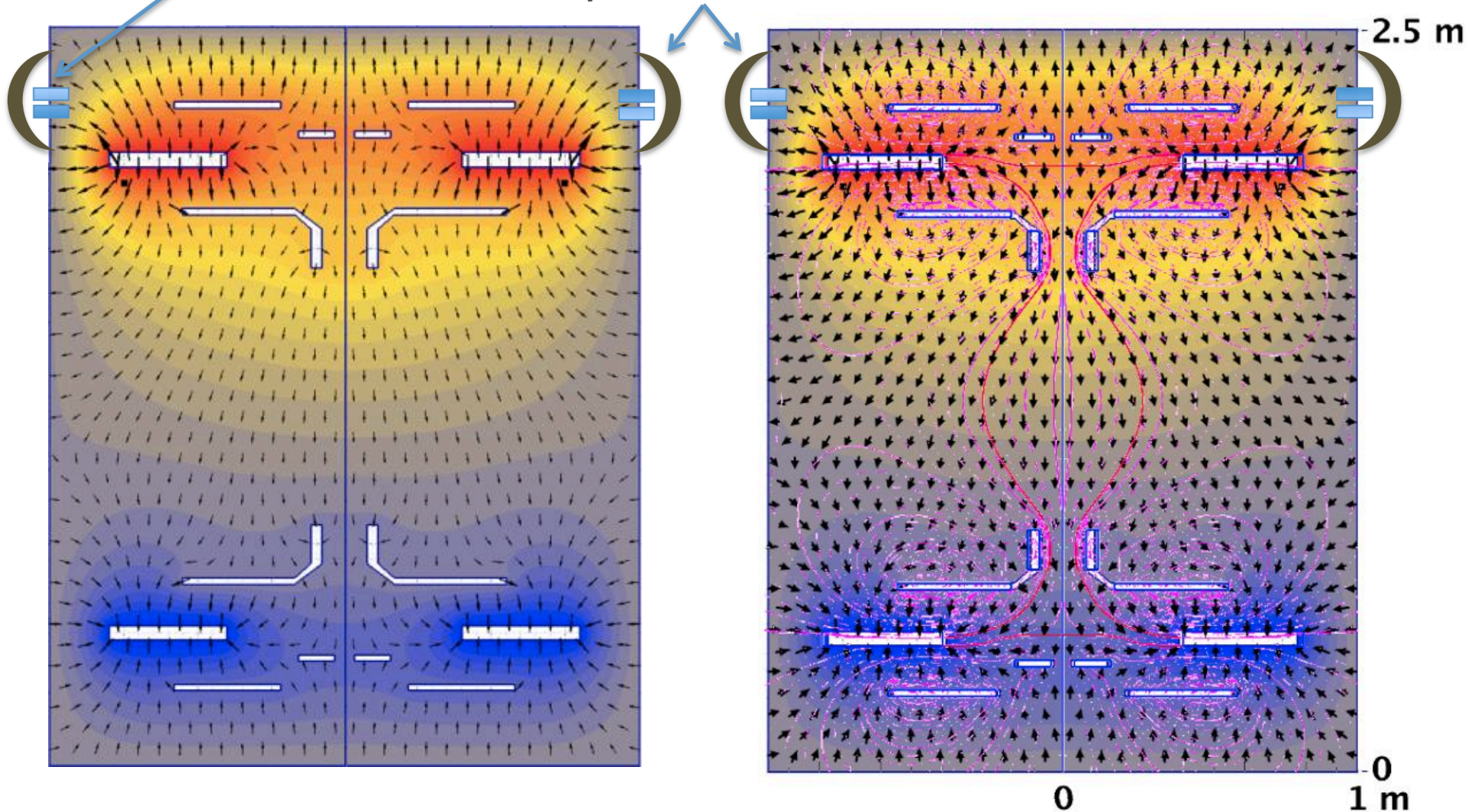
The port where the polycarbonate lining was cut, in order to allow for vacuum gauges measurements, has to be closed & the gauges moved elsewhere



Disaster if top lid & top extension are not floating!

#649 kA Argon Plasma centerpost (June 2017)

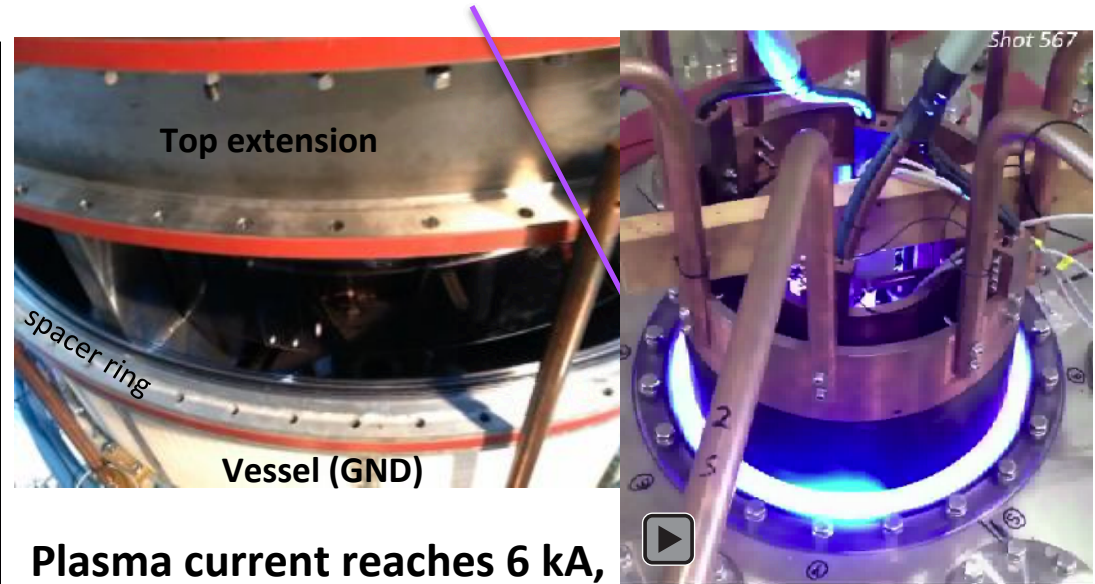
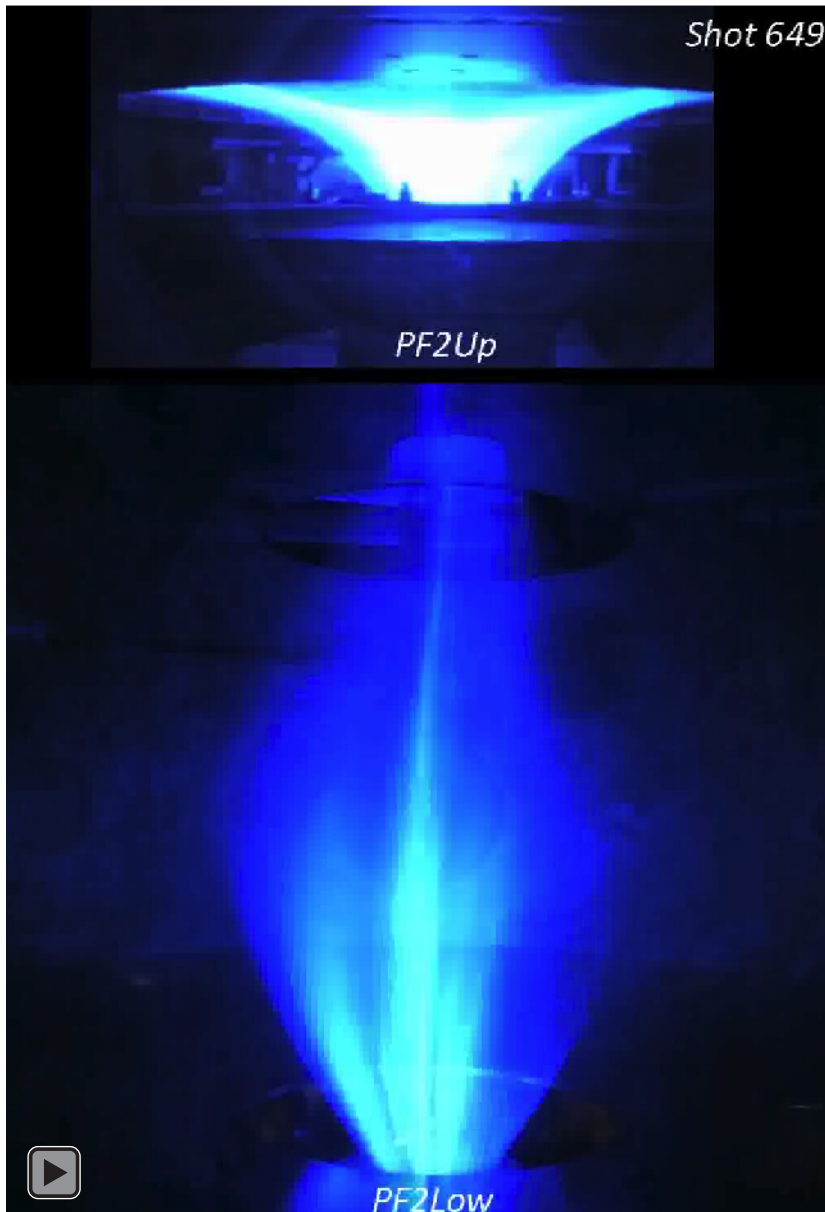
Polycarbonate spacer ring insulating top lid and top extension from vessel (GND)
have been put back in contact with vessel



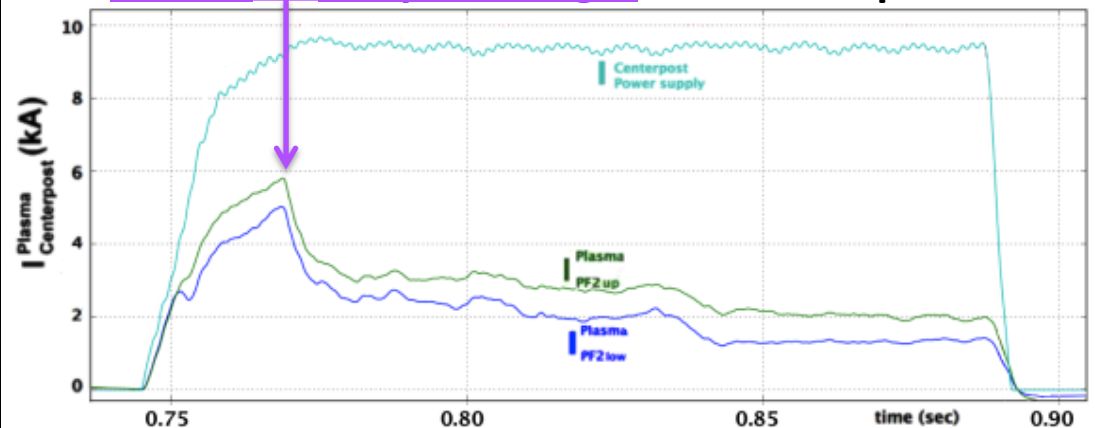
Color contours: *electrostatic potential*, Arrows: E field

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

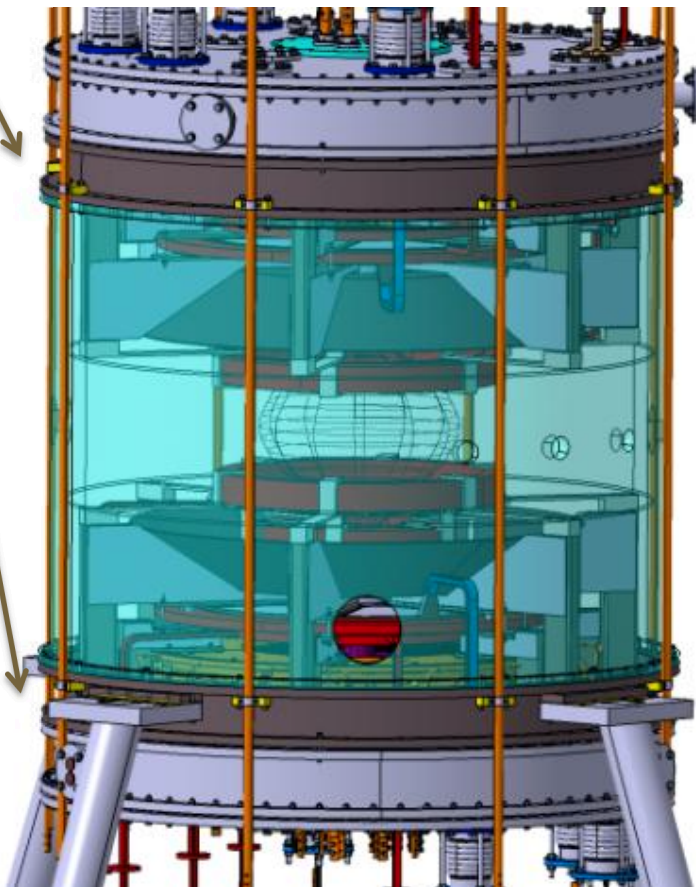


Plasma current reaches 6 kA,
but after secondary discharges current drops to 3 kA

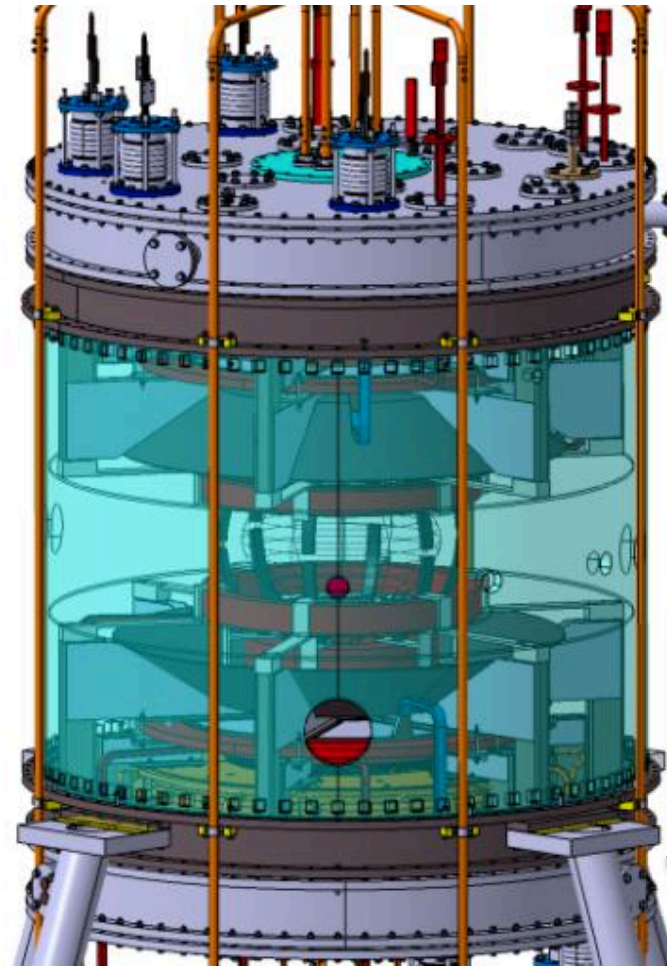


To achieve full centerpost current in **Hydrogen (250 V break-down)** needs a **new insulating vacuum vessel**

A new insulating & transparent vacuum vessel has to be built: will be Phase-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 $\varnothing$, 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

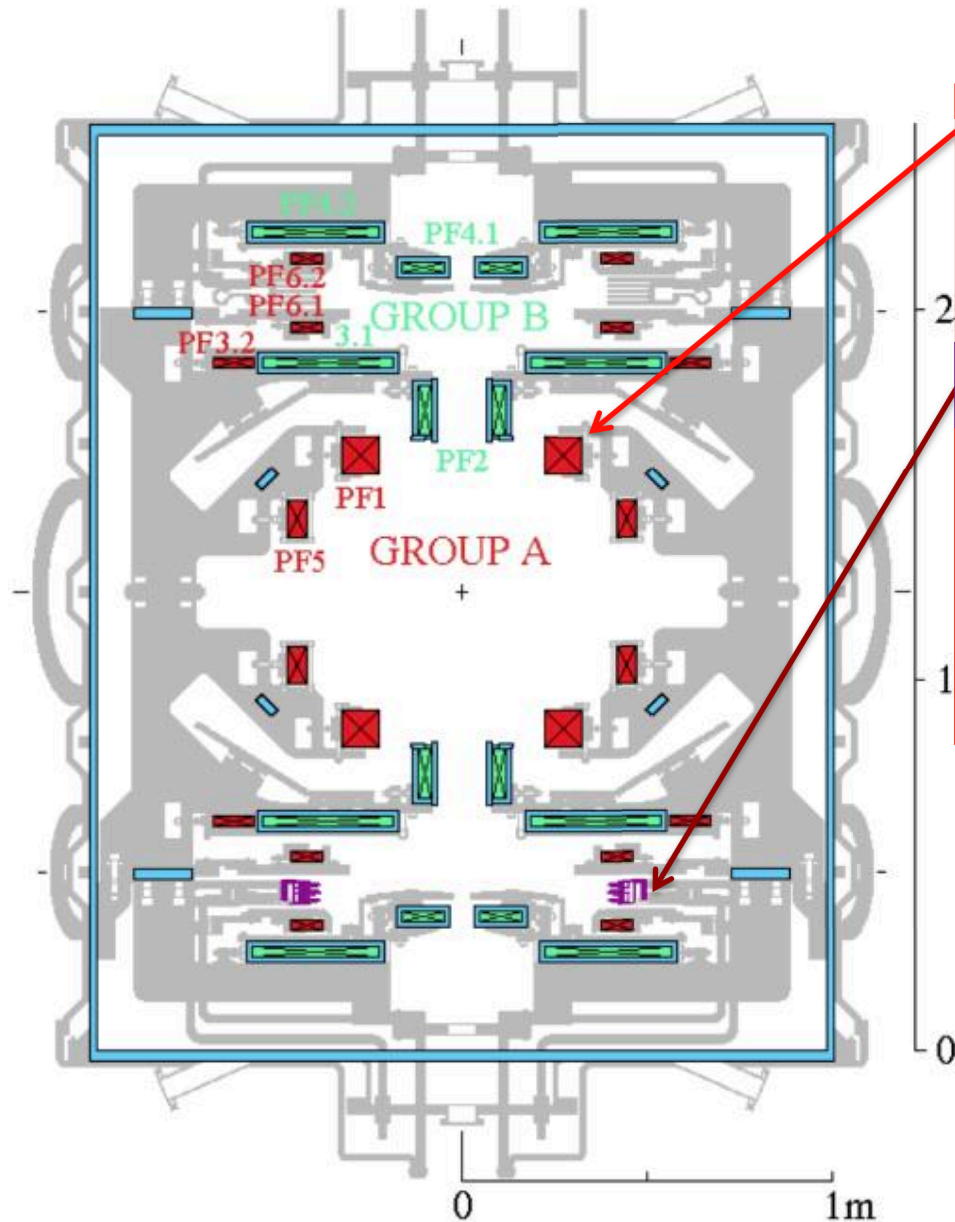


flanged PPMA cylinder



carved PPMA cylinder

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 ~ 0.5 M€

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

Final Power Supplies for:

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

SuperCapacitors will be used

Cost up to now ~ 2.0 M€

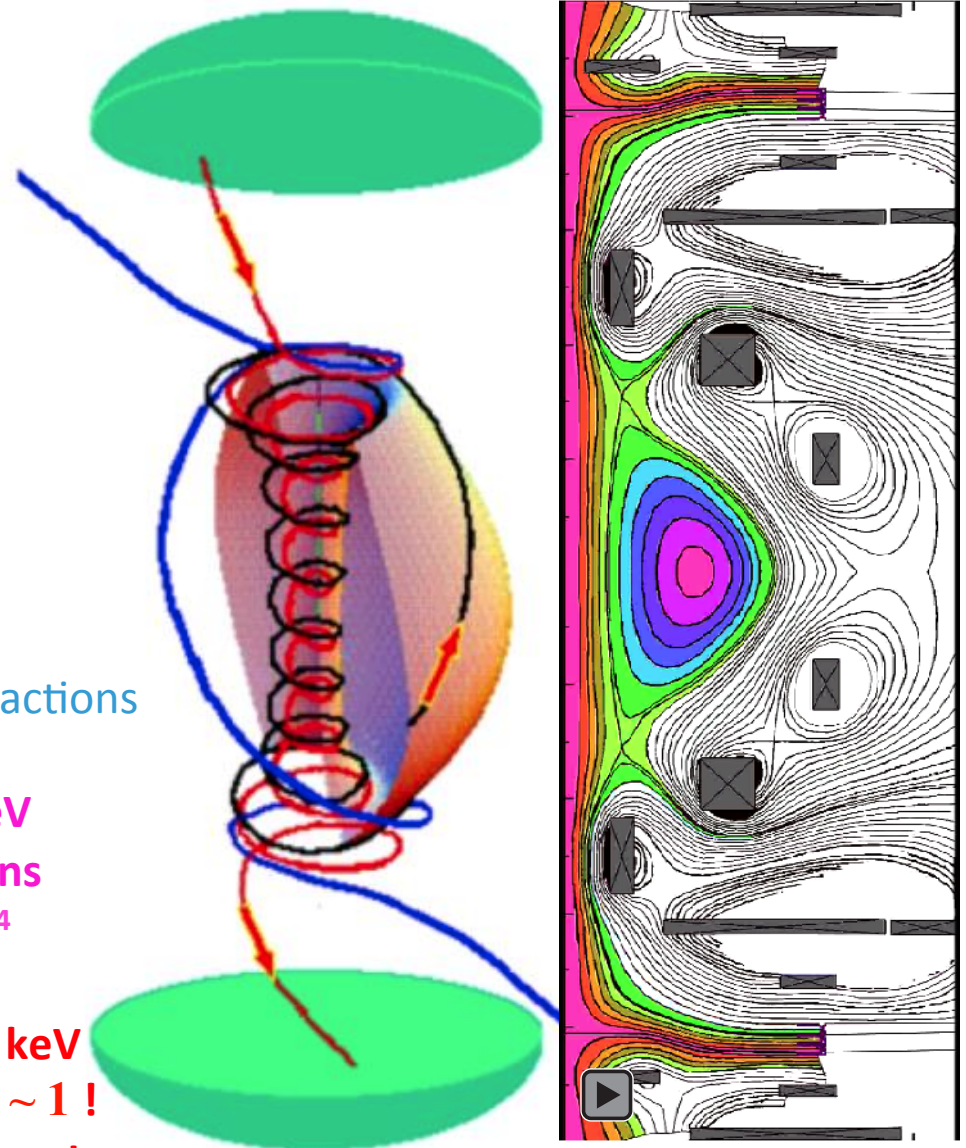
Cost for final stage of experiment ~ 1.6 M€

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:

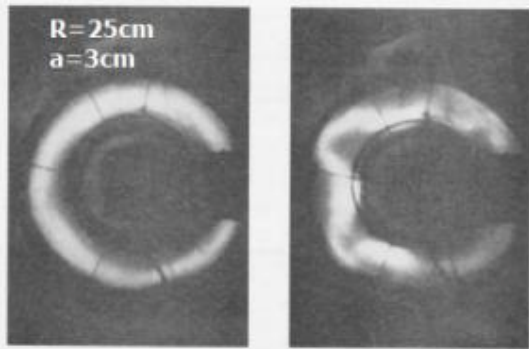
- should it be zero, then ST plasma $T = 10 \text{ eV}$
PROTO-SPHERA studies plasma-electrode interactions
- should it be 1 MW, then ST plasma $T = 100 \text{ eV}$
PROTO-SPHERA studies magnetic reconnections
at relevant magnetic Lundquist number, $S=10^4$
- should it be many MW, then ST plasma $T = 1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



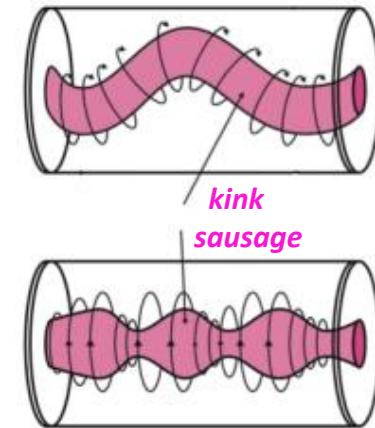
Why a new and different magnetic confinement device? one reason is ... "disruption"

Alan Ware & Thomson
Imperial College 1947.

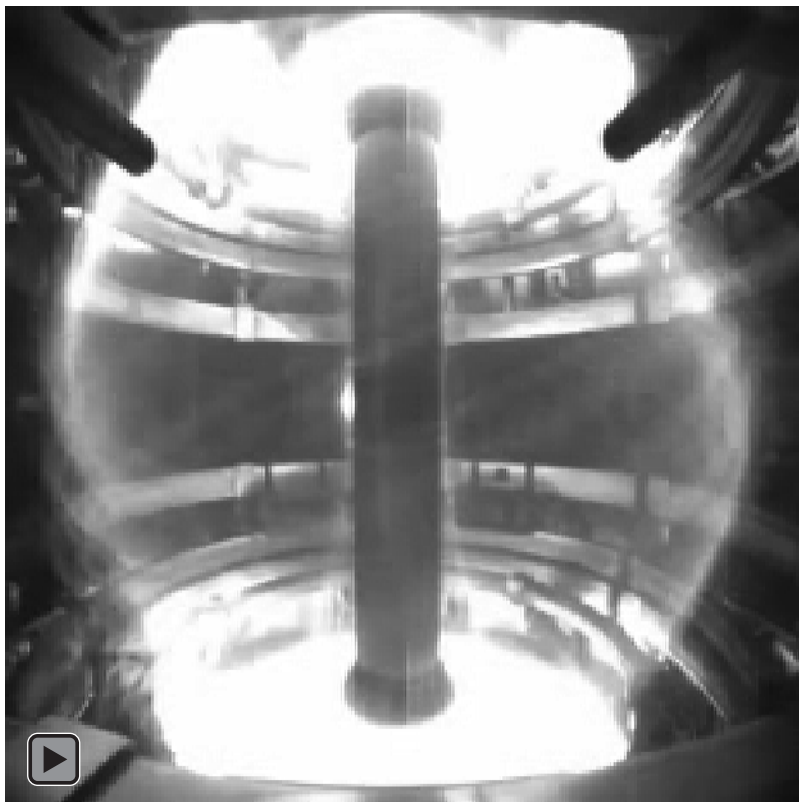
... Even if the muttered mantra is that tokamak physics is perfectly known ...



MHD instabilities appeared since the earliest toroidal magnetic confinement devices

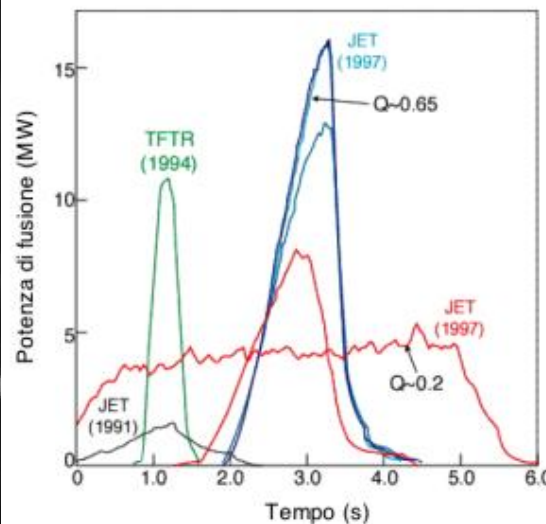


Mast 2004



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

... Only Stellarator configurations (without a net toroidal current) can 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, ...**

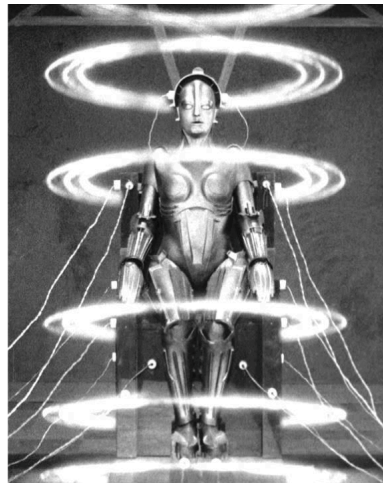
**In case of disappearance of toroidal current the configuration can re-form:
DC helicity injection in NSTX Spherical Tokamak (with metal centerpost)
plasmoids are born & reborn**



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

In case of disappearance of toroidal current the configuration can re-form:
DC helicity injection in NSTX Spherical Tokamak (with metal centerpost)
plasmoids are born & reborn

Fritz Lang's
Metropolis (1926)



Kink unstable configuration of PROTO-SPHERA
is maintained indefinitely, notwithstanding:

wobbling centerpost
& even more wobbling cathode plasma → |

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

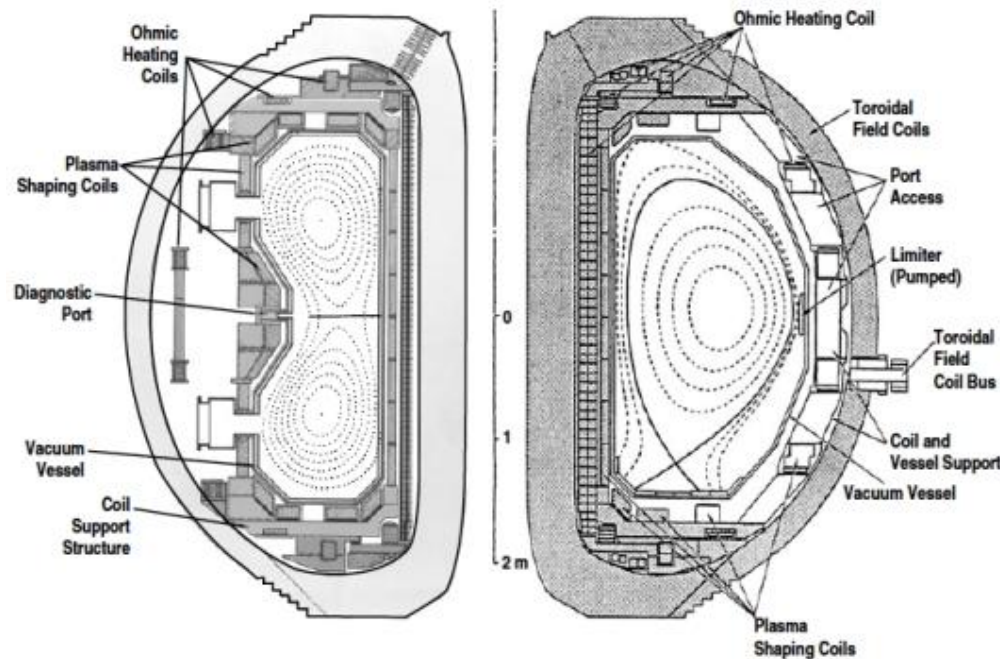
... Even if the muttered mantra is that tokamak physics is perfectly known ...

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

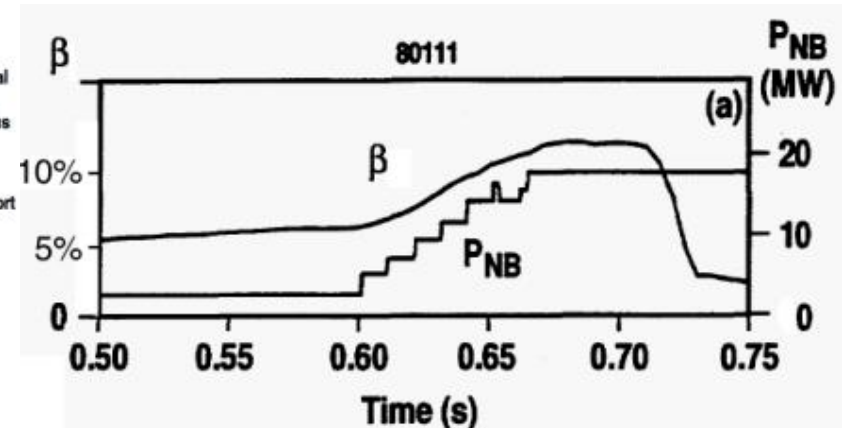
$$\beta = 2\mu_0 \int p dV / \int B^2 dV \quad \text{but in tokamak experimental data one often uses } \beta_{T0}$$

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

DIII-D in 1994 reached the highest value of β tokamak at all time



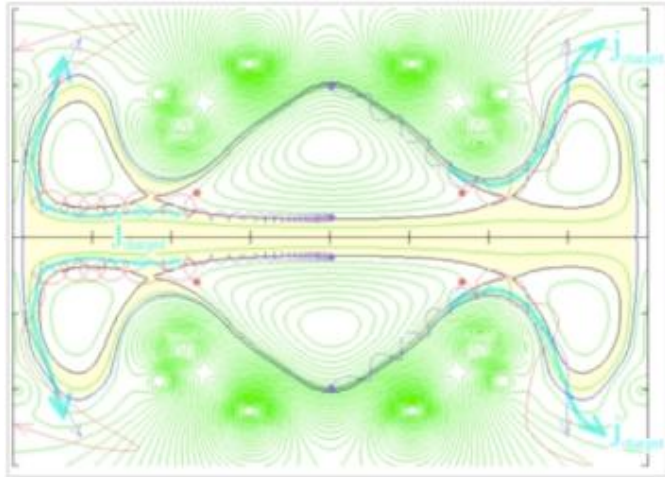
**DIII-D reached $\beta_{T0} = 12.5\%$,
but...the plasma “disrupted”
vanished in ~ 1 msec !**



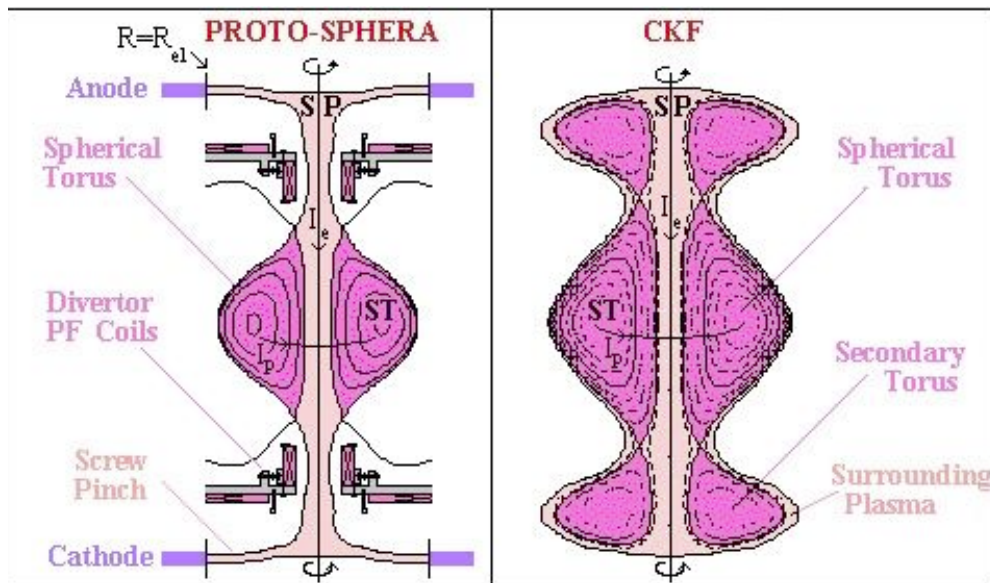
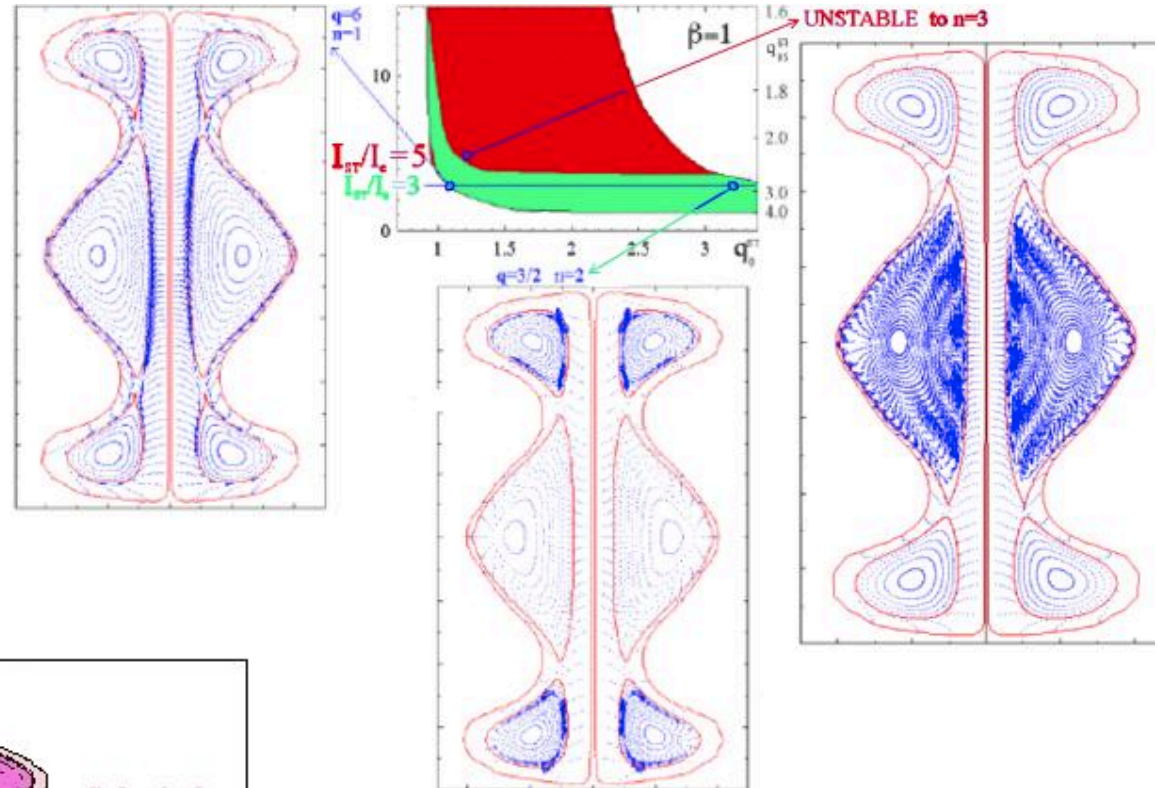
- Beta ...**plasma** pressure few % of magnetic pressure → **cost, size, ...**

Different orbits of co- & counter-circulating charged fusion products:

...preferential thrust through one of the two degenerate X-points



CKF thruster ideal MHD stable up to $\beta = 1$

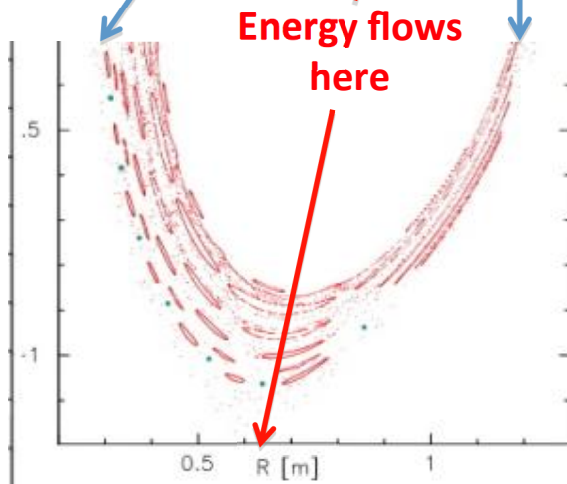
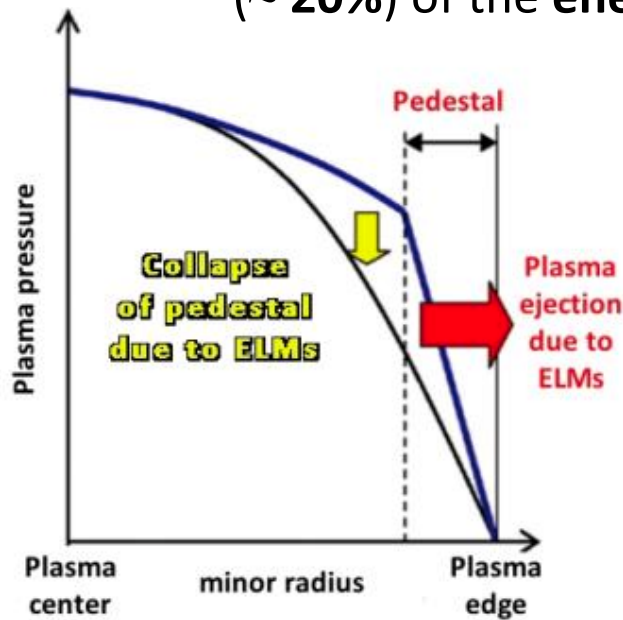
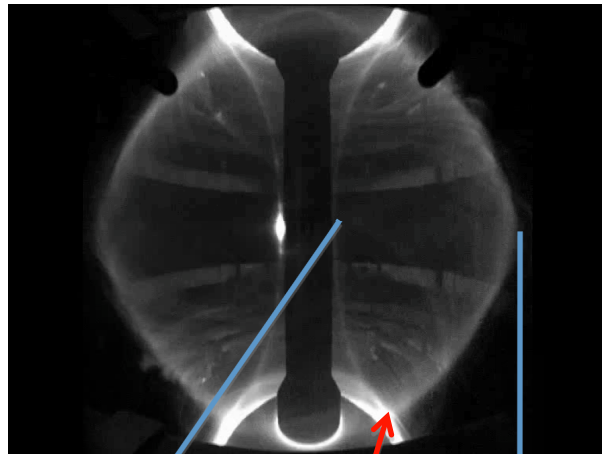


Chandrasekhar-Kendall-Furth configuration
CKF an extrapolation of PROTO-SPHERA:

- **internal PF coils** replaced by **secondary Tori of Plasma**
- **Centerpost hitting electrodes** replaced by **Surrounding Plasma**

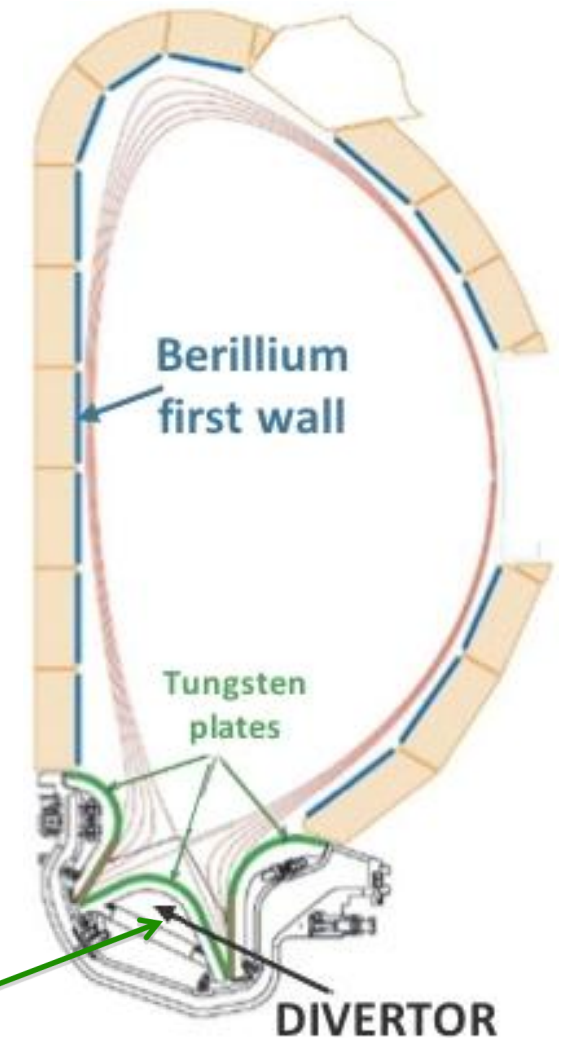
Why a new and different magnetic confinement device? still another reason are...
"ELMs" (unstable edge localized modes)

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



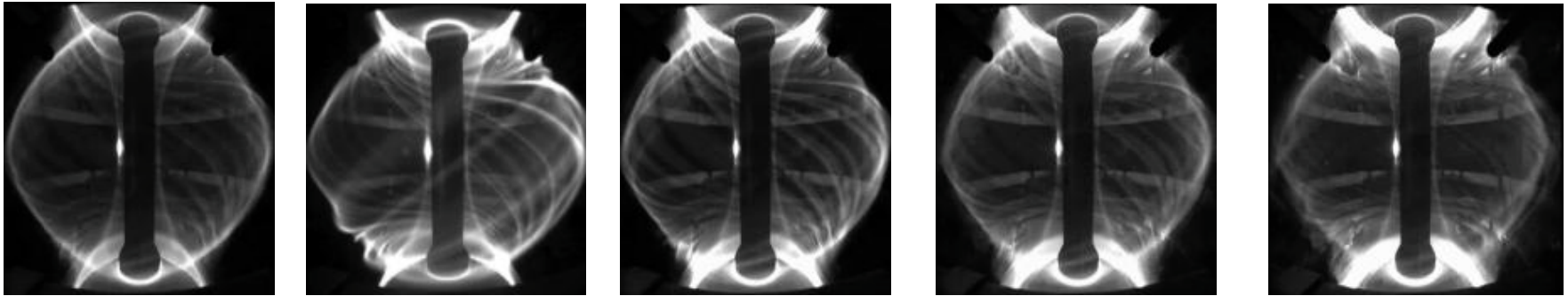
This happens in a
very short time (250 μ s) as
the **plasma edge becomes ergodic**
(ELM filaments carry current)

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

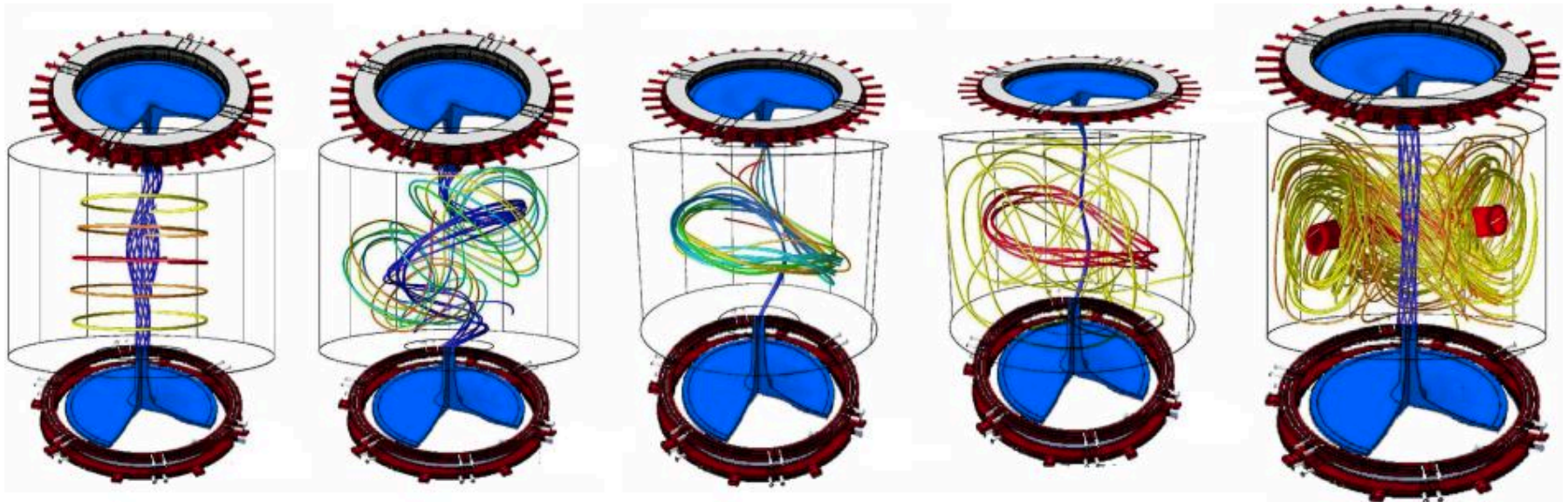


"ELMs" (unstable edge localized modes)

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



be put to fruition in PROTO-SPHERA?



Status

>22 years after 2nd ST Workshop – Princeton (1995) the “aggressive proposal” PROTO-SPHERA is producing its first unstable centerpost plasmas ...*better late than never!*

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

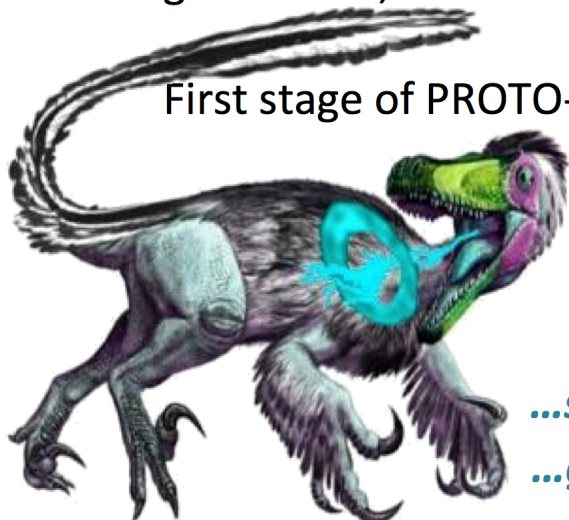
To achieve full current of 10 kA requires patient learning of how to tailor boundary conditions:

- insulating material as first container of plasma
- magnetic field by additional coils external to the vessel

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

First stage of PROTO-SPHERA only an appetizer for the production of the Spherical Torus



。。。放龙如海! fànglóng rùhǎi

...set free the Dragon into the sea!

...give a chance to the Dragon to show his endowments into the sea!

Perspective

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 even more challenging than 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

