Laboratory reconnections between plasma Jets and Tori: the PROTO-SPHERA Experiment

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AGILE, 16th Science Workshop

ASI Headquarter, Roma, May 18 2018

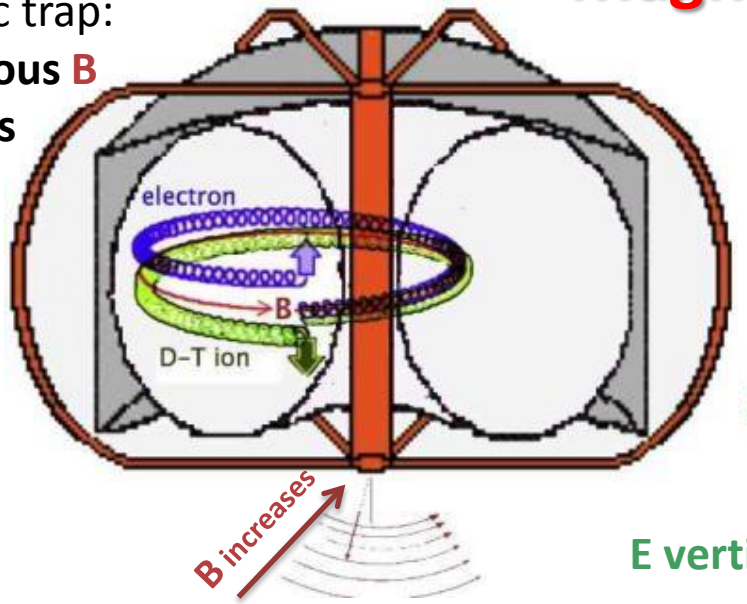
Outline

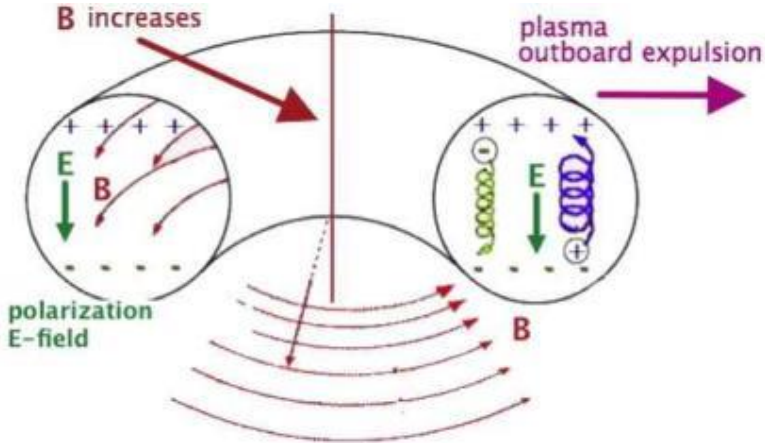
- **PROTO-SPHERA has achieved the full Phase-1 current (10 kA) of Plasma Centerpost**
- **Surprise: the experiment now produces routinely Argon & Hydrogen Toroids**
- **DC voltage on Centerpost electrodes drives Toroidal Current (magnetic reconnections)**
- **In 2019: an intermediate Phase-1½ for moving to Phase-2 on sound bases**
- **End of 2021: Phase-2 experiment ready to produce plasma**

Magnetic confinement basics

Toroidal magnetic trap:
the inhomogeneous B separates charges

e.g. e^- → **up**
ions$^+$ → **down**

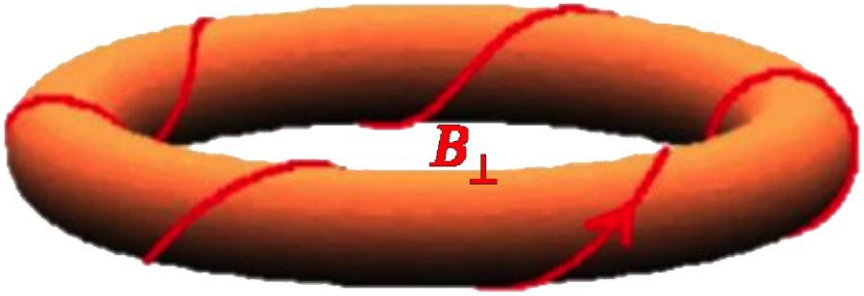


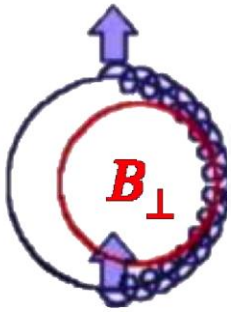


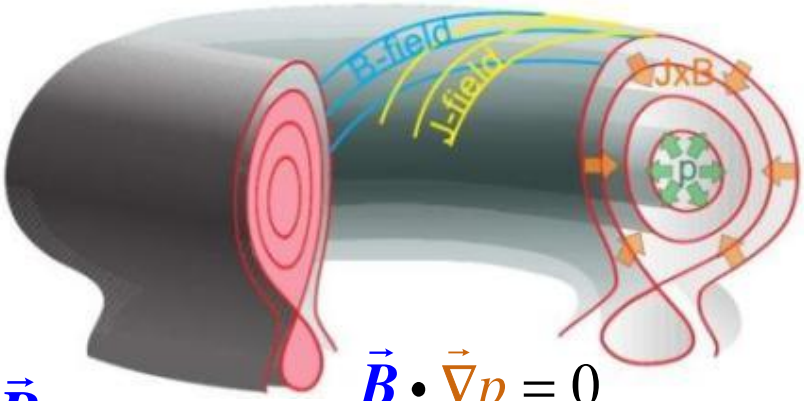
E vertical field, through **E∧B**, **…ejects plasma**

A poloidal $\mathbf{B}_\perp$ magnetic field is required to contrast particle drifts

→ toroidal current has to flow in an axisymmetric plasma







(magneto-hydrostatic equilibrium) $\vec{\nabla} p = \vec{j} \wedge \vec{B}$ → $\vec{B} \cdot \vec{\nabla} p = 0$, $\vec{j} \cdot \vec{\nabla} p = 0$

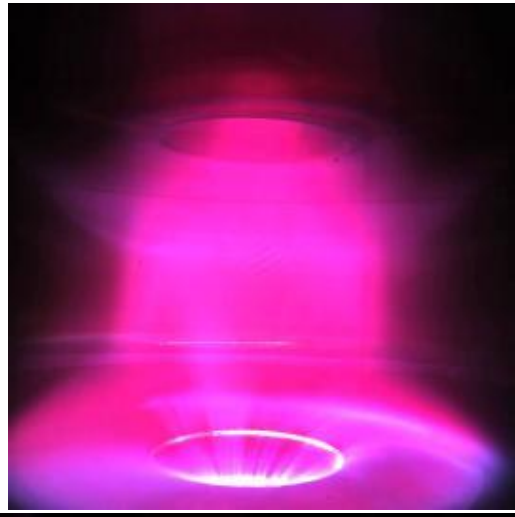
flux (…also *p* & *j*) surfaces must be Tori

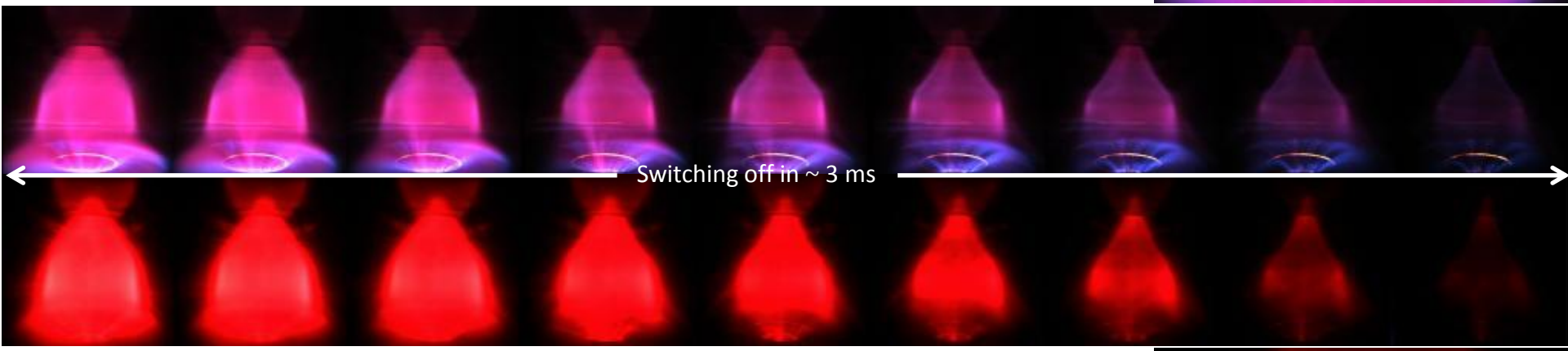
Magnetic confinement basics at work!

Switch-off of PROTO-SPHERA discharges containing a torus:

the brightness of the torus is the last to vanish, both in the full spectrum of visible light

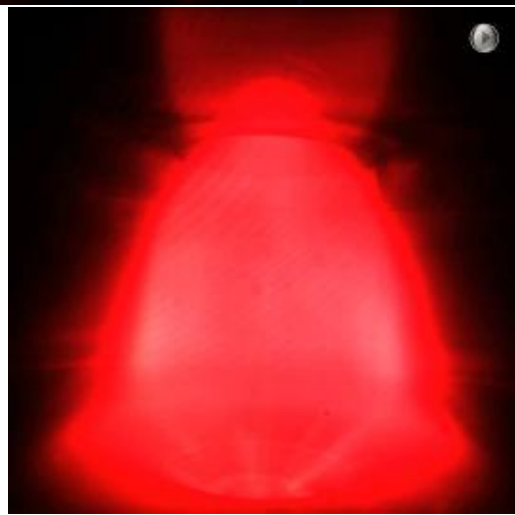
#1224, 10 kA Hydrogen





#1219, 10 kA Hydrogen

as well as observed trough a Balmer-alpha filter



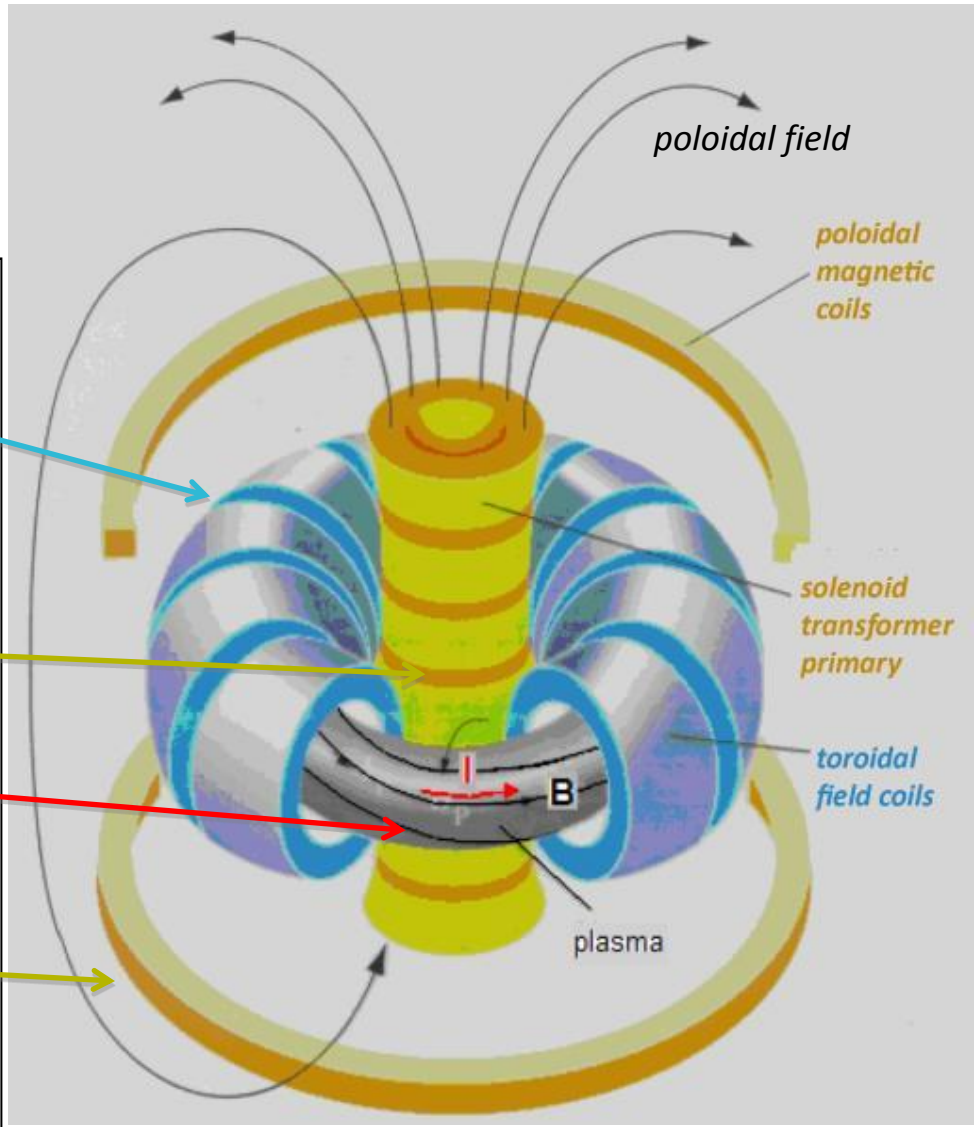
Tokamaks (1953)

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 torus
- The central solenoid induces the plasma current (*break-down*) and heats the plasma torus

  (ohmic heating,

  through plasma resistivity)
- Other poloidal field coils control the radial position of the plasma torus

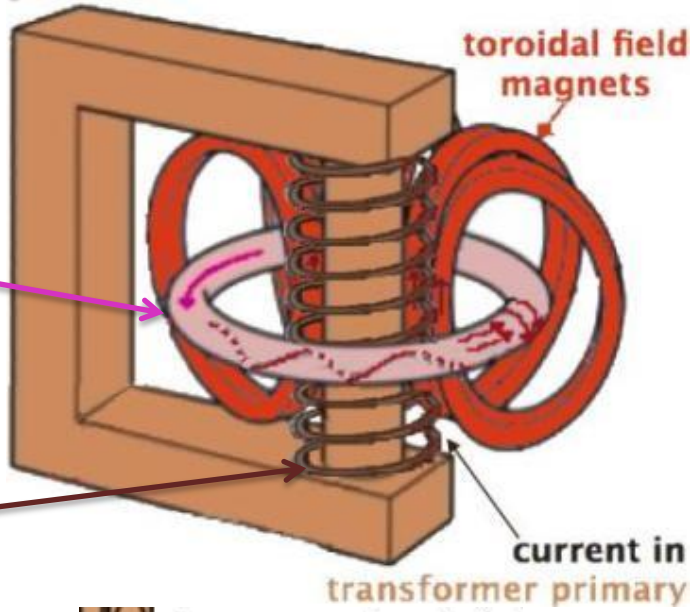


Tokamak drive: AC currents, induction

Plasma confining current inside Torus:

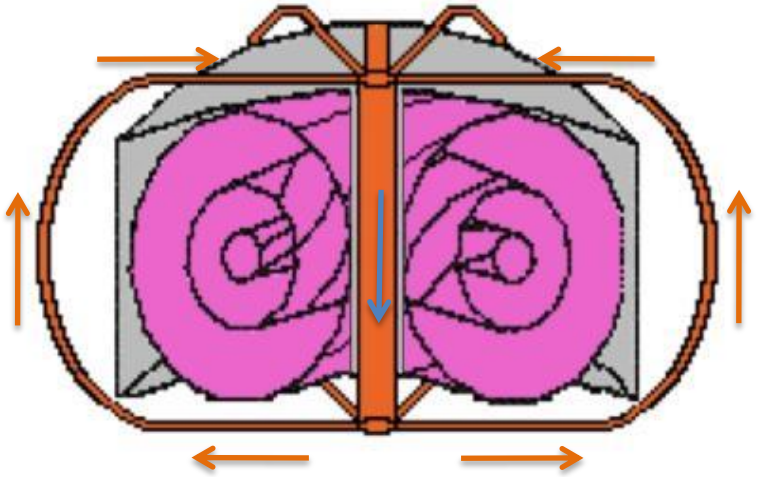
induced and sustained by a transformer

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: moving closed flux surfaces, "feeding" the plasma from outside, they are dissipated while they move toward the magnetic axis**
- **In tokamaks this process is due to the transformer current change:**
- **Tokamaks cannot have steady drive!**

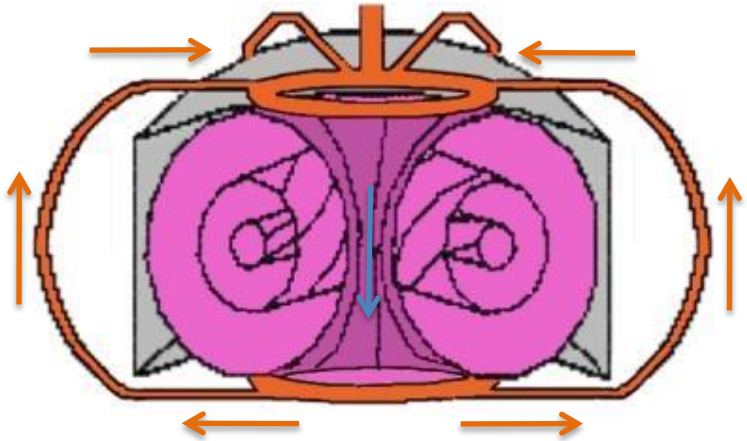
The main idea of PROTO-SPHERA



Electric current flow

- "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 return the current

Cylindrical geometry of Vacuum vessel

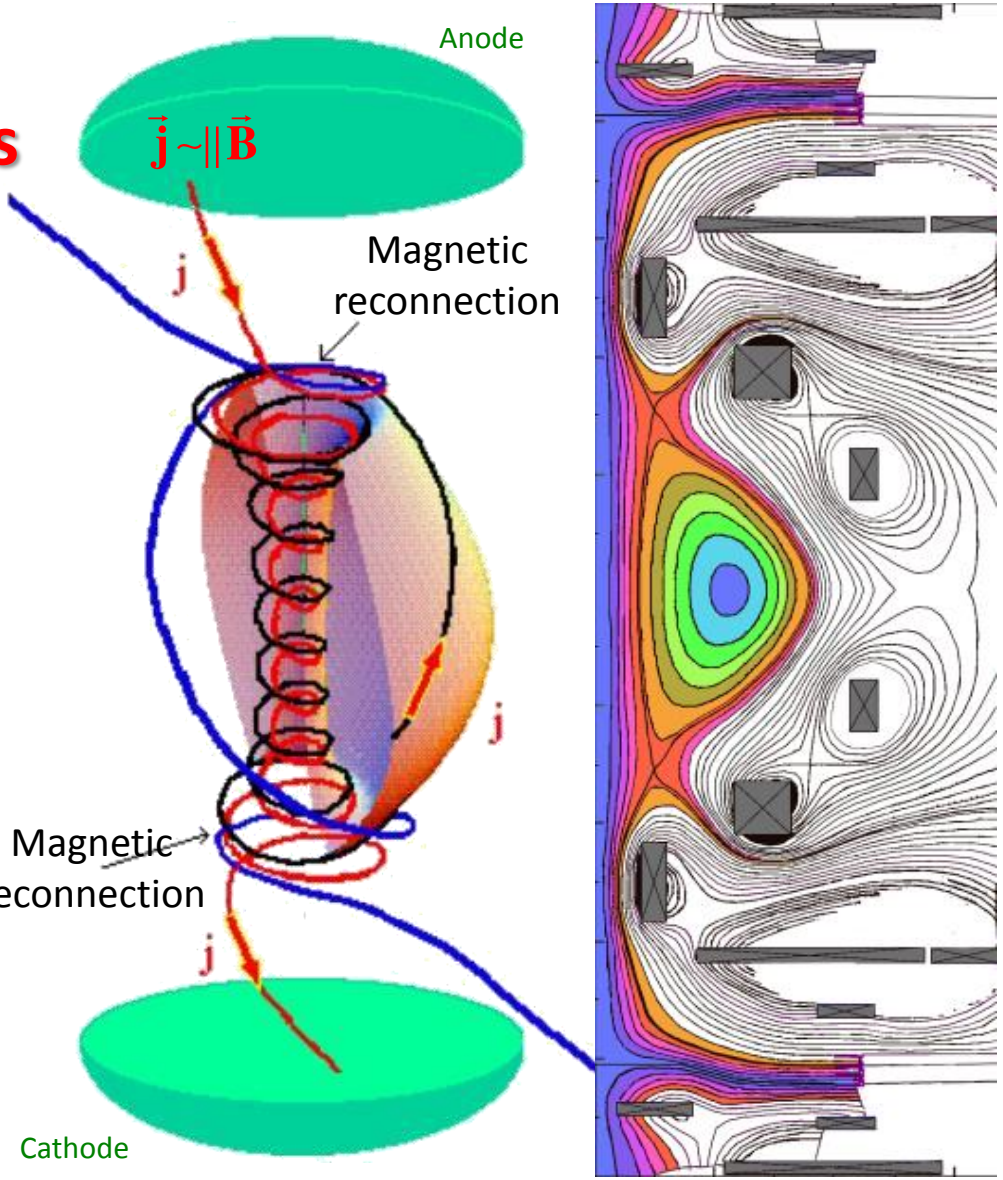
…but electrodes required inside vessel

Cylindrical vacuum vessel geometry has obvious advantages!

easy to access & and to repair…

PROTO-SPHERA drive: DC currents, reconnections

- **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**

SUSTAINMENT OF TOROIDAL CURRENT BY RECONNECTIONS OBTAINED in 2018 & IS FOREVER!

Reconnections of Jets and Tori a common occurrence in Nature!

Hydrodynamics examples

Plasma examples: Solar Flares
Magnetic Reconnections, Coronal Heating

PROTO-SPHERA (max 1 s plasma) aim was:
sustain Torus for 1 resistive time ~ 70 ms

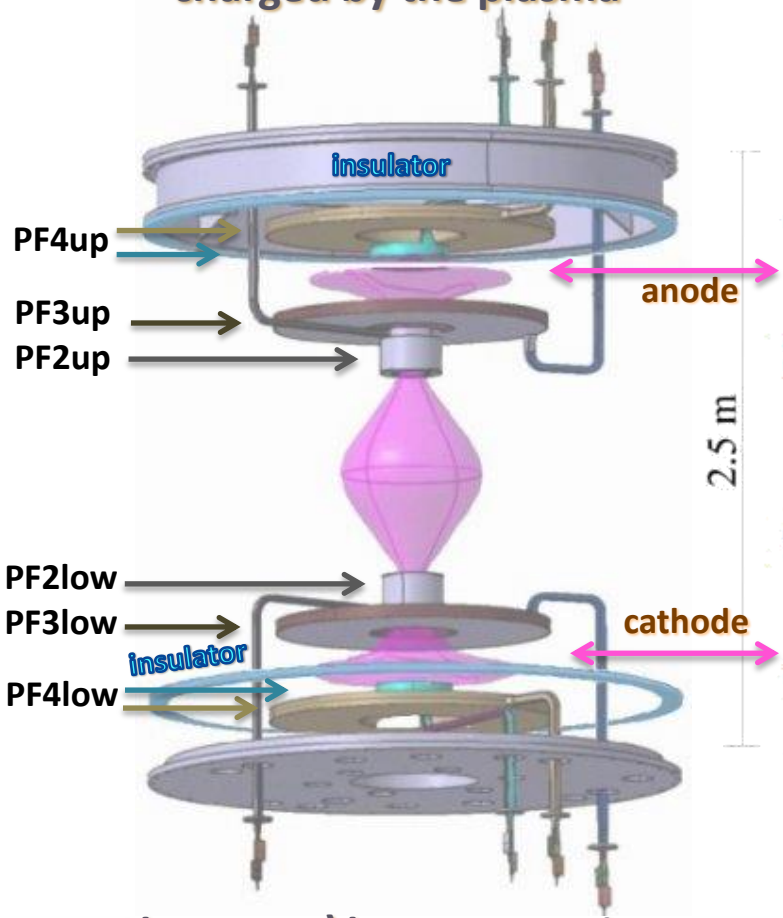
PROTO-SPHERA has already sustained a low current torus (5 kA) for ½ sec

The two Phases of PROTO-SPHERA

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

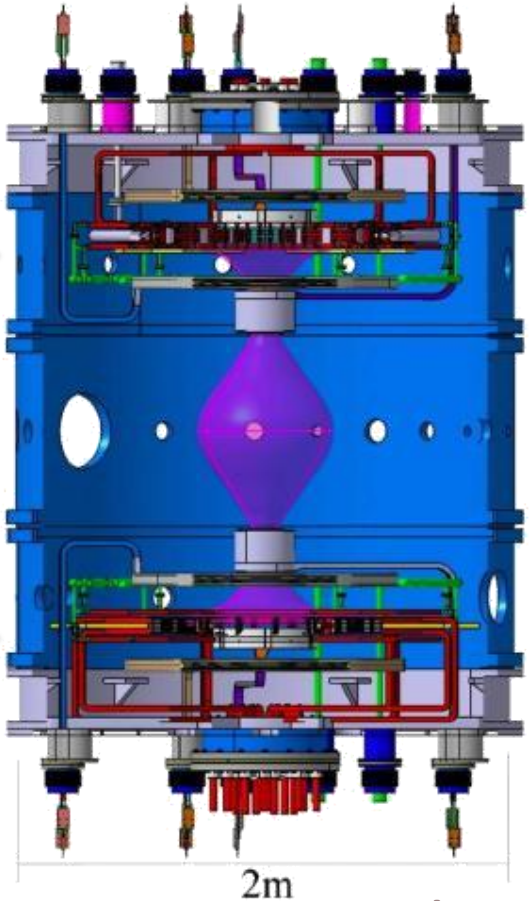
- Phase-1: demonstrate Plasma Centerpost's (fear of anode arc anchoring…)
- Phase-2: machine completed such as to produce the Spherical Torus

PF coils casings built as floating, charged by the plasma



Also upper\lower extensions & lids are floating

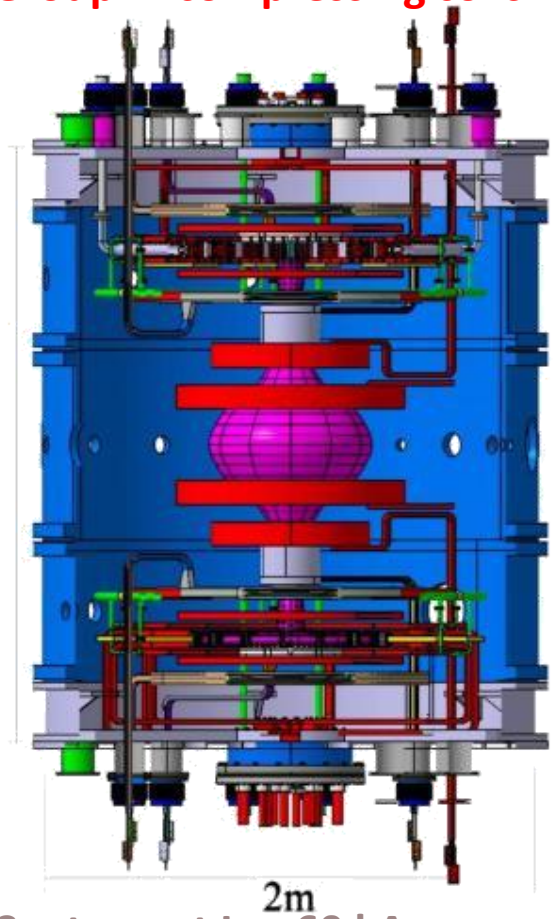
Phase-1: **8 PFcoils**
'Group B' shaping coils



Centerpost I_e= 10 kA

…2018 Torus I_{ST}= 5 kA…!

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

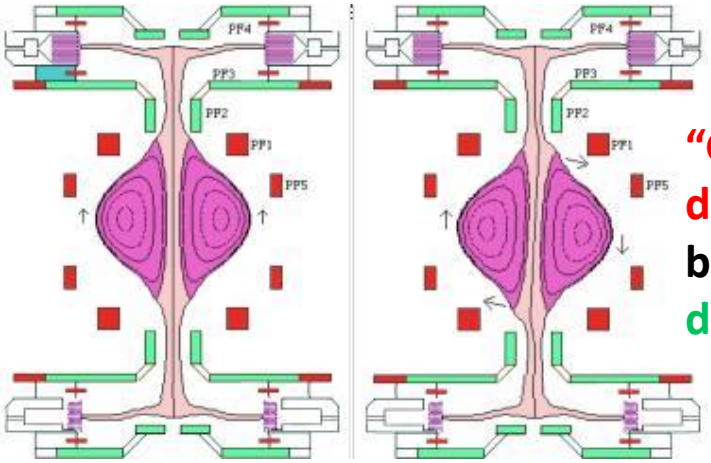


Centerpost I_e= 60 kA

ST current I_{ST}= 120÷240 kA

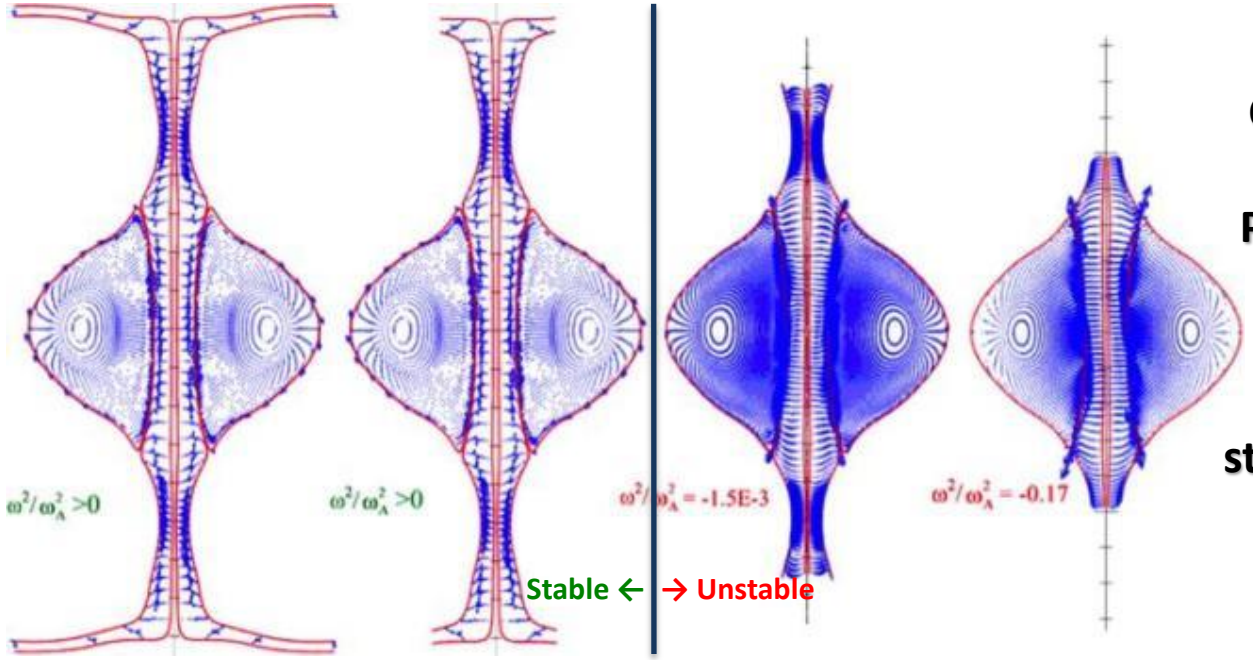
Ideal MHD stability of PROTO-SPHERA

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



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

DISK-SHAPED ELECTRODE-FACING PLASMA GUARANTEES IDEAL MHD STABILITY



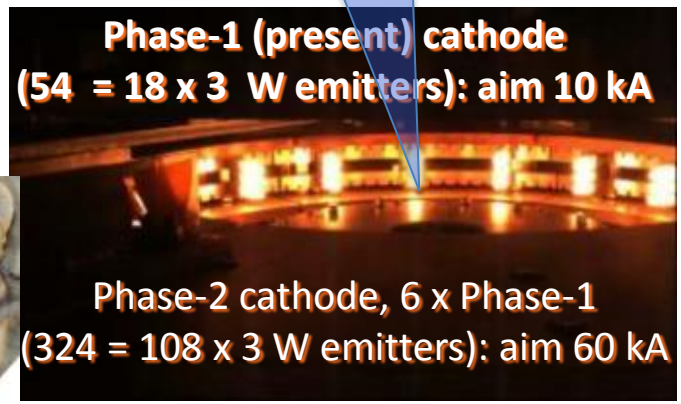
Cutting shorter & shorter
the plasma centerpost
PROTO-SPHERA at 120 kA
of toroidal current in ST
gets destabilized;
in absence of cutting
stability extends to 240 kA
of toroidal current in ST

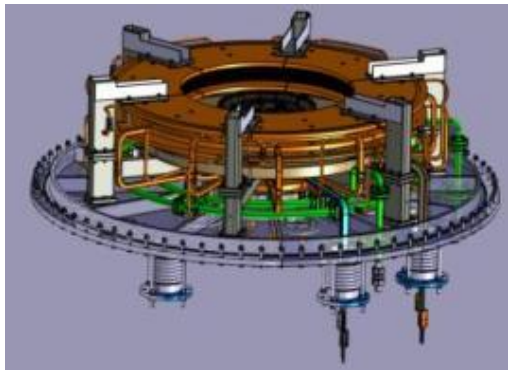
PROTO-SPHERA Electrodes

Low voltage (100-350 V)
between electrodes

at high-field tokamak
plasma density ~ few • 10^{20} m^{-3}

Down: 3000º K heated cathode





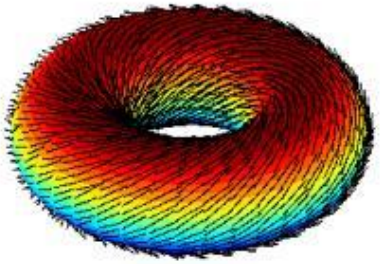
"Caduceus"-like W emitting spirals
have now survived > 1500 cycles

A SPACE-THRUSTER forerunner?

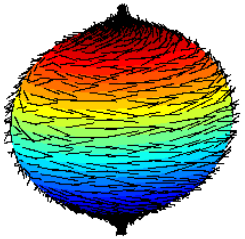
abandon vacuum vessel toroidal geometry, move to cylindrical one

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

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



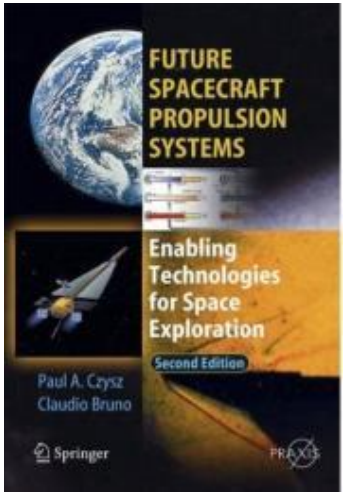
a hairy torus
can be combed



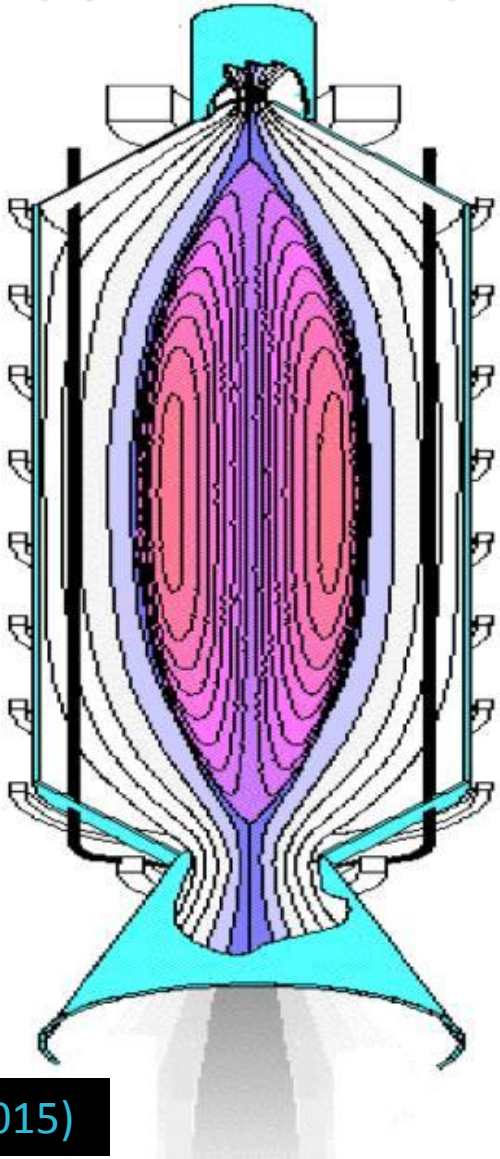
a hairy sphere
cannot!

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)



PROTO-SPHERA Plasma Centerpost rotates & therefore avoids anode arc-anchoring

Anode arc-anchoring means that a plasma arc discharge is localized on an anode spot

#614, 8.5 kA Argon
break-down V_e ~ 90 V, steady V_e ~ 200 V

#977, 10 kA Hydrogen
break-down V_e ~ 320 V, steady V_e ~ 220 V

Plasma rotation in Tokamaks always stabilizes the plasma

best way of injecting fuel is from inboard (high field side)

(*Pisa University & its PlasmaTech spin-off*) line-averaged electron density on plasma equator:

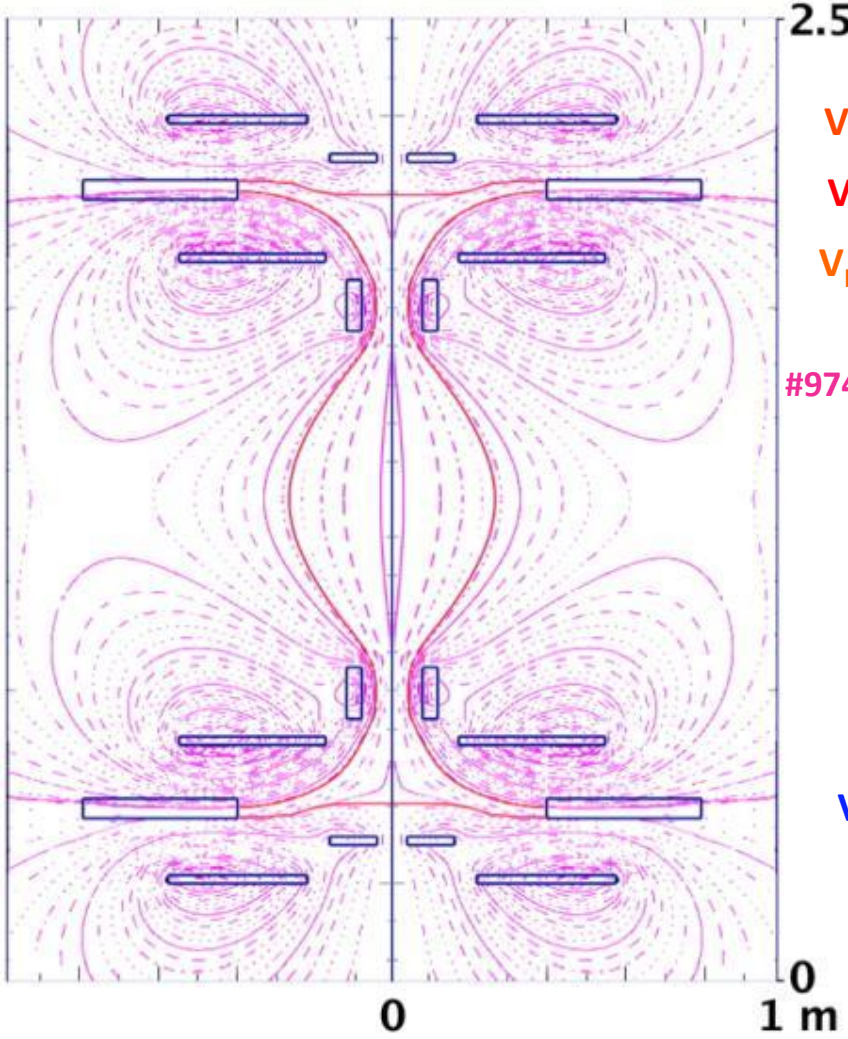
in Argon Centerpost $\langle n_e \rangle \sim I_e$
at I_e =10 kA, $\langle n_e \rangle \sim 4 \cdot 10^{20}$ m^{-3}

in Hydrogen Centerpost
at I_e =10 kA, $\langle n_e \rangle \sim 1.5 \cdot 10^{20}$ m^{-3}

No Anode-Arc Anchoring: Electrostatic plasma effects!

$\vec{E} \wedge \vec{B}$ plasma rotation does the trick!

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



V_{LidUp} ~ +95 V

V_{PF4up} ~ +95 V

V_{anode} ~ +139 V

$V_{PF2\text{-}3up}$ ~ + 50 V

#974 10kA Hydrogen

GND

$V_{PF2\text{-}3low}$ ~ -12 V

$V_{cathode}$ ~ -80 V

V_{PF4low} ~ -41 V

$V_{LidDown}$ ~ -56 V

Lines: magnetic field

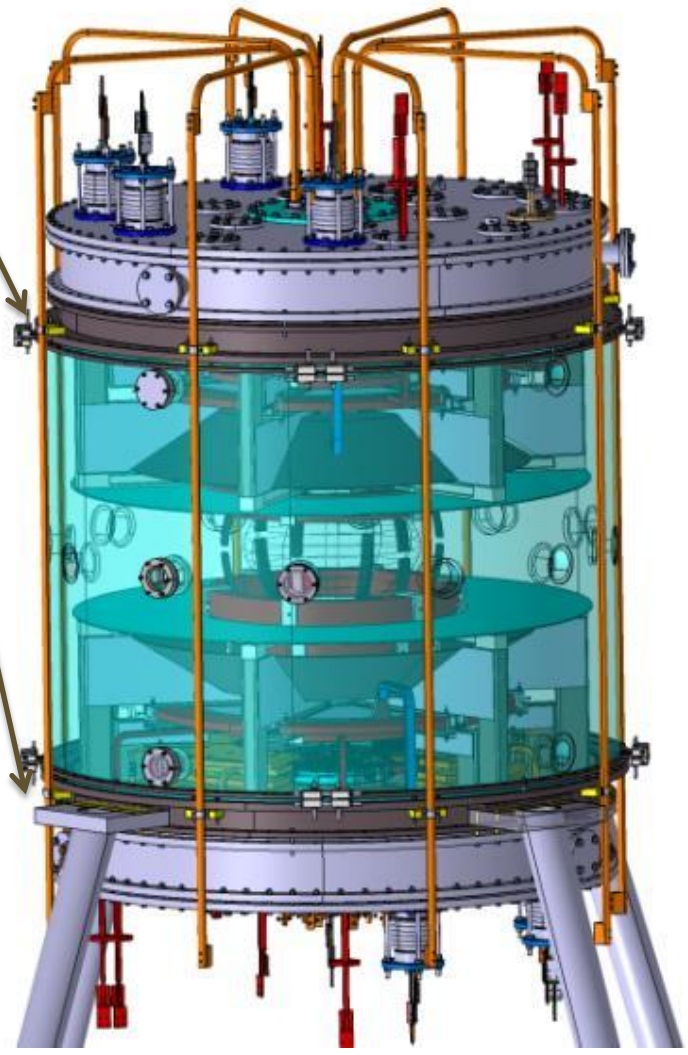
Color contours: *electrostatic potential*, Arrows: E field

Insulating & transparent vessel being built for Phase-2

will substitute the Aluminum vacuum vessel with a Polymetacrylate (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

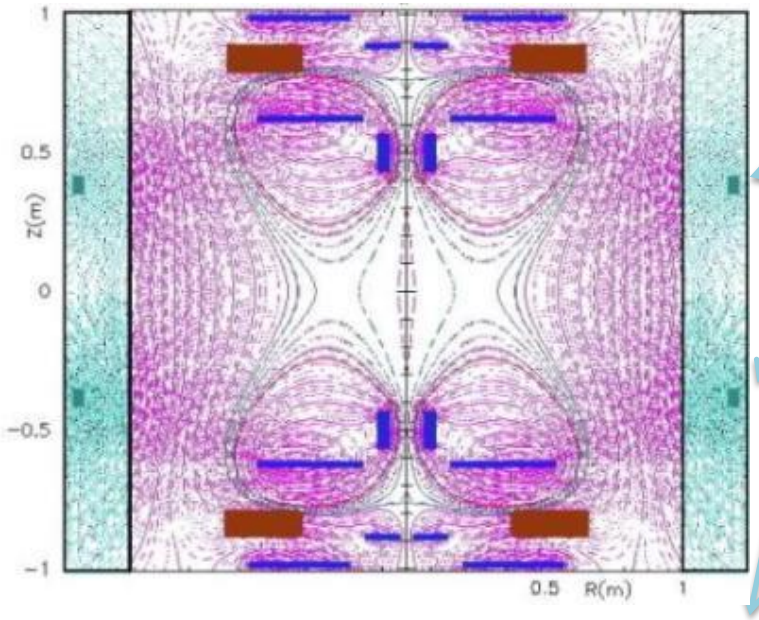
“Magnetic Boundary Conditions” changed

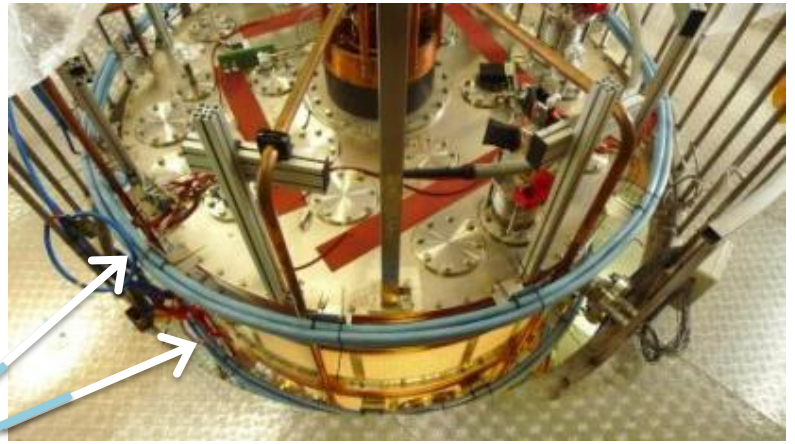
4 external PF coils added …fed in series with the internal PFInt coils, from April 2018 a further Super-Capacitor power supply feeds some of the PFExt coils

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 0.75 s of PF current
to allow for skin current diffusion in Al vessel

#983, 10 kA Hydrogen

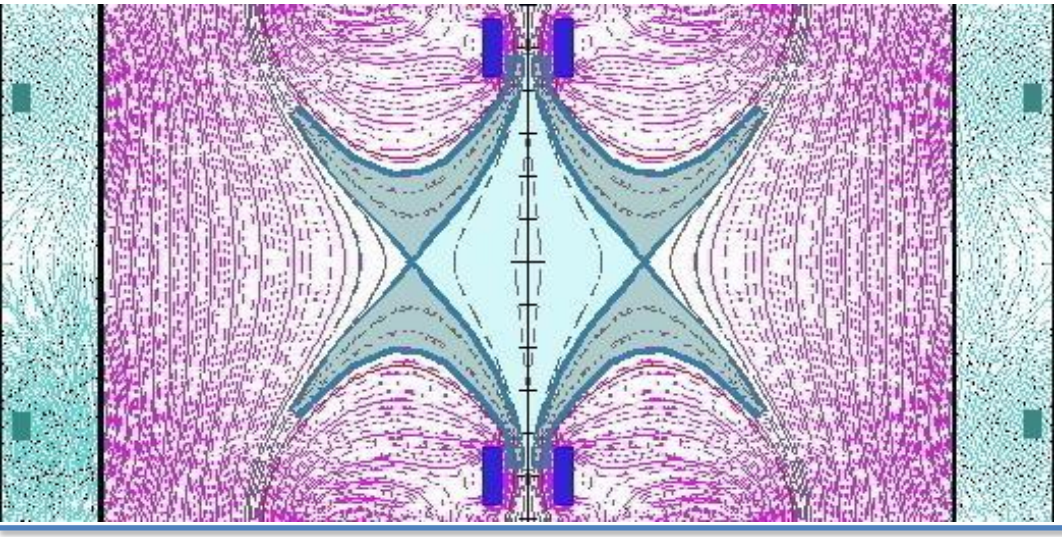




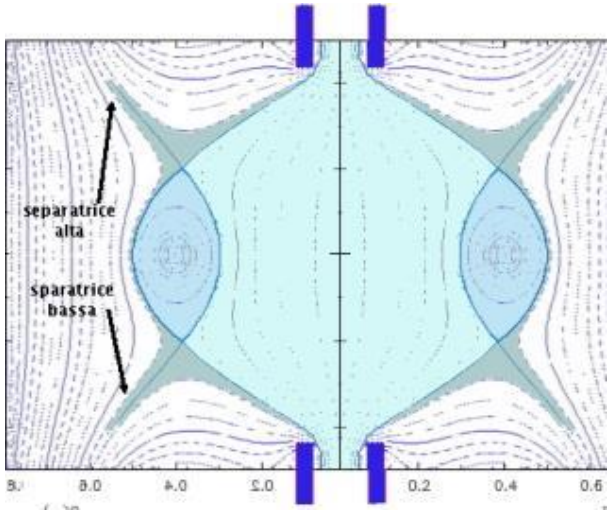
4 external PFExt (each 16 wires 25 mm^2)

March 2018 Torus formed in Argon plasmas

In absence of Torus formation



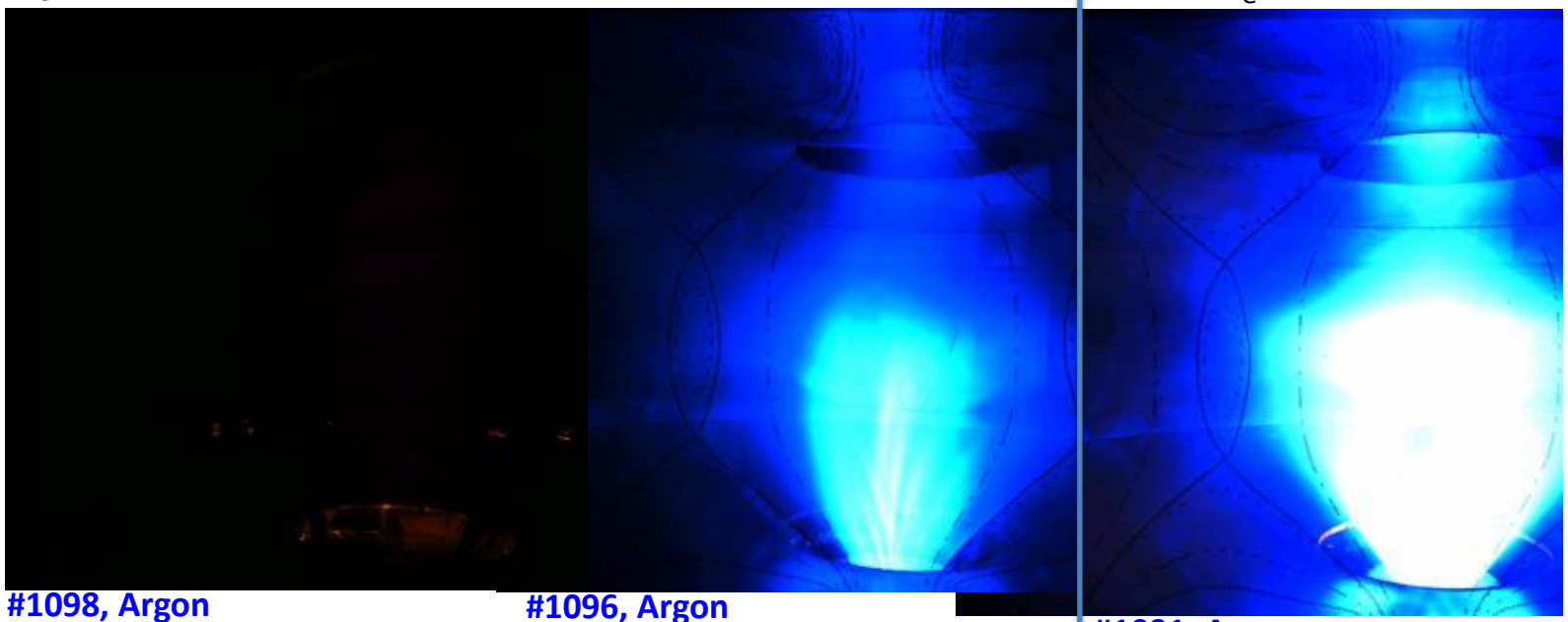
With Torus formation



I_e= 3 kA

I_e= 5 kA

I_e= 10 kA



#1098, Argon

#1096, Argon

#1091, Argon

Torus forms at the expected current: $I_e \sim 8$ kA

I_{Torus}= 5 kA

The “gentle Divertor” of the (barely visible) Argon Torus

#1149, Argon

#1160, Argon

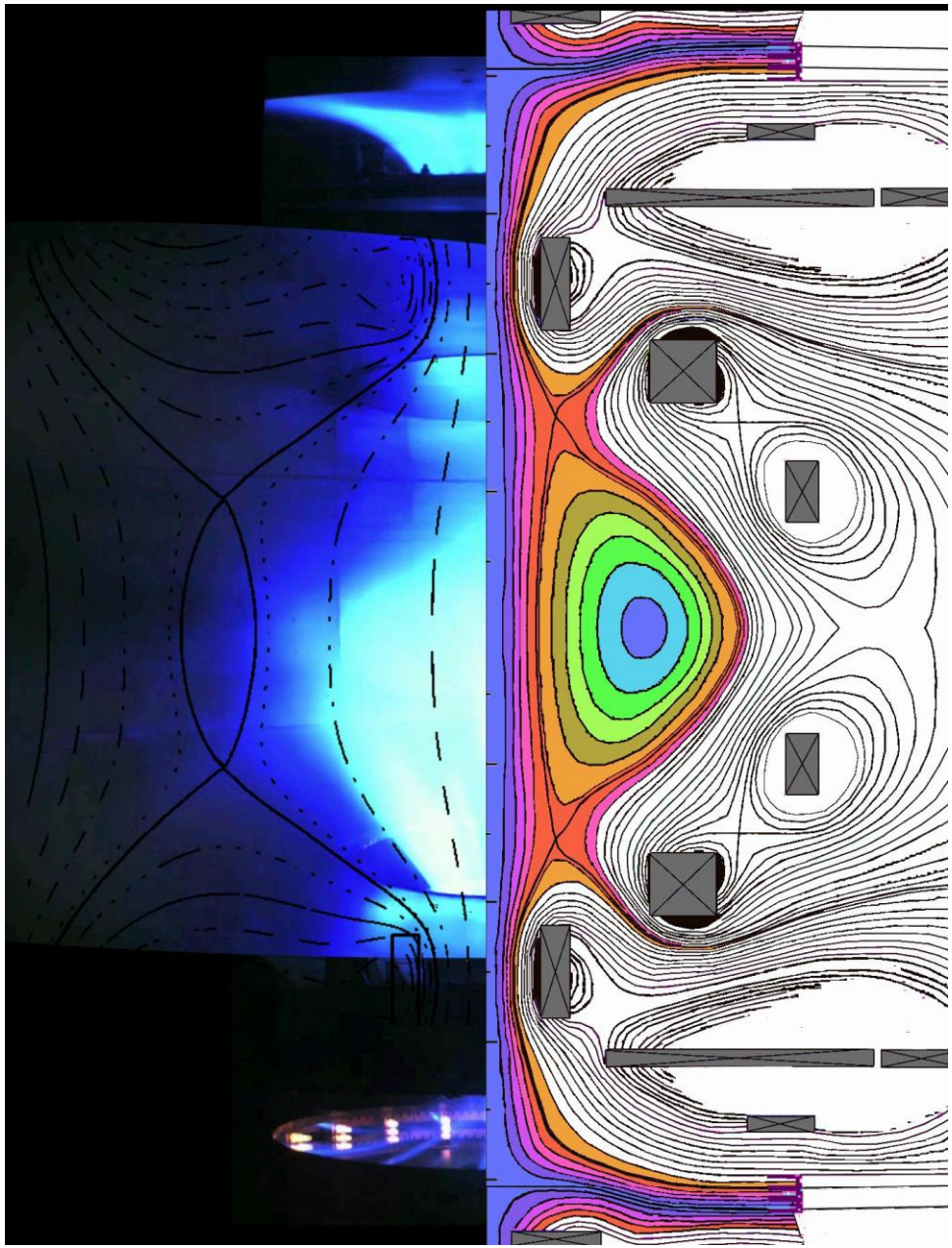
lower Divertor fan is dominant & slightly shifts down the Torus

The Argon Torus has been sustained for up to ½ sec

Argon Torus

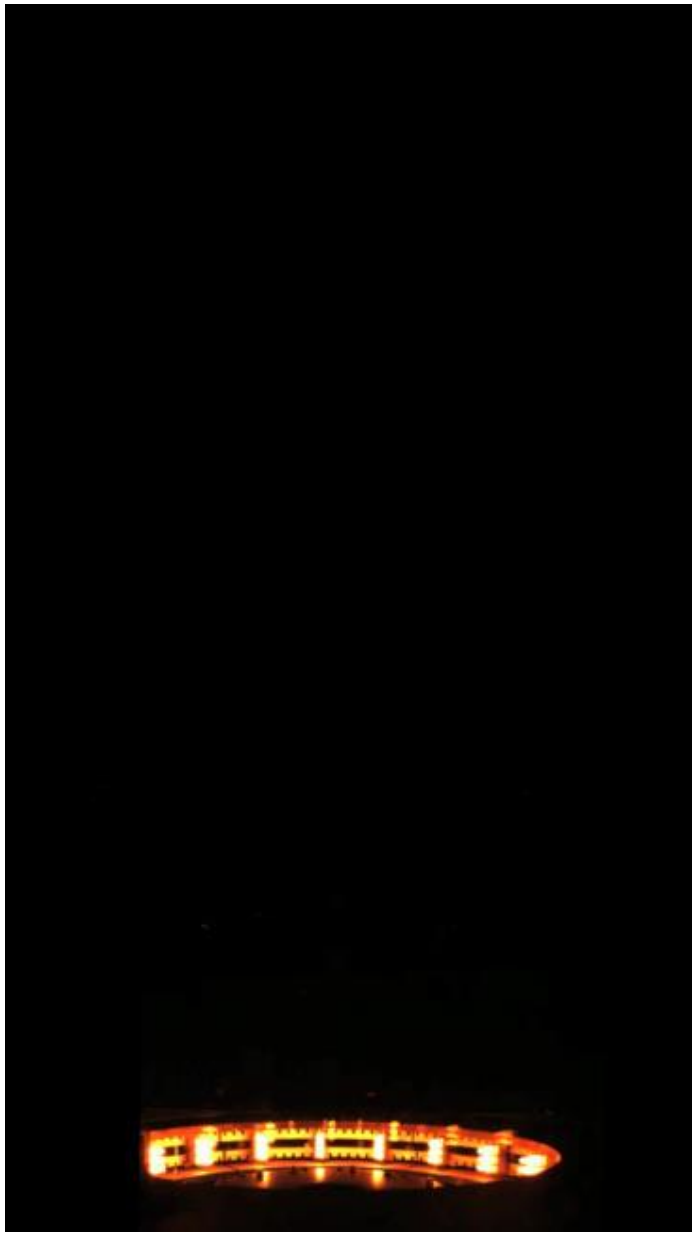
break-down V_e ~ 200 V

steady V_e ~ 220 V



#1160, Argon, X-points fit I_{ST}=5 kA

April 2018 Torus formed in Hydrogen Plasma

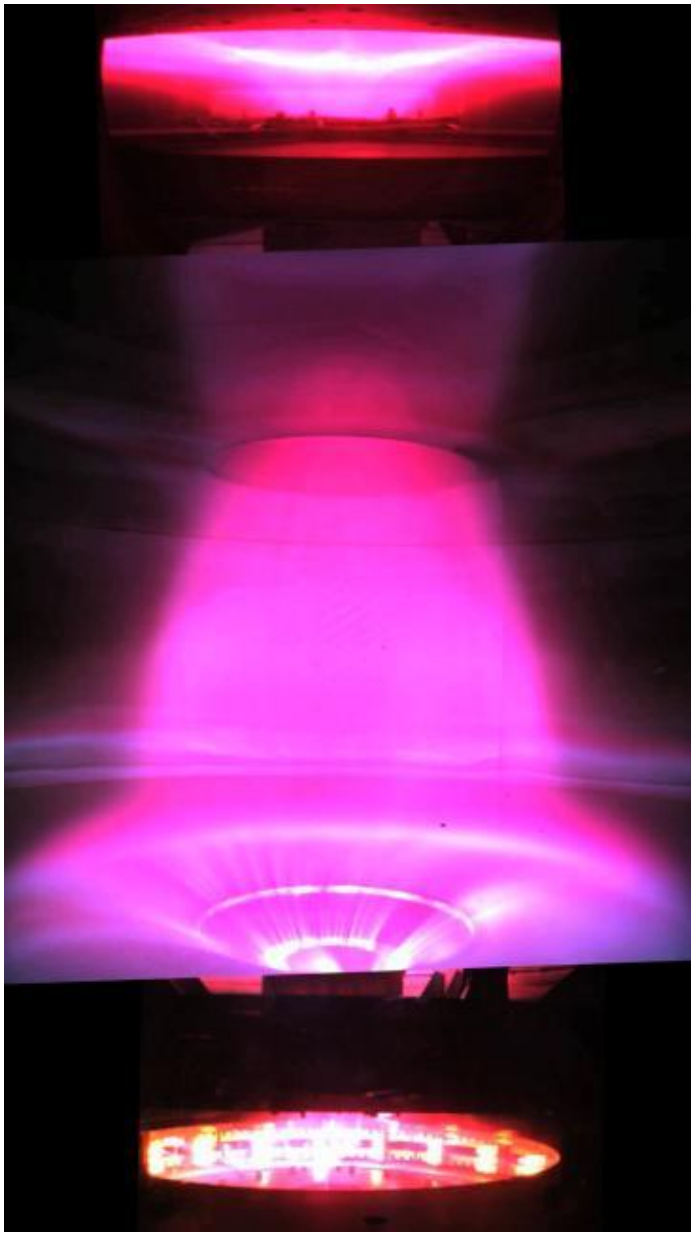


evident at plasma breakdown

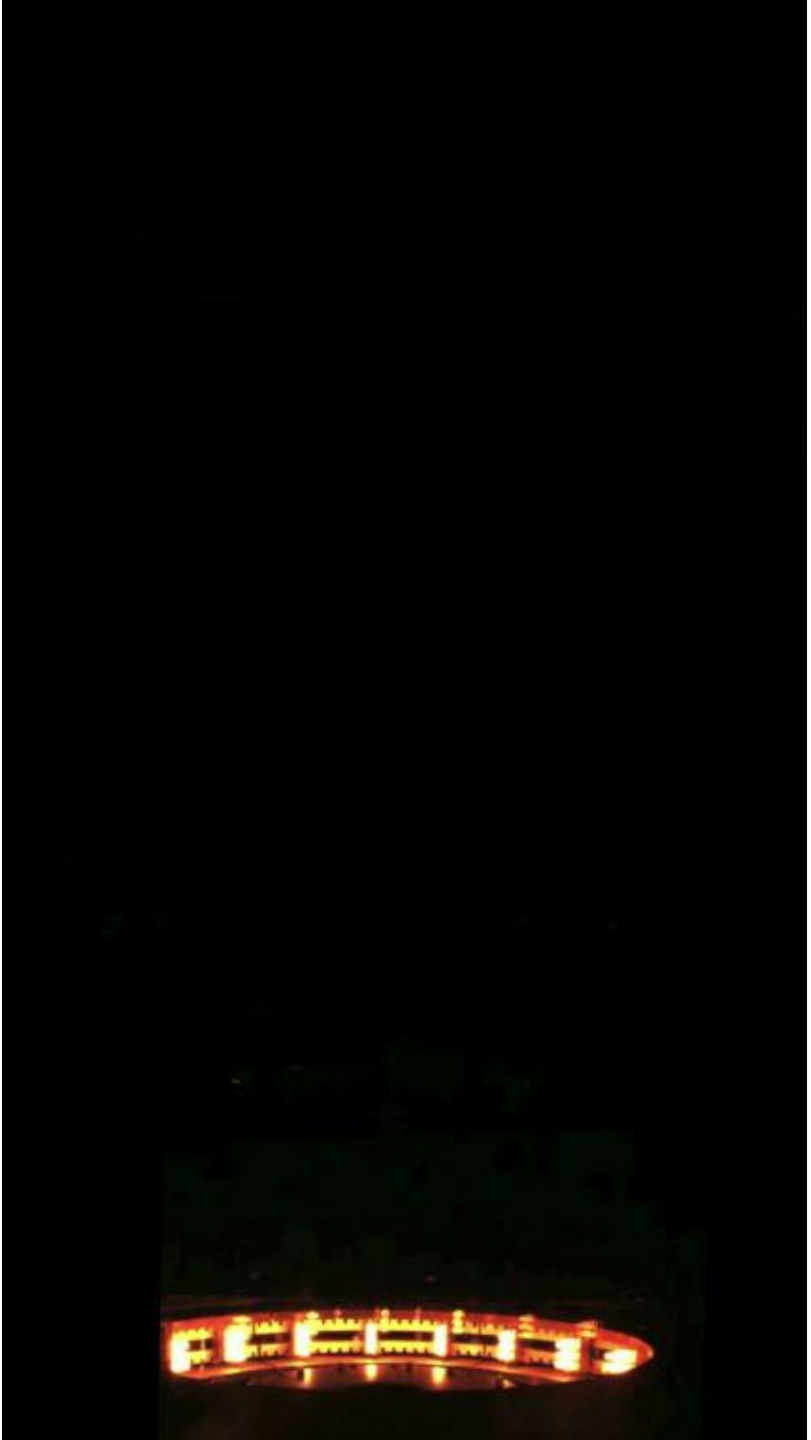
Hydrogen Torus
break-down
$V_e \sim 360$ V
steady $V_e \sim 320$ V

#1202, Hydrogen

& …after ¼ sec



at plasma switch-off



The “uncouth Divertor” of the Hydrogen Torus

The present divertor plate
is the lower polycarbonate diaphragm:
an unsuitable choice of material!

But when we put it inside PROTO-SPHERA
we did not expect to be able to form a Torus!

A new lower metal diaphragm being built now;
in 2019 PROTO-SPHERA will have 2 suitable plates

#1202, Hydrogen

Reconnections, Helical States & Double Tori

#1211
Hydrogen

Vertical field in eccess? …Double Torus!

#1225
Hydrogen

…or Helical States …or lop-sided Tori!

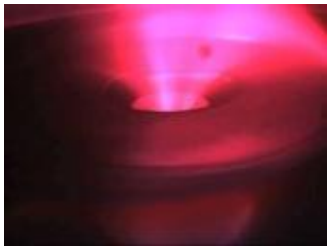
The only occurrence you should never ever consider is plasma disruption: gone for good!

PROTO-SPHERA will not need additional heating…?

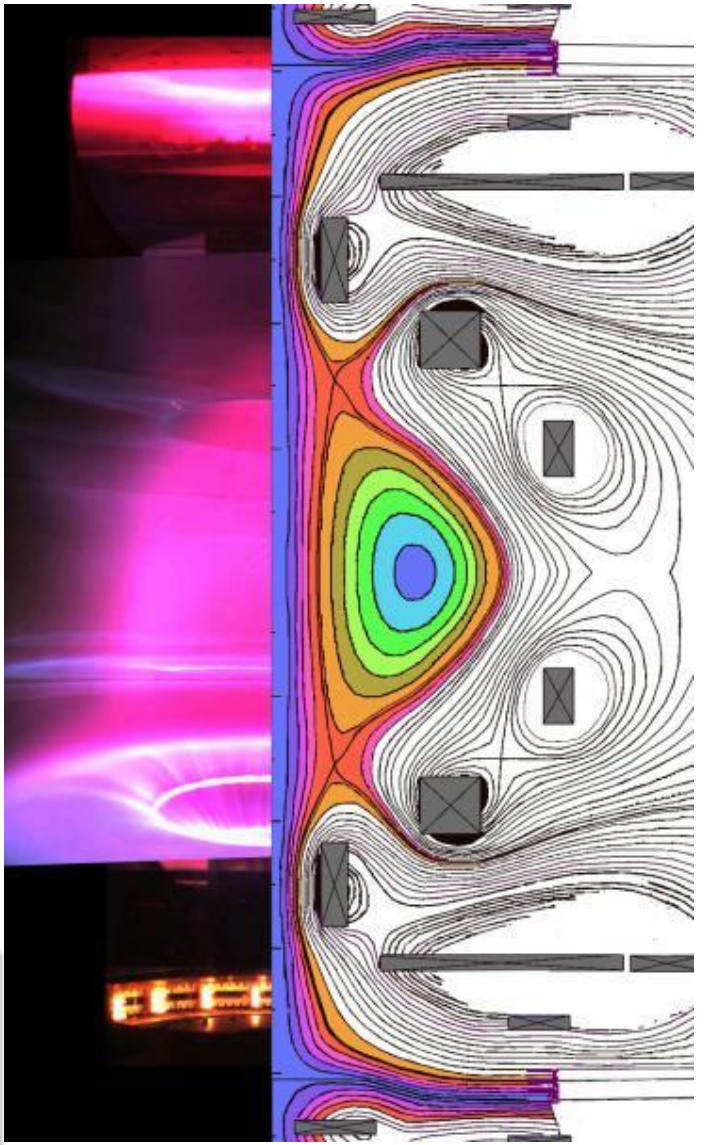
…magnetic reconnections heat the Solar Corona!

Phase-2 power injected into plasma > 250 V • 60 kA = 15 MW …how much into Torus?

~ 0 MW, T = 10 eV
"cold" plasma:
divertor studies



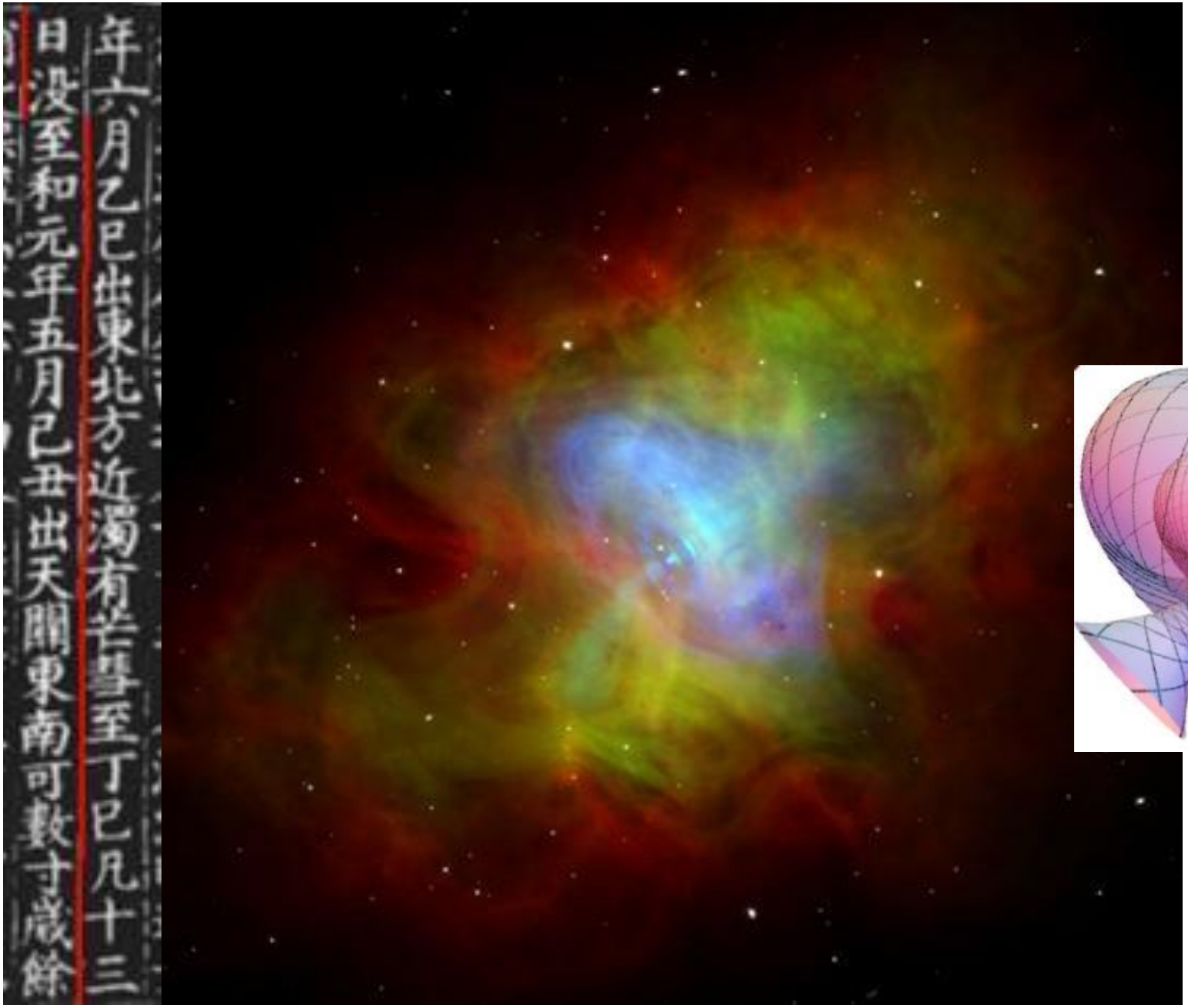
< 1 MW, T = 100 eV
"lukewarm"plasma:
magnetic reconnection
studies at S ~ 10^4

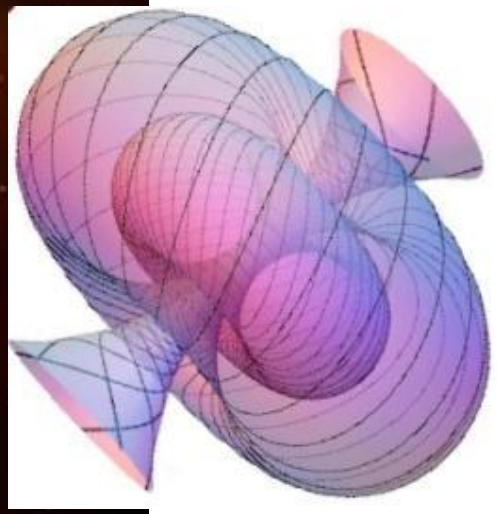


Fritz Lang's Metropolis (1926)

a few MW, T =1 keV, "hot" plasma at β ~ 1, no disruptions
no additional heating & no current drive required,
same T as a Tokamak, but 1/100 of the cost!

Crab Nebula remnant



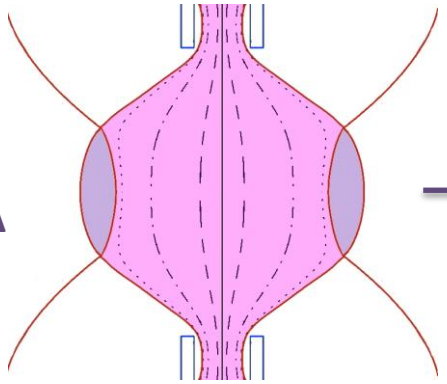


Hopf foliation

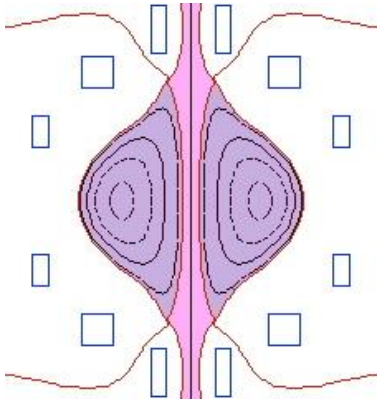
Major surprise: Torus forms in a static field

Plasma operations will be easier in Phase-2, which will produce Spherical Tori with I_{ST}= ¼ MA

from now
I_{ST} = 5-7 kA



to Phase-2
I_{ST} = ¼ MA



Perspectives

PROTO-SPHERA will assess a new magnetic confinement configuration:

- simply connected (easy to build, maintain & modify)
- sustained (indefinitely) by magnetic reconnections induced by DC voltage
- mixed magnetic & electrostatic confinement, plasma flow being paramount
- could provide laboratory examples and insight into cosmic reconnection phenomena
- (if high T from magnetic reconnections) plasma β ~ 1: small size future Fusion reactor?
- a forerunner for a (far future) Fusion Space Thruster?

+ Other authors