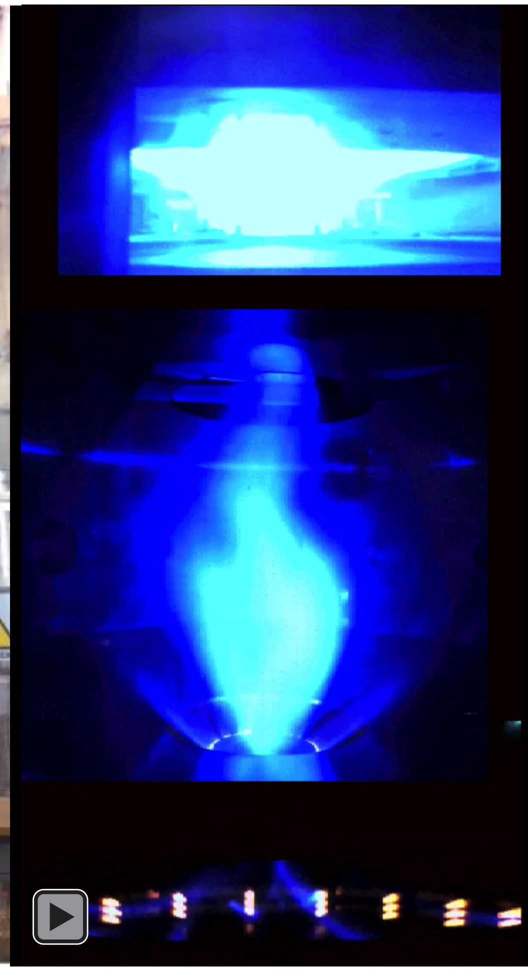
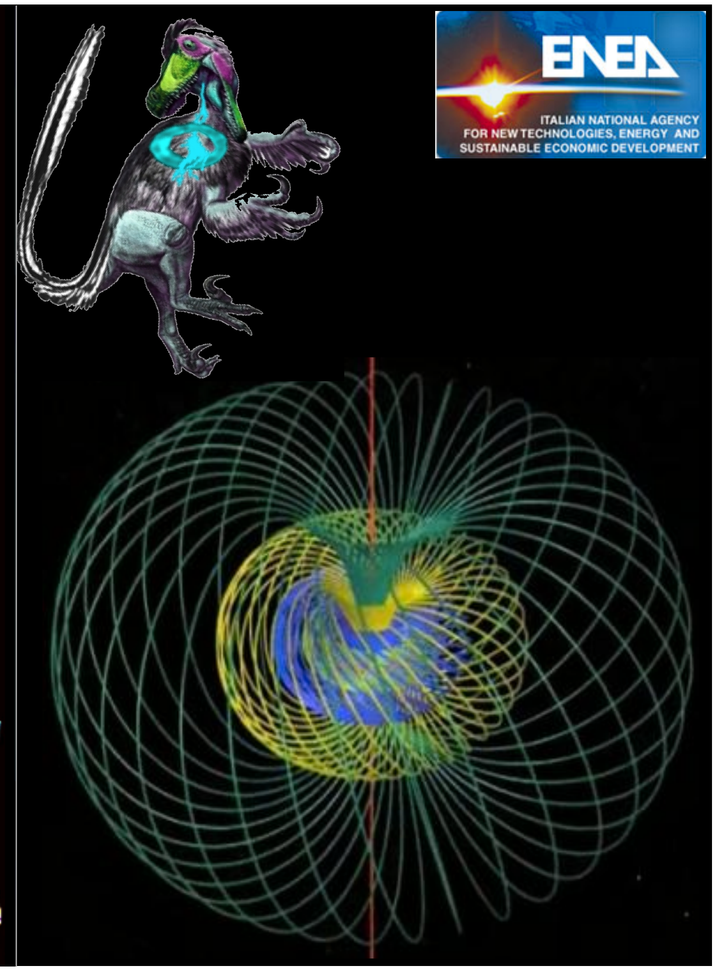
The PROTO-SPHERA experiment, a new magnetic confinement scheme for Fusion

Franco Alladio, *CR-ENEA Frascati*





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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 (plasma pressure\magnetic pressure ~ 1)**
- **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 (poloidal field) coils**
  - **insulating materials near the plasma,**

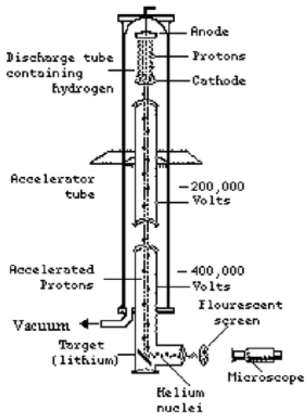
  have allowed achievement of full plasma current in Argon
- **Plasma configuration resilient to accidents**
- **Spontaneous rotation of Plasma Centerpost**
- **Mixed magnetic & electrostatic confinement**
- **A new vacuum vessel for Hydrogen discharges?**
- **Perspective**

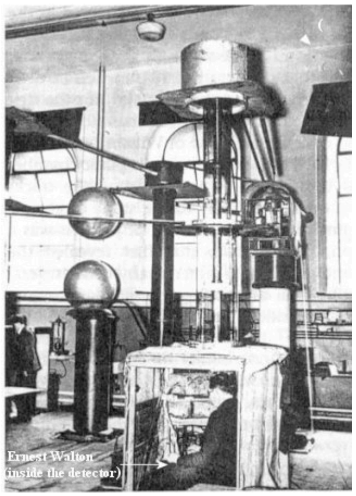
。。。二龙抢珠 **èrlóng qiǎngzhū**

Two Dragons are snapping at a pearl!

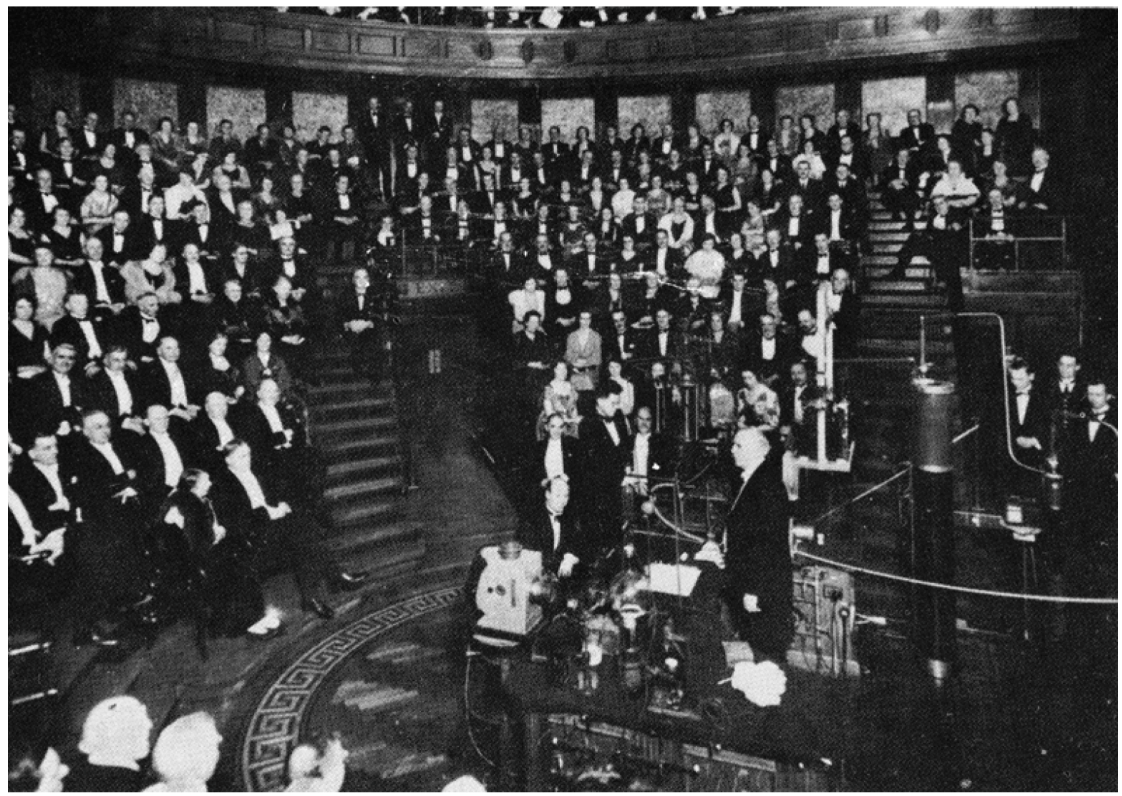
1932-34: Accelerator origin of Fusion experiments

Sir Mark Oliphant (1901-2000) used accelerators to obtain in 1932 the first Fusion reactions in laboratory & discovered the **'reactive isotopes'** of Hydrogen ^{2}D (Deuterium p+n) , ^{3}T (Tritium p+2n): such isotopes fuse together 'easily' and deliver an enormous energy





1934: Fusion with Accelerators makes her debut …at the Royal Society of London!



Unscreened Nuclear Fusion Reactions by Lord Rutherford in front of an unprotected & unaware Royal Society of London (1934)

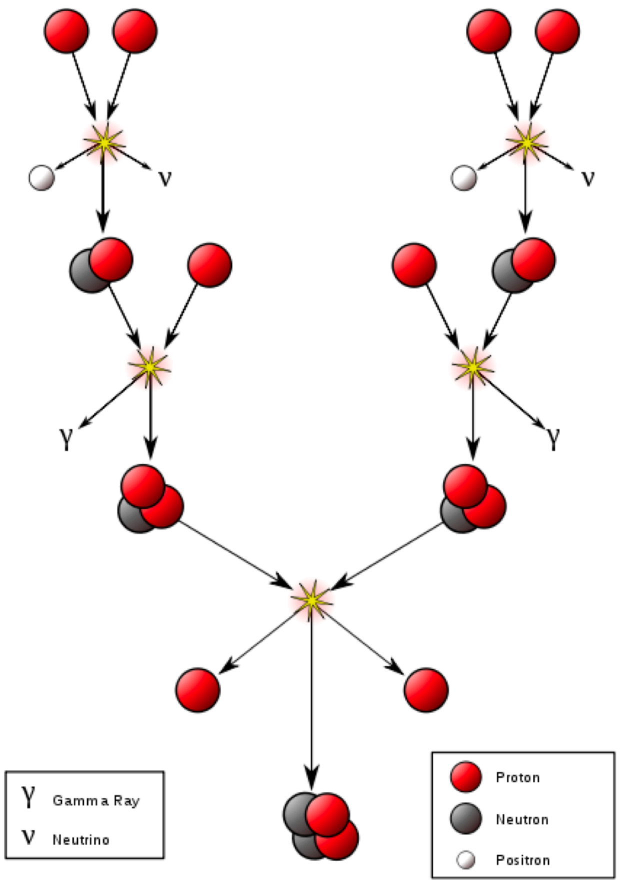
1938: The Alchemy of the Sun, a huge 'nearby' plasma

Hans Bethe
(1906-2005)

The final exit of the Bethe's cycle is:

$^{1}H+^{1}H+^{1}H+^{1}H \rightarrow ^{4}He + 25$ MeV

But such a cycle has to go through the bottleneck of the first reaction, the one that joins 2 protons into Deuterium:



$p+p \rightarrow ^{2}D+e^{+}+\nu$

The very low probability of such a reaction allows the Sun to last for 10 Billion years!

The following nuclear reactions :

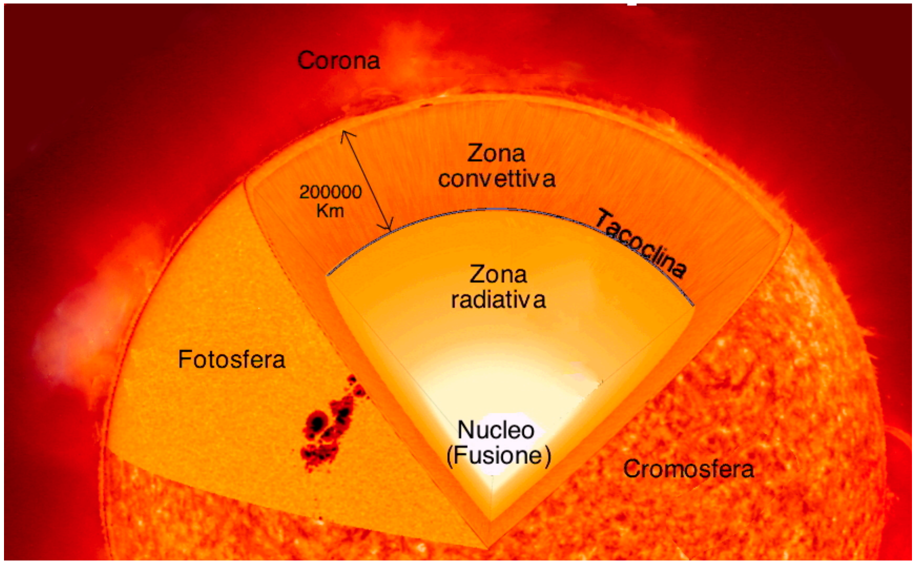
$^{2}D+p \rightarrow ^{3}He+\gamma$

$^{3}He+^{3}He \rightarrow ^{4}He+p+p$

would make the Sun burning up in a few millions years!

...lucky we are!

The Heaven's Alchemy cannot descend upon Earth!



Inside the Sun Fusion reaction occur only inside ¼ of total radius:

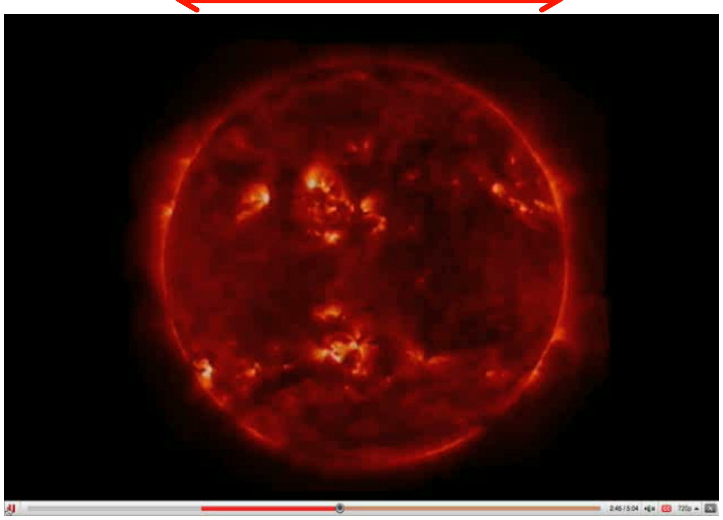
- **plasma density = 8 x Gold density**
- **plasma temperature 14 million ºC**

The power emitted in the innermost Sun per unit volume is only **300 W/m^3** **Human metabolism 900 W/m^3!**

Sun's metabolism is a 'reptile' one or that of a 'compost heap'!

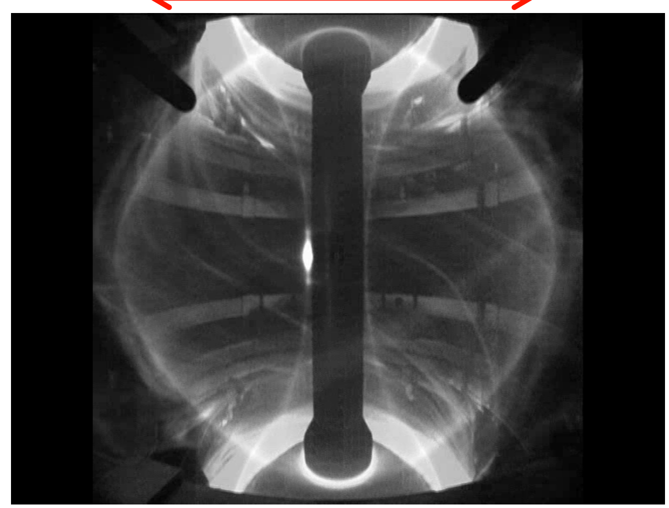
Fusion experiments are similar to the Sun only in their instabilities!

1.4 Billion meters



Solar Chromosphere filaments

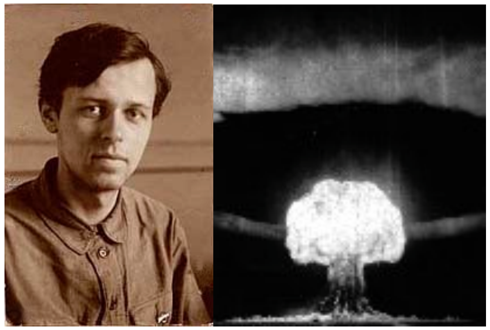
1.4 meters



MAST (UK fusion experiment)

'1940-'1950: the far different Alchemy upon Earth!

Dmitri Ivanovich Sakharov, USSR (1921-1989)

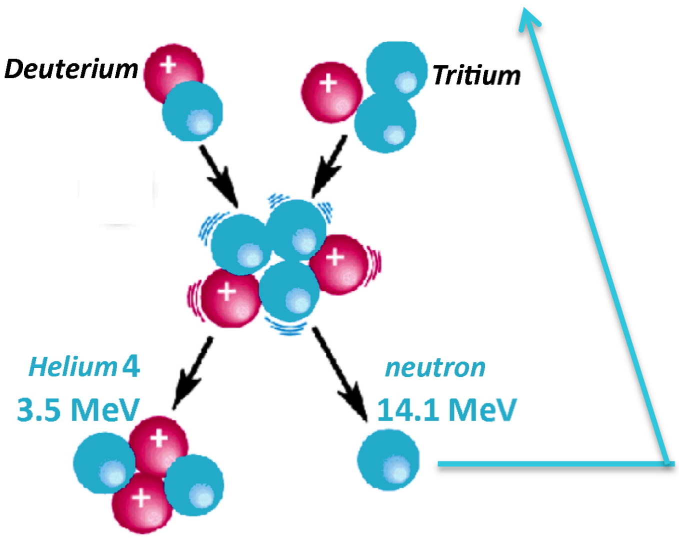


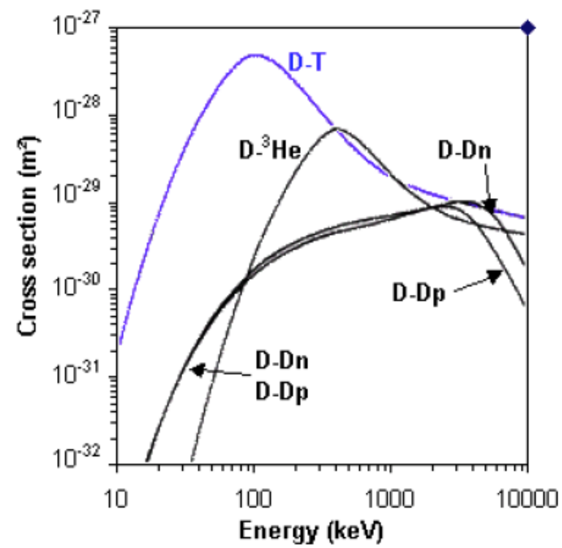
Edward Teller, USA (1908-2003)

The Bethe's cycle (very slow Hydrogen reaction) requires gravitational confinement

Fusion on Earth requires D-T (Rutherford was right in 1934!):

$^{2}D + ^{3}T \rightarrow ^{4}He + n + 17.6$ MeV which is the highest efficiency one





The energetic output of Fusion reaction per kg of reactants (400 g ^{2}D & 600 g ^{3}T) is 1 million times greater than the energetic output of the combustion of 1 kg of oil (from eV to MeV)

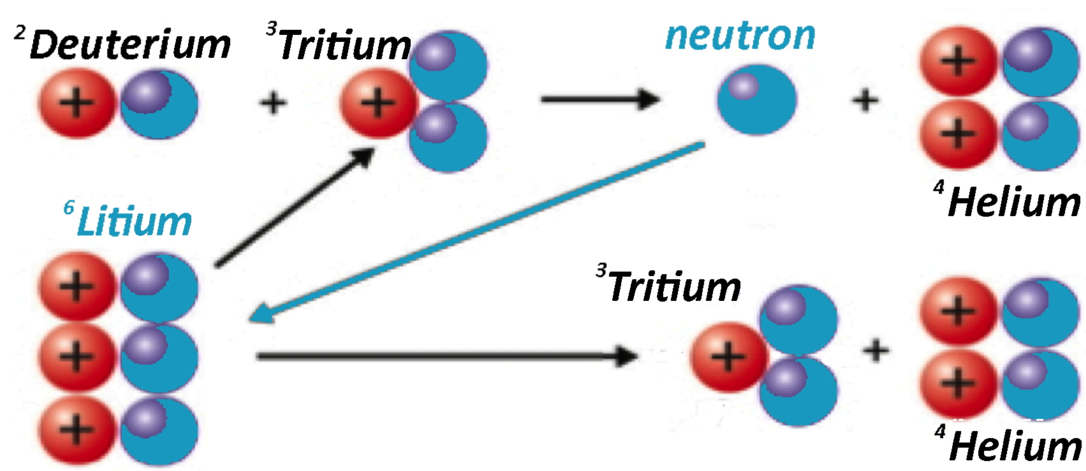
The far different Alchemy upon Earth!

Tritium decays with half time ~ 12 years, it can be produced in Fission reactors moderated by heavy water (D_2O), but its production would be insufficient…

A D-T Fusion reactor has to be fertilized by neutrons*,
a Litium mantel surrounding the D-T plasma, which emits neutrons, can provide through other nuclear reactions the required Tritium!

$n + {}^6Li \rightarrow {}^3T + {}^4He$

$n + {}^7Li \rightarrow {}^3T + {}^4He + n$



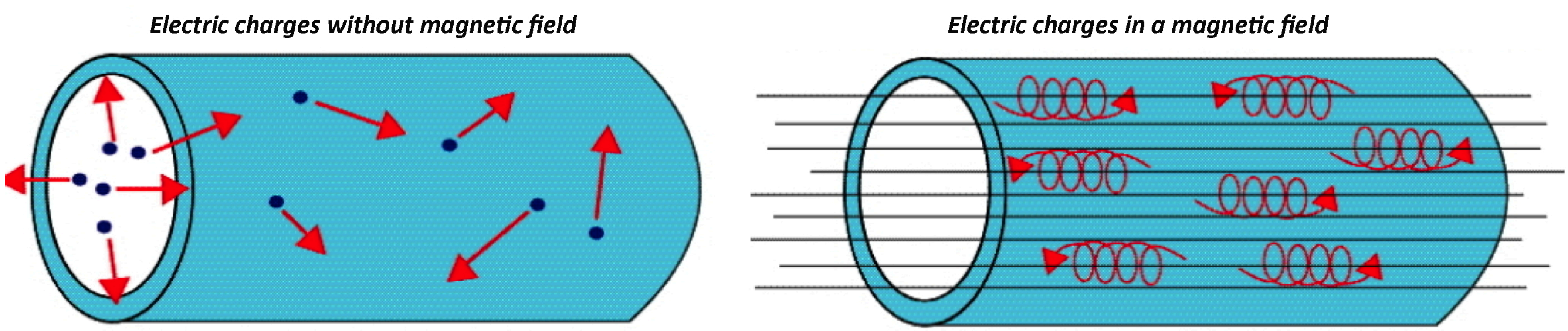
** which remains to be demonstrated in practice!*

Magnetic Confinement (plasma 1/100 thousandth less dense than air)

Requires:
- temperature T ~ 20 keV (200 millions °C)
- density n ~ 2•10 ^{20} m^{-3} (1/100 thousandth less dense than air)
- containment time of energy $\tau_E \sim 1$ s

→ plasma pressure ~ 10 bar (100 m under water) looks tiny …it isn't!

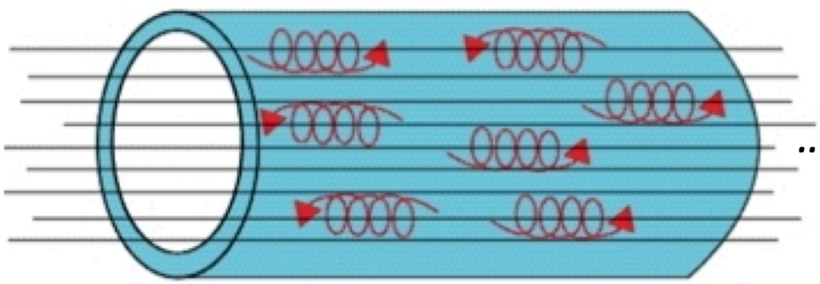
~ 1 Fusion collision every 20 s – mean free path ~ 20˙000 km!



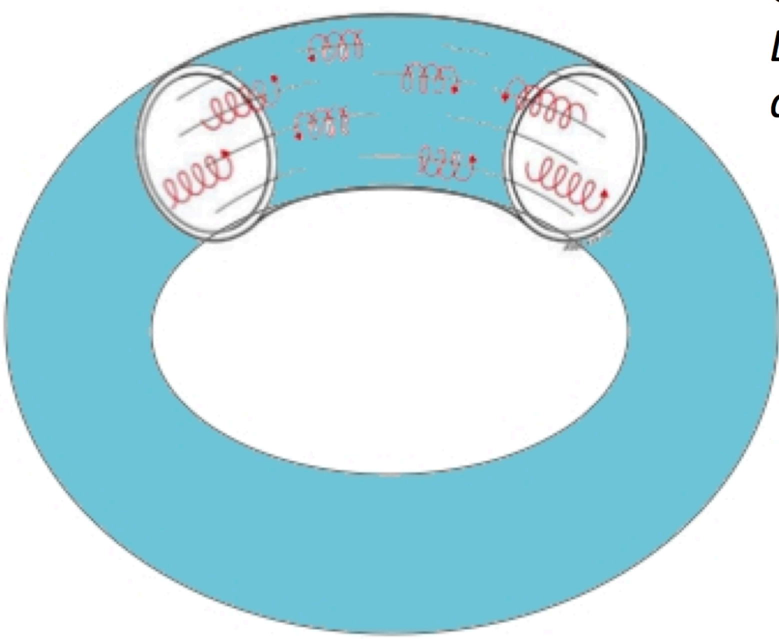
Magnetic fields are required to contain ^{2}D & ^{3}T reacting nuclei

Magnetic Confinement: do all doughnuts have holes?

^{2}D , ^{3}T ions ~ 100 collisions with electrons/second – mean free path ~ 10 km!

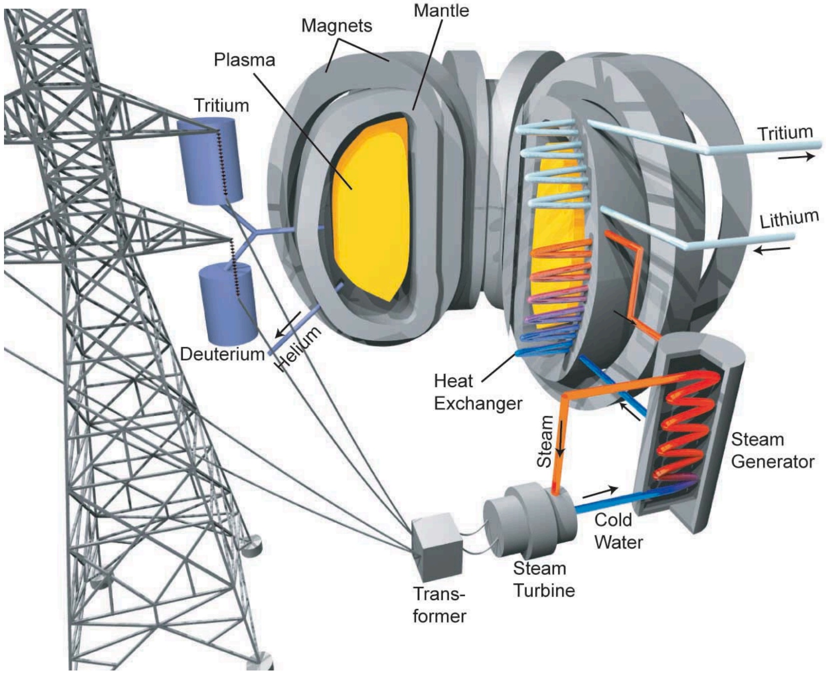


…would be too long as a magnetic trap!



One has to bend the magnetic trap into a doughnut: *Deuterium & Tritium nuclei still run 10 km, but in a doughnut shaped racetrack!…*

Magnetic confinement D-T-Li cycle



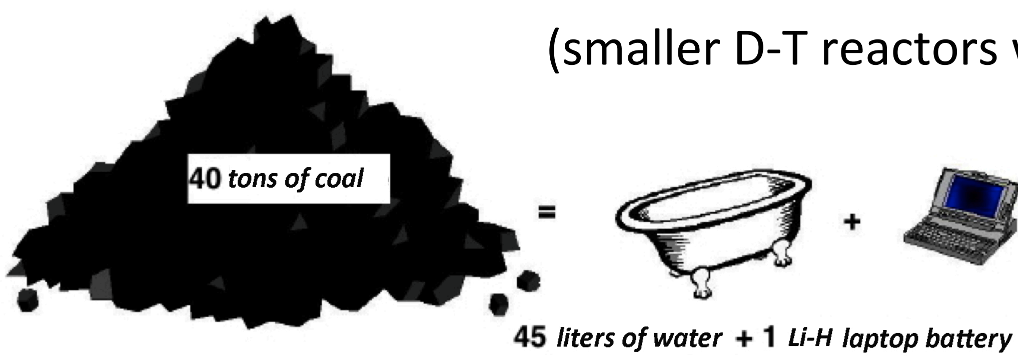
110 kg of ^{2}D & 380 kg of ^{6}Li per year to provide 1 GW of electricity

Dimensions constrained by: **Tritium production in a Litium mantle around the plasma**

The space required by **the full braking of 14.1 MeV neutrons is ~ 1m**

Vacuum vessel dimension is therefore at least a few meters

(smaller D-T reactors would not close the D-T-Li fuel cycle *)



to provide 200000 kWh
(30 years consumption of a European)

*^{3}He isotope could help in obtaining Neutronless Fusion reactions (very sustainable …will not cause any nuclear activation)

Unfortunately ^{3}He is practically absent on Earth, should be recovered mining the Lunar soil! …& **10 MeV** plasma temperature!

Magnetic field & dimensions ...almost right!

Tokamak plasma stability considerations impose a **magnetic pressure** which is more than 10 times the plasma pressure (10x10 bar = **100 bar**)

β= plasma beta= $$\frac{plasma\ pressure}{confining\ magnetic\ field\ pressure} = \frac{1}{10}$$

Luckily enough: vacuum chamber a few m wide are feasible:
superconducting magnets*: their limit $\sim$ 5 Tesla $\sim$ 100 bars = 10 x 10 bars plasma!

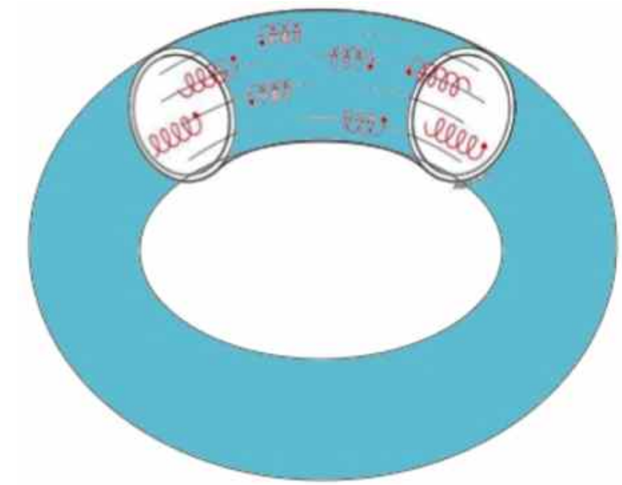
Magnetic confinement Fusion with Tokamaks is engineering-wise almost feasible (some difficulties to be overcome ...neutron fertilization of Lithium mantle)

...the real obstacle is the Physics!

***A Magnetic Fusion reactor requires superconducting coils**: ...otherwise the electric power dissipated in normal conducting coils would be much greater than the produced Fusion power!

Simple doughnuts with holes are not enough…

Toroidal trap: a few m radius

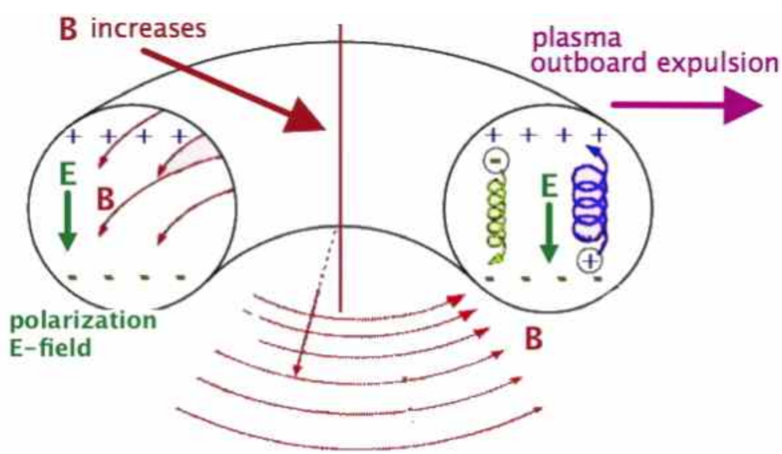


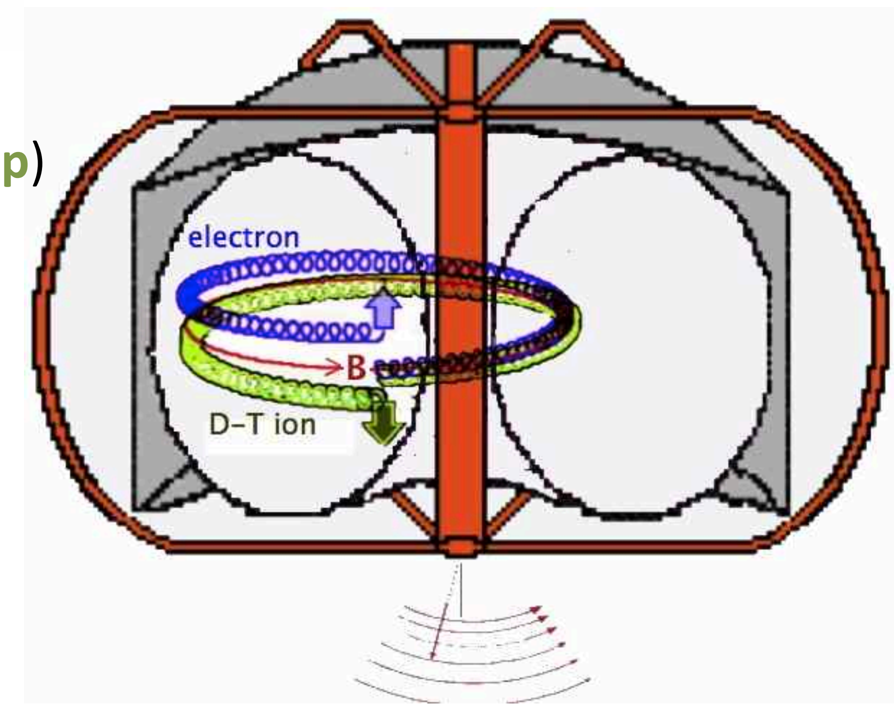
Scheme of the toroidal trap is like the *toroidal tranformer of an appliance*

inhomogeneous B field

separates charges (b.e. **e^- → down**, **D^+,T^+ → up**)

E vertical field, through **E∧B**, **…ejects plasma**



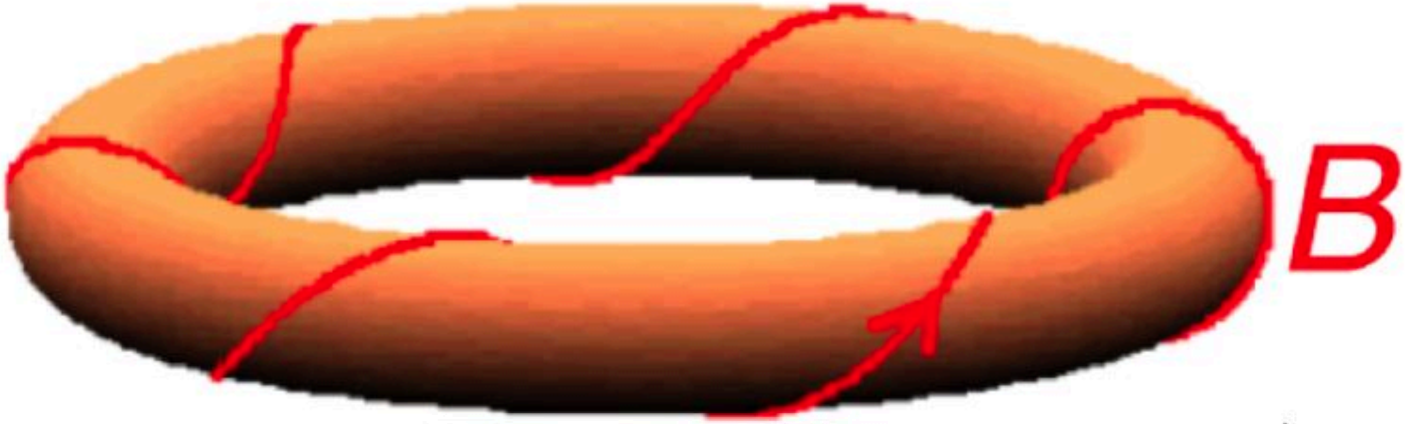


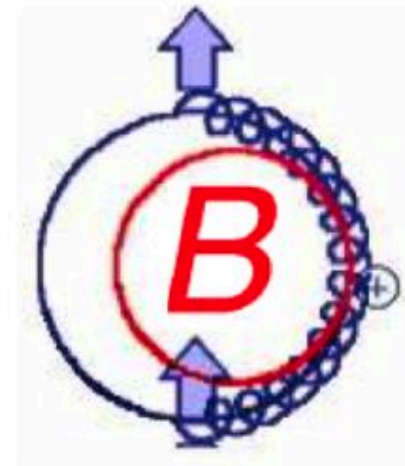
A confining current is required in axisymmetric doughnuts!

Particle drifts & current density $\perp$ to B constrasted by a $\mathbf{B}_\perp$ (poloidal) component:

→ toroidal current flowing in axisymmetric plasma (Tokamak)

→ or non-axisymmetric configuration (Stellarator)

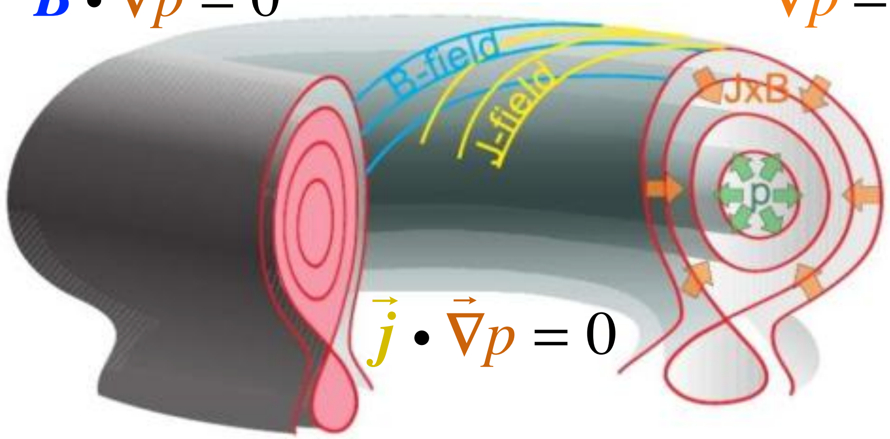




To avoid plasma ejection requires 2D flux & pressure surfaces, not 1D lines

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

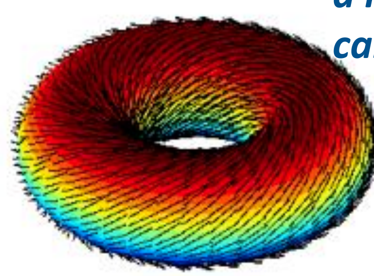
$\vec{\nabla} p = \vec{j} \wedge \vec{B}$ **(magneto-hydrostatic equilibrium)**



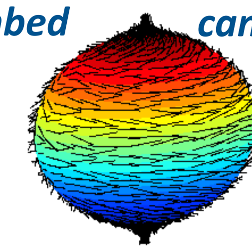
$\vec{j} \bullet \vec{\nabla} p = 0$

flux surfaces must be Tori:

a hairy torus can be combed



a hairy sphere cannot!



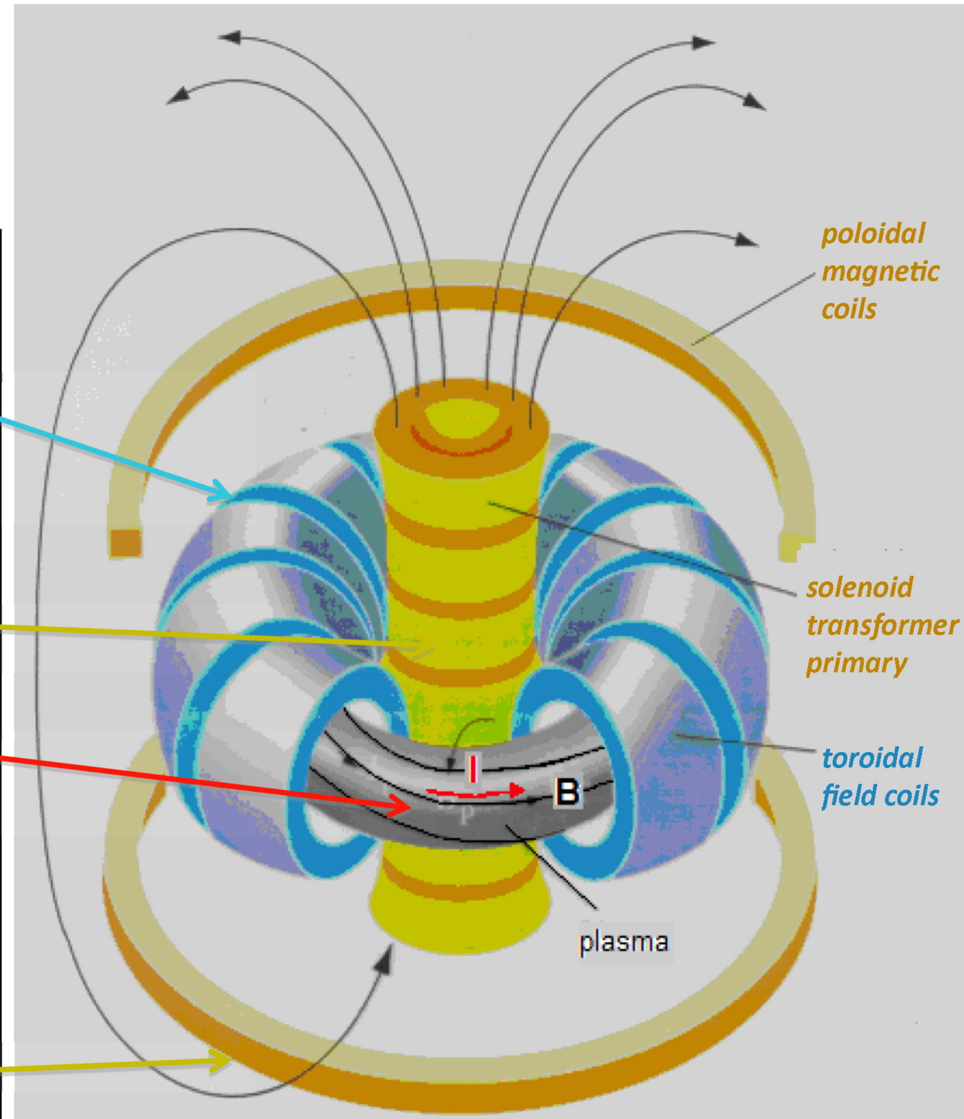
"Hairy ball theorem": no continuous field tangent to a sphere unless there is at least upon one point $\vec{B} = 0$ *and* $\vec{\nabla} p = 0$

Tokamaks (1953): Soviet creatures!

Igor Yevgenyevich Tamm (1895-1971)
Dmitri Ivanovich Sakharov (1921-1989)

- The toroidal component of the magnetic field is produced by coils wound around the plasma doughnut
- The central solenoid induces the plasma current (*break-down*) and heats the plasma doughnut

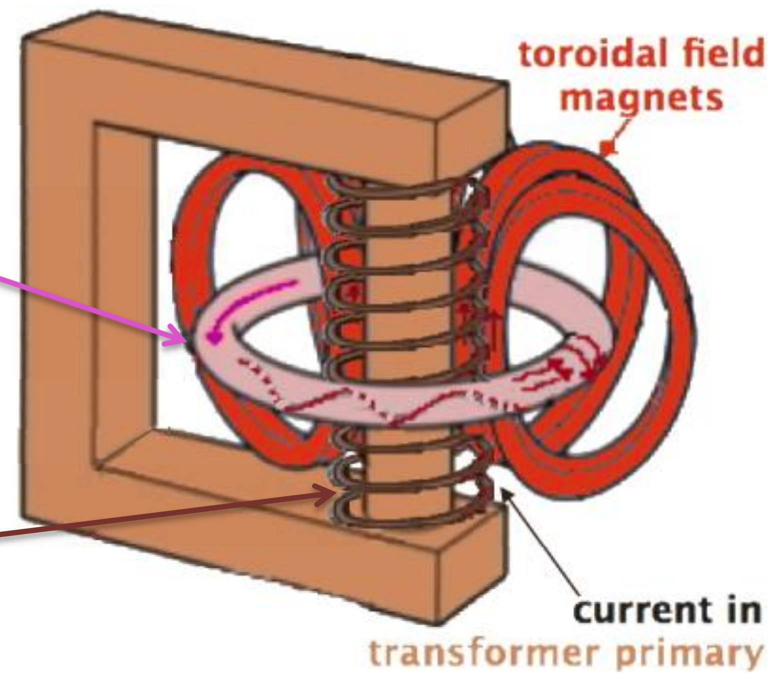
  (ohmic heating, just like the current through the resistors of an electric stove)
- Other coils control the position of the plasma doughnut



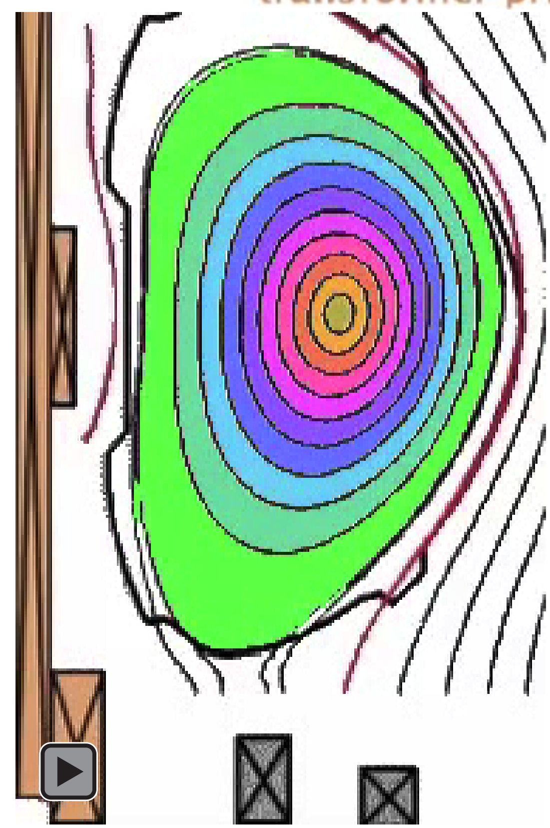
Therefore a **plasma confining current has to flow inside the Torus**:

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…

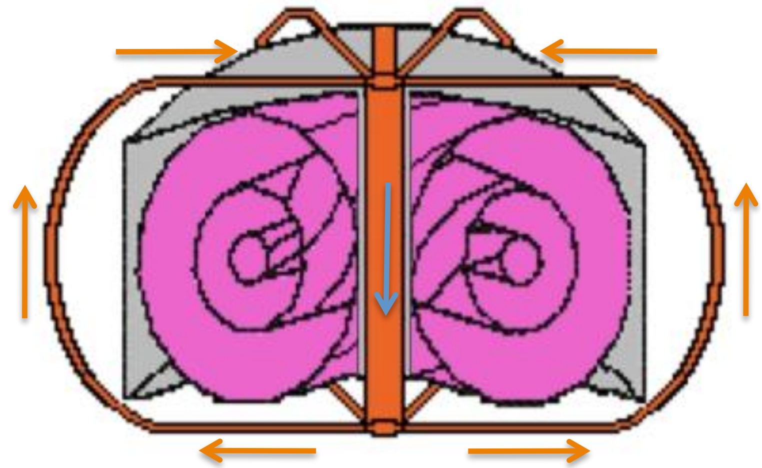


- **The plasma ohmic drive in a Tokamak can be seen as motion of closed flux surfaces, that from outside 'feed' the plasma, which dissipates them while they move toward the magnetic axis**
- **In tokamaks this process is due to the transformer current change:**
- **Tokamaks cannot have steady drive!**



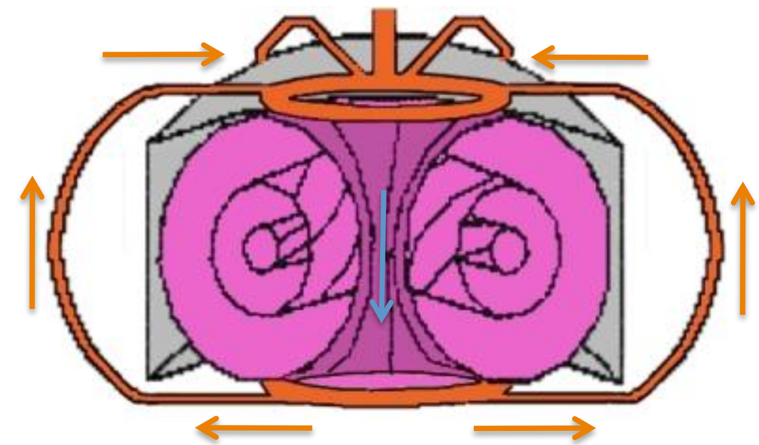
The main idea of PROTO-SPHERA

- "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

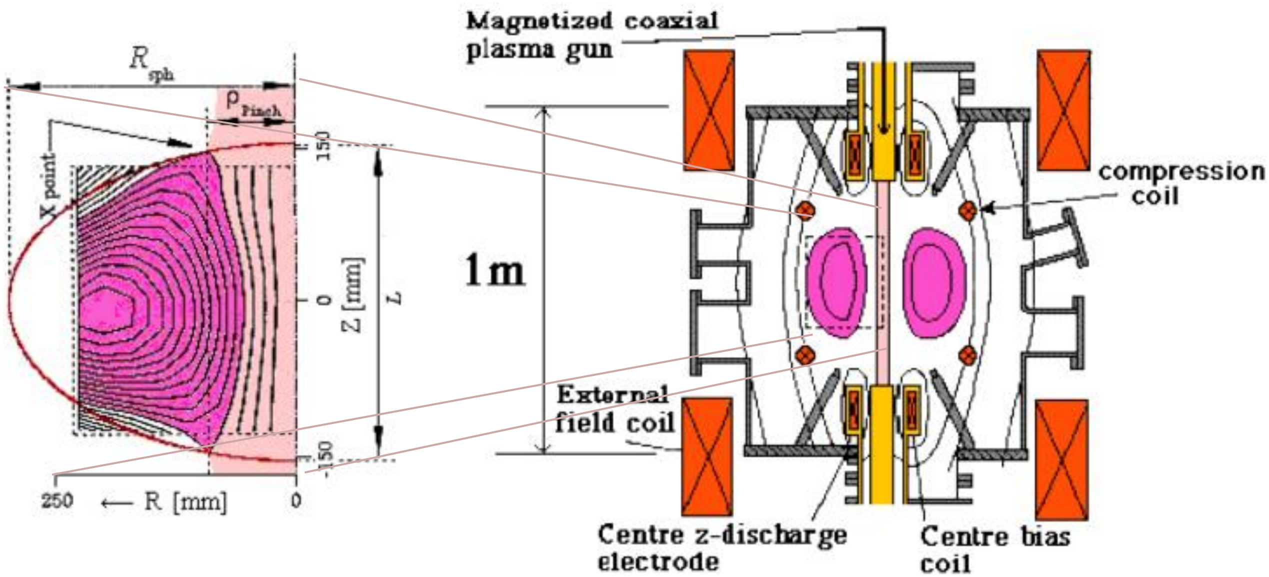
Abandon vacuum vessel complicated geometry, move to a cylindrical vacuum vessel!

→ easy of access & of repair...

PROTO-SPHERA Japanese precursor

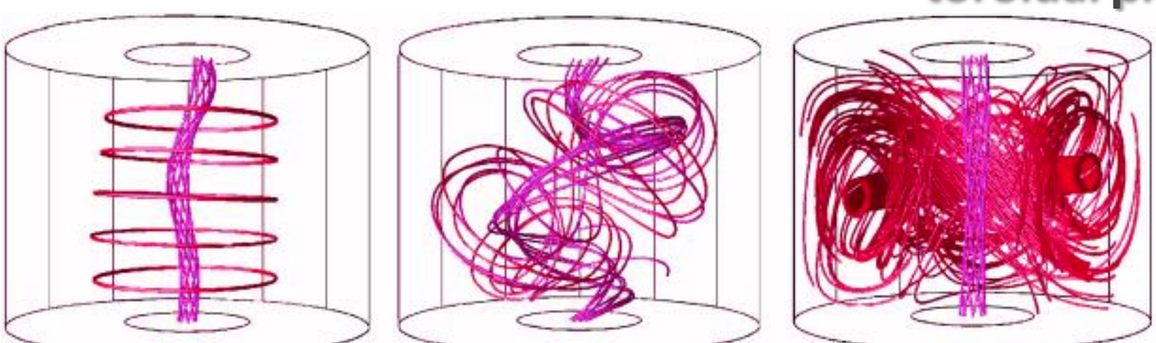
TS-3 (**Tokyo University**): plasma toroids **magnetic reconnection** around a metal centerpost

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



non-linear "kink" instability formed a Spherical Torus

toroidal plasma current 50 kA < I_{ST} < 100 kA



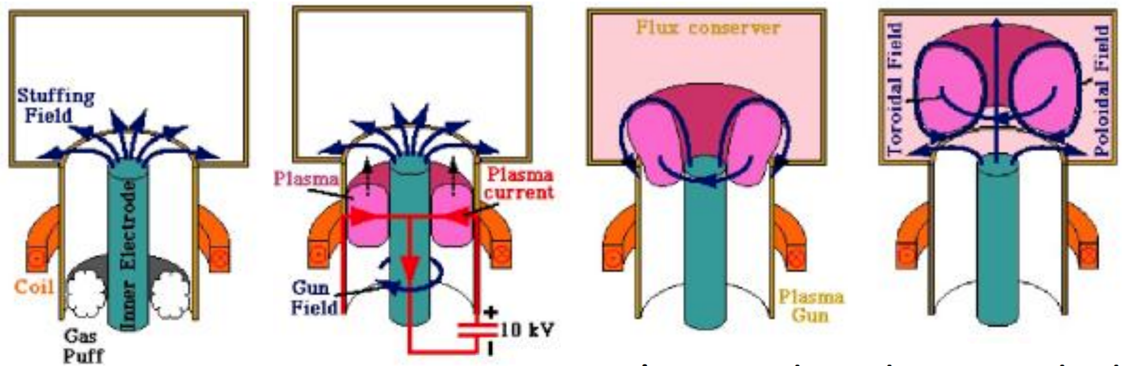
Stable Plasma Centerpost | Instability & Magnetic Reconnection | Plasma Centerpost & Torus

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

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

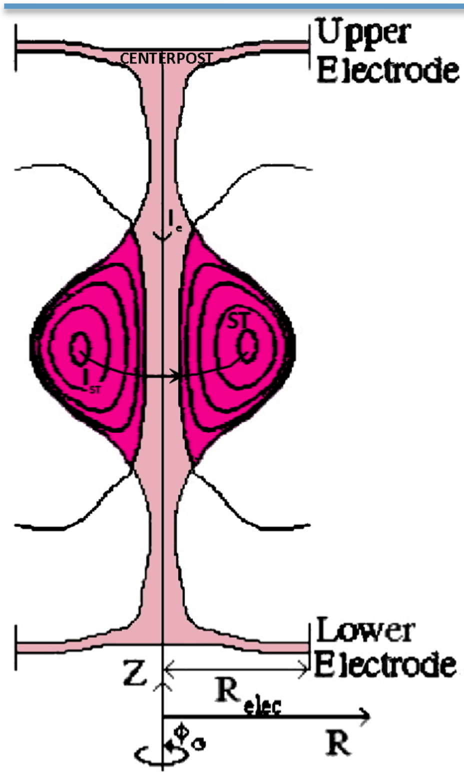
Breakdown in **small spaces**, with extremely **high filling pressures** and **10 kV voltages**

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

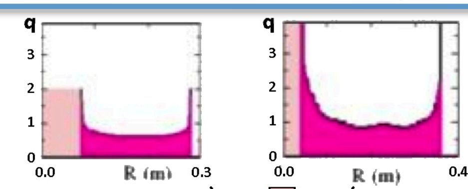


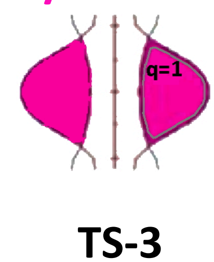
PROTO-SPHERA key differences

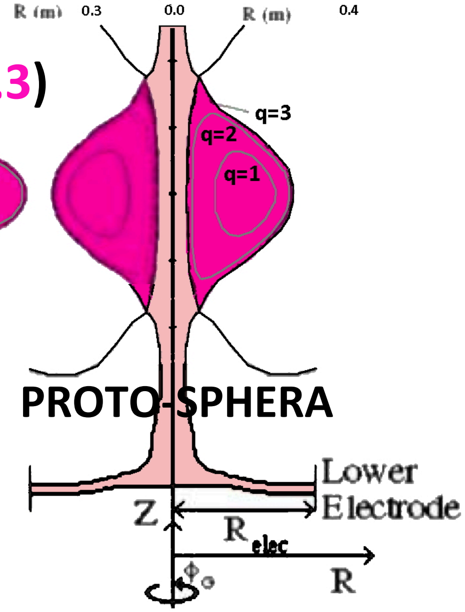
- **Designed for a Tokamak-like field-line rotational trasform ($q_0 \geq 1$, $q_{edge} \sim 3$) (aspect ratio $A = R/a \geq 1.2$, elong. $k = b/a \sim 2.3$)**

- **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**





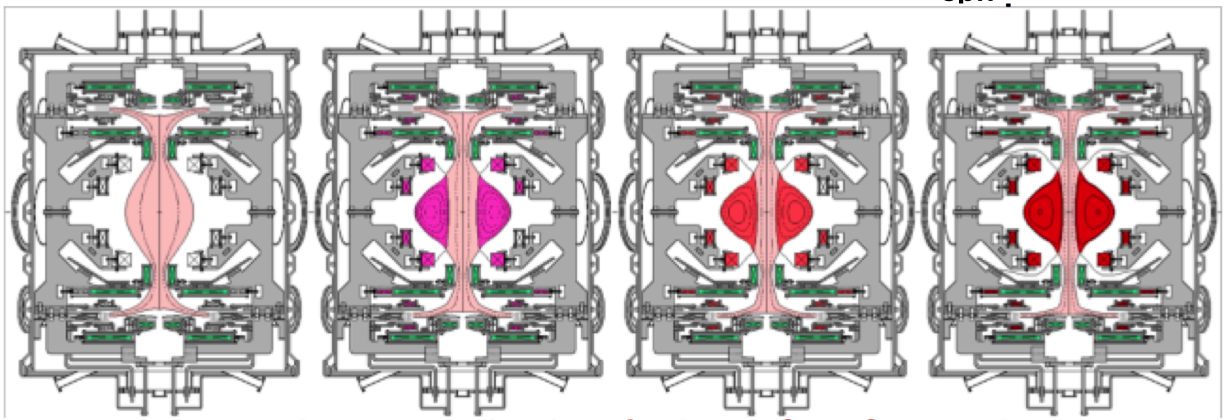


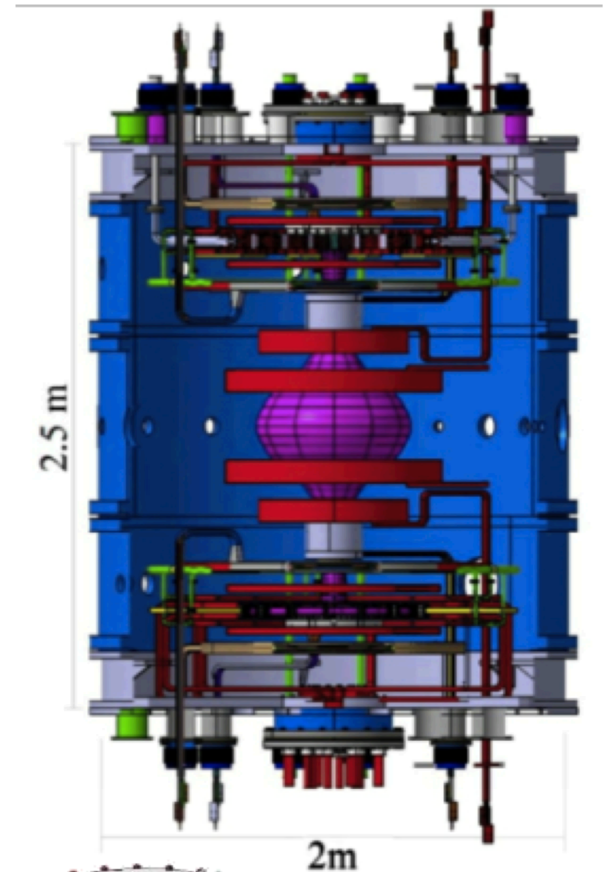
PROTO-SPHERA main design parameters:

Centerpost current I_e = 60 kA

ST toroidal current I_{ST} = 120÷240 kA

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



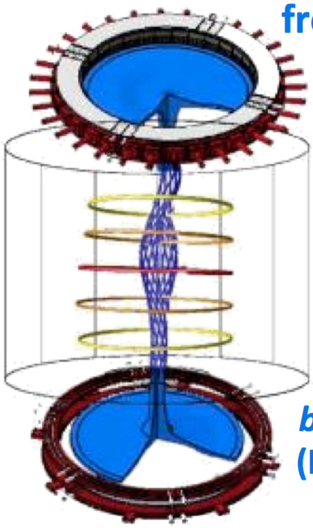


Axisymmetric simulation of ST formation

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

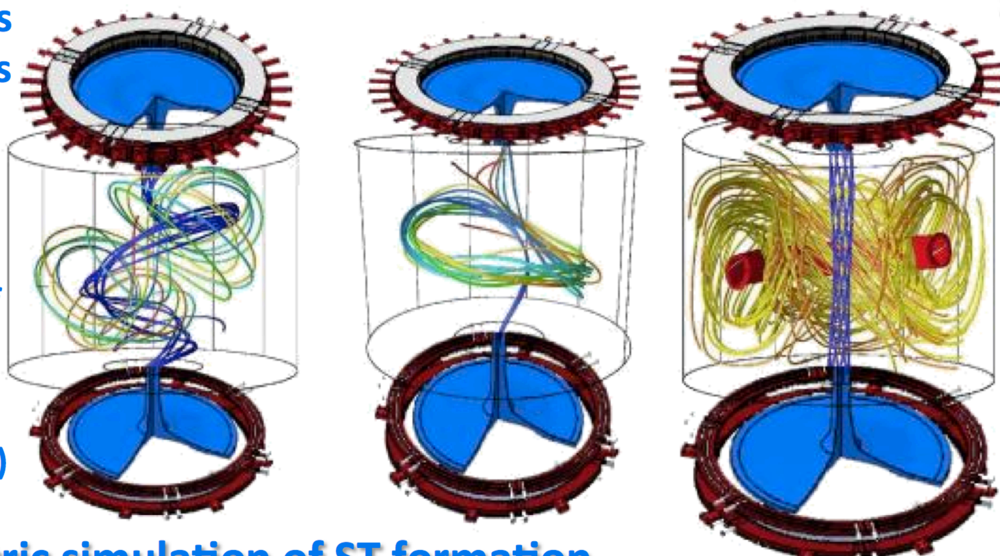
from $\tau_{Alfvén} \sim$ 0.5 μs

$\tau_{Resist} \sim$ 70 ms



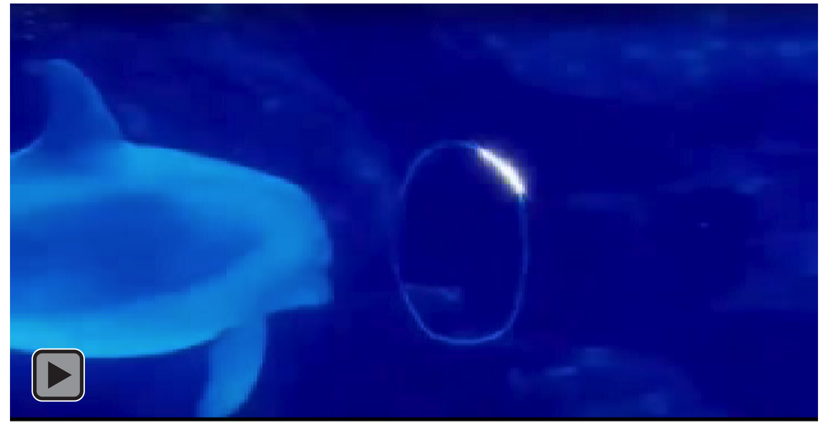
Resistive MHD simulations of ST formation

by Ricardo Farengo (ISTW2008-Frascati)



Non-axisymmetric simulation of ST formation

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

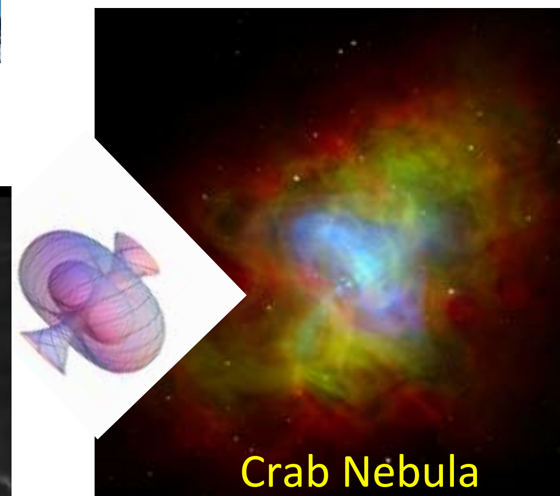


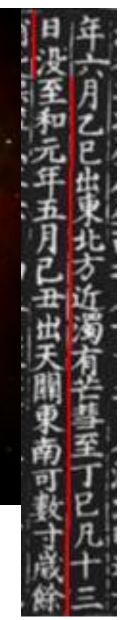
Aim is to sustain the Plasma Torus
for at least 1 resistive timescale: $\tau_{Resist} \sim 70$ ms
...but PROTO-SPHERA designed for 1 sec sustainment!

Fluid dynamics examples

William Irvine-University of Chicago

Plasma dynamics example

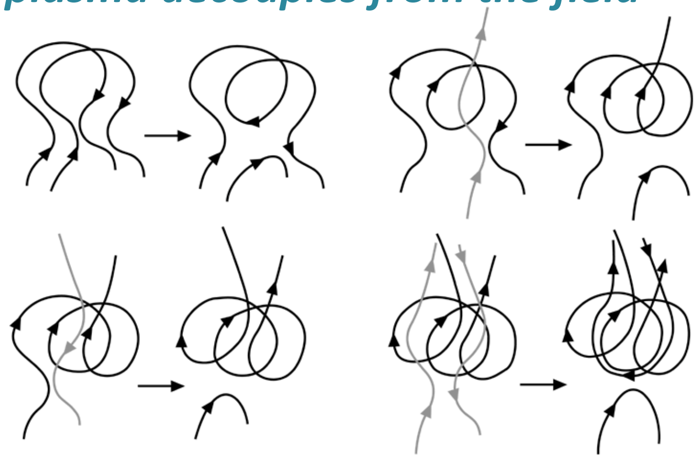


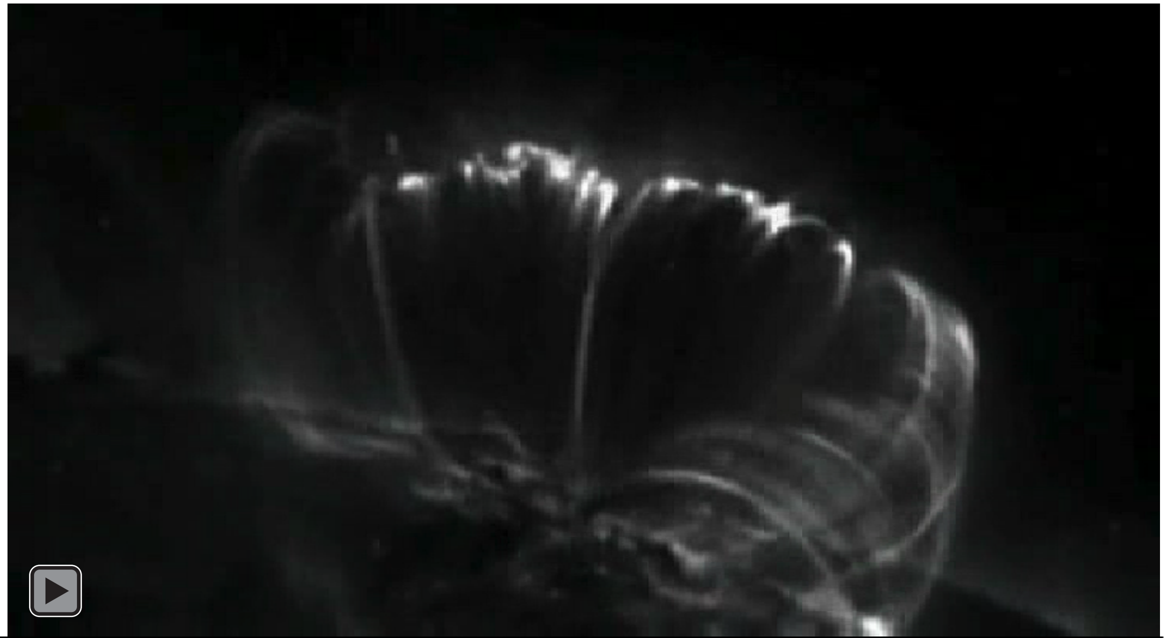


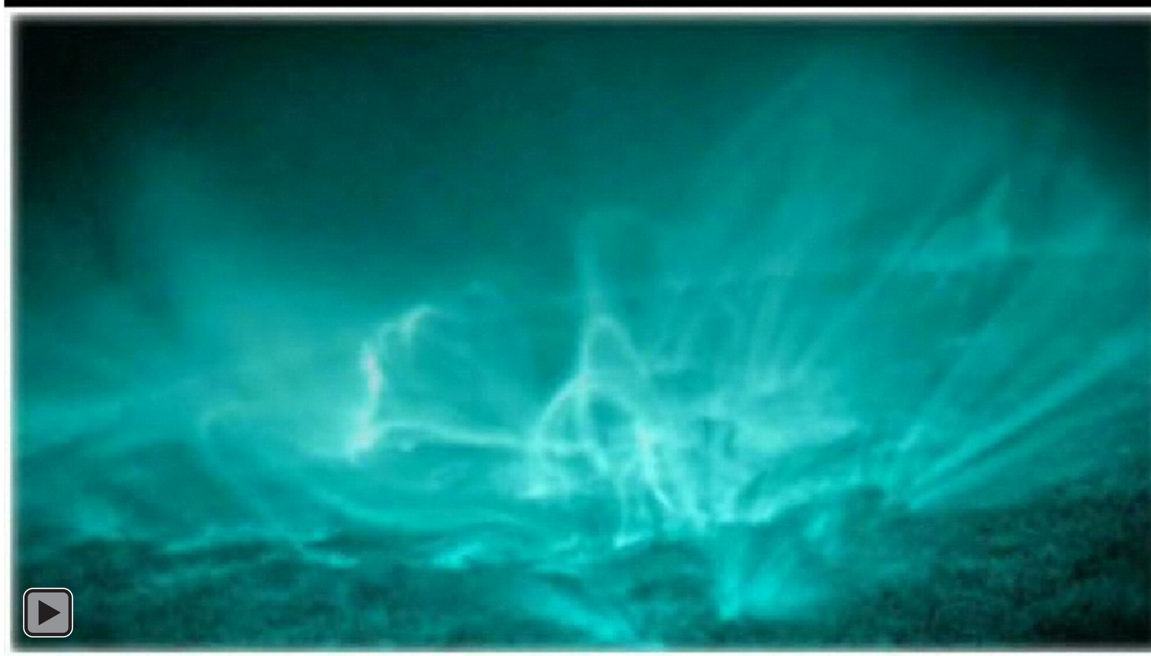
Solar Flares & Magnetic Reconnections: Coronal Heating

If the plasma were a perfect electric conductor, it would not decouple from the lines of force:
magnetic advection
To displace the lines of force means introducing further plasma currents:
matter flow→ electric currents

In presence of electric resistance if neighboring lines of force have "X-points" structures, they can break & reconnect, then the plasma decouples from the field





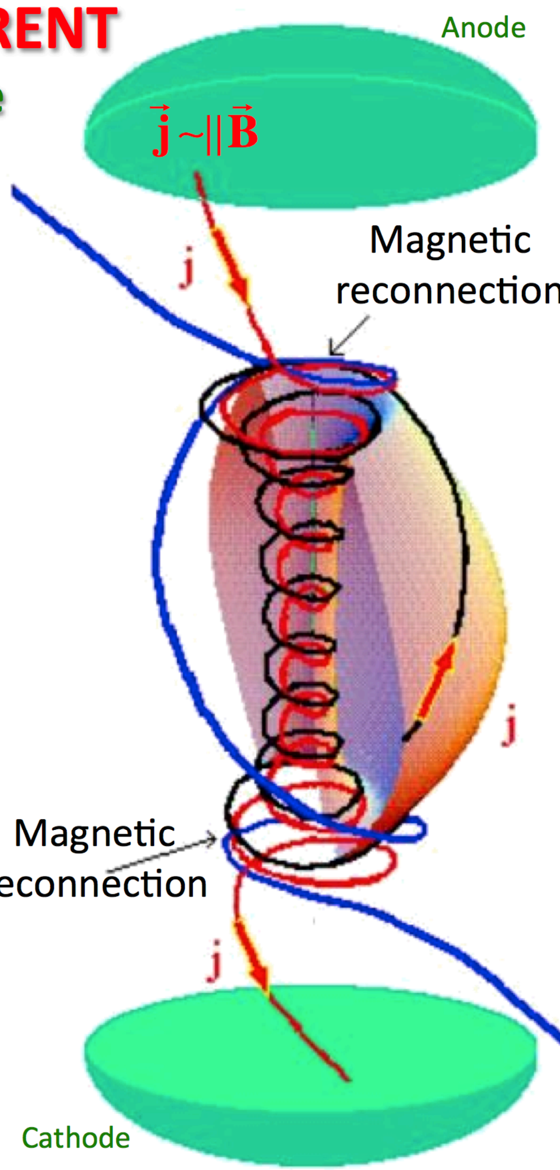


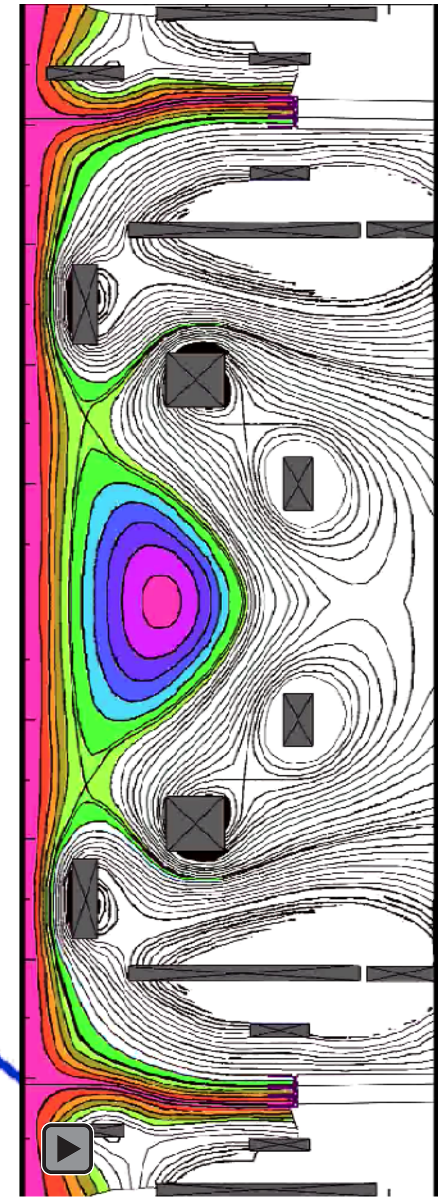
In the "Solar Corona" the plasma follows the field

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

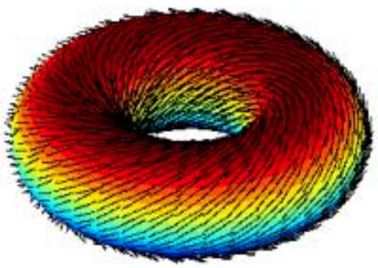
HOW EFFICIENT THE SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS?

Space Thruster?

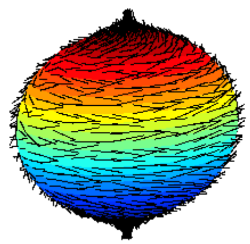
abandon vacuum vessel toroidal geometry, move to cylindrical one

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

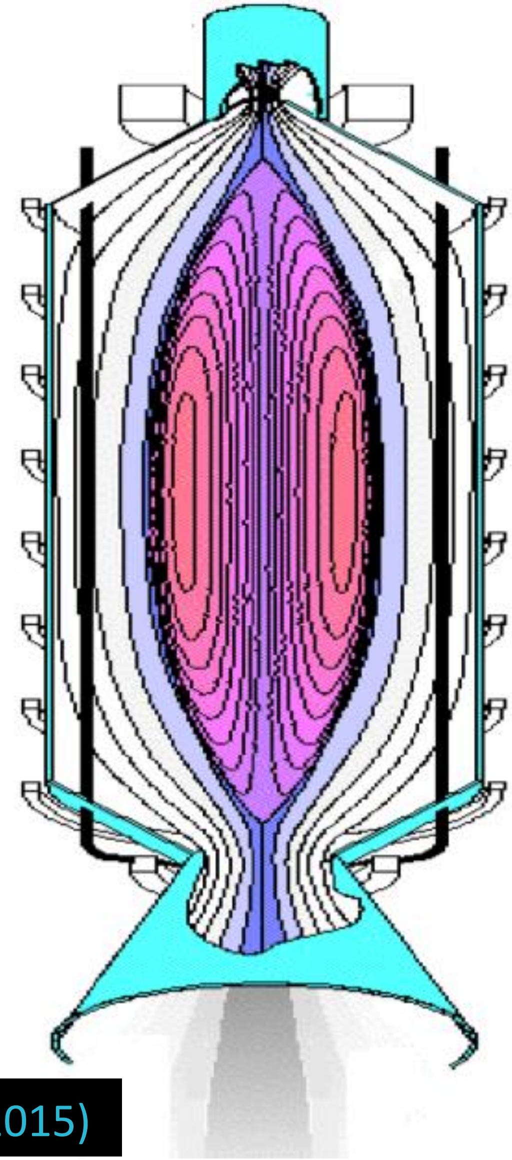
Due to filamentary nature of B field
a fundamental mathematical difference appears:



a hairy torus can be combed

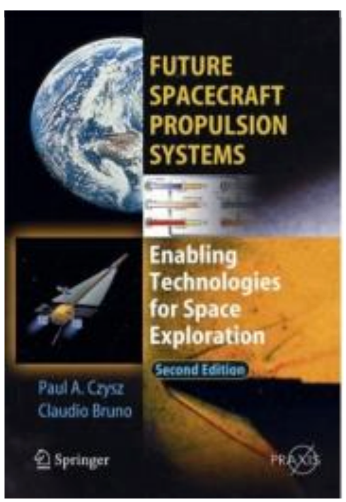


a hairy sphere cannot!



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

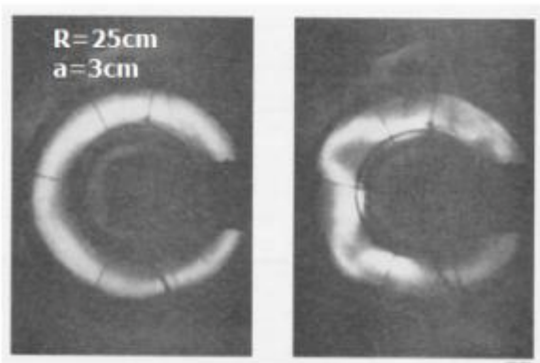
Possible future application as a Space Fusion Thruster…



Nozzle observed in PROTO-SPHERA experiment (2015)

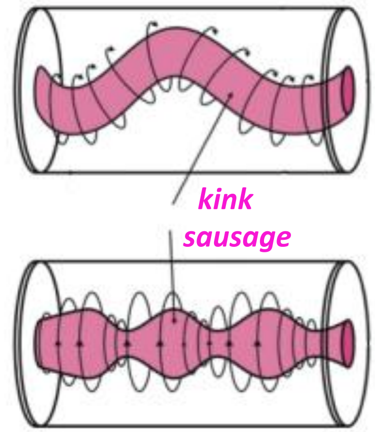
Why a new and different magnetic confinement device? one reason is ..."disruption"

Alan Ware & Thomson
Imperial College 1947.

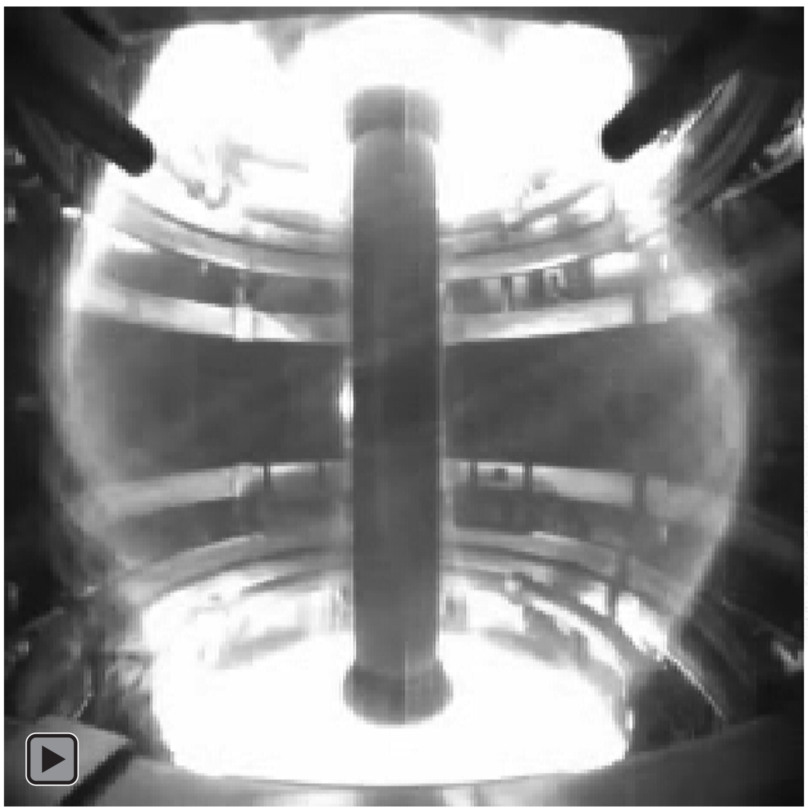


... Even if the muttered mantra is that Tokamak physics is perfectly known ...

MHD instabilities appeared since the earliest toroidal magnetic confinement devices

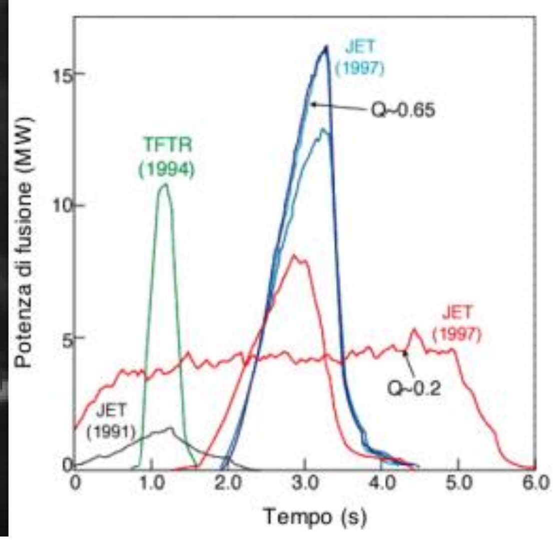


Mast 2004



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

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

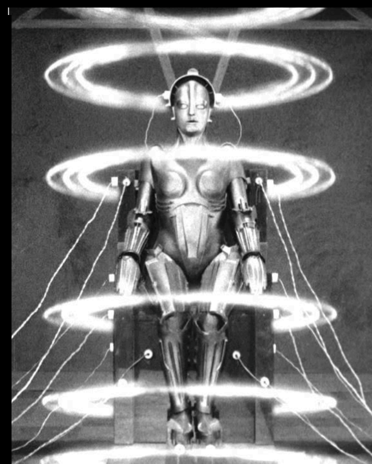


In D - T experiments:
JET 1991- TFTR 1994
JET 1997

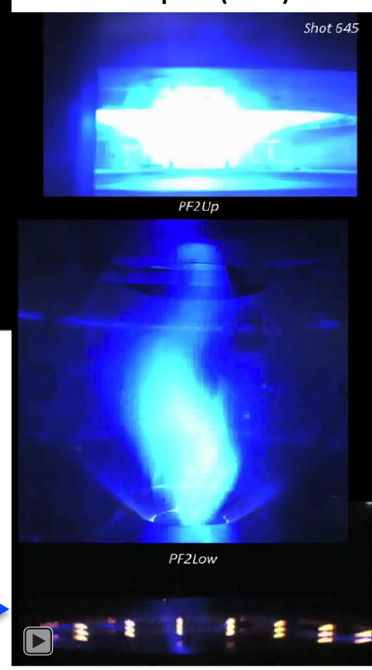
The highest neutron yield ...terminates in a disruption

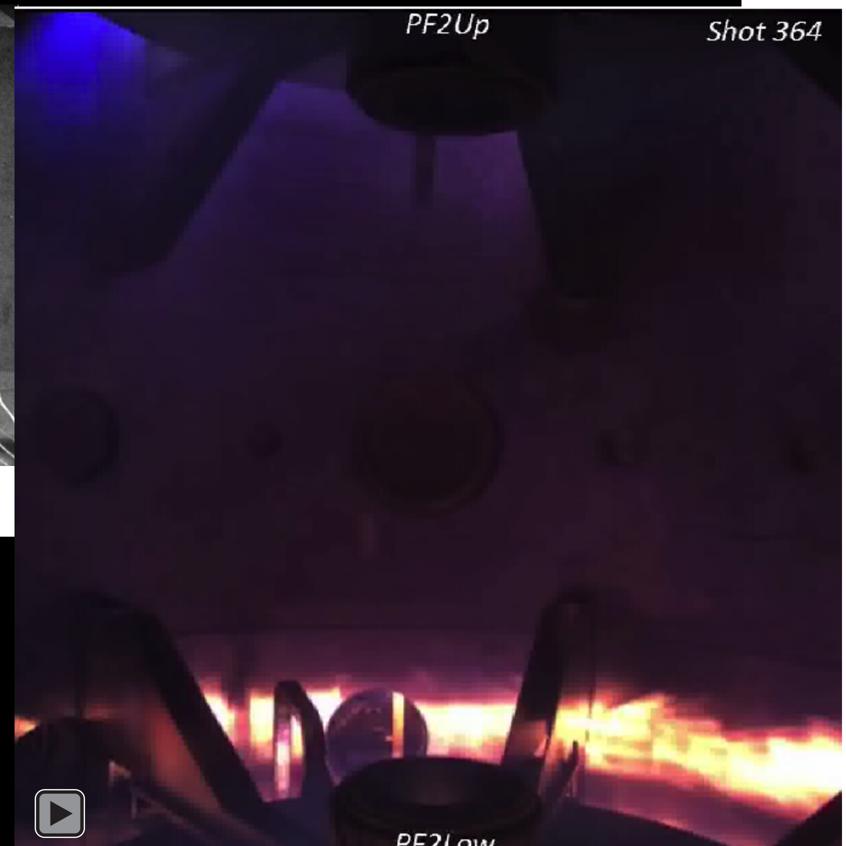
• **Disruptions …toroidal plasma vanishes → damages, very long plasma restart, …**

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)





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

Kink unstable configuration of PROTO-SPHERA iss maintained indefinitely (0.7 s), notwithstanding:

wobbling centerpost

& even more wobbling cathode plasma →

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

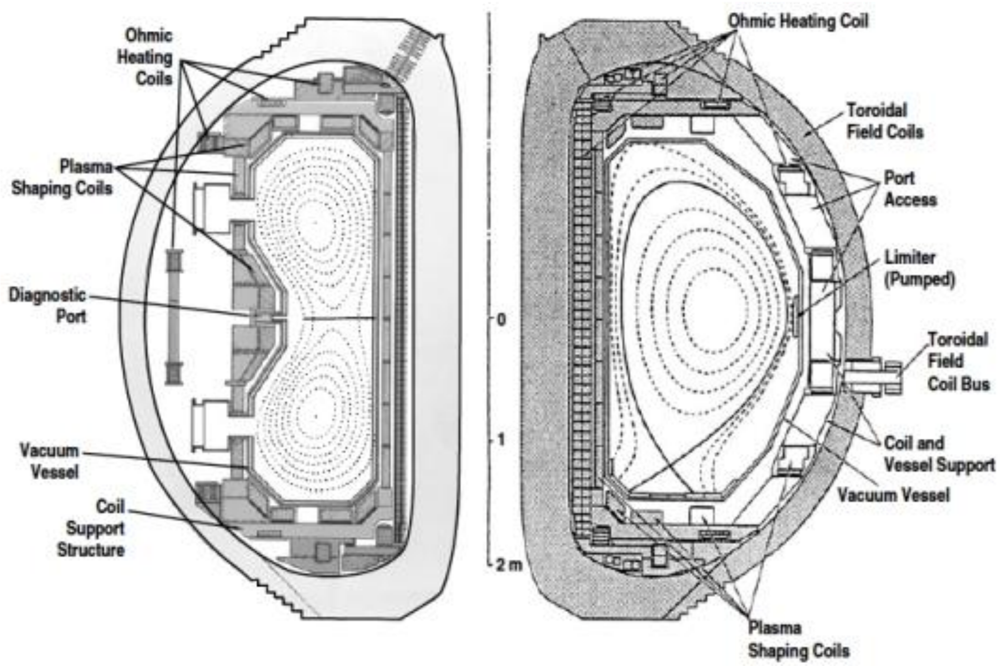
... Even if the muttered mantra is that tokamak physics is perfectly known ...

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

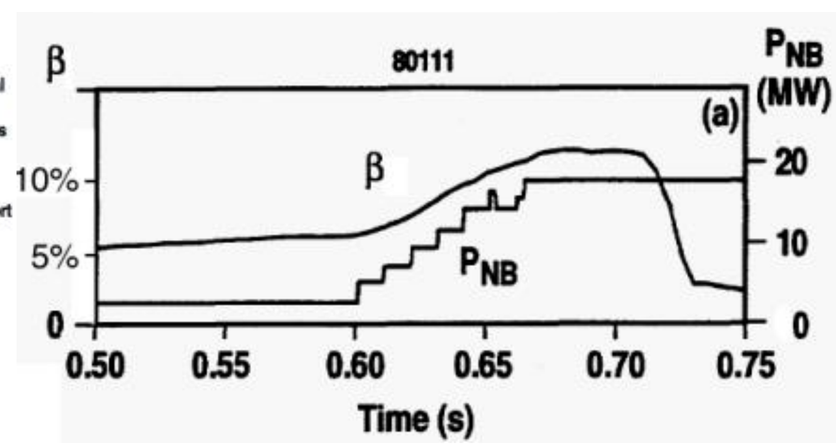
$\beta = 2\mu_0 \int p\, dV \Big/ \int B^2\, dV$ — but in tokamak experimental data one often uses β_{T0}

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

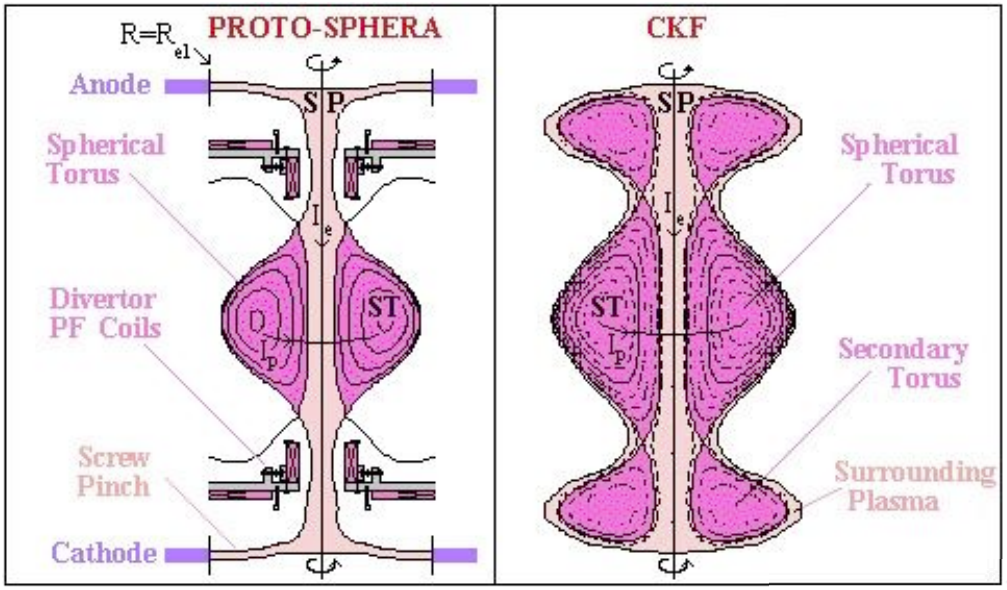
DIII-D in 1994 reached the highest value of β in conventional Tokamaks



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

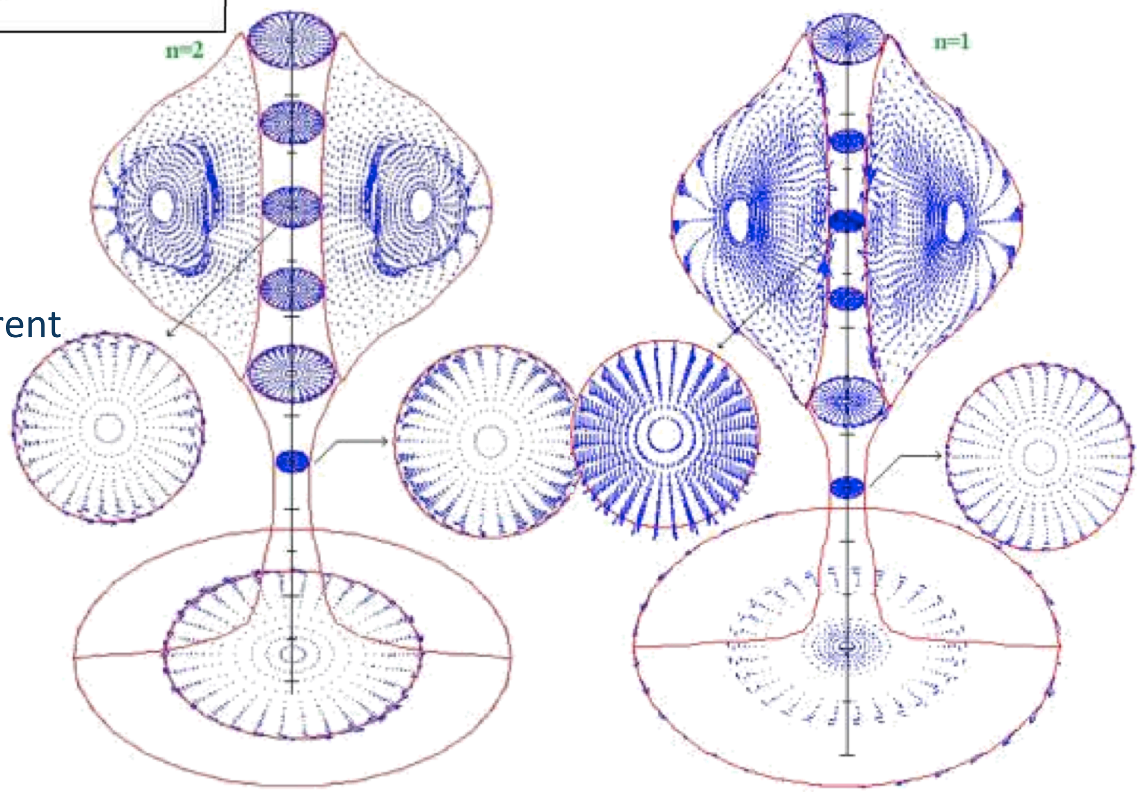
ratio of the two plasma currents

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

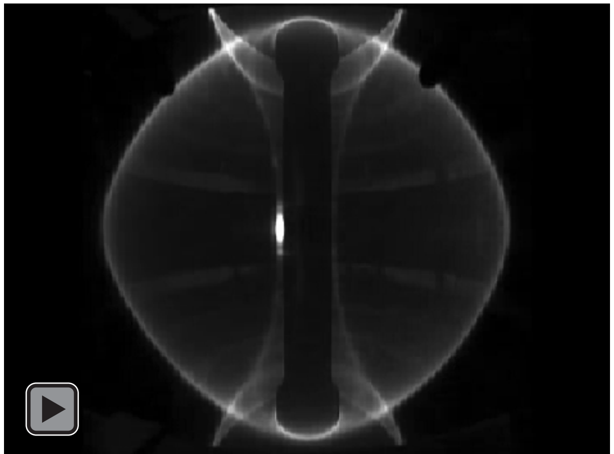
- up to β = 21÷26% , I_{ST}/I_e = 0.5 - 1
- up to β = 14÷15% , I_{ST}/I_e = 2-4

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

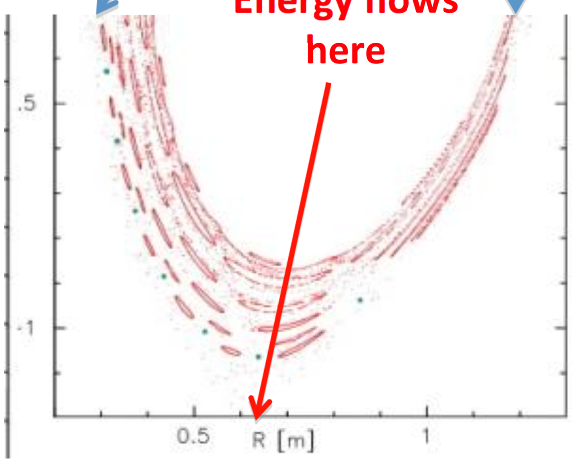
- up to β_{T0} =28÷29% , I_{ST}/I_e = 0.5 - 1
- up to **β_{T0} =72÷84% , I_{ST}/I_e = 2-4**



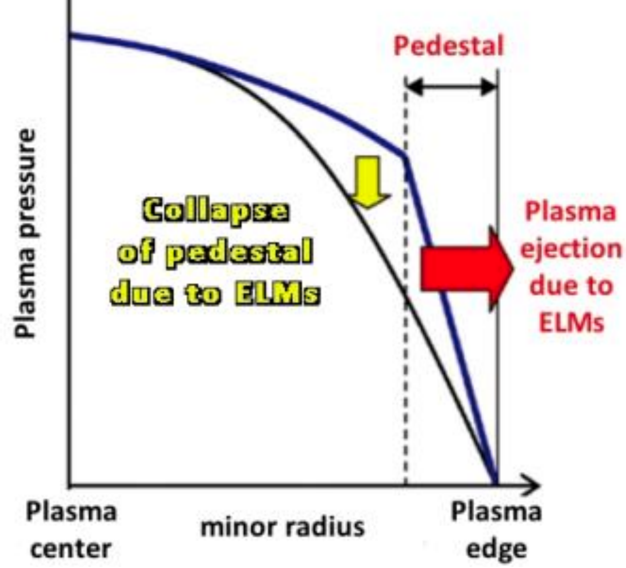
Why a new and different magnetic confinement device? still other reason are... "ELMs" (unstable edge localized modes)



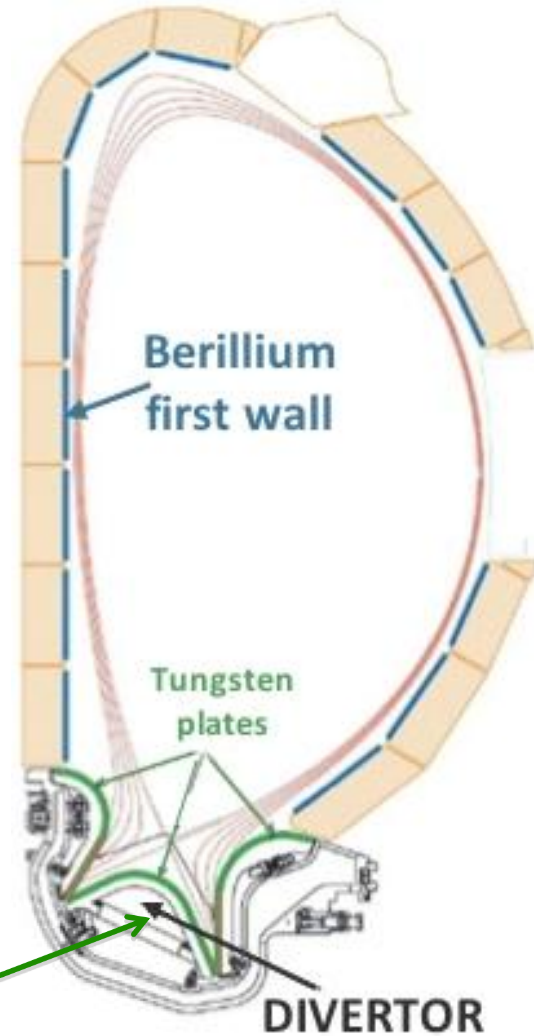
Energy flows here



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



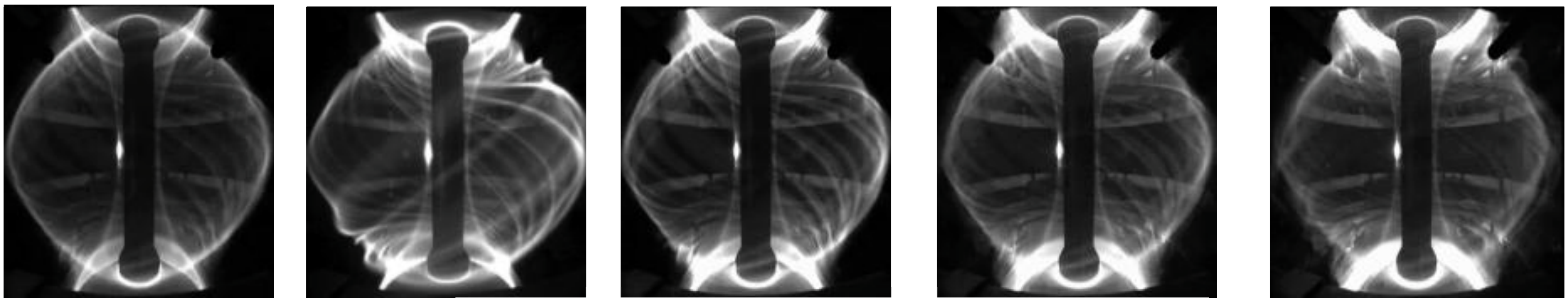
This happens in a **very short time (250 μs)** as the **plasma edge becomes ergodic** (**ELM** filaments carry current)



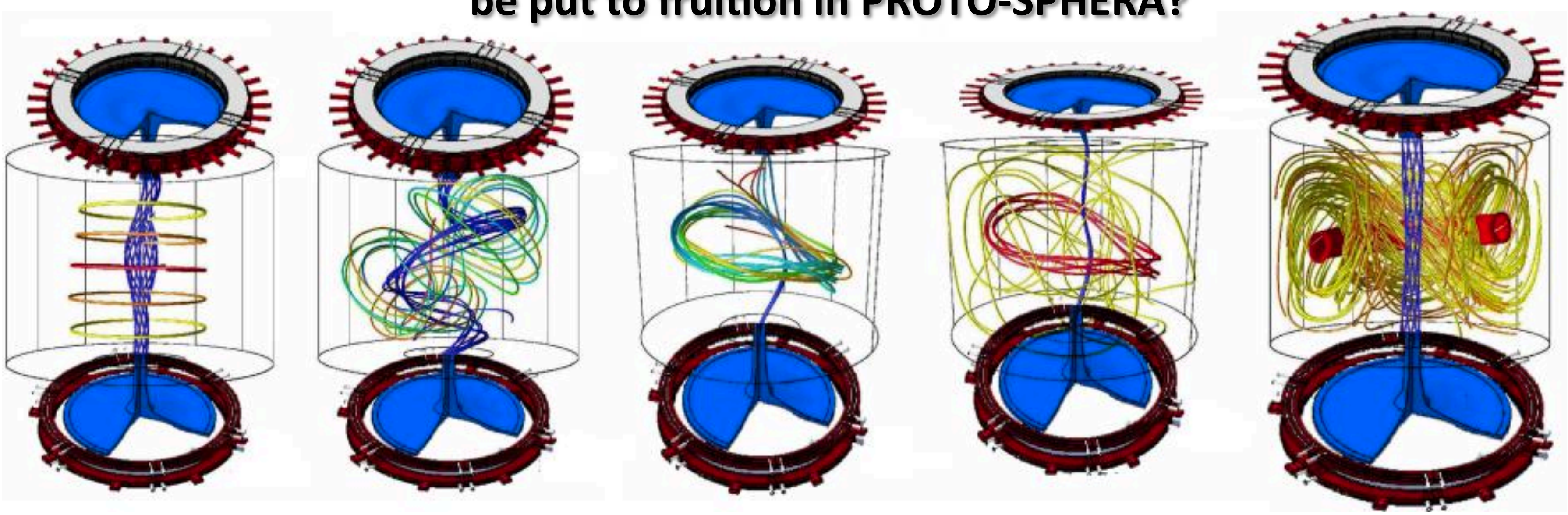
On **ITER** an **ELMs carrying > 3% of pedestal energy** can even **melt or sublimate** the **Tungsten of the Divertor plates**

"ELMs" (unstable edge localized modes):

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



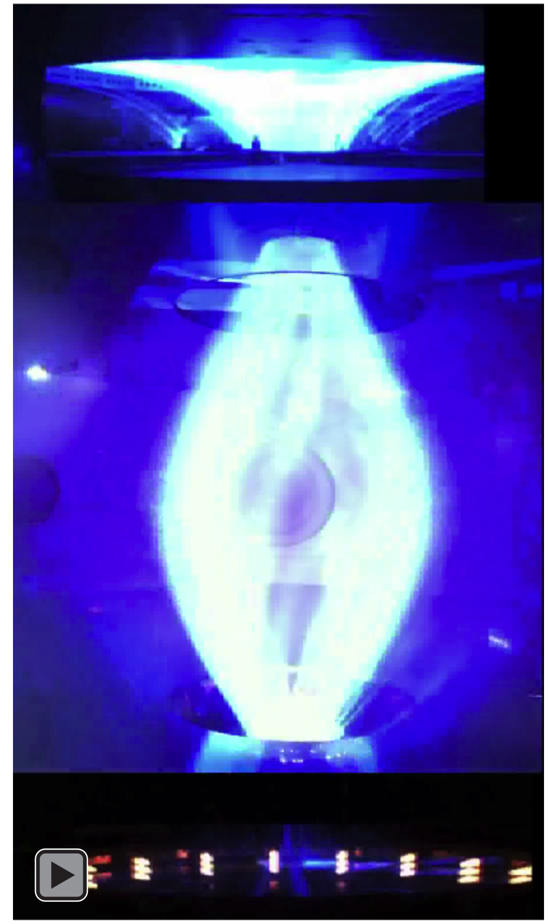
be put to fruition in PROTO-SPHERA?



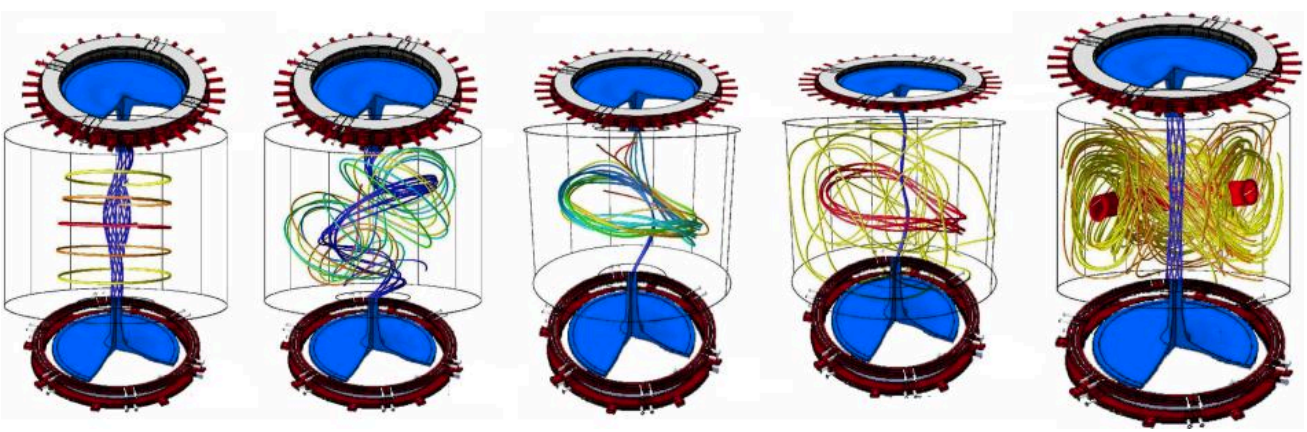
Plasma rotation in Tokamaks extremely advantageous, as it stabilizes the torus

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 inboard (high field side)**



Gas puffed hollow anode

1990': SPHERICAL TOKAMAKS

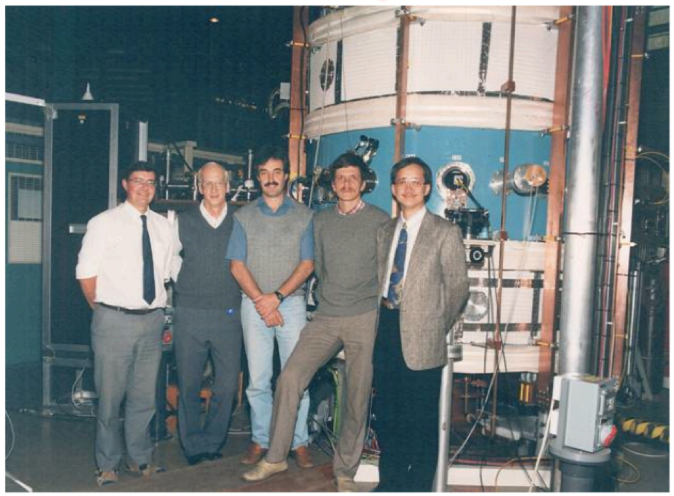
β = plasma beta = $\dfrac{\textit{kinetic plasma pressure}}{\textit{confining magnetic field pressure}}$

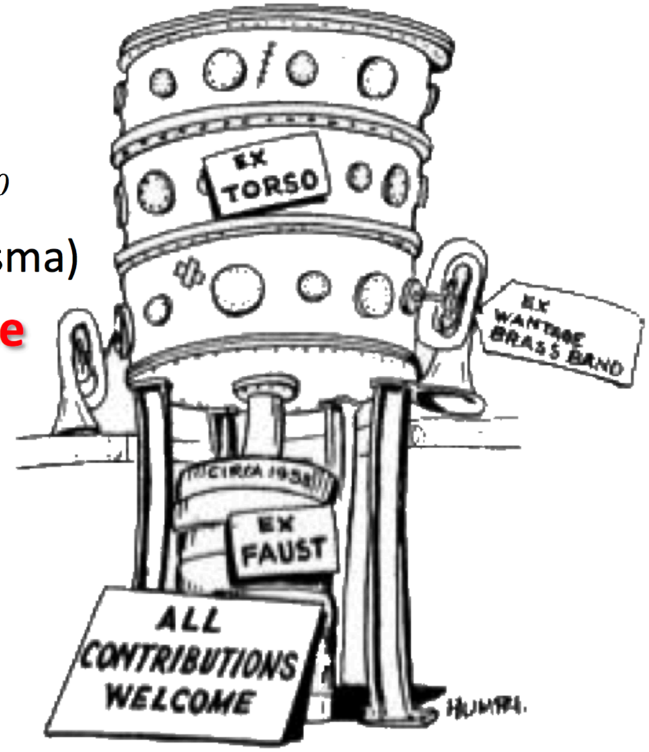
$\beta = 2\mu_0 \int p\, dV \Big/ \int B^2\, dV$, but in tokamak data one often uses β_{T0}

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

to increase its β the Tokamak deserves a spherical shape

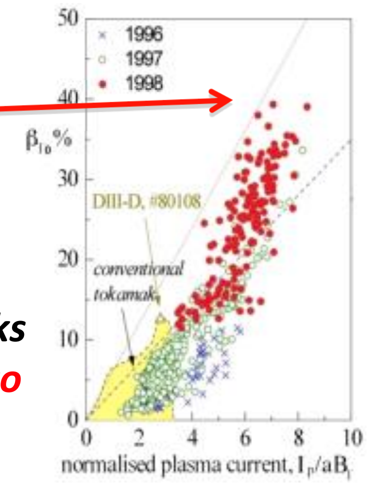
1991: Culham (UK) built the START Spherical Tokamak

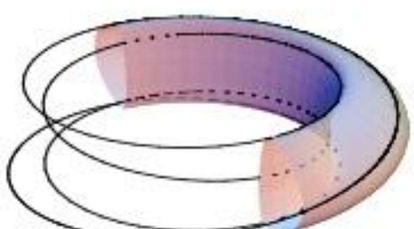




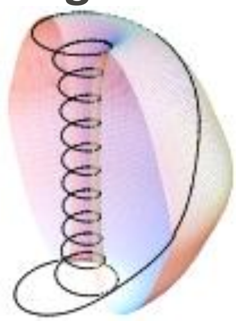
...revamping an *old vacuum vessel*

endowed with **NBI heating START** reached β_{T0} ~ **40%** **(3 x DIII-D)**





Conventional Tokamak



Spherical Tokamak

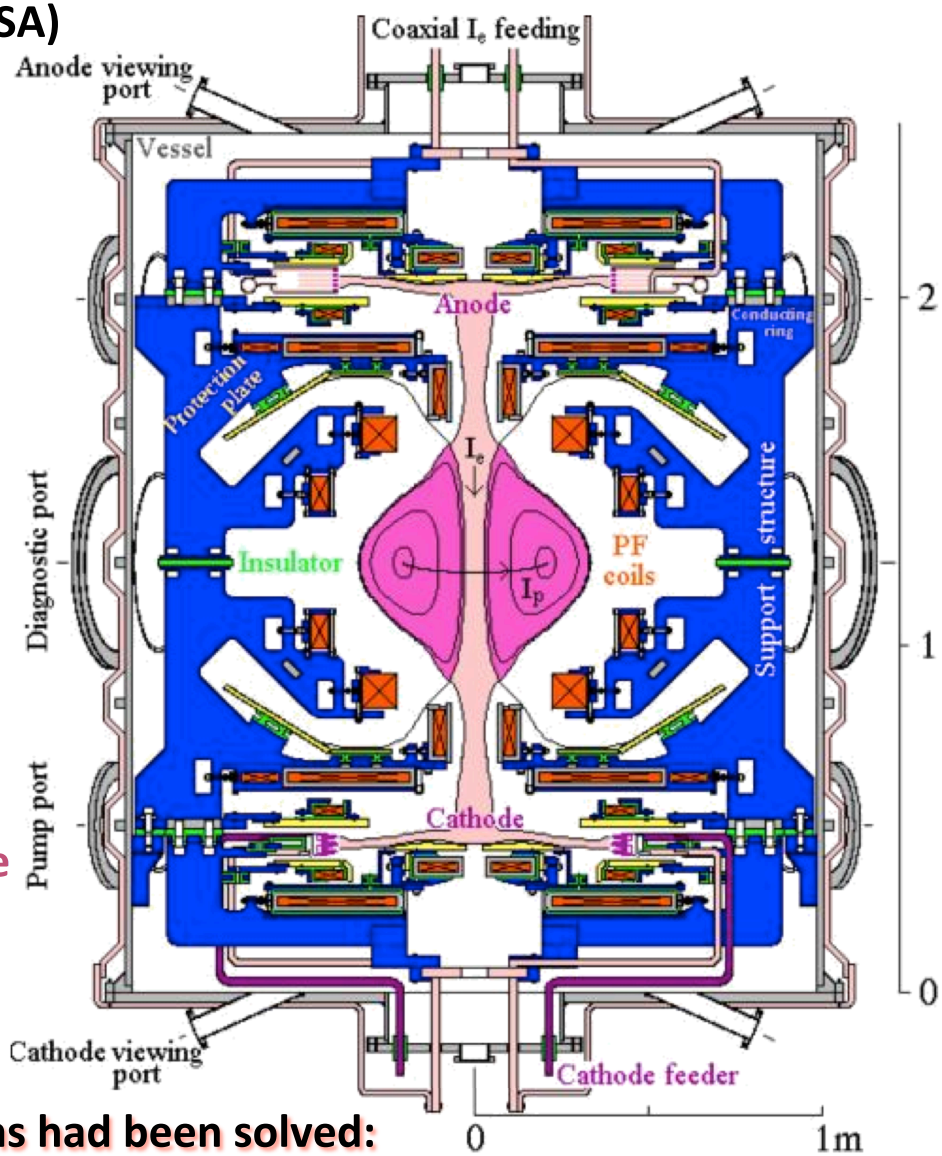
Favourable properties of Spherical Tokamaks are due to lines of force that are very near to the geodesic lines of the magnetic surfaces

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

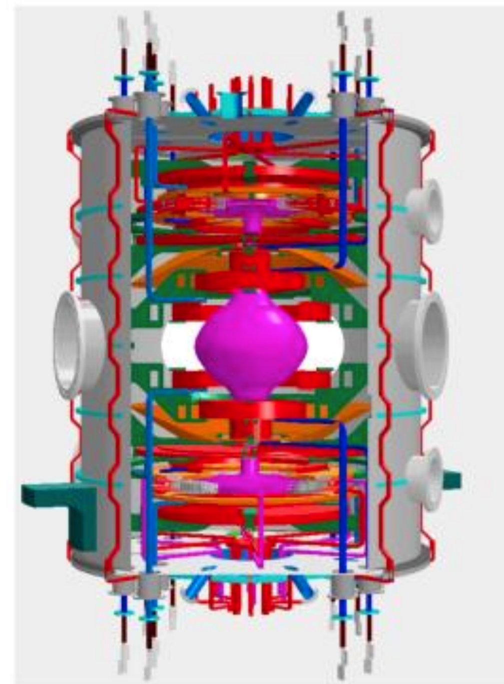
Quasi-separate chamber for anode

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

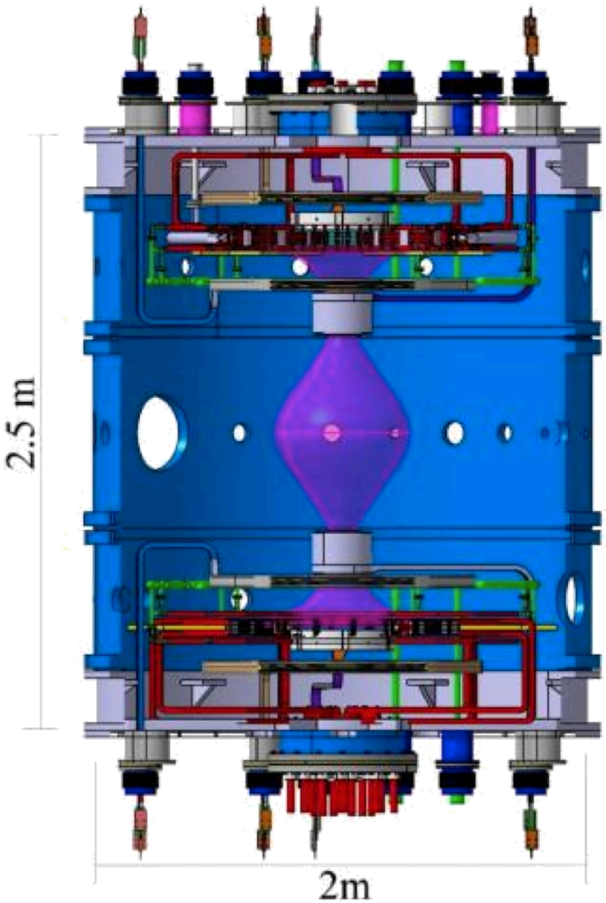
Two main problems had been solved:

- **restrictions imposed by Ideal MHD stabilities**
- **building durable electrodes**

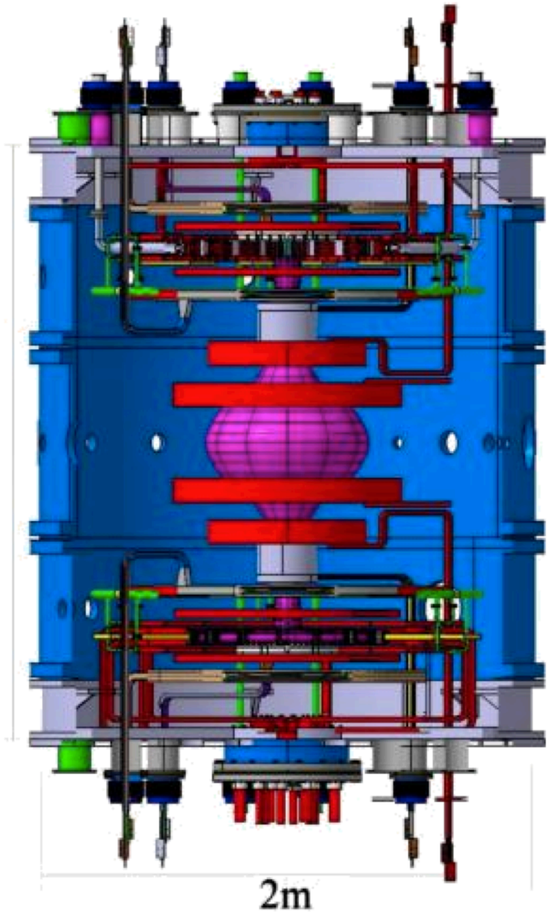
In **2002** at Frascati an **International Workshop** advised to build the machine in 2 steps:

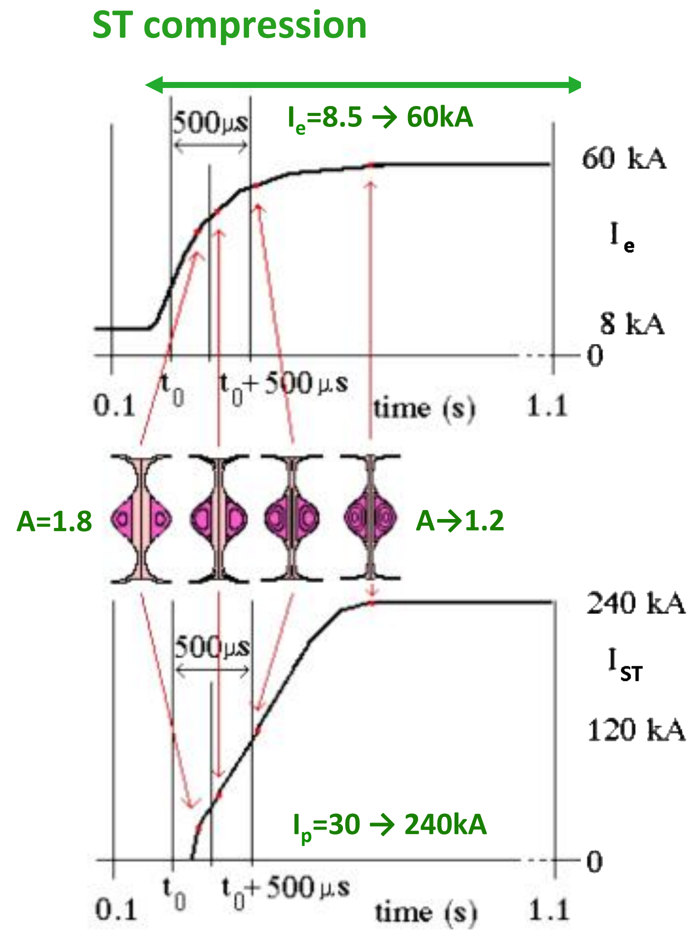
- **Phase 1:** demonstrate Plasma Centerpost's feasibility
- **Phase 2:** machine completed such as to produce the Spherical Torus

Phase1: 8 PFcoils
Centerpost shape



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



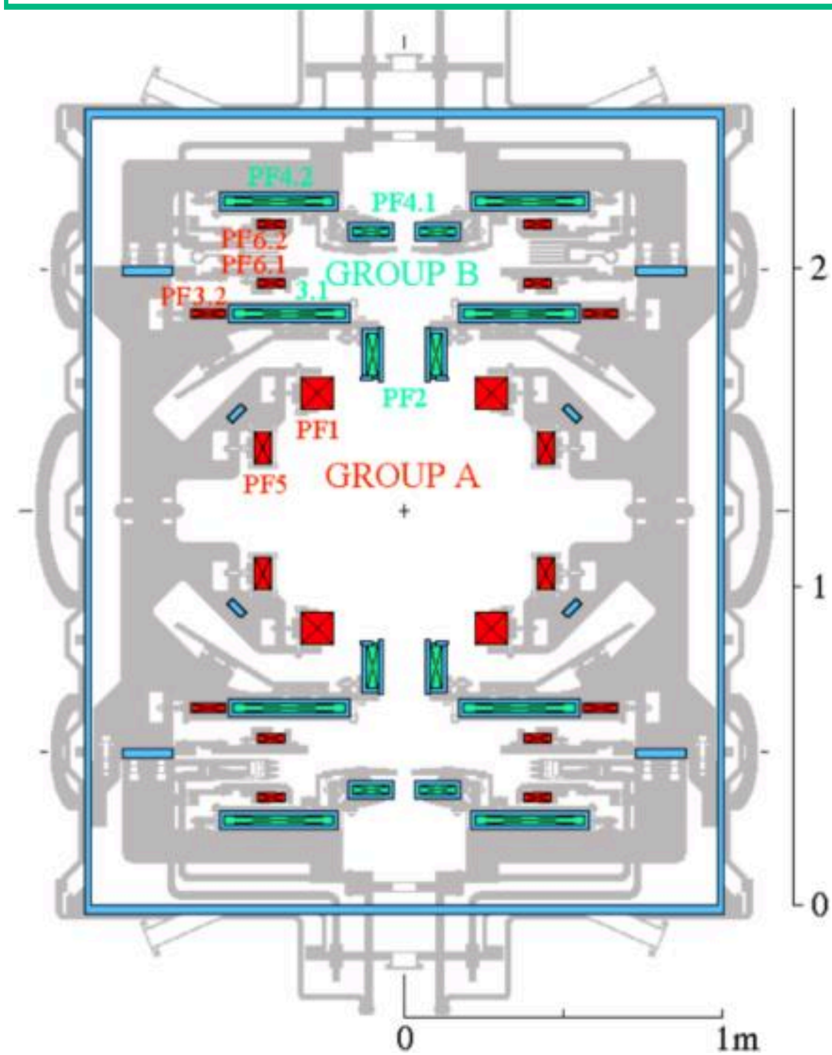


Centerpost current I_e= 10 kA
No ST toroidal current

Centerpost current I_e= 60 kA
ST toroidal current I_{ST}= 120÷240 kA

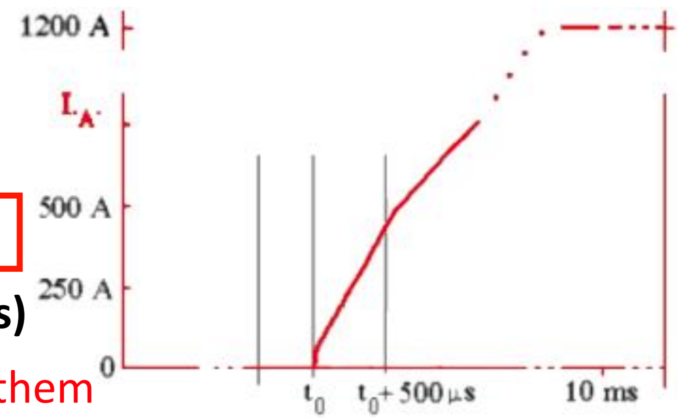
The PF coils have been designed as two sets, each connected in series

Group B (4+4 coils): Centerpost shaping PF coils …**thick AISI casings (τ ~ 2ms),** *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



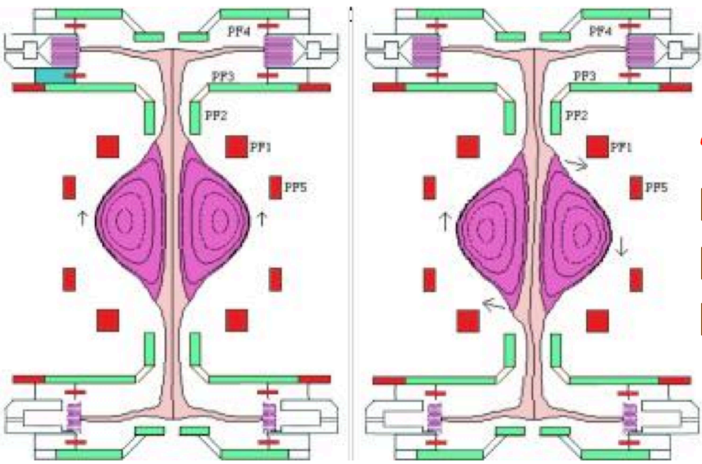
Group A (5+5 coils): ST compression PF coils …*not yet built*

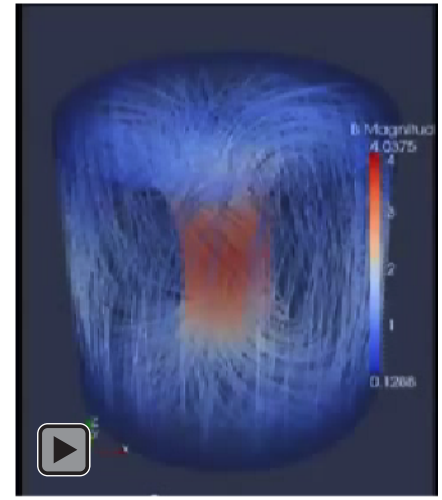
high voltage (~ **20 kV**) insulation: **fast current increase (0.5 ms)**

thin Inconel casings allow for **B diffusion in τ ~ 200** µs across them

IDEAL MHD STABILITY of PROTO-SPHERA

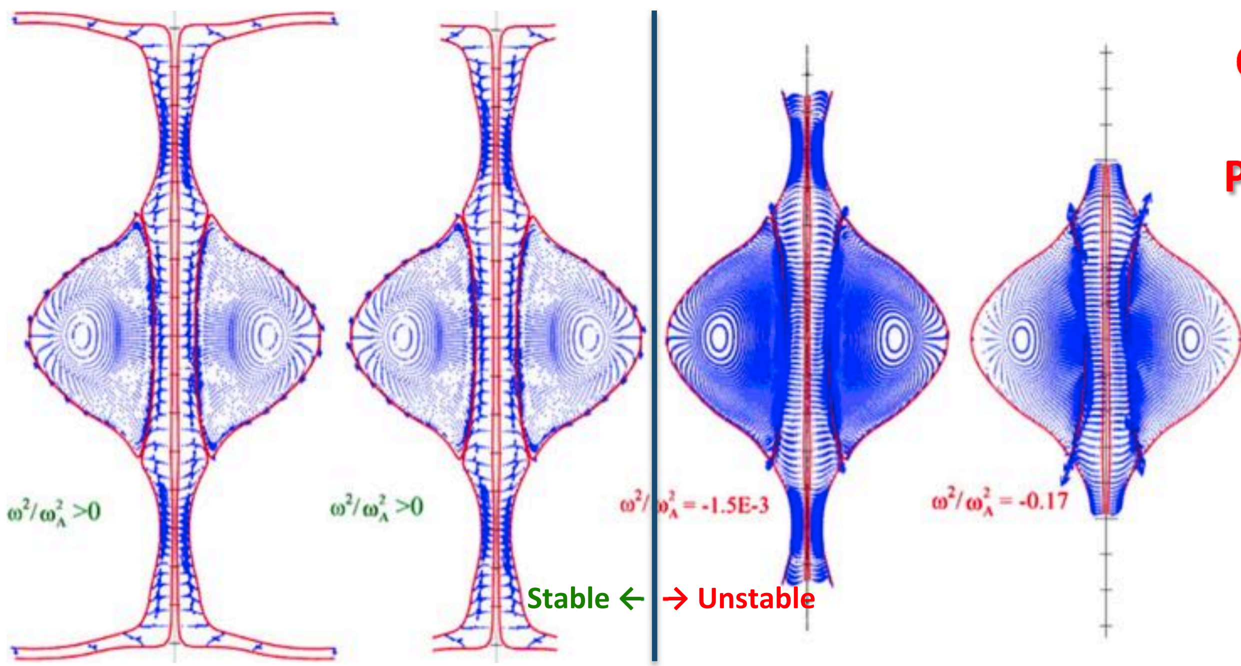
Spheromak tilt instability is due to
dipole of containing field opposite to **toroidal plasma current dipole**





"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**

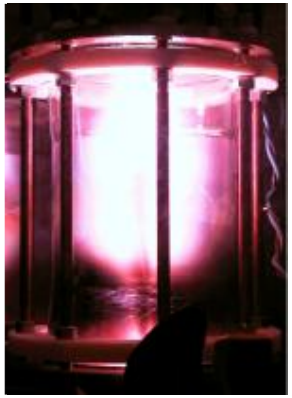
DISK-SHAPED CENTERPOST PLASMA: IMPORTANT FOR THE IDEAL MHD STABILITY

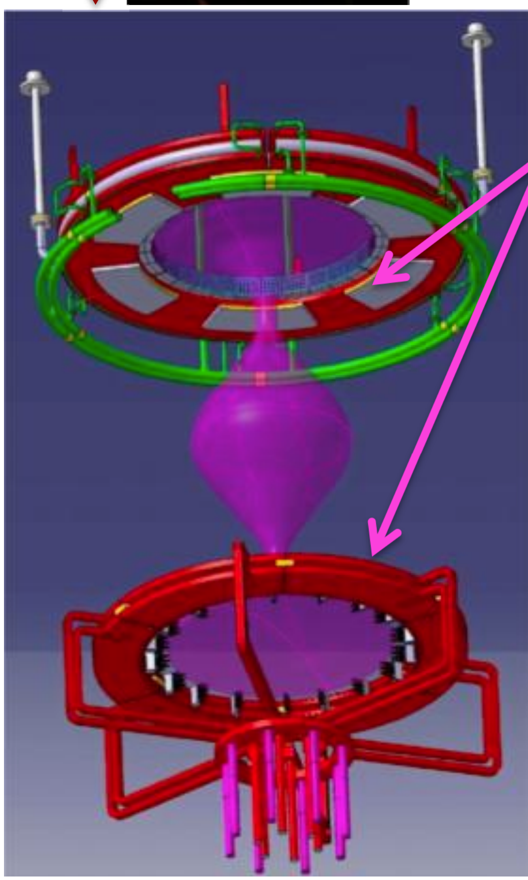


**Cutting shorter & shorter
the plasma centerpost
PROTO-SPHERA at 120 kA
gets destabilized**

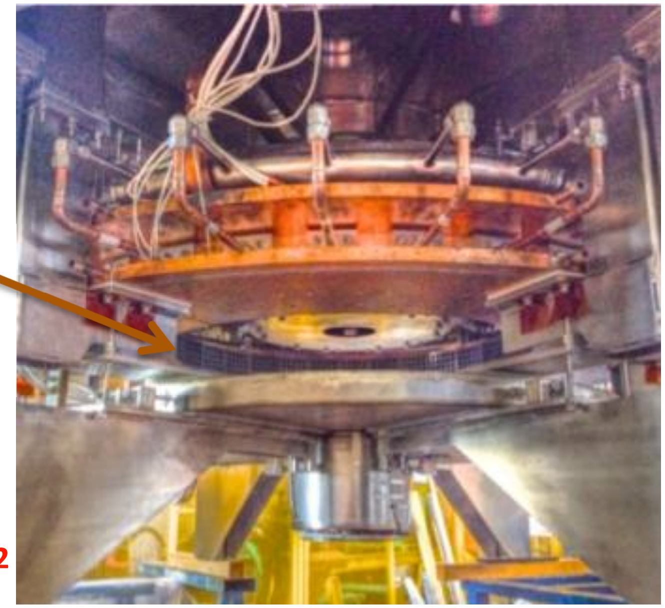
PROTO-PINCH testbench (1998-2000) developed the electrodes for PROTO-SPHERA
at a current and power density that is relevant for a **Biased Divertor of a Reactor-Grade Plasma**

50 cm





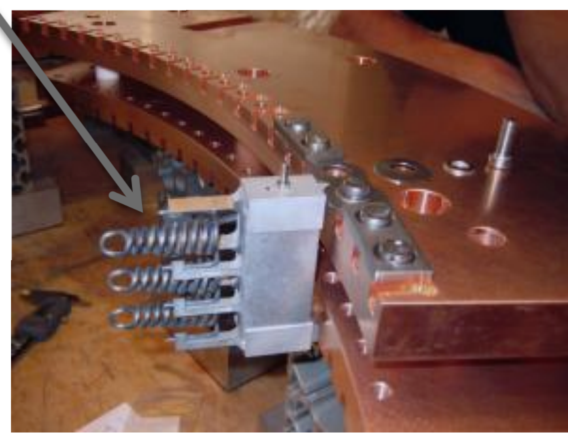
- **@ low (100-200 V) voltage on electrodes**
- **@ Tokamak-like density**



Modular annular electrodes:
Gas puffed hollow anode

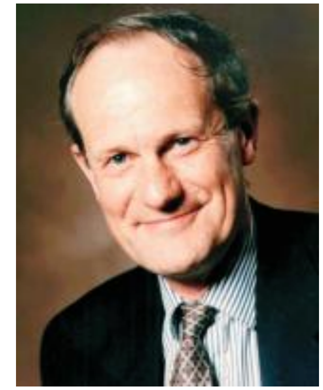
Plasma centerpost at electrode interfaces mushroom-shaped

Plasma current density j_e= 1MA/m^2
Power density P_e= 20÷30 MW/m^2
W directly heated filament cathode

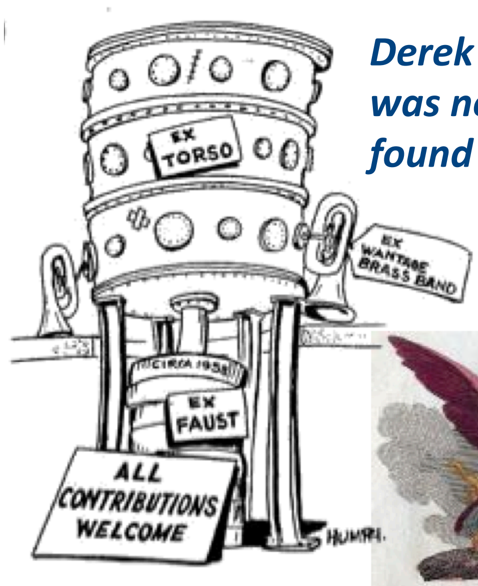


PROTO-PINCH

Derek Robinson
1941-2002

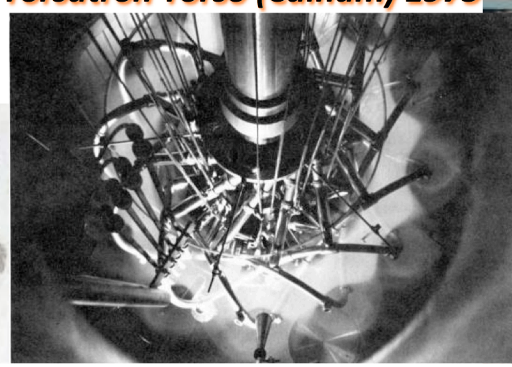


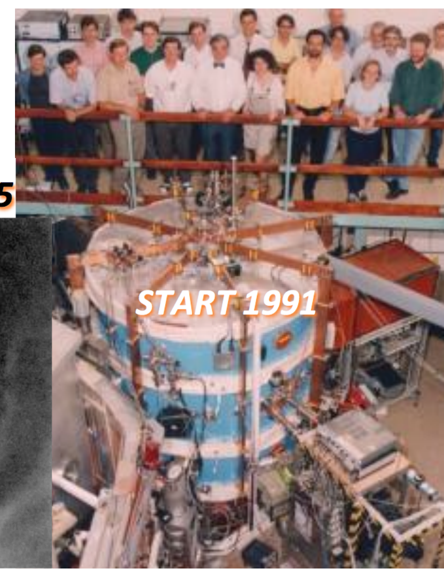
Derek Robinson *(director of Culham from 1991)*
was very interested in the "Champagne bottle" experiment:
in 1999 he proposed to build at Culham PROTO-SPHERA,
inside the START vessel



Derek Robinson's proposal unfortunately was not accepted… but the "Old Vessel" found anyway its road …to Rome!

Torsatron Torso (Culham) 1975



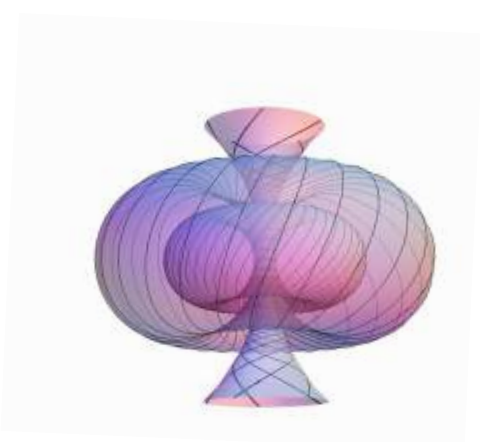


START 1991

PROTO-SPHERA 2010

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

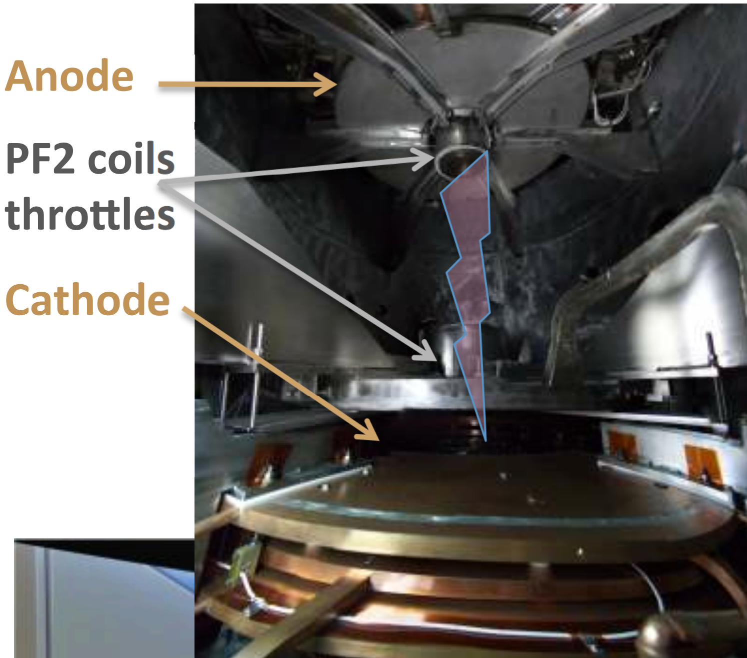
PROTO-SPHERA was built (2006-2009) by ASG Superconductors of Genoa, cost 1 M€



Years 2004 - 2010:

…from ideas → *…to detailed design* → *…to hard metal*

PROTO-SPHERA POWER SUPPLY



To fire the **plasma centerpost**
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: →

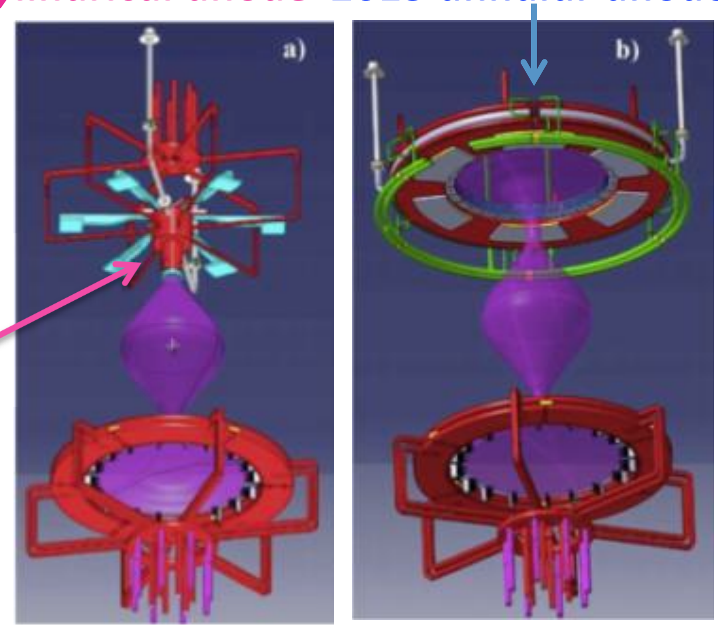
Cylindrical anode

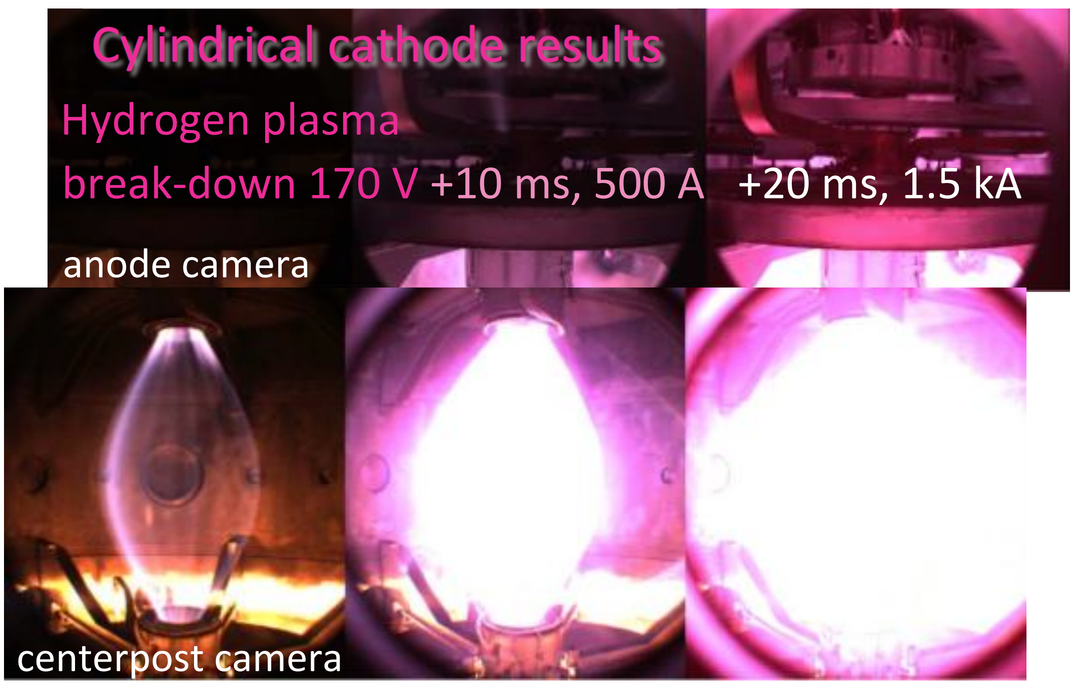
Being afraid of **Anode Arc Attachment,** *often observed in arc discharges (arc welding, plasma torches)*

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!

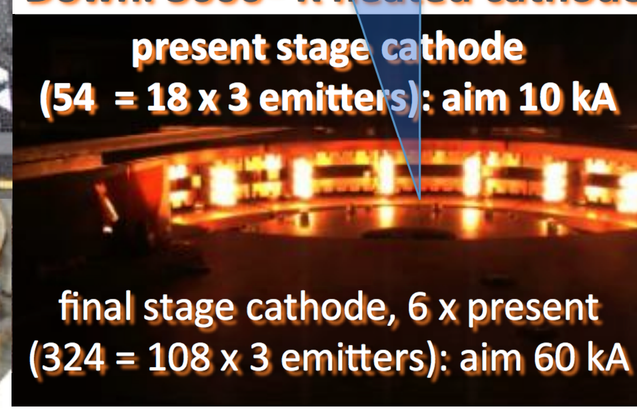
2014 cylindrical anode *2015 annular anode*





April 2015 Annular Anode installed

Down: 3000º K heated cathode



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

Stainless steel up\down new extensions

PF4up

PF3up

PF2up

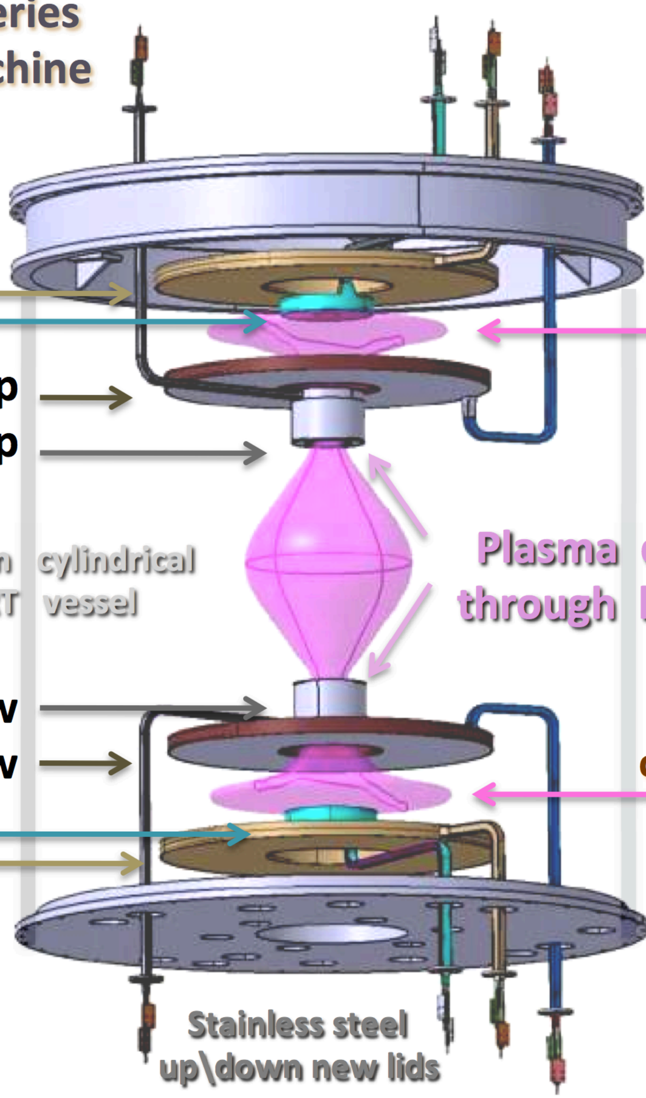
Aluminium cylindrical START vessel

PF2low

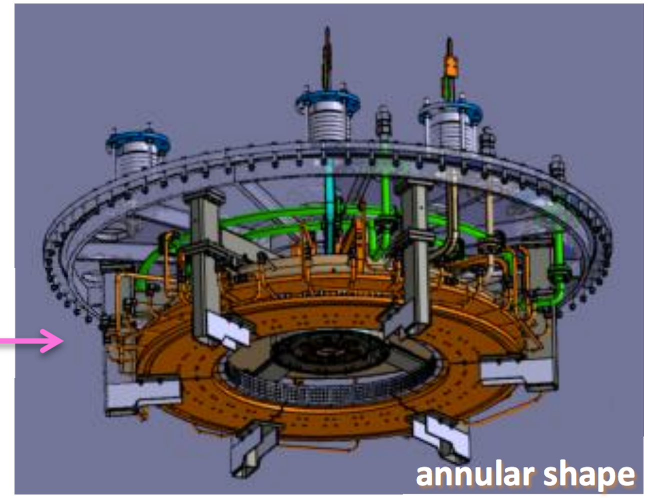
PF3low

PF4low

Stainless steel up\down new lids

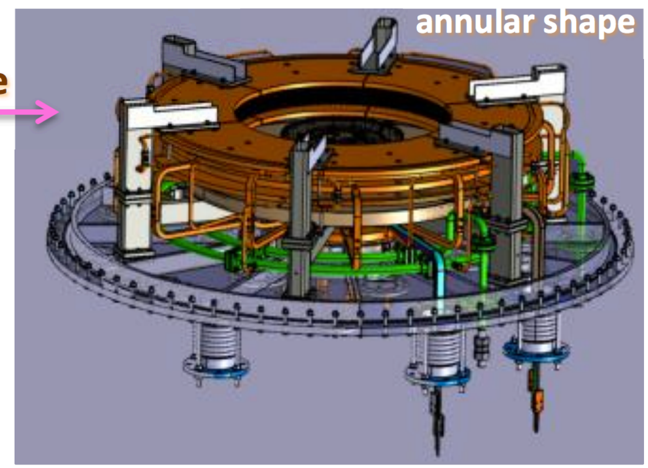


anode



Plasma current must run through both PF2 throttles

cathode

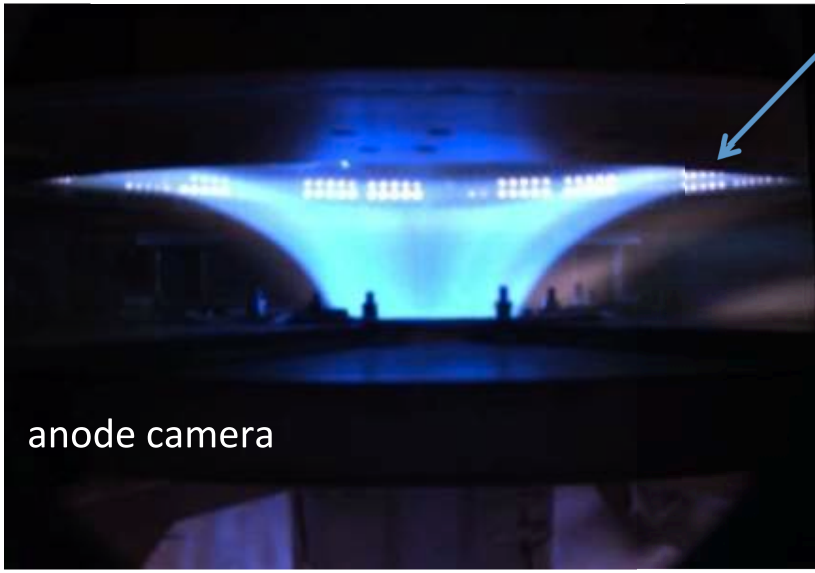


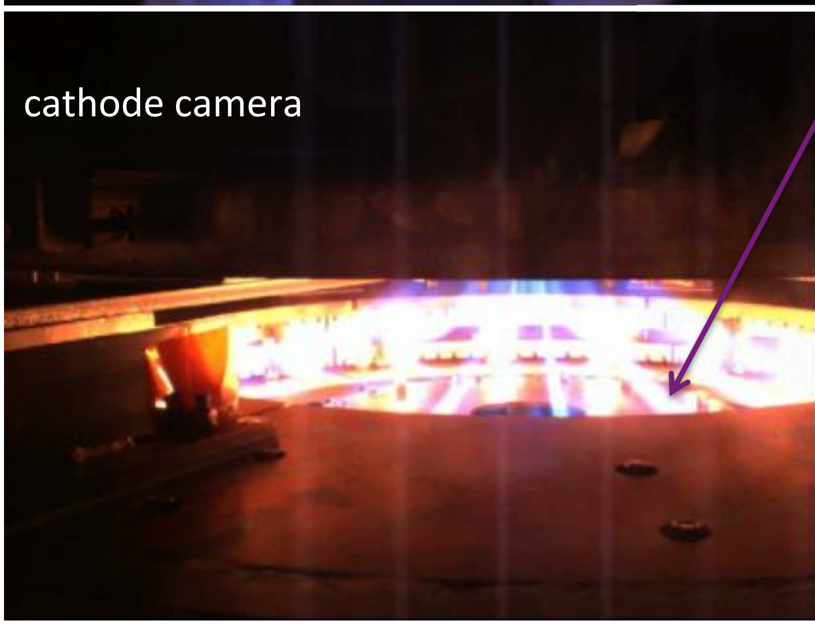
vacuum vessel is GND potential

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

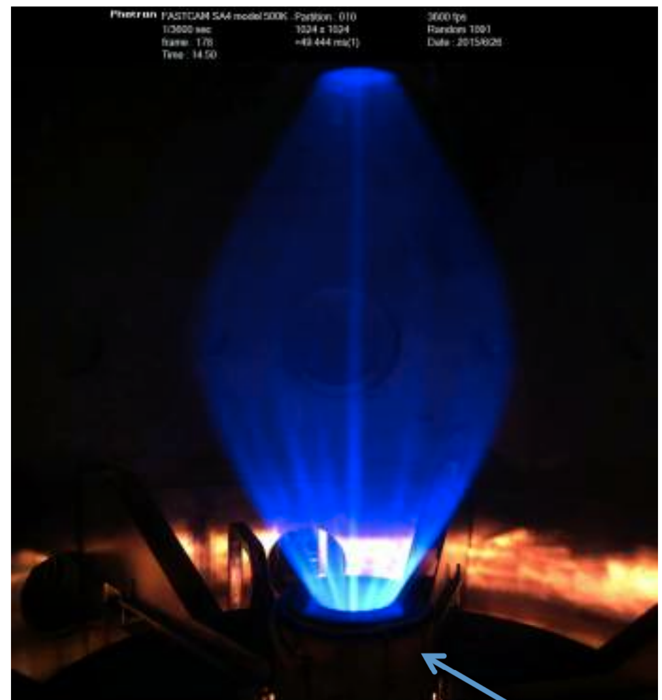




Hollow annular anode performs

- 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)



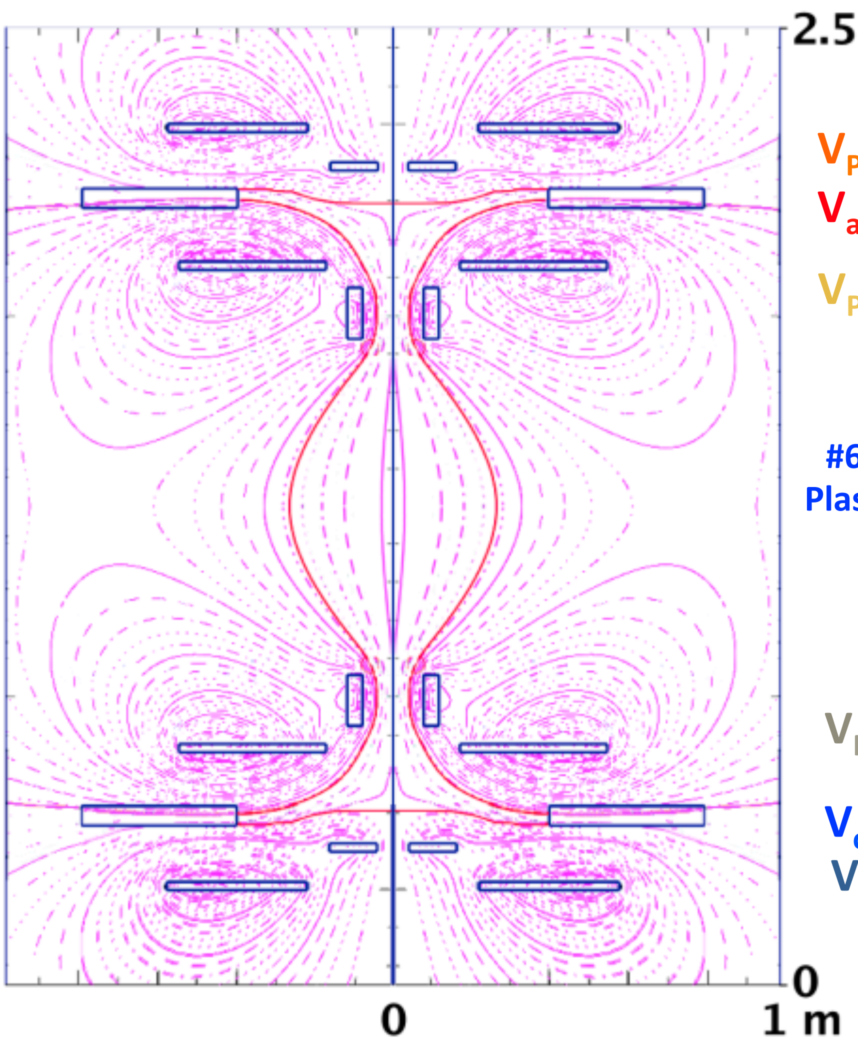
even plasma centerpost is in part filamented
(...cathode switched off before the plasma...)

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



$V_{PF4up} \sim +78$ V

$V_{anode} \sim +121$ V

$V_{PF2\text{-}3up} \sim +49$ V

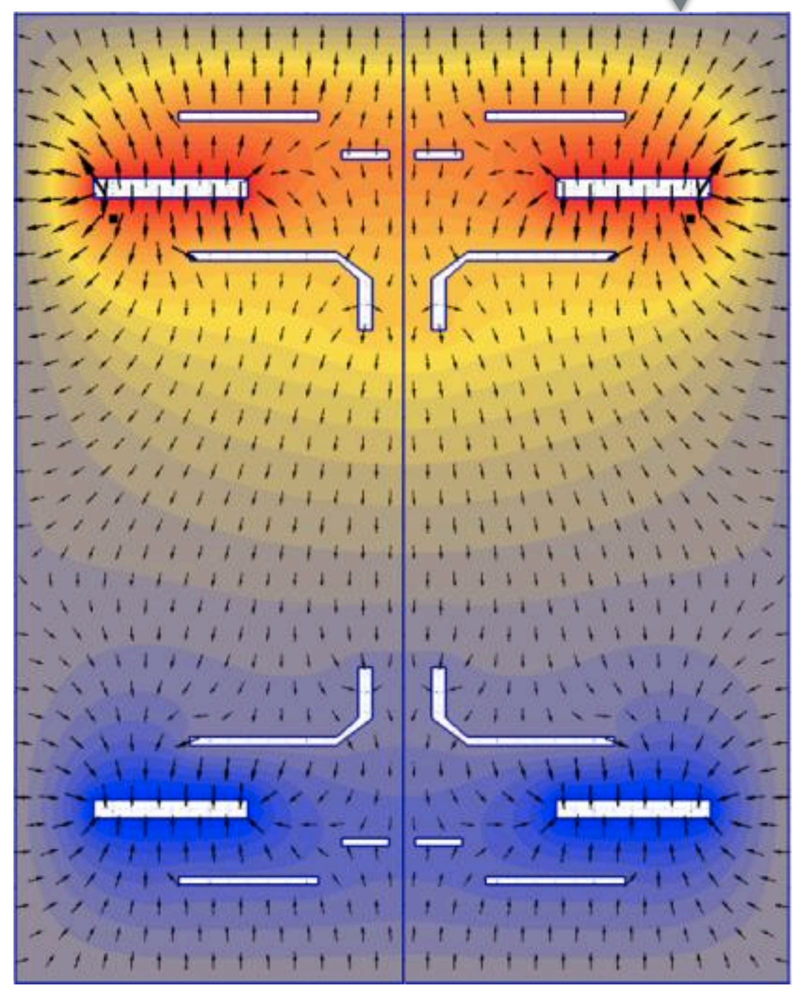
#649 6kA Argon
Plasma centerpost
(June 2017)

$V_{PF2\text{-}3low} \sim -8$ V

$V_{cathode} \sim -51$ V

$V_{PF4low} \sim -20$ V

vacuum vessel at GND 0V



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

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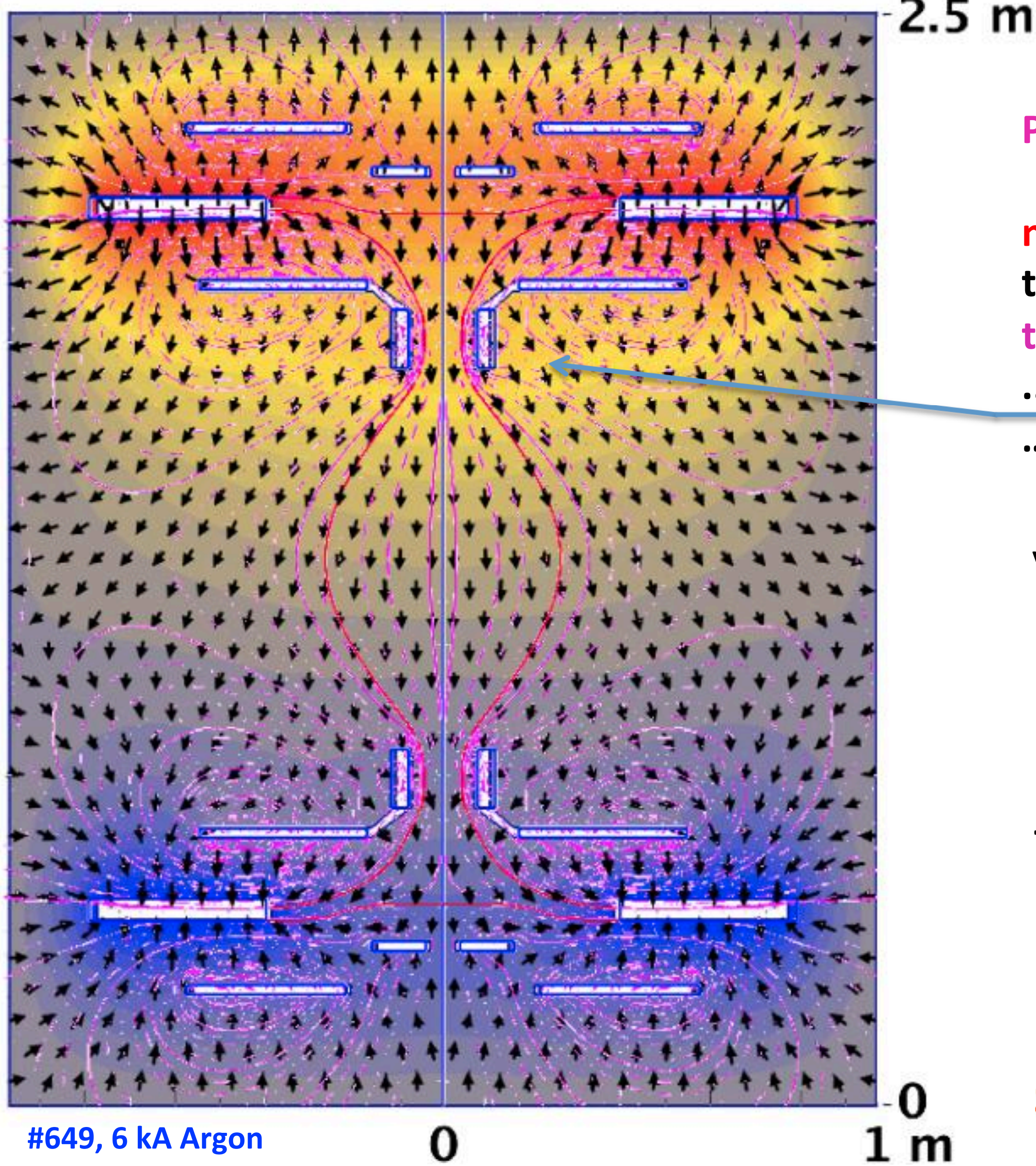


Lines: magnetic field

Plasma-induced electric potential:

near the annular anode
the E field is in part perpendicular
to the B field
... $\vec{E} \wedge \vec{B}$ azimuthal plasma rotation
... starting from PF2up throttle

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

May 2015 Hydrogen & Argon plasma centerpost

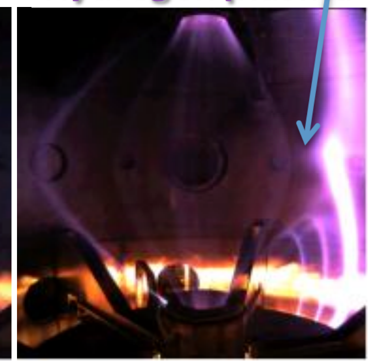
half of the plasma current: (1 kA\2 kA)
was going around the required path due the

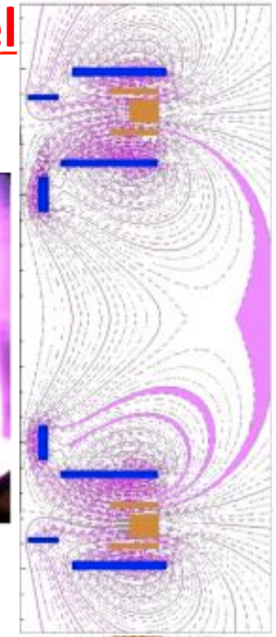
Equatorial X-point inside the vessel

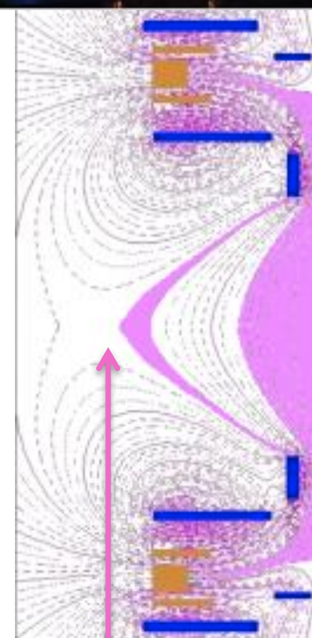
Shot 78

Argon plasma

Hydrogen plasma



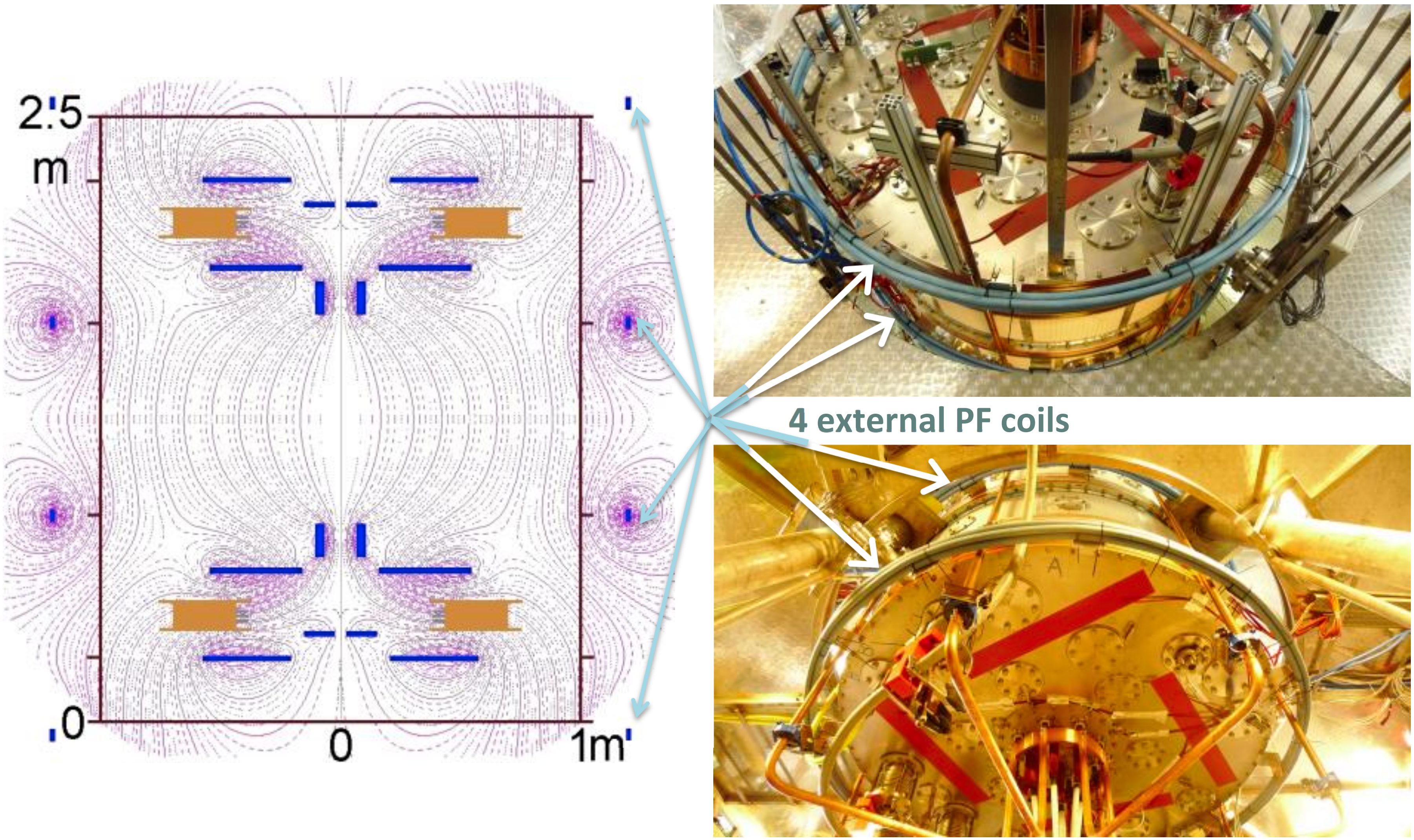




discharges along field lines near X-point

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)

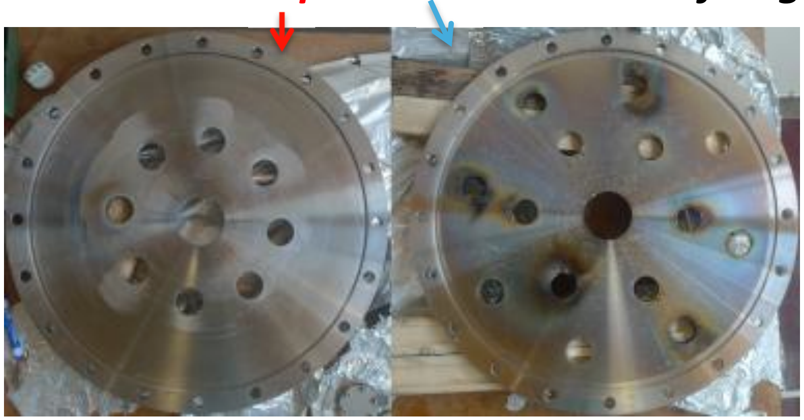


Plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids
Within 2017 a new Super-capacitor based Power Supply for External coils should be online!

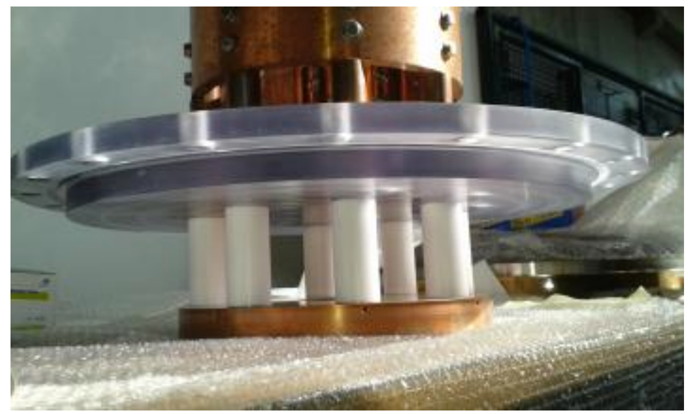
2015/16 experiments produced a heavy metallization on top (anode) & bottom (cathode) bus-bar vacuum entrance flanges, associated with magnetic "nozzles"

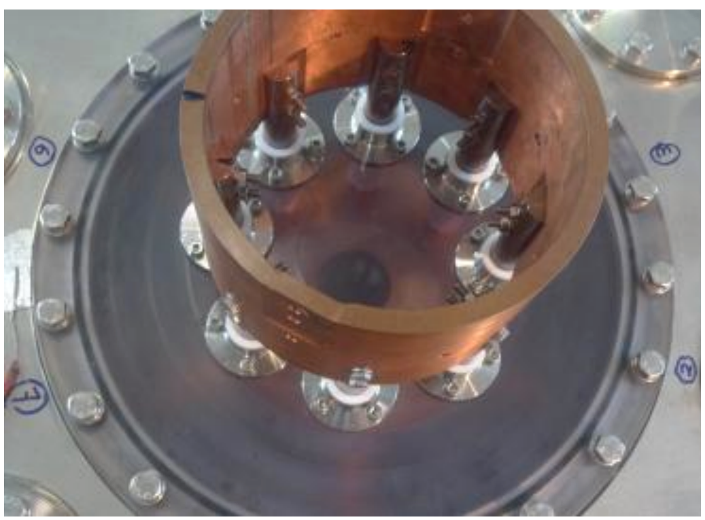
June 2016: insertion of Polycarbonate (transparent) anode bus-bar flange on top of machine

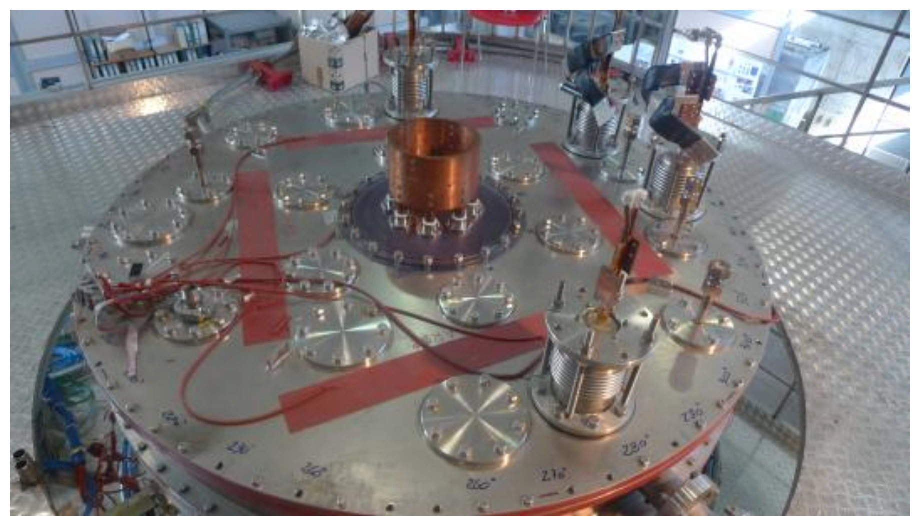
Heavily metallized top & bottom bus-bar flanges



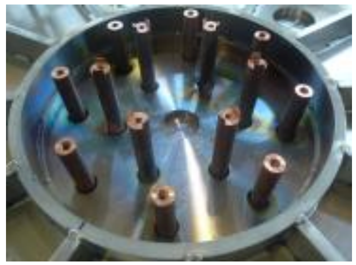
4 cm thick Polycarbonate (required by atmospheric pressure)







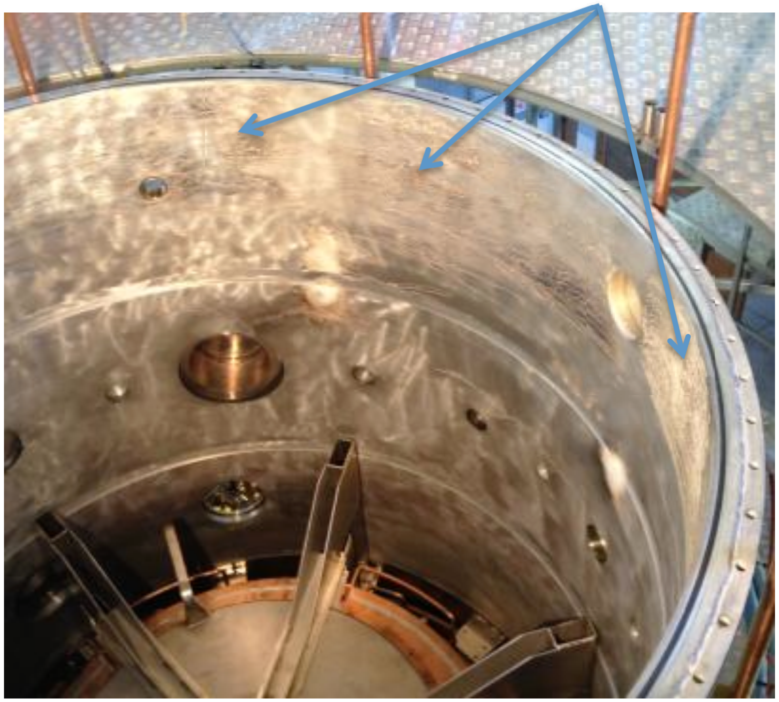
At the bottom (near cathode) a SS flange, pierced by 14 bus-bars, such a flange has been substituted by a Polycarbonate one



July 2016: Polycarbonate flange on machine bottom

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

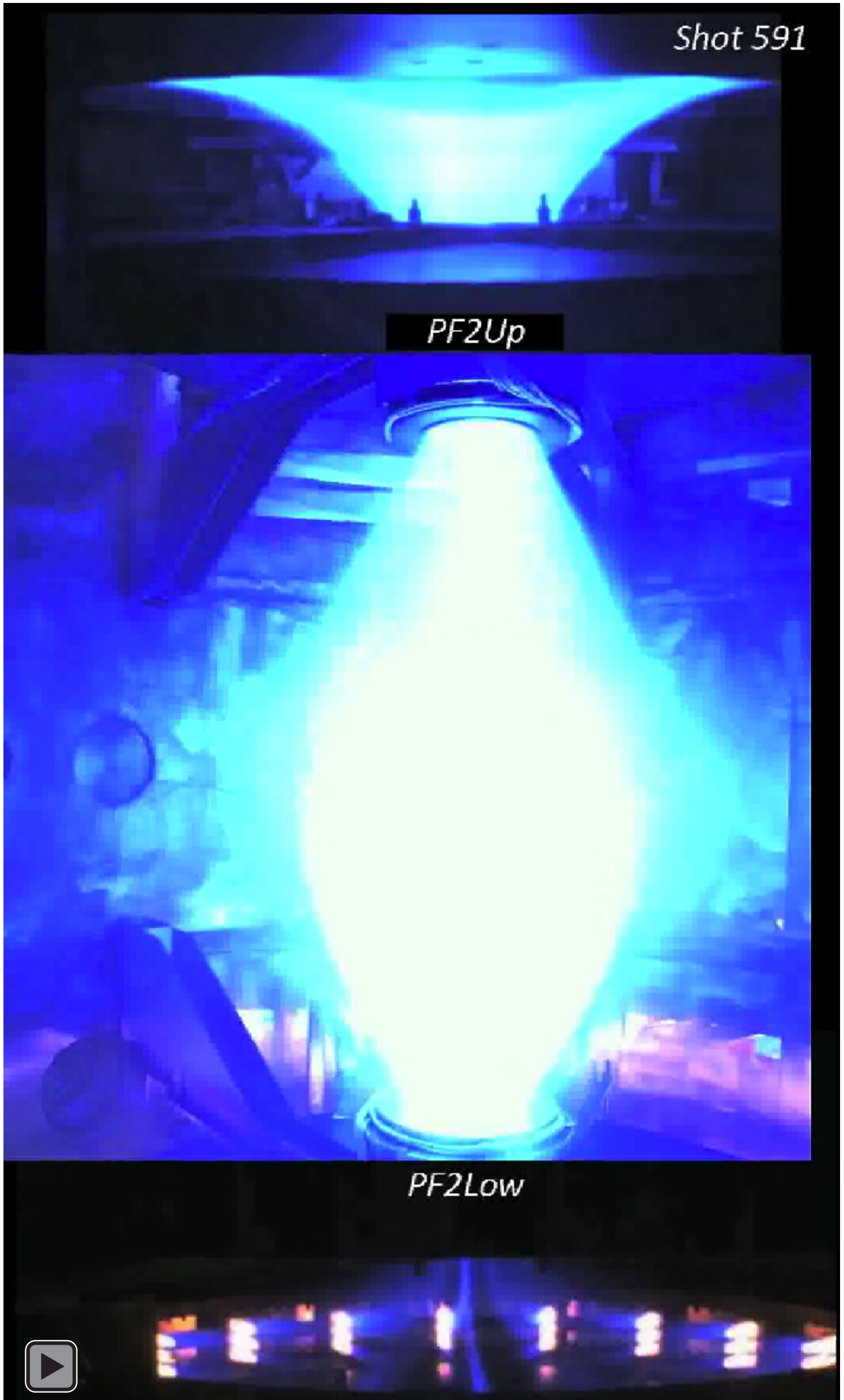
I_e= 2.7 kA



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

December 2016

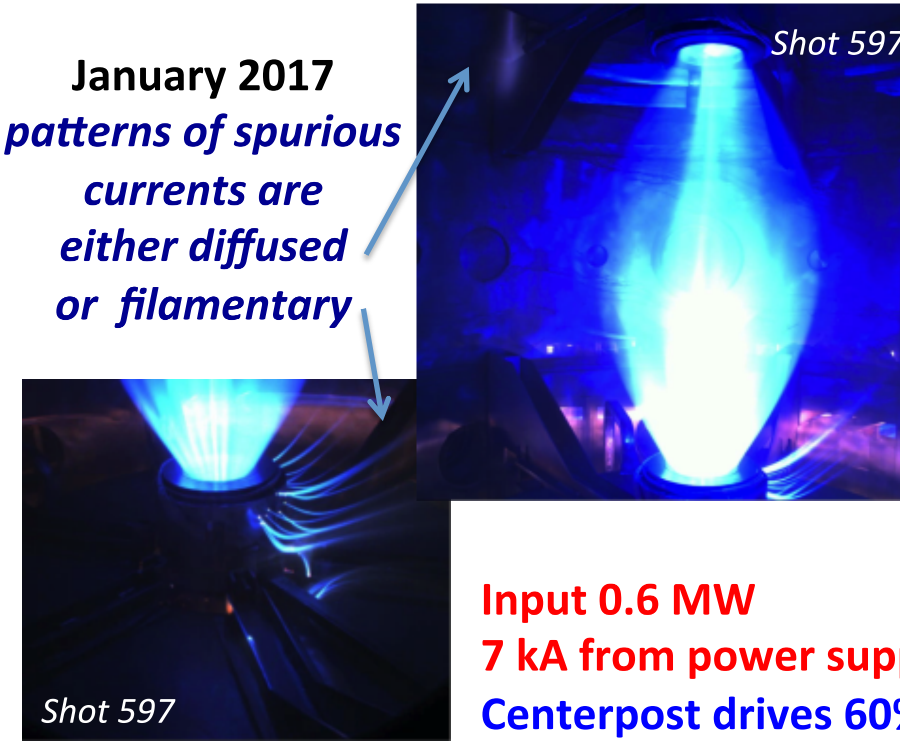
secondary 2mm thick Polycarbonate screen surrounds rear of anode



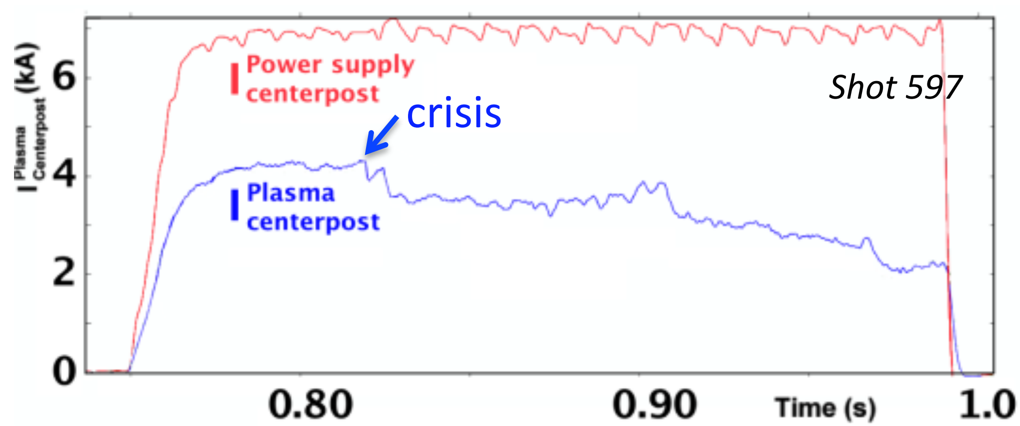
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but Spurious plasma currents still flow outside the centerpost (albeit inside the vacuum vessel)

January 2017

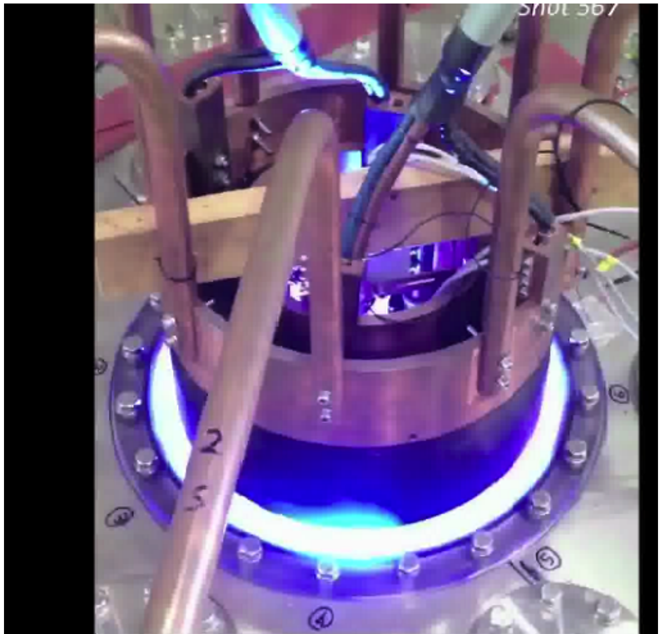
patterns of spurious currents are either diffused or filamentary



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

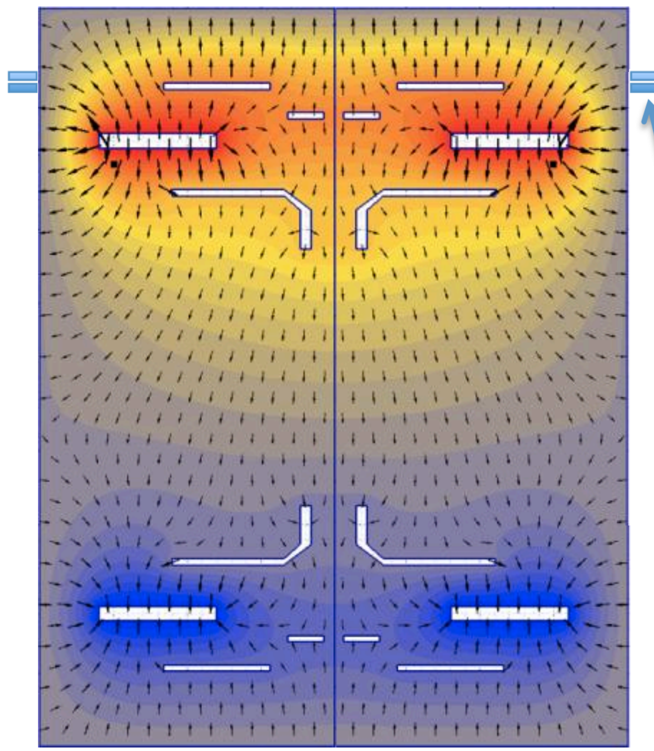


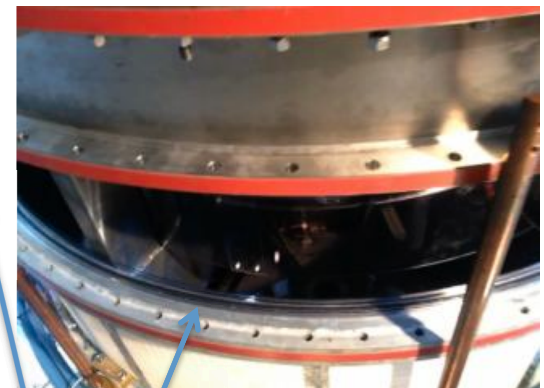
January 2017



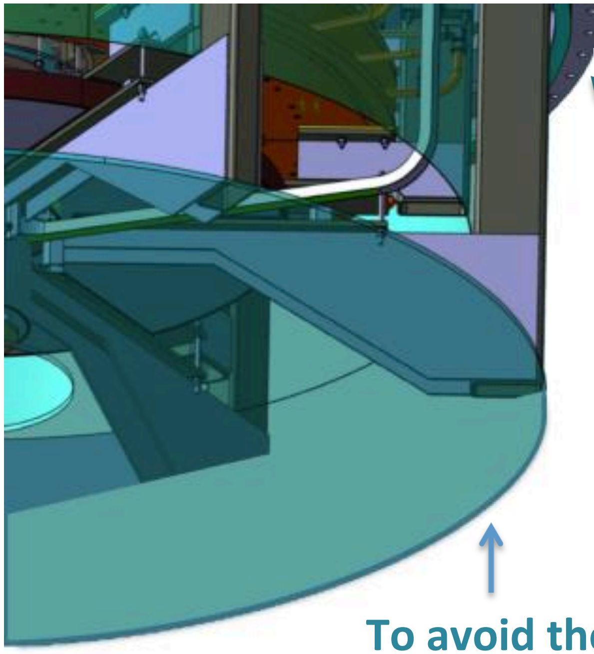
Secondary discharges hitting vacuum vessel wall have been cured by Polycarbonate lining, but
In Hydrogen (250 V breakdown) there was still a problem of current through the vessel,
this was triggered in Argon (80 V breakdown),
connecting the common star potential of the six-phased cathode power supply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

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



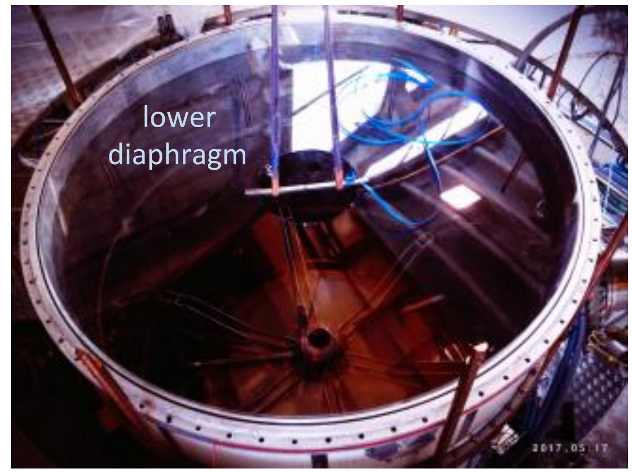


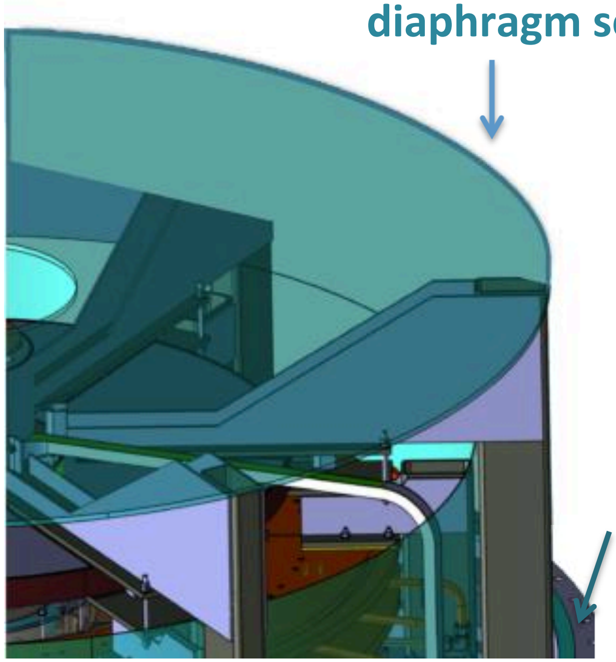
A spacing insulating ring was inserted in **May 2017**



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

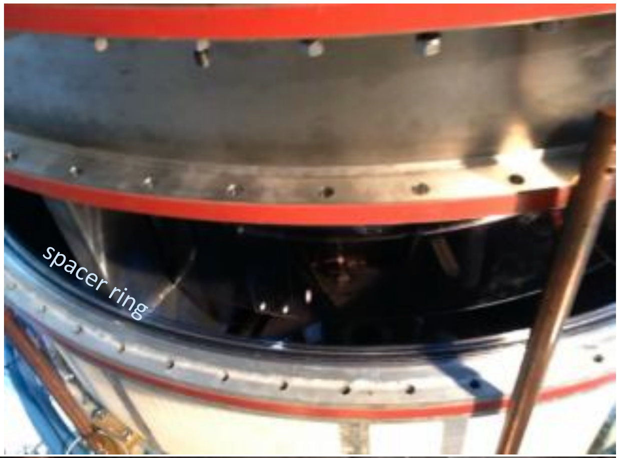


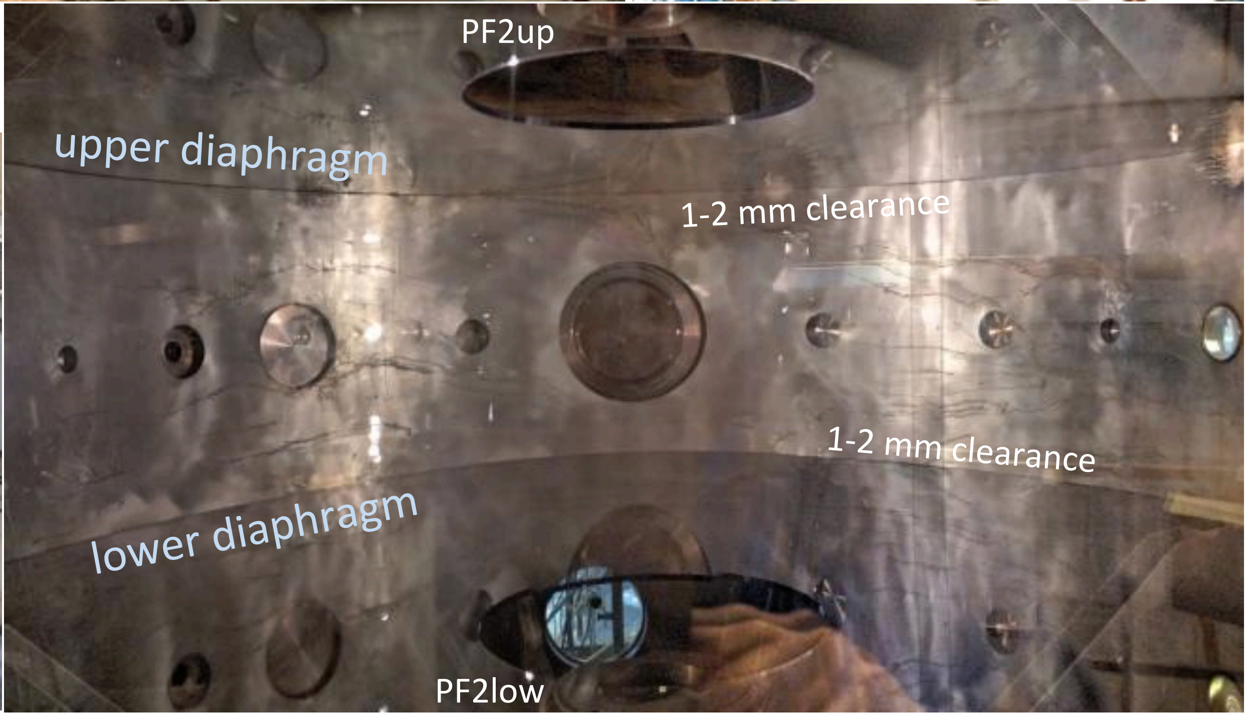


May 2017: Insertion of
Polycarbonate lower diaphragm

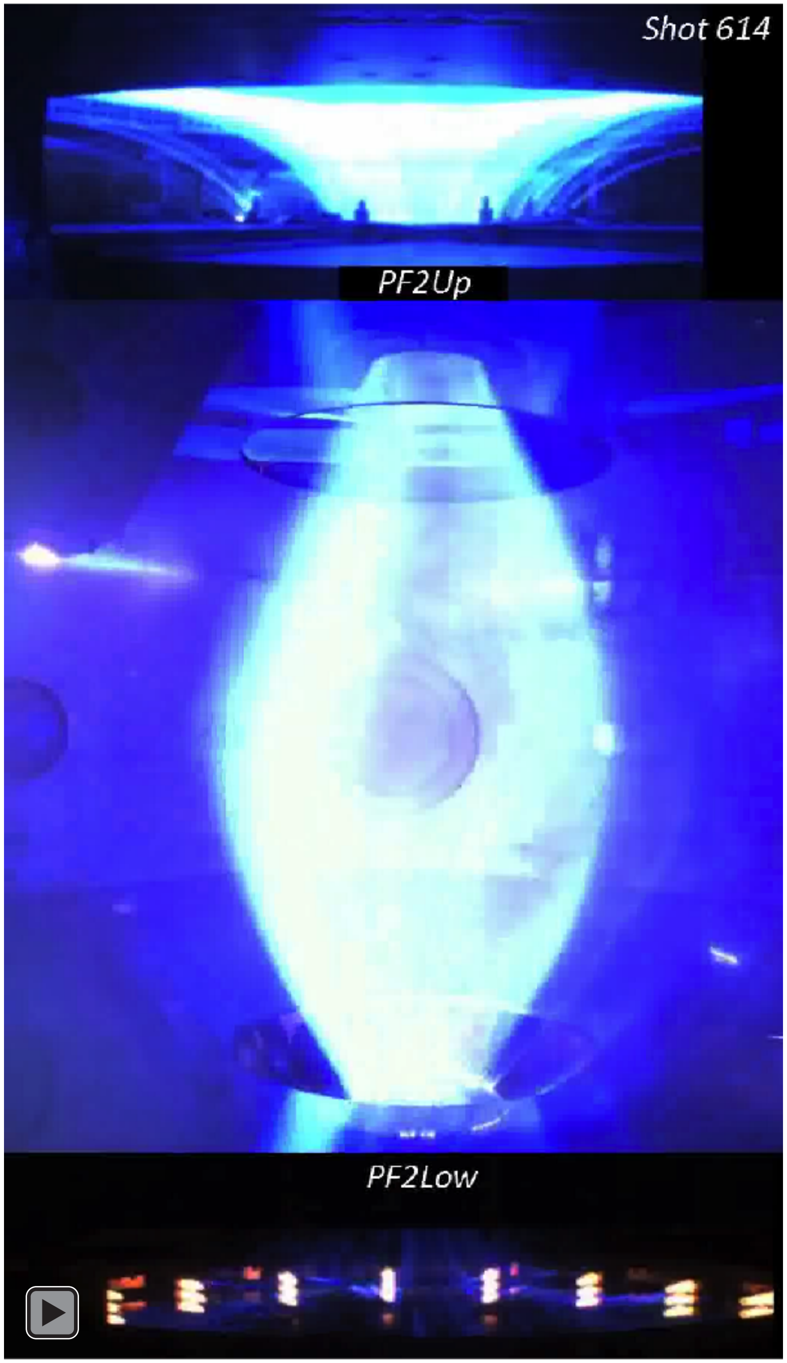
Lower spacer ring not yet inserted

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



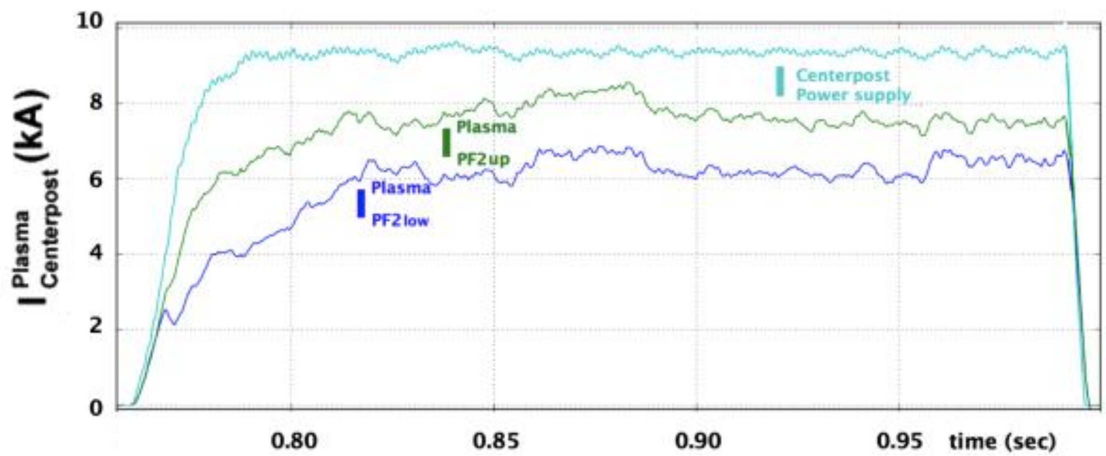


June 2017: Plasma with Polycarbonate two diaphragms & upper Polycarbonate spacer ring



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)

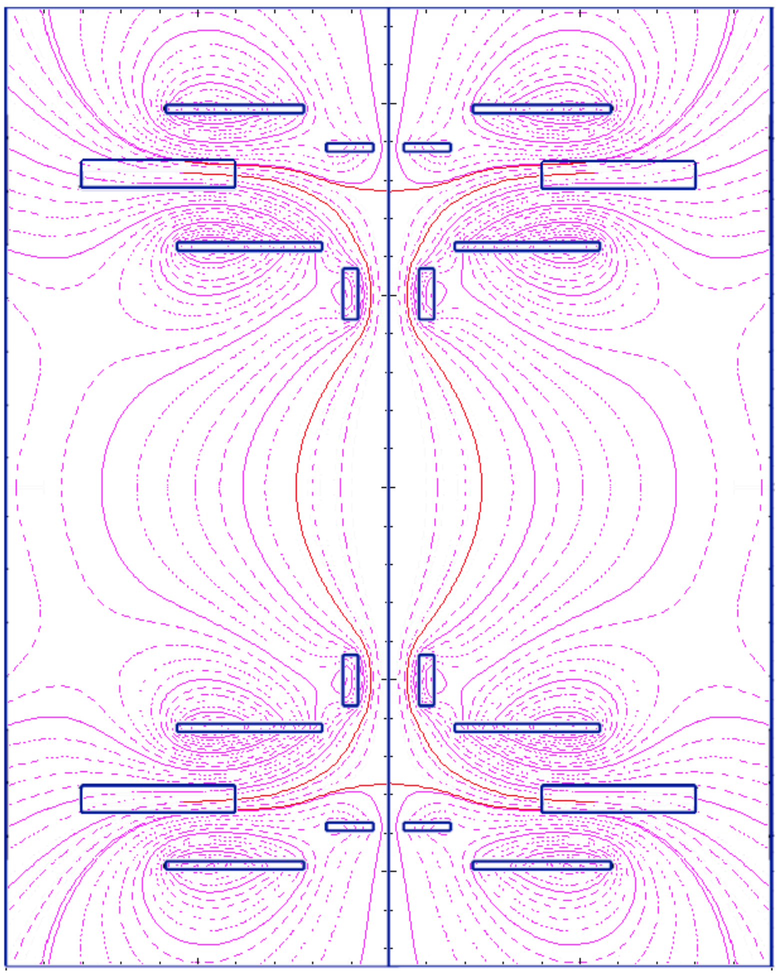
the spurious plasma current closes on the ouside of PF2low, producing bright filaments

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!**

Upper lid & extension also better left floating!

through Polycarbonate spacer ring



$V_{PF4up} \sim 130$ V

$V_{anode} \sim +150$ V

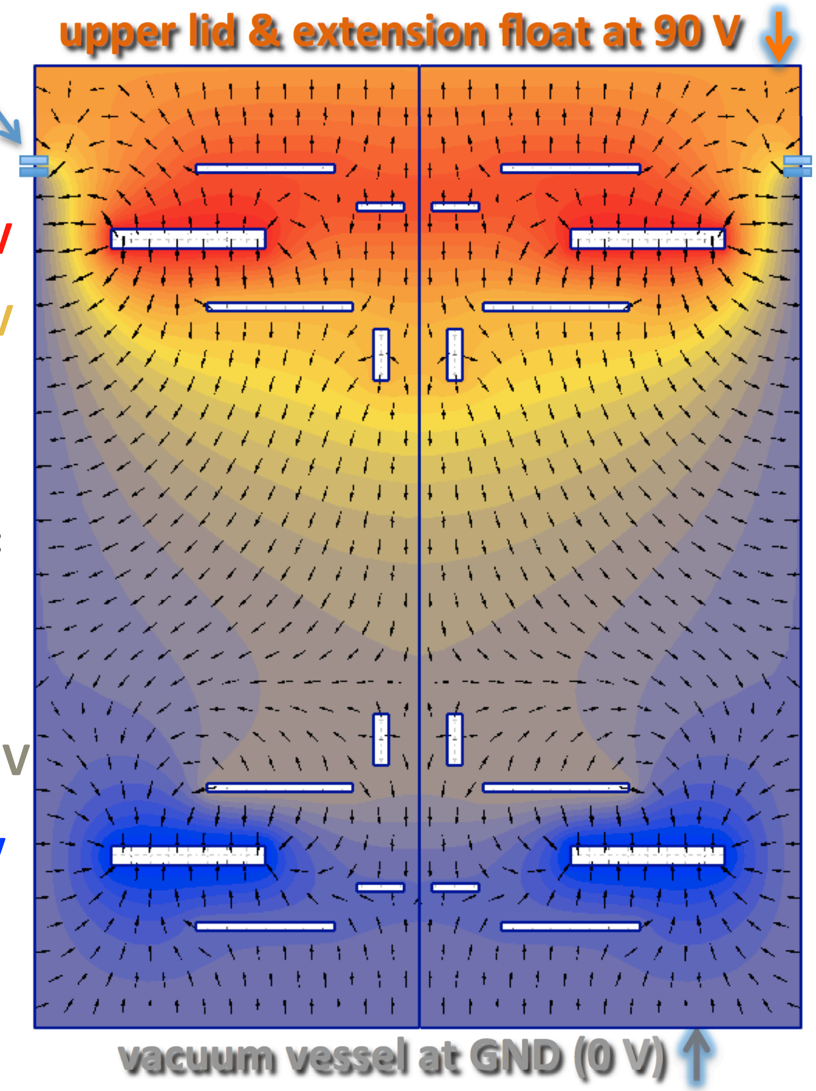
$V_{PF2\text{-}3up} \sim +75$ V

#614, 8kA Argon
Plasma centerpost
June 2017

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

$V_{cathode} \sim -45$ V

$V_{PF4low} \sim -7$ V

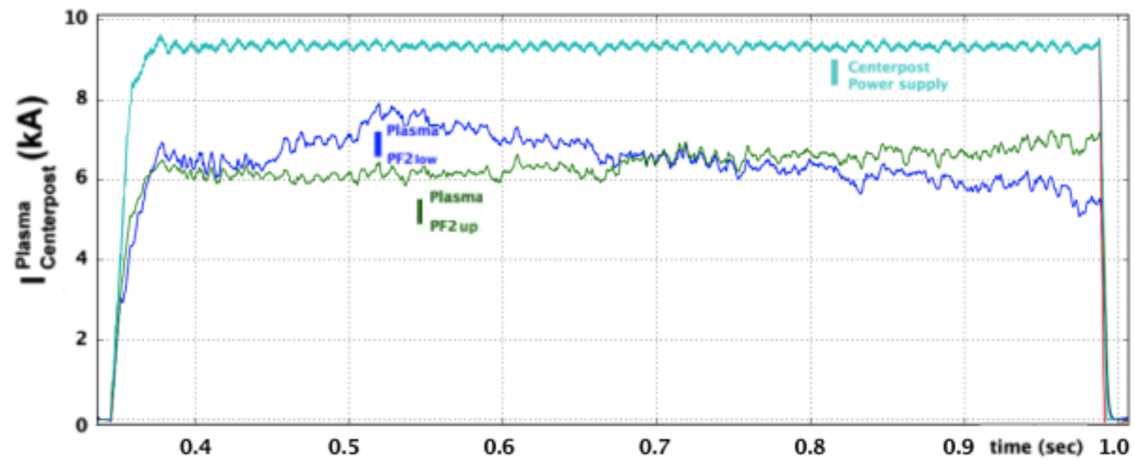


Lines: magnetic field

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

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

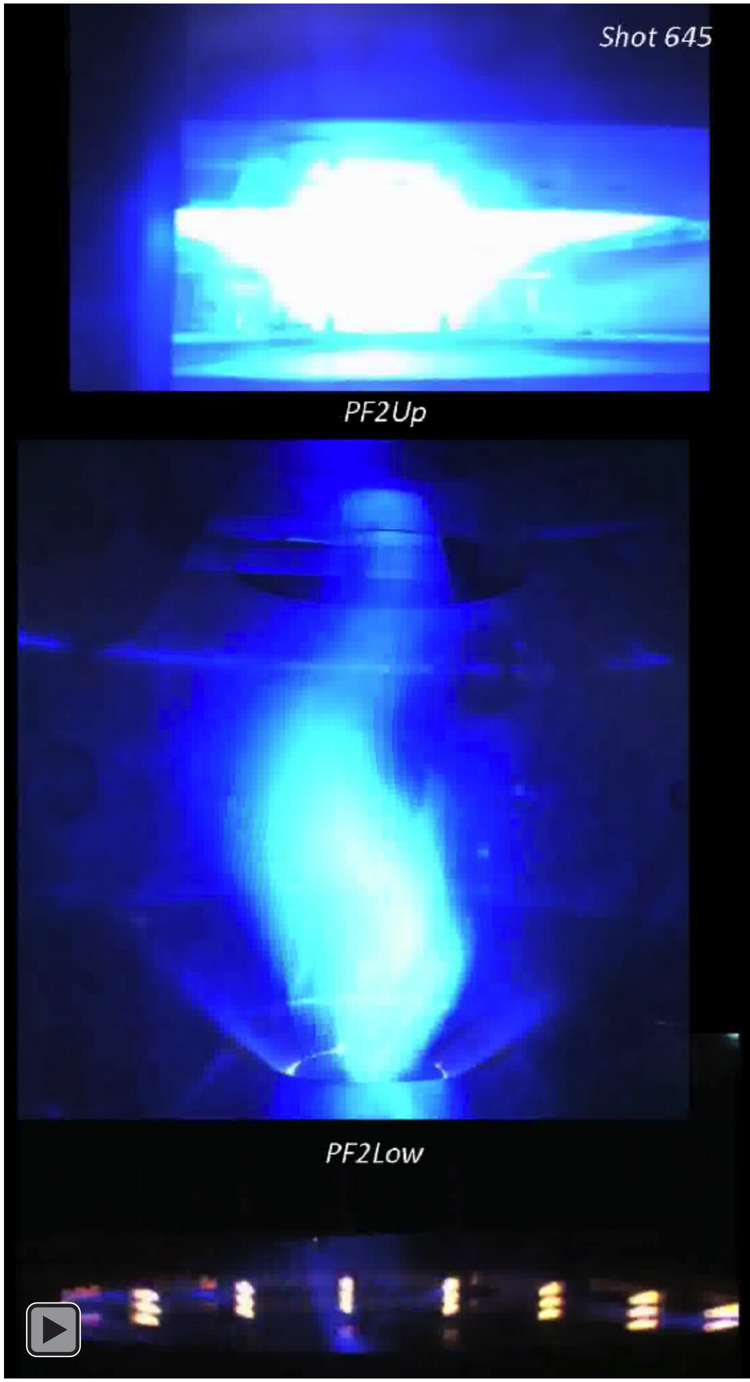
Switching off the external PF coils, long duration plasma centerposts have been obtained with plasma currents through the PF2 coils ~ 6 \ 7 kA



This plasma centerpost discharge is quite near to the rotational trasform value $\iota \sim ½$ ➔ ($q_{Centerpost} \sim 2$)

Autumn 2017: the narrow clearance <u>will be closed completely by a bonding material</u> able to sustain the diaphragms weight

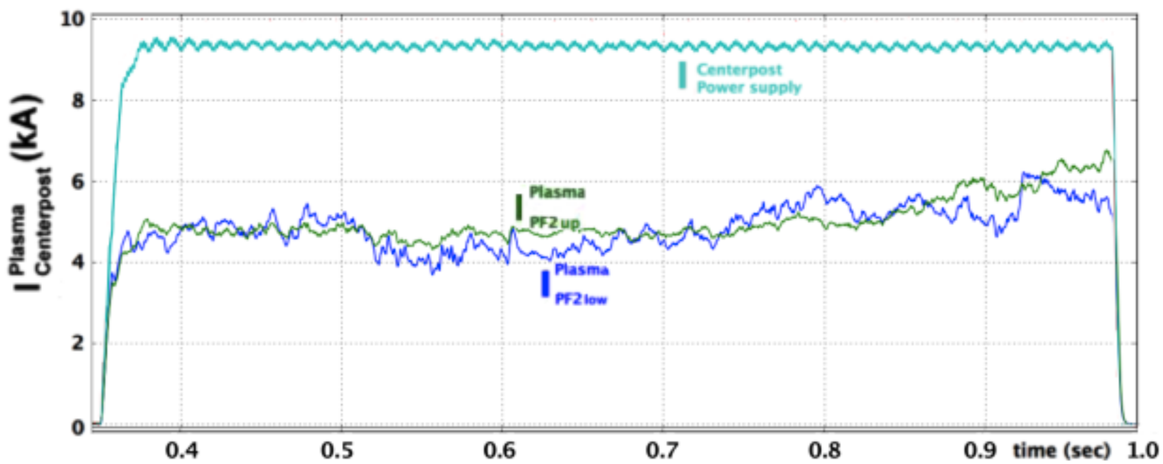
Kink destabilization mantained in 0.7s long discharge



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

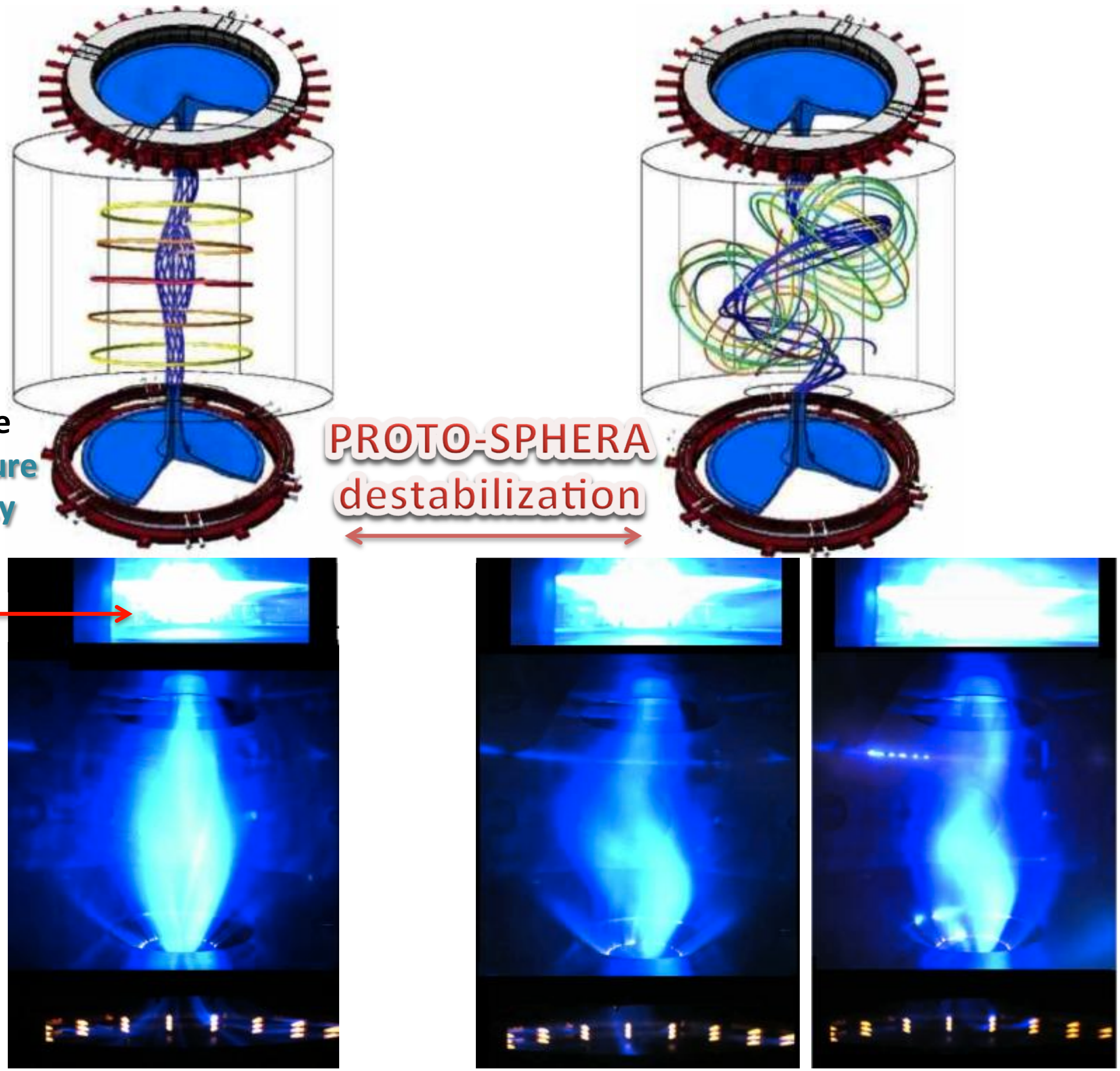


This plasma kink-bended centerpost discharge survives at a rotational trasform value $\iota \sim 1.66$ ➔ ($q_{Centerpost} \sim 0.6$)

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

Physics Design
1997-2008

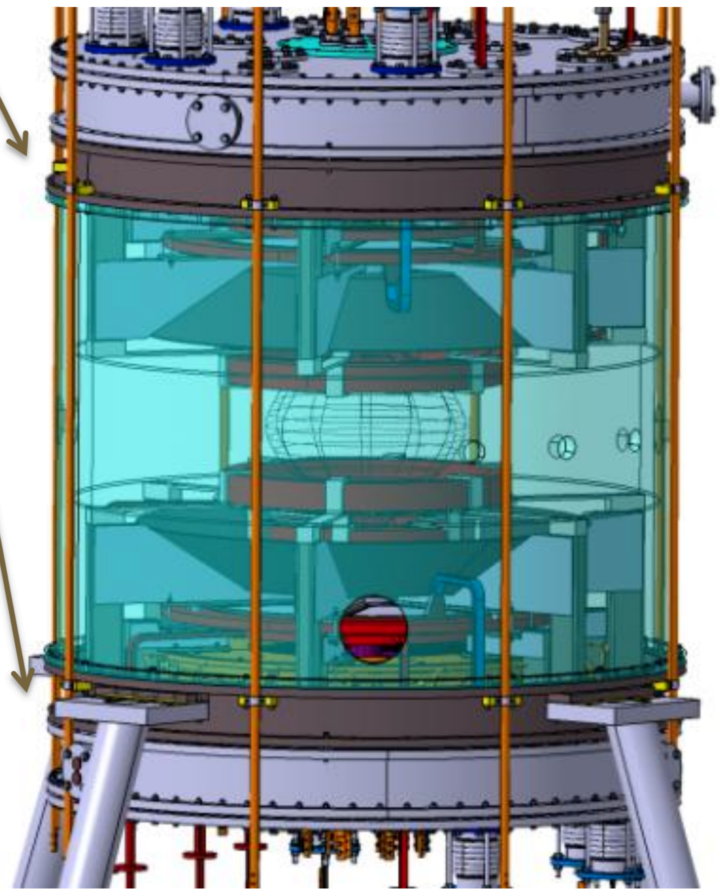
Langmuir probe measurements give
10÷3 eV temperature
2÷5·10^{19} m^{-3} density
at edge of anodic plasma mushroom



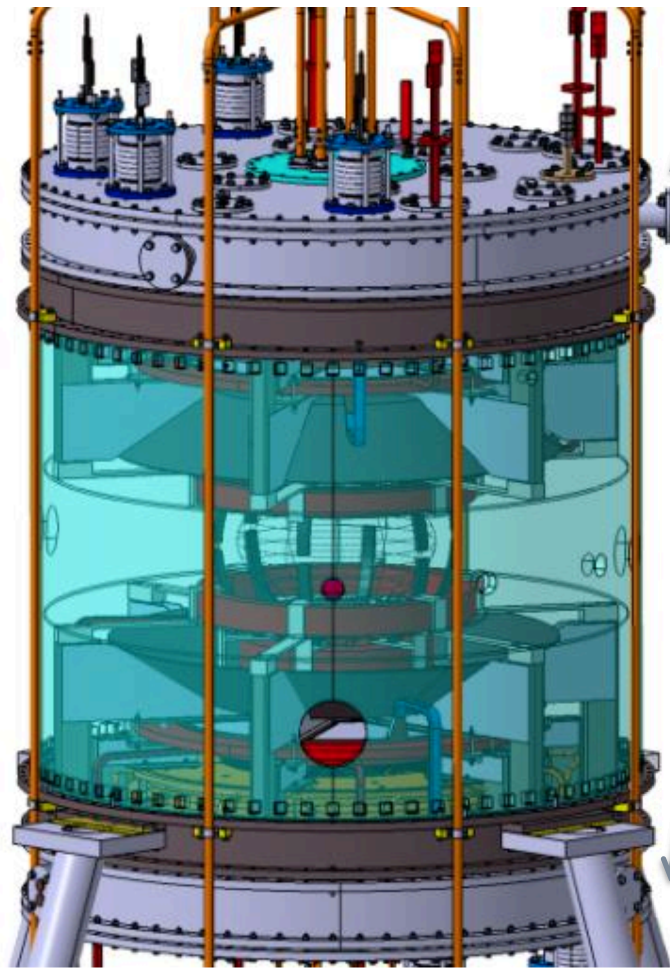
Experiment
2017

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

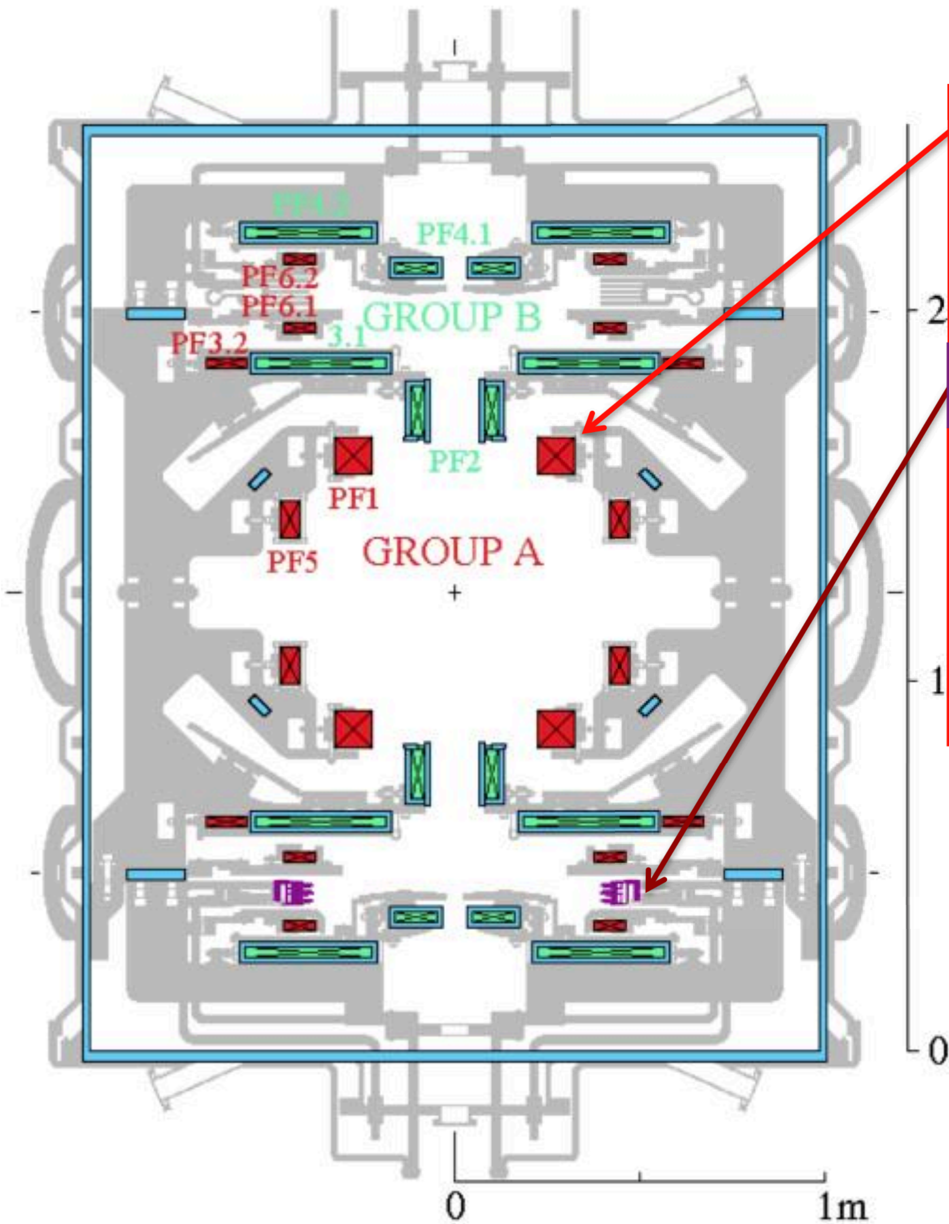


flanged PPMA cylinder



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:

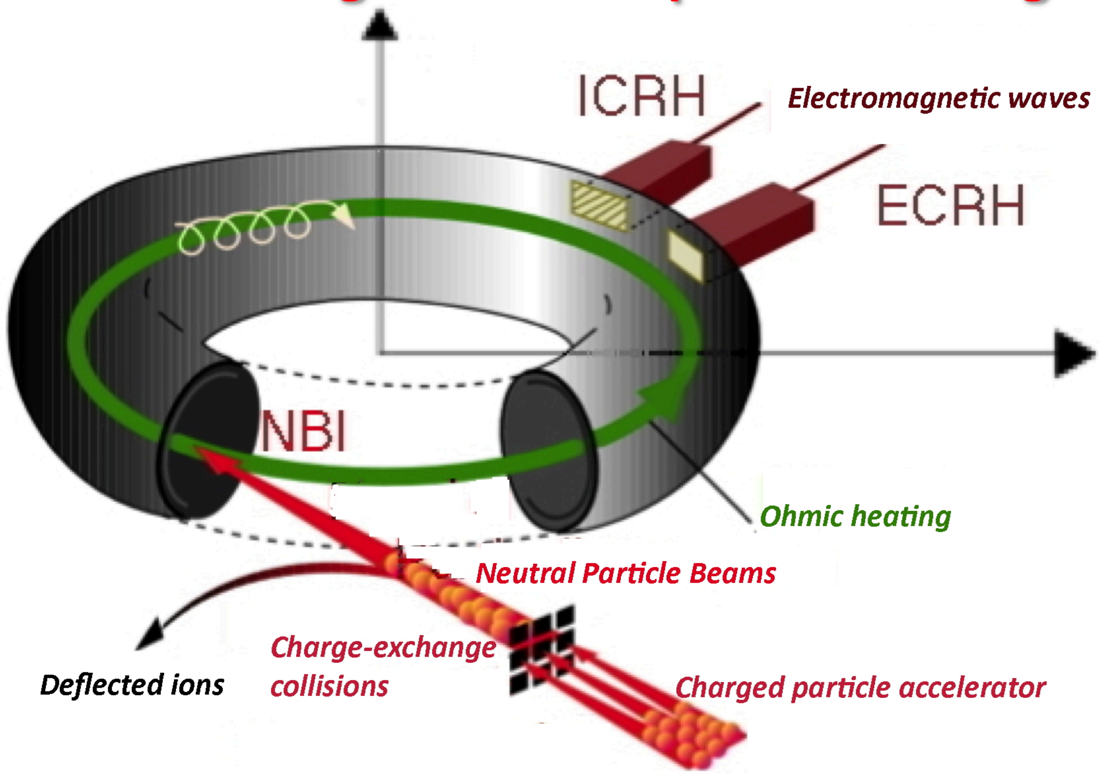
1) Group A PF coils cost ~ 0.1M€
2) Cathode ($\mathbf{I_{cath}}$ **10 → 60 kA**) cost ~ 0.2M€
3) Centerpost ($\mathbf{I_e}$ **10 → 60 kA**) cost ~ 0.6M€

SuperCapacitors will be used

Cost up to now ~ 2.0 M€

Cost for final stage of experiment ~ 1.6 M€

Additional heatings …if the fireplace doesn't ignite, try a flame-thrower!



But the energy confinement time dimishes more and more as more power is injected into the Tokamak

It is like, trying to increase the water level, one opens the tap but the wall hides a perverse mechanism that enlarges the sinkhole!

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 <u>magnetic reconnections</u>?

No one is able to predict:

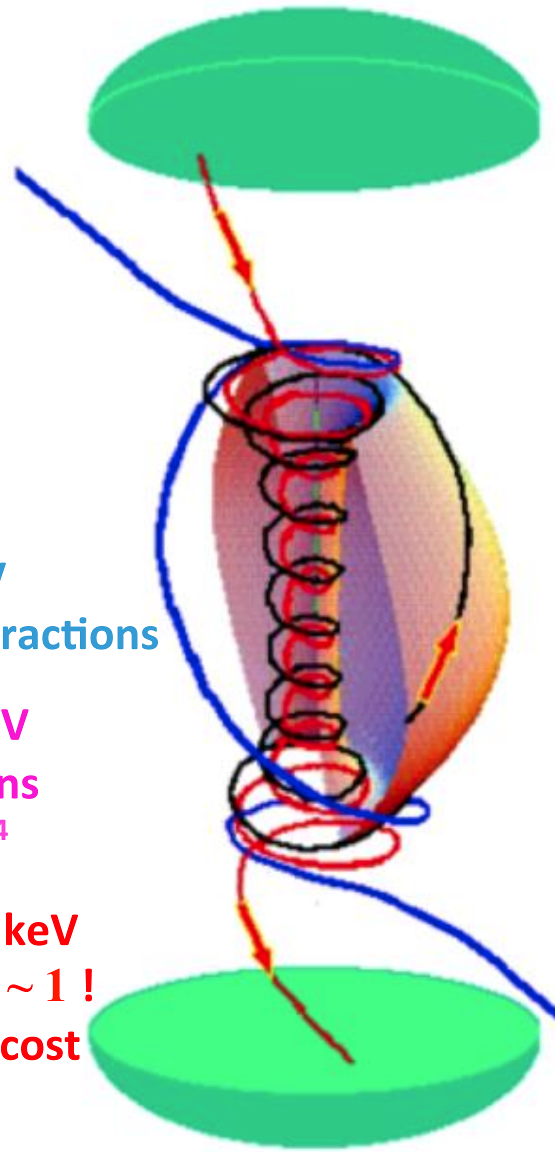
• should it be ~ zero, then ST plasma T = 10 eV PROTO-SPHERA studies plasma-electrode interactions

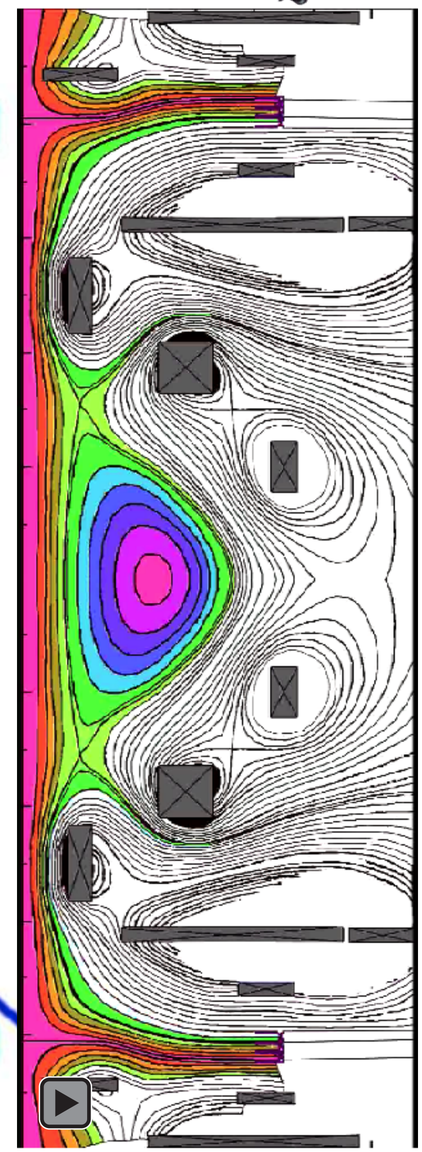
• should it be 1 MW, then ST plasma T = 100 eV PROTO-SPHERA studies magnetic reconnections at relevant magnetic Lundquist number, $S=10^4$

• 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 rùhǎi
…set free the Dragon into the sea!

Proto-Sphera will assess a new magnetic confinement configuration

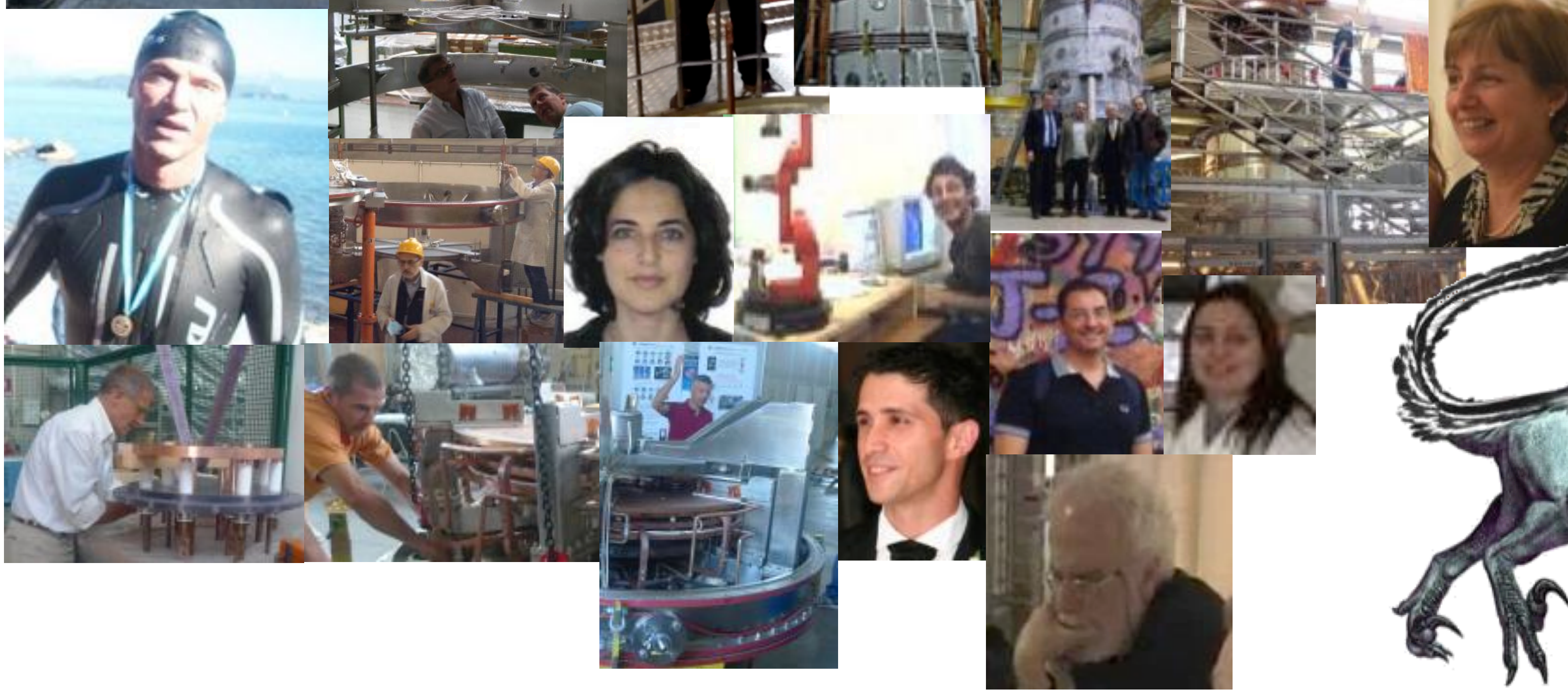
- simply connected (easier construction & maintenance)
- sustained (indefinitely?) by helicity injection, through magnetic reconnections
- mixed magnetic & electrostatic confinement, major role of plasma velocity?
- (if magnetic reconnection efficient) high plasma beta? (minimal geometrical size)

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 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