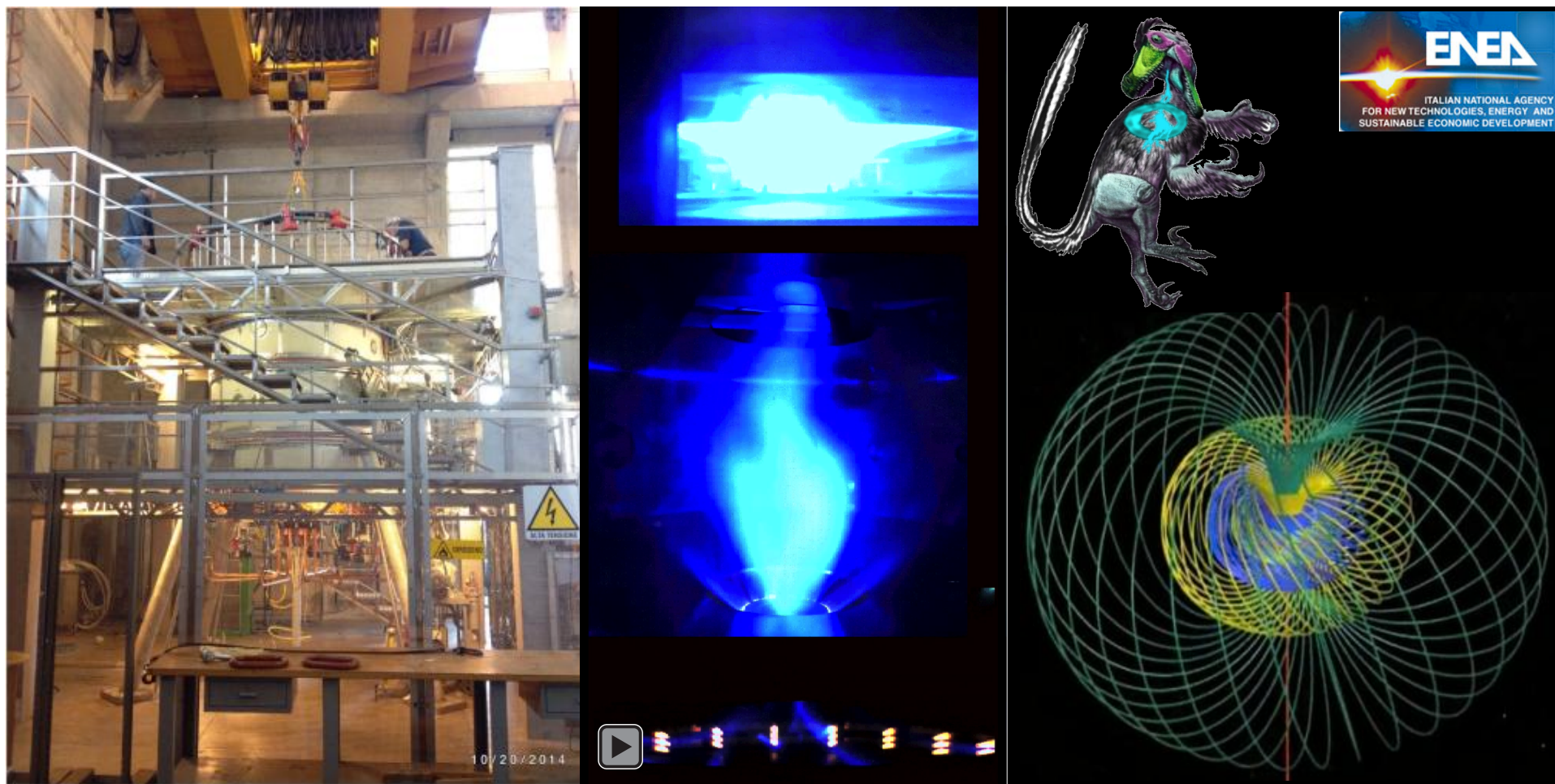


PROTO-SPHERA puo' essere utile *per l'Astrofisica?*

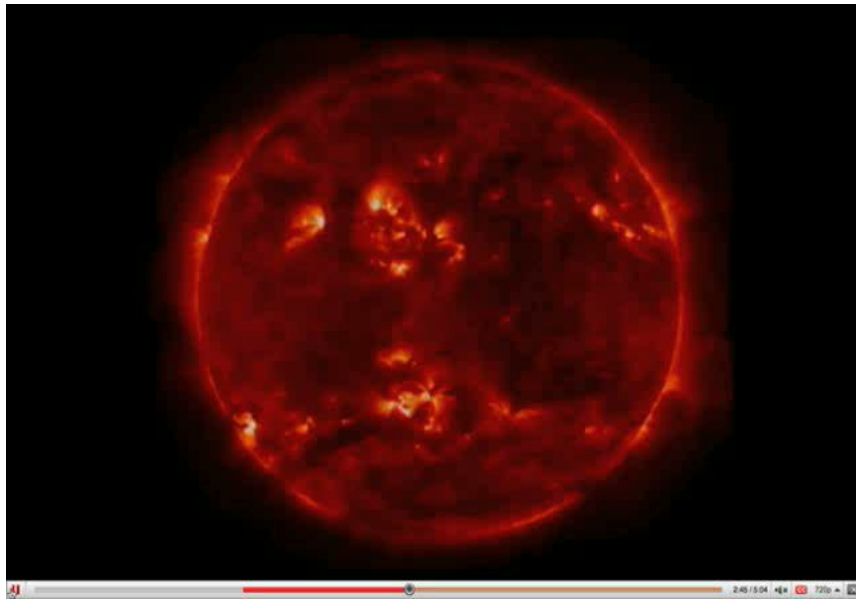
Franco Alladio, CR-ENEA Frascati



16 Gennaio 2018, Frascati

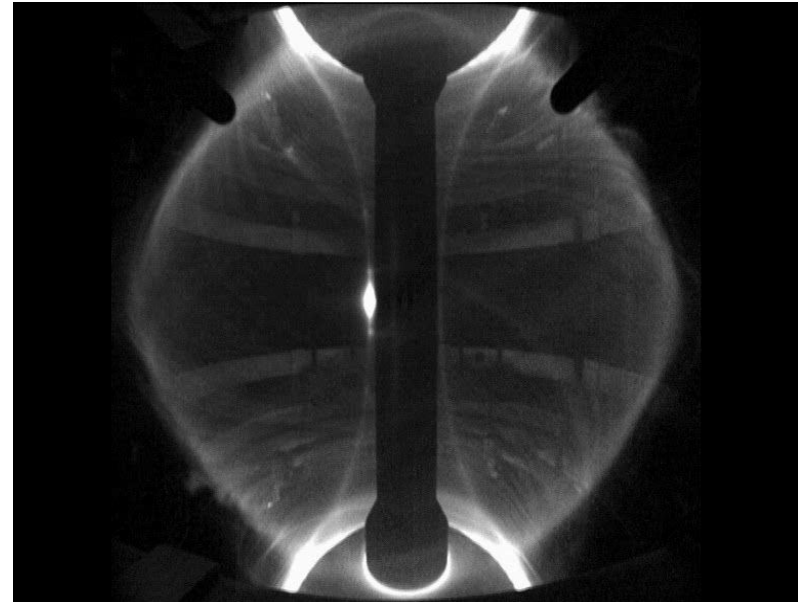
Fusion experiments are similar to the Sun in their instabilities!

1.4 Billion meters



Solar Chromosphere filaments

1.4 meters

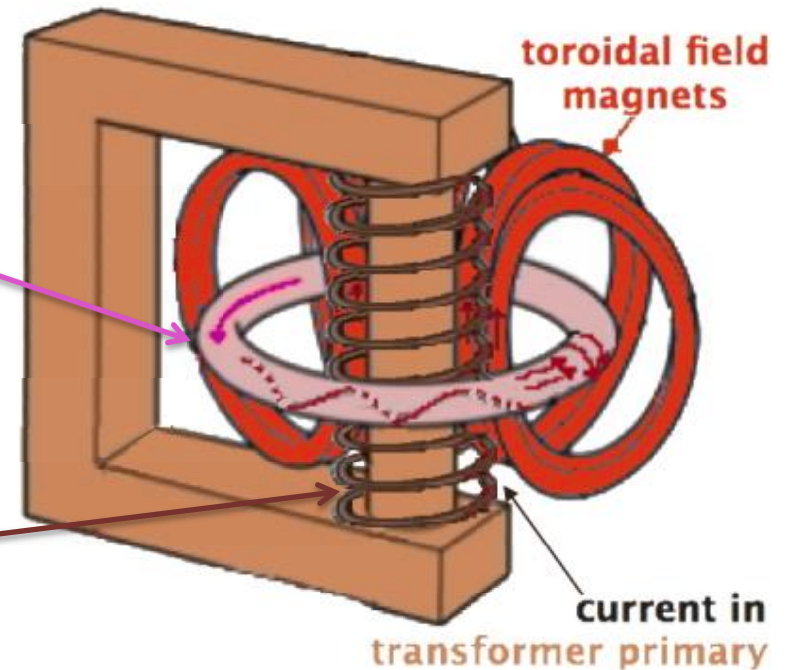


MAST (UK fusion experiment)

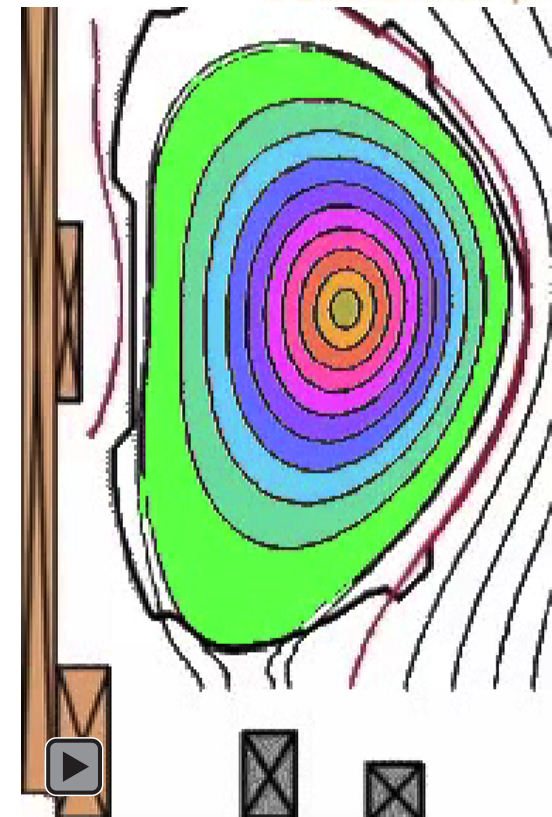
Therefore a **plasma confining current has to flow inside the Torus:**

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

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



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

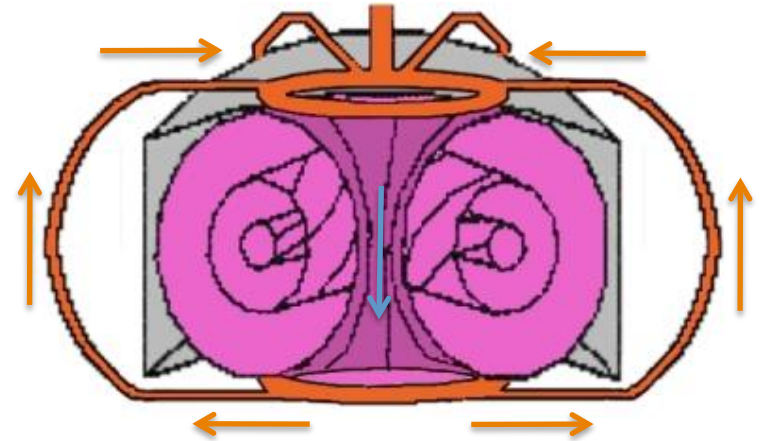
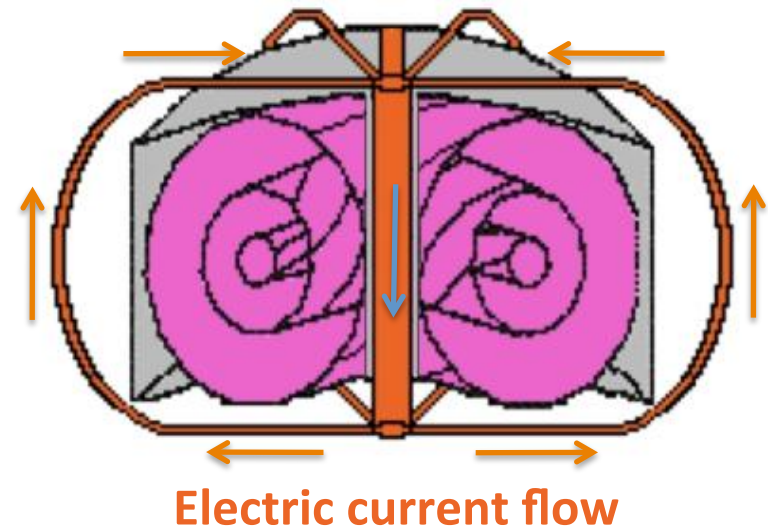


The main idea of PROTO-SPHERA

- “Conventional Tokamak”: **magnetic surfaces of toroidal plasma** surround a “**Metal Centerpost**”
- *Vacuum vessel has toroidal geometry*
- **PROTO-SPHERA: magnetic surfaces of toroidal plasma** surround a “**Plasma Centerpost**”; **only current return external legs are made of metal**
- *Vacuum vessel has cylindrical geometry*
...but electrodes are required inside vacuum

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

→ easy of access & of repair...



PROTO-SPHERA main design parameters:

Centerpost current

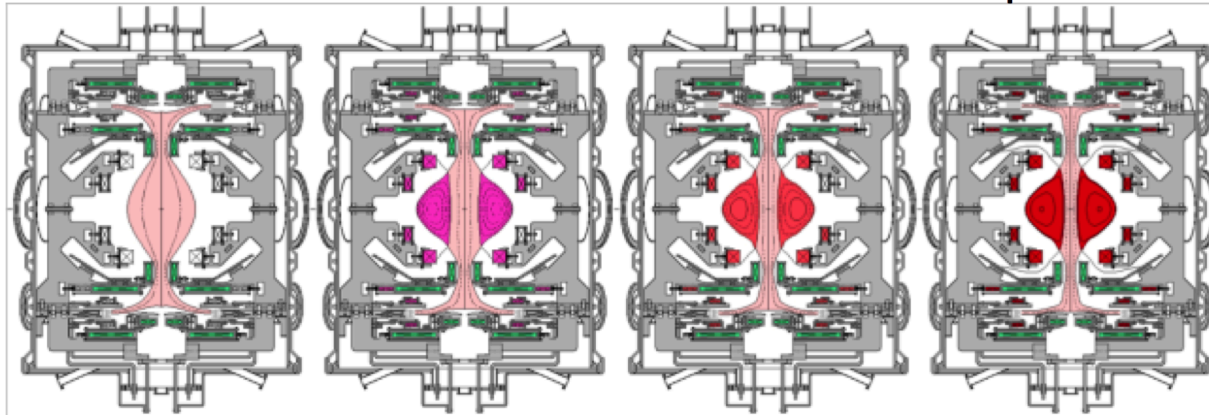
$I_e = 60 \text{ kA}$

ST toroidal current

$I_{ST} = 120 \div 240 \text{ kA}$

ST diameter

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

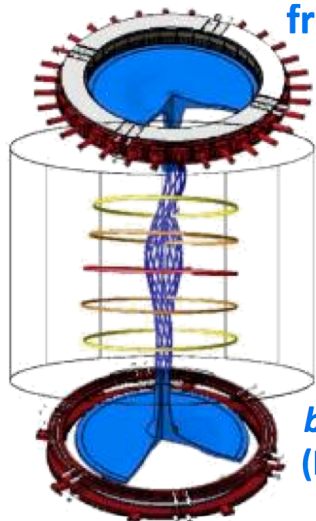


Axisymmetric simulation of ST formation

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

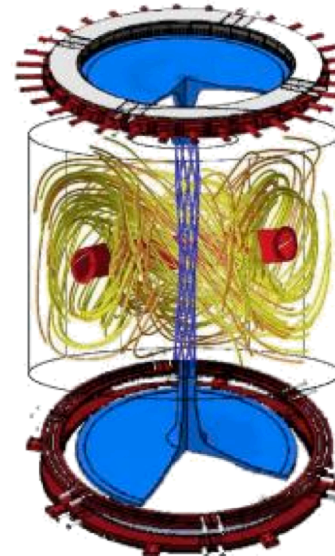
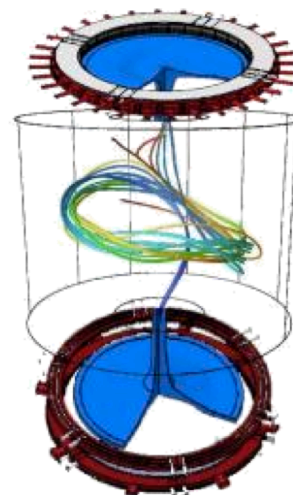
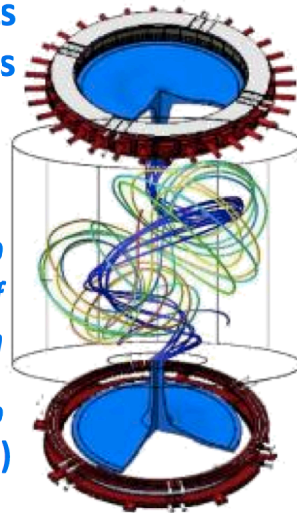
from $\tau_{\text{Alfvén}} \approx 0.5 \mu\text{s}$

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

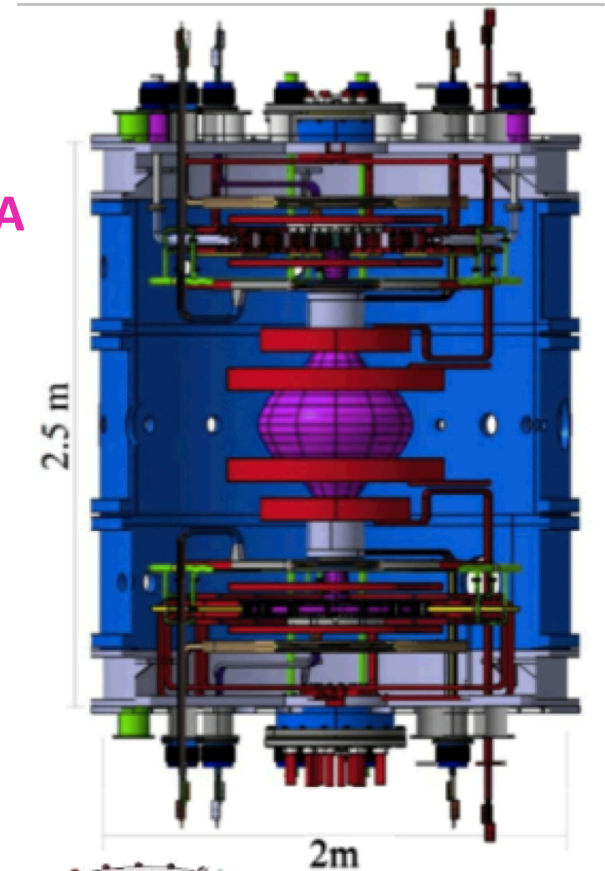


*Resistive MHD
simulations of
ST formation*

*by Ricardo Farengo
(ISTW2008-Frascati)*



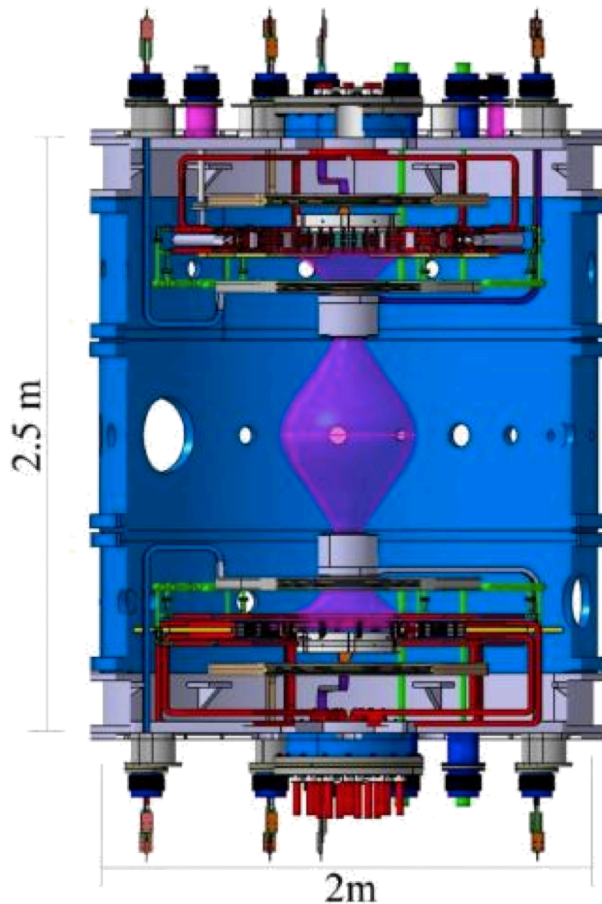
Non-axisymmetric simulation of ST formation



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

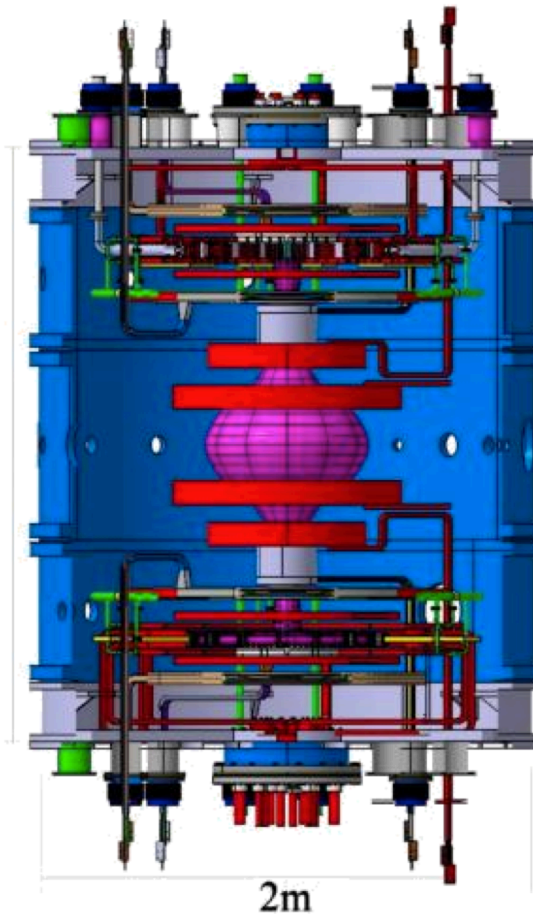
- Phase 1: demonstrate Plasma Centerpost's feasibility
- Phase 2: machine completed such as to produce the Spherical Torus

Phase1: 8 PFcoils
Centerpost shape



Centerpost current $I_e = 10 \text{ kA}$
No ST toroidal current

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



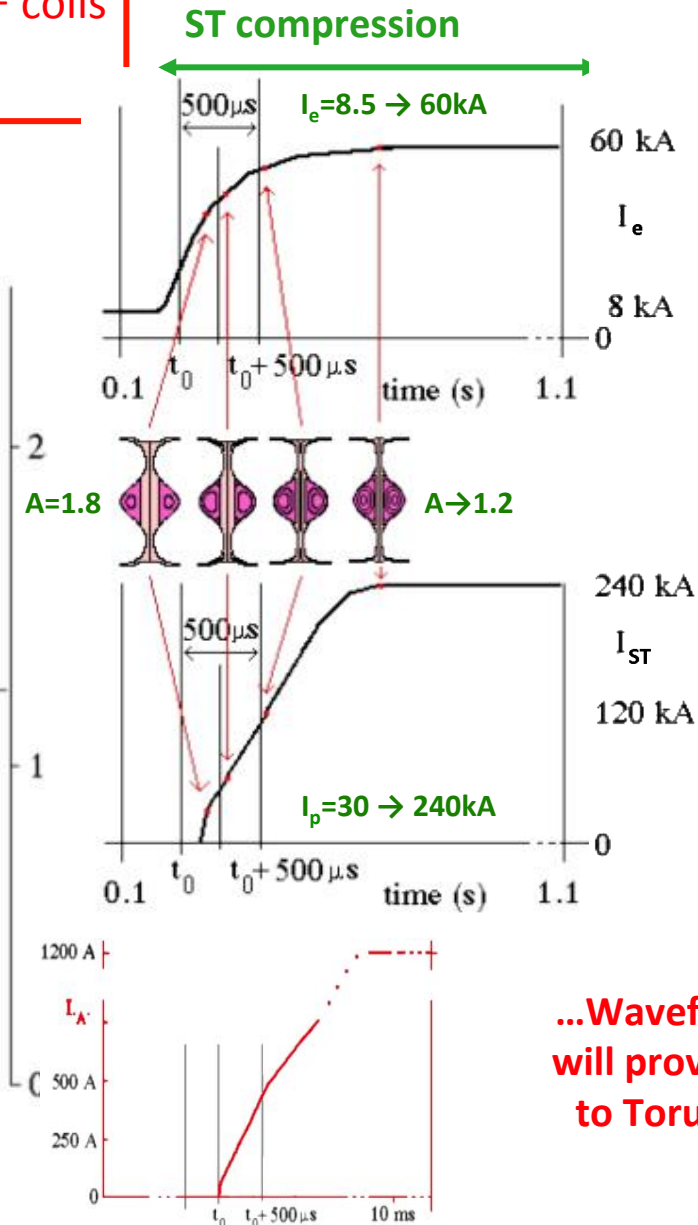
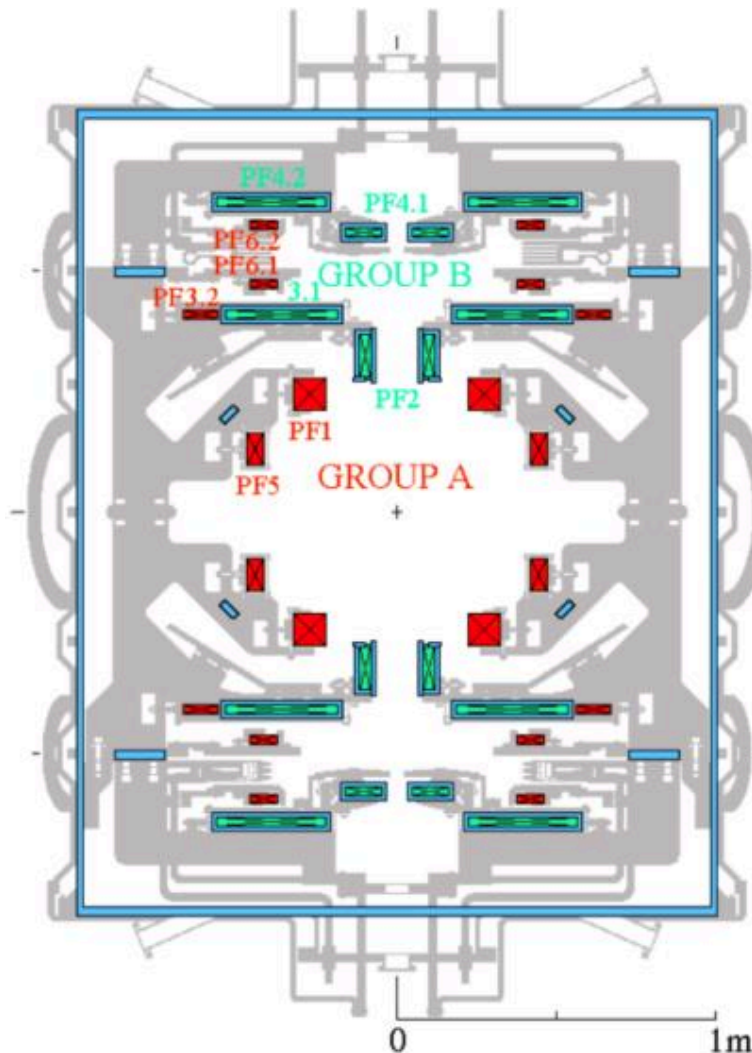
Centerpost current $I_e = 60 \text{ kA}$
ST toroidal current $I_{ST} = 120 \div 240 \text{ kA}$

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

Group B (4+4 coils): Centerpost shaping PF coils, *now inside machine*

Group A (5+5 coils): ST compression PF coils

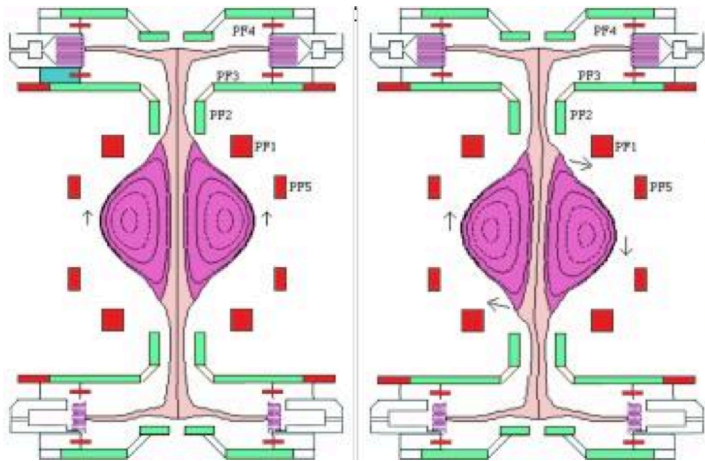
... fast increase: **0.5 ms**



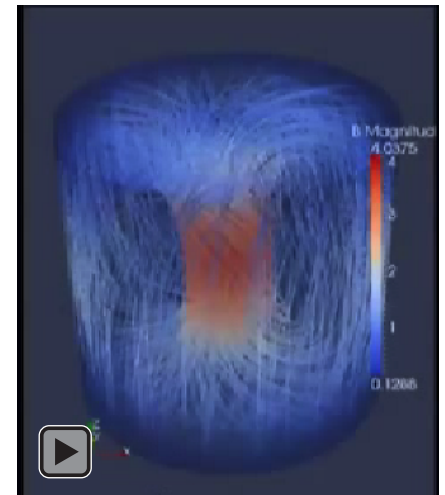
...Waveform of Group A
will provide ohmic drive
to Torus up to 120 kA

IDEAL MHD STABILITY of PROTO-SPHERA

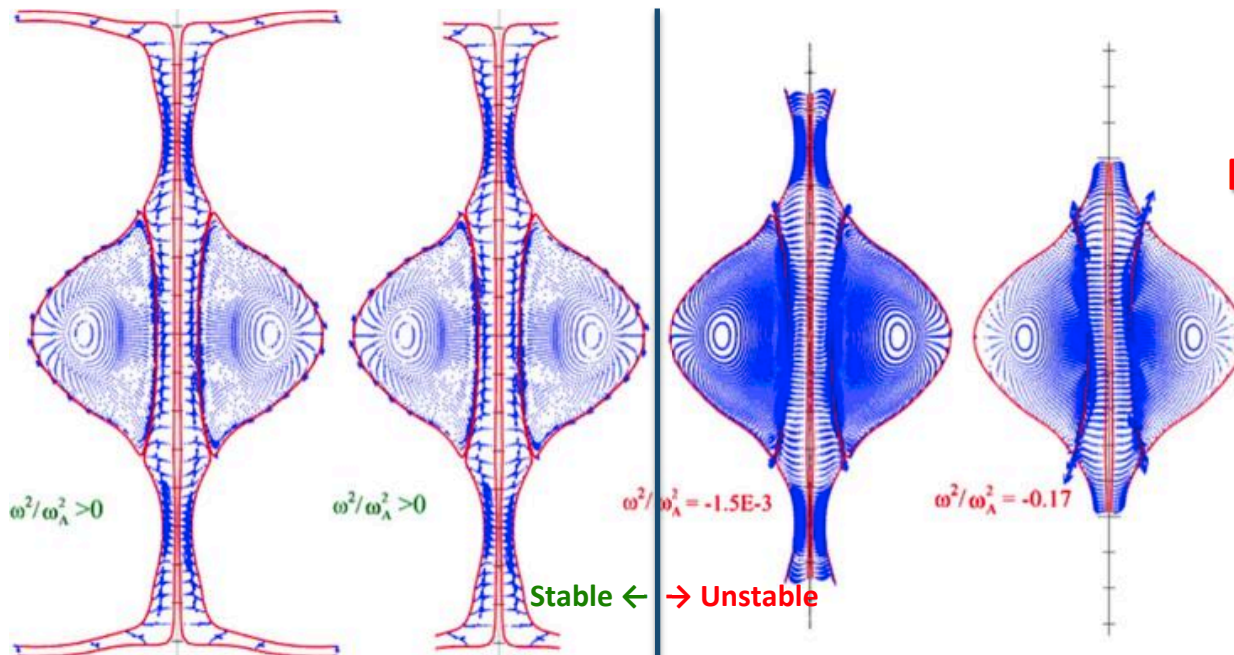
Spheromak tilt instability is due to
dipole of containing field opposite to toroidal plasma current dipole



“Group A” PF coils (compression coils) has dipole moment opposite to Plasma but “Group B” PF coils (shaping coils) has dipole moment aligned to Plasma

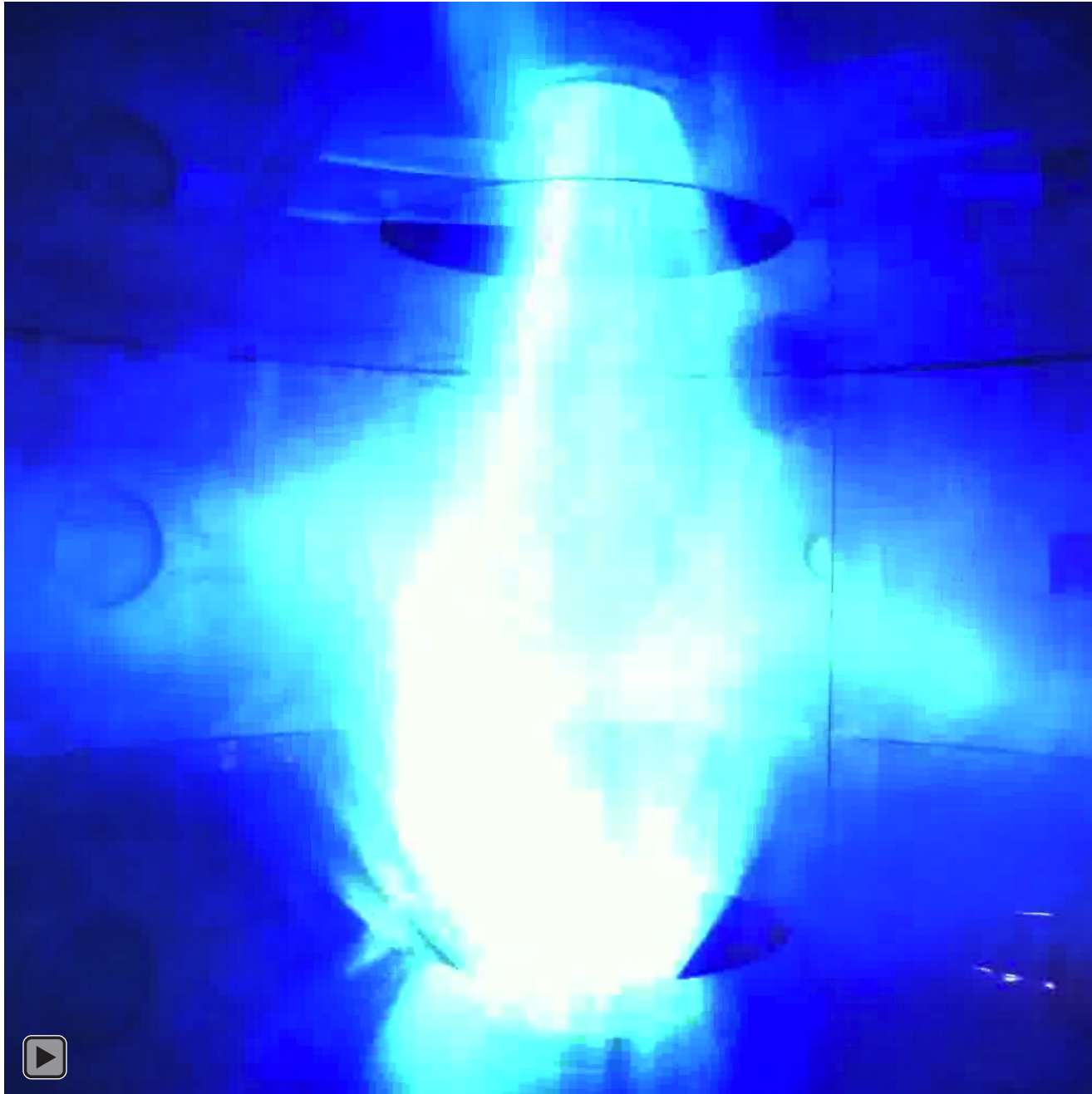


DISK-SHAPED CENTERPOST PLASMA: IMPORTANT FOR THE IDEAL MHD STABILITY



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

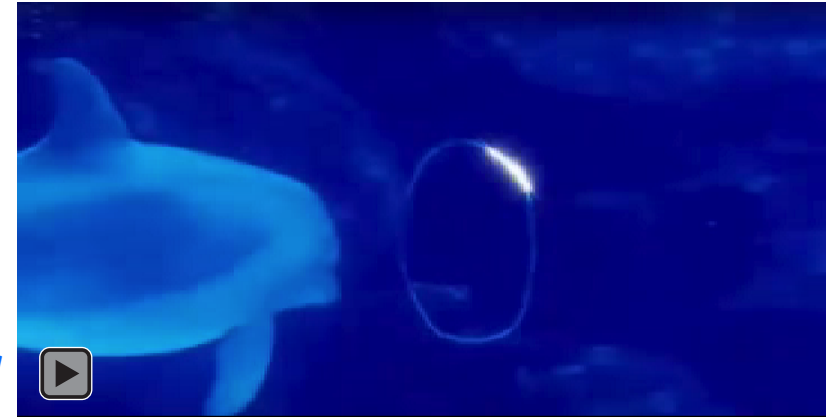
Albeit at 10 kA (not at 60 kA) and without vertical field (no **GroupA** PF coils)...



Shot #845
Dec. 2017

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

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

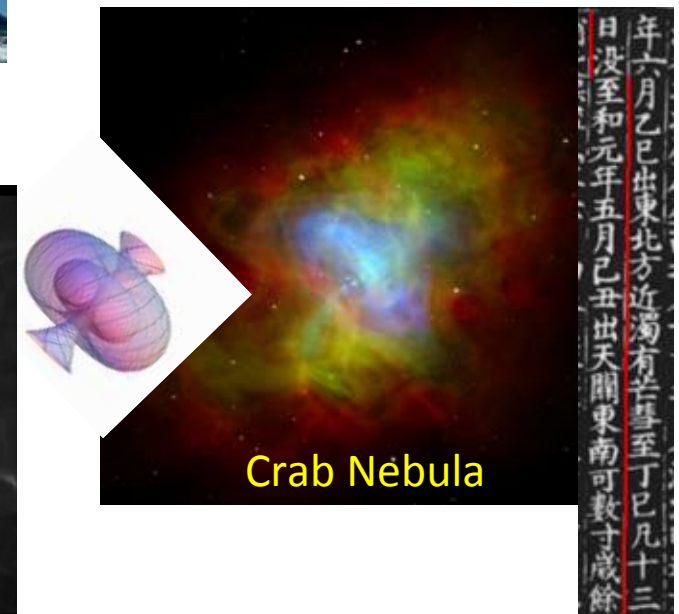


William Irvine-University of Chicago



Fluid dynamics examples

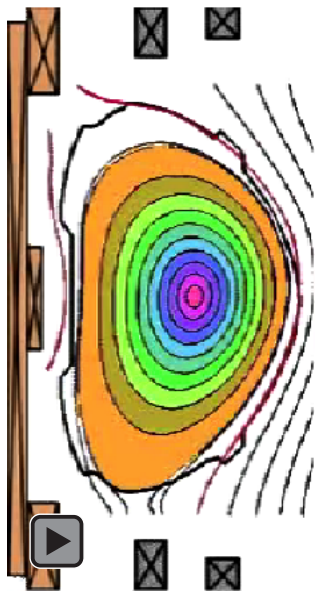
Plasma dynamics example



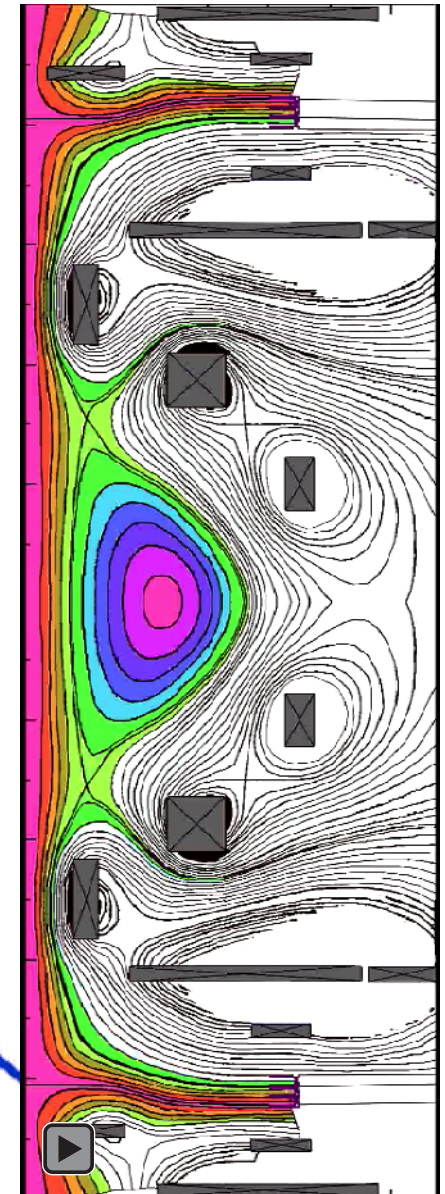
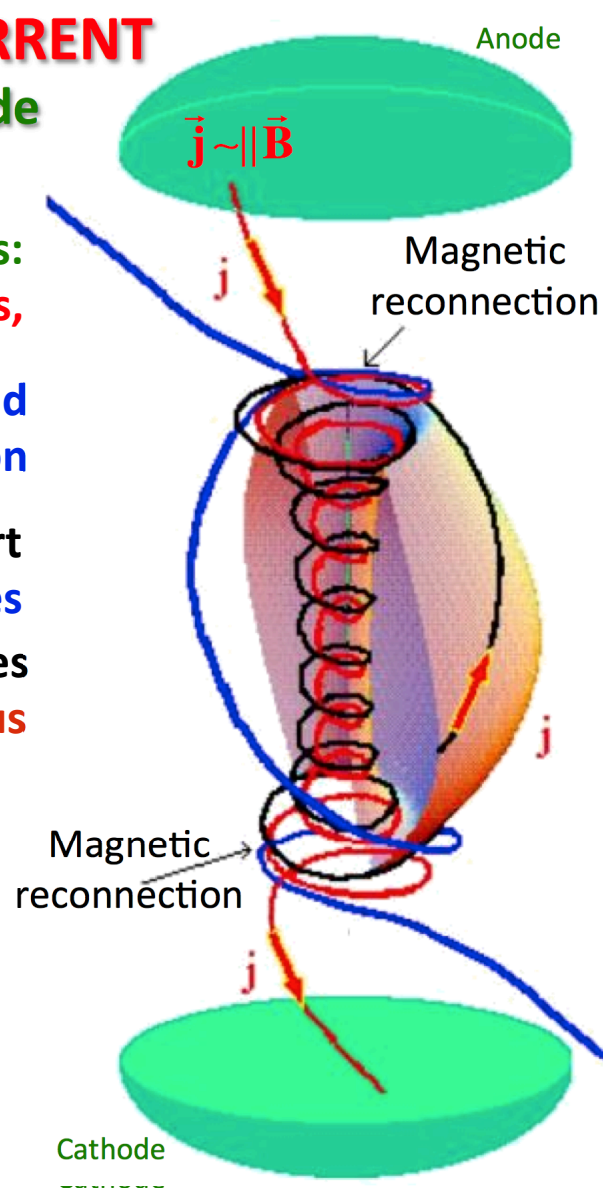
SUSTAIN THE CONFINING CURRENT

by DC voltage from anode to cathode

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



E of Tokamaks relies on induction
efficient but not forever...



E of PROTO-SPHERA relies on ∇B
associated with magnetic reconnections



Solar Flares & Magnetic Reconnections: Coronal Heating

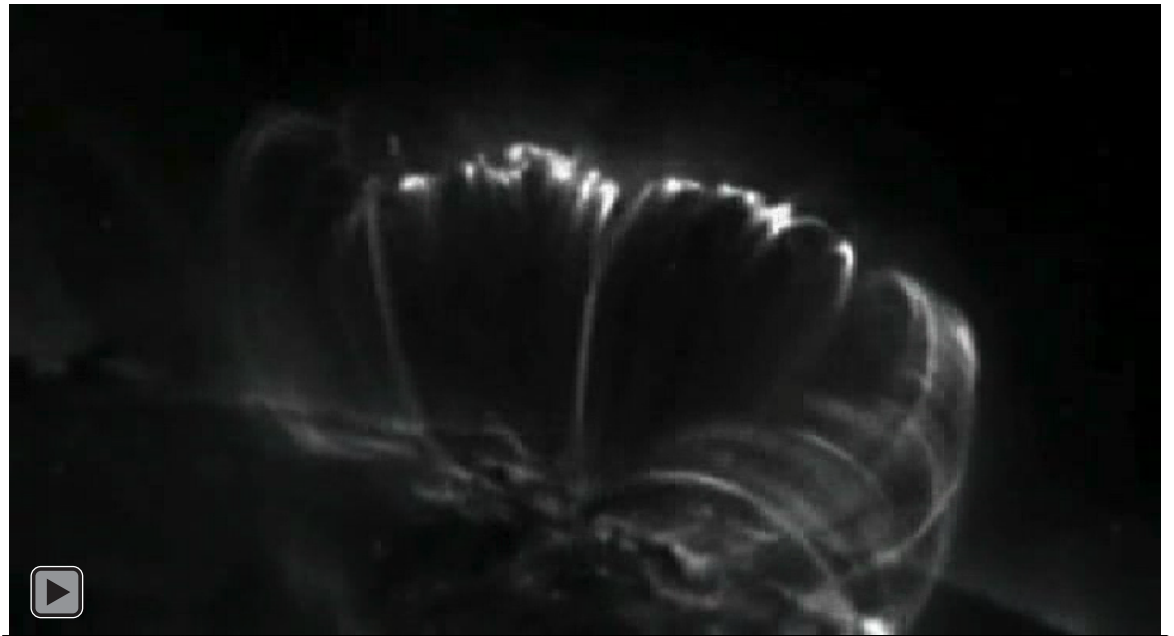
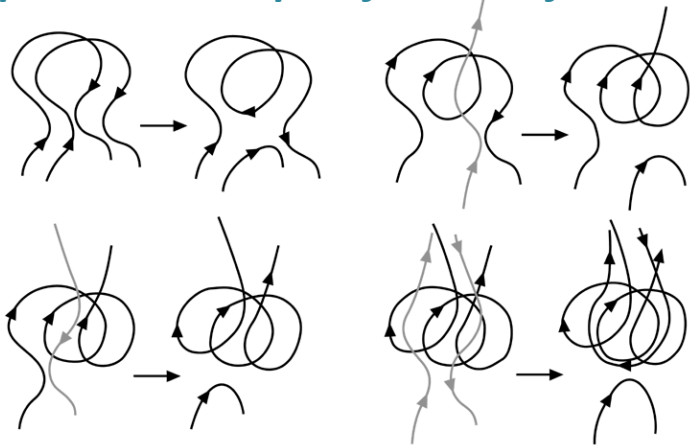
If the plasma were a perfect electric conductor, it would not decouple from the lines of force:

magnetic advection

To displace the lines of force means introducing further plasma currents:

matter flow $\rightarrow$ electric currents

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



No additional heatings for PROTO-SPHERA?

...magnetic reconnections quite efficient in heating up the Solar Corona!

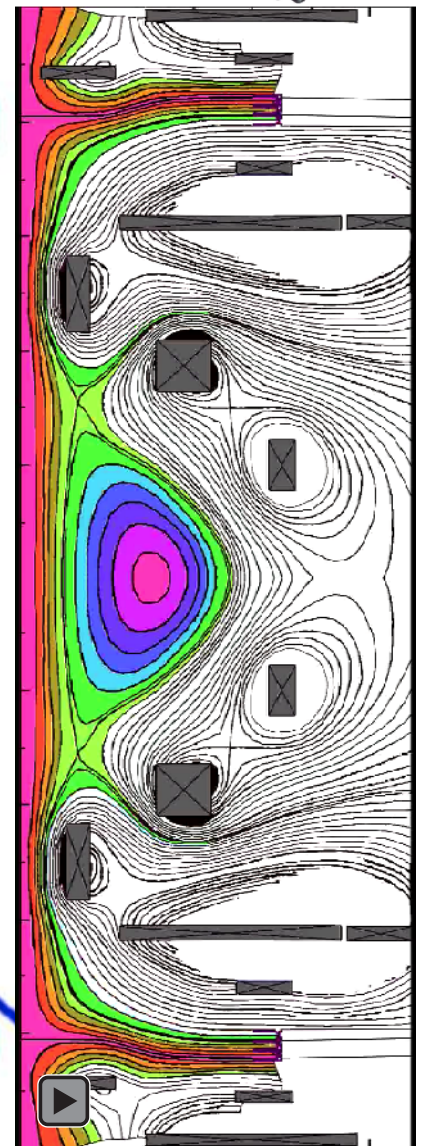
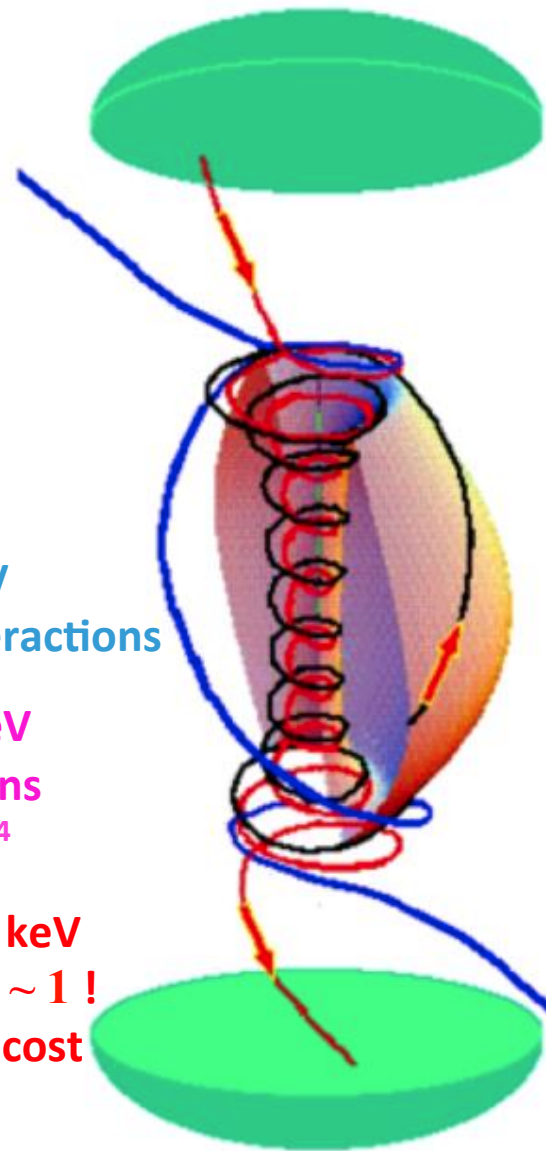


Power injected into the centerpost
should be $> 250 \text{ V} \bullet 60 \text{ kA} = 15 \text{ MW}$...

It is a huge power into such a small plasma
...however how much will go into
the confining Spherical Torus,
through magnetic reconnections?

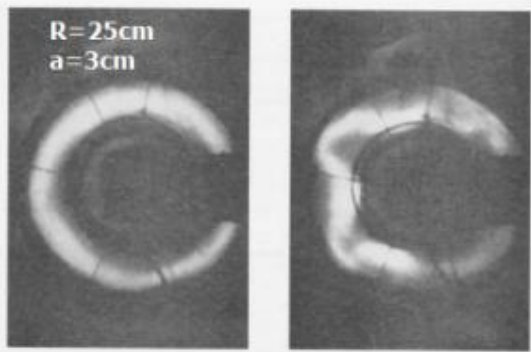
No one is able to predict:

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

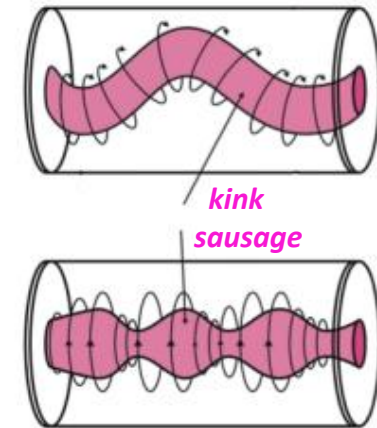


Why a new and different magnetic confinement device? one reason is ... "disruption"

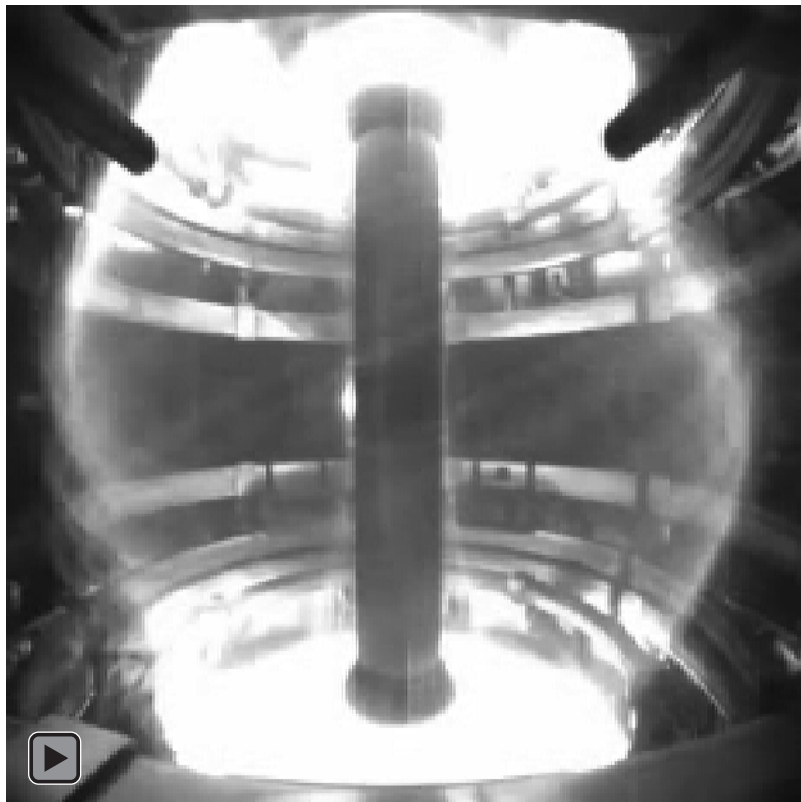
Alan Ware & Thomson
Imperial College 1947.



MHD instabilities appeared since the earliest toroidal magnetic confinement devices

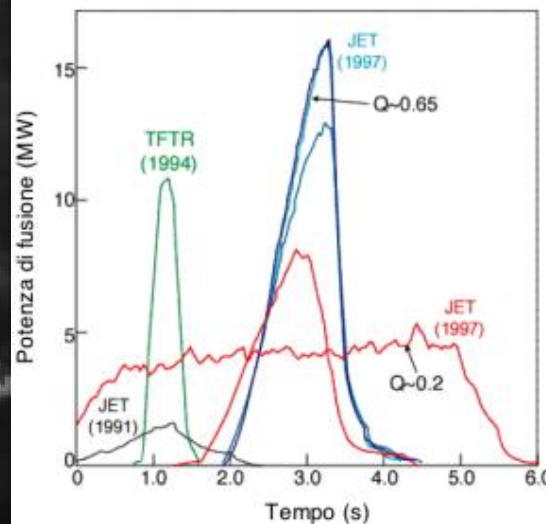


Mast 2004



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

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

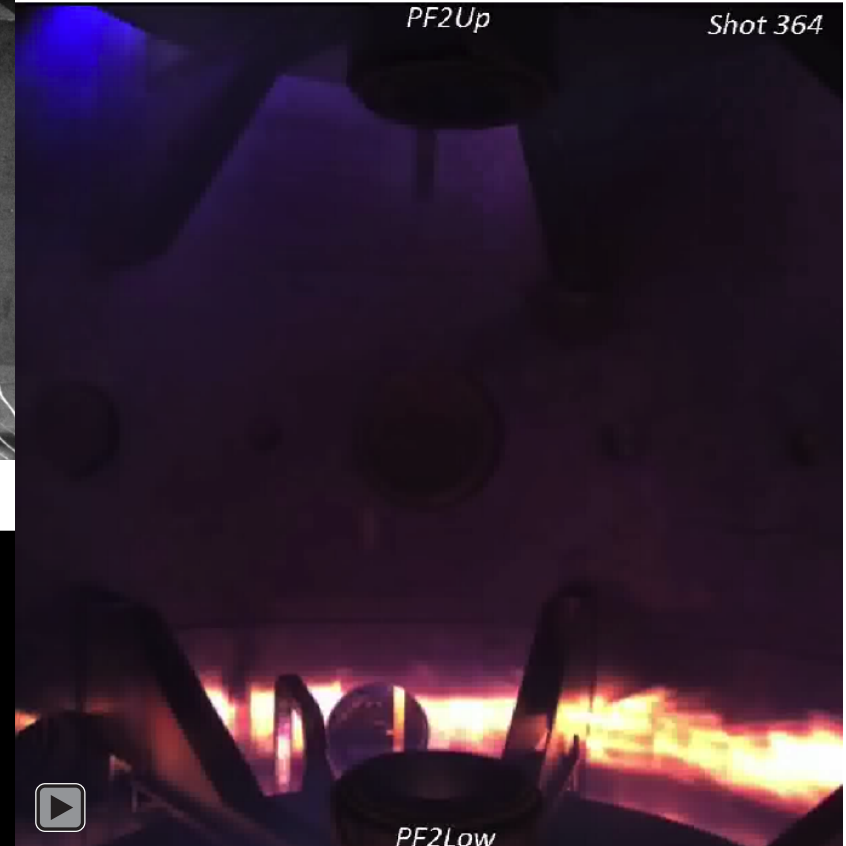
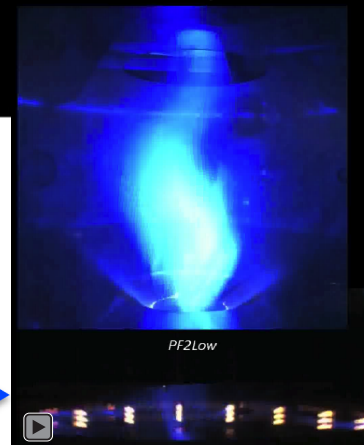
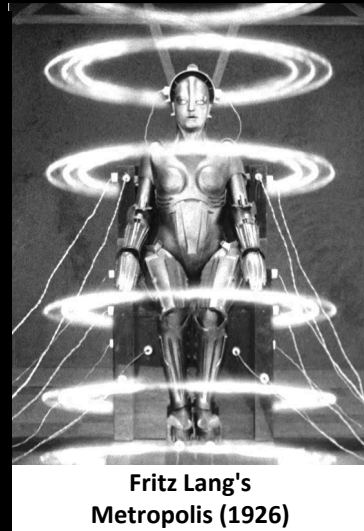


**In D - T experiments:
JET 1991- TFTR 1994
JET 1997**

**The highest neutron yield
...terminates in a
disruption**

- Disruptions ...toroidal **plasma** vanishes → **damages, very long plasma restart, ...**

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



Kink unstable configuration of PROTO-SPHERA is maintained indefinitely (0.7 s), notwithstanding:
wobbling centerpost
& even more wobbling cathode plasma →

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

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

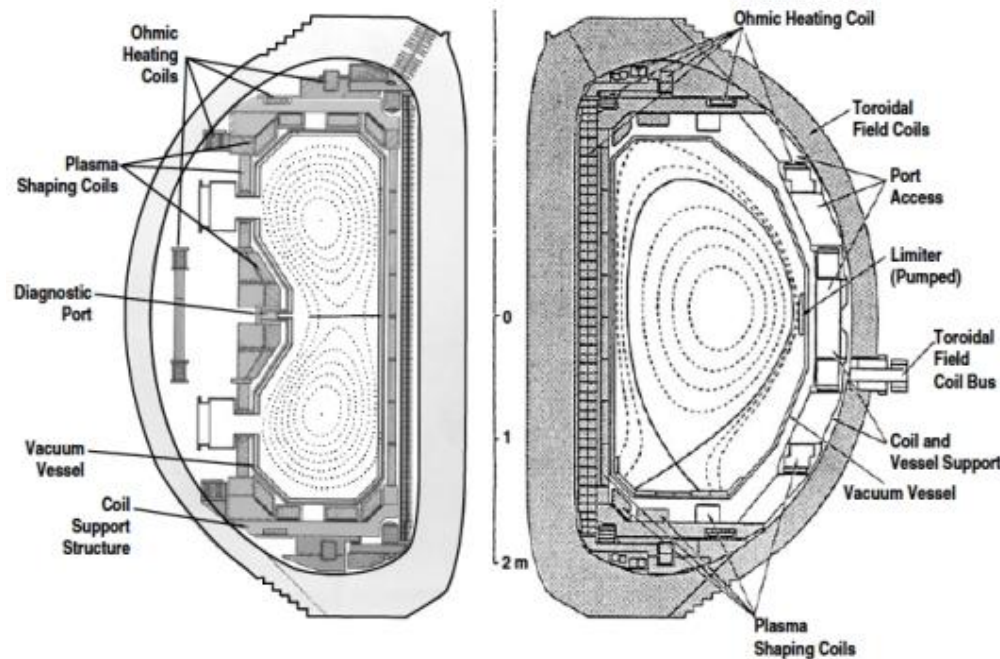
... Even if the muttered mantra is that tokamak physics is perfectly known ...

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

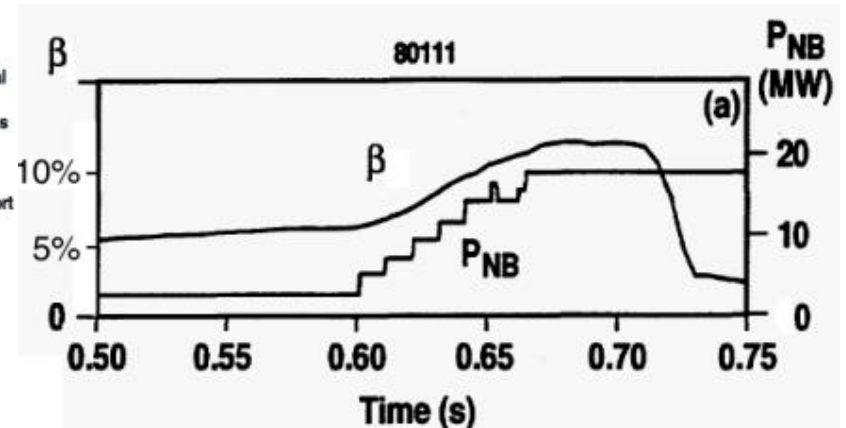
$$\beta = 2\mu_0 \int p dV / \int B^2 dV \quad \text{but in tokamak experimental data one often uses } \beta_{T0}$$

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

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



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



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

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

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

ratio of the two plasma currents

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

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

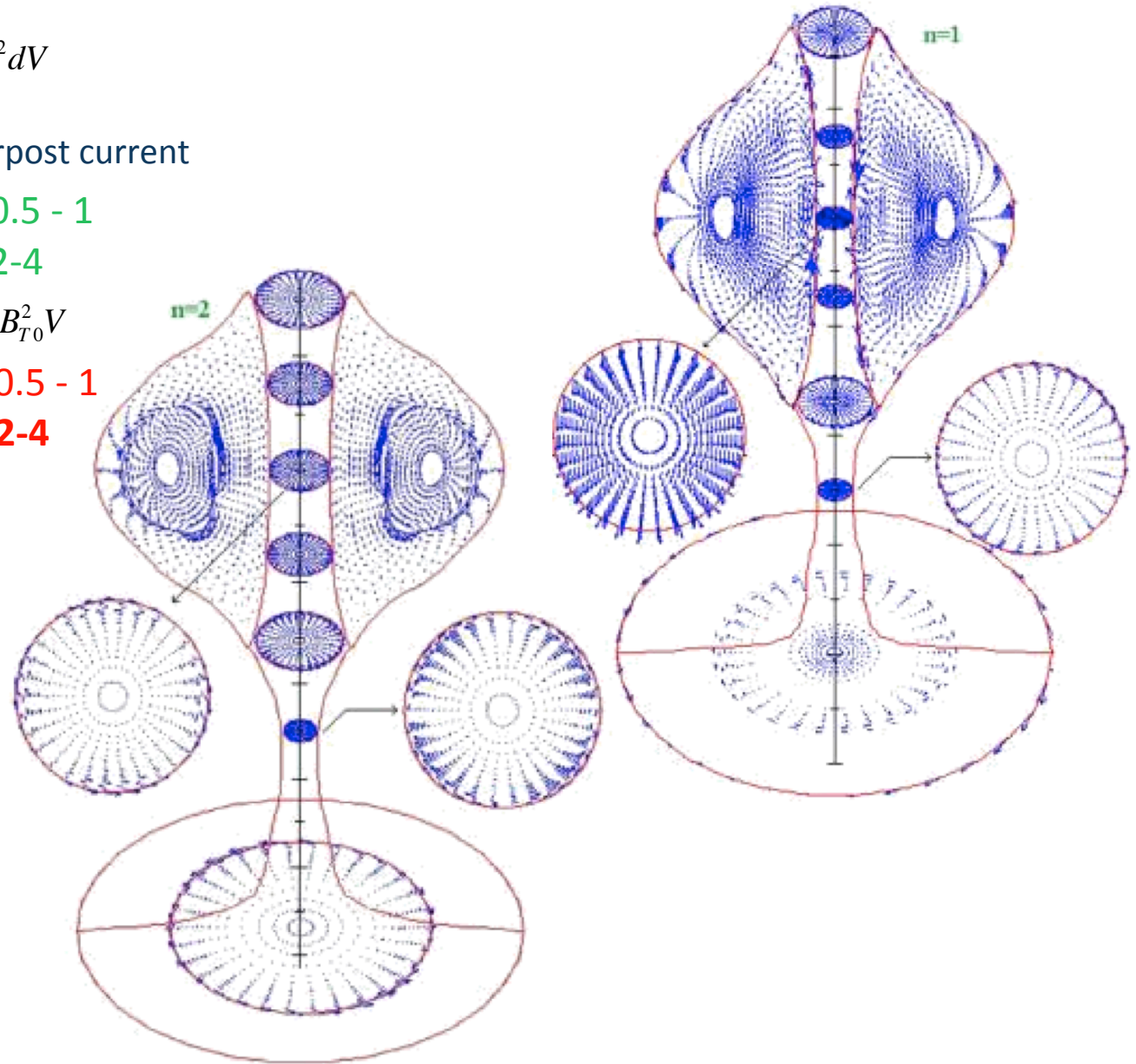
- up to $\beta = 14 \div 15\%$, $I_{ST} / I_e = 2-4$

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

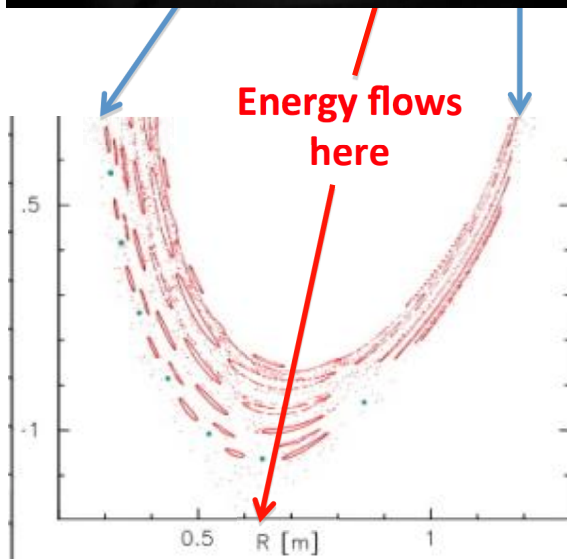
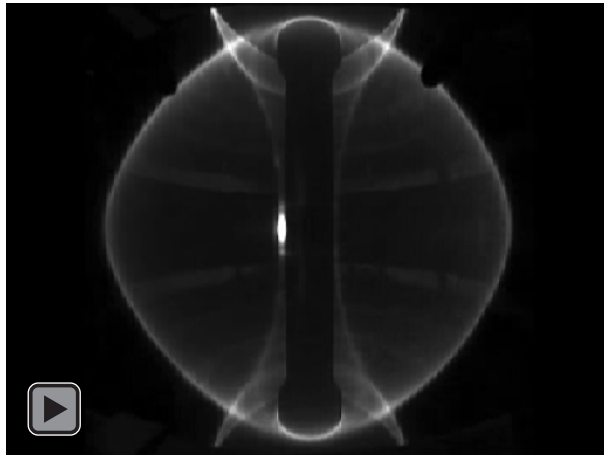
- up to $\beta_{T0} = 28 \div 29\%$, $I_{ST} / I_e = 0.5 - 1$

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

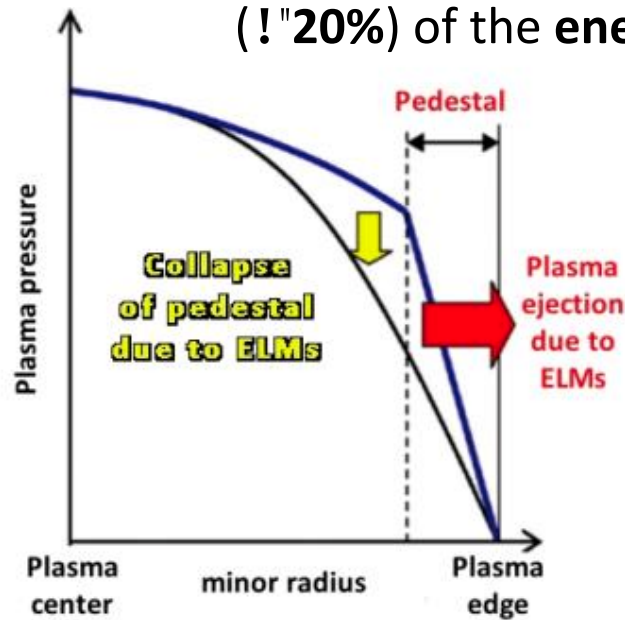
PROTO-SPHERA can approach $\beta = 1$



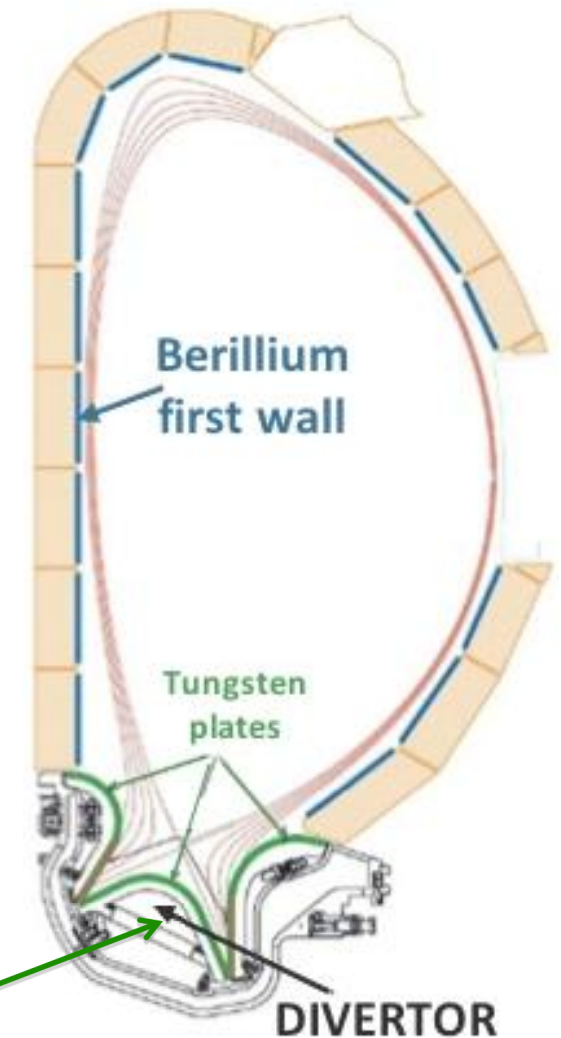
Why a new and different magnetic confinement device? still other reason are...
"ELMs" (unstable edge localized modes)



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



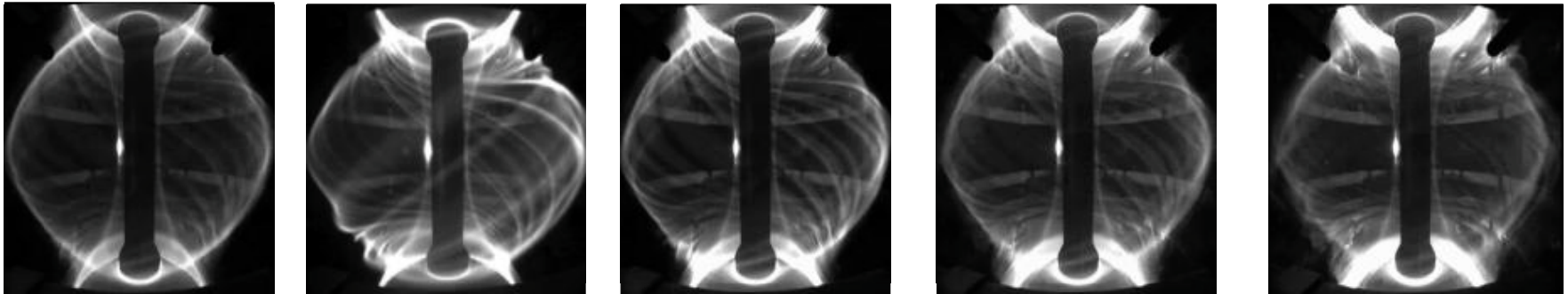
This happens in a very short time (250 μ s) as the plasma edge becomes ergodic (ELM filaments carry current)



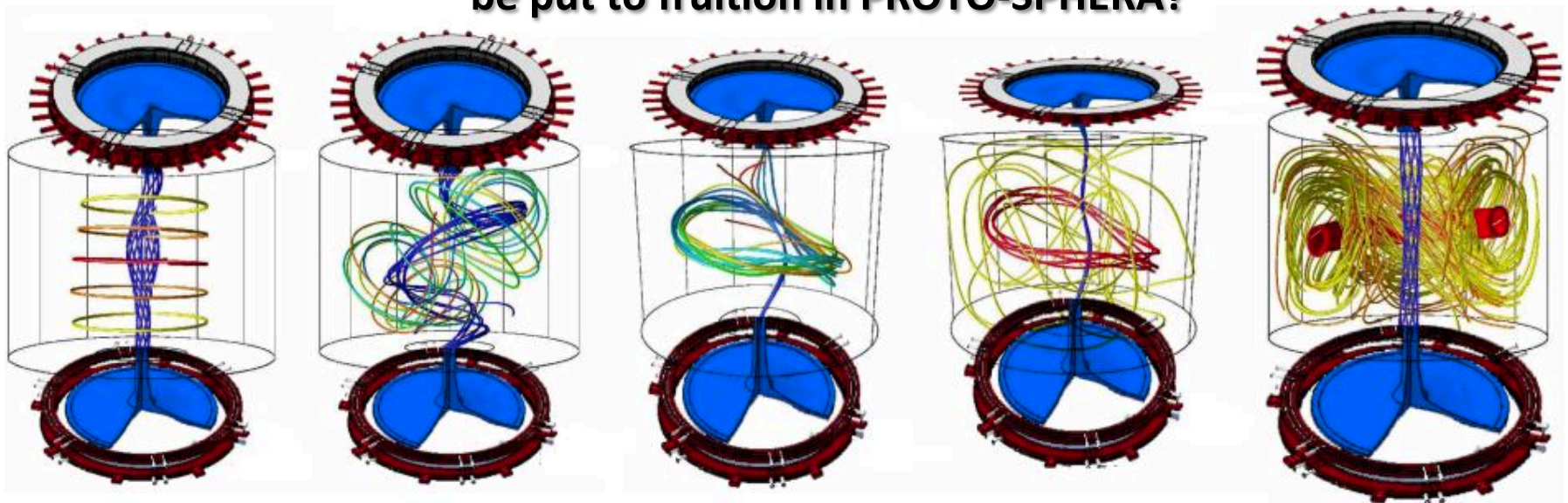
On ITER an ELMs carrying > 3% of pedestal energy can even melt or sublimate the Tungsten of the Divertor plates

"ELMs" (unstable edge localized modes):

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



be put to fruition in PROTO-SPHERA?

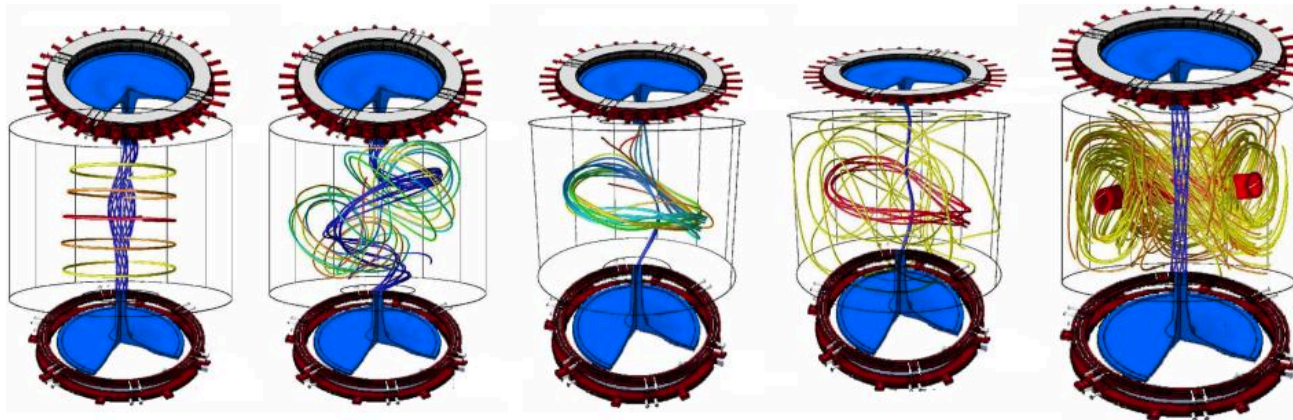
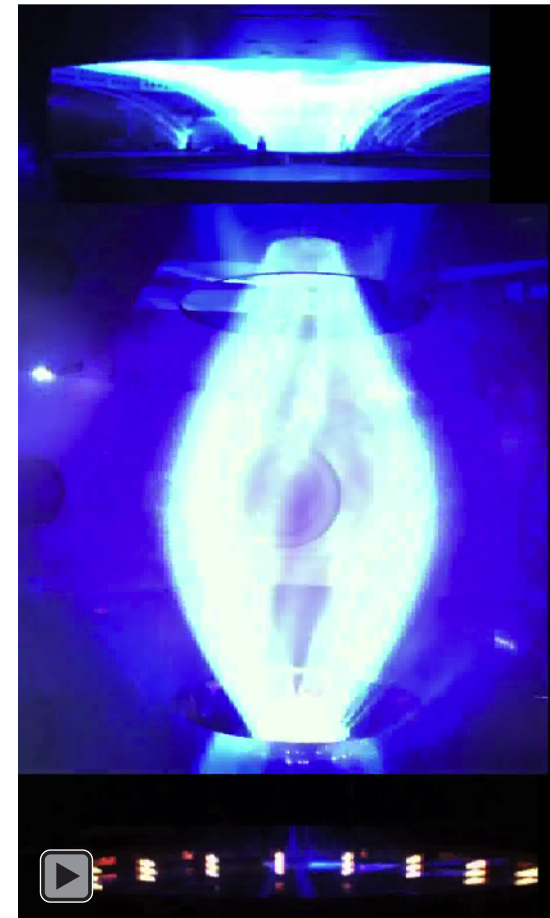


Plasma rotation in Tokamaks extremely advantageous, as it stabilizes the torus

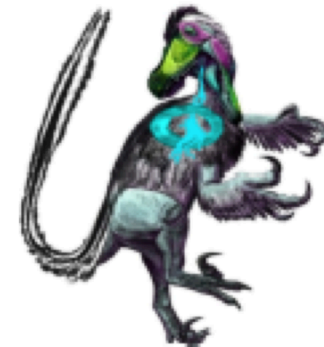
Plasma rotation induced by additional heatings (Neutral Beam Injection, NBI), becomes more & more difficult on larger tokamak experiments

Plasma Centerpost of PROTO-SPHERA rotates!

Operational experience in Tokamaks shows that the **best way of puffing fuel is from the inboard (high field side)**



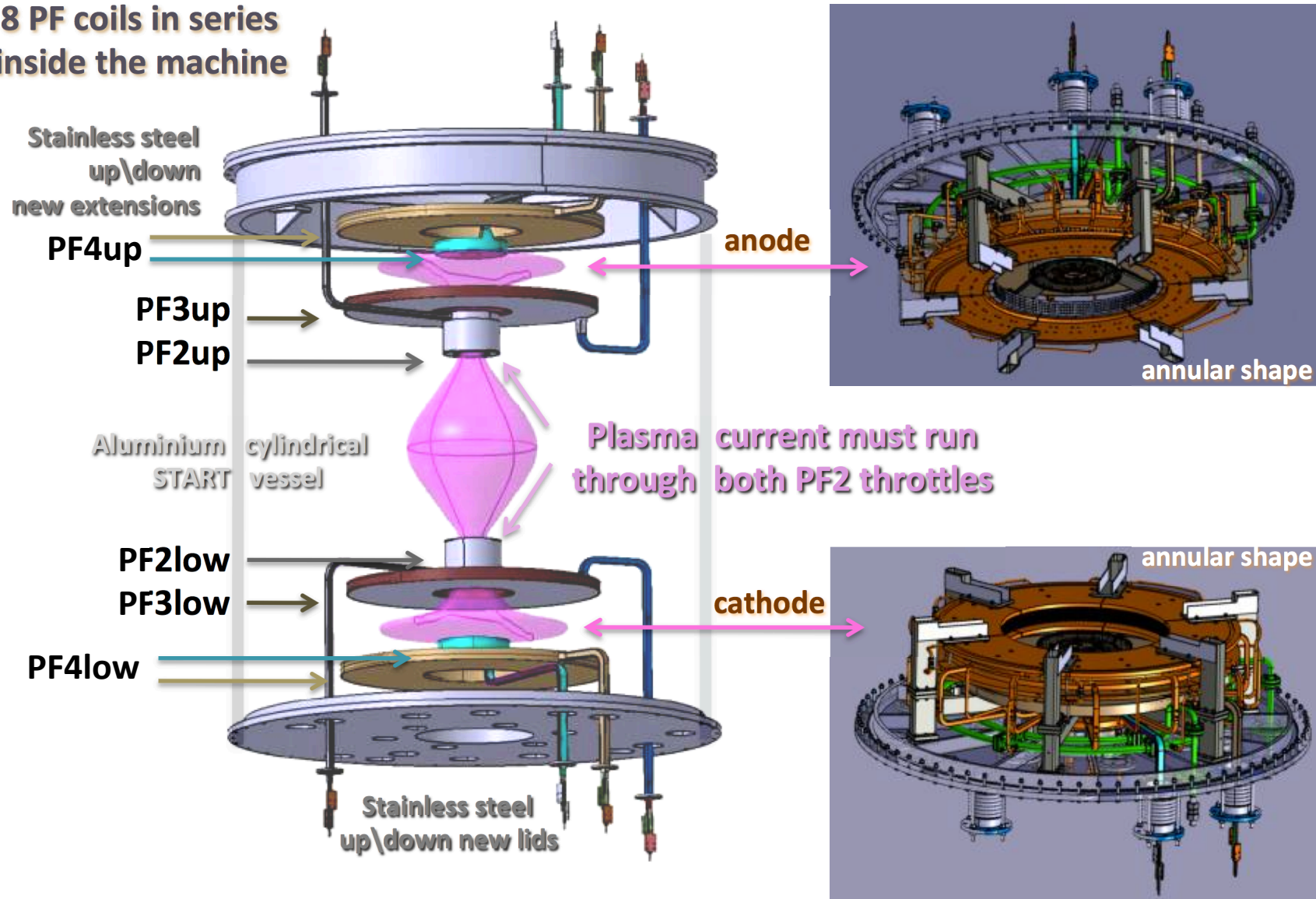
Gas puffed hollow anode



INSULATIONS

8 PF coils in series
inside the machine

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



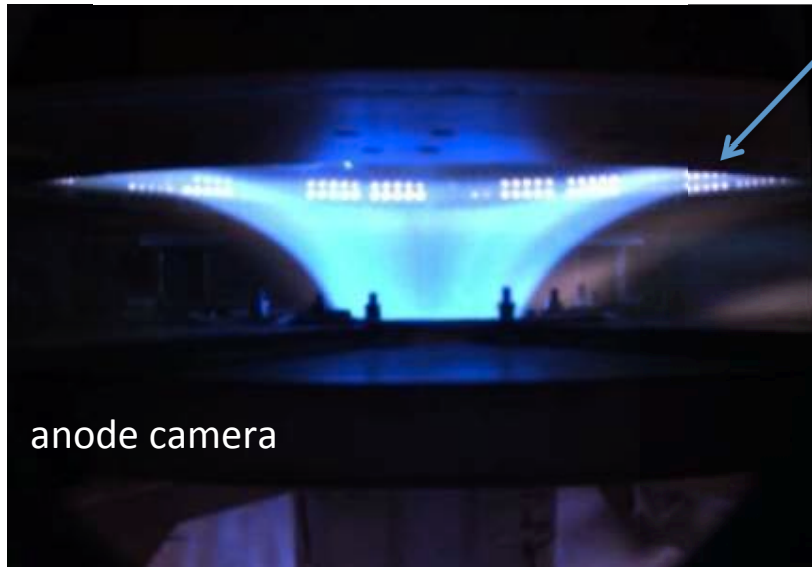
vacuum vessel is GND potential

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

PF coils casings built as floating,

No Anode Arc Attachment!

Argon plasma: break-down 80 V



anode camera



cathode camera

Hollow annular anode performs

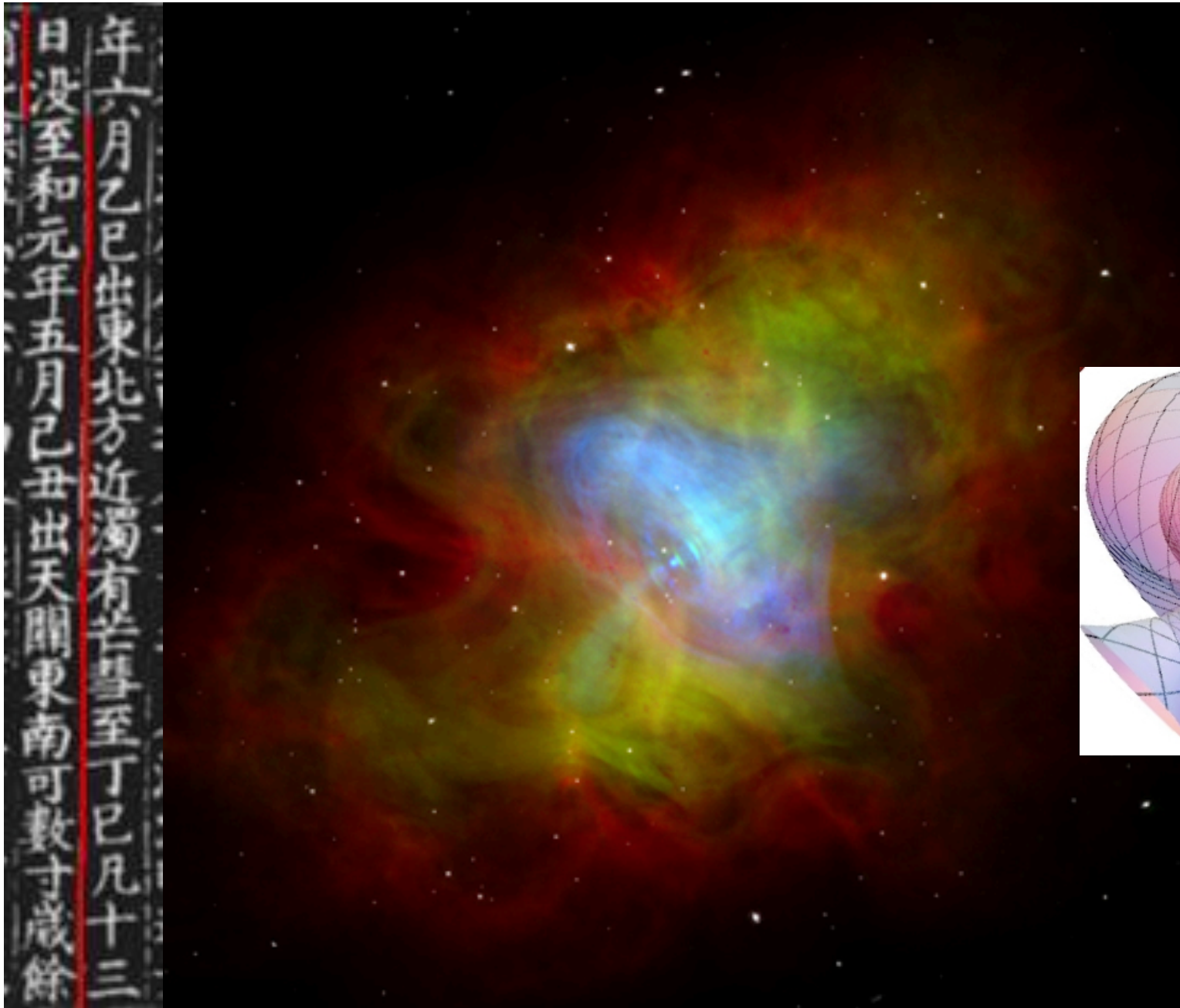
- plasma goes through both PF2 throttles
- plasma enters anode gas-puffing holes
- no sign ($I_e < 8.6 \text{ kA}$) of anode attachment
- filling pressure $10^{-3} - 10^{-2} \text{ mbar}$

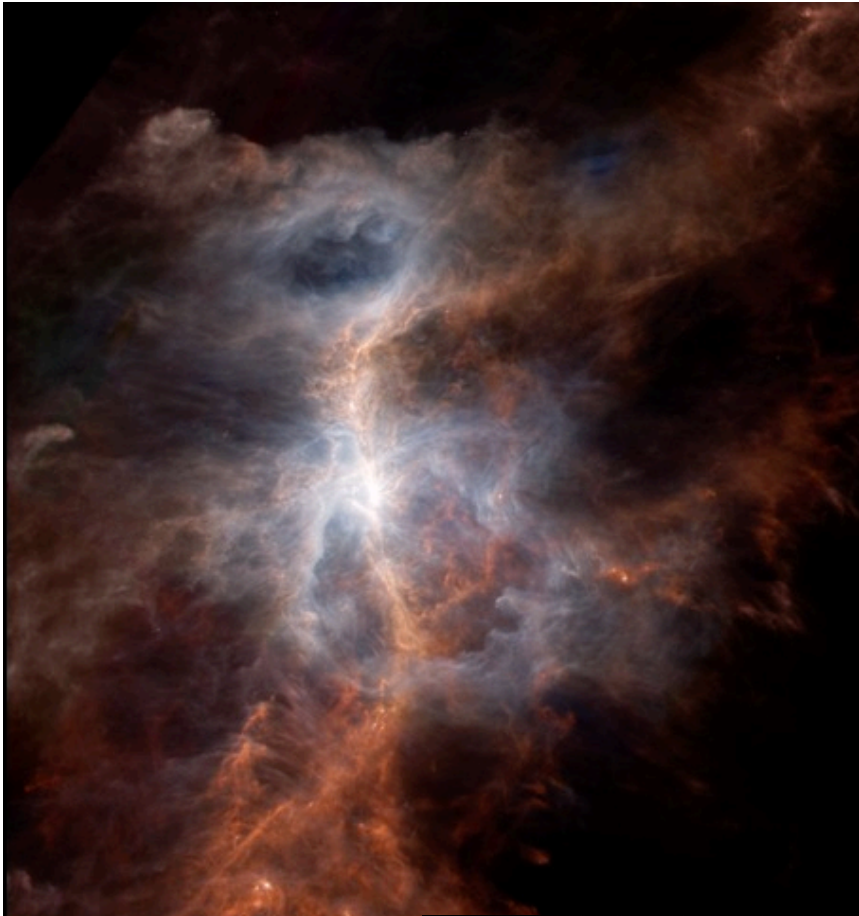
annular anode plasma is never filamented
whereas annular cathode plasma is filamented (due to sparse emitters)



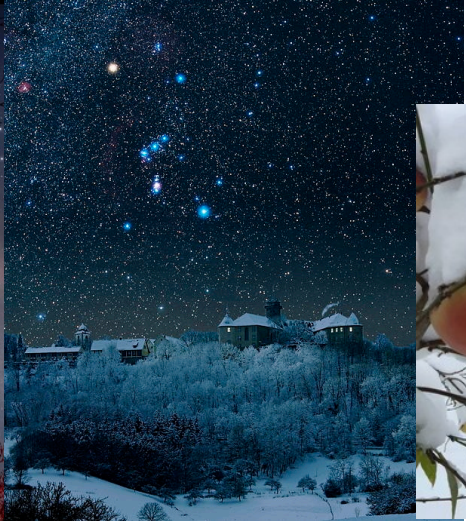
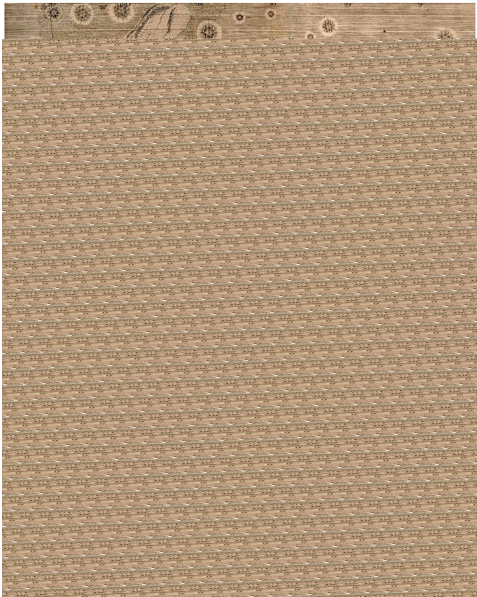
even plasma centerpost is in part filamented
(...cathode switched off before the plasma...)

Crab Nebula remnant





osi

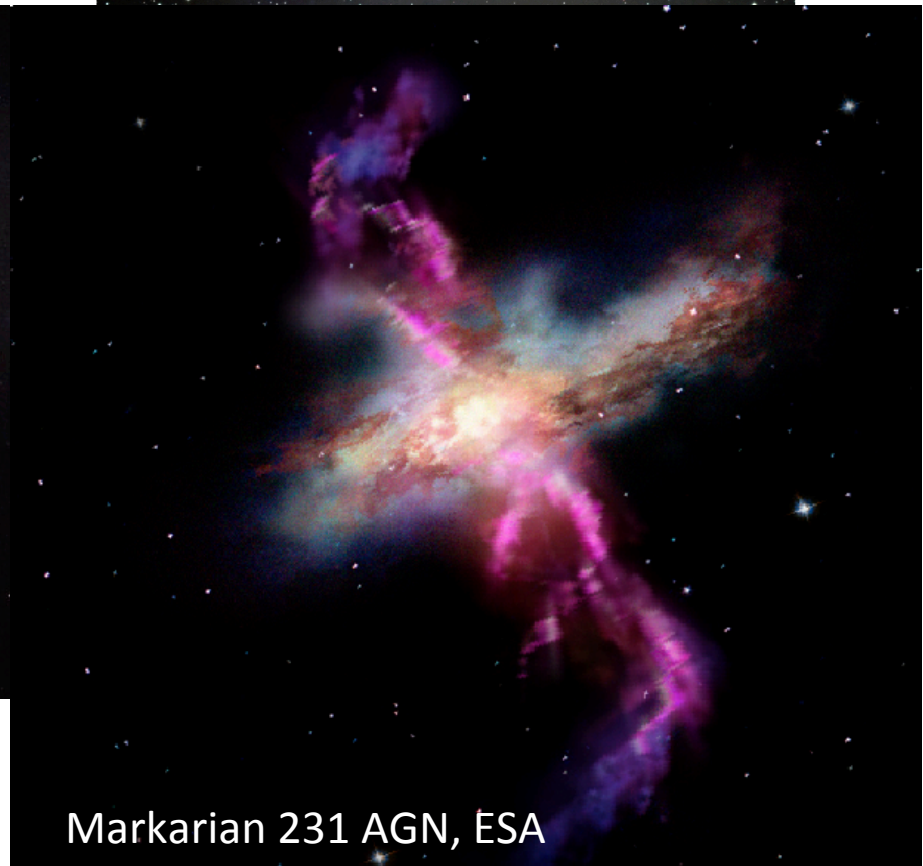


Centaurus A AGN, ESO+Chandra

Active Galactic Nuclei



M82 AGN, Hubble



Markarian 231 AGN, ESA

In computer simulations Black Holes are predicted to launch Tori

