PROTO-SPHERA experimental results in 2018

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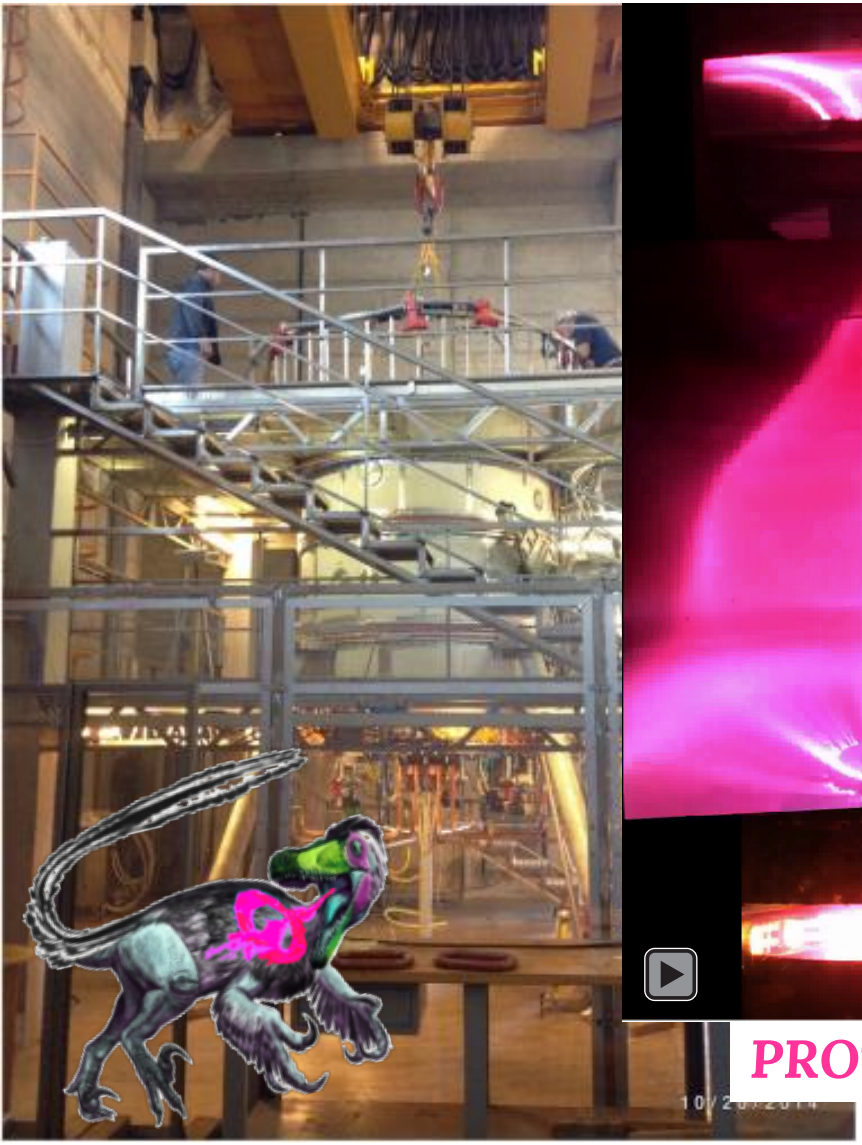
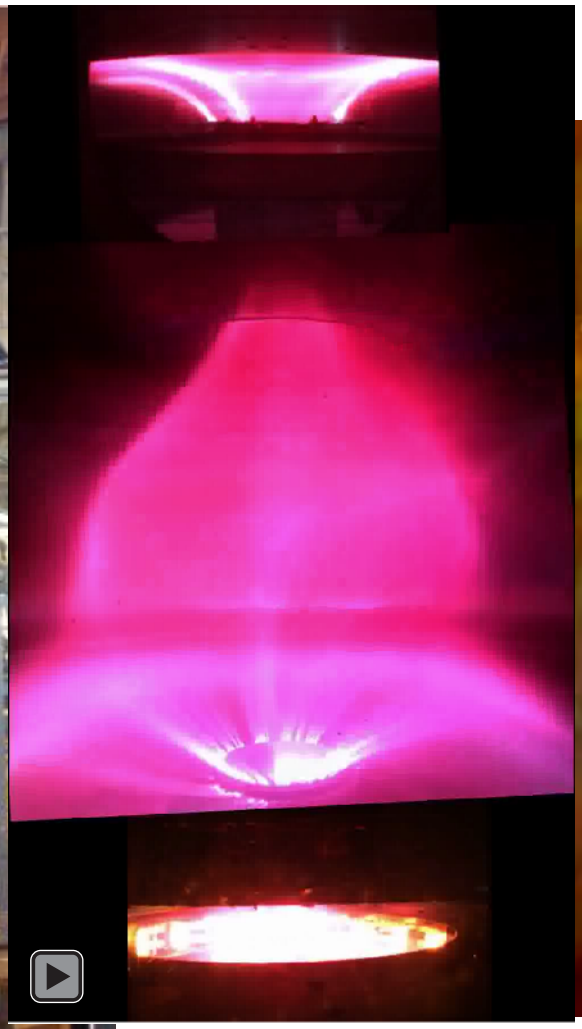




PROTO-SPHERA

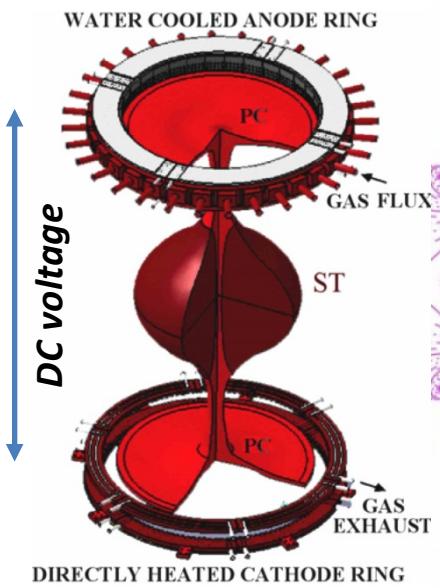


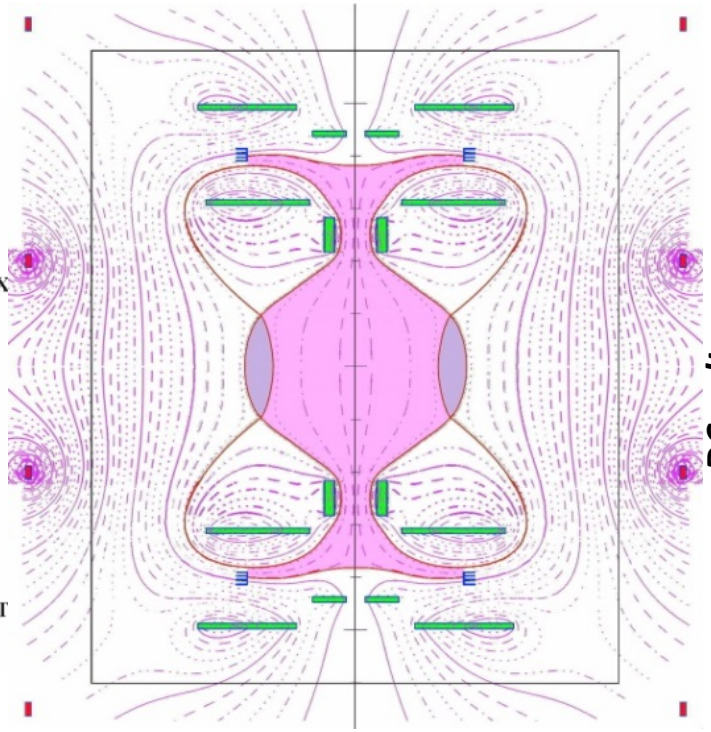
Crab Nebula remnant

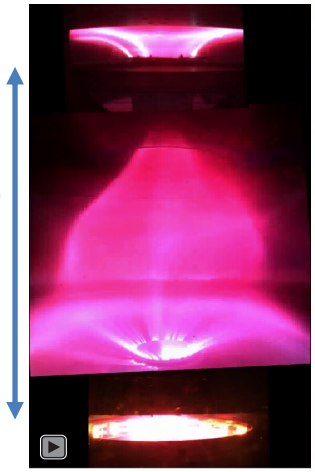
Consorzio RFX, Area di Ricerca CNR, Padova 15 Gennaio 2019

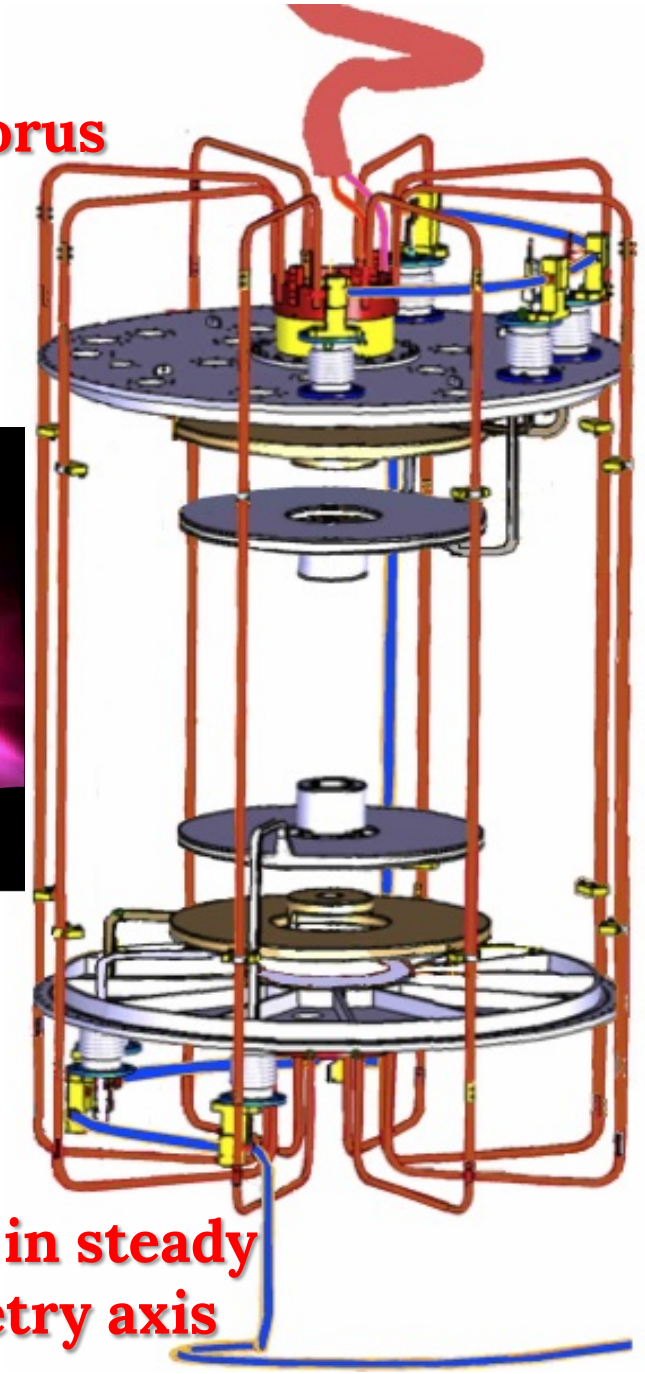
Main Points:

- **An axisymmetric high density confined plasma torus can be produced in absence of a toroidal magnet**









- **This toroidal current carrying torus is sustained in steady state just by a DC voltage applied along the symmetry axis**

- **Apart from the plasma current driven by the DC voltage the rest of the confining field is purely magnetostatic**



SUMMARY

- **Main Idea of PROTO-SPHERA: a Plasma-Centerpost Spherical Torus**

- **Why to explore a new magnetic confinement device?**

- **2 experimental Phases; Phase-1: struggle with $\vec{E}$ & $\vec{B}$ boundary conditions**

- **Phase-1 finished in 2018: a rotating high-density Plasma-Centerpost**

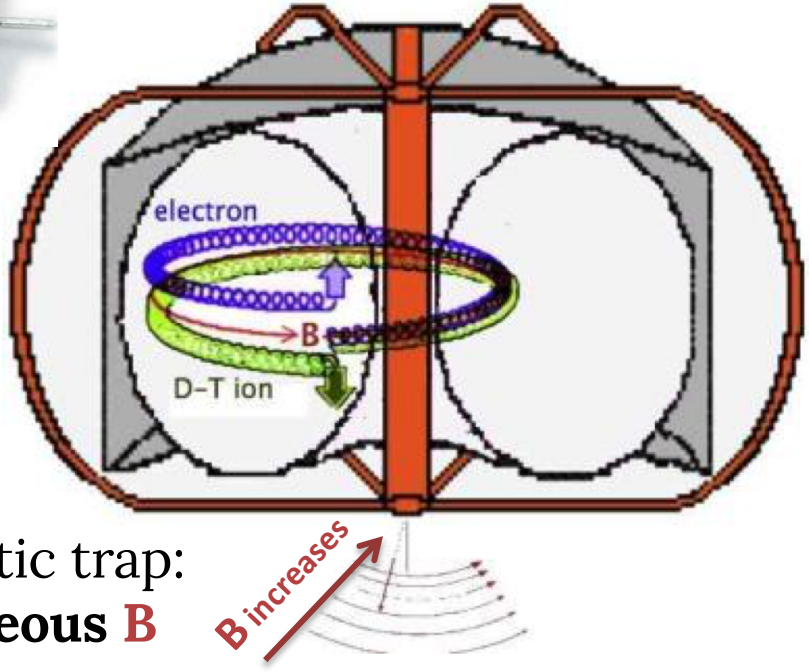
- **Around the I_e=10 kA Plasma-Centerpost, again in 2018**
Confined Plasma-Tori have been produced with toroidal currents up to I_{ST}=7 kA, always endowed with a divertor

- **A steady-state current drive is provided to a high-density Plasma by magnetic reconnections, transferring the plasma current from the Plasma-Centerpost to the Plasma-Torus**

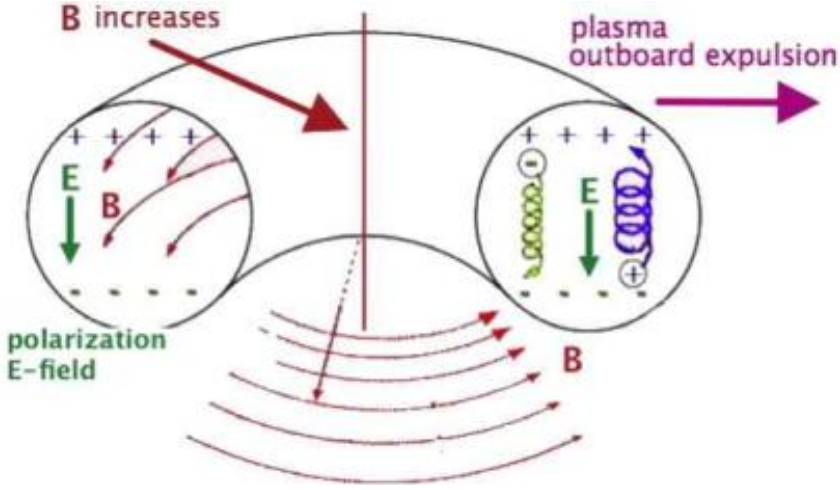
First Magnetic Confinement basics



e.g. $e^- \rightarrow$ up
ions$^+ \rightarrow$ down



Toroidal magnetic trap:
the inhomogeneous B separates charges

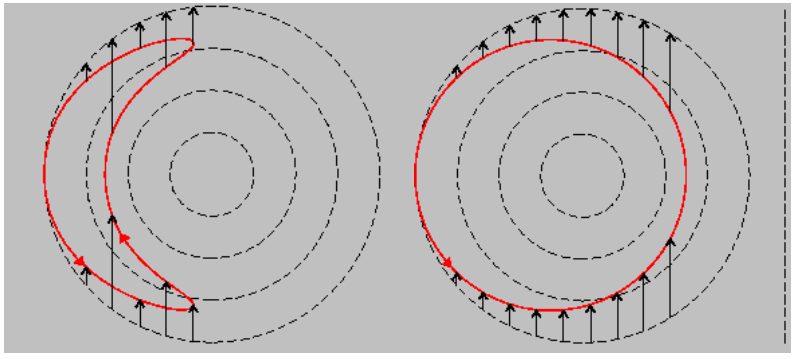


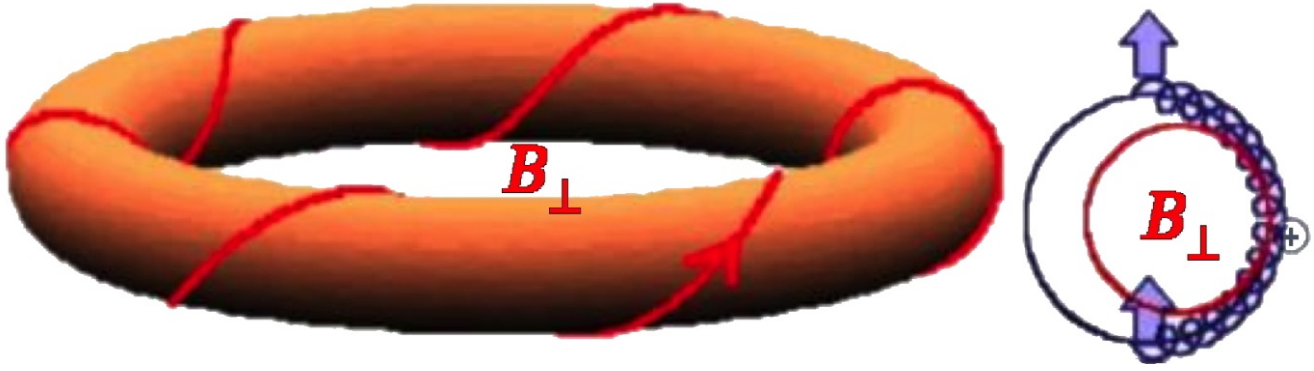
E polarization field,
through E∧B, ...ejects plasma

wind the magnetic field in the poloidal direction

to contrast particle drifts

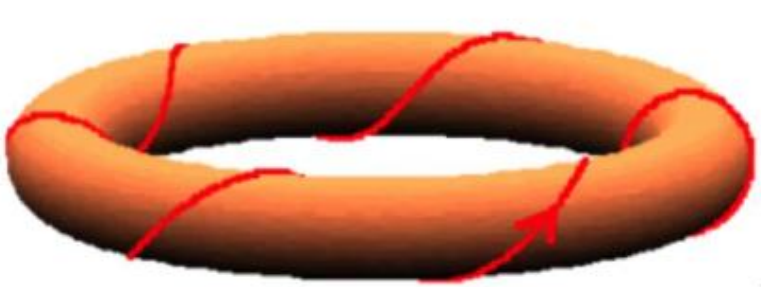
Poloidal field drifts for particles trapped & circulating

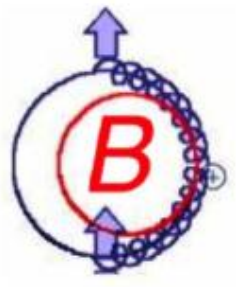


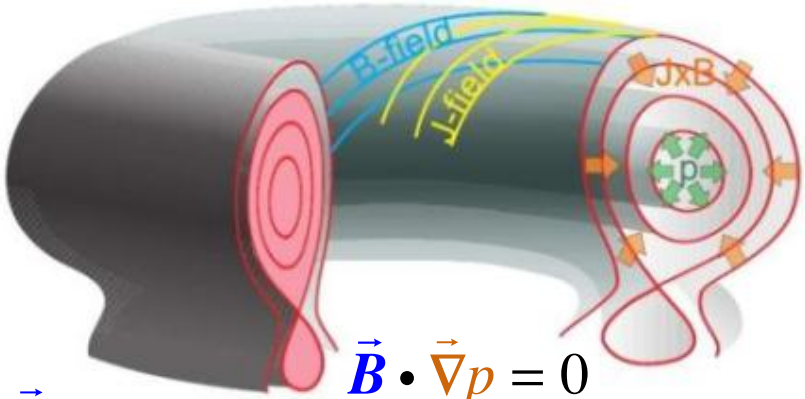


First & Second Magnetic Confinement basics

A poloidal $B_\perp$ magnetic field is required to contrast particle drifts
→ a toroidal current has to flow in an axisymmetric plasma





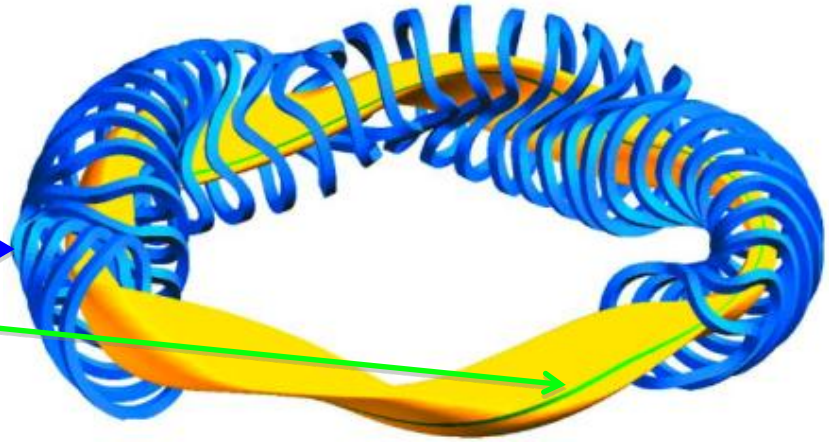


(magneto-hydrostatic equilibrium) $\vec{\nabla} p = \vec{j} \wedge \vec{B}$ →

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

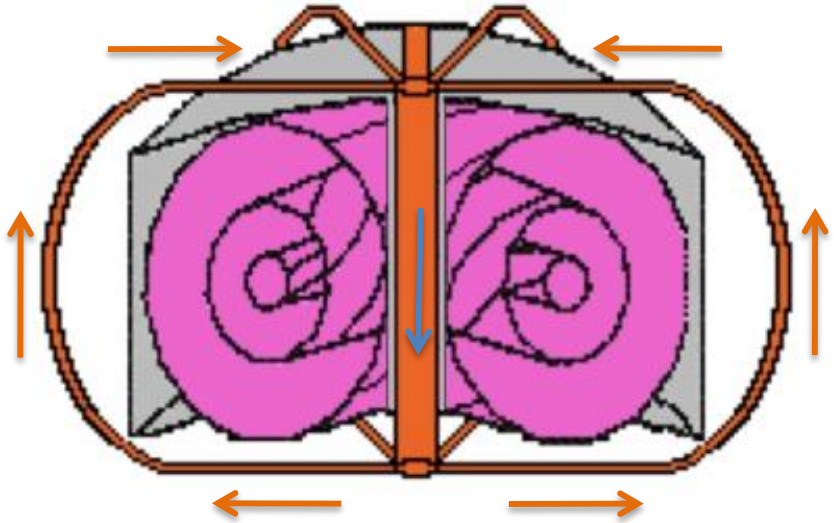
flux (…also *p* & *j*) surfaces must be Tori

Stellarators can avoid toroidal currents:
non axisymmetric magnetic coils →
engender a poloidally wound field
but a price has to be payed is:
the breaking of a symmetry



Main idea of PROTO-SPHERA: get rid of First Magnetic Confinement basics

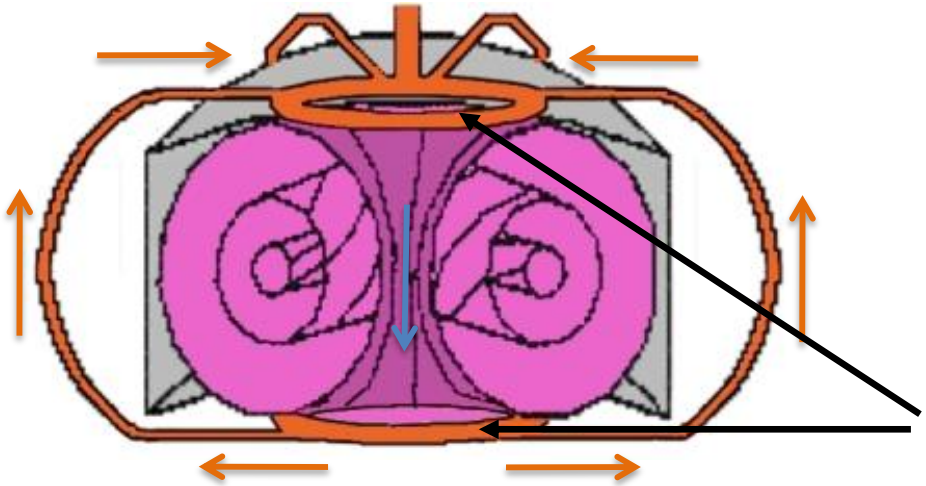




Electric current flowing in metal

- **Conventional Tokamak:**
  magnetic surfaces of toroidal plasma surround a "Metal Centerpost"

  …toroidal geometry of Vacuum vessel



- **PROTO-SPHERA:**
  magnetic surfaces of toroidal plasma surround a "Plasma Centerpost"; slim metal external legs current returns

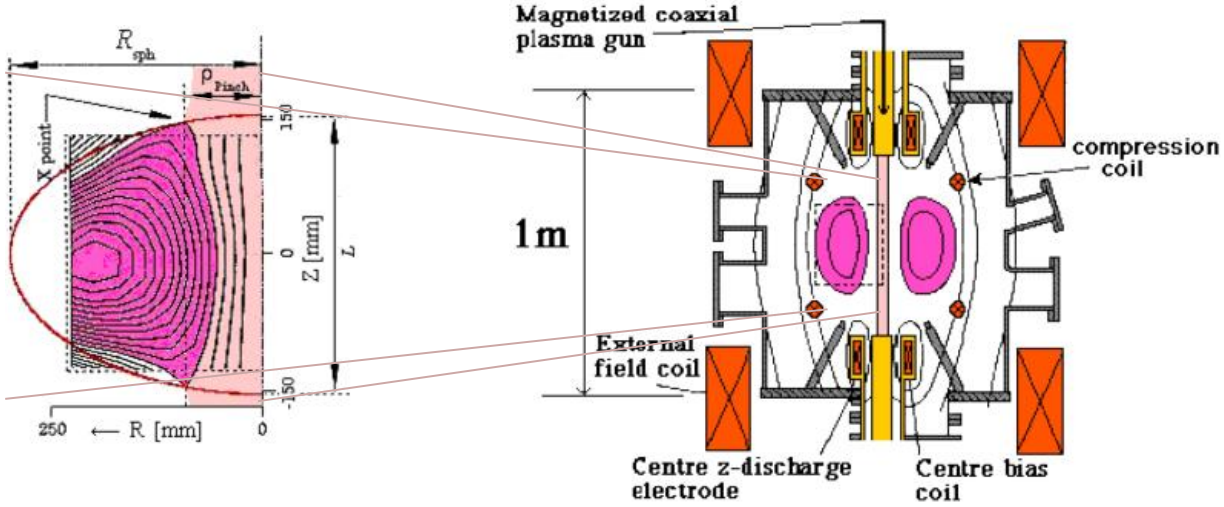
  …cylindrical geometry of Vacuum vessel
  …but electrodes are required inside vacuum

As far as the toroidal field is concerned there isn't a big difference with a Toroidal Pinch:
Ampere's law applies to both

PROTO-SPHERA: TS-3, the Japanese precursor

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

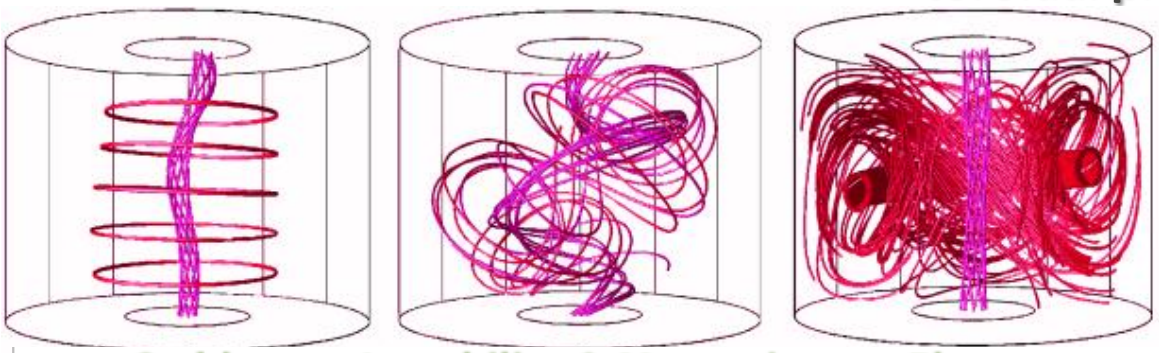
In **1993 TS-3** **removed the metal centerpost**, applied **1kV** between two plasma guns, produced a I_e = **40 kA Plasma Centerpost**





non-linear "kink" instability formed a Spherical Torus

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

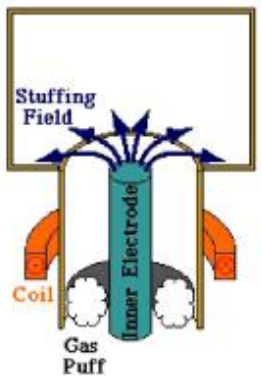


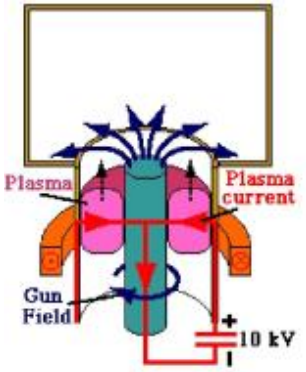
Stable Plasma Centerpost | Instability & Magnetic Reconnection | Plasma Centerpost & Torus

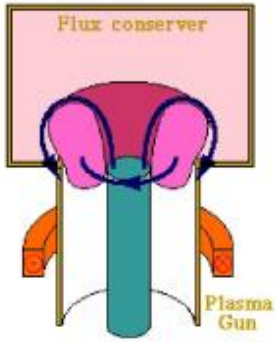
60 µs formation
20 µs sustainment
total duration **80 µs ~ 100** $\tau_{Alfvén}$
(short but significant…)

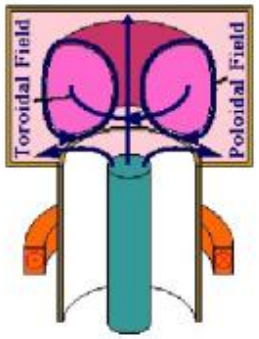
PROTO-SPHERA vs GUN-INJECTED FLUX-CORE-SPHEROMAKS

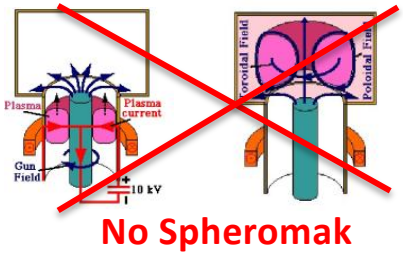
Breakdown in **small spaces**, at extremely **high filling pressures, 10 kV voltages, fast formation**





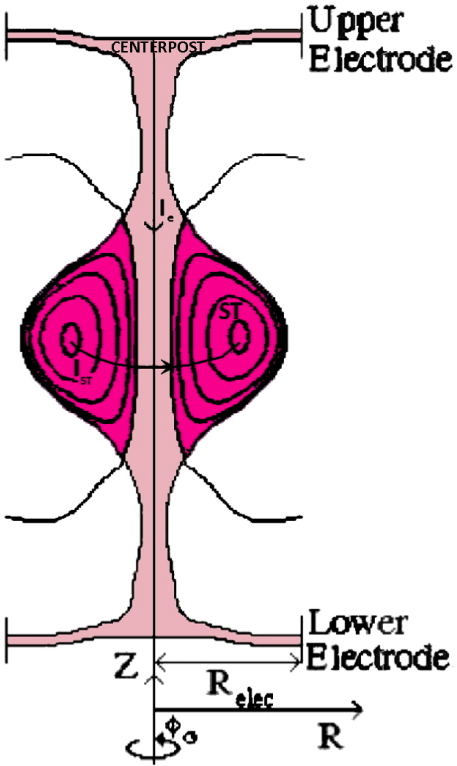




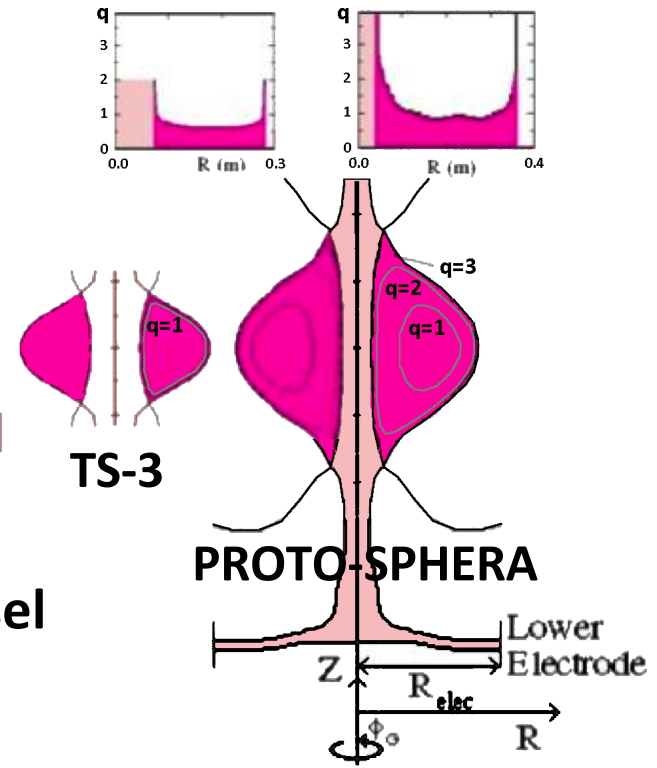


Spheromak accelerated and expanded into a **flux conserver**

PROTO-SPHERA ISN'T A SPHEROMAK: no flux conserver



- **Tokamak-like field-line rotational trasform** ($q_0 \geq 1$, $q_{edge} \sim 3$)
  aspect ratio $A = R/a \geq 1.2$
  elongation $k = b/a \sim 2.3$
- **Plasma Centerpost mushroom-shaped in front of electrodes**
- **At low voltage (< 1 kV), inside big vessel**
- **PROTO-SPHERA static/slow formation**



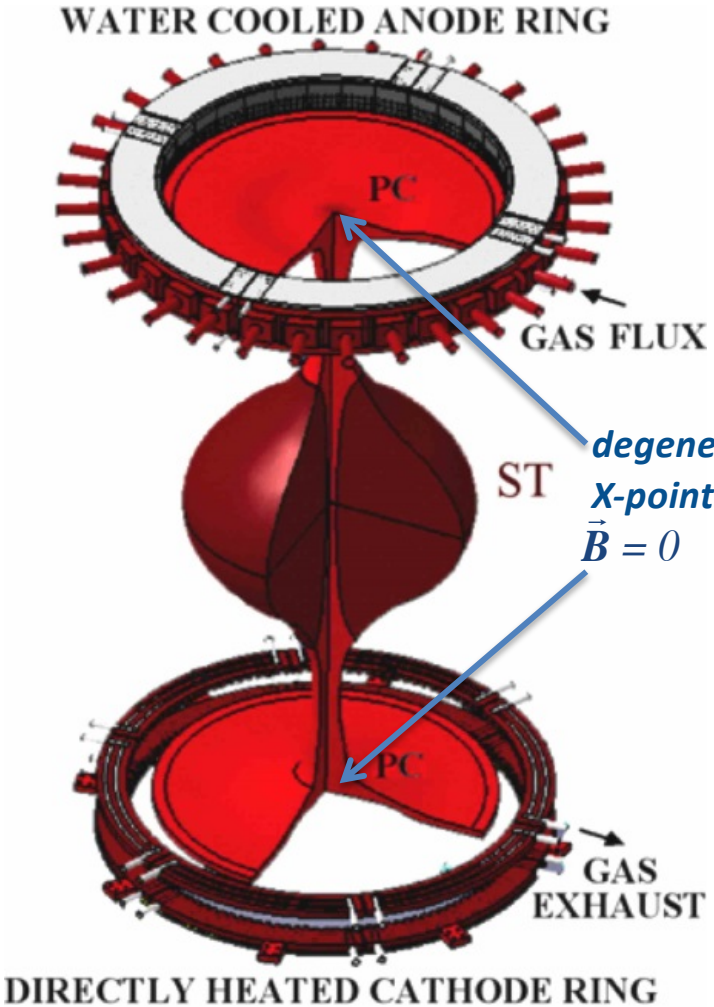
Main idea of PROTO-SPHERA:

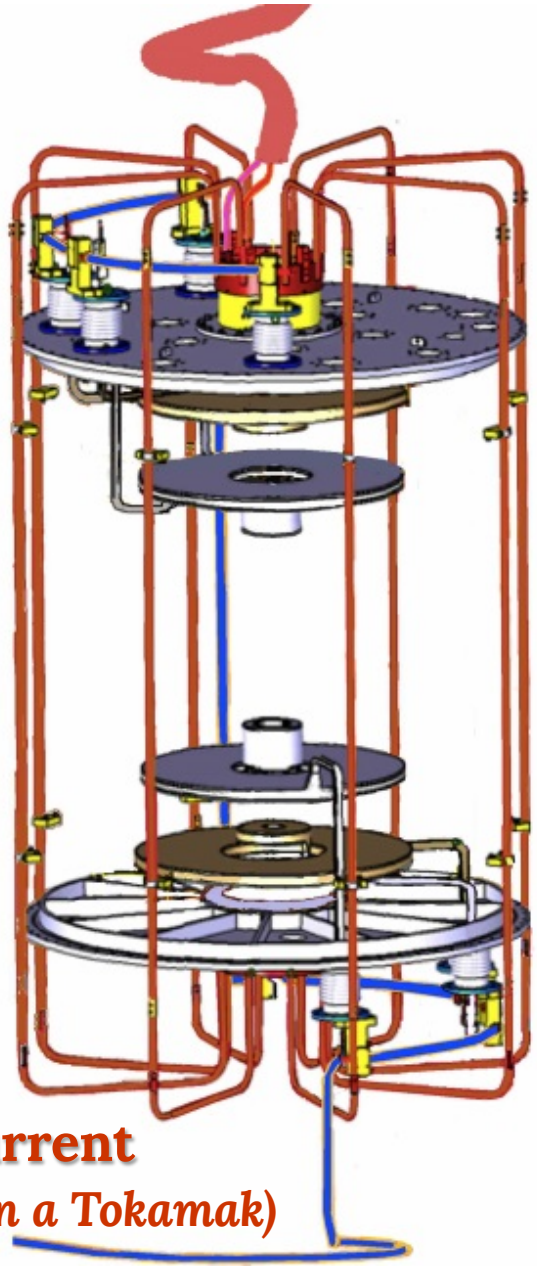
A current carrying plasma Torus: toroidal current I_{ST} around a **plasma Centerpost: electrode current I_e**



cylindrical geometry of Vacuum vessel

Electrodes inside vacuum vessel





slim metal external legs return the Plasma-Centerpost current

(outside the vessel & reminiscent of a toroidal magnet in a Tokamak)

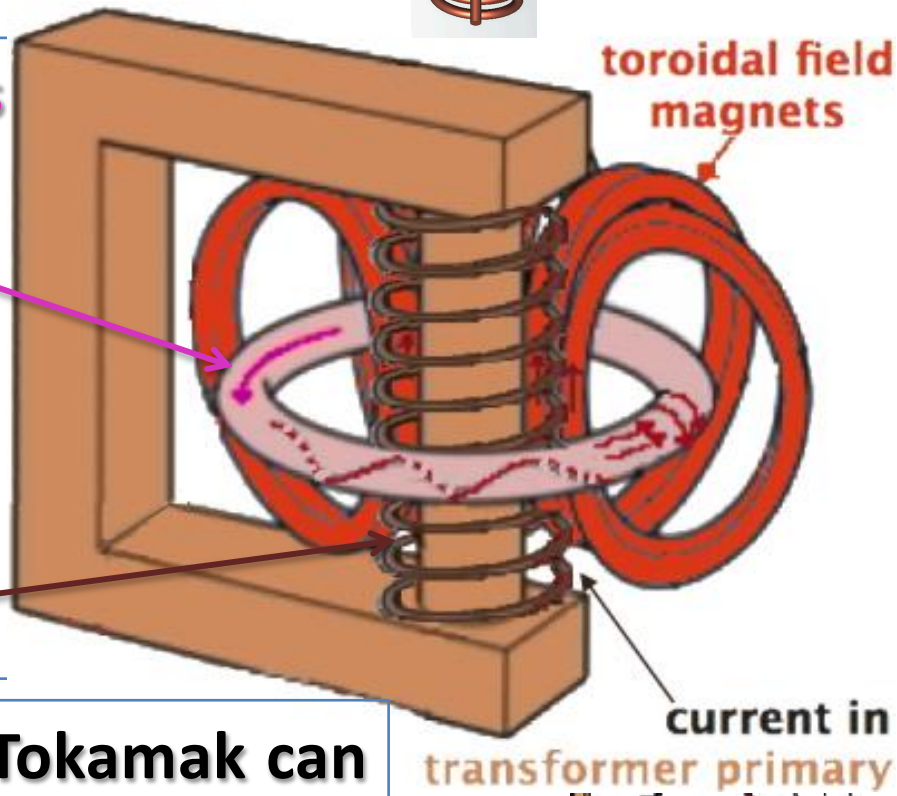
Second Magnetic Confinement basics



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



$\vec{E}$ **of Tokamaks relies on induction, efficient but not forever**

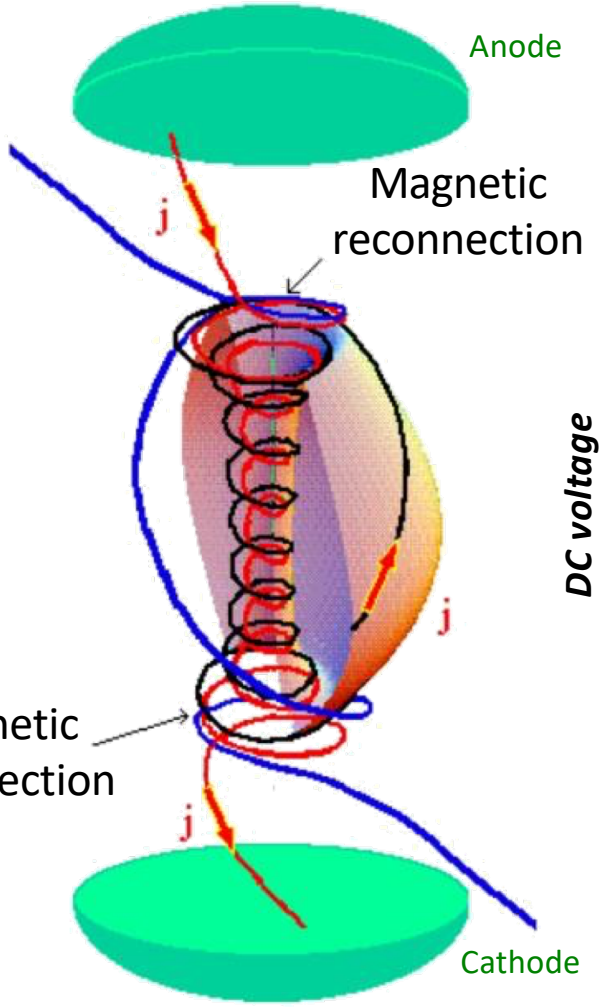
Main idea of PROTO-SPHERA: Second Magnetic Confinement

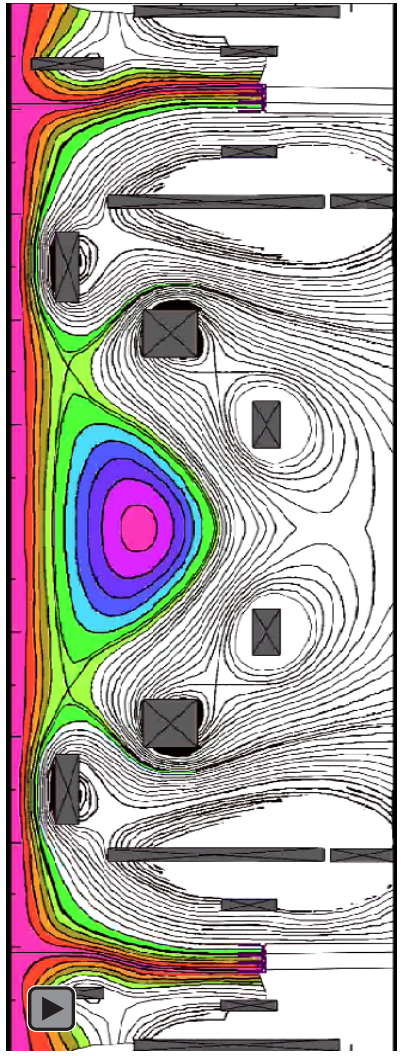


also get rid of basics

But as the toroidal current is concerned there is a huge difference with a Toroidal Pinch: Maxwell equations do not imply that a DC voltage between electrodes can sustain a toroidally winding current!

DC voltage from anode to cathode
CAN SUSTAIN THE CONFINING CURRENT
by Magnetic Reconnections





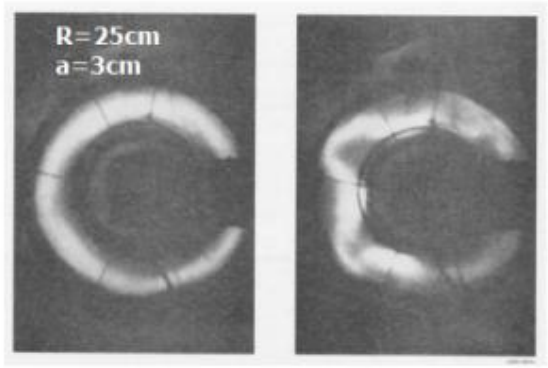
Get rid of RF-surfing Current Drive



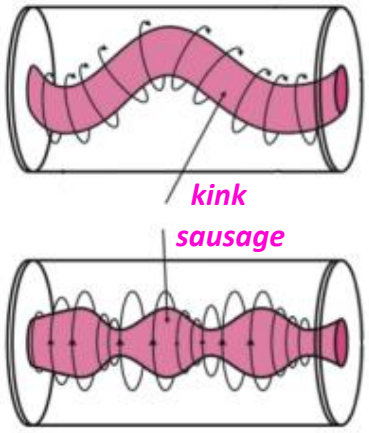
$\vec{E}$ of PROTO-SPHERA relies on $\vec{v} \wedge \vec{B}$ associated with magnetic reconnections

Why to explore a new magnetic confinement device? one reason is …"disruption"

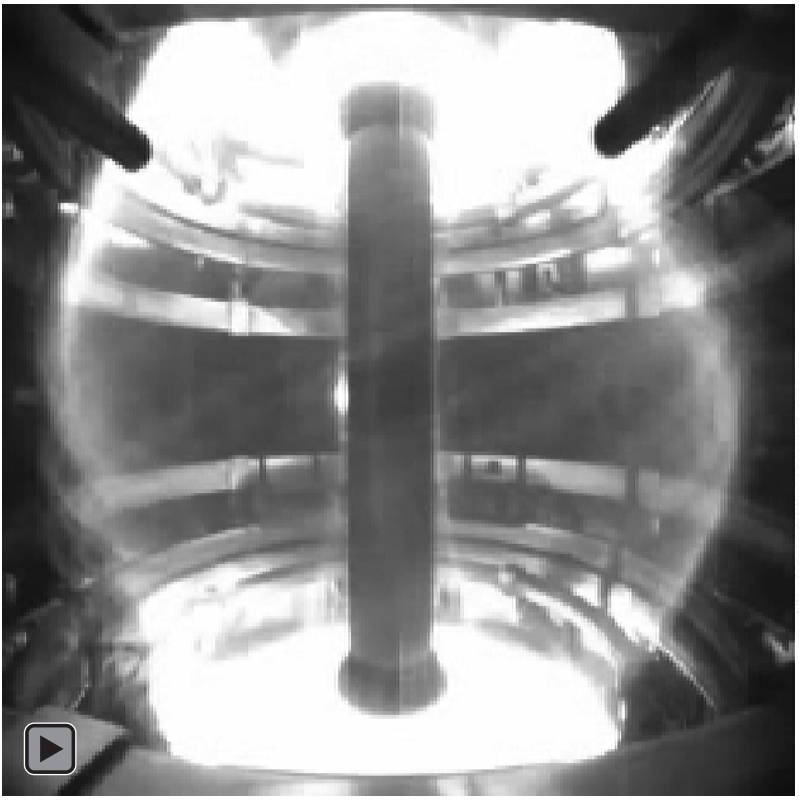
Alan Ware & Thomson
Imperial College 1947.



MHD instabilities appeared since the earliest toroidal magnetic confinement devices

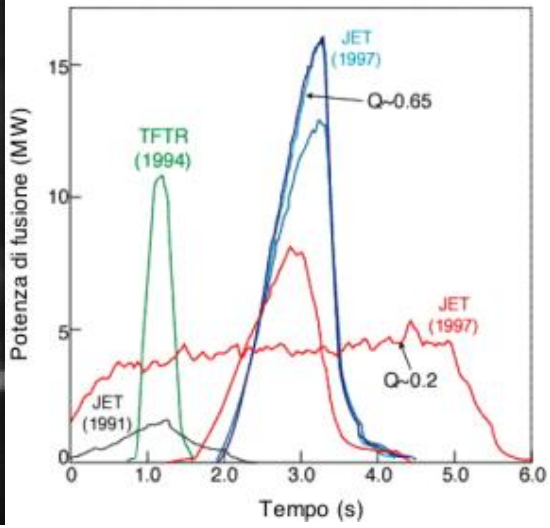


Mast 2004



…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

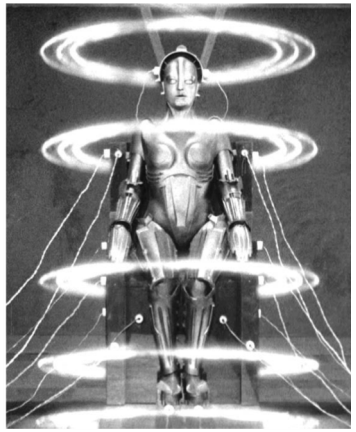
The highest neutron yield
…terminates in a disruption

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

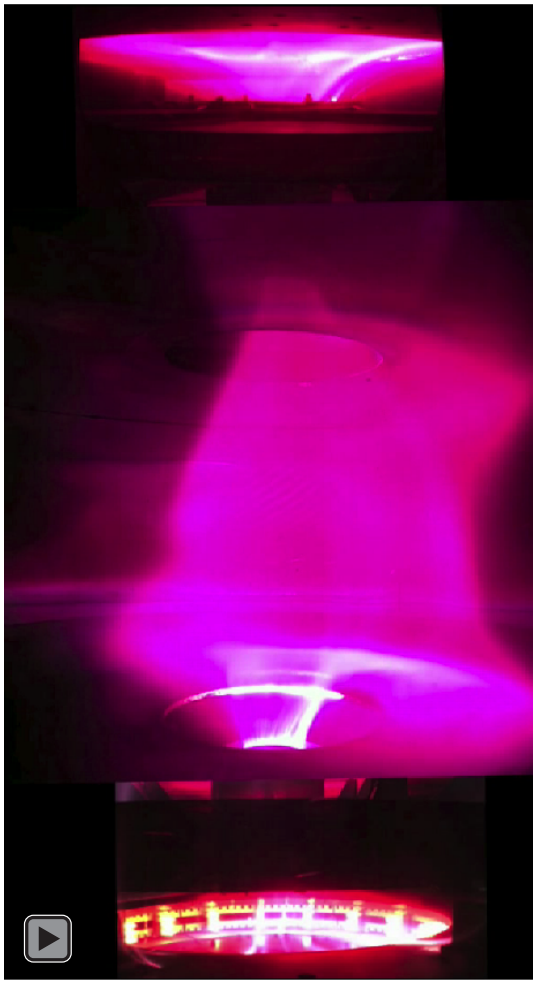
In a configuration based on DC Helicity Injection the plasma does not vanish

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





Fritz Lang's
Metropolis (1926)



PROTO-SPHERA #1225 (2018)
Plasma maintained notwithstanding huge helical kinks

Why to explore a new magnetic confinement device?

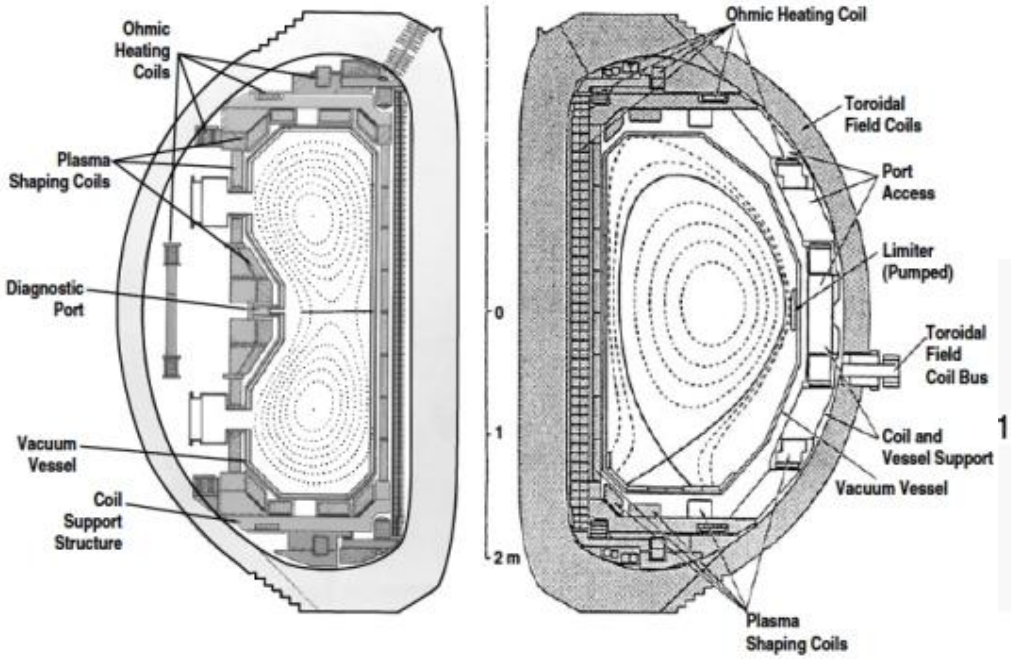
another reason is ... "β limit"

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

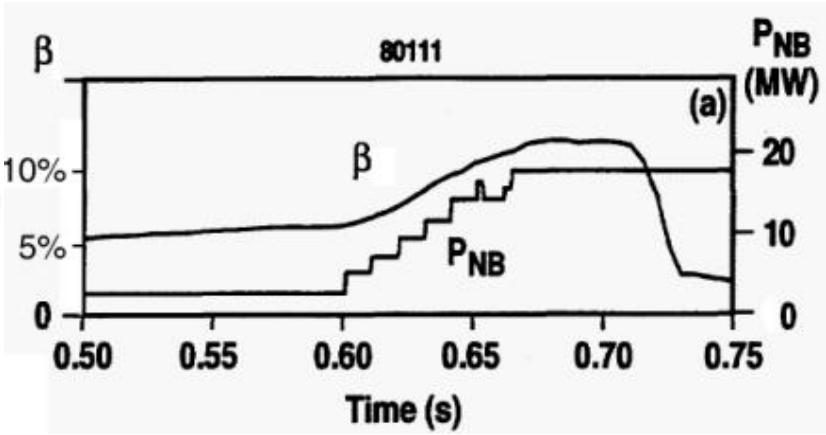
$\beta = 2\mu_0 \int p\,dV \Big/ \int B^2\,dV$ but in tokamak experimental data one often uses β_{T0}

$\beta_{T0} = 2\mu_0 \int p\,dV \Big/ B_{T0}^2 V$ 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 → huge cost, huge size, …**

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

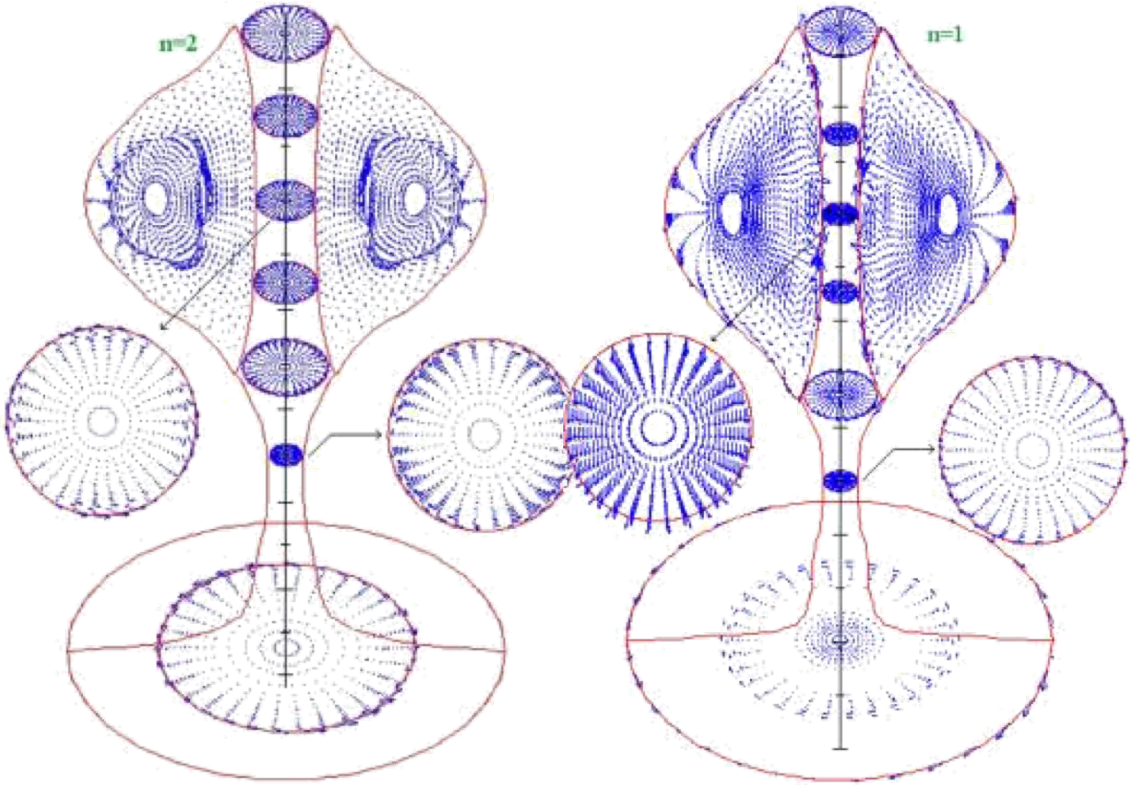
expressed with $\beta = 2\mu_0 \int p\,dV \Big/ B^2 dV$
ratio of the two plasma currents
I_{ST} /I_e = toroidal ST current/centerpost current

- 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 $\beta_{To} = 2\mu_0 \int p\,dV \Big/ B_{T0}^2 V$

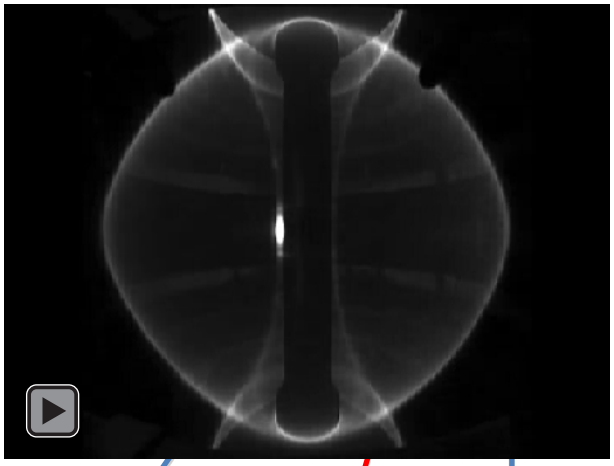
- up to β_{T0} =28÷29% , I_{ST}/I_e = 0.5 - 1
- up to **β_{T0} =72÷84% , I_{ST}/I_e = 2-4**

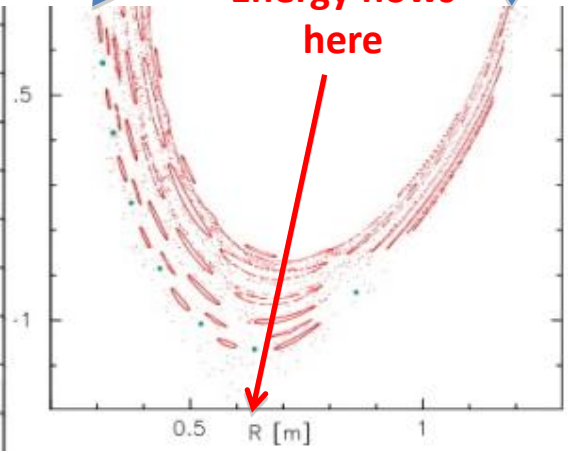
PROTO-SPHERA can approach β =1



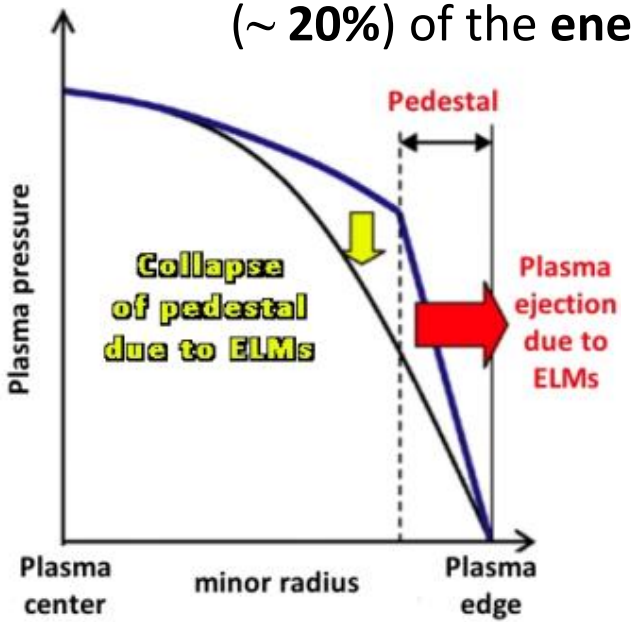
Why to explore a new magnetic confinement device? still other reasons are…

"ELMs" (unstable edge localized modes)

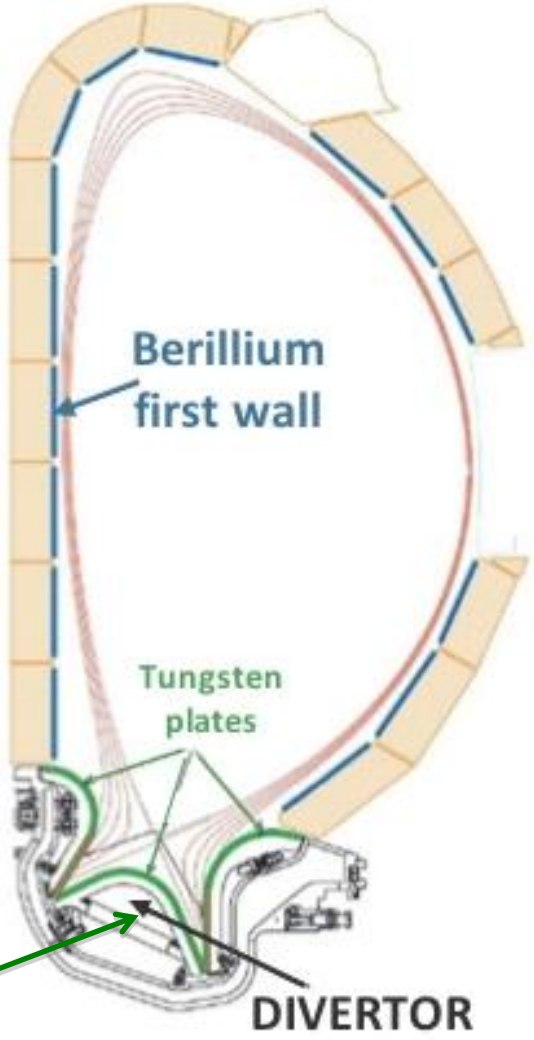




"**ELM**" mode throw upon the divertor a sizeable portion (~ **20%**) of the **energy in the pressure pedestal**



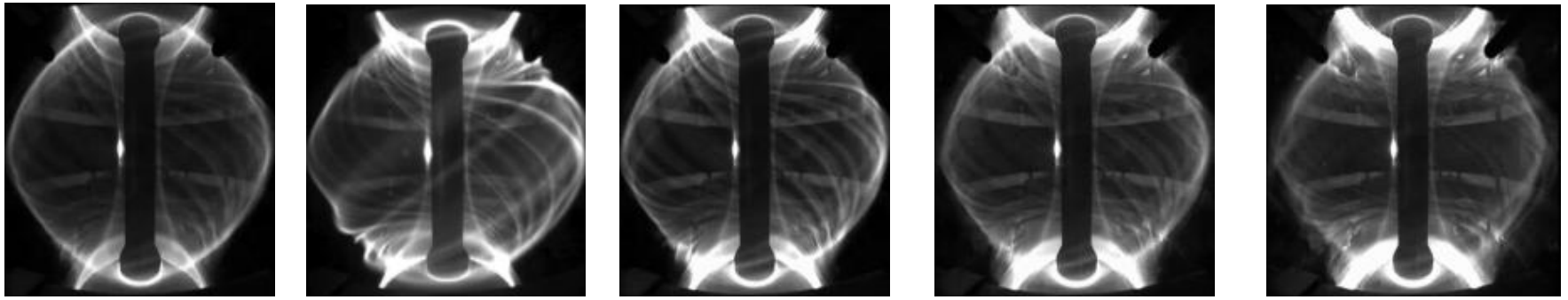
This happens in a **very short time (250 µs)** as the **plasma edge becomes ergodic** (**ELM** filaments carry current)



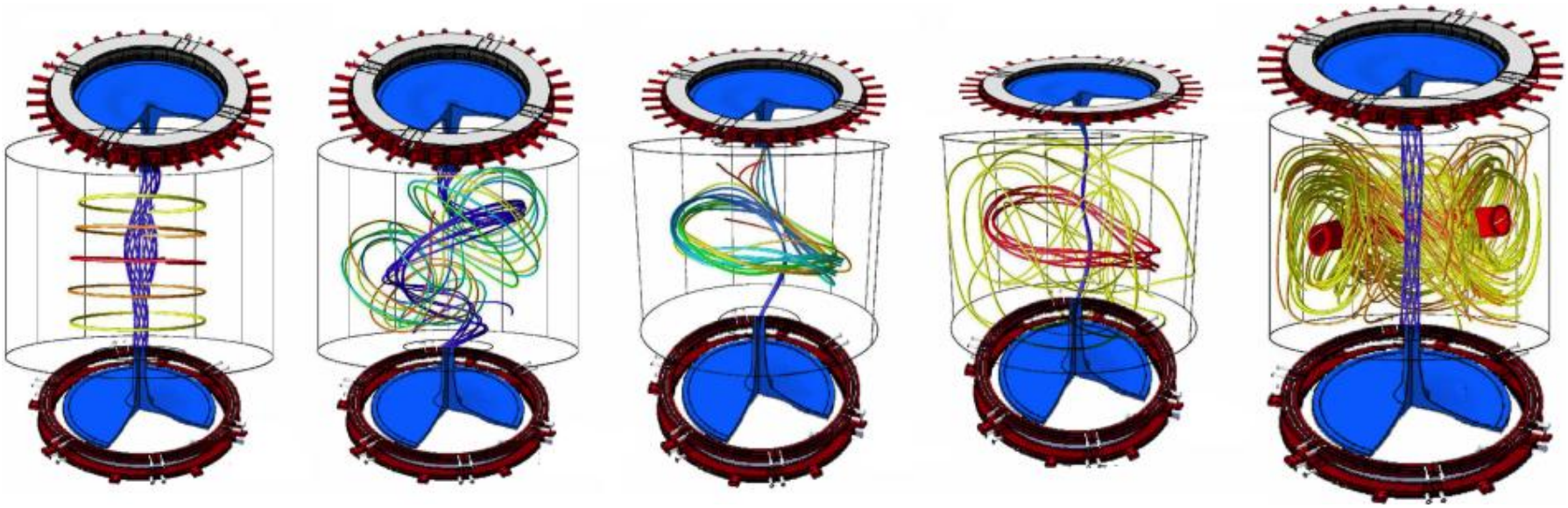
On **ITER** an **ELMs carrying > 3% of pedestal energy** can even **melt or sublimate** the **Tungsten of the Divertor plates**

"ELMs" (unstable edge localized modes):

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



be put to fruition in PROTO-SPHERA?



Why to explore a new magnetic confinement device?
…advantages?

Operational experience in Tokamaks shows that the

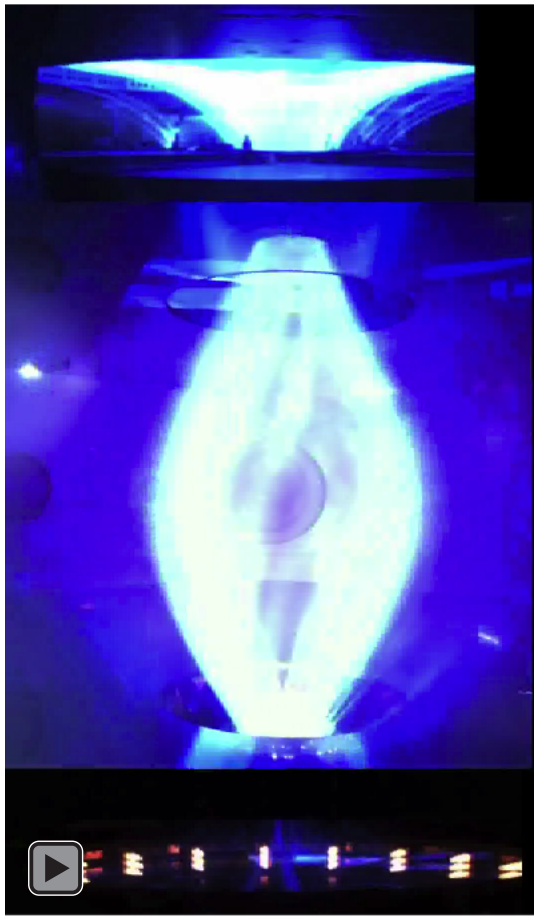
- **Best way of puffing fuel is from the inboard (high field side)**

- **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!

Gas puffed hollow anode





…cylindrical geometry of Vacuum vessel

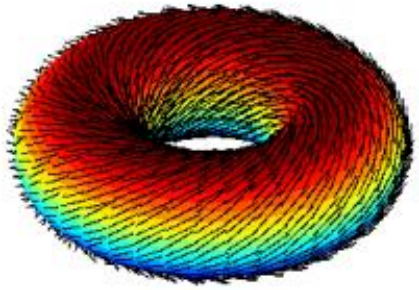
Cylindrical vacuum vessel geometry has obvious advantages:

easy to access & to repair!

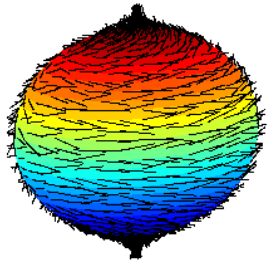
Last Confinement Surface spherical, but Tori inside

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

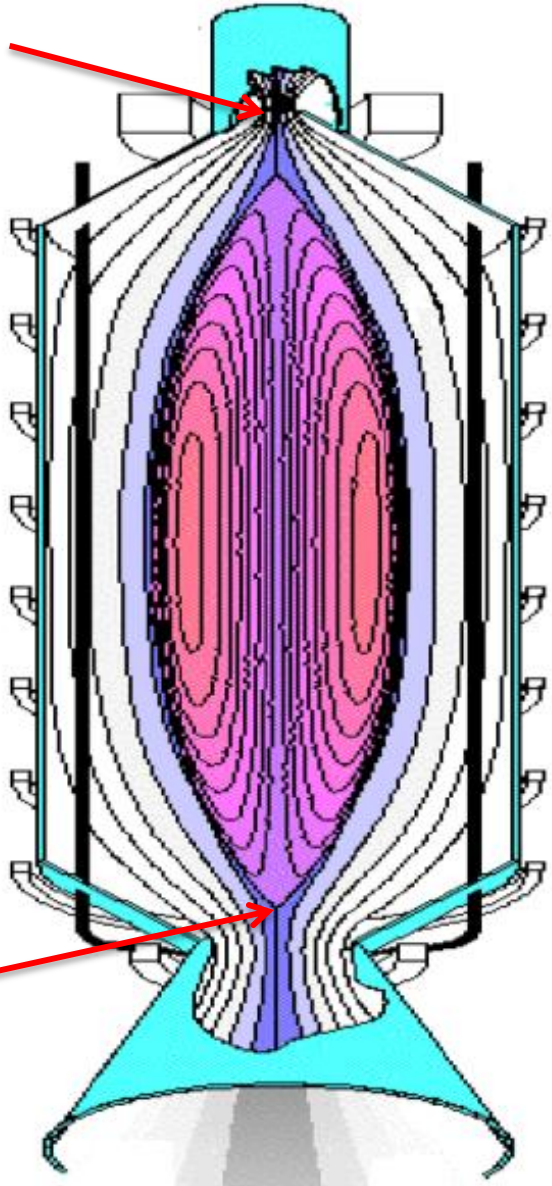
degenerate* X-*points



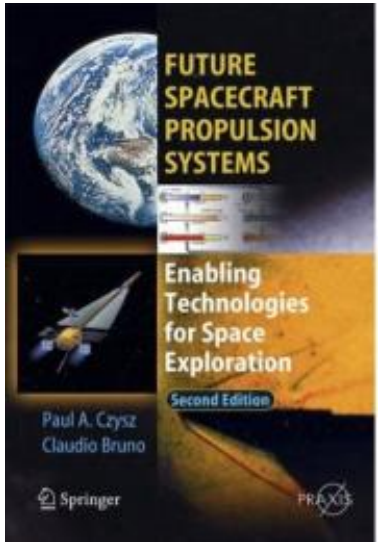
a hairy torus can be combed

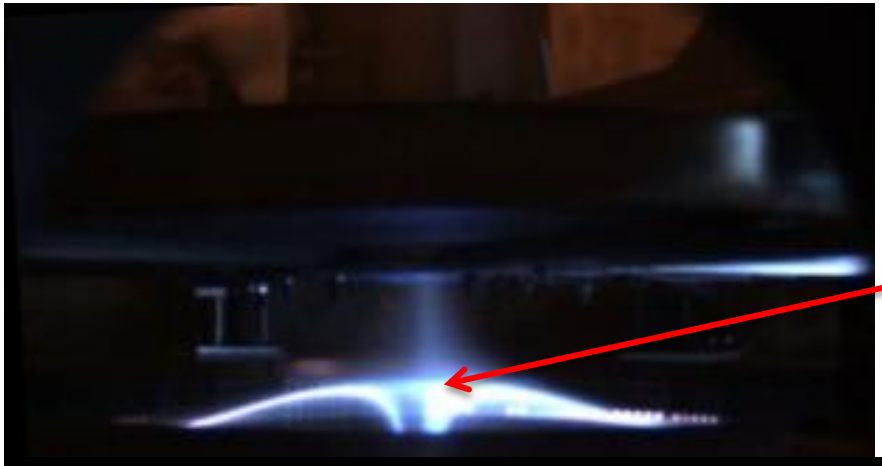


a hairy sphere cannot!



One of the "***tufts***" of the sphere is predominant
in expelling charged fusion products
A SPACE-THRUSTER forerunner?





Nozzle observed in PROTO-SPHERA experiment (2015)

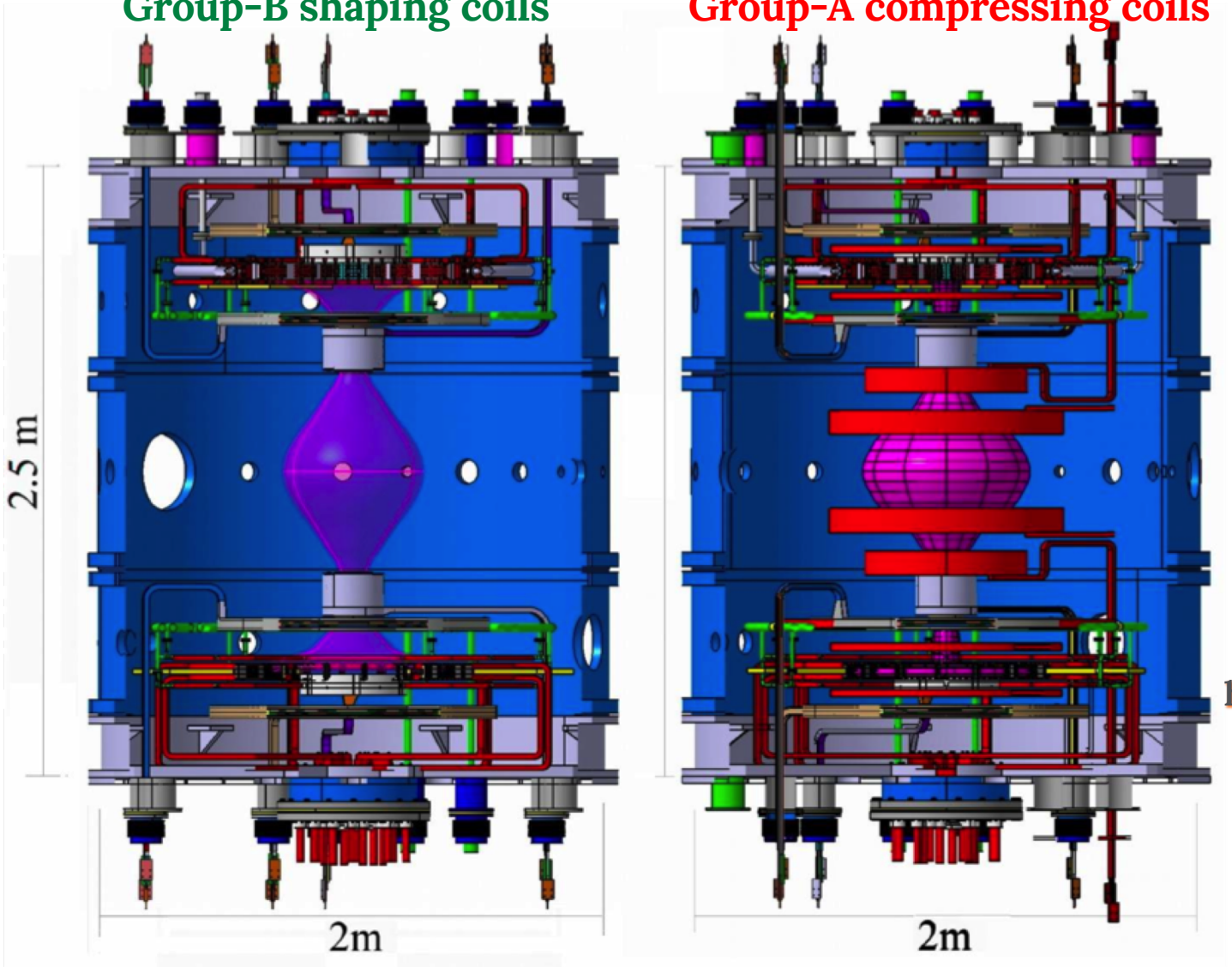
Phase-1 & Phase-2 of the experiment

The experiment now in Phase-1 is a partial set-up of the final machine



Phase-1: 8 PF coils
Group-B shaping coils

Phase-2: 8 PF coils + 10 PF
Group-A compressing coils



Gas-puffed anode

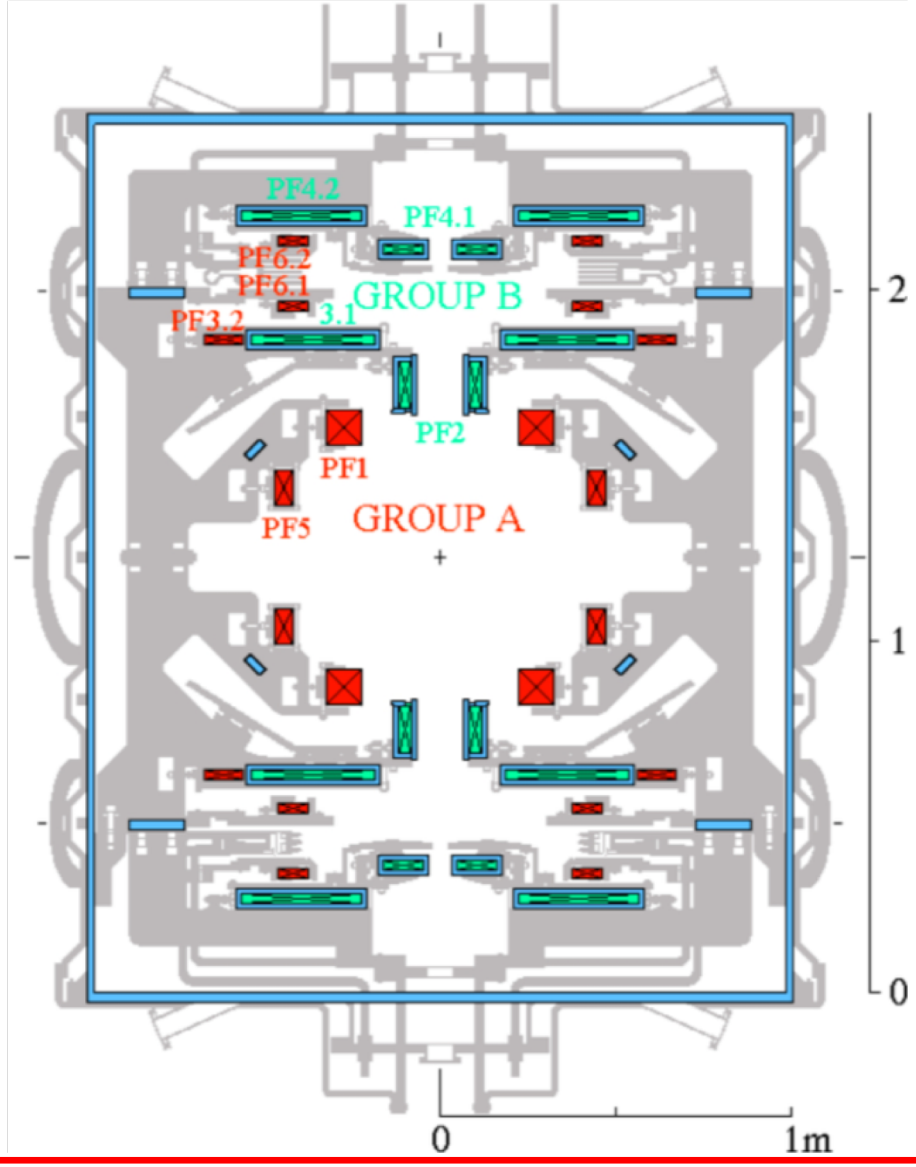
2900°C heated cathode

Centerpost I_e = 10 kA
...2018 Torus I_{ST}= 7 kA...!

Centerpost I_e = 60 kA
ST current I_{ST}= 240 kA

The PF coils are composed by 2 sets, each connected in series

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

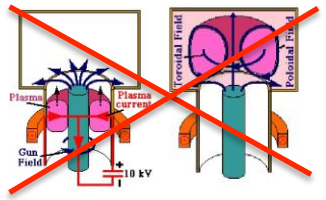




Group A (5+5 coils): ST compression PF coils …*not yet built,* ***but impromptu version in 2019***

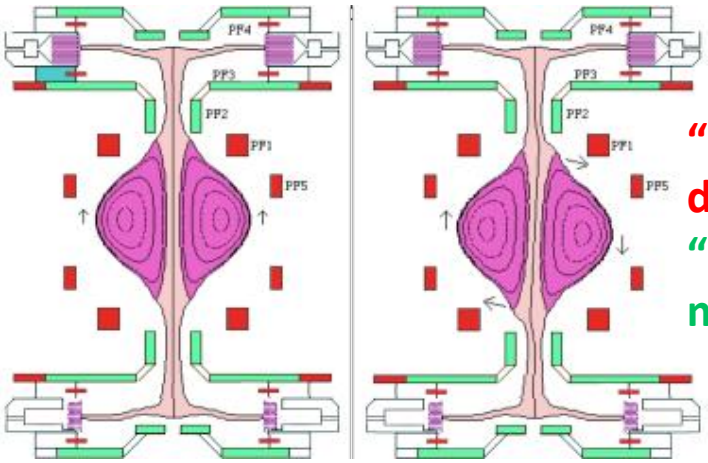
As current increase in Group A should be not faster than 20 ms, coils will be similar to Group B

Ideal MHD stability of PROTO-SPHERA

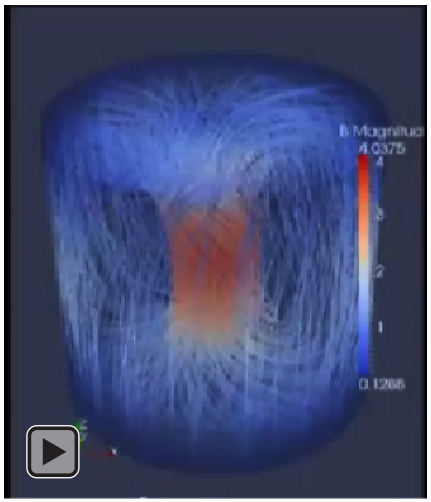


No Spheromak

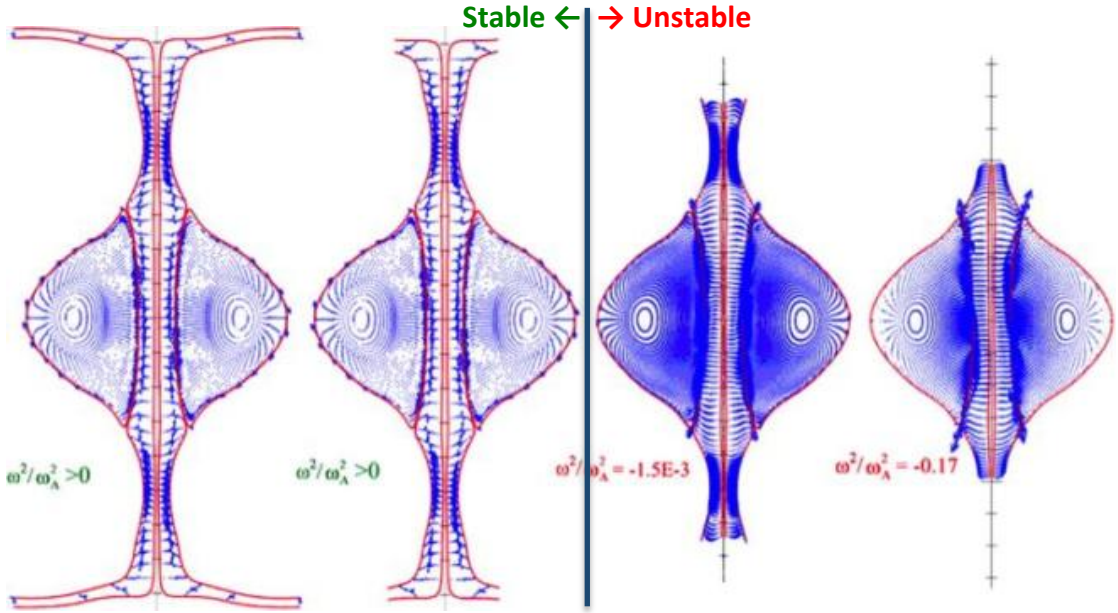
Spheromak tilt instability is due to dipole of containing field opposite to toroidal plasma current dipole



"Group A" PF coils (compression) dipole moment opposes Plasma dipole
"Group B" PF coils (shaping) dipole moment aligned to Plasma dipole



DISK-SHAPED ELECTRODE-FACING PLASMA GUARANTEES IDEAL MHD STABILITY



Cutting shorter & shorter the Plasma Centerpost PROTO-SPHERA at current of 120 kA inside Torus gets destabilized; in absence of any cutting its stability extends to current of 240 kA inside Torus

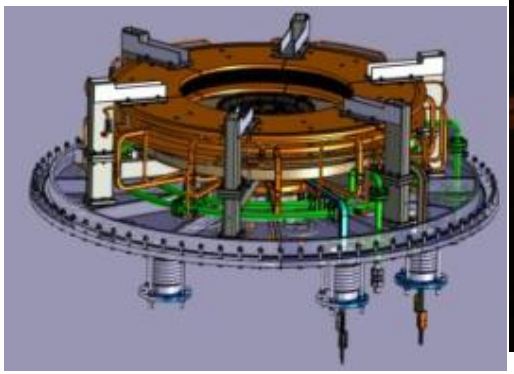
PROTO-SPHERA Electrodes

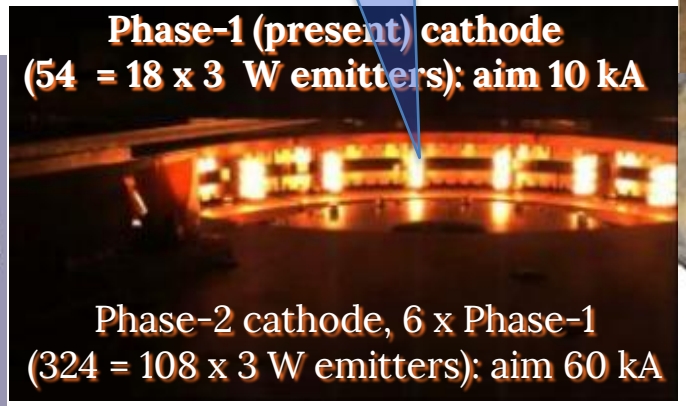






Down: 3000° K heated cathode



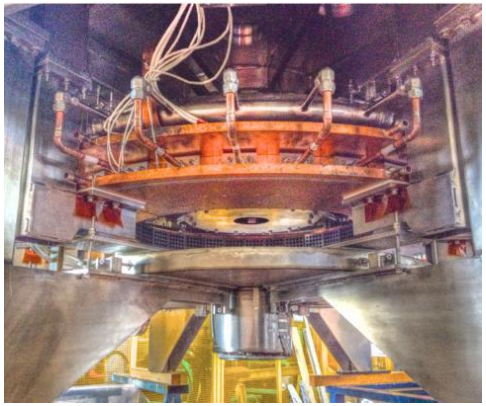


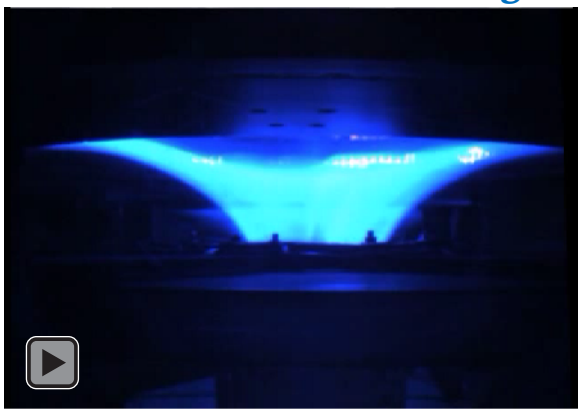


The gas-puffed hollow anode

On top of the anode
degenerate X-point
acts as "plasma-nozzle"

#954 Argon



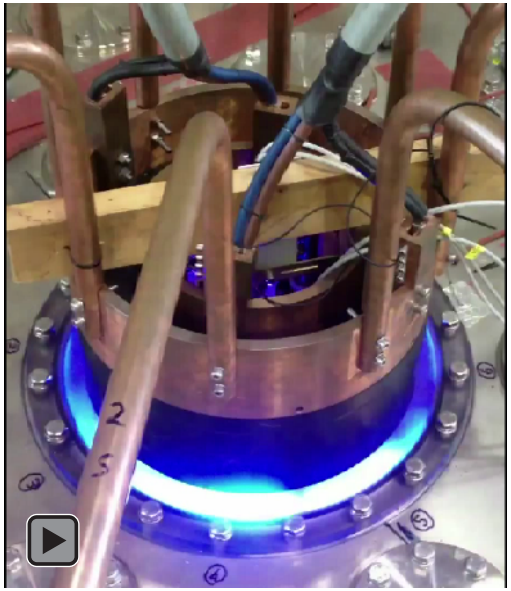




Copper-Tungsten faces plasma
gas puffed from 100s holes

...plasma enters into holes

plasma "nozzles"
produced a metallization on anode & cathode bus-bar flanges:

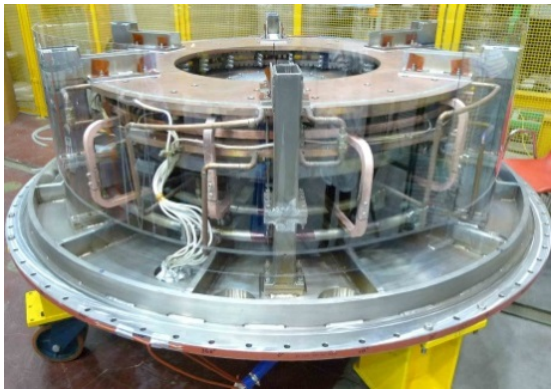


Polycarbonate electrode bus-bar flanges
had to be introduced **on top & bottom**

#567 Argon

The directly heated cathode

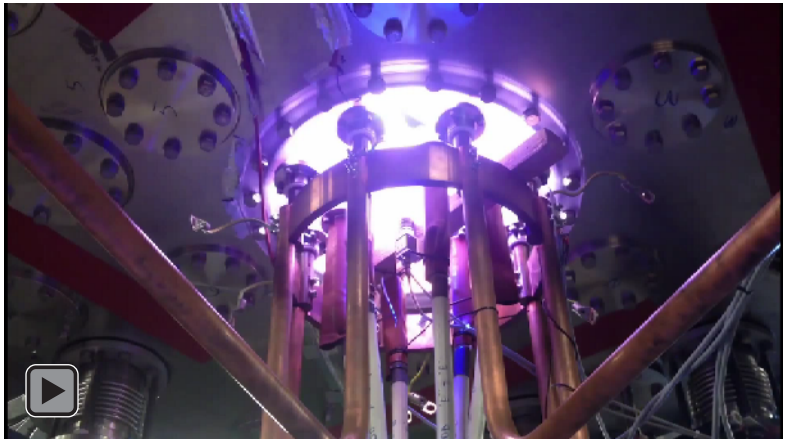
#954 Argon







Directly heated Phase-1 cathode only partially filled
with doubly wound Tungsten-VM filament modules



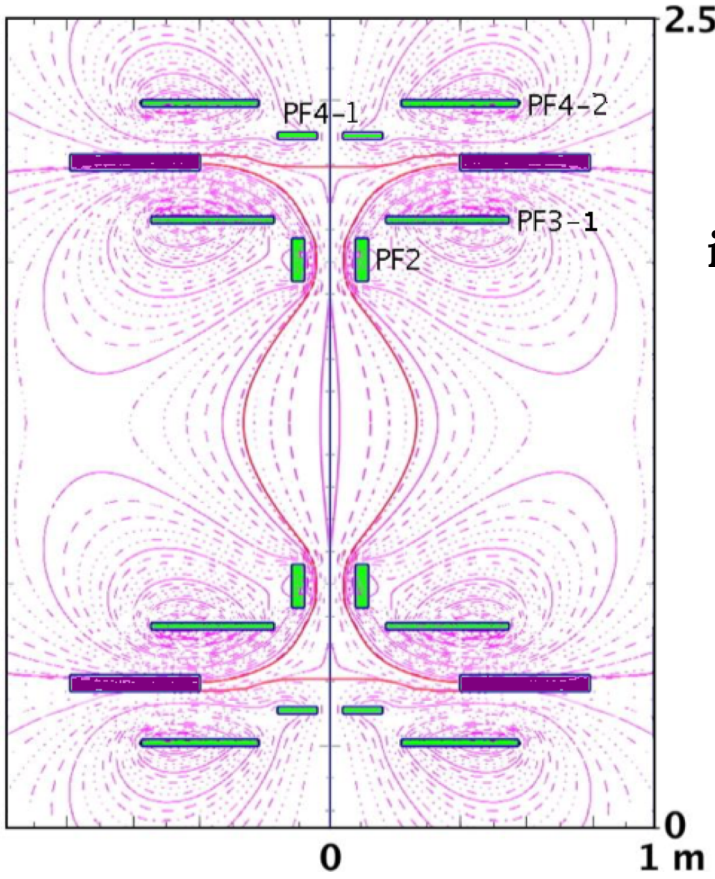
#569 Argon

To obtain the Plasma-Centerpost:

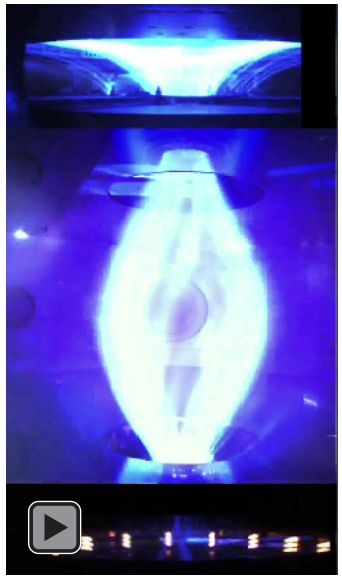
Cathode heated ~30 sec before the plasma,
when at 2900 °C the Group-B-PFInt coils fired,
within ~ 10's ms the Centerpost power supply
fired and the screw pinch plasma is produced

The Plasma-Centerpost produced in Phase-1

Shaping field produced inside the 4 cm thick Aluminum vessel



#614



anode-to-cathode voltage break-down ~90 V increases up to ~200 V at 10 kA

in Argon, equatorial line-averaged electron density $\langle n_e \rangle \propto I_e$
$\langle n_e \rangle = 4 \cdot 10^{20}$ m^{-3} at I_e=10 kA

The Plasma-Centerpost rotates at ω ~ 2π (500) radians/sec

#977



anode-to-cathode voltage break-down ~320 V decreases up to ~220 V at 10 kA

in Hydrogen, equatorial line-averaged electron density $\langle n_e \rangle = 1.5 \cdot 10^{20}$ m^{-3} at I_e=10 kA

These are high-field Tokamak densities!

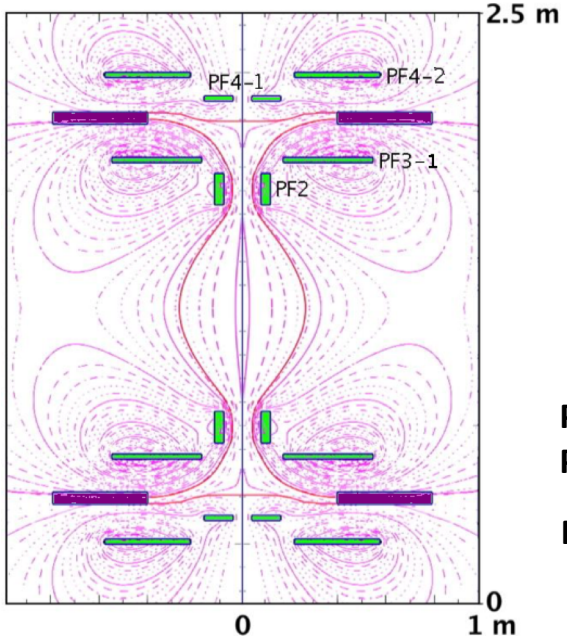
$\vec{E} \wedge \vec{B}$ plasma rotation: no anode-arc-anchoring

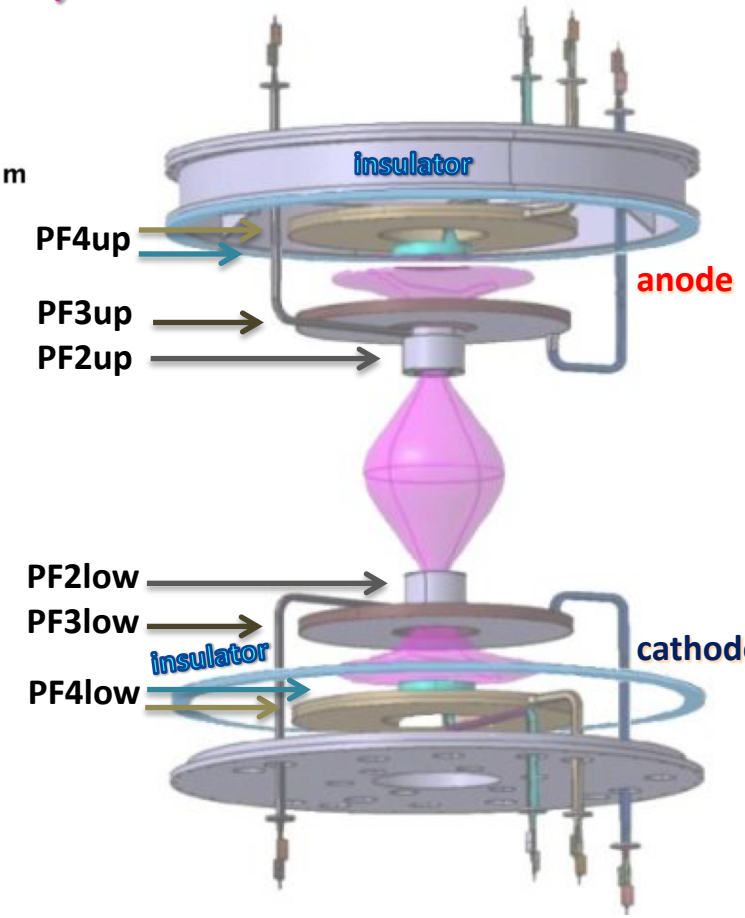


PF coils casings built as floating, charged by the plasma
also upper\lower extensions & lids are floating

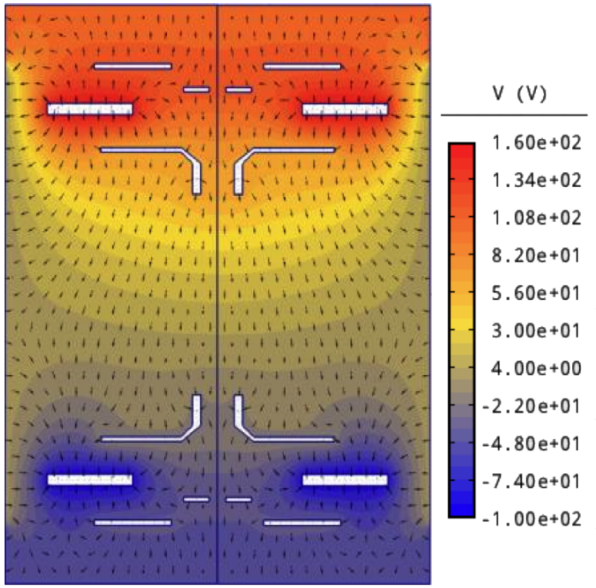
magnetic field is up\down symmetric but electrostatic field not up\down symmetric

B↑





E↓



$\vec{E} \wedge \vec{B}$ drift opposite in the anode and cathode region, but not compensated:
the top anode dominates & determines a clockwise plasma rotation (from top of machine)

Taking care of electrostatic boundary conditions



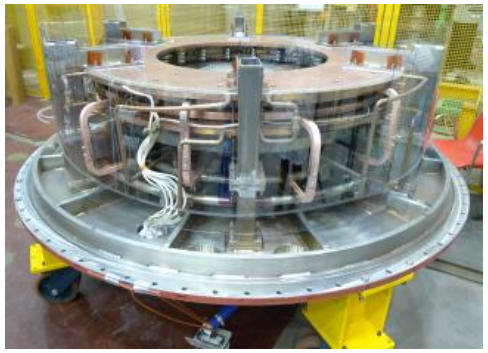
2mm thick Polycarbonate linings for:

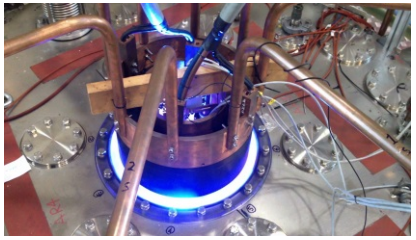
*internal Al vessel



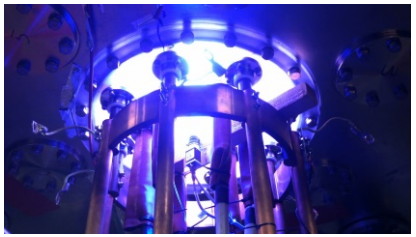
*rear of anode

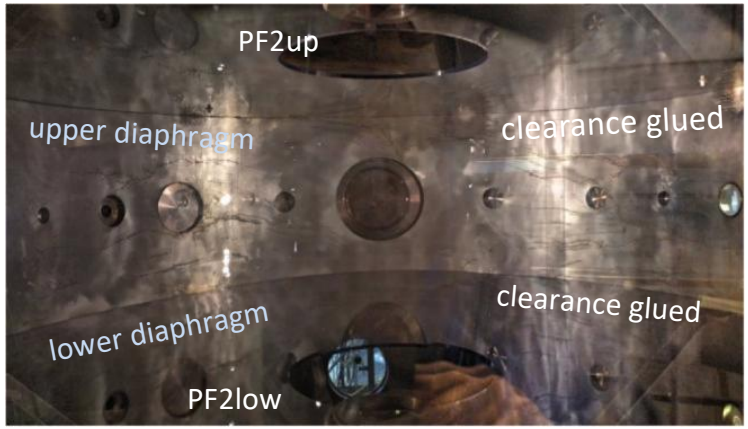
*rear of cathode



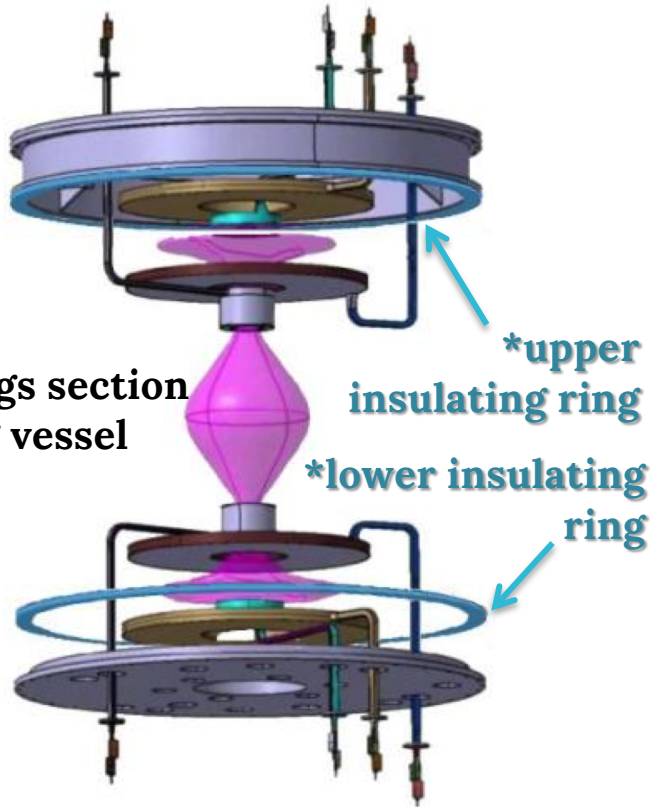


*4cm thick Polycarbonate flanges for bus-bars





*2 Polycarbonate diaphragms glued to the internal lining



2 insulating rings section the conducting vessel

*upper insulating ring

*lower insulating ring

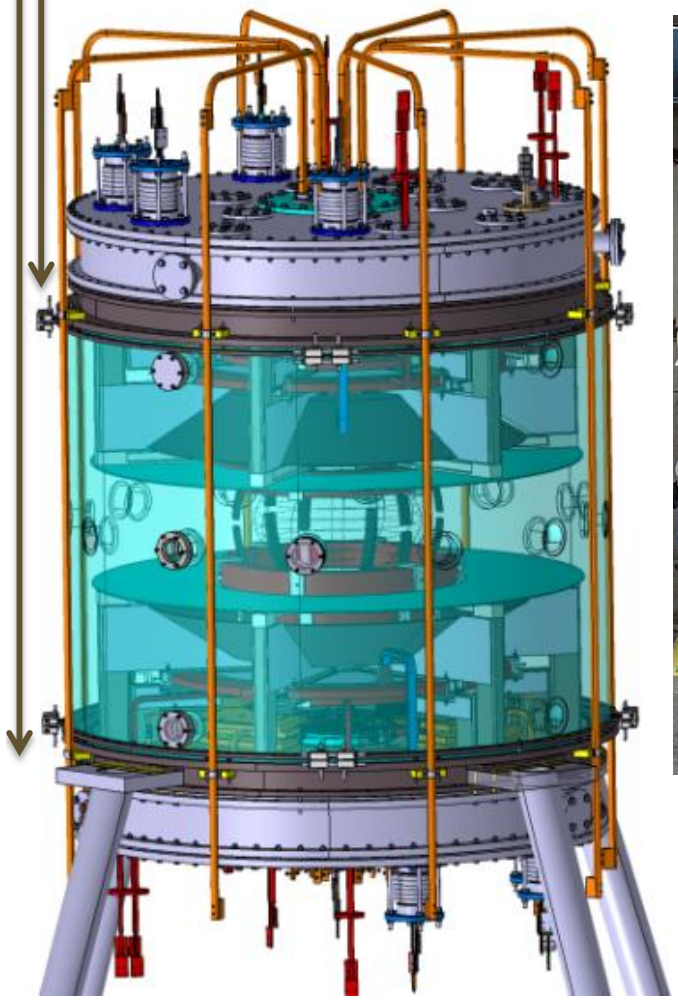
January 2018:
all these cures allowed to obtain Hydrogen plasmas

Insulating & transparent new vessel in 2019

will substitute the Aluminum vacuum vessel with a Poly methyl methacrylate (PMMA) transparent and insulating vessel (9.5 cm thick, 2m ⦸, 1.7 m high), endowed with 20 ports

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



Reynolds
POLYMER TECHNOLOGY, INC.
Building the Impossible





Magnetic Boundary Conditions changed

4 external PF coils added ...fed in series with the Group-B-PFInt coils,

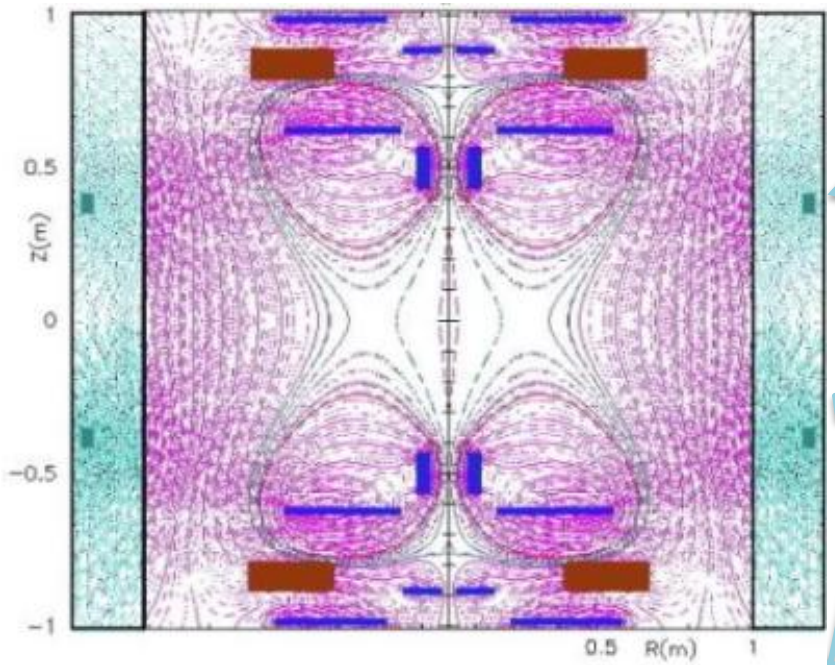
from April 2018 a further Super-Capacitor power supply feeds some of the PFExt coils

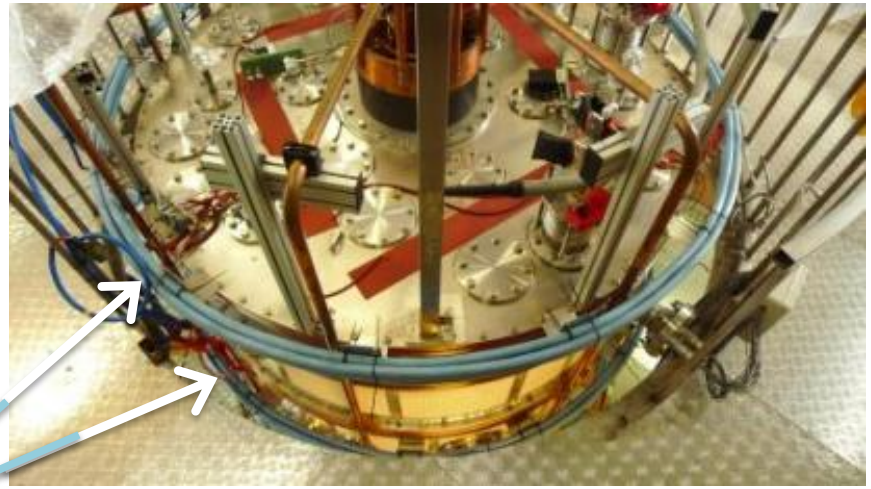
Hydrogen Centerpost at full current =10 kA seemed quite inclined to eject a Torus ...an added vertical field ...was used as midwife!

Plasma fired after 0.60 s of PF current
to allow for skin current diffusion in Al vessel



#983, 10 kA Hydrogen





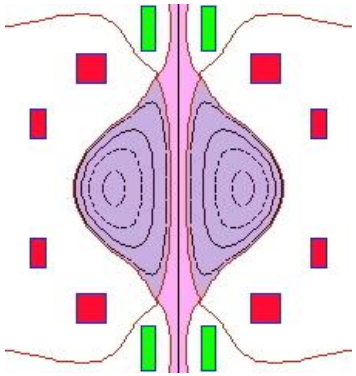
4 external PFExt (each 16 wires 25 mm^2)



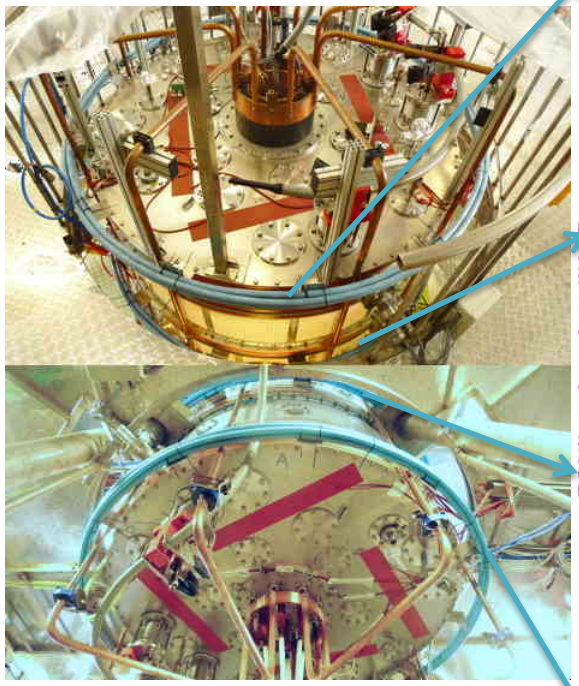
Plasma tori foreseen for Phase-2 tried in Phase-1

4 external PFExt coils added

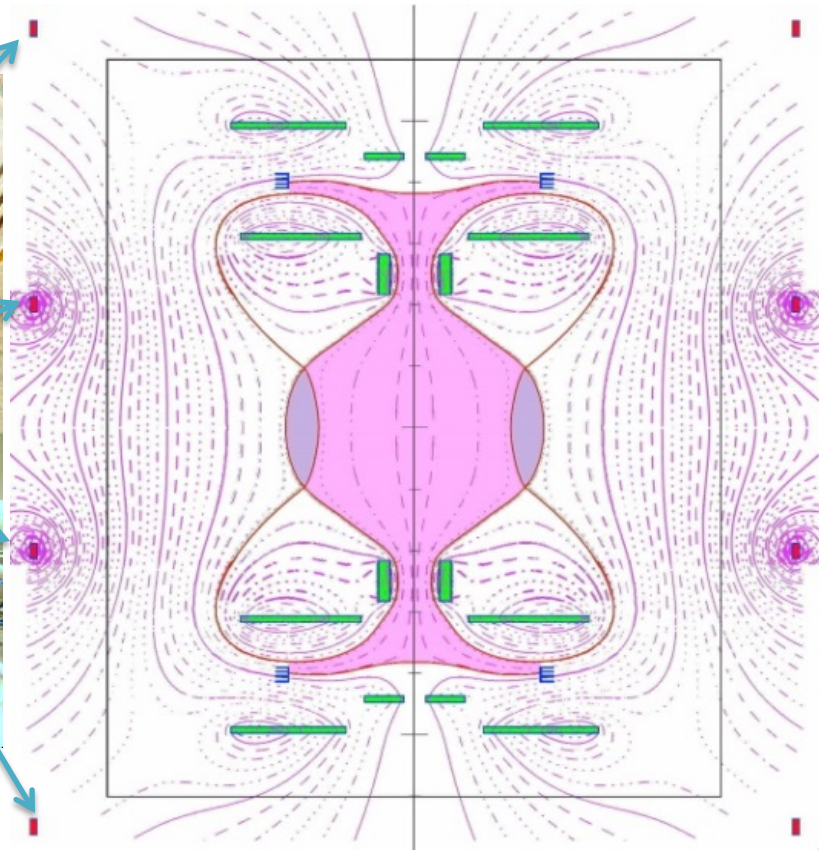
Phase-2 Spherical Torus:
Phase-1 Centerpost I_e=8.5kA, then in 20 ms up to I_e =60kA



along with increase of coil current in Group-A-PFInt



in 2 PFExt near equator current flows in opposite direction to toroidal current inside the Plasma-Centerpost

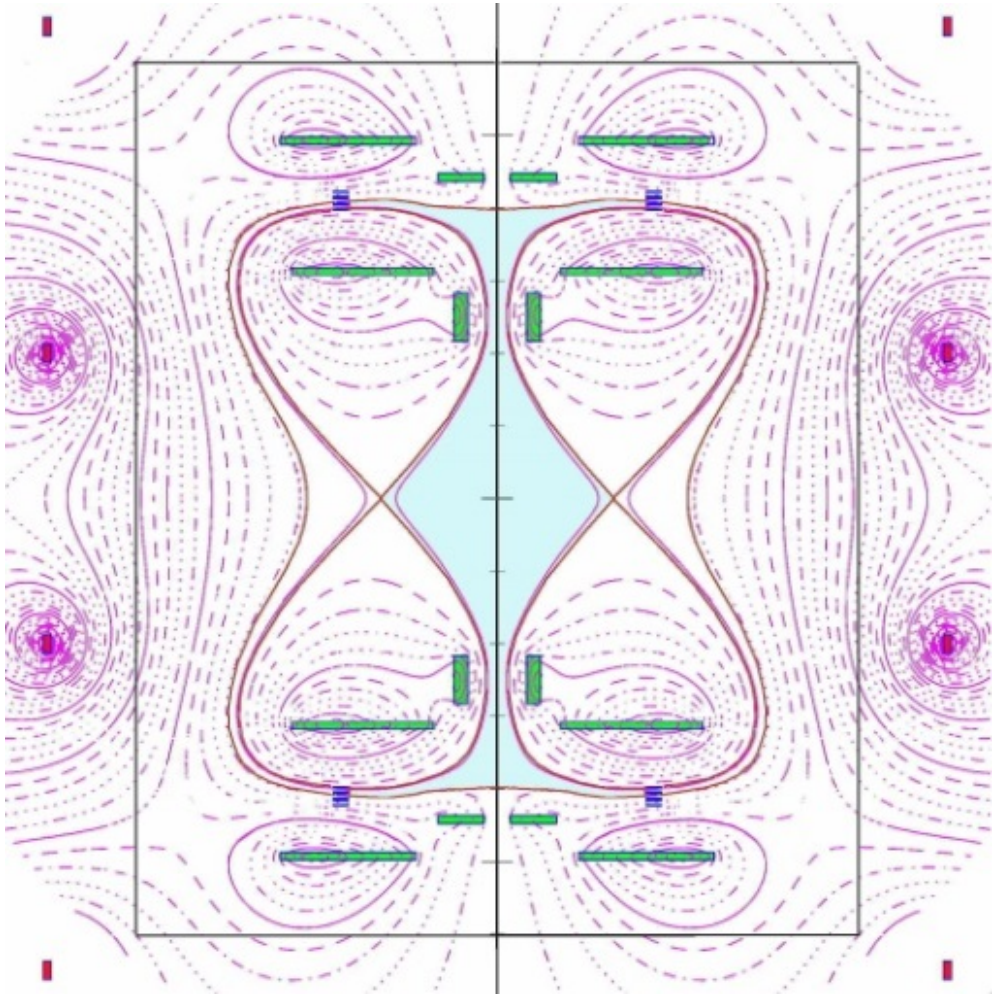


If torus forms, outward force due to toroidal plasma current enlarges the Plasma-Centerpost into a portion of sphere

Plasma fired after 0.60 s of PF current (skin current diffusion in Al vessel)
limits torus duration to 0.5 sec and imposes static magnetic field at torus formation

Argon tori not obtained below I_e current threshold

If the torus does not appear, the calculated equilibrium of Plasma-Centerpost has 2 ordinary X-points (B_{pol}=0) on equator ~32 cm from symmetry axis, a quite narrow Plasma-Centerpost



#1098



I_e~3 kA

below electrode plasma current threshold I_e~ 8.5kA narrow Plasma-Centerpost

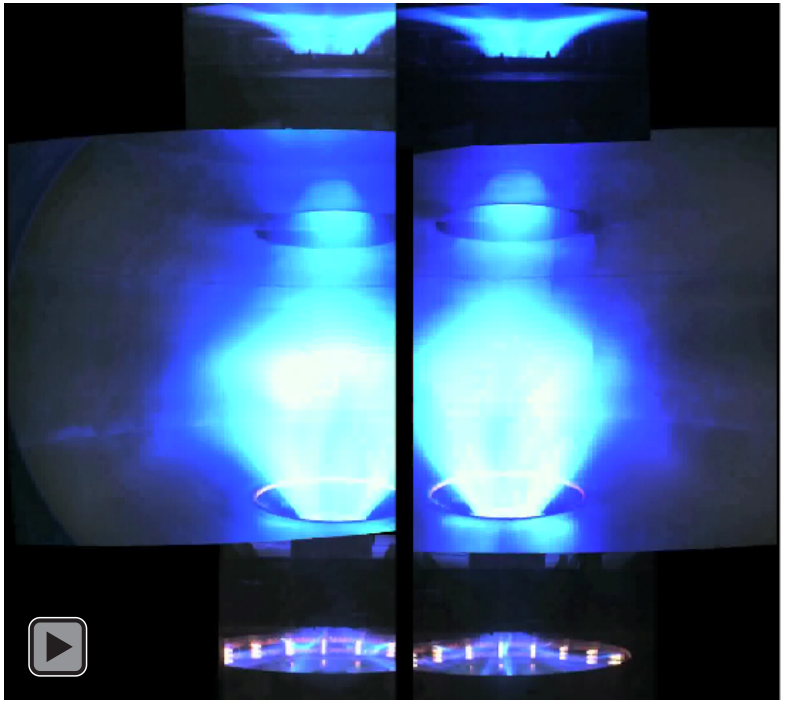
threshold expressible as $\iota_e \geq 1/2$
(rotational transform ι_e **=toroidal turns of lines of force from cathode to anode)**

Argon tori obtained above I_e current threshold

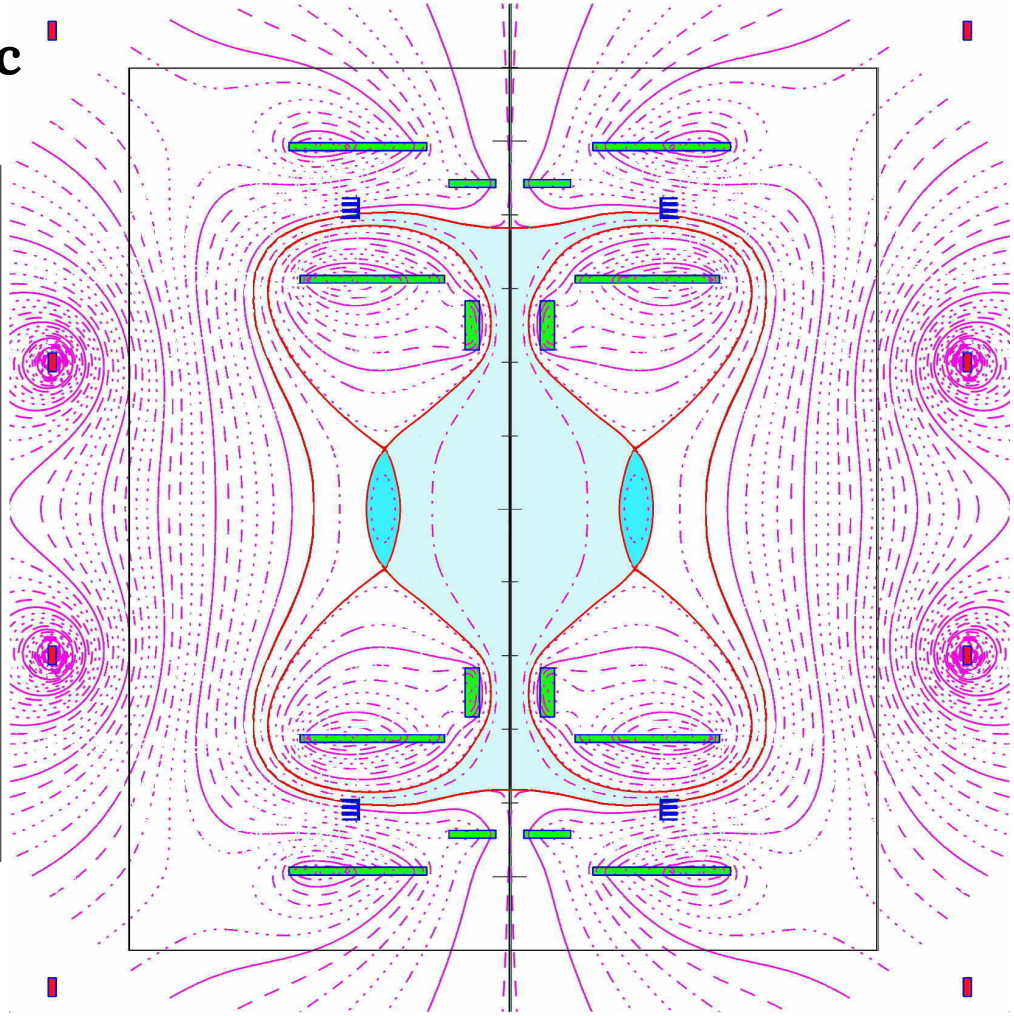
When the current exceeds I_e ~ 8.5 kA, rotational transform of the Plasma-Centerpost $\iota_e \geq 1/2$

Argon Centerpost takes the shape due to the torus formation

in presence of an axisymmetric double-null (DN) divertor



#1149 & #1160



#1160

break-down ~ 200V with torus (80 *without*)
increases up to ~220 V at 10 kA (200 *without*)

Argon tori have been sustained up to 0.5 sec

fitting the distance between the 2 X-points of the divertor:
I_{ST}=5 kA in the Argon-torus

The SuperCapacitor power supply allowed for H-tori

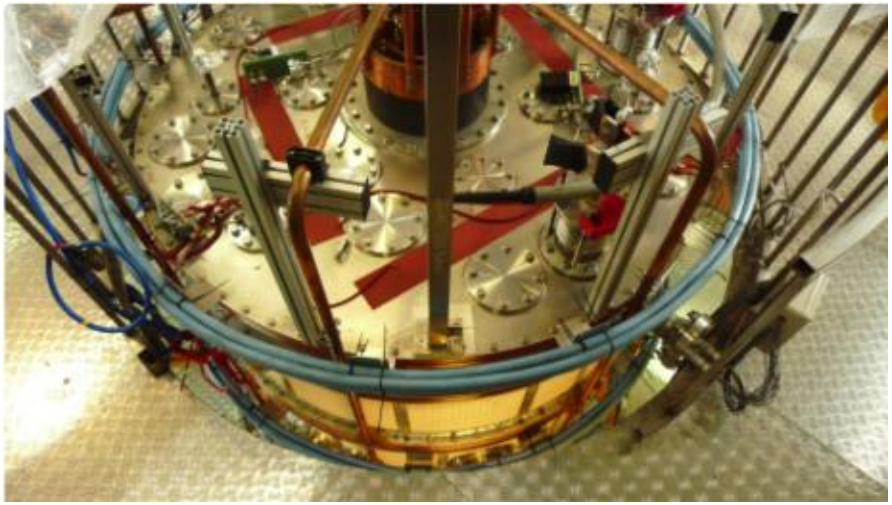
A new Super-Capacitor power supply (90 V, 2 kA, many sec) essential for Hydrogen Tori: Group-B-PFInt power supply was already delivering its maximal Voltage & Current, an additional + 25% Amperes•turns were fed by Super-Capacitor



The production of Argon Tori was obtained fine tuning by -12.5% the maximum Ampere•turns of the Group-B-PFInt power supply:

$$\frac{1.25\ Bvert}{0.825\ Bvert} = \frac{7\ \text{kA in H-tori}}{5\ \text{kA in Ar-tori}}$$

upper PFExt: + 8 turns•1.9 kA in series PFInt



upEquator PFExt: -8 turns•1.9 kA in series PFInt

PFExt: -4 turns•1 kA SuperCap

downEquator PFExt: -4 turns•1 kA SuperCap

PFExt: -8 turns•1.9 kA in series PFInt



lowest PFExt: + 8 turns•1.9 kA in series PFInt

Hydrogen tori

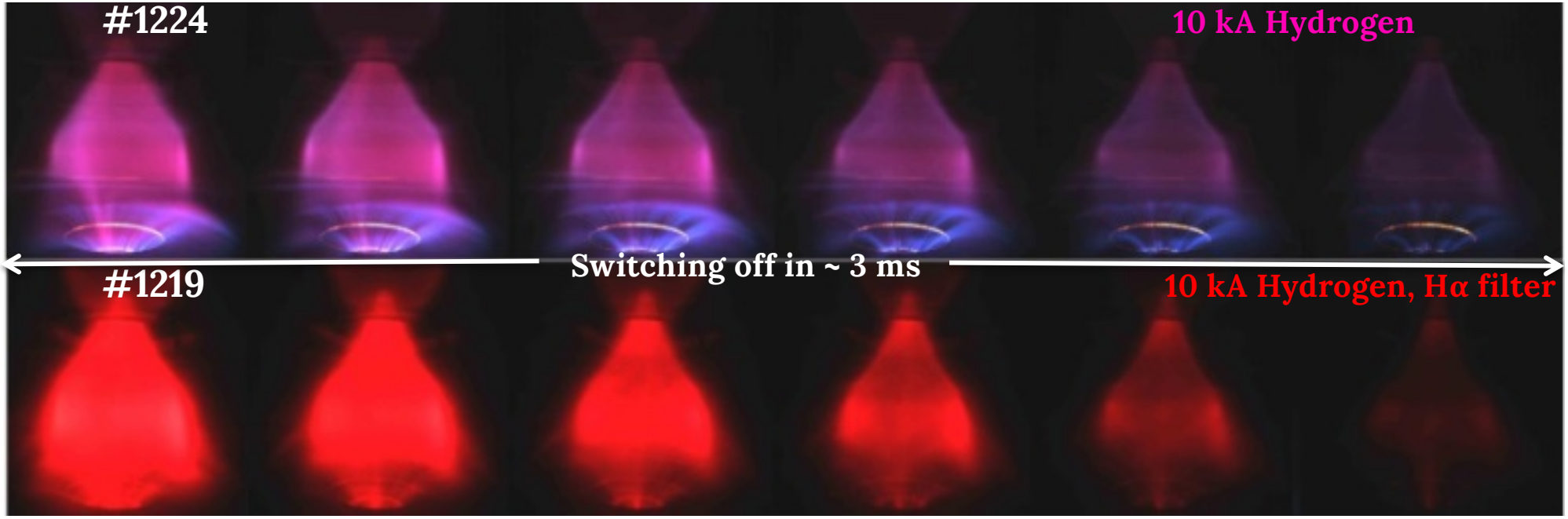
5 ms after break-down, ç reaches flat-top in ~6 msec

#1202



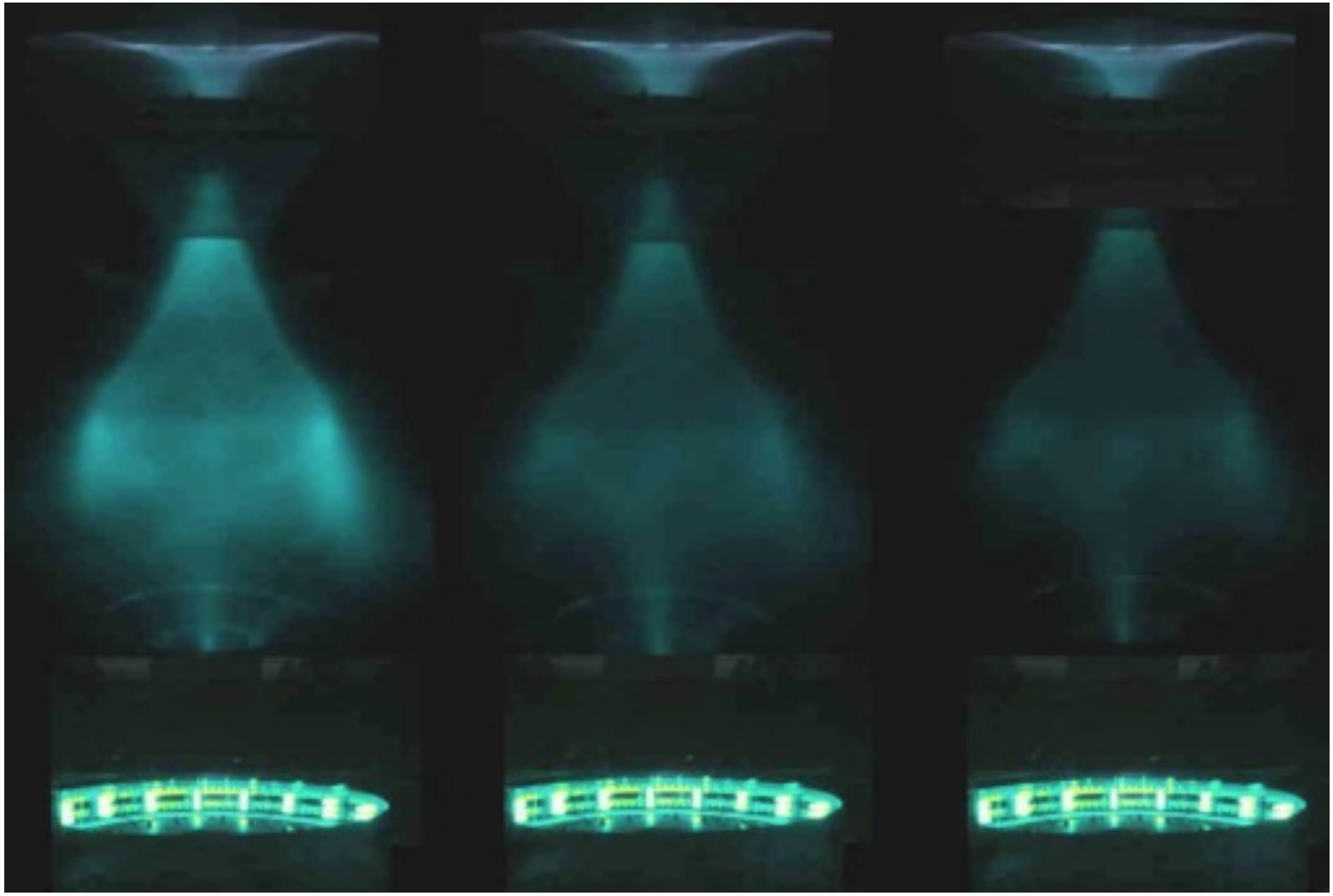
$\frac{1\ frame}{ms}$

Hydrogen-tori most evident shortly after the plasma break-down or during its ramp-down



A Magnetic Confinement scheme sustainable by permanent magnets?

Toroidal current is confined



#1219, 10 kA Hydrogen, Hα filter, but shown by cold-warm color involution

The confined toroidal current flowing inside the torus persistence longer than the current flowing between electrodes: the torus in the last ms is kink unstable:

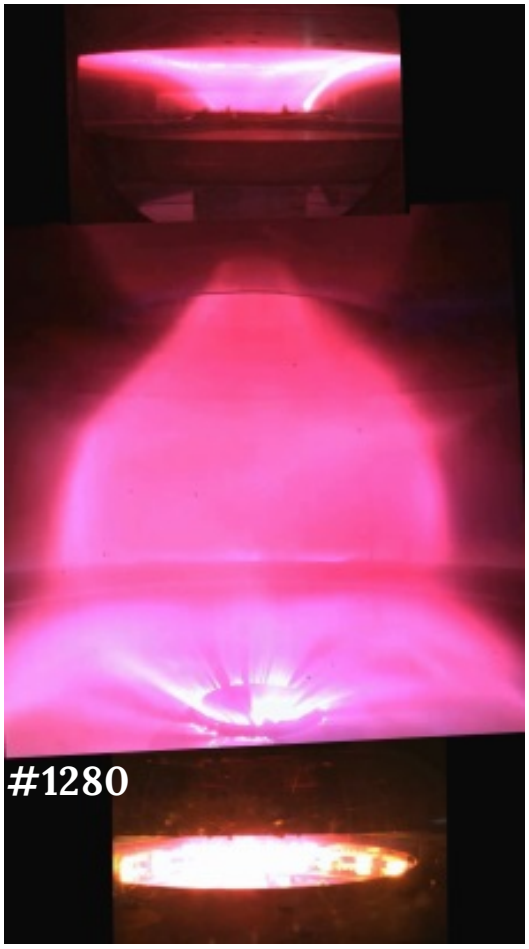
$$\frac{\text{torus poloidal field}}{\text{torus toroidal field}} = \frac{\text{toroidal confined current}}{\text{Plasma–Centerpost current}}$$ becomes too large

The dominance of the lower (cathode) divertor fan

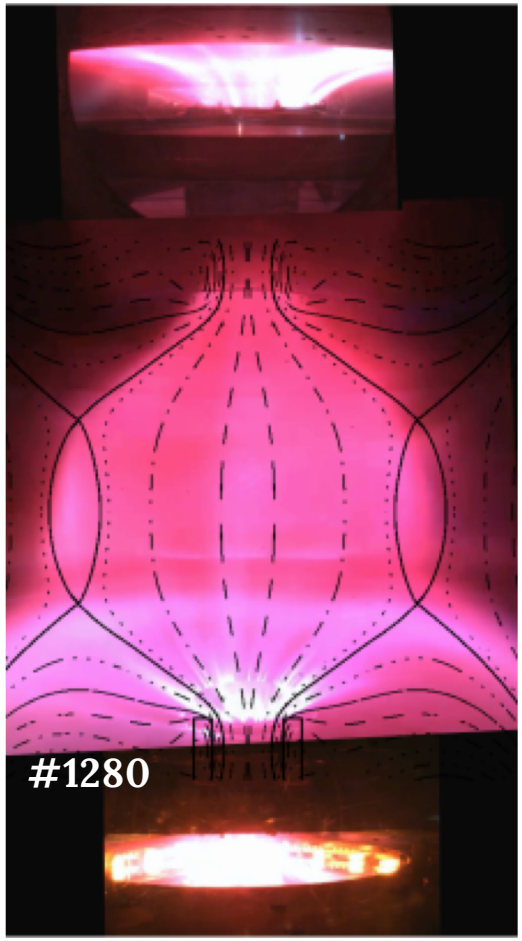
Tori are limited by a magnetic separatrix with 2 conical divertor fans.
In Argon Hydrogen the lower (cathodic) divertor fan divertor is dominant



lower divertor with lower polycarbonate diaphragm (April 2018)



lower divertor with lower AISI304 divertor plate (July 2018)

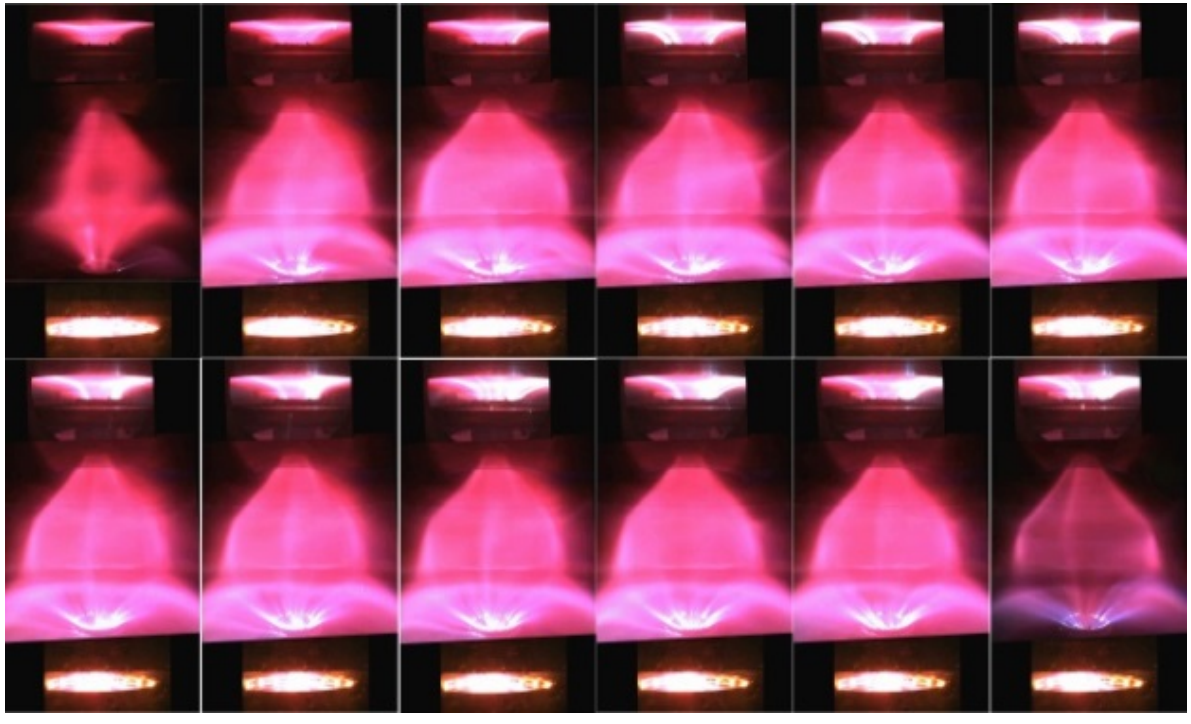


fitting the distance between the 2 X-points of the divertor: I_{ST}=7 kA in the Hydrogen-torus

Indeed caused by deterioration of cathode, will be cured in Spring 2019

Torus persists till anode-cathode voltage is applied

#1280 with AISI340 divertor plate



break-down ~ 360 V with torus (320 V *without*)
increases up to ~ 250 V at 10 kA (220 V *without*)

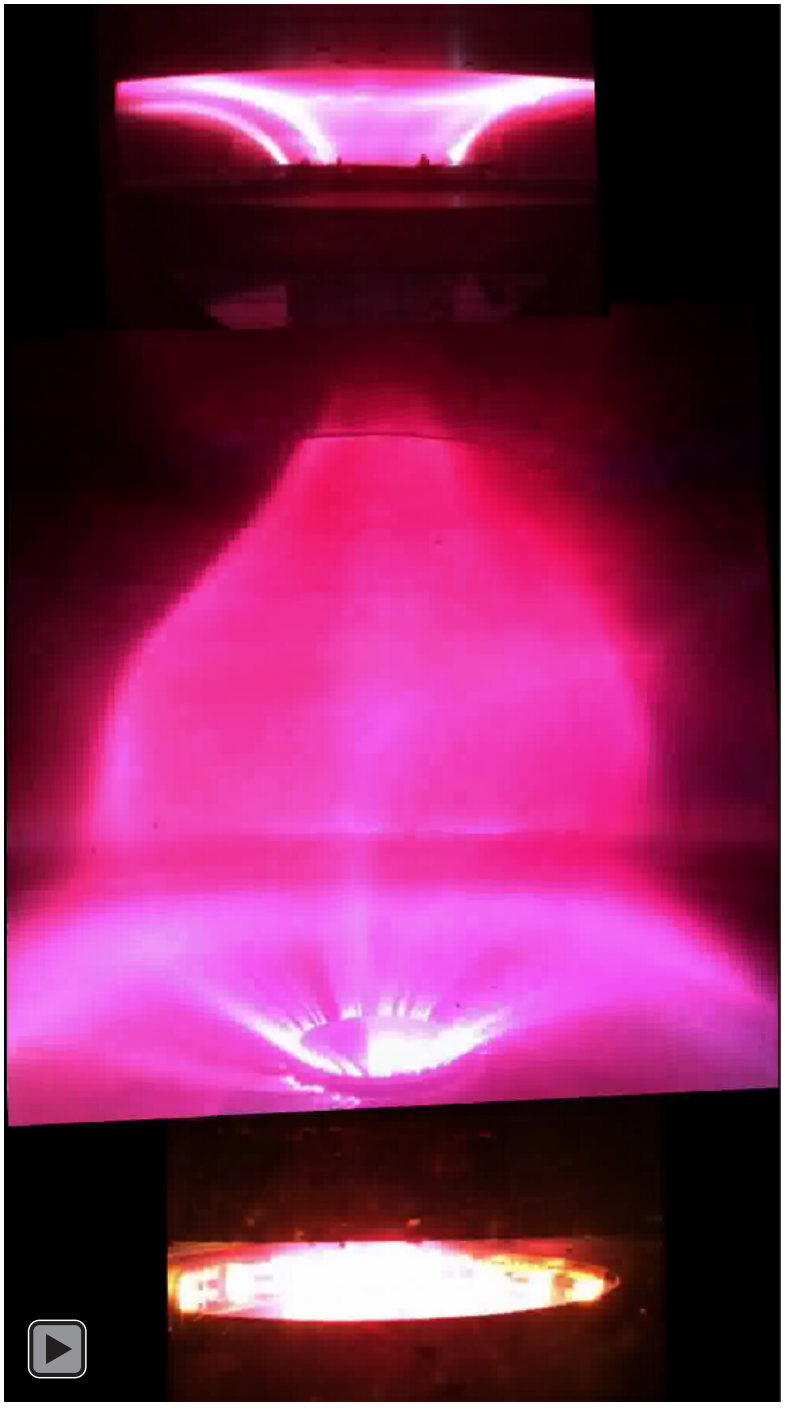
Hydrogen tori have been sustained up to 0.25 sec
(*to avoid damages due to spurious plasma current*)

Slim tori aspect-ratio A=R/a~7
& elongation b/a=κ~3.5

...in a Tokamak could not even be produced & sustained

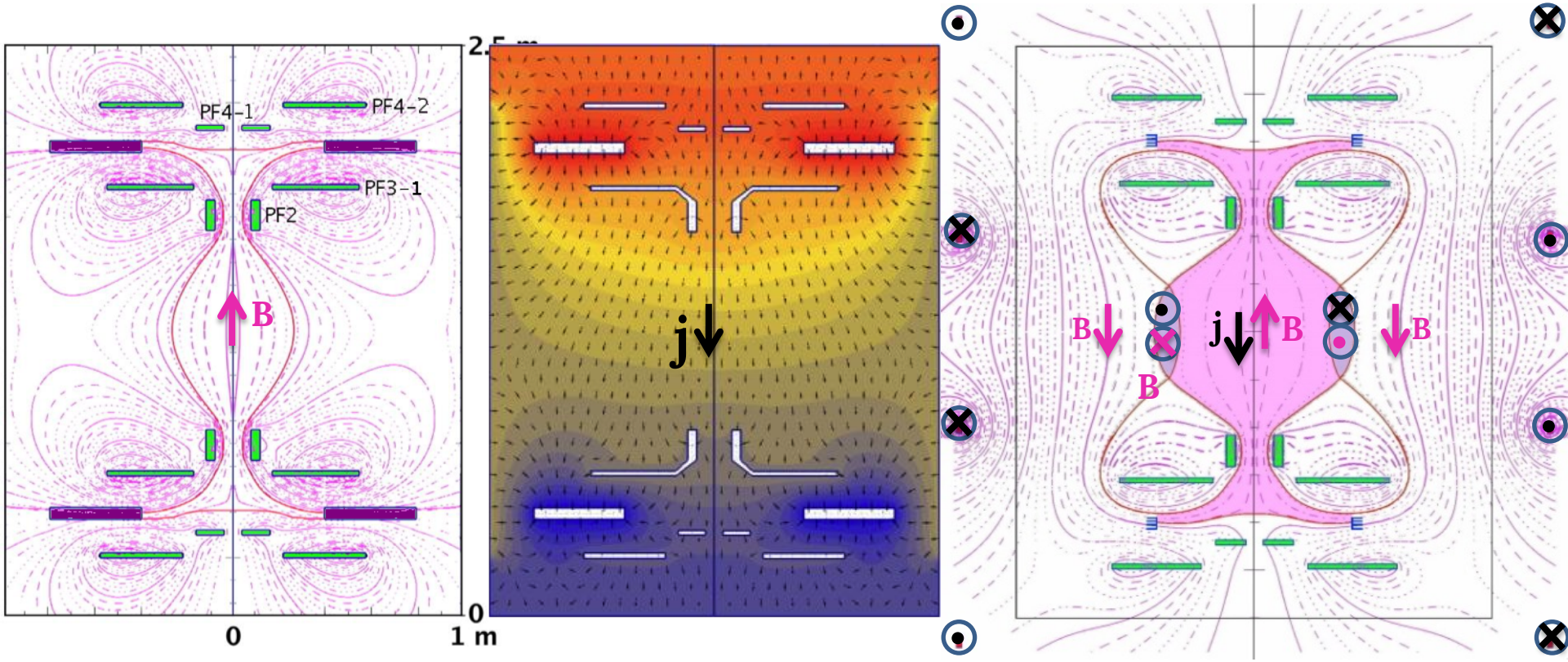


DC voltage



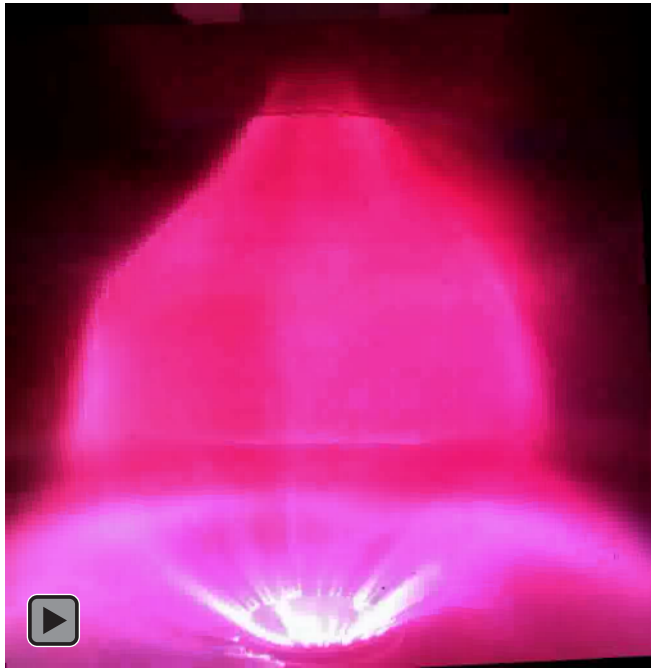
Same sign $j \cdot B$ all over the plasma: helicity injection

direction of j *in the plasma torus: opposite to direction of* j *in equatorial PFExt coils*
sign of $j \cdot B < 0$ *is negative in the Plasma-Centerpost*
sign of $j \cdot B < 0$ *is negative as well in the plasma torus*

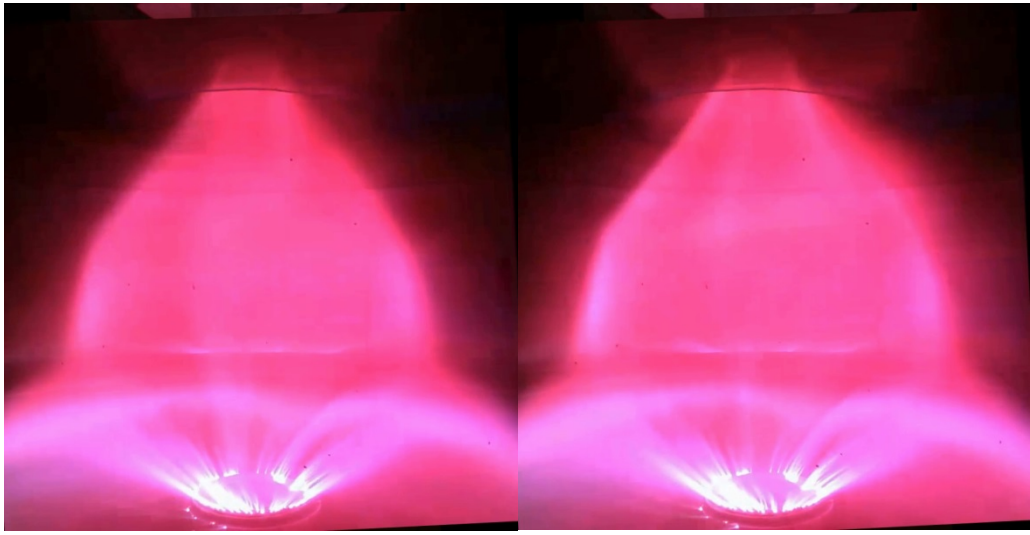


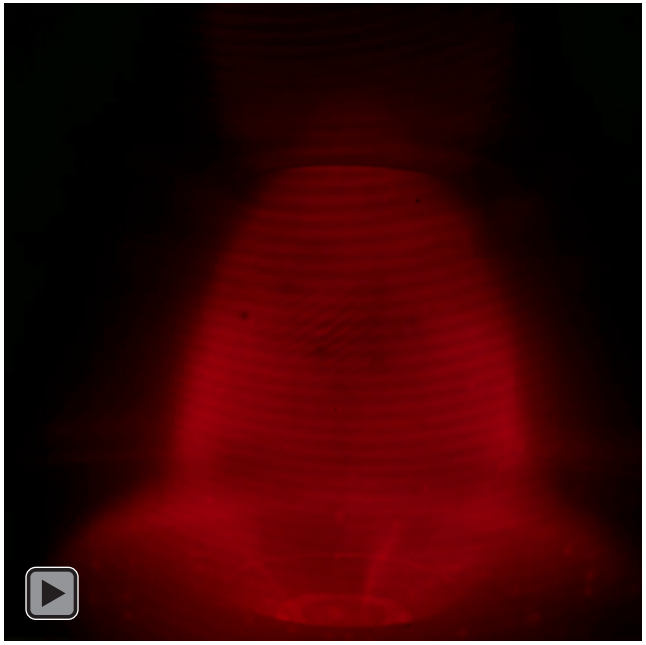
This is a clear sign that DC Helicity Injection is in charge of transferring plasma current from the centerpost to the torus, just as it was imagined when the PROTO-SPHERA experiment was designed

Reconnection bursts shake the plasma, every 2-3 ms

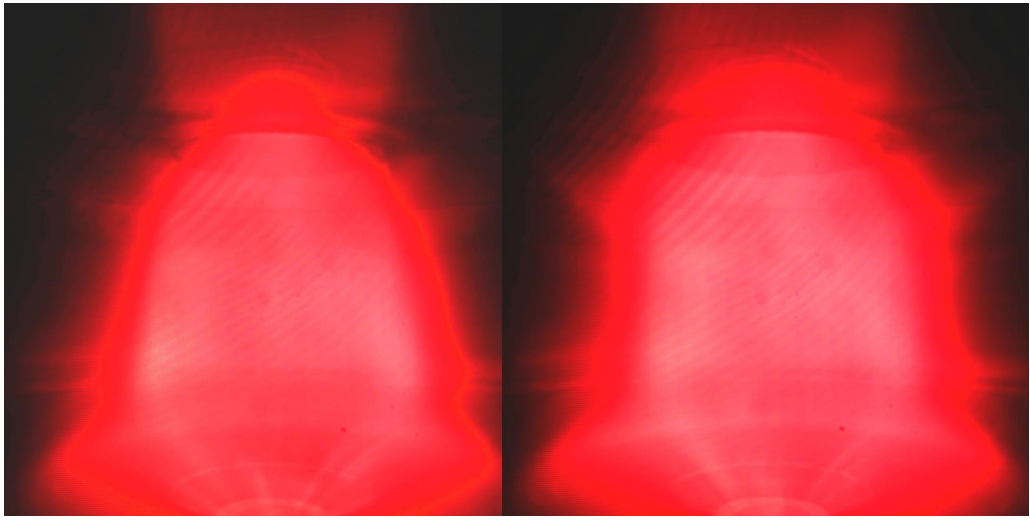


#1280
Visible
light



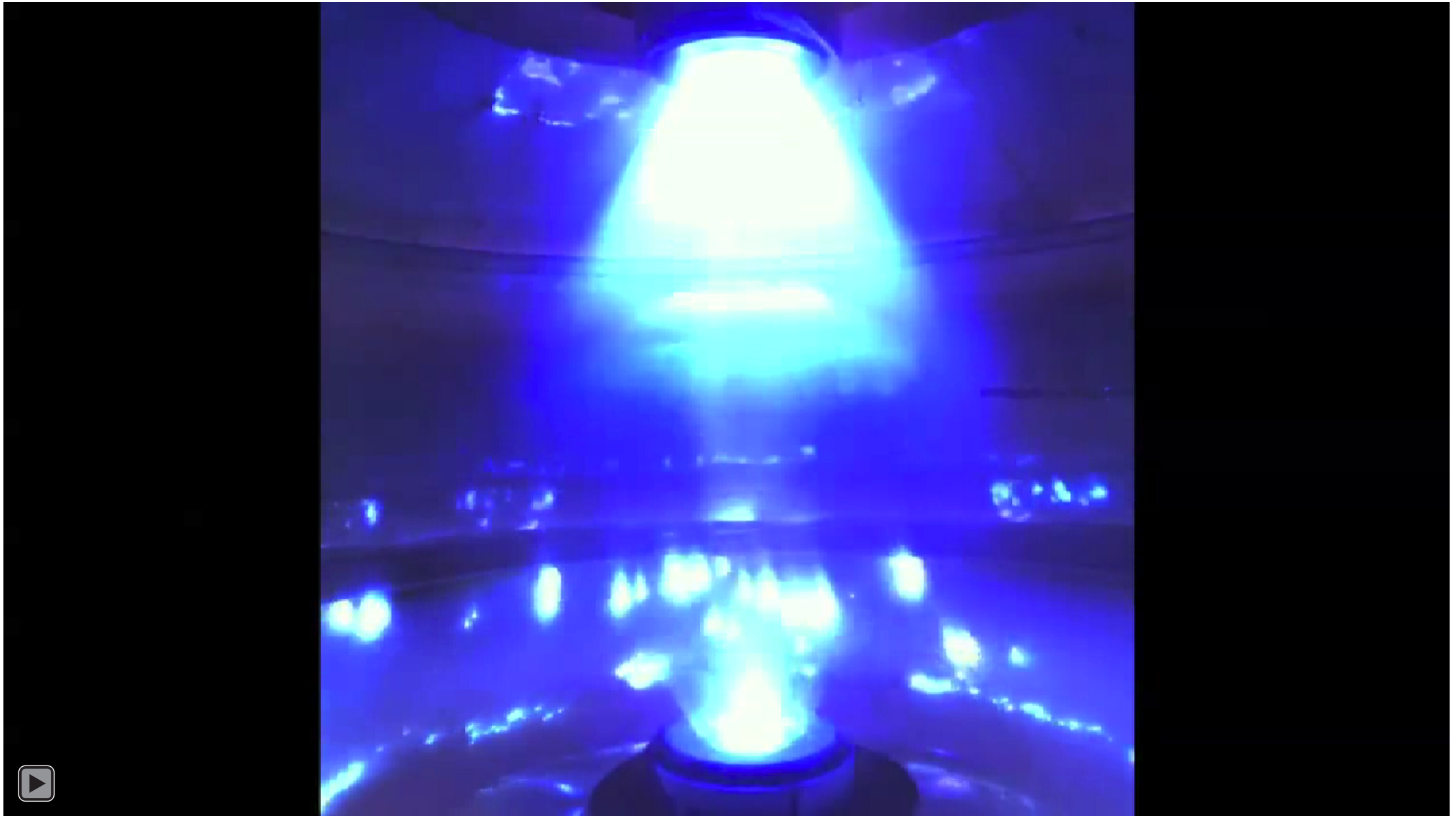


#1219
H-alpha
filter



2D approx. magnetic reconnections at ordinary X-points
3D effects: diffused (ergodic) character of the X-points

Differential rotation as a further indication of reconnections



...differential rotation of Argon plasma on lower divertor plate...
evidenced in “Christmas-tree plasma” on Yuletide Eve, Dec 20 2018!
...due to totally deteriorated cathode conditions

Major surprise: current carrying torus formed and sustained in an external magnetostatic B

But in Phase-2 operations, a "slow" current ramp (~20 ms) will be required to produce Spherical Tori with I_{ST}= ¼ MA

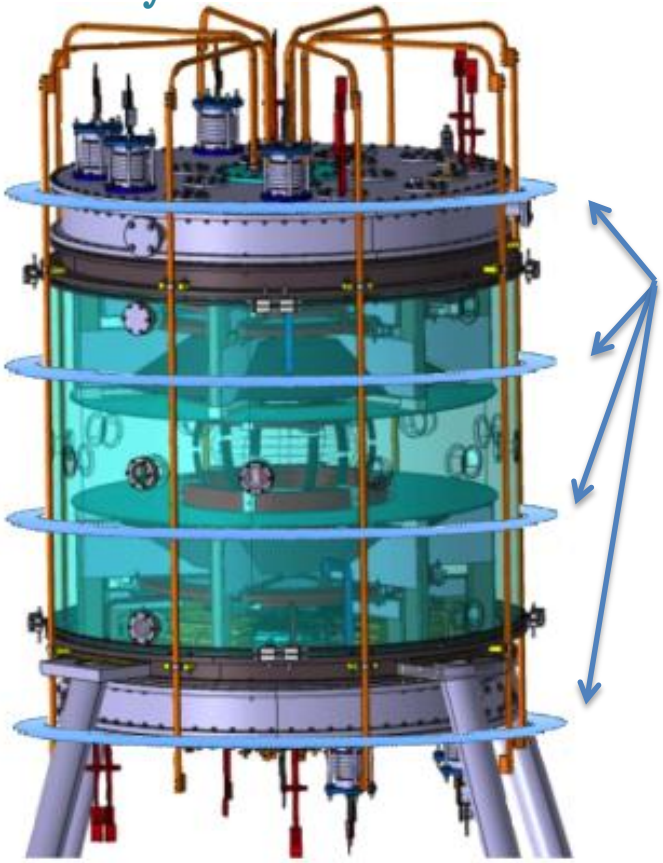
Up to 3.5 MW of plasma light!



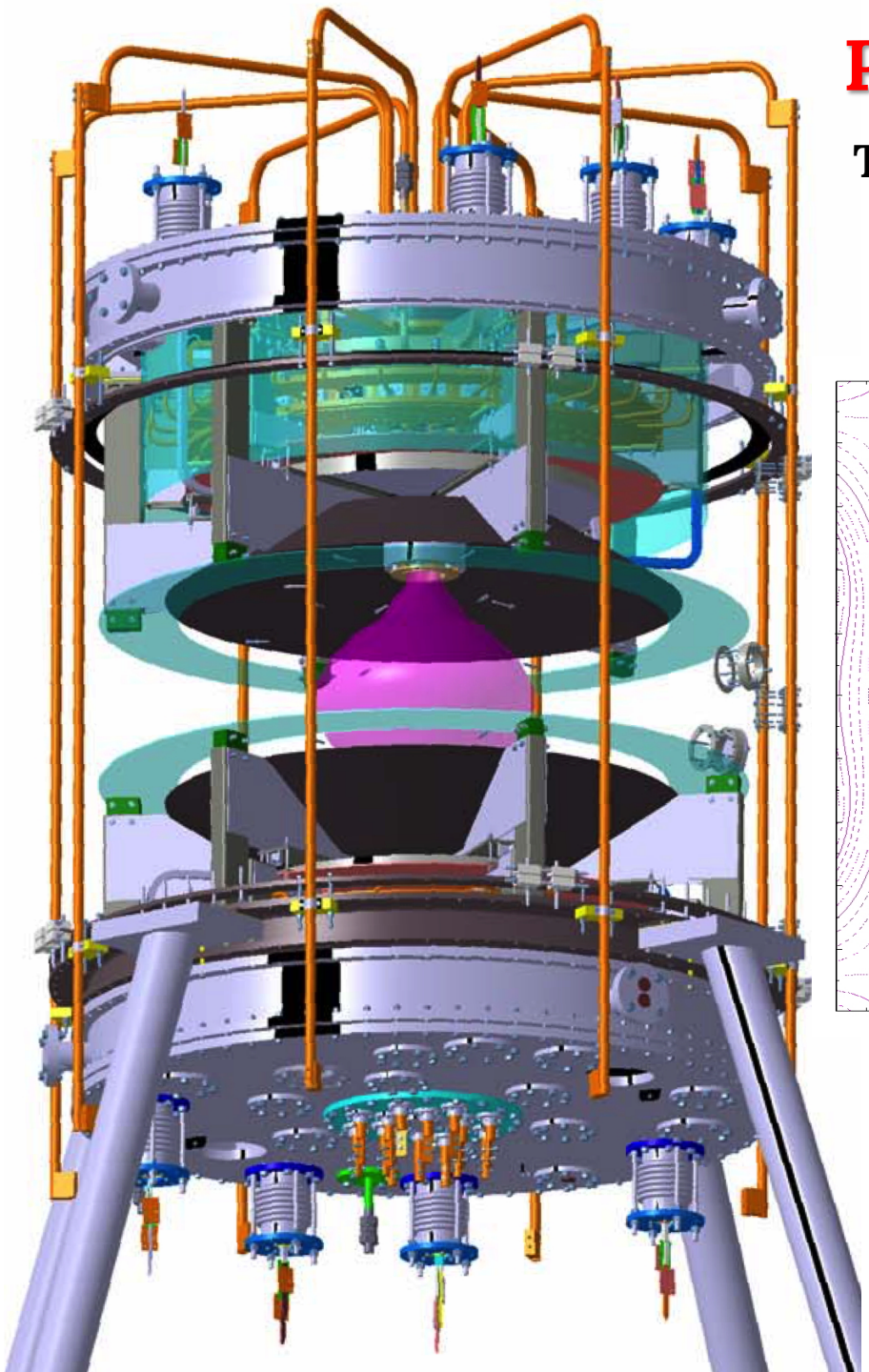


Soldering goggles in control room!

In 2019, new insulating PMMA Vessel (no vessel skin effect) will allow to form from preexisting Plasma-Centerpost & create Hydrogen Tori with 20 ms rise time, try and assess differences with static formation

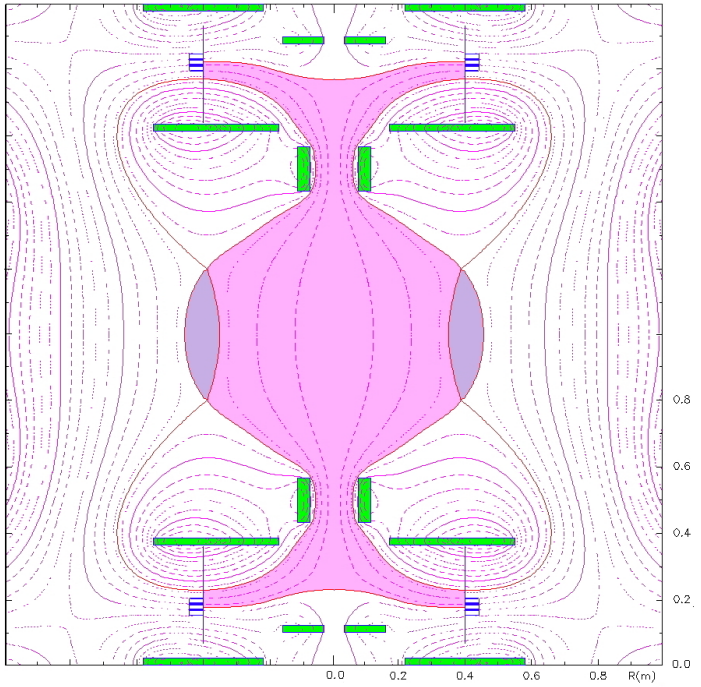


substitute impromptu PFExt coils with larger cross-section (240 mm^2) flexible cables 8+12+12+8 turns (top to bottom) flexible turn number, fed by Super-Capacitor power supply

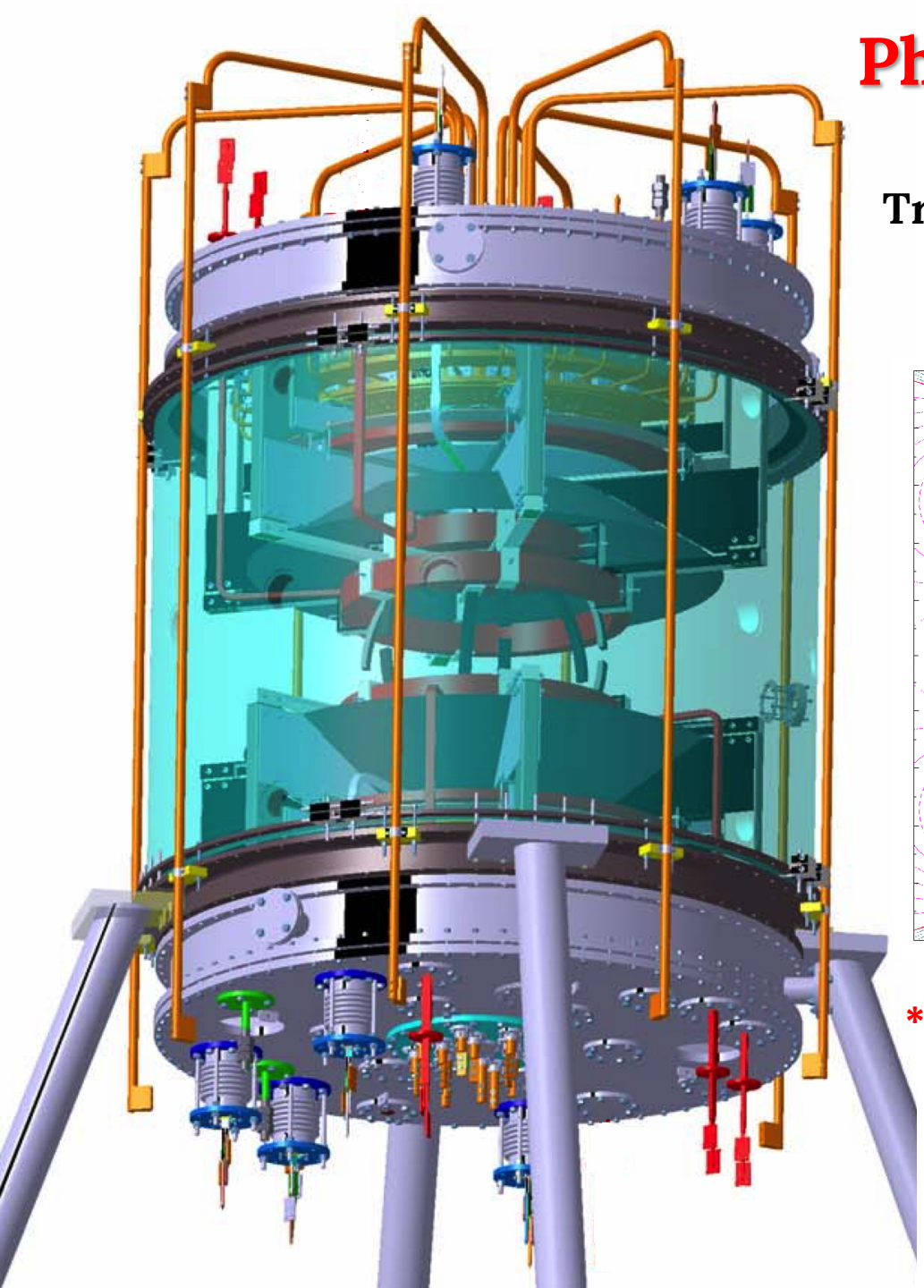


Phase 1+1/4: Spring 2019

Tori as in Phase-1: I_e= 10 kA, I_{ST}= 7 kA
but formed "slowly" ~ 20 ms
and sustained for 1 s



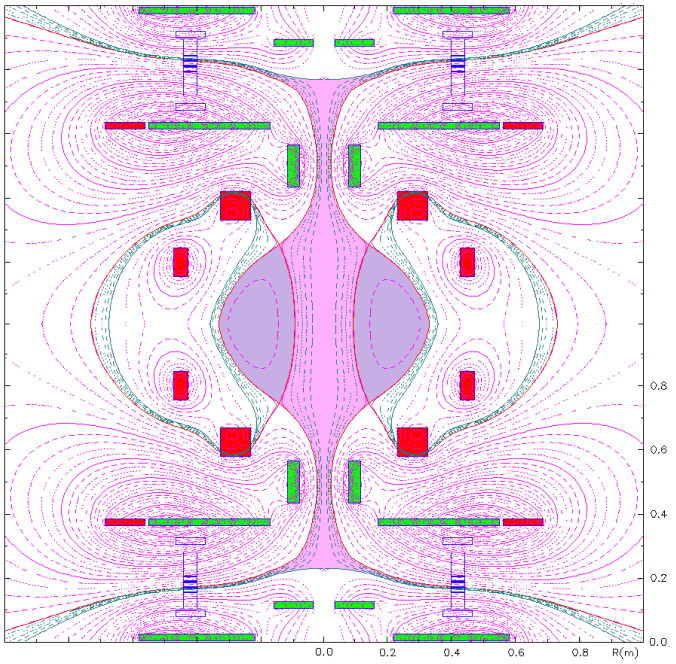
Will it help in understanding the unexpected formation dynamics?



Phase 1+1/2: Summer 2019

6 new compression PFC

Try Spherical Tori: I_e= 10 kA, I_{ST}= 20 kA
"slow" ~ 20 ms and static formation sustainable* for 1 s?



*Red copper cable covered with Teflon

…try & see the gamble before Phase-2

Planned escalation of performances

2018-2019
2.5 MW overall power to plasma

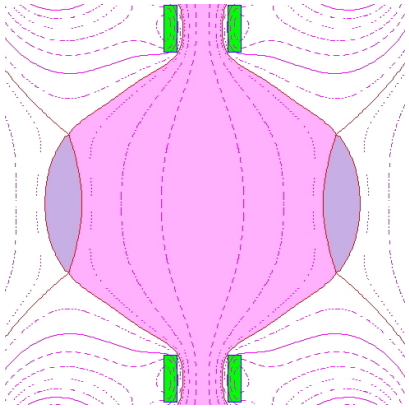
2019
up to 3.5 MW overall

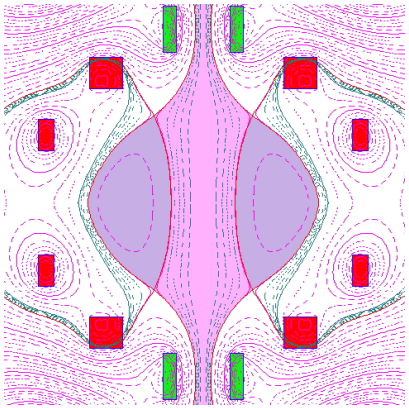
end 2021
up to 21 MW overall

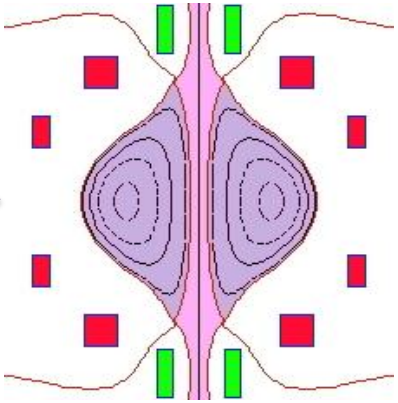
From Phase-1
I_e = 10 kA
I_{ST} = 5-7 kA

to Phase-1+1/2
I_e = 10 kA
I_{ST} = 20 kA

to Phase-2
I_e = 60 kA
I_{ST} = ¼ MA







From 7% Torus/Sphere volume
7% of Power input to Torus

to 70% Torus/Sphere volume
? of Power input to Torus

To 95% Torus/Sphere volume
? of Power input to Torus

…Phase-2 Coils and Power Supplies will be designed able to handle I_{ST} = ½ MA…

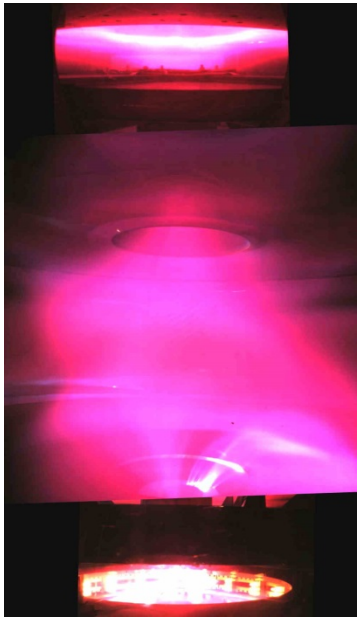


PROTO-SPHERA does not need additional heating…?

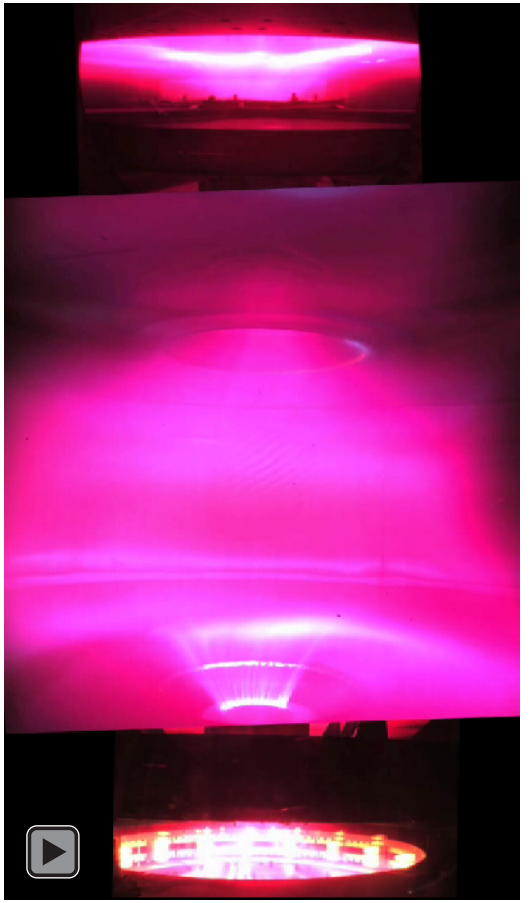
…magnetic reconnections heat the Solar Corona!

Plasma is resilient to double & lop-sided tori

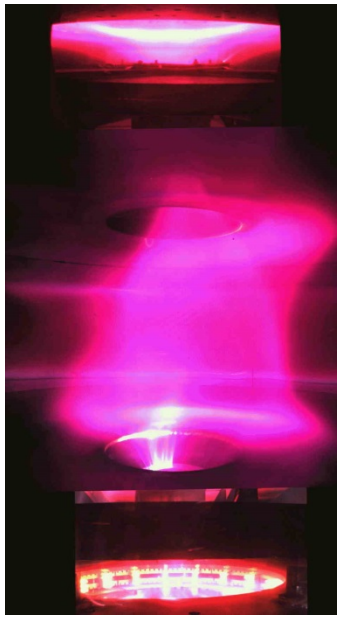
With a vertical field in slight excess (+10%) of optimal value, the Plasma-Centerpost produces odd configurations like Double-Tori

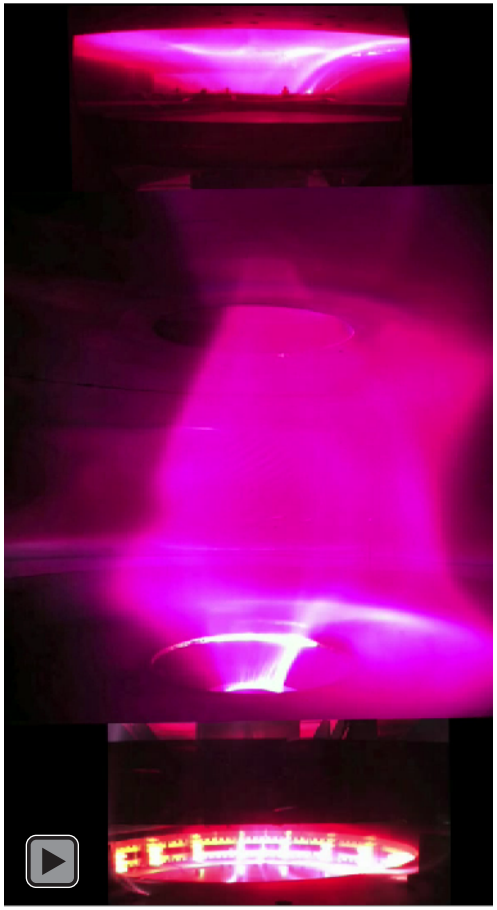


#1211



#1225





and Lop-sided-Tori,

all with visible helical components however the plasma never disrupts

The only occurrence you should never ever consider is plasma disruption: gone for good!

Metamorphosis of an hexapolar cusp into a torus

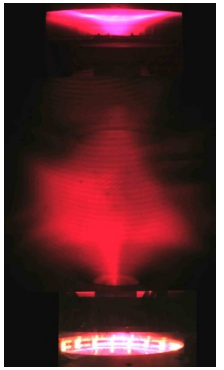


With even larger vertical fields:

the plasma exhibits an hexapolar cusp shape

& a reduced current start-up: I_e<5 kA

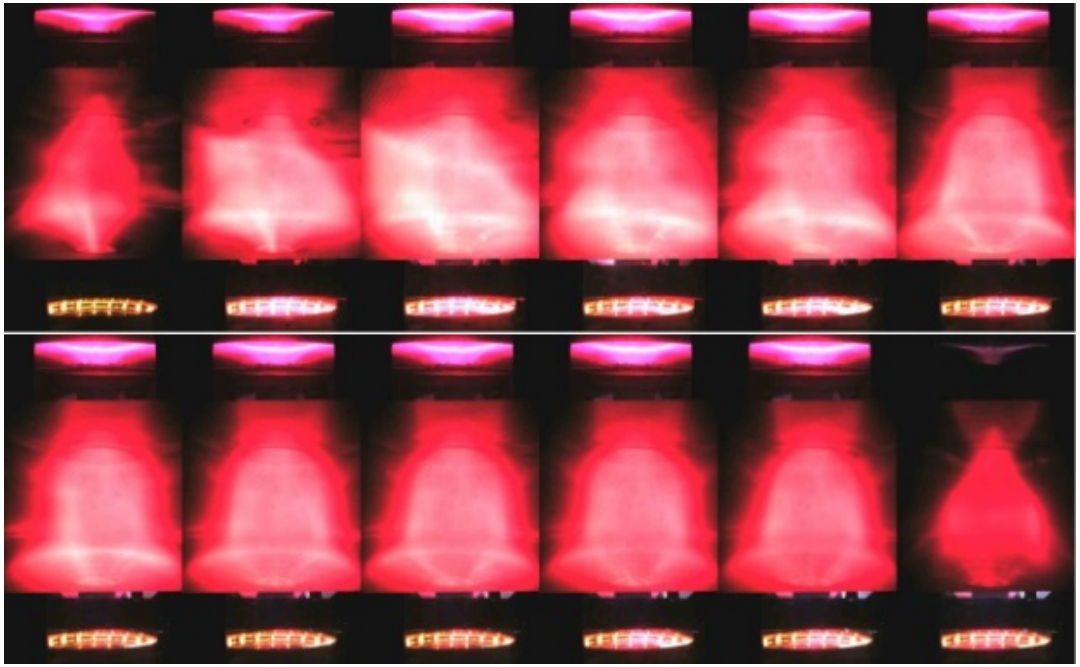
such state can last up to 0.15 sec,



#1221

later the centerpost current reaches I_e=10 kA

and a proper Plasma-Centerpost+Torus

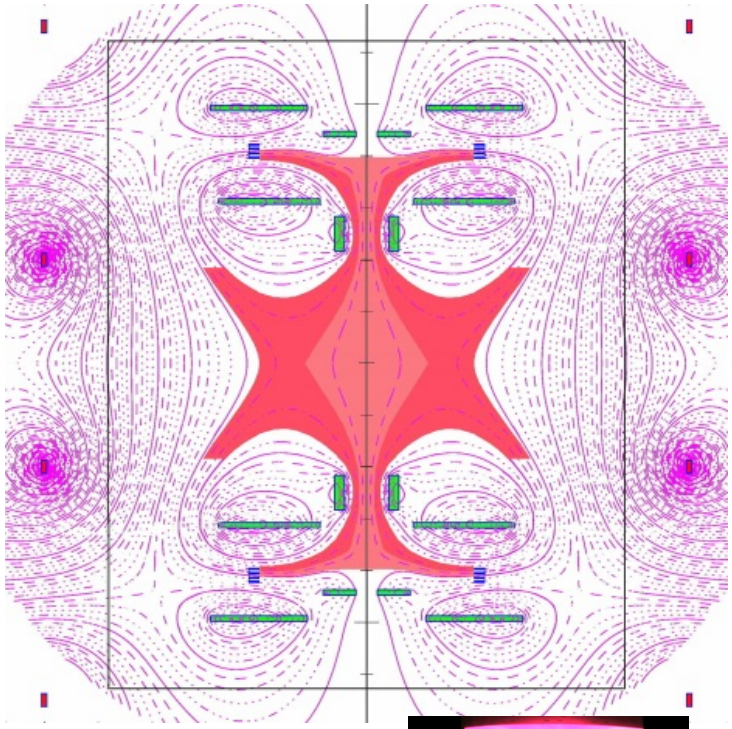


#1219

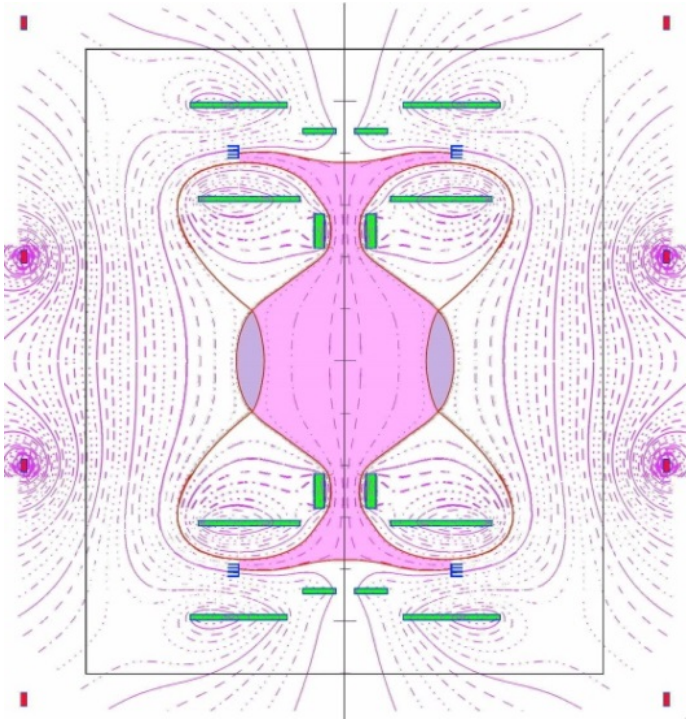
From hexapolar cusp to compressed torus

#1221

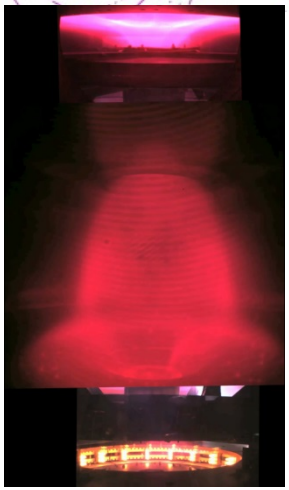




the plasma discharge has a part with current flowing in the Plasma-Centerpost but the rest of the plasma is trapped in a configuration ~axisymmetric-toroidal-cusp



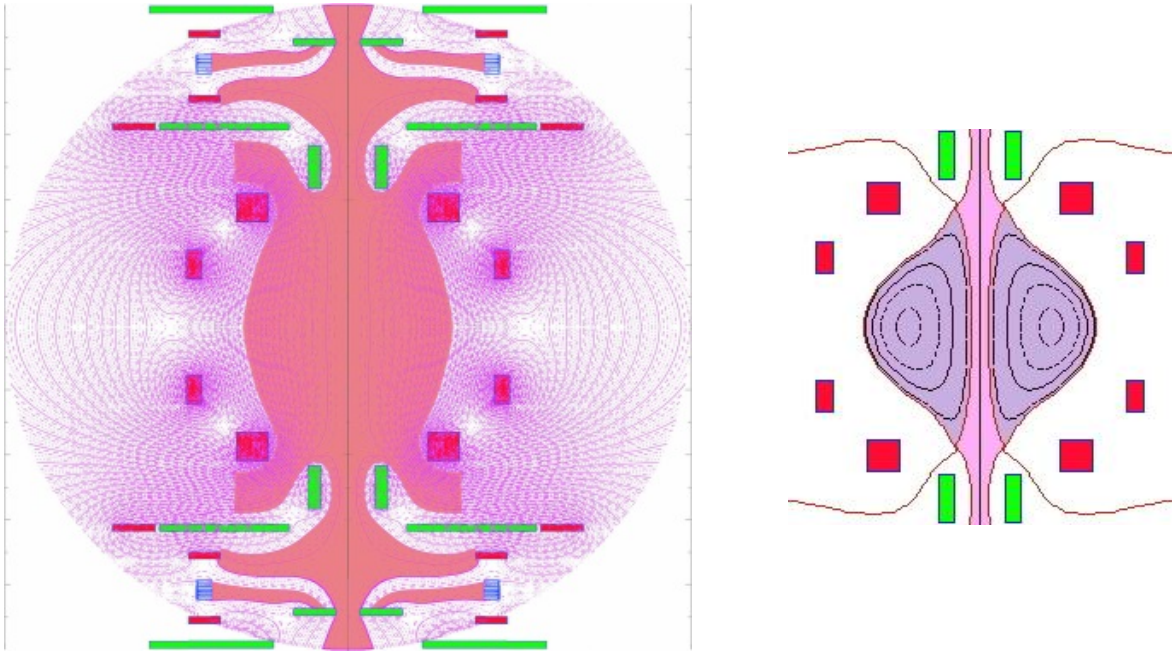
proper Plasma-Centerpost + Torus is narrower due to higher B_{vert}



#1221

Feedback-controlled Spherical-Torus formation?

Also the poloidal field required for PROTO-SPHERA in Phase-2, for shaping and compressing the Spherical-Torus at I_{ST}=¼ MA, has an hexapolar character, but the two electrodes are magnetically disconnected from each other

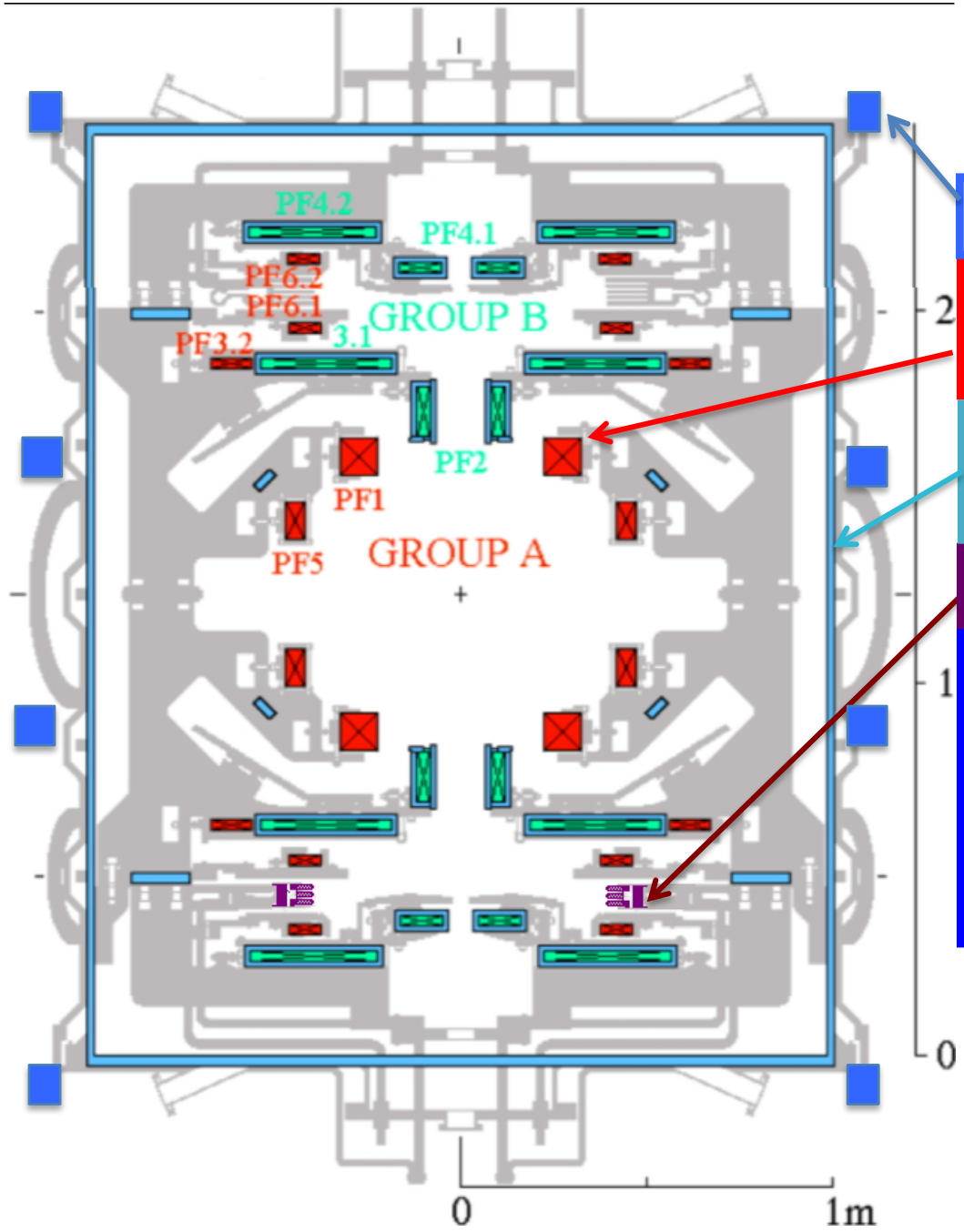


field in absence of plasma I_{ST}=¼ MA *plasma configuration*

it is possible that PROTO-SPHERA in Phase-2 will form up increasing:
the Plasma-Centerpost current I_e to 60 kA & the current in the Group-A-PFInt coils
...but on a slow time scale ~20 msec

this opens the possibility of a feedback-controlled Spherical-Torus formation

What remains to be built to achieve a ¼ MA Spherical Torus (end 2021)



PFExt* 8+12+12+8, 240 mm² each cost ~ 40 k€

Group A: compression coils (5+5 in series)
cost ~ 0.5 M€

PMMA Vacuum vessel[1] cost ~ 0.2 M€
including vacuum components, divertor plates

W cathode Filaments[1] **(54→324)** cost ~ 0.1 M€

Electric power supplies:
1) Group A cost ~ 0.1 M€
2) Cathode (**I_{cath} 10→60 kA**) cost ~ 0.2 M€
3) Centerpost.(**I_e 10→60 kA**) cost ~ 0.6 M€
Super-Capacitors will be used

Cost incurred so far **~ 2.0 M€**
Cost for completion **~ 2.0 M€**

[1, 1] **Under construction,** * **to be delivered Feb. 2019**

Conclusions: dispensability of toroidal magnet & formation in magnetotatic field

Toroidal magnet are dispensable for producing magnetically confined tori:
a Plasma-Centerpost discharge, sustained by DC voltage electrodes, is sufficient

The tori are produced in a pre-existing axisymmetric magnetostatic poloidal field:
no variations are needed in the poloidal fields containing the plasma (virial theorem)

The confined tori are sustained until anode-to-cathode DC voltage is applied:
magnetic reconnections provide a steady-state current drive to the toroidal plasma

No disruption phenomena occur in the PROTO-SPHERA configuration:
it can produce tori at aspect ratio A=7 & elongation κ=3.5, that Tokamaks could never do



Can magnetic reconnections be put to work?

Magnetic reconnections are the nightmare of magnetic containment schemes ...but has a useful application of such plasma phenomena appeared in magnetic confinement?

Hopefully this will be confirmed by more powerful plasma discharges in the near future & a vigorous self-organized plasma heating could be obtained in Phase-2 of PROTO-SPHERA, where a total power of ~ 21 MW is expected to be input into the overall plasma

To assess the potential of this new configuration, Phase-2 will increase from <8% to >95%. the flux surfaces volume the torus carves from the spherically shaped Plasma-Centerpost

If the properties observed in Phase-1 will be confirmed and the energy confinement time will be long enough, this configuration could solve many issues pending in Tokamaks:

- **the removal of the disruption problem**
- **the necessity of powerful plasma heating and current drive that, instead of requiring complex external systems, will become embedded into the magnetic configuration itself and will rely upon the spontaneous natural phenomenon of magnetic reconnections**

Magnetic confinement by permanent magnets?

The dispensability of toroidal magnet & the confined tori formed in a magnetostatic field hint that magnetic confinement devices for Controlled Fusion *could in principle be built using axisymmetric permanent magnets only*, able to provide a poloidal magnetostatic field pre-existent to the plasma

A Plasma-Centerpost fed by two electrodes will produce and sustain the confined torus in such a poloidal field; in case the two electrodes become disconnected from each other, in terms of the pre-imposed field configuration, currents of short duration, in simply conducting coils, could be required in addition

However the currents of these coils would be gradually switched off after the plasma break-down and would vanish when the final confinement configuration, to be sustained by permanent magnets only, is achieved

Metamorphosis of Tokamaks into tori confined by permanent magnets?



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Giuseppe Galatola Teka, Matteo Iafrati