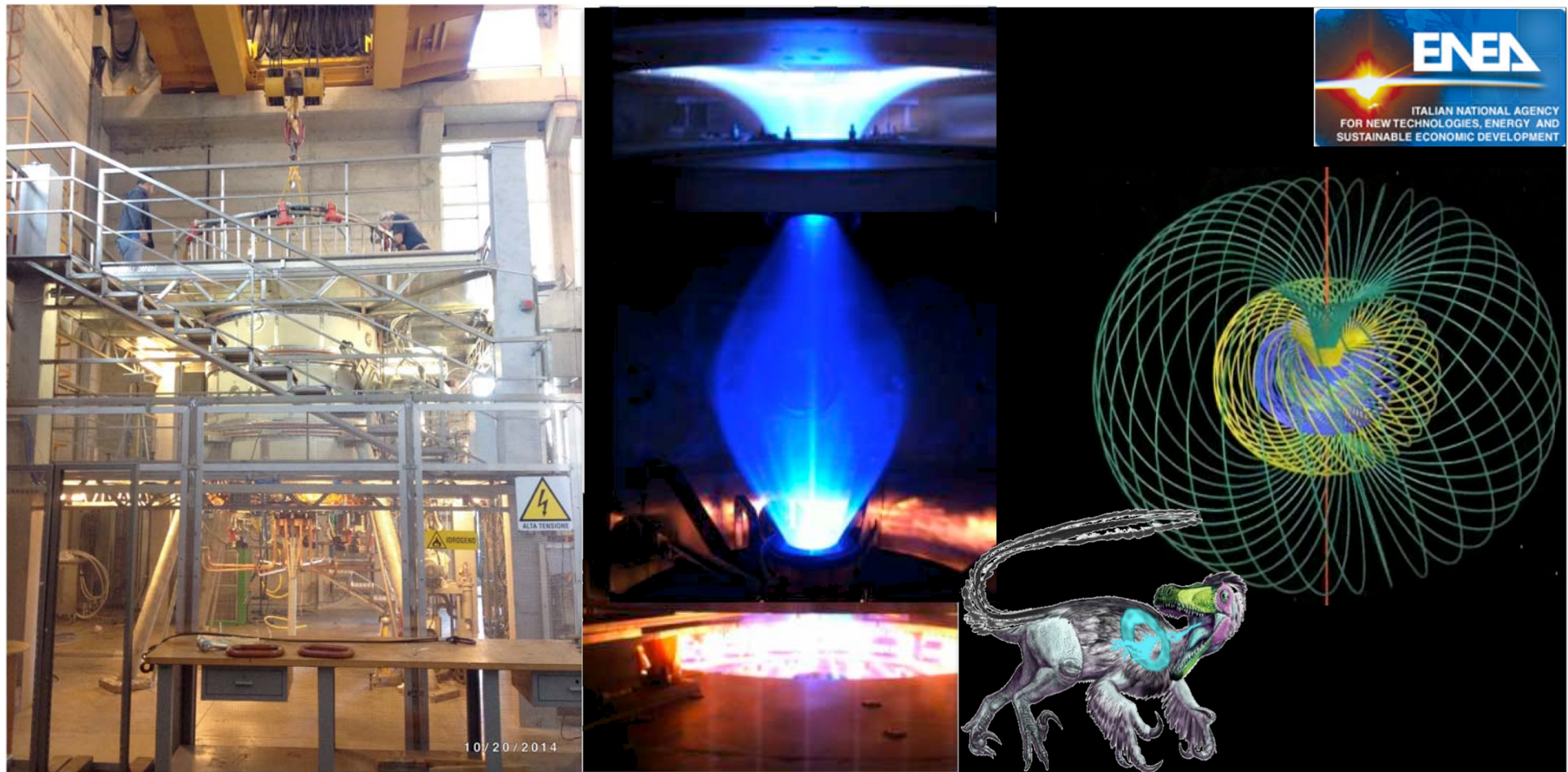


The plasma centerpost obtained in the PROTO-SPHERA experiment

*F. Alladio, L. Boncagni, F. Causa, F. Crescenzi, E. Giovannozzi, A. Grosso, A. Lampasi,
G. Maffia, A. Mancuso, P. Micozzi, V. Piergotti, G. Rocchi, A. Sibio, B. Tilia, V. Zanza*

Centro Ricerche ENEA, Frascati C.P. 65 (Roma) franco.alladio@enea.it



二龍戲珠 èrlóng xìzhū

...two dragons a playing with a pearl

OUTLINE

How to form a Spherical Torus around a Plasma Centerpost:

1994-1997

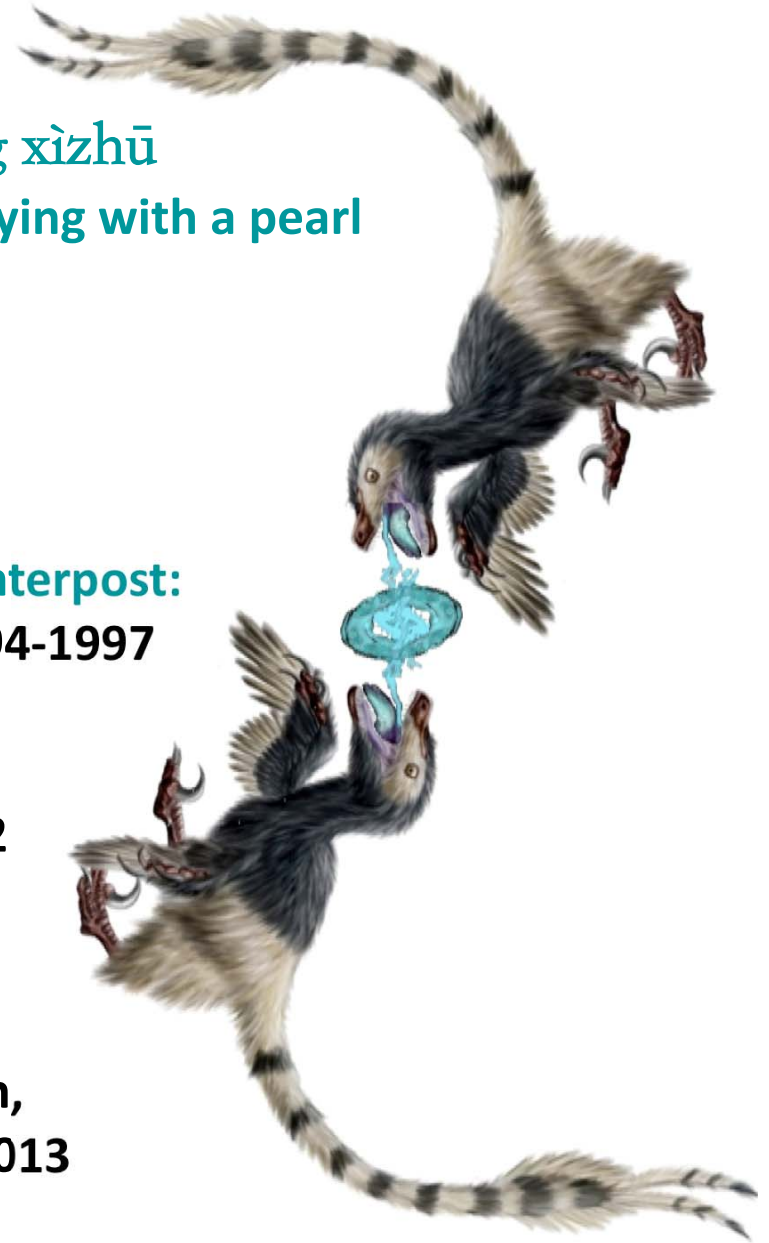
Before the construction of the experiment

two issues were addressed: 1997-2002

- reliability of electrodes
- ideal MHD stability of the magnetic configuration

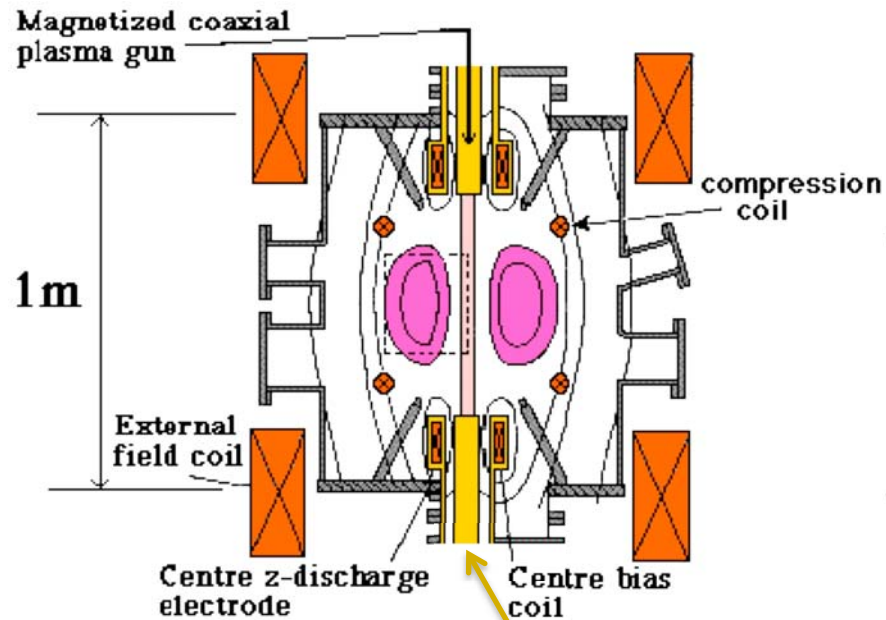
An old vacuum chamber, as a gift from Great Britain,
started the construction of the experiment: 2003-2013

PROTO-SPHERA got its first plasma centerpost: 2014-2015

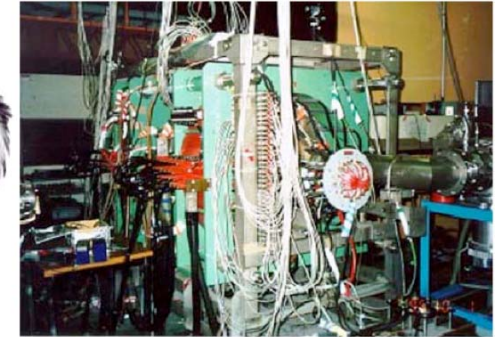


TS-3 experiment at the Tokyo University:

it studied **magnetic reconnection** of **plasma toroids** around a **metal centerpost**

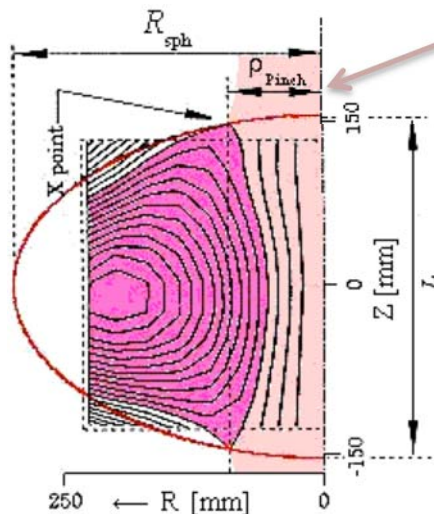


Yasuchi Ono



In 1993 TS-3 removed the metal centerpost, applied **1kV** between two plasma guns (used as cylindrical electrodes) and produced a

"**Plasma Centerpost**" carrying a plasma current $I_e = 40\text{kA}$, which through non-linear "kink" instability engendered around itself a **Spherical Torus (ST)** carrying a toroidal plasma current $50\text{kA} < I_{ST} < 100\text{kA}$



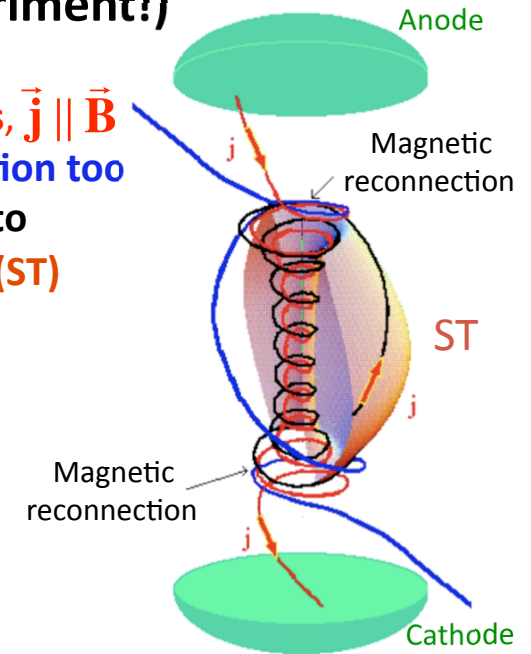
60 μs formation

20 μs sustainment

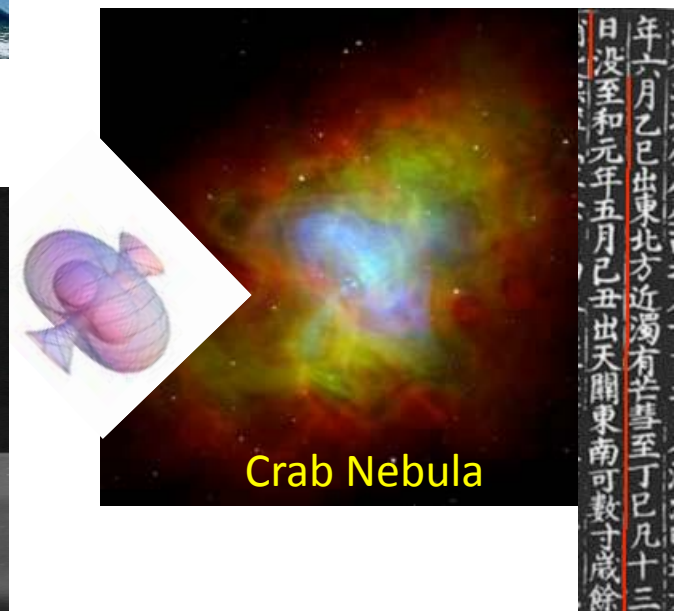
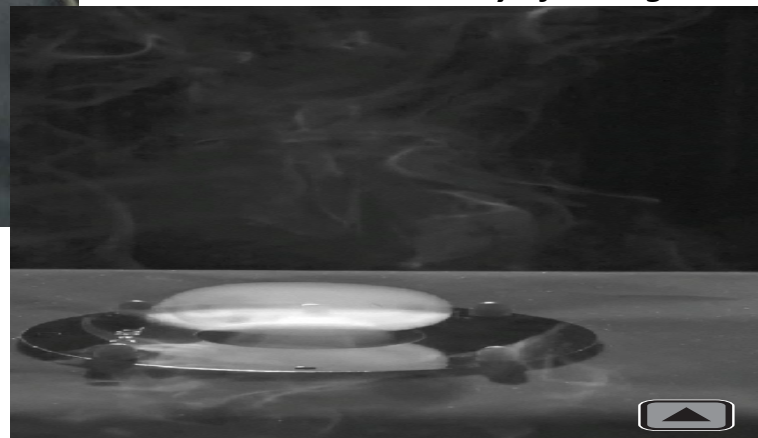
total duration **80 μs ~ 100 $\tau_{\text{Alfvén}} < \tau_{\text{res}}$** resistive time

Helicity injection to sustain the plasma torus: relaxation of Plasma centerpost forms & sustains the ST (how efficiently? ...experiment!)

- in front of the electrodes: open magnetic field lines, $\vec{j} \parallel \vec{B}$
- open magnetic field lines wound in a circular direction too
- Magnetic reconnections convert open $\vec{B}$, $\vec{j}$ lines into closed $\vec{B}$, $\vec{j}$ lines wrapped around a Spherical Torus (ST)



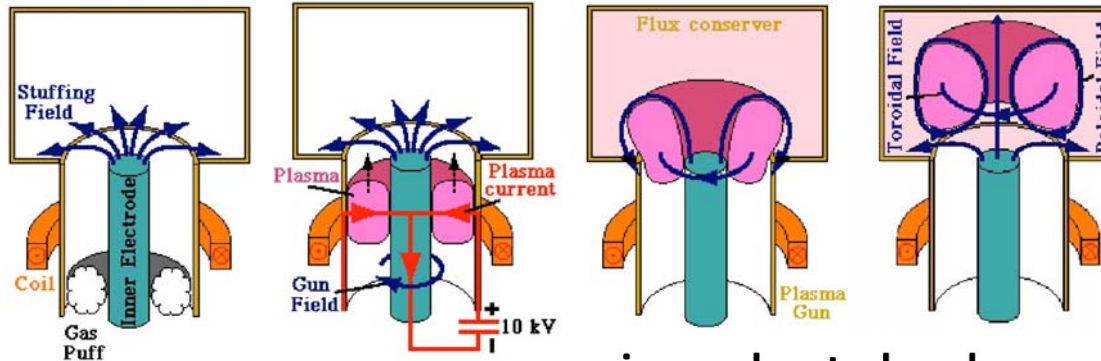
William Irvine-University of Chicago



GUN INJECTED FLUX-CORE-SPHEROMAKS

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

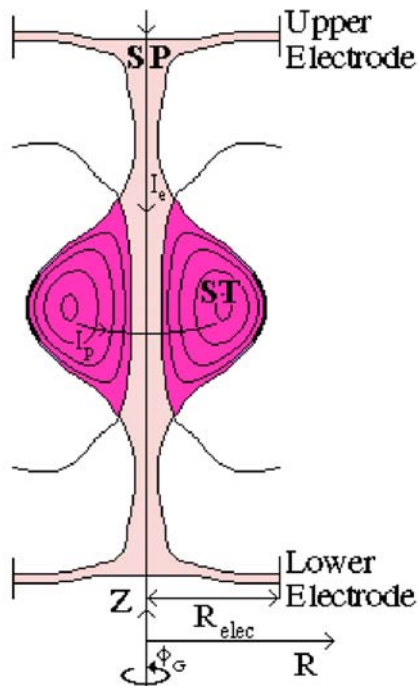
Neutrals and impurities are released from the gun



After the formation, the **Spheromak**

is accelerated and expanded into a **flux conserver** field errors already present in the gun are amplified

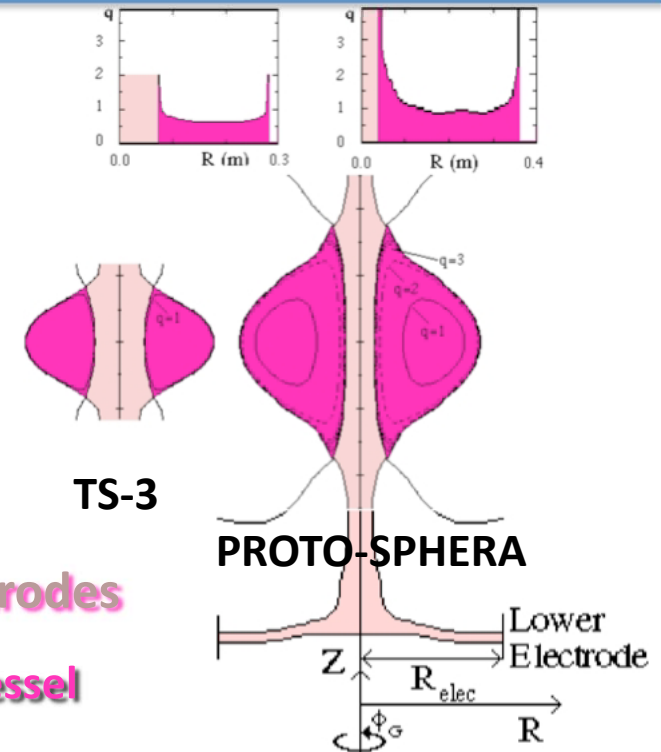
PROTO-SPHERA



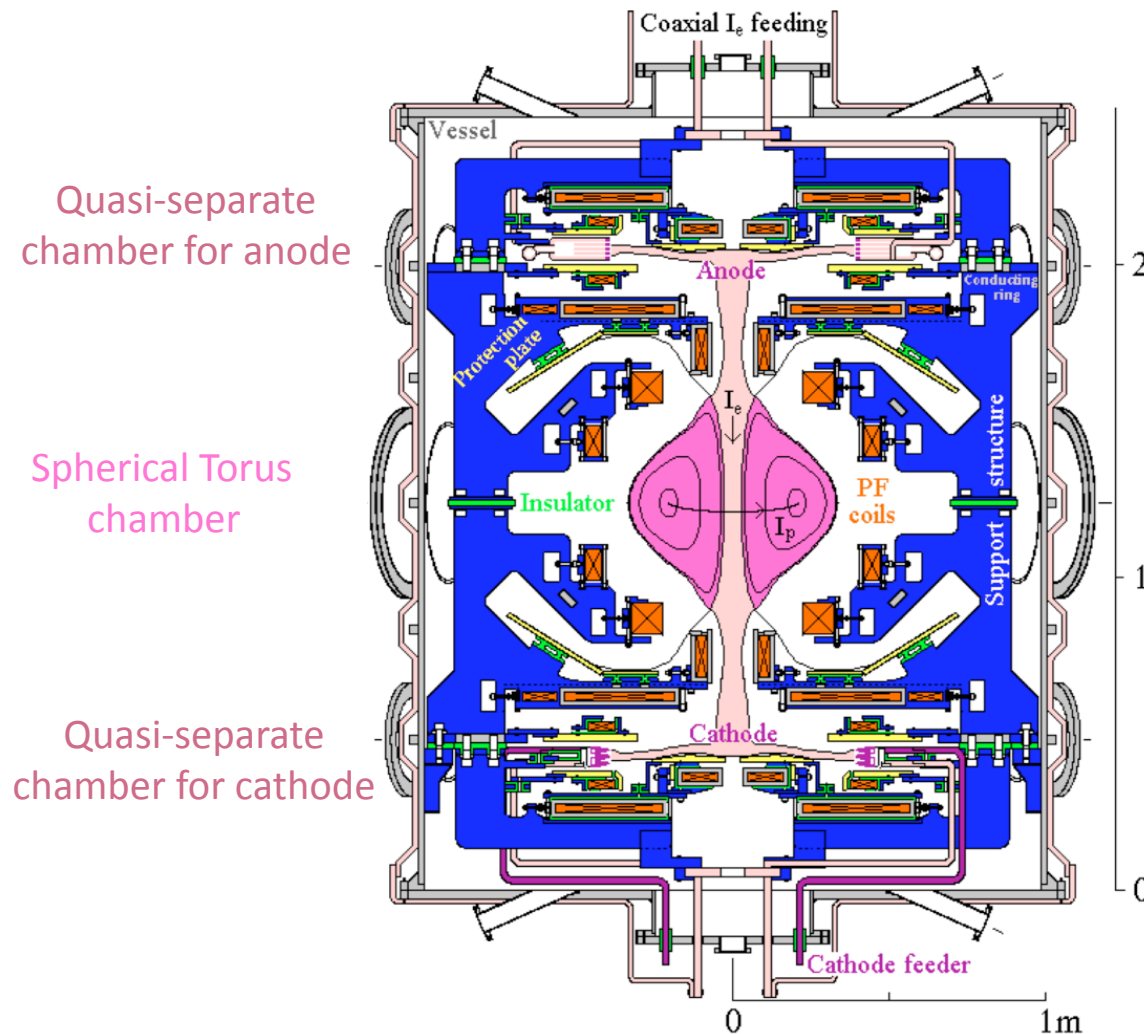
Designed to get a Tokamak-like MHD safety factor ($q_0 \geq 1$, $q_{\text{edge}} \sim 3$) ($A=R/a \geq 1.2$, $\kappa=b/a \sim 2.3$)

PROTO-SPHERA formed "slowly" as a **prolated low aspect ratio Spherical Torus (ST)** from the pre-existing **plasma centerpost mushroom-shaped in front of electrodes**

Breakdown at low voltage 100 V, big vessel



2001 PROTO-SPHERA final design report



PROTO-SPHERA parameters:

SP centerpost current $I_e = 60$ kA

ST toroidal current $I_p = 120 \div 240$ kA

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

MHD safety factor $q_0 \geq 1$, $q_{edge} \sim 3$

Sustainment $\tau_{res} > 70$ ms resistive time
(...experiment will tell)

Electrode plasmas ~separated from
main plasma: large number (18) of
PF (poloidal field) coils

Two main problems had been solved:

- building durable electrodes
- restrictions imposed by the ideal MHD stability

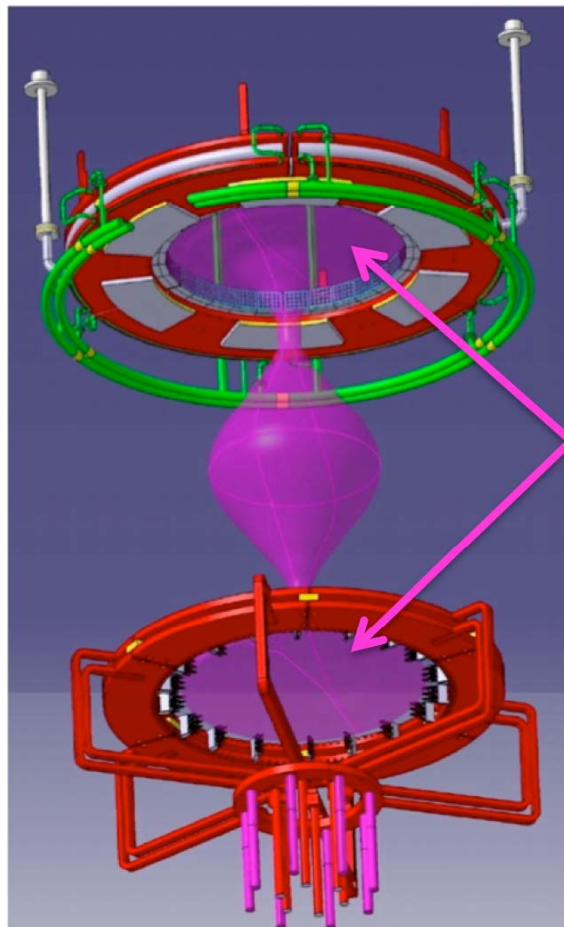
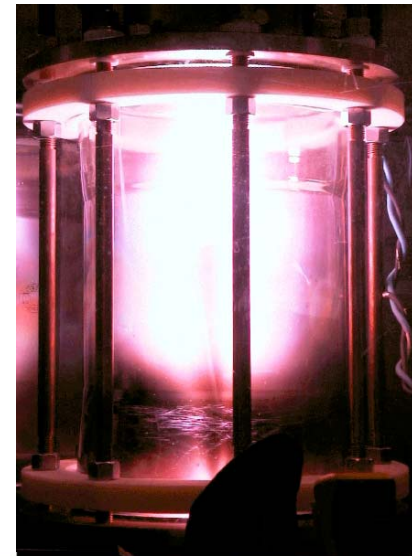
F. Alladio, P. Micozzi and F. Rogier
Ideal MHD stability of flux-core spheromaks
ICPP2000, Quebec City (Canada)



In the years 1998-2000, PROTO-PINCH testbench found the recipe for the electrodes of PROTO-SPHERA. although they were simple cylindrical electrodes



- low (100-200 V) voltage on electrodes
- tokamak-like density



Modular annular electrodes:

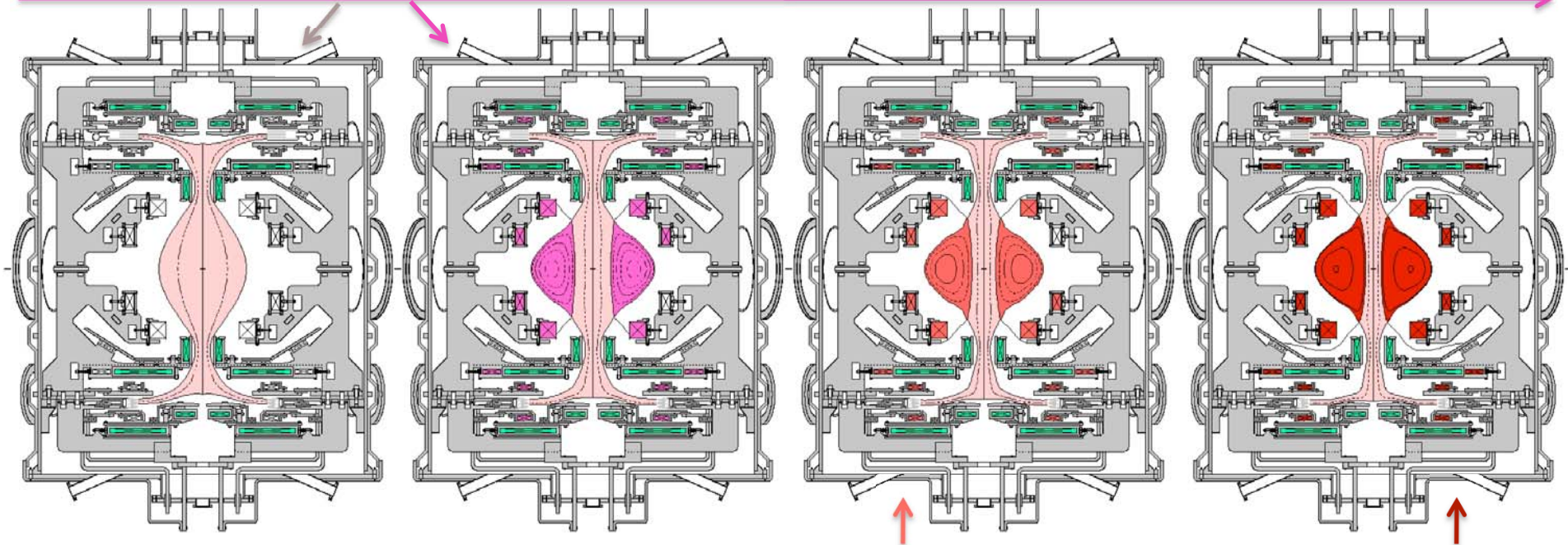
plasma current density $j_e = 1 \text{ MA/m}^2$
power density $P_e = 20 \div 30 \text{ MW/m}^2$

plasma centerpost at electrode
interfaces mushroom-shaped

W- directly heated cathode



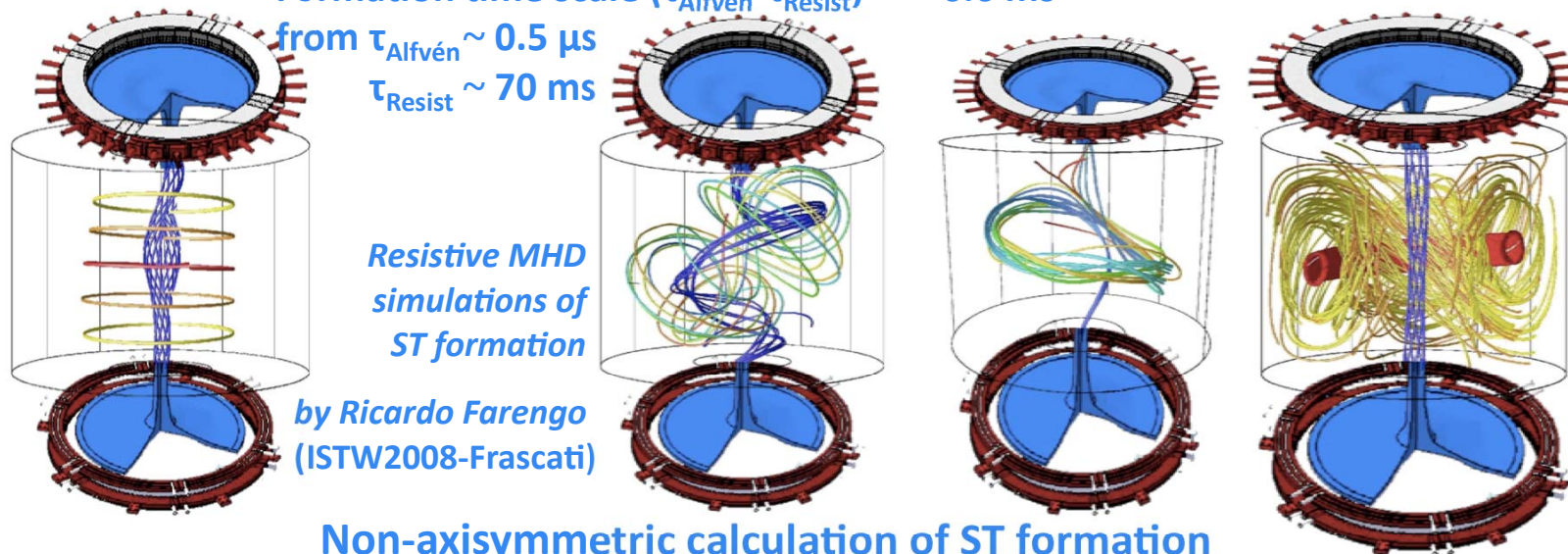
Plasma centerpost I_e 10 $\rightarrow$ 60 kA ...ST plasma formation ... Calculated assuming axisymmetric equilibria



0.6 ms increase of Group A current induces in ST $\rightarrow I_{ST}=120\text{kA}$, then Helicity Injection $\rightarrow I_{ST}=240\text{kA}$

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

from $\tau_{\text{Alfvén}} \sim 0.5 \mu\text{s}$
 $\tau_{\text{Resist}} \sim 70 \text{ ms}$



Resistive MHD
simulations of
ST formation

by Ricardo Farengo
(ISTW2008-Frascati)

Non-axisymmetric calculation of ST formation



Ricardo Farengo
CNEA Bariloche
(Argentina)

IDEAL MHD STABILITY of PROTO-SPHERA: the results



François Rogier
ONERA-Toulouse

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

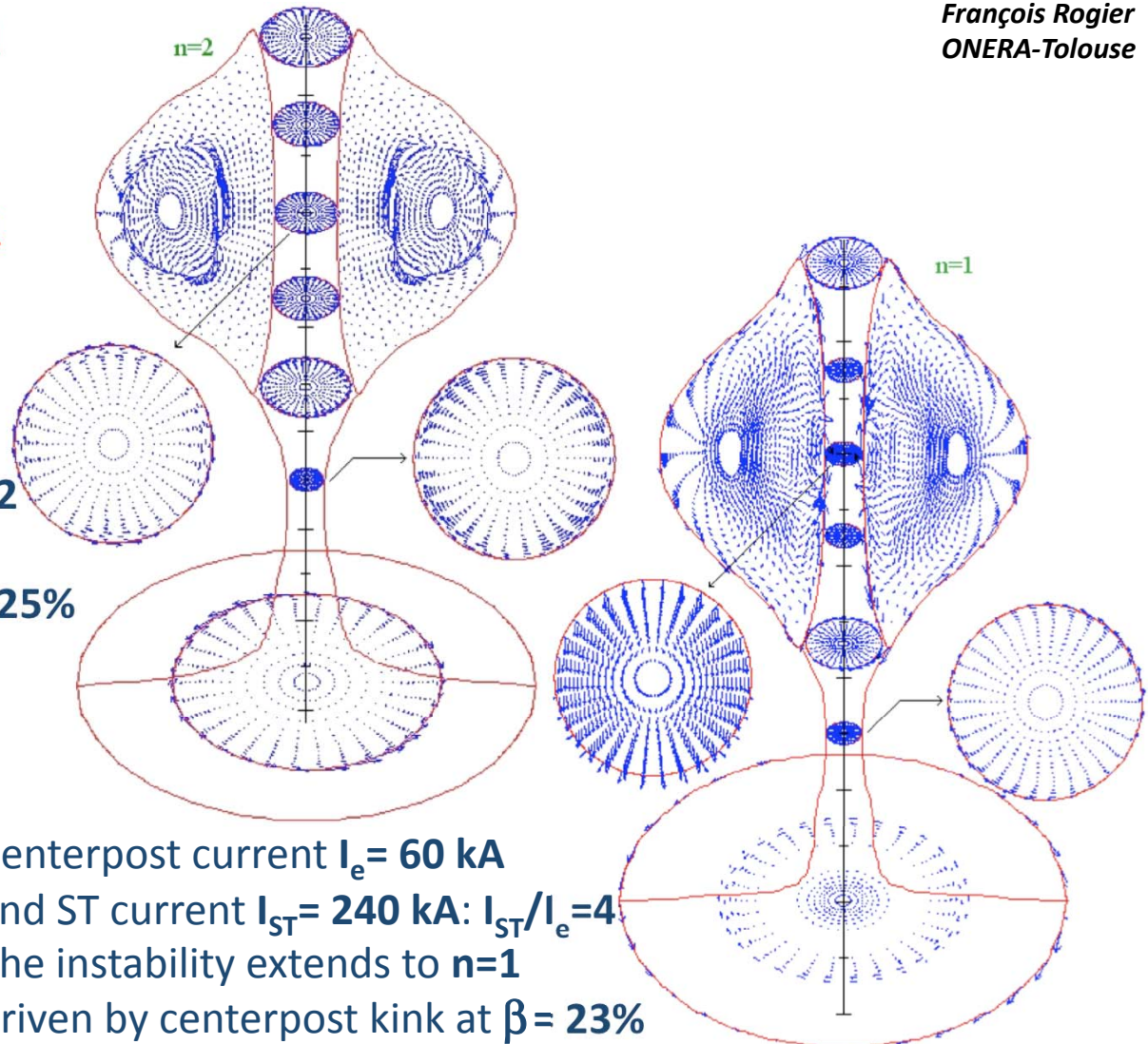
- up to $\beta_{T0} = 28 \div 29\%$, $I_{ST}/I_e = 0.5 - 1$
- up to $\beta_{T0} = 72 \div 84\%$, $I_{ST}/I_e = 2-4$

Centerpost current $I_e = 60$ kA
and ST current $I_{ST} = 120$ kA: $I_{ST}/I_e = 2$
The instability is limited to $n=2, 3$
driven by $q=3/2$ resonance at $\beta = 25\%$



F. Alladio, A. Mancuso, P. Micozzi and F. Rogier
Ideal MHD stability calculations in presence of
magnetic separatrices ICPP 2004, Nice (France)

Ideal MHD analysis to assess I_p/I_e & β limits
(Micozzi P. et al., 2010 Nucl. Fusion **50** 095004)



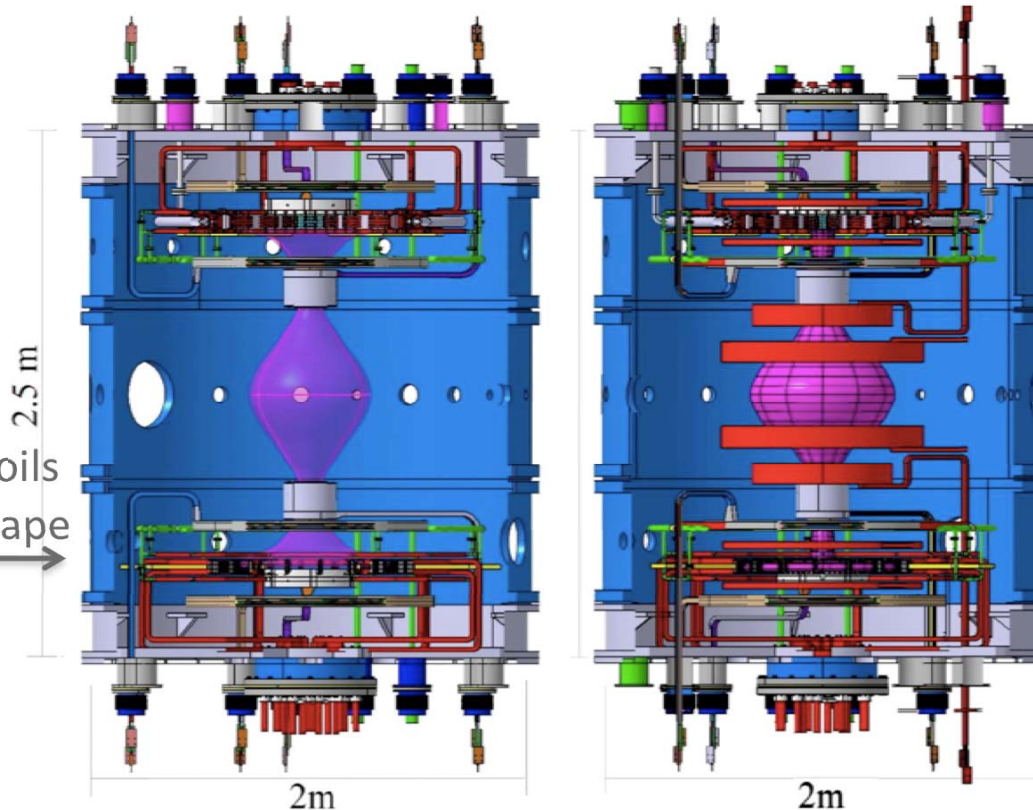
In **2002** at Frascati an **International Workshop**, chaired by **Martin Peng**, advised to build in two steps:

- first step: check Plasma Centerpost's feasibility
- second step: the machine would have been completed such as to produce the Spherical Torus



Martin Peng

Phase1: 8 PFcoils
Centerpost shape



Anode arc anchor
was feared, as it
is often observed
in arc welding,
plasma torches...



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

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

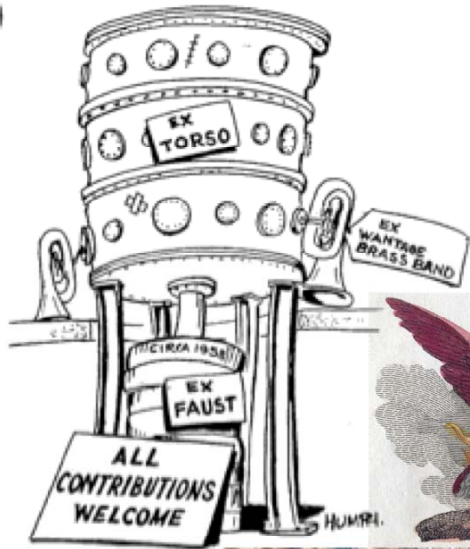
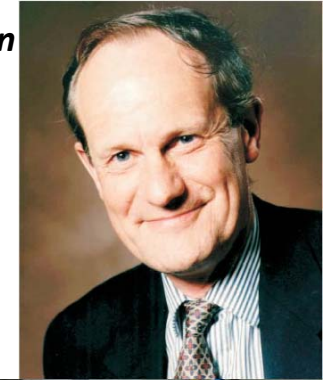
Group B (4+4 coils): Centerpost shaping PF coils ...thick AISI casings ($\tau \sim 2\text{ms}$), *now inside machine*

Group A (5+5 coils): ST compression PF coils ...not yet built thin Inconel casings B diffusion in $\tau \sim 200 \mu\text{s}$

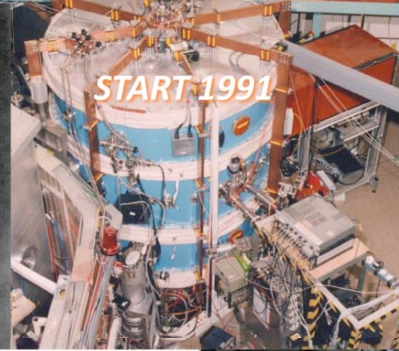
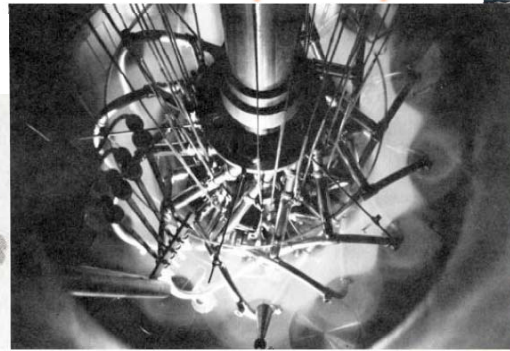


Derek Robinson (director of Culham from 1991) was very interested in the “Champagne bottle” experiment: in 1999 he proposed to build at Culham PROTO-SPHERA inside the START vessel

Derek Robinson
1941-2002



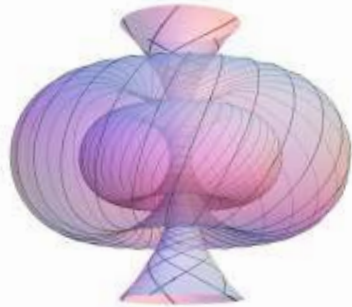
Torsatron Torso (Culham) 1975



From Culham the old vacuum vessel found its way to Frascati 2004



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



Years 2004 - 2010:



...from ideas

...to detailed design

...to hard metal

Anode

PF2 coils

Throttles

Cathode



- Cathode heating 6 x(1.7 kA,25 V)rms
- PF coils: 2kA, 350 V
- Plasma centerpost: 10 kA, 350 V

Electrical power supplies built by EEI of Vicenza, cost 0.7 M€

Years 2011 - 2014:

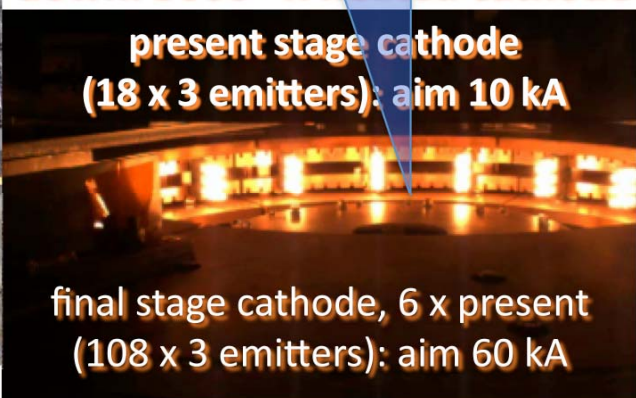


May 2015 annular
anode lowered
on top of machine



up: hollow gas-puffed anode

down: 3000° K heated cathode



present stage cathode
(18 x 3 emitters): aim 10 kA

final stage cathode, 6 x present
(108 x 3 emitters): aim 60 kA



“Caduceus”-like emitting spirals
have now survived > 1000 cycles



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

8 PF coils in series
inside the machine

Stainless steel
up\down
new extensions

PF4up

PF3up

PF2up

Aluminium cylindrical
START vessel

PF2low

PF3low

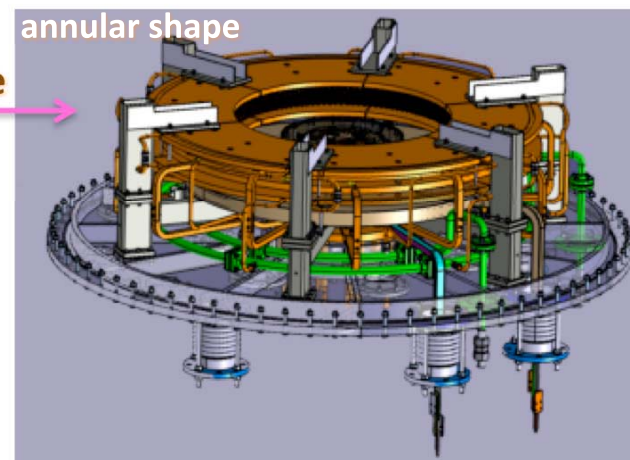
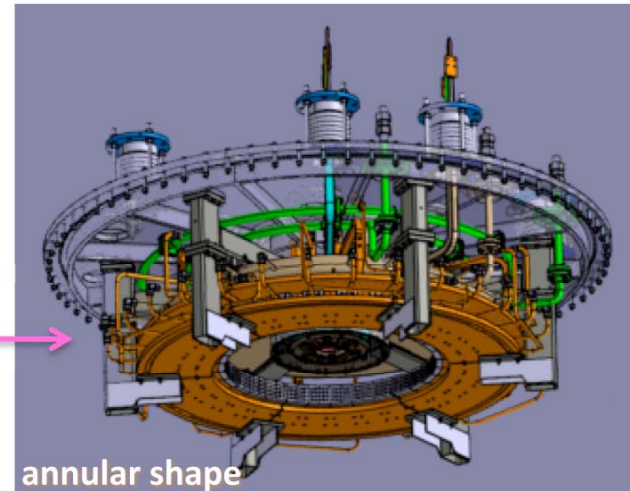
PF4low

Stainless steel
up\down new lids

anode

Plasma current must run
through both PF2 throttles

cathode



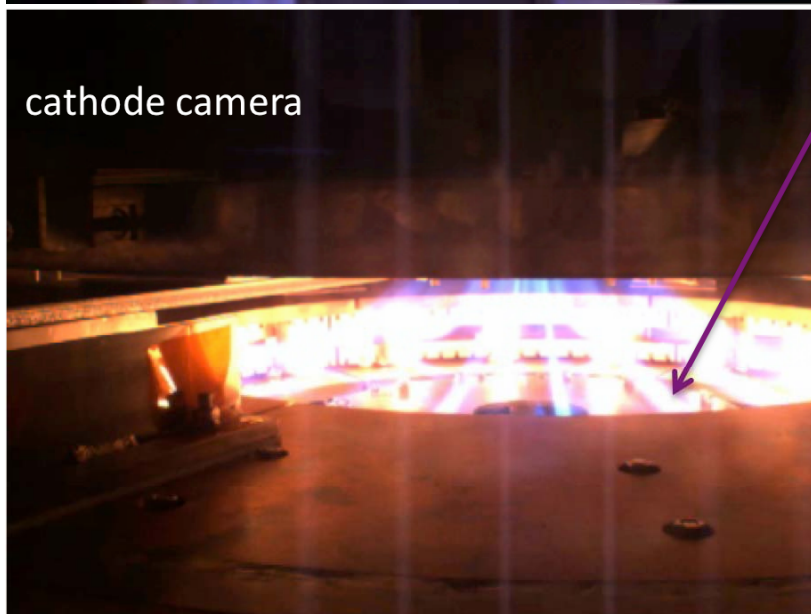
vacuum vessel is GND potential

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

A good surprise:
no anode arc anchoring



anode camera



cathode camera

hollow annular anode performs

- plasma goes through both PF2 throttles
- plasma enters anode gas-puffing holes
- no sign ($I < 3.5$ kA) of anode attachment
- filling pressure $10^{-3} - 10^{-2}$ mbar

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



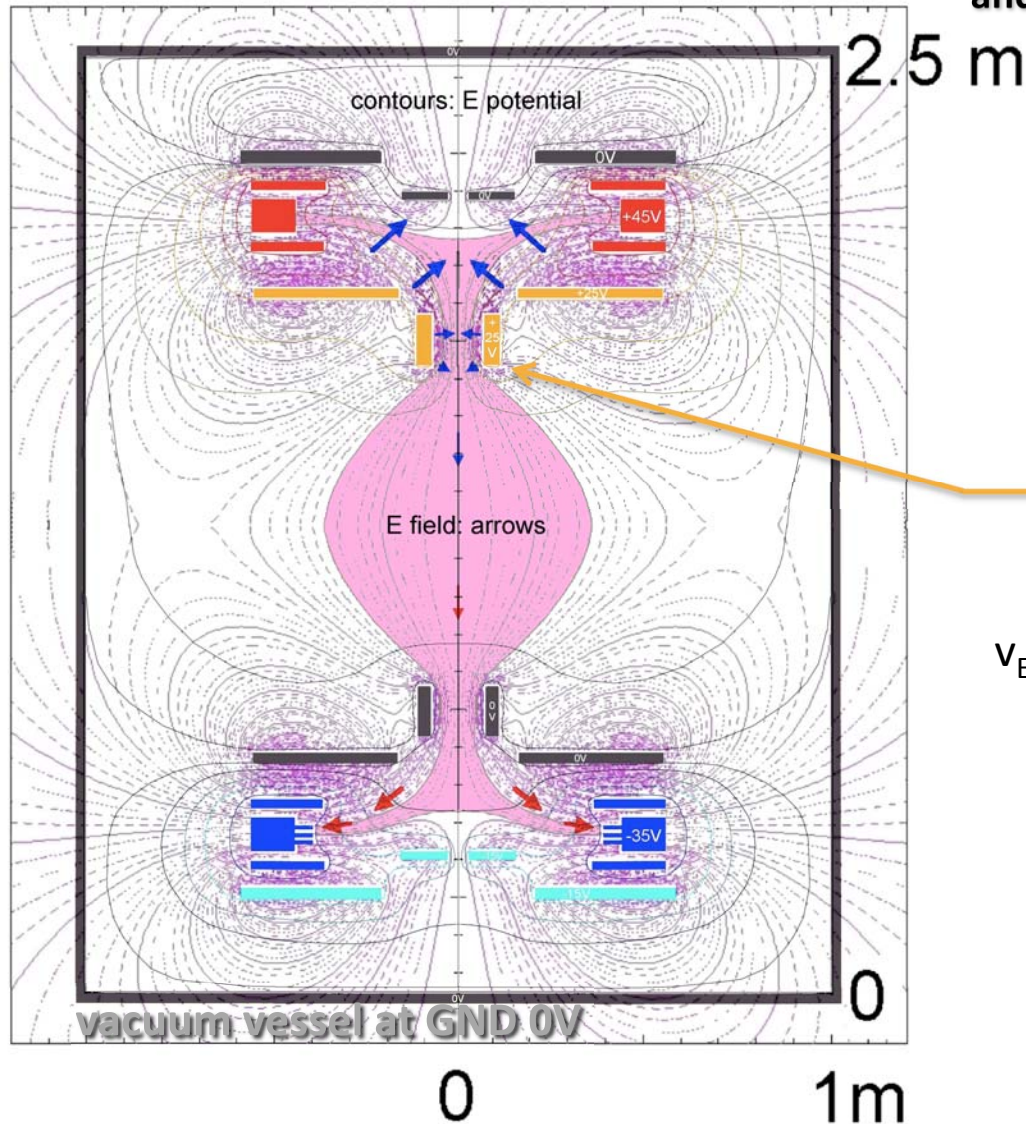
even plasma centerpost is in part filamented

Electrostatic plasma effects

The electrostatic potential distribution is dominated by the plasma

the magnetic field is up\down symmetric

but the electrostatic field is not up\down symmetric
and is different near the anode or near the cathode



Plasma-induced electric potential:

near the annular anode

the E field is in part perpendicular
to the B field

... $\mathbf{E} \times \mathbf{B}$ azimuthal plasma rotation

... starting from PF2up throttle

$$v_{\text{ExB}} = (E/B) \sim 10^4 \text{ m/s} \sim v_{\text{drift}} \sim v_{\text{thi}}$$

near the annular cathode

the E field is parallel to B field

... no $\mathbf{E} \times \mathbf{B}$ plasma rotation



May 2015 annular anode experiment
 half of the plasma current: (1kA\2kA)
 was going around the required path due to
equatorial X-point inside the vessel

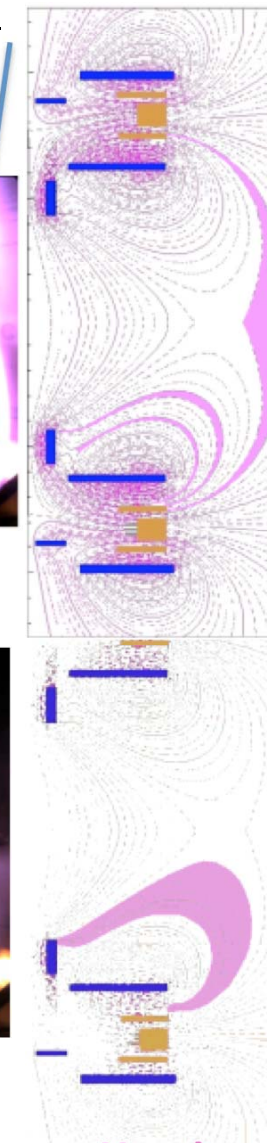
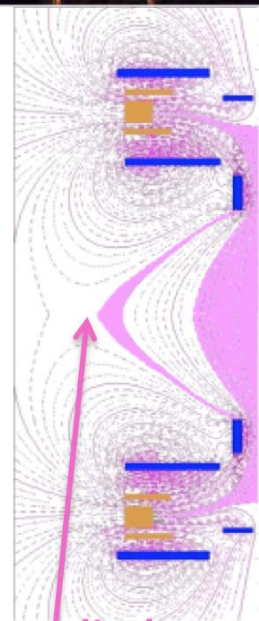
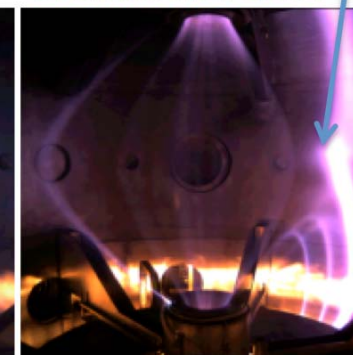


Shot 78

Argon plasma
breakdown 80V



Hydrogen plasma
breakdown 180V

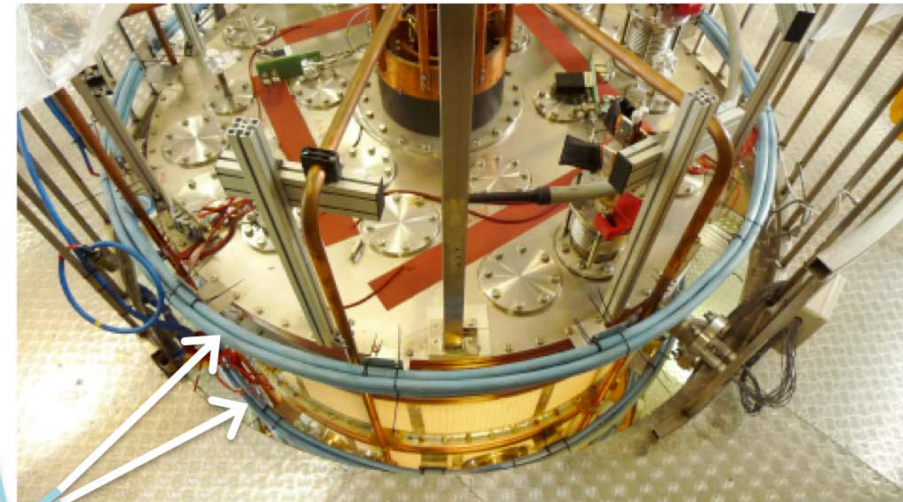
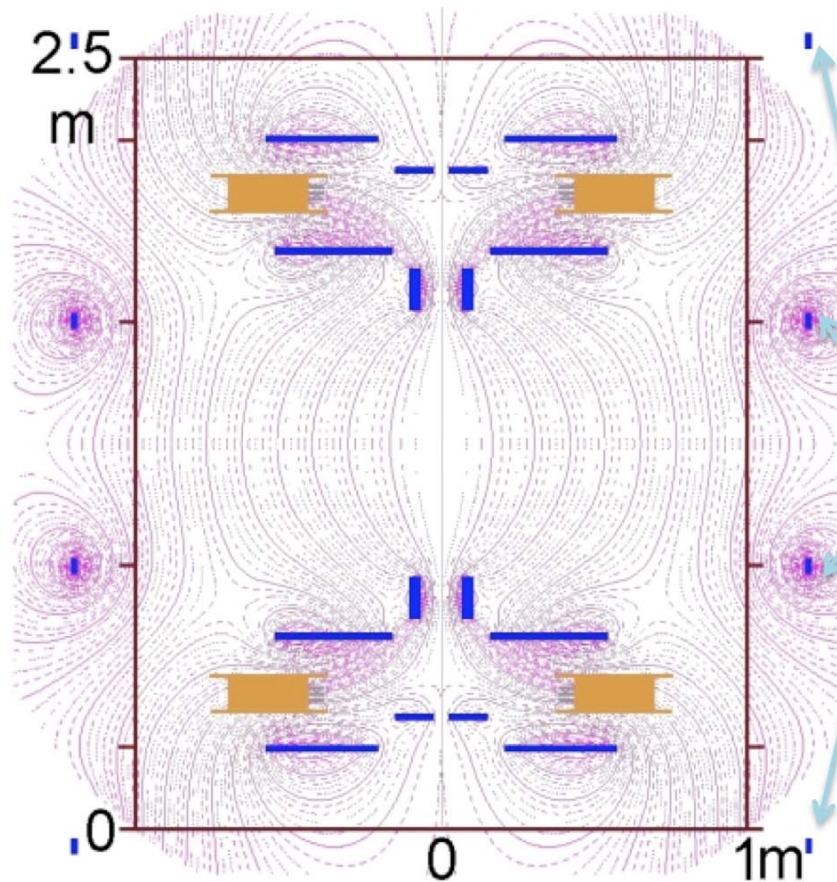


discharges along field lines near X-point

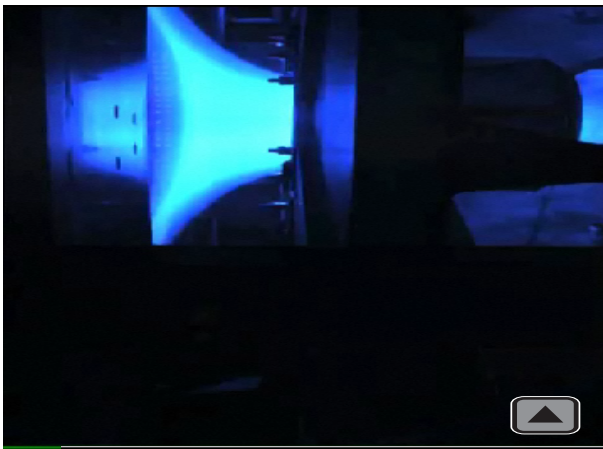
The equatorial X –point has been removed from inside the vessel

4 external PF coils have been added (home-made from spare connection cables)

...and fed in series with the internal PF coils (PF coils power supply has sufficient margin)



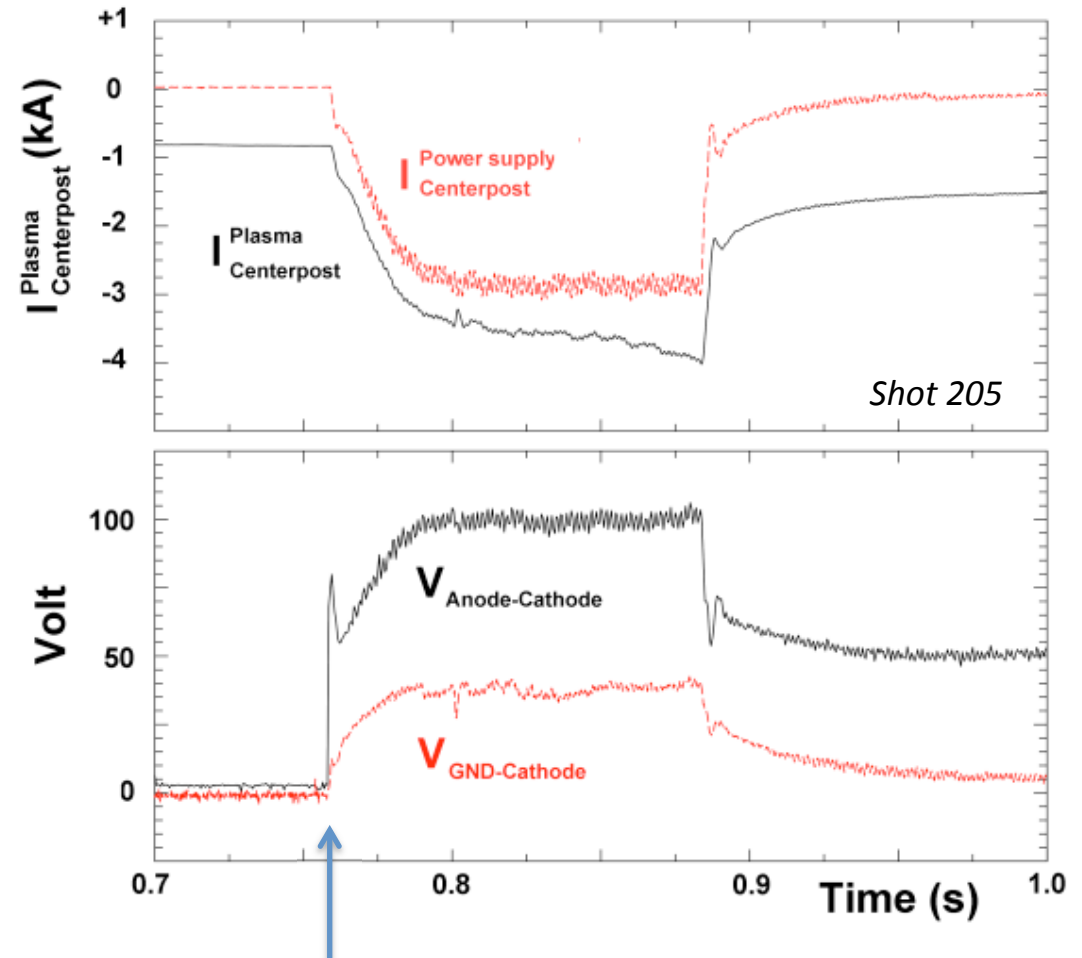
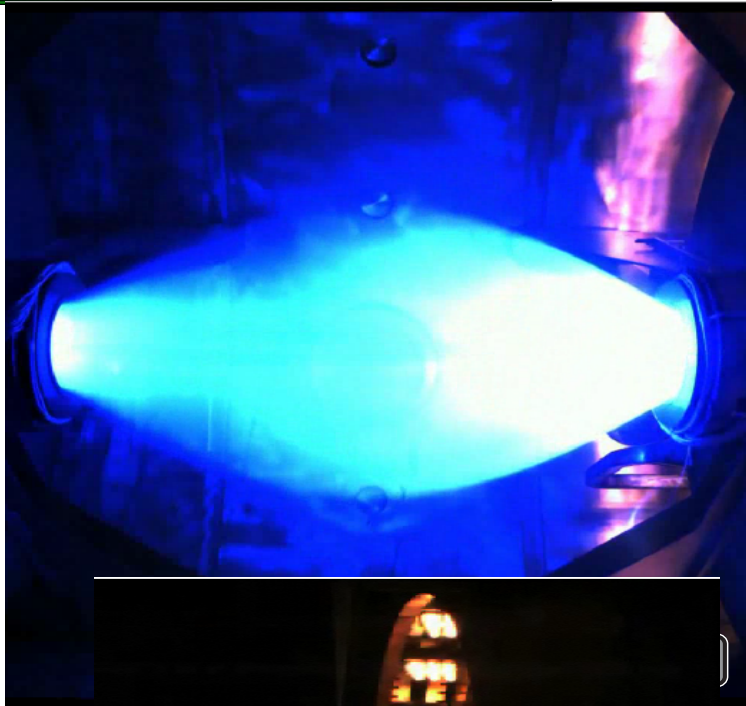
plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids



October 2015 experiments with external PF coils:

Argon discharge reaching 3 kA for 0.15 s

the whole plasma current runs through both PF2 throttles



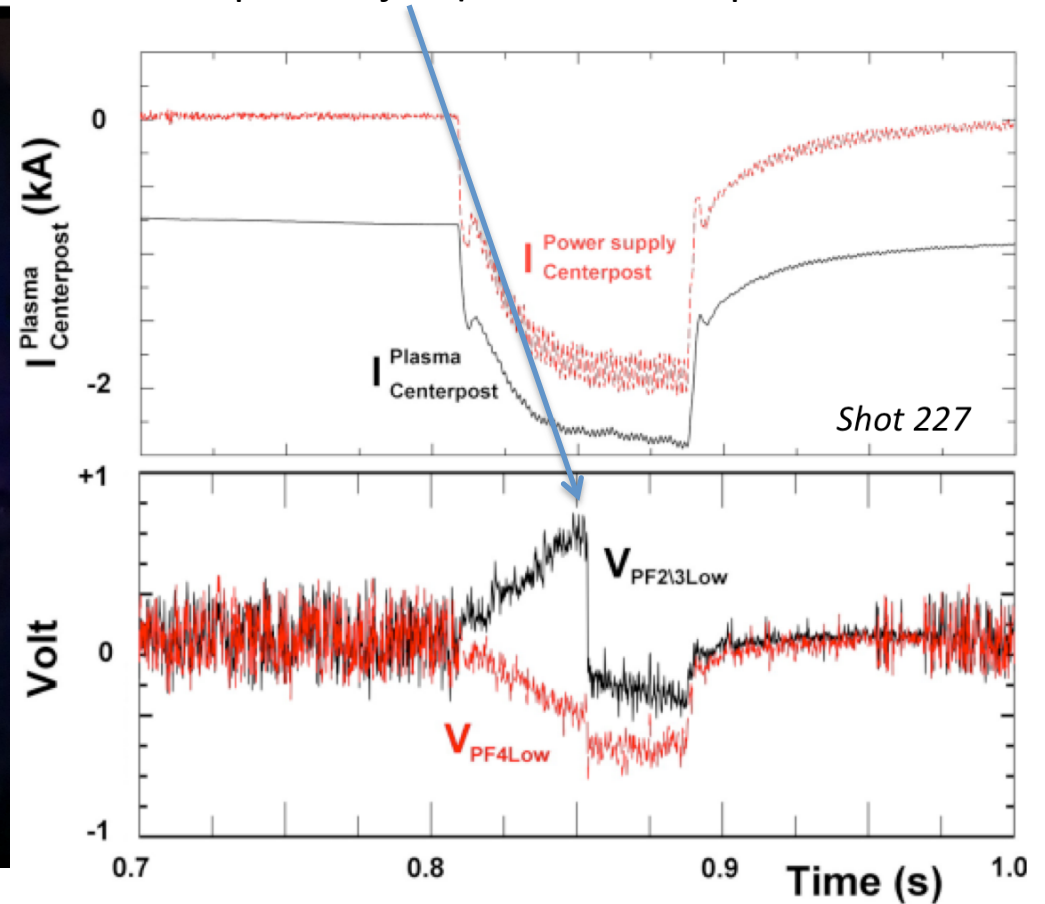
plasma fired after 0.75 s of PF current
(skin current time to remove X-point from inside vessel)

- straighter grounding of lower PF coils
 - flowing current only in the two external PF coils nearer to equator
- allows for a better filling of the cathode and quieter centerpost plasma

Argon plasma 2kA

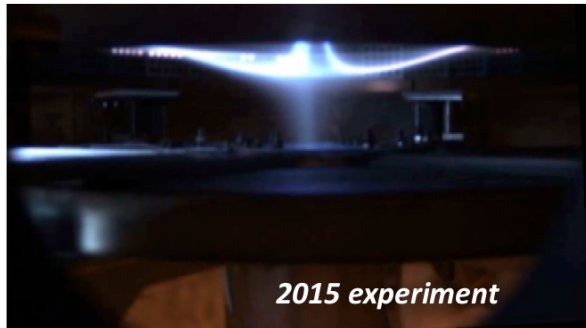


voltage spikes have been eliminated on PF2/3low, after 1 V amplitude jump even small sparks vanish



CKF configuration is a possible evolution of the Proto-Sphera concept

Degenerate X-points on Proto-Sphera anode (and cathode) are nozzles

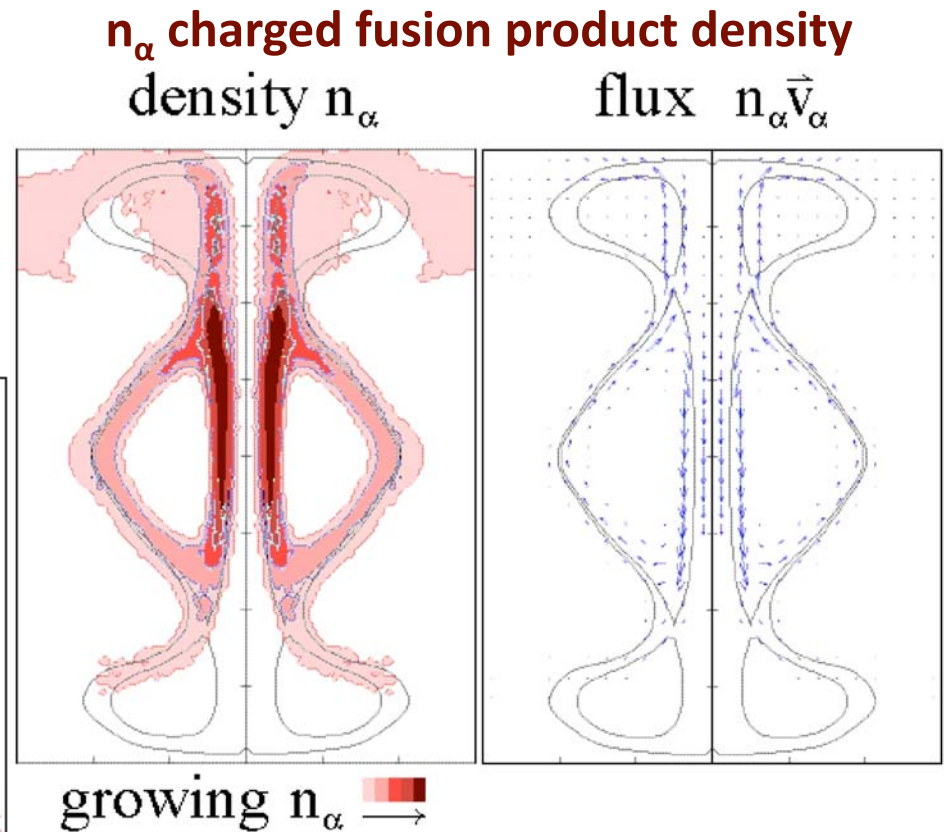
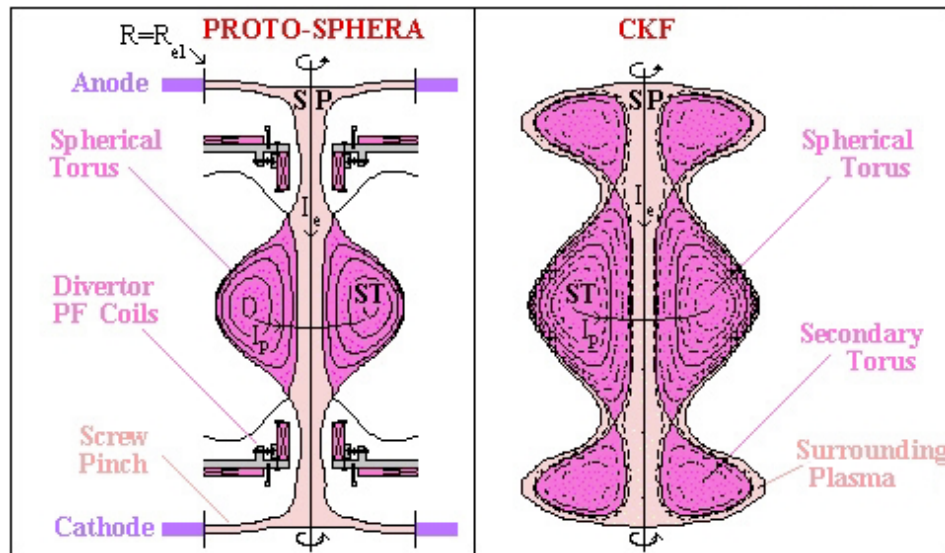


2015 experiment

Different orbits of co\counter-circulating charged fusion products
...preferential thrust through one of the two degenerate X-points

CKF found to be ideally MHD stable up to $\beta=1$

...promising for future fusion space thrusters?

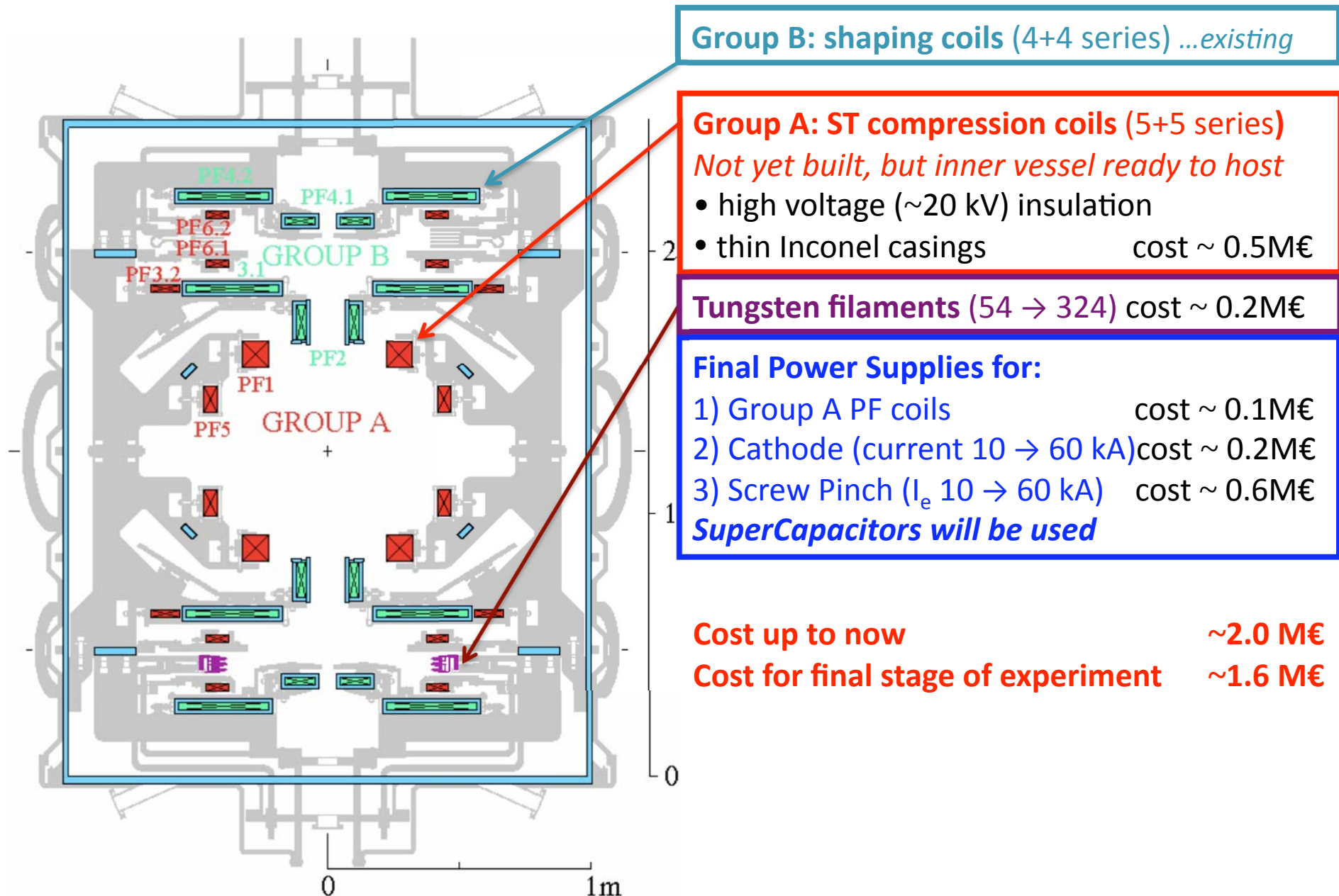


F. Rogier, G. Bracco, A. Mancuso, P. Micozzi, F. Alladio
Simply Connected High-beta Magnetic
Configurations ICPP 2002, Sidney (Australia)

Proto-Sphera: a CKF whose
surrounding Plasma terminates upon electrodes
and whose Secondary Tori are substituted by PF2/3 coils



To be build after 10 kA plasma centerpost routinely achieved



Group B: shaping coils (4+4 series) ...existing

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

Not yet built, but inner vessel ready to host

- high voltage (~ 20 kV) insulation
 - thin Inconel casings
- cost ~ 0.5 M€

Tungsten filaments (54 $\rightarrow$ 324) cost ~ 0.2 M€

Final Power Supplies for:

- 1) Group A PF coils cost ~ 0.1 M€
- 2) Cathode (current 10 $\rightarrow$ 60 kA) cost ~ 0.2 M€
- 3) Screw Pinch (I_e 10 $\rightarrow$ 60 kA) cost ~ 0.6 M€

SuperCapacitors will be used

Status

PROTO-SPHERA is producing its first centerpost plasmas ...*better late than never!*

Hollow gas puffed anode is a success, no any anode arc attachment

(plasma induced electrostatic effect, $E \times B$ drift rotation of the plasma)

Target 8.5kA in plasma centerpost: **3.5 kA = 40% has been sustained in Argon plasma**

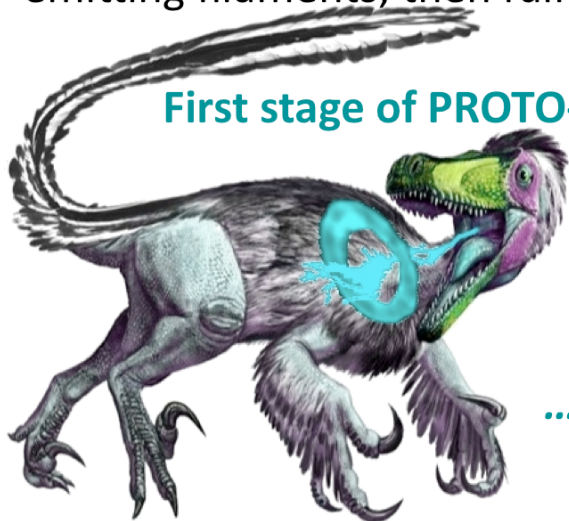
To achieve full current of 8.5 kA boundary conditions must be adjusted:

- **electrostatically** by connecting PF coils casings, built floating with respect to the vessel
- **magnetically** by additional PF coils external to the vacuum vessel

After Argon centerpost is tamed (80 V breakdown), start fight with Hydrogen centerpost (180 V)

If full current of plasma centerpost(10 kA) is achieved and sustained with 54 sparsely spaced emitting filaments, then full current (60 kA) will be even better achieved with 324 filaments

First stage of PROTO-SPHERA is only a first step ...



...放龍入海! fànglóng rùhǎi

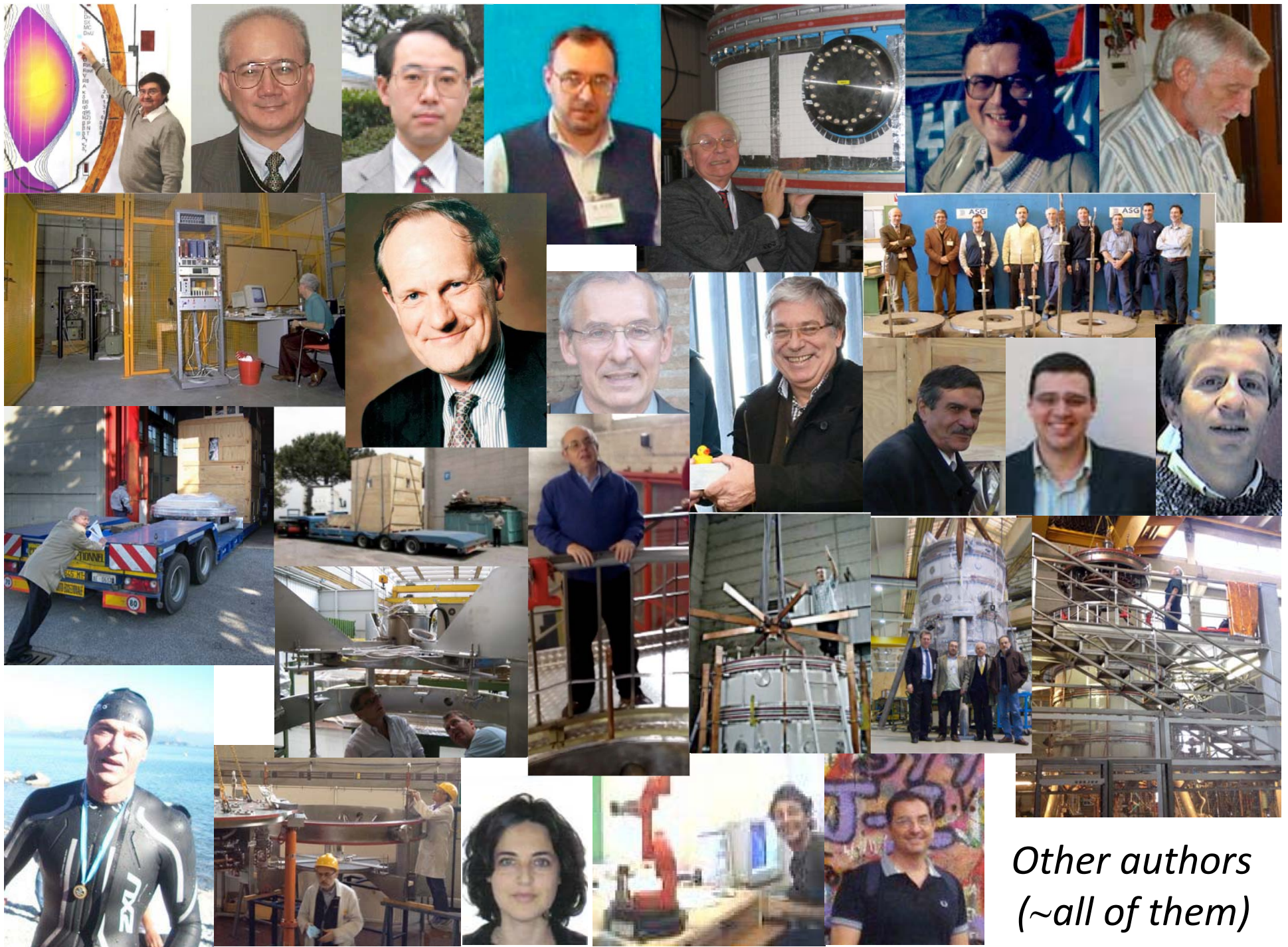
...give a chance to the dragon to show his endowments into the sea!

Perspective

Proto-Sphera will assess a new magnetic confinement configuration

- simply connected (easier construction & maintenance)
- with high plasma β capability
- sustained by magnetic helicity injection instead of ohmic drive

**Proto-Sphera can develop this program:
at very low costs ($\sim 1.6\text{M€} + 2\text{M€}$ already spent)
in a flexible way (new components can be easily added)**



*Other authors
(~all of them)*