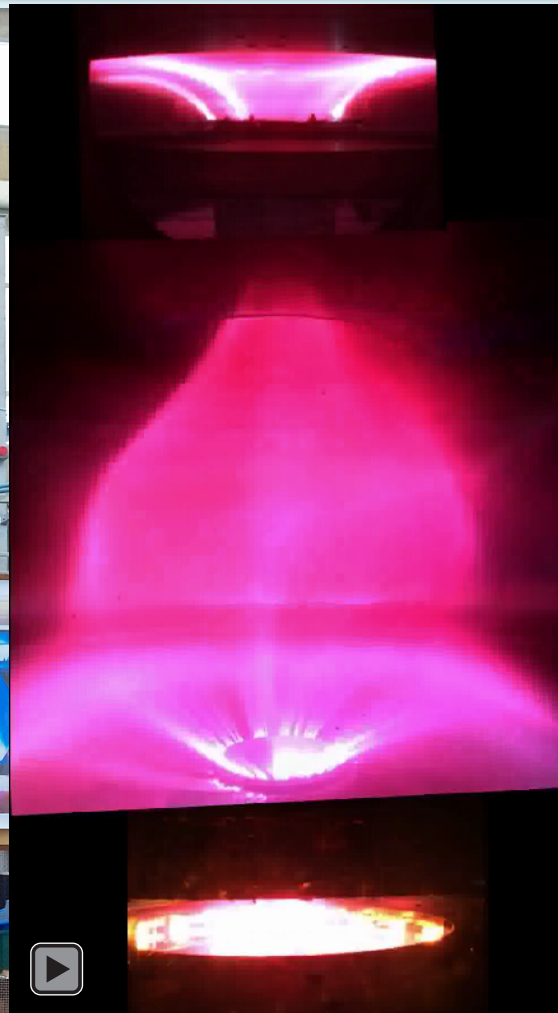


Status of the art & operation plans of the Experiment

PROTO-SPHERA

Franco Alladio, CR-ENEA Frascati



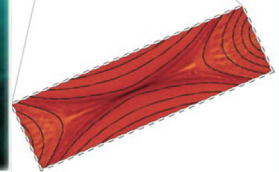
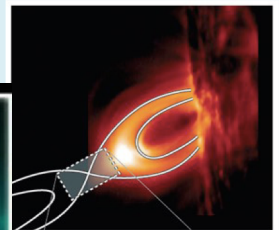
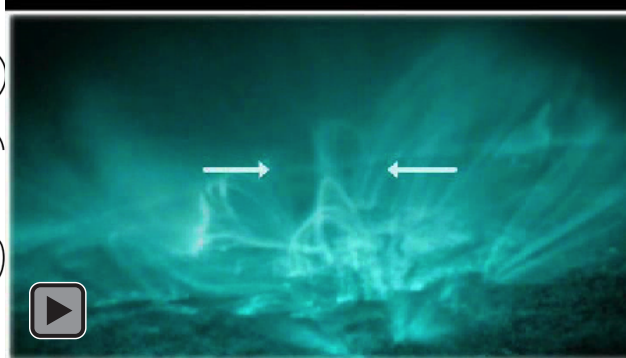
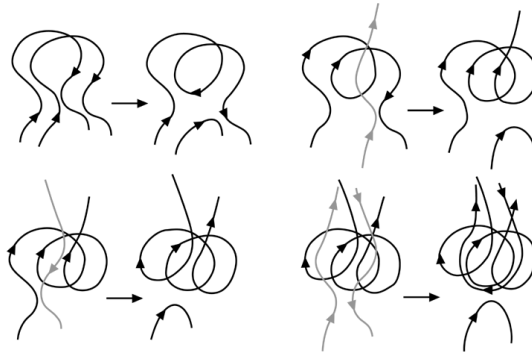
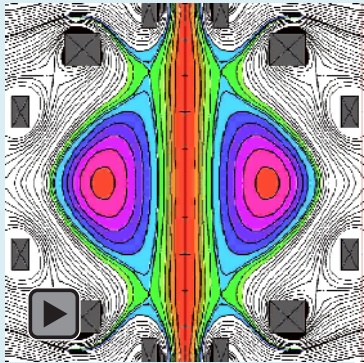
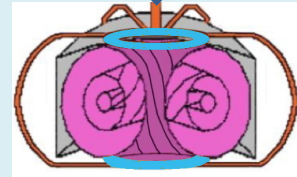
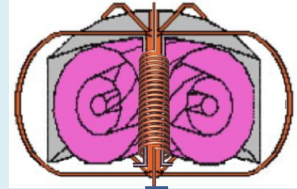
PROTO-SPHERA



Crab Nebula remnant

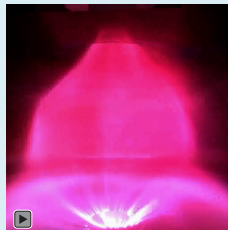
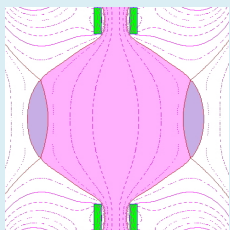
SUMMARY

- PROTO-SPHERA replaces the two central metal conductors of Tokamaks by a Centerpost Plasma (with helically wound B lines)
- Underlying physics is the «magnetic reconnection of a plasma». At ordinary magnetic field X-points, a «tear» is operated followed by a different «mending»; this transfers magnetic flux & electric current; magnetic field energy converts to plasma temperature

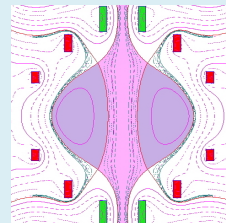


- In Phase-1 (2018) the obtained plasma tori, filled 7% of the total plasma volume. In Phase-1.5 (2019), 6 new magnetic coils are being inserted inside a new insulating vacuum chamber, the spherical tori will fill 70% of the plasma volume. Phase-2 will fill 95%: power densities $\sim 100 \text{ MW/m}^3 \sim$ fission reactors

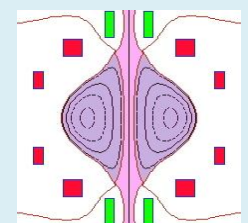
2018
2.5 MW



2019
3.5 MW



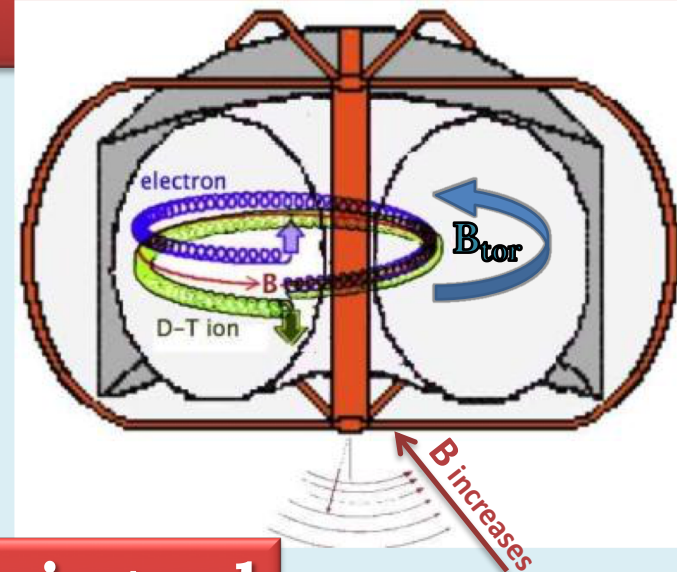
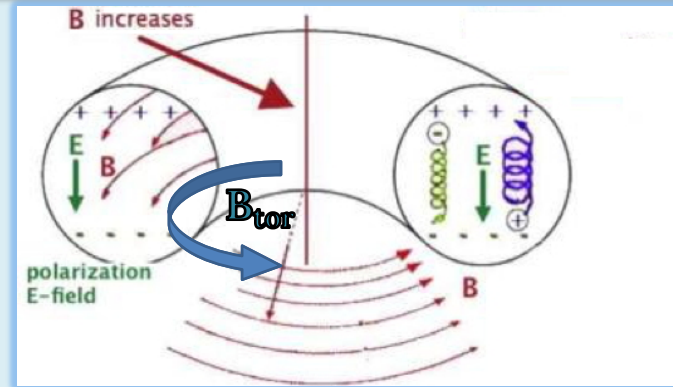
2021
 $\sim 20 \text{ MW}$



Axisymmetric
confinement



First Magnetic Confinement basic tool a toroidal field B_{tor}

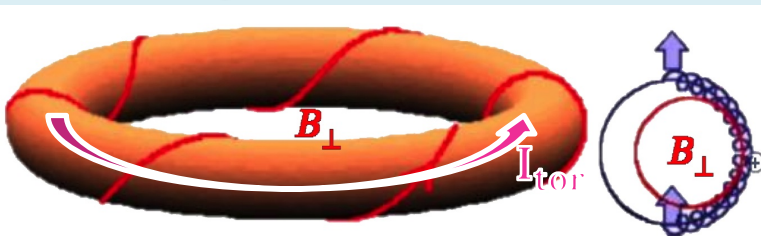


but toroidal magnet
...alone not enough...
drift of particles!

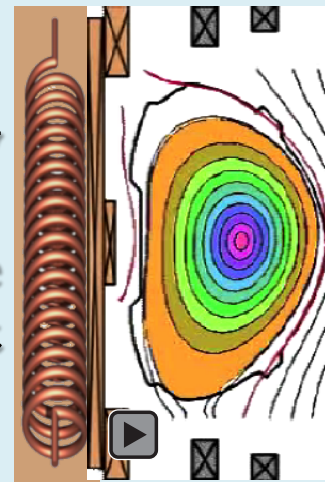
Second Magnetic Confinement basic tool a toroidal current I_{tor}

the magnetic field winds in the poloidal direction over
the magnetic surfaces to contrasts the drift of particles

Tokamak
central
solenoid

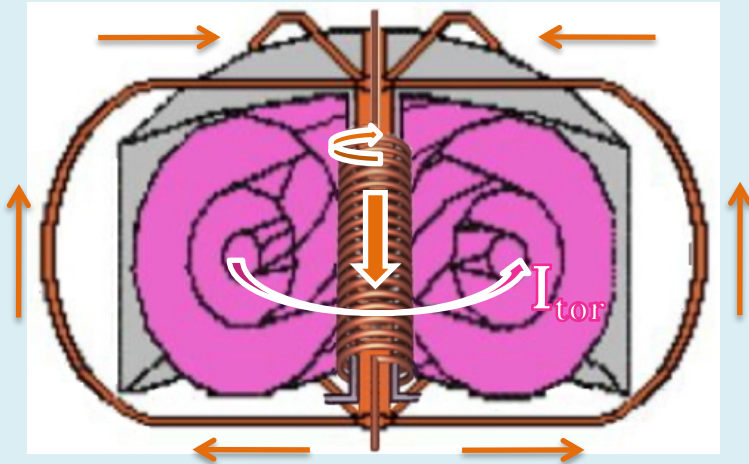


Plasma current induced by
time-varying solenoid current:
flux enters from edge
plasma resistivity dissipates it



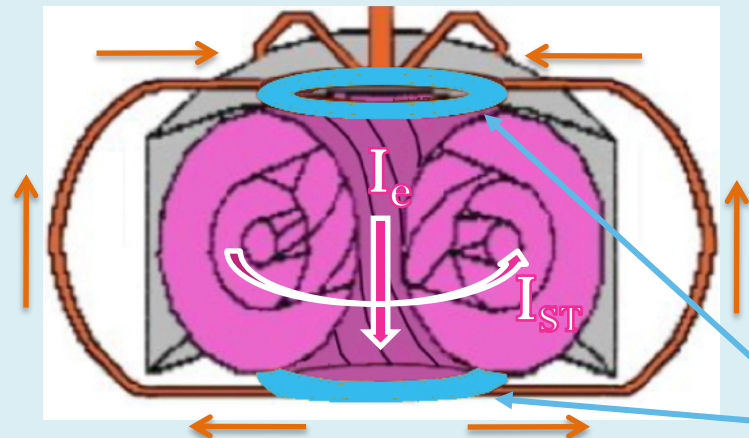
Equilibrium $\vec{\nabla}p = \vec{j} \wedge \vec{B}$ relation
creates magnetic surfaces in axisymmetry

PROTO-SPHERA gets rid of 1st Magnetic Confinement basic tool!



Electric current flowing in metal

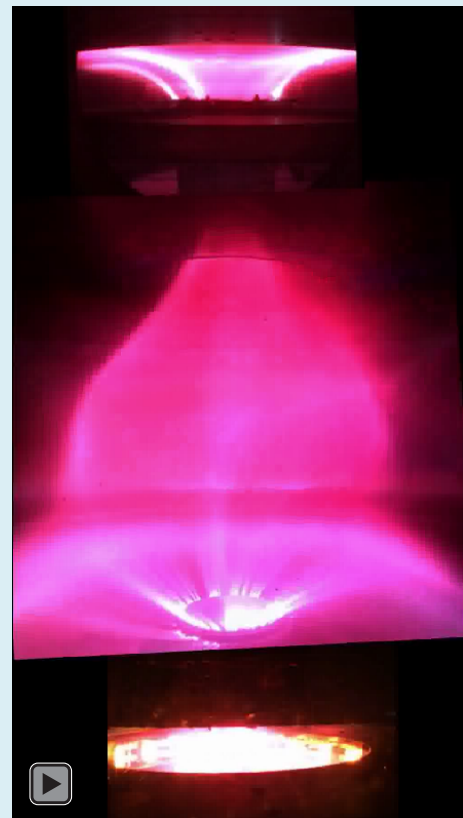
- **TOKAMAK:**
magnetic surfaces of toroidal Plasma surround a “Metal Centerpost”
...toroidal geometry of vacuum vessel



- **PROTO-SPHERA :**
...cylindrical geometry of vacuum vessel
toroidal plasma (current I_{ST}) around a “Plasma Centerpost” (current I_e)
external metal legs as current return
...but electrodes are required inside vacuum

Toroidal field , just as in a Tokamak: Ampere’s law!

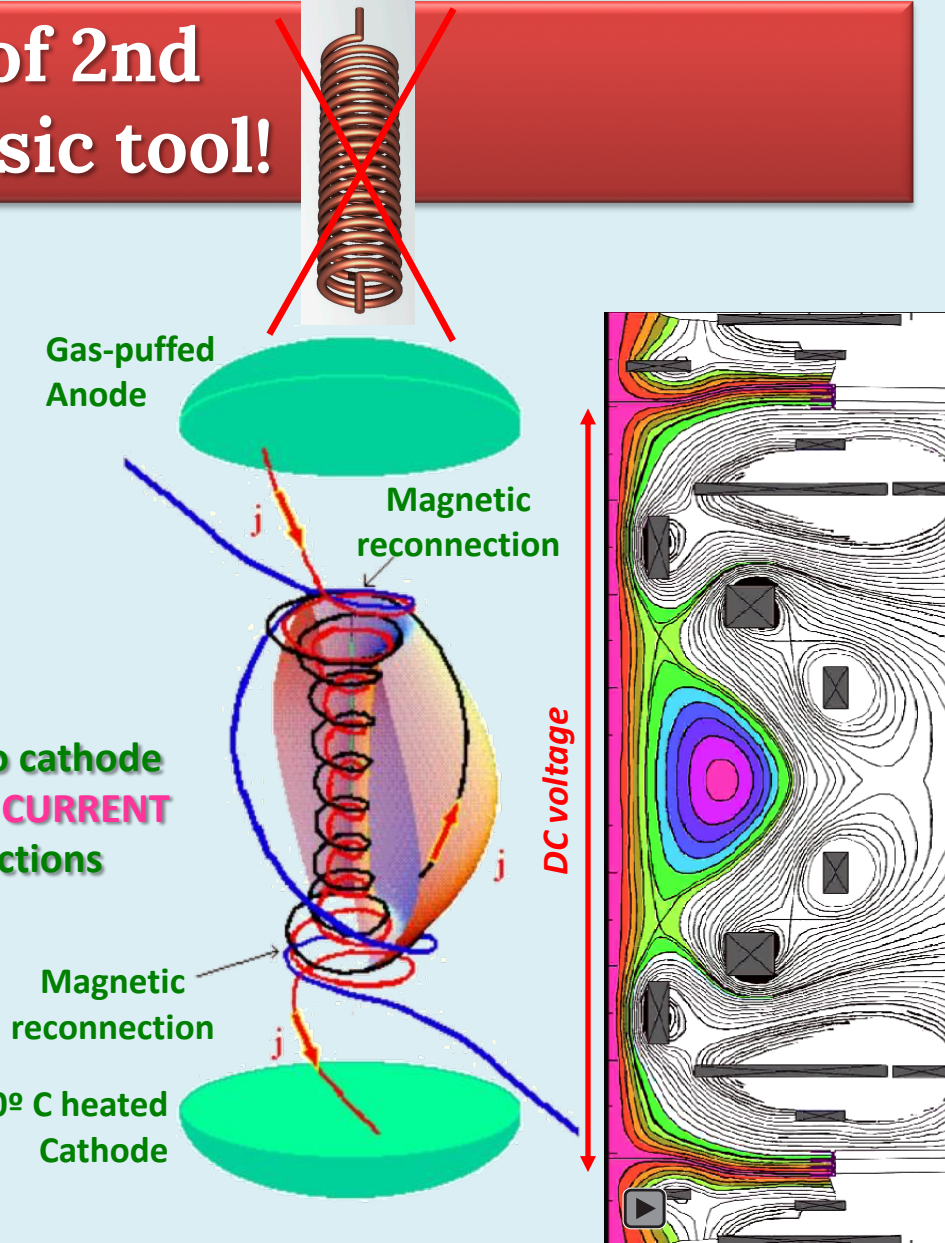
PROTO-SPHERA gets rid of 2nd Magnetic Confinement basic tool!



DC voltage from anode to cathode
SUSTAINS THE TOROIDAL CURRENT
by Magnetic Reconnections



2900° C heated Cathode



Maxwell equations do not imply that a DC voltage between electrodes can sustain a toroidal current: Magnetic Reconnections do the trick!

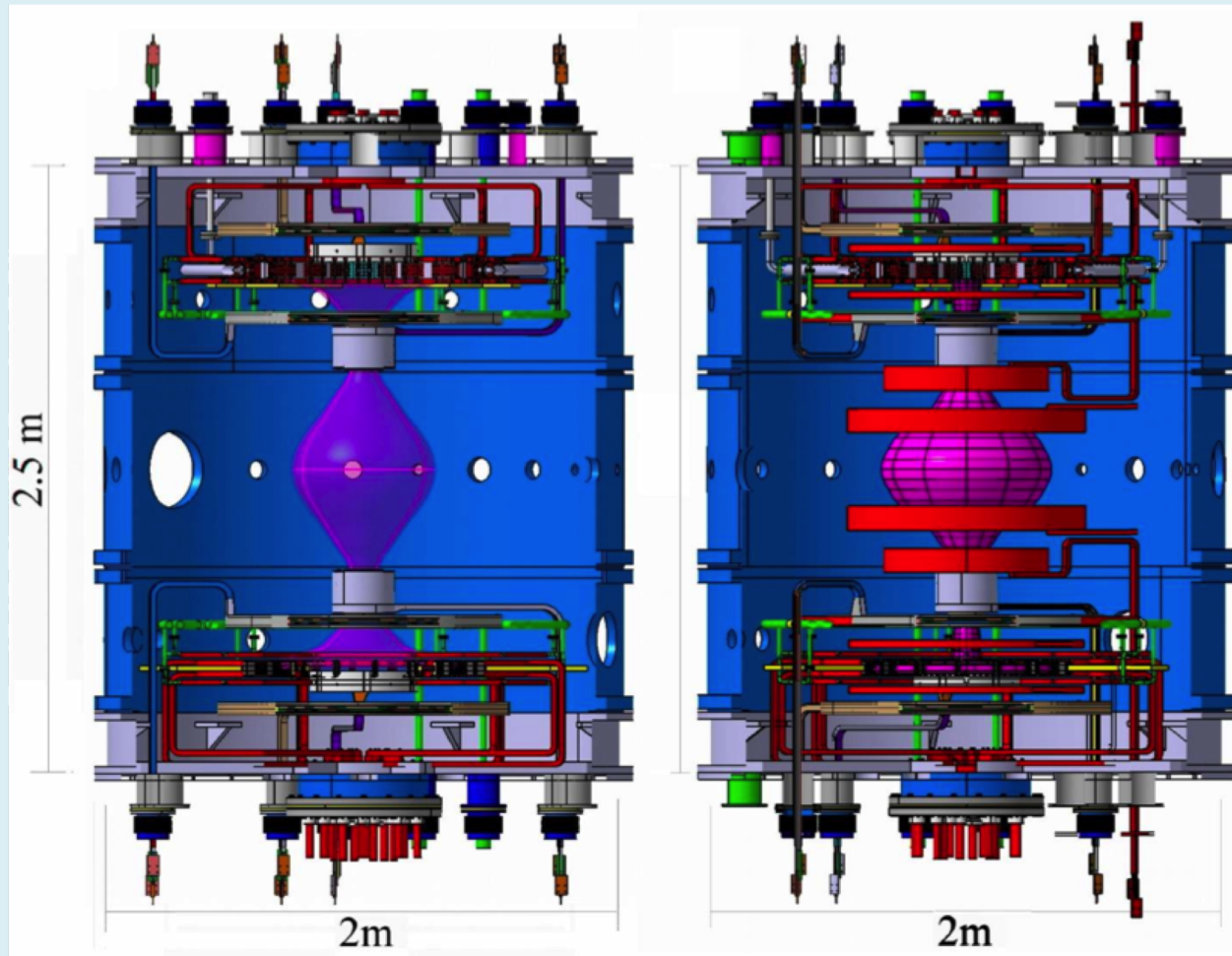
Phase-1 & Phase-2 of the experiment

...as they were originally conceived (2001)

As built 2014, Phase-1:
8 PF coils Group-B shaping coils

Phase-2: 8 PF coils + 6 PF
Group-A compression coils

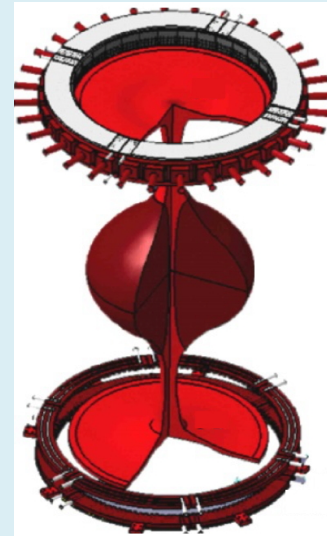
2016 Phase-1
Argon plasma



Centerpost $I_e = 10 \text{ kA}$
...ST current $I_{ST} = 7 \text{ kA}...$

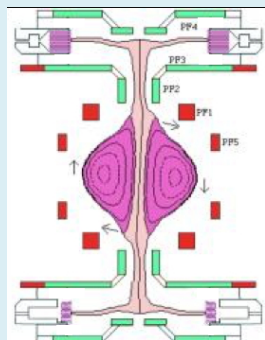
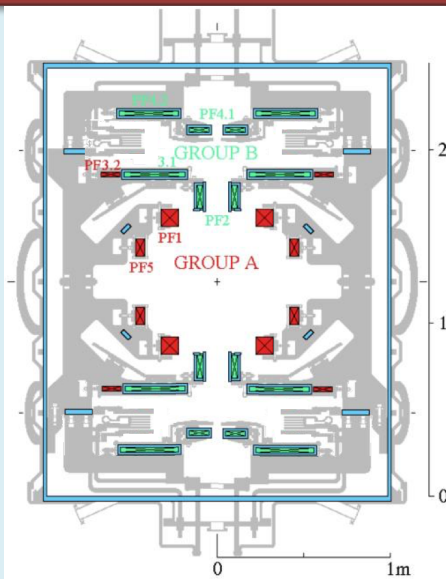
Centerpost $I_e = 70 \text{ kA}$
ST current $I_{ST} = 280 \text{ kA}$

Gas-puffed
anode



2900°C
heated cathode

Ideal MHD stability of PROTO-SPHERA



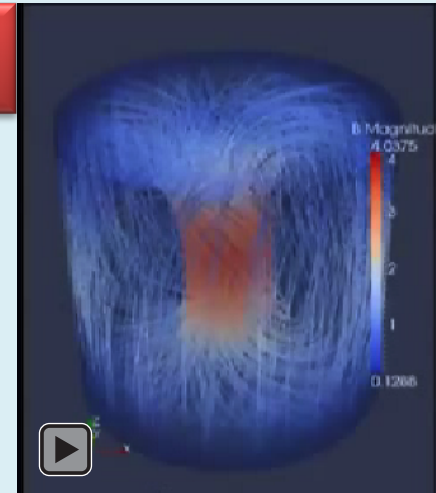
Tilt instability: toroidal dipole of vertical field overturns plasma current toroidal dipole

But PROTO-SPHERA dipoles:

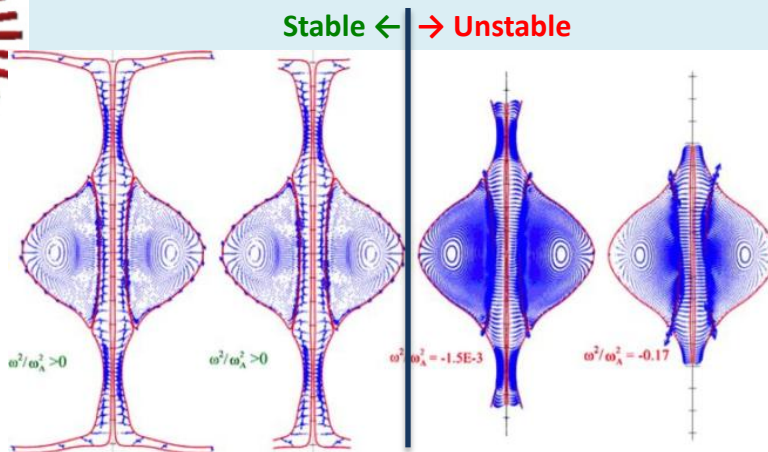
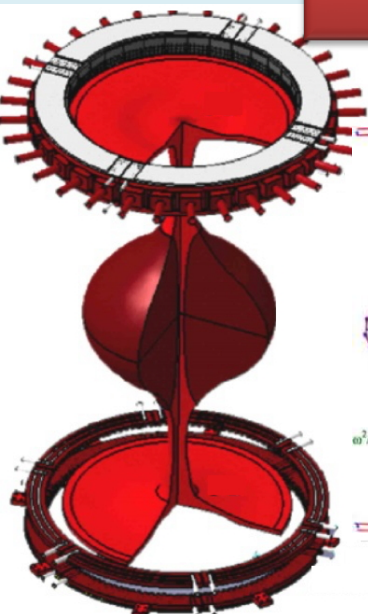
“Group A” PF compression coils against Plasma dipole

“Group B” PF shaping coils aligned to Plasma dipole

Net result: rigid tilt instability is stabilized



Stability in terms of β = plasma beta = $\frac{\text{kinetic plasma pressure}}{\text{confining magnetic field pressure}}$



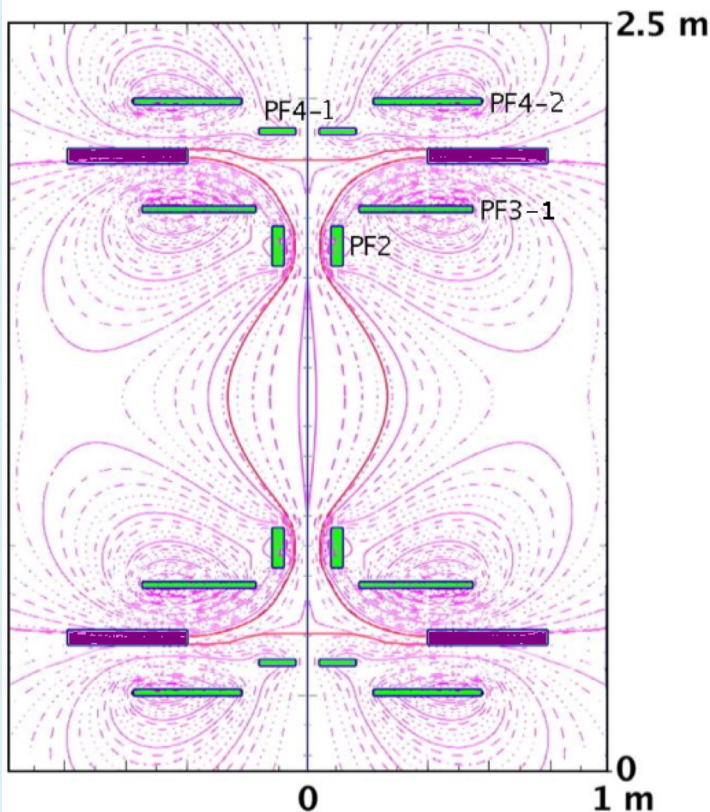
ELECTRODE-FACING DISK-SHAPED PLASMA CENTERPOST PROVIDES IDEAL MHD STABILITY

(cutting shorter & shorter the Plasma Centerpost destabilizes the configuration)

PROTO-SPHERA $\beta = 1$ is achievable, faraway metal vessel is irrelevant

Rotating Plasma-Centerpost produced 2016-2018

Shaping field inside
4 cm thick Aluminum vessel



January 2018:
objectives of Phase-1 achieved

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

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

Rotation $\omega \sim 2\pi (500) \text{ radians/sec}$

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

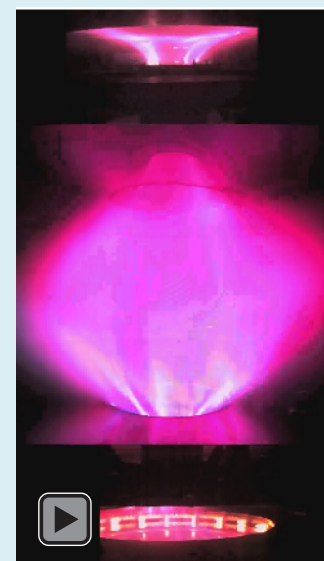
Hydrogen, equator line-averaged
electron density
 $\langle n_e \rangle = 1.5 \cdot 10^{20} \text{ m}^{-3}$ at $I_e = 10 \text{ kA}$

High-field Tokamak densities!

#614

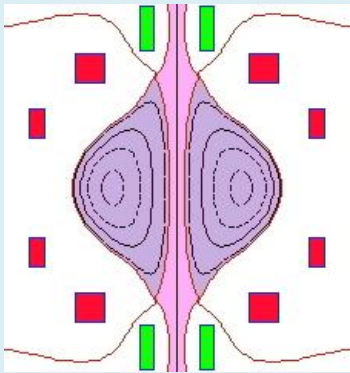


#977



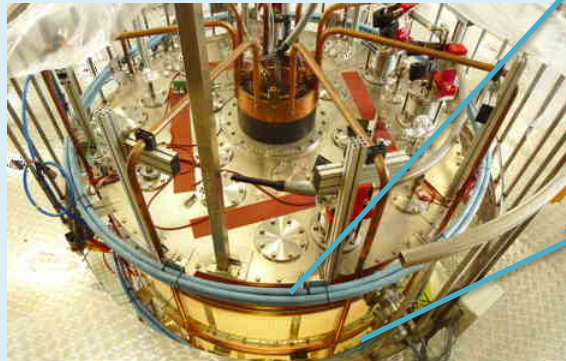
Plasma tori obtained & sustained during year 2018

Phase-2 Spherical Torus:

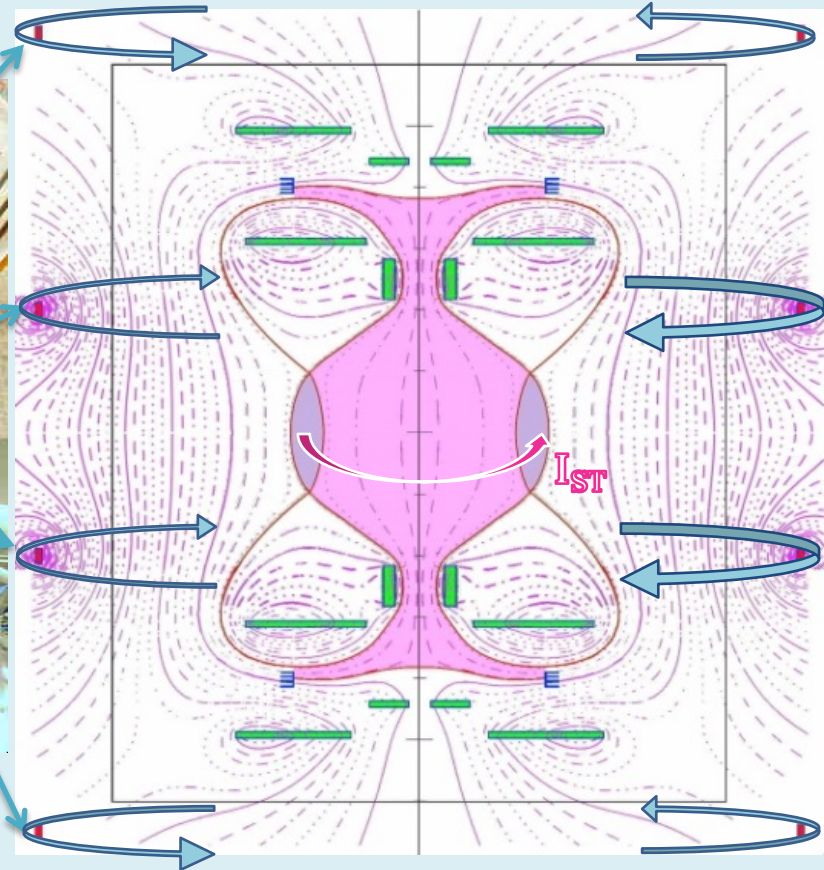


not feasible without
internal compression coils

A simpler vertical field built-up by adding 4 PFExt coils
external to the vessel



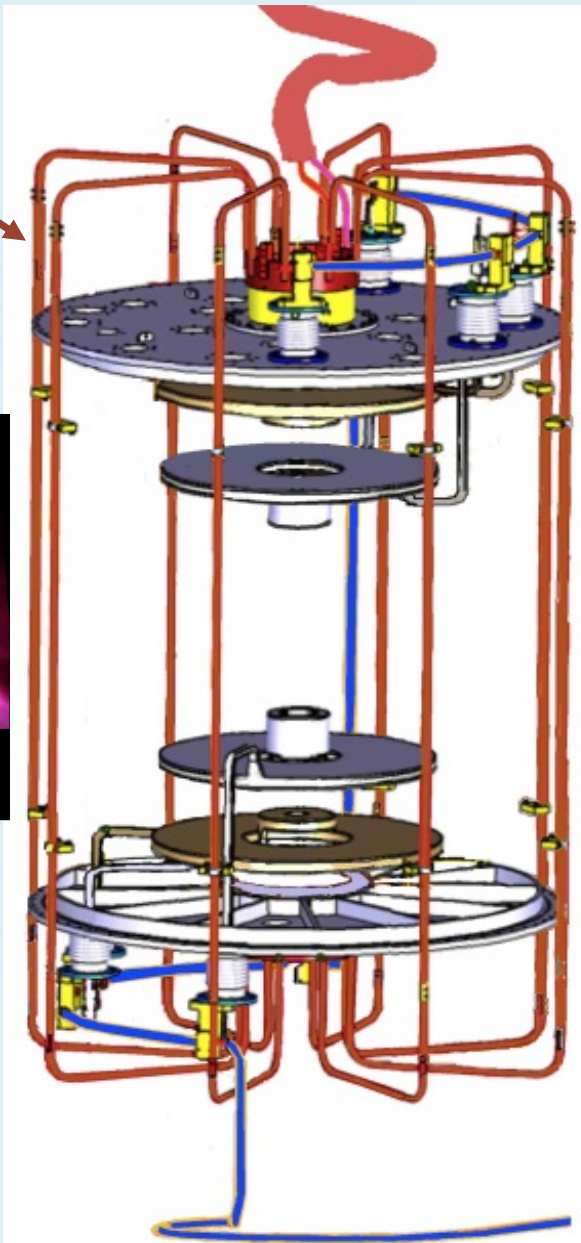
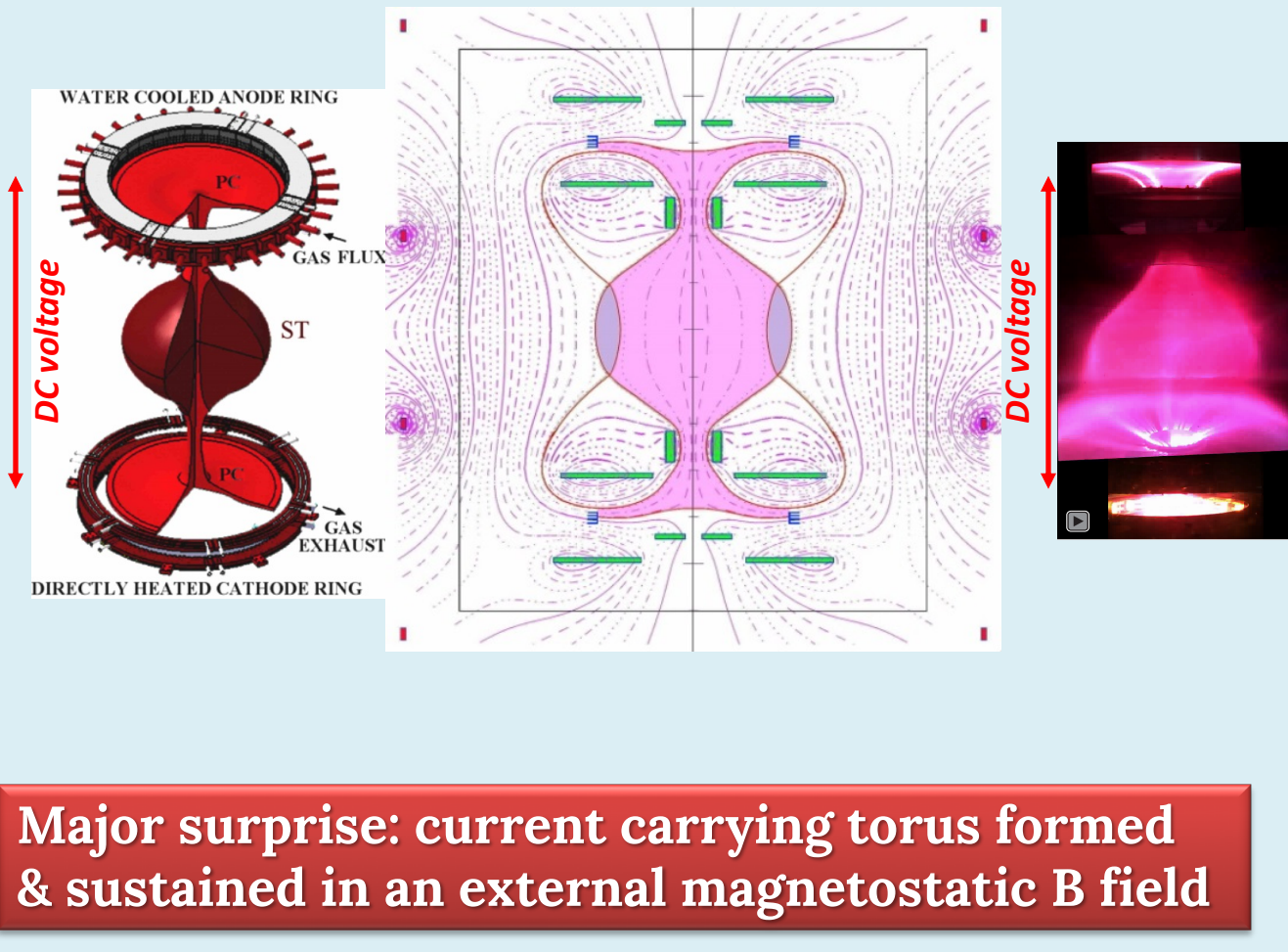
in 2 PFExt near equator
the current flows in opposite direction to
toroidal current inside the Plasma-Centerpost



New PFExt 2019

Plasma fired 0.60s after PF current (skincurrent time, 4 cm thick Al vessel)
torus duration limited to 0.5 sec → magnetostatic field at torus formation

- An axisymmetric high density confined torus is produced in absence of a toroidal magnet: only external metal legs

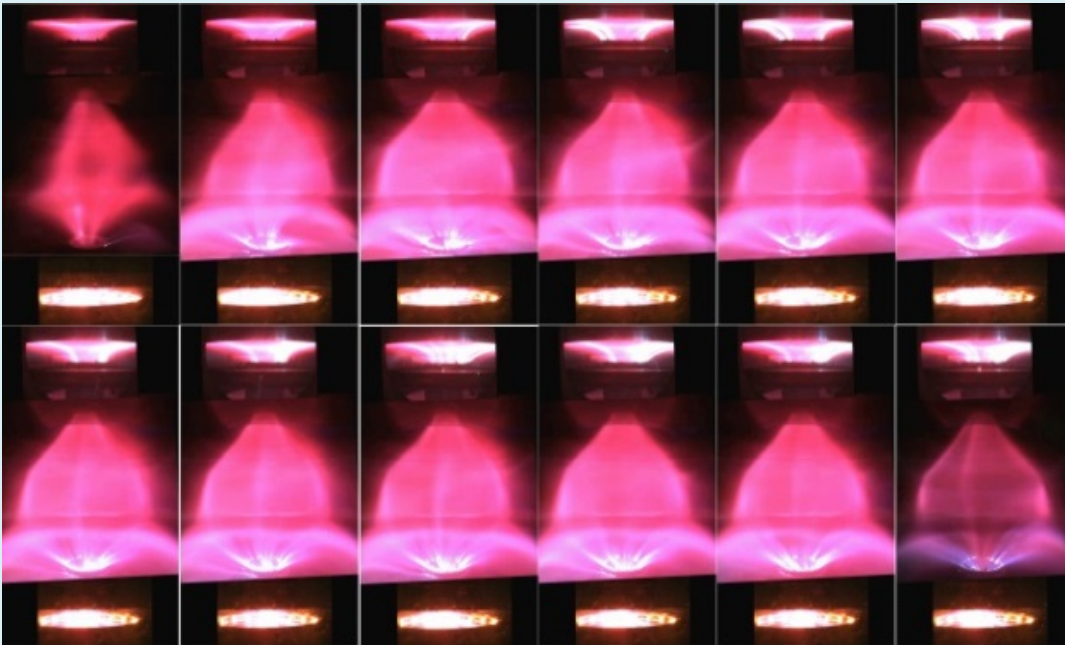


Major surprise: current carrying torus formed & sustained in an external magnetostatic B field

Apart from the field due to the plasma current, driven by the DC voltage, the overall field that confines the torus is purely magnetostatic

Torus persists till anode-cathode voltage is applied

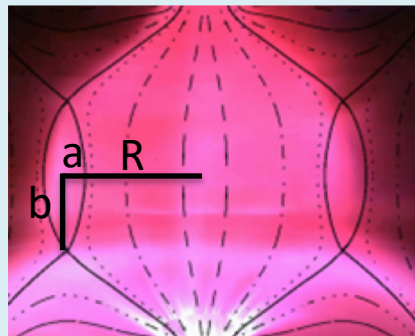
#1280 with AISI340 divertor plate



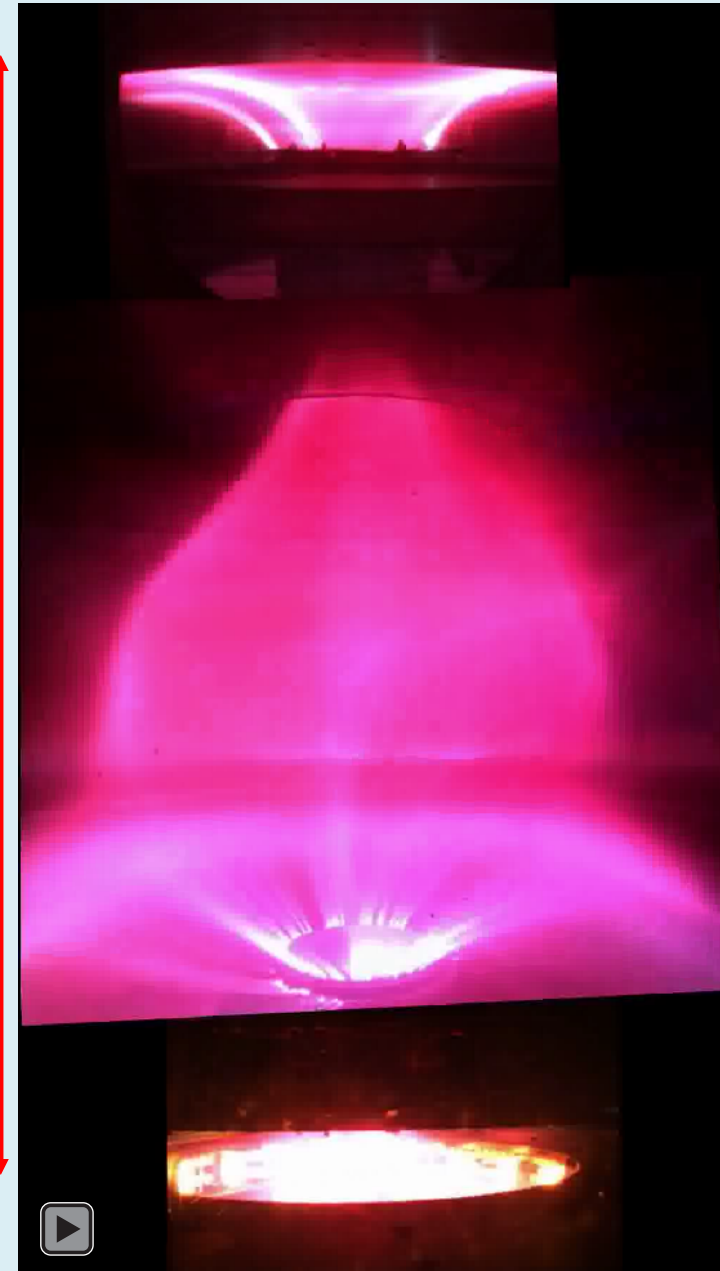
break-down ~ 360 V
at 10 kA ~ 250 V

Hydrogen tori have been sustained up to 0.25 sec
(cathode insulation was progressively degraded)

Slim tori aspect-ratio $A=R/a \sim 7$
& elongation $b/a = \kappa \sim 3.5$
...unfeasible in a Tokamak!



DC voltage



**Torus formation remains to be understood
Plasma sustainment remains to be lengthened to 1 sec**

**New insulating PMMA Vessel
(no skin effect) Plasma Centerpost
will “slowly” form Tori (in 20 ms)**

Reynolds
POLYMER TECHNOLOGY, INC.
Building the Impossible

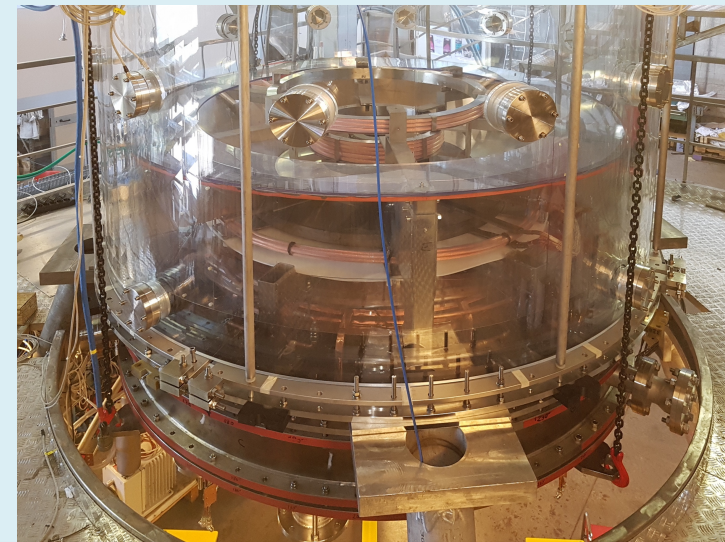
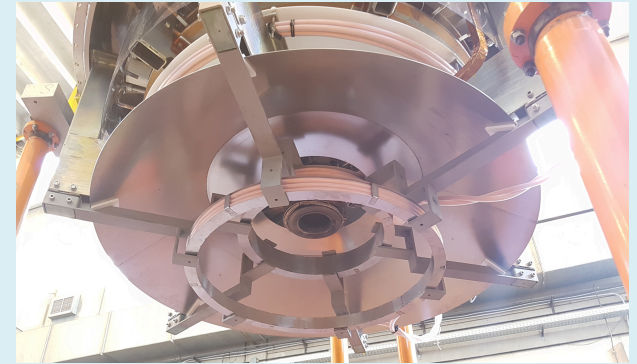
**the gas blanket
around the plasma
will cushion the vessel**



**Low-vacuum
test (10^{-2} mbar)
successfull**



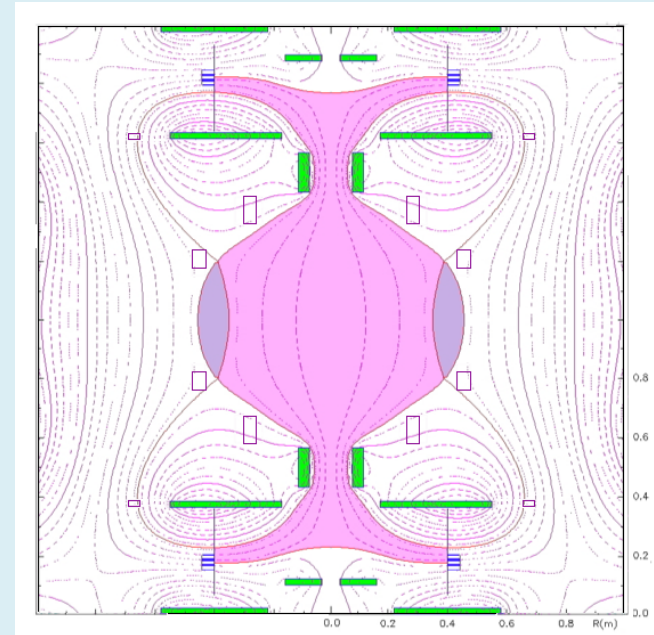
**High-vacuum
this week**



**Try Torus formation from Centerpost & assess difference with magnetostatic one
Get rid of prejudice that confined plasma stability requires a metal wall nearby**

Early Phase 1.5 Summer 2019

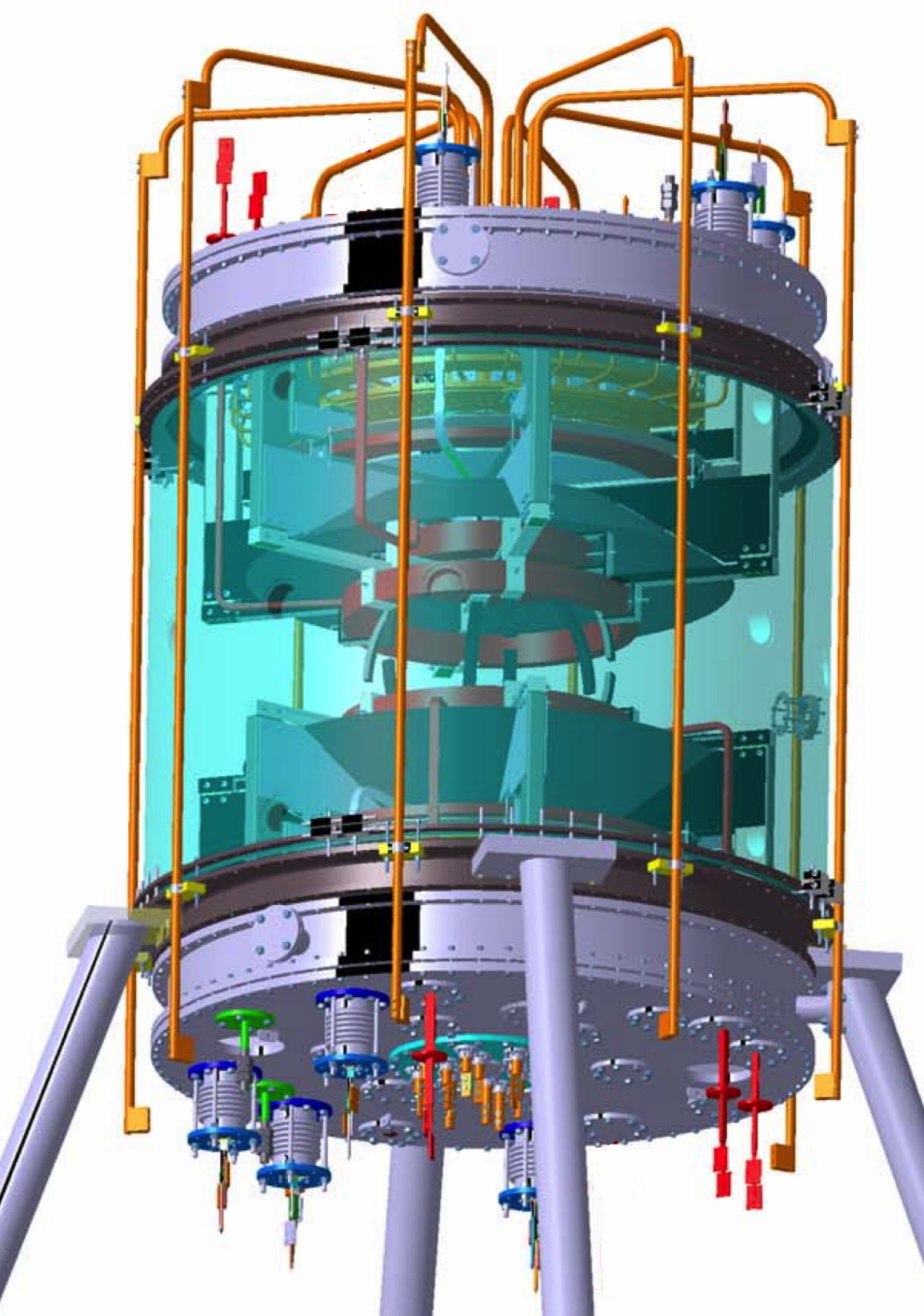
Tori as in Phase-1: $I_e = 10$ kA, $I_{ST} = 7$ kA
but formed “slowly” in ~ 20 ms
and sustained for 1 s



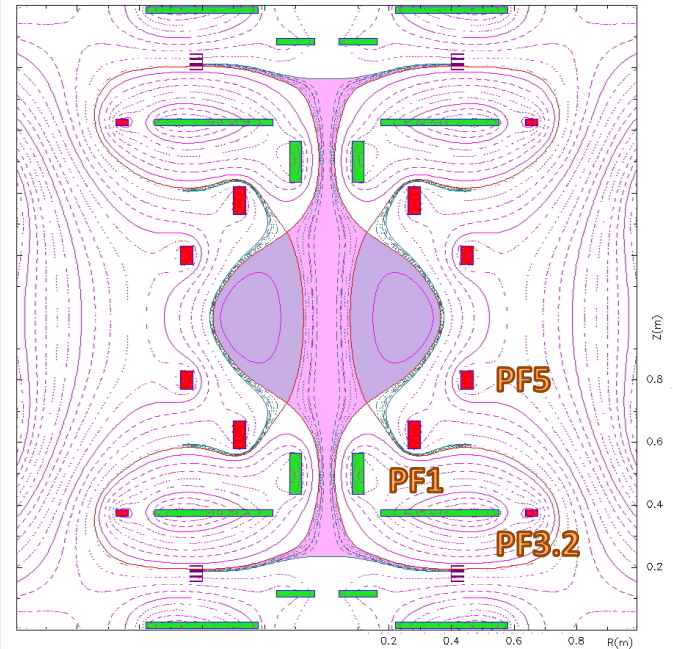
Will it help in understanding the
unforeseen formation dynamics?

Phase 1.5: Autumn 2019 6 new compression coils

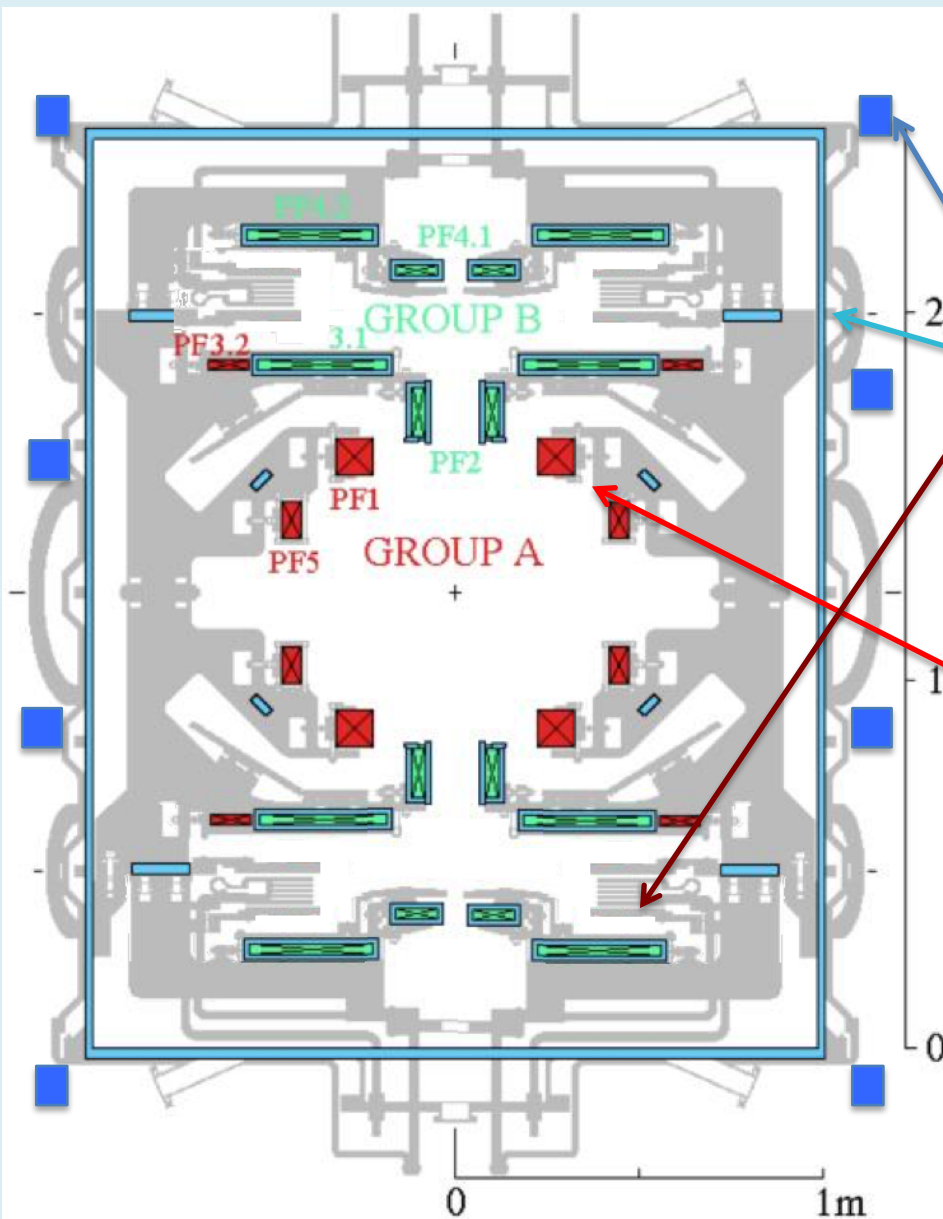
Try Spherical Tori: $I_e = 10$ kA, $I_{ST} = 40$ kA



Red copper cable covered with Teflon



To be built to achieve 1/3 MA Spherical Torus (Phase-2 2021)



Already built, for Phase 1.5, June 2019

PFExt 8+12+12+8, 240 mm²

PMMA Vacuum vessel

W cathode Filaments(54→378) (still 54 now)

To be built, at the end of Phase 1.5

Group A: compression coils (3+3 in series)

Electric power supplies based on *Super-Caps*

- Compression **Group A** (fit up to $I_{ST}=0.5$ MA)
- Cathode (I_{cath} 10→70 kA)
- Centerpost (I_e 10→70 kA)

Cost incurred so far (2019) ~ 2.5 M€

Cost for completion (Phase-2) ~ 1.5 M€

Planned escalation of performances

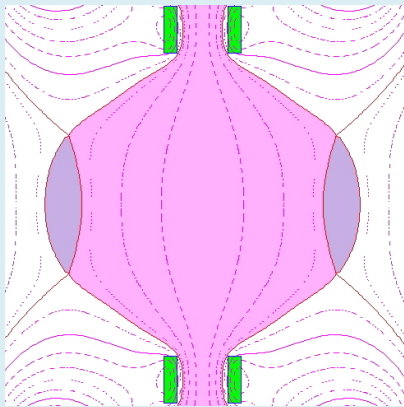
2018-2019

2.5 MW power to overall plasma

From Phase-1

$I_e = 10 \text{ kA}$

$I_{ST} = 7 \text{ kA}$



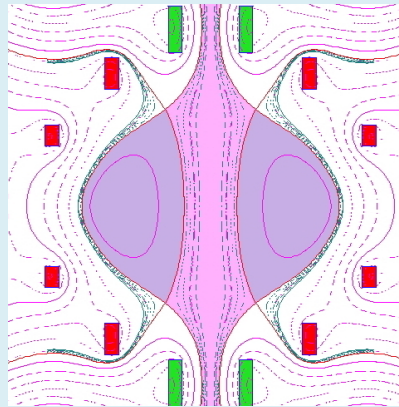
2019

up to 3.5 MW overall

to Phase-1.5

$I_e = 10 \text{ kA}$

$I_{ST} = 40 \text{ kA}$



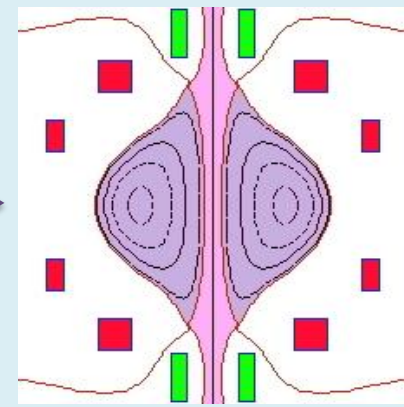
end 2021

up to ~ 20 MW overall

to Phase-2

$I_e = 70 \text{ kA}$

$I_{ST} = 0.28 \text{ MA}$



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

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

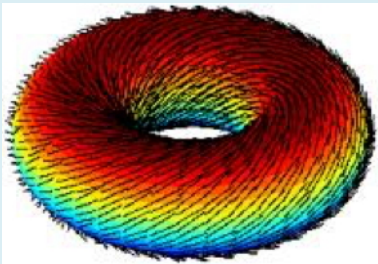
to 95% Torus/Sphere volume
? of Power Input to Torus

No additional heating systems (reconnection heating)

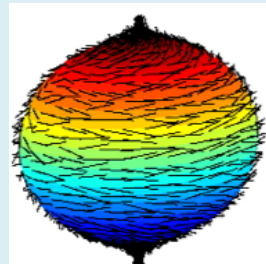
$\beta \sim 1 \diamond$ cost is 1% of a Tokamak ($\beta \sim 1\%$), with same power input into plasma

Last Confinement Surface spherical, but Tori inside

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



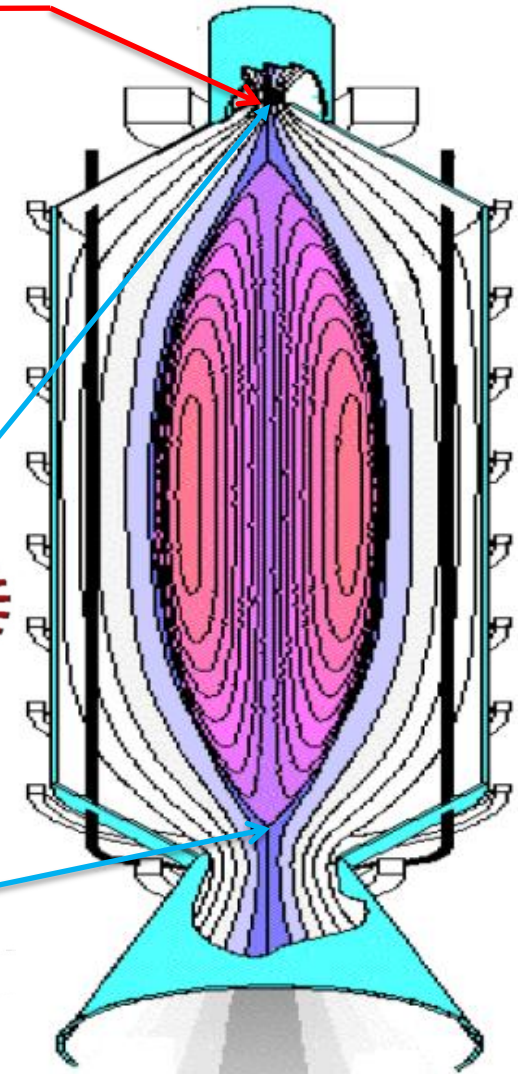
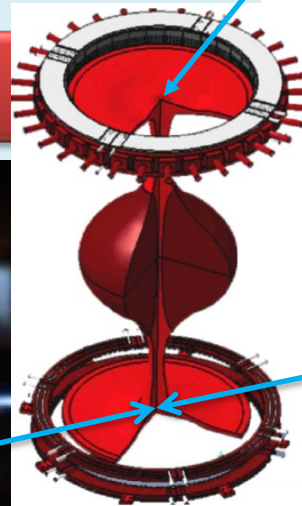
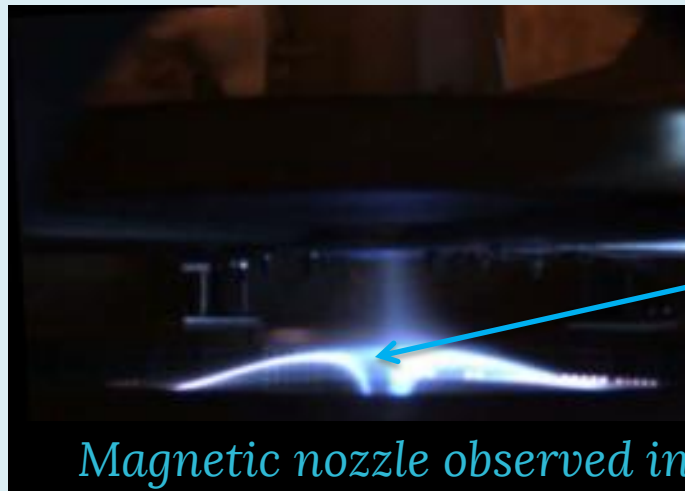
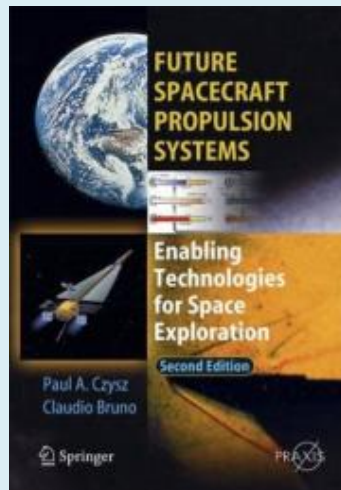
a hairy torus
can be combed



a hairy sphere
cannot!

One of the "tufts" of the sphere is predominant
in expelling charged fusion products

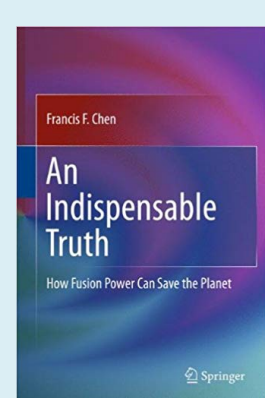
Space-thruster forerunner?



Magnetic nozzle observed in PROTO-SPHERA experiment (2015)

Remarks:

- **The machine** does not aim at refining previously achieved results, but to be **ground-breaking**
- Until now **the physics ideas seem sound**: Phase-1 aims were achieved & tori were sustained
- **Technically** it can achieve Phase-2 **without design uncertainties, with limited corrections**
- Until now these **corrections have dealt with boundary conditions** (magnetic & electrostatic)
- The **progress of the machine** must follow a **step by step path**: no hazards, ...no double steps(?)
...btw: complete successfully Phase-1.5 before moving to Phase-2 PF coils & Power Supplies
- Fusion might be a dream, but **magnetic reconnections studies must aim at world excellence**
*...& must accommodate **experiments of astrophysical interest***
- **Excellence in reconnection studies** cannot be achieved without **excellence in diagnostics**
- But there's a dream: a **permanent magnets confined arc discharge** as ultimate fusion machine



Francis Chen: An Indispensable Truth, How Fusion Power Can Save the Planet - Springer Science & Business Media 2011
Part II - 10 Fusion Concepts for the future - **Ultimate Fusion** pag. 413 ...the very end of the book

One hundred years from now, what will a fusion reactor look like?

They may look like those of the Chandrasekhar–Kendall–Furth force-free configuration shown in Fig. 10.56.

The exterior regions above and below the divertor necks can be expanded like those of an axisymmetric mirror.

High-energy alpha particles leaving the divertors can be channeled into direct converters to generate high-voltage DC directly. The central core can be slid up or down continuously to be refreshed without a shutdown.

This is a dream, but we can hope