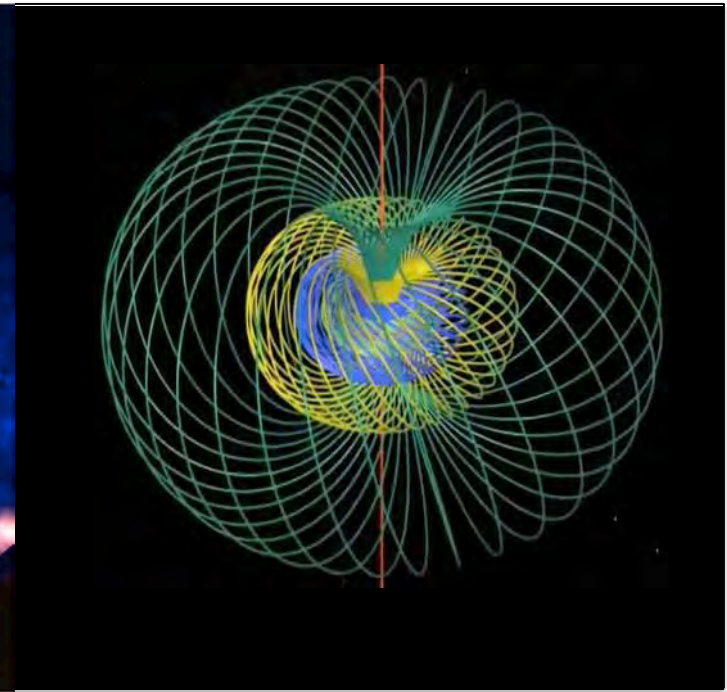


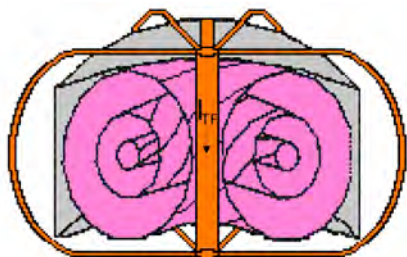
First results and perspectives of the PROTO-SPHERA experiment

***P. Micozzi¹, F. Alladio, L. Boncagni, F. Causa, E. Giovannozzi, A. Grosso, A. Lampasi,
G. Maffia, A. Mancuso^{retired}, V. Piergotti, G. Rocchi, A. Sibio, B. Tilia, V. Zanza^{retired}***

Centro Ricerche ENEA, Frascati C.P. 65, Rome, Italy ¹e-mail: paolo.micozzi@enea.it



Spherical Tokamaks allow to obtain:



High plasma current I_p with low B_T , high β
and more compact devices

But, for a reactor/CTF extrapolation:

- No space for central solenoid (Current Drive requirement more severe)
- No neutrons shield for central stack (no superconductor/high dissipation)

Intriguing possibility $\Rightarrow$ substitute central rod with Screw Pinch plasma ($I_{TF} \rightarrow I_e$)

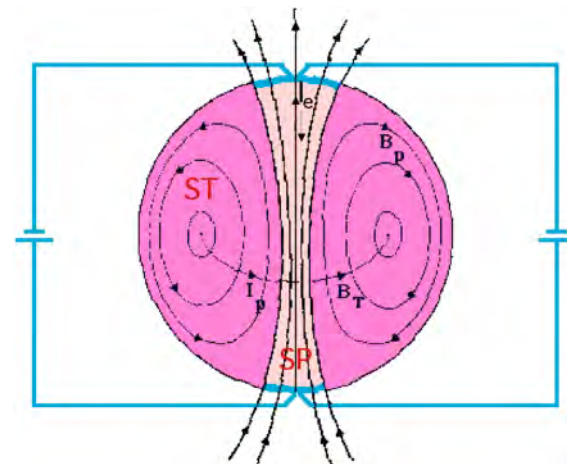
Potentially two problems solved:

- Simply connected configuration (no conductors inside)
- I_p driven by I_e (Helicity Injection from SP to ST)

Flux Core Spheromak (FCS)

Theory: Taylor & Turner, Nucl. Fusion 29, 219 (1989)

Experiment: TS-3; N. Amemiya, et al., JPSJ 63, 1552 (1993)



But Flux Core Spheromaks are:

- injected by plasma guns
- formed by ~10 kV voltage on electrodes
- high pressure prefilled
- with ST safety factor $q \leq 1$

New configuration proposed

(Alladio F. et al. 2006 Nucl. Fusion **46** S613):

PROTO-SPHERA

“Flux Core Spherical Tokamak” (FCST), rather than FCS

Disk-shaped electrode driven Screw Pinch plasma (SP)

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

SP electrode current

$$I_e = 60 \text{ kA}$$

ST toroidal current

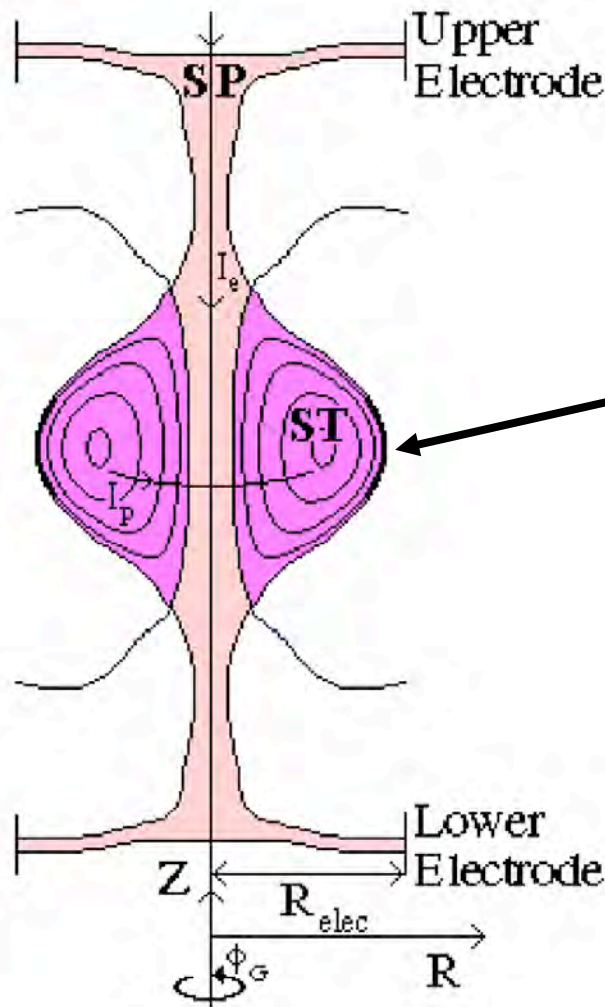
$$I_p = 120 \div 240 \text{ kA}$$

ST diameter

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



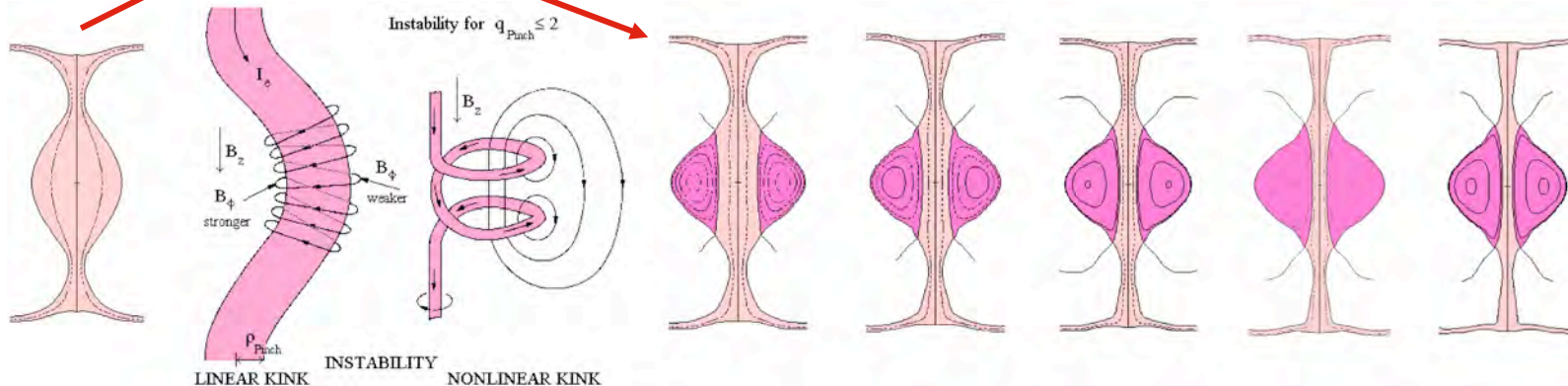
Stability should be improved and helicity drive may be less disruptive than in conventional Flux-Core-Spheromak



PROTO-SPHERA formation follows TS-3 scheme (SP kink instability)

Tunneling (ST formation)

ST compression ($I_p/I_e \uparrow, A \downarrow$)



T0

$I_e = 8.5$ kA

$I_e 8.5 \rightarrow 60$ kA

T3

$I_p = 30$ kA
 $A = 1.8$

T4

$I_p = 60$ kA
 $A = 1.5$

T5

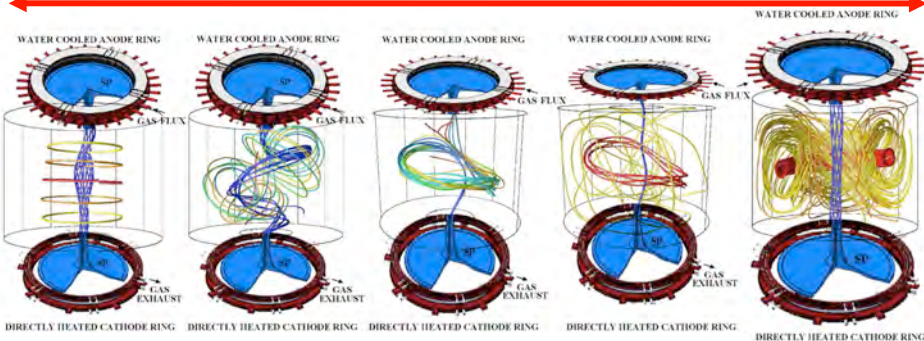
$I_p = 120$ kA
 $A = 1.3$

T6

$I_p = 180$ kA
 $A = 1.25$

TF

$I_p = 240$ kA
 $A = 1.2$



Formation time scale:

Alfvén MHD growth time $\tau_A \sim 0.5 \mu s$

Resistive diffusion time $\tau_R \sim 70$ ms

$(\tau_R \tau_A)^{1/2} \sim 0.6$ ms for $I_{ST} = 120$ kA ($2 \times I_e$)

Garcia-Farengo, PoP 16,112508 (2009)

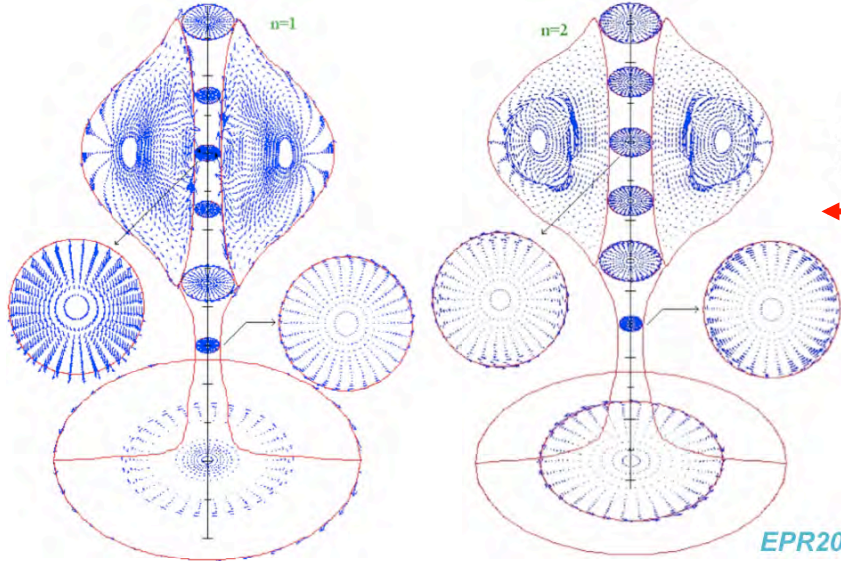
Farengo, ISTW2008 - Frascati

Key points of PROTO-SPHERA design

- Stable Screw Pinch formed at Tokamak pressures ($10^{-3} \div 10^{-2}$ mbar) & with low voltage break-down (100-200 V)
- I_p/I_e ratio relevant parameter (strong energy dissipation in SP)
- MHD equilibria computed both with *monotonics* well as *reversal safety factor profiles*



magnetic configuration is quite robust



Examples of $n=1$ & 2 instabilities at high β

Some level of low n resistive instability needed (reconnections to inject helicity from SP to ST)

but

SP+ST must be ideally stable at any time slice



Ideal MHD analysis to assess I_p/I_e & β limits

(Micozzi P. et al., 2010 Nucl. Fusion **50** 095004)



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

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

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

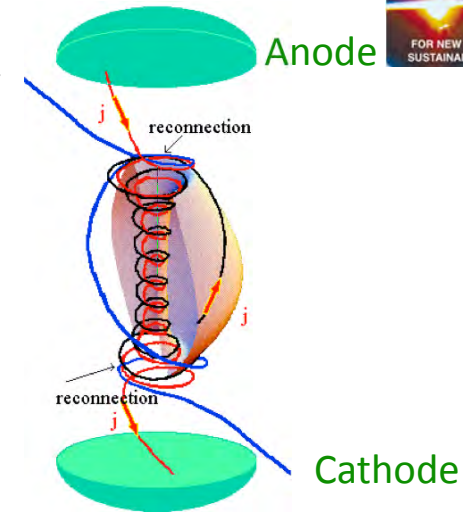
- up to $\beta_{T0} = 72 \div 84\%$, $I_{ST}/I_e = 2-4$

Critical points of PROTO-SPHERA

Helicity Injection to sustain the plasma torus:

driven relaxation of Plasma Central Column forms & sustains the ST

- electrode plasma - open field lines - has $\vec{j} \parallel \vec{B}$
- the open field lines also wind toroidally
- magnetic reconnections convert open $\vec{j}, \vec{B}$ lines into closed $\vec{j}, \vec{B}$ lines winding on a spherical torus
- $I_{ST} = 240 \text{ kA } (4xI_e)$ really achievable?
- Can it be sustained by H.I. for at least $\tau_R \sim 70 \text{ ms}$?
- Resistive MHD stability & confinement?

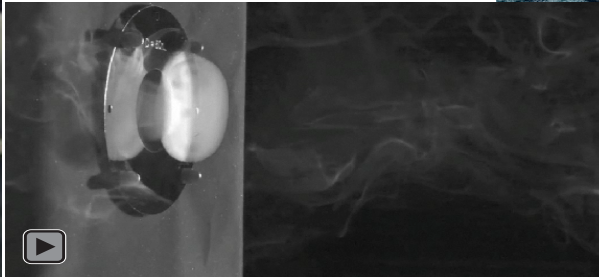


"Smoke-ring like
self-organization"

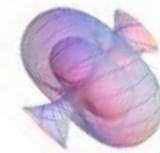


Beluga

William Irvine
University of Chicago

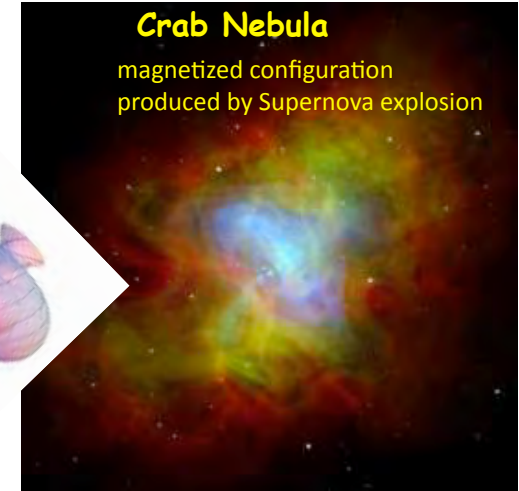


Etna volcano



Crab Nebula

magnetized configuration
produced by Supernova explosion



Cylindrical vacuum vessel was START vacuum vessel, donated by Culham in 2004



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



...from ideas

...to detailed design

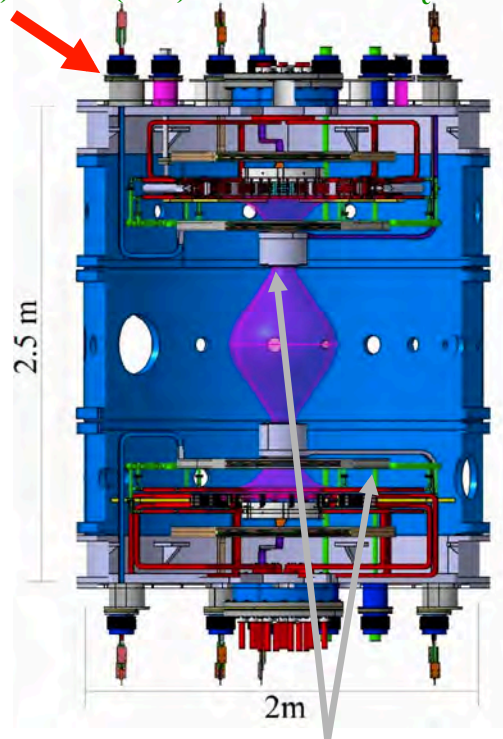
EPR2016 | Auburn, 23-26 February

...to hard metal

PROTO-SPHERA Phase-1

Aims:

- 1) Breakdown
- 2) Stable formation of plasma 'mushrooms'
- 3) Stable (≈ 1 s) achievement of $I_e = 8.5$ kA



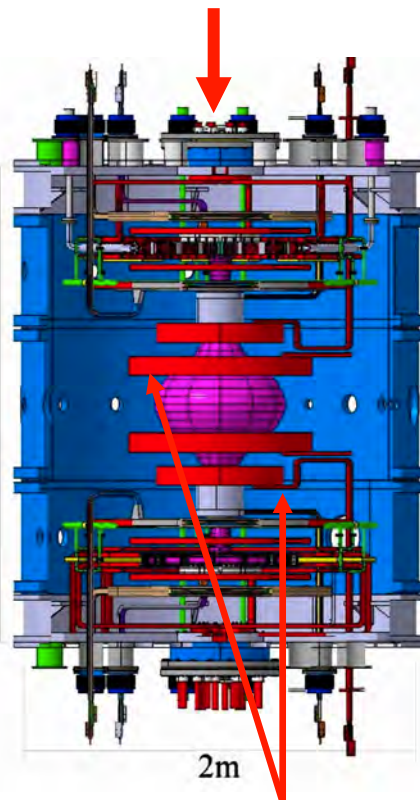
8 PF coils

Centerpost only

PROTO-SPHERA Phase-2

Aims: ST formation, compression & sustainment

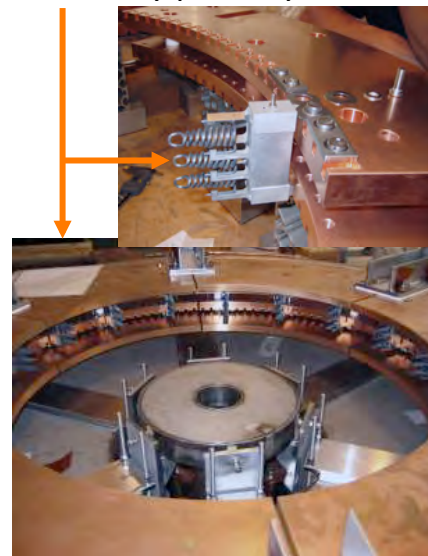
(All parts will be reused)



8 + 10 PF coils

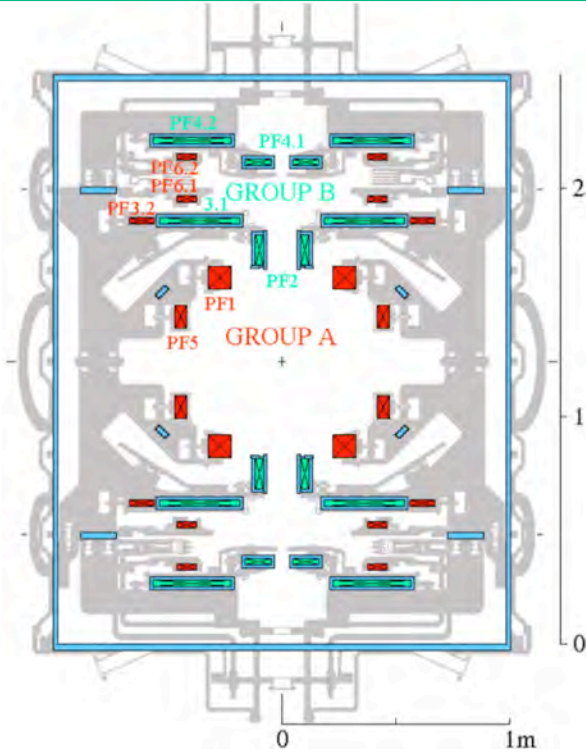
By adding:

- 5 pair of new PF coils
- New power supplies
- Full amount of Tungsten wires (324 Vs 54) on the directly heated cathode now only partially filled



The poloidal field (PF) coils designed as two sets each connected in series

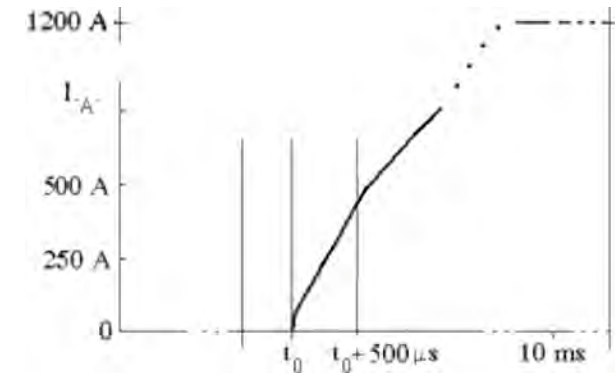
Group B (4+4 coils): Centerpost shaping PF coils ...**thick AISI casings ($\tau \sim 2\text{ms}$)**, *now inside machine*



To fire the plasma centerpost
3 Power Supplies have been built

- Cathode heating 6 x(1.7 kA, 25 V)_{rms}
- PF coils: 2kA, 350 V
- Plasma centerpost: 10 kA, 350 V
(cost 700 k€)

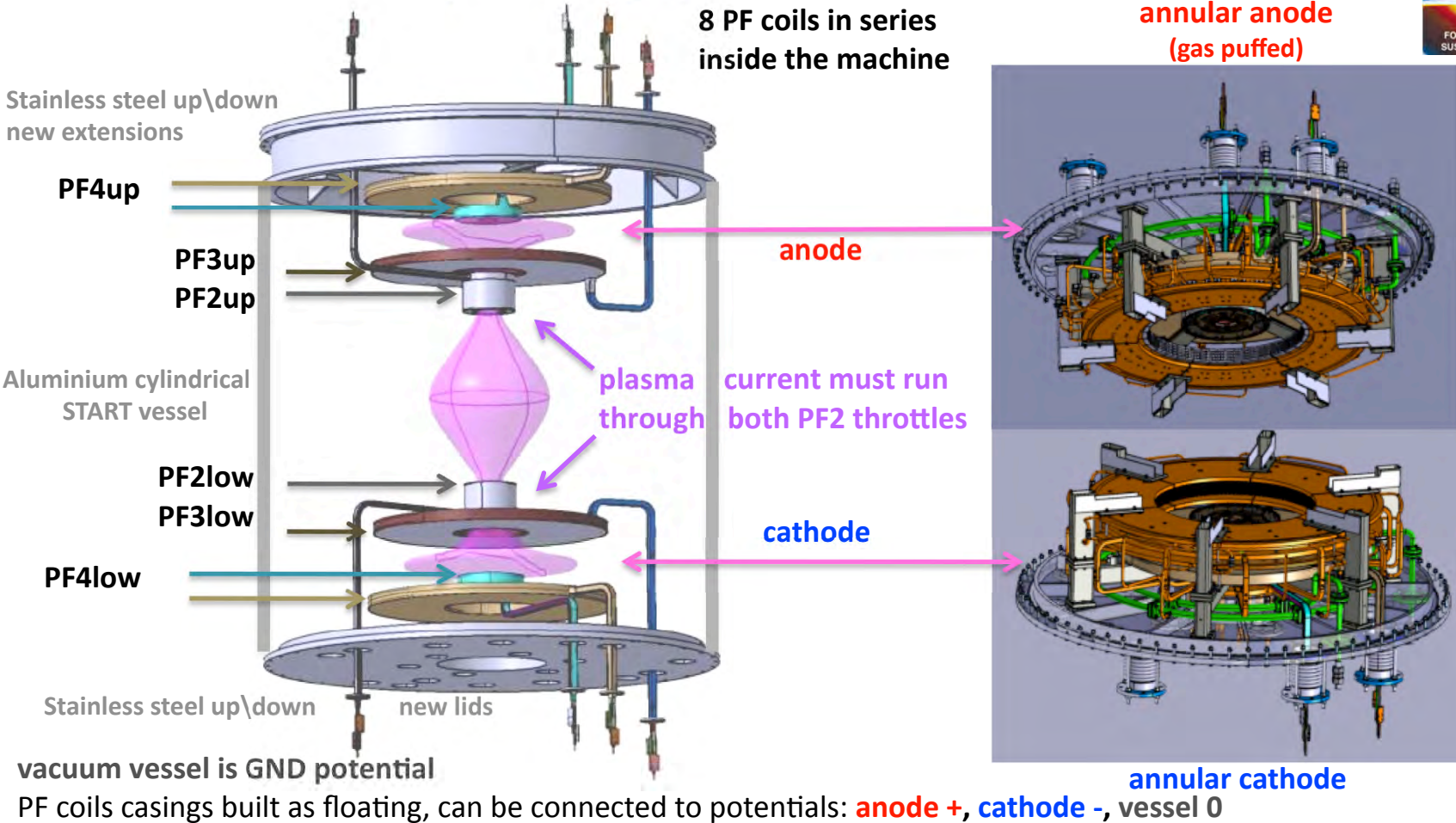
Paradigm reversal:
ohmic drive followed
by Helicity Injection
...waveform of **Group A**
current provides ohmic
drive to torus up to 120 kA



Group A (5+5 coils): Spherical Torus compression PF coils ...**not yet built**

- High voltage ($\sim 20\text{ kV}$) insulation: fast current increase (0.5 ms)
- **Thin Inconel casings to allow for B diffusion in $\tau \sim 200\text{ }\mu\text{s}$ across them**

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



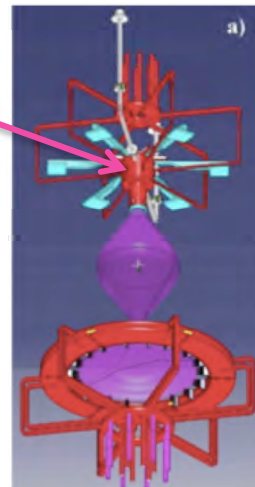


Being afraid of anode attachment, often observed in arc discharges
(arc welding, plasma torches)

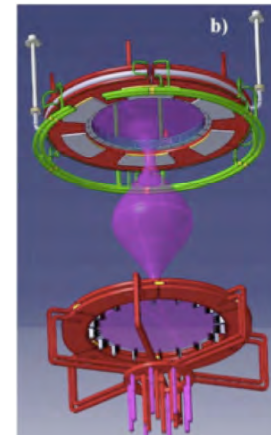
← the first rounds of experiments
had a simple cylindrical anode

break-down was easily achieved,
apart from this the cylindrical anode was just a source of troubles

2014 cylindrical anode



2015 annular anode



Cylindrical cathode results

break-down 170 V +10 ms, 500 A +20 ms, 1.5 kA

Anode camera



Centepost camera

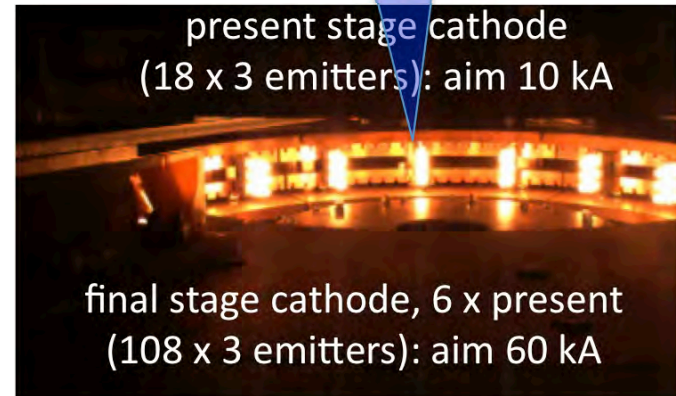
April 2015: annular anode installed



May 2015
Annular anode lowered on top of machine



down: 3000°K heated cathode
present stage cathode
(18 x 3 emitters): aim 10 kA

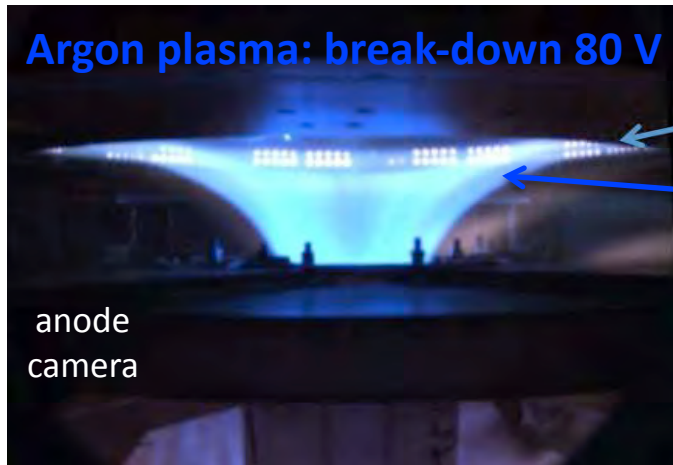


final stage cathode, 6 x present
(108 x 3 emitters): aim 60 kA

Emitting W spirals up to now survived ~ 1000 cycles

Good surprise!

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 ($I < 3.5$ kA) of anode attachment
- filling pressure 10^{-3} - 10^{-2} mbar

annular anode plasma is never filamented



Cathode
plasma
filaments
disappear
going
towards
anode

**whereas annular cathode plasma (sparse emitters)
and even plasma centerpost are filamented**

Electrostatic plasma effects

vacuum vessel at GND →

PF coil casings can either be at floating potential or can be connected to:

anode +, **cathode -**, vessel 0
through $\sim 1 \Omega$ resistors

but the electric potential distribution is dominated by the plasma

PF2\3up to anode (1Ω)\PF4up cathode (10Ω)

$V_{PF4up} \sim 0 \text{ V}$

$V_{anode} \sim +45 \text{ V}$

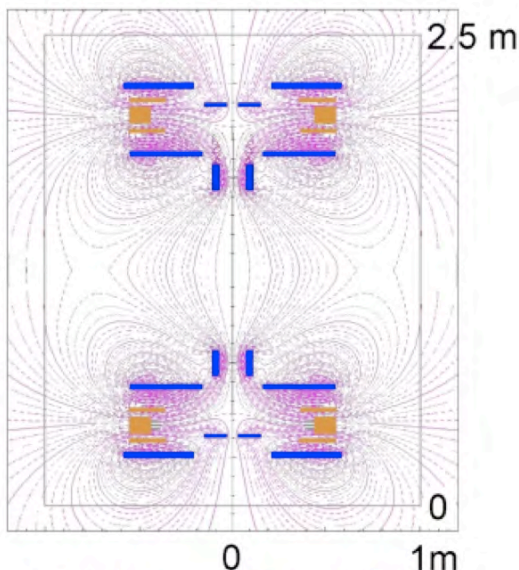
$V_{PF2-3up} \sim +25 \text{ V}$

$V_{vessel} = 0 \text{ V (ground)}$

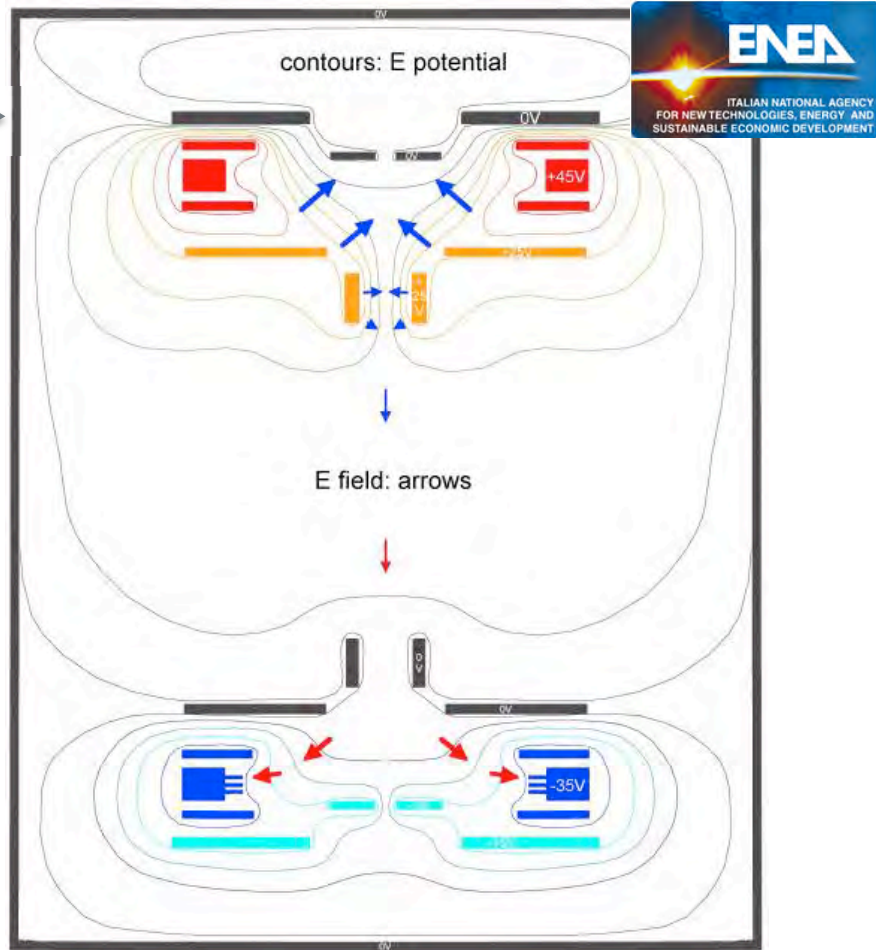
$V_{PF2-3low} \sim 0 \text{ V}$

$V_{cathode} \sim -35 \text{ V}$

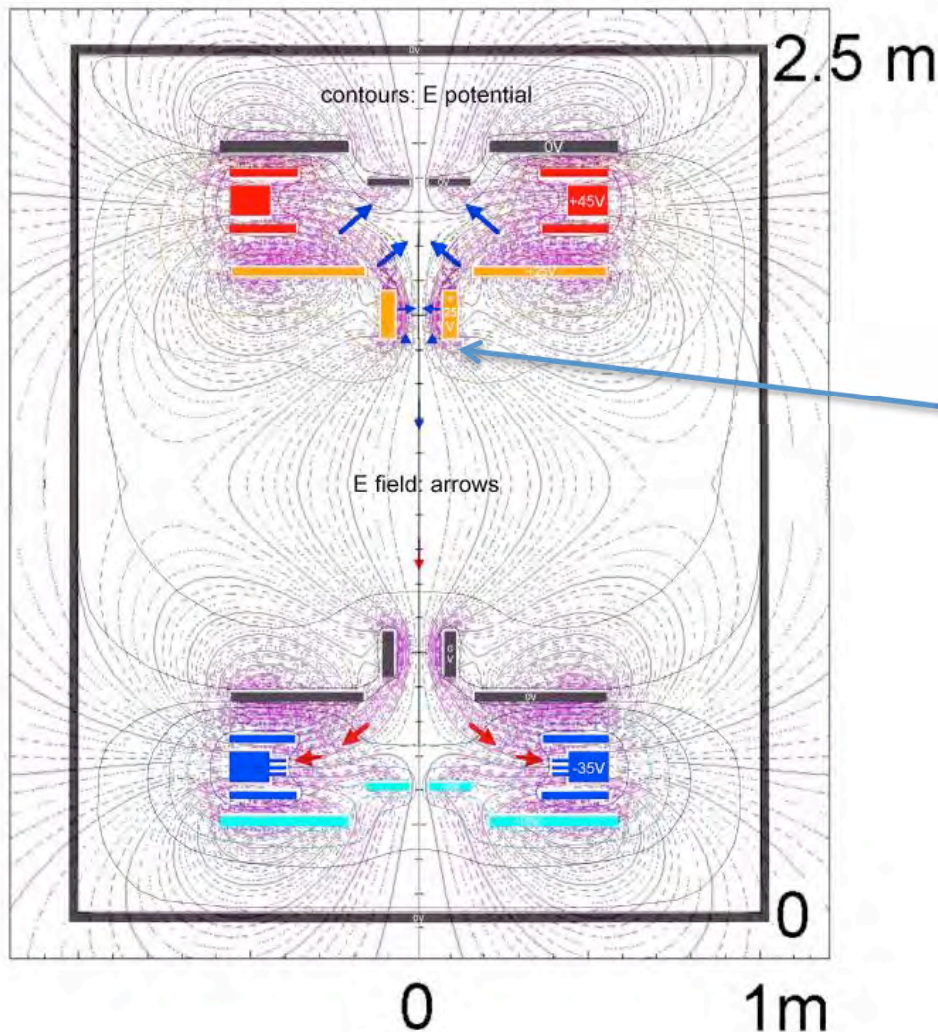
$V_{PF4low} \sim -15 \text{ V}$



PF2\3low to GND (1Ω)\PF4low cathode (0.5Ω)



distribution of **electric potential** is not up-down symmetric: near both anode and cathode the uppermost PF coil casings is at GND



Plasma-induced **electric potential**
near the **annular anode**:

E-field is perpendicular to B-field
... **$E \wedge B$** azimuthal plasma rotation
...starting from PF2up throttle

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

Plasma-induced **electric potential**
near the **annular cathode**:

E-field is parallel to B-field
...no **$E \wedge B$** plasma rotation

*self-organization at work inside
annular electrodes plasma...*

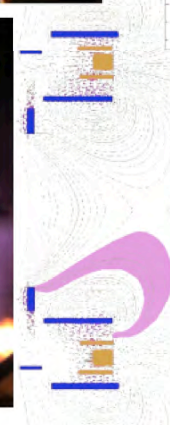
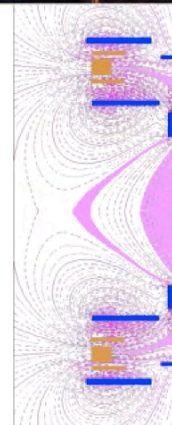
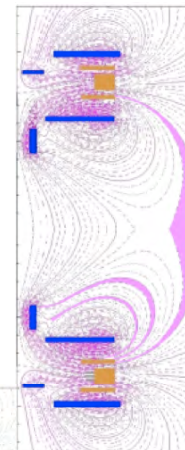
May 2015 annular anode experiment
half of the plasma current: (1kA\2kA)
was going around the required path due to
equatorial X-point inside the vessel



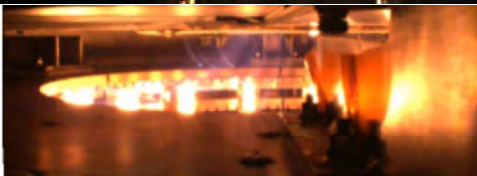
Argon plasma



Hydrogen plasma



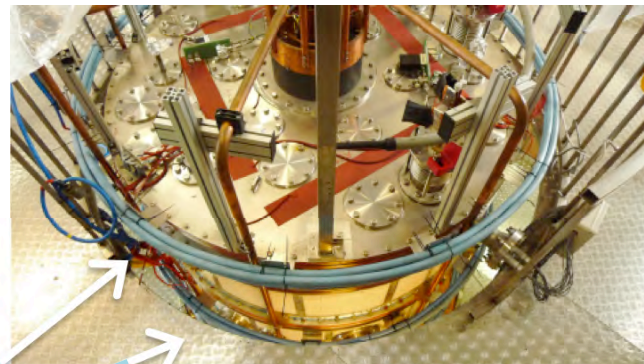
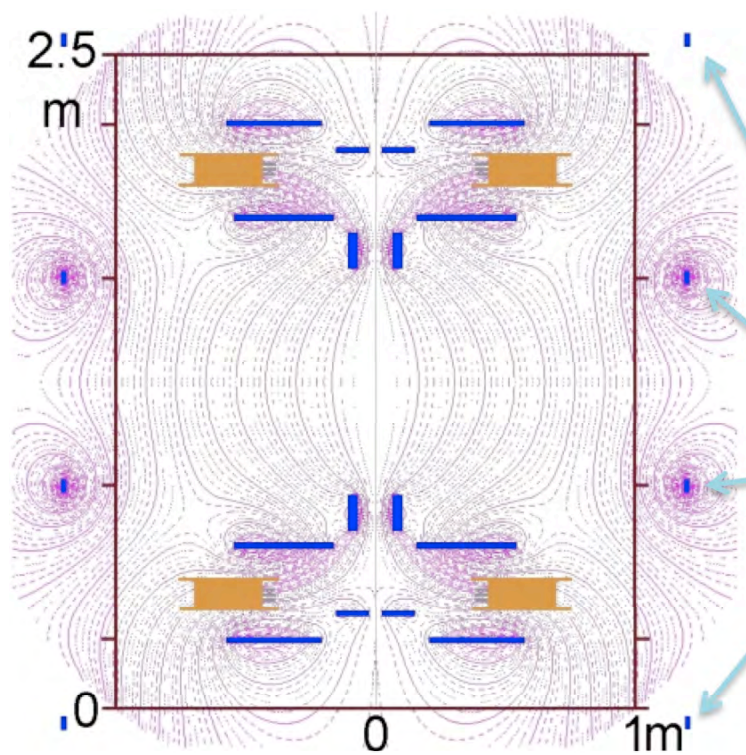
Shot 78



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)



4 additional external PF coils

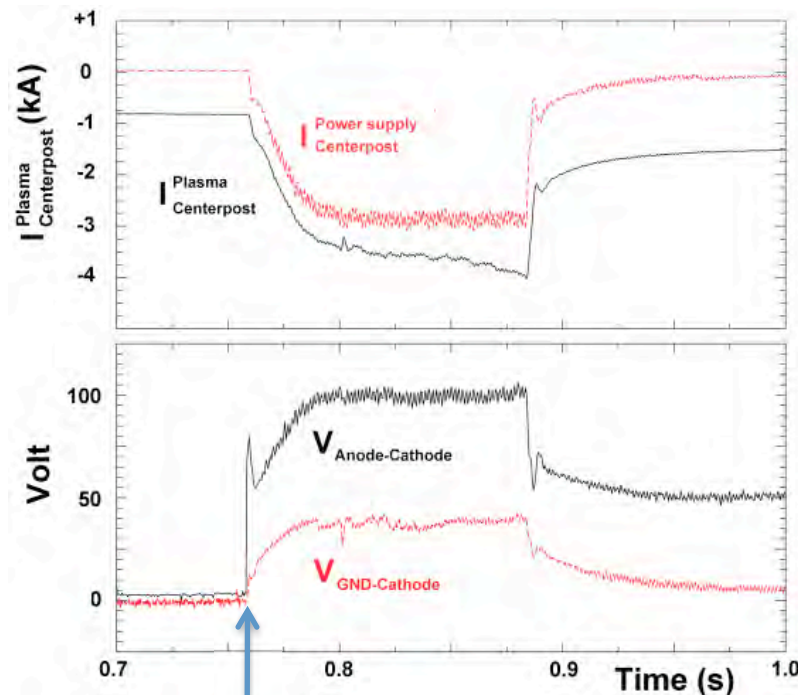


plasma fired after 0.75 s of PF current to allow for skin current diffusion in Al vessel and SS lids

October 2015 experiments with external PF:

Argon discharge reaching 3 kA for 0.15 s

the whole plasma current runs through both PF2 throttles

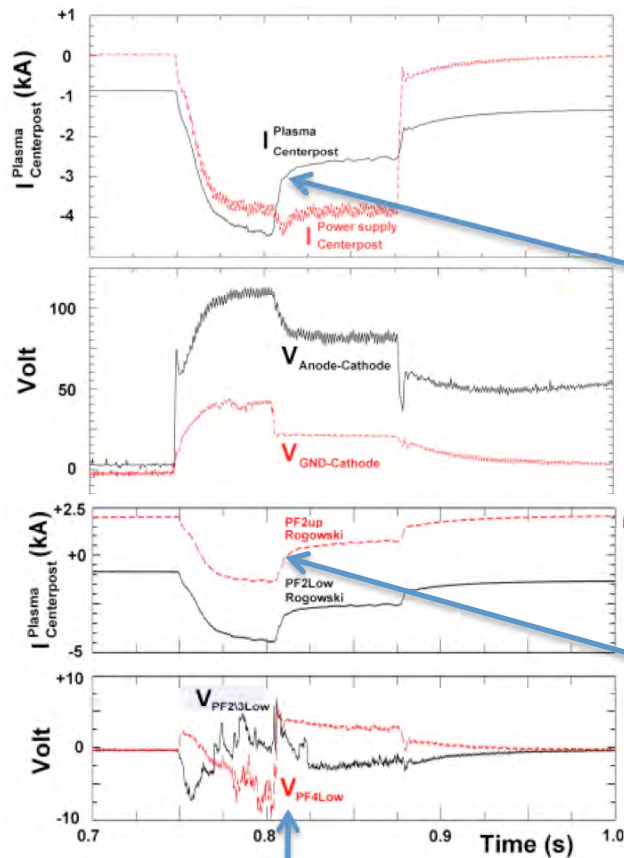


Shot 205

plasma fired after 0.75 s of PF current

(skin current time to remove X-point from inside vessel)

Plasma current outer paths for $I > 3$ kA



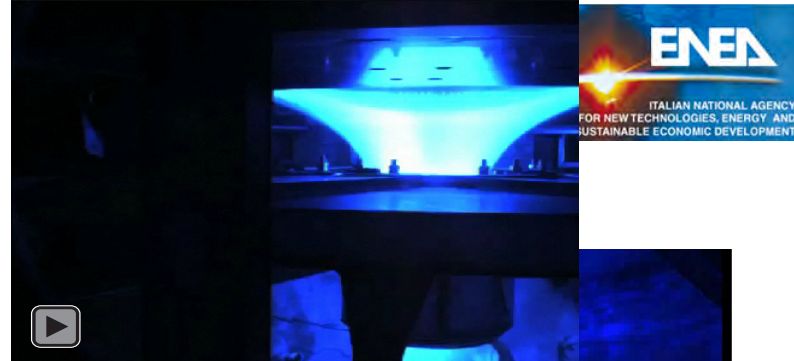
Argon plasma
aiming to 4 kA
reaches 3.5 kA

~ 1.5 kA lost
from main plasma

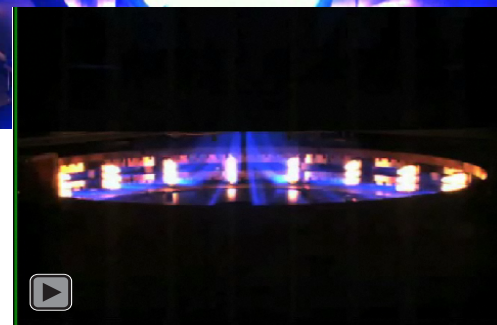
in discharge from
cathode down to
lid\ vessel

plasma current
lost on both
PF2 throttles

10 V spikes appearing on floating voltages on lower PF coils
are associated with plasma current outer path



Shot 208

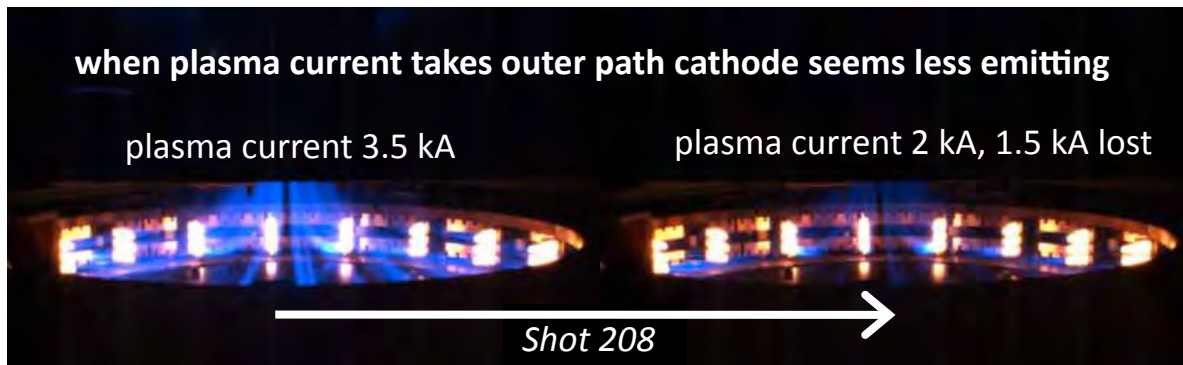


Magnetic tailoring in order to have a better filling of electrodes

when plasma current takes outer path cathode seems less emitting

plasma current 3.5 kA

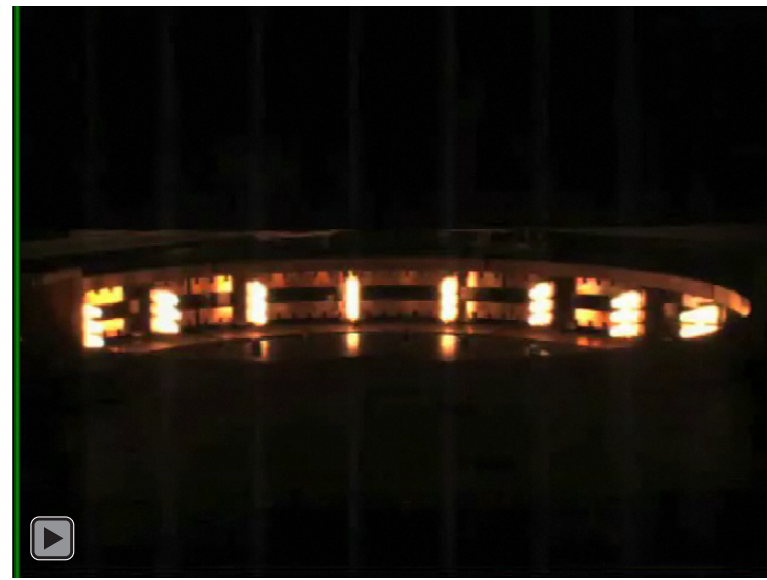
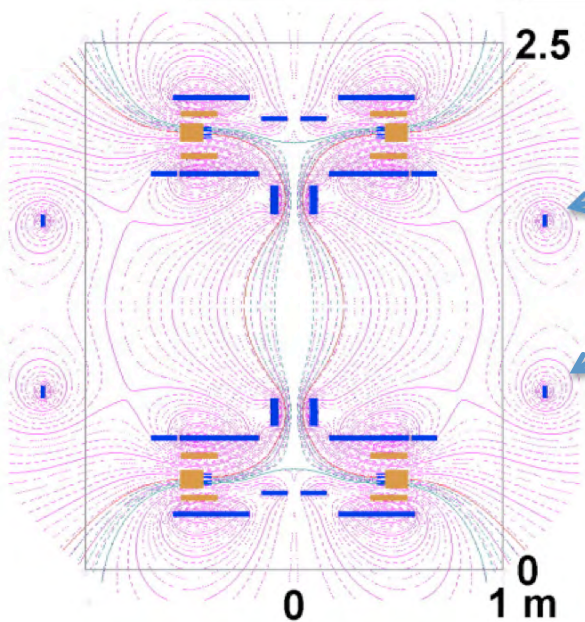
plasma current 2 kA, 1.5 kA lost



Shot 208

2.5 m current flows only in external PF near equator

Shot 227



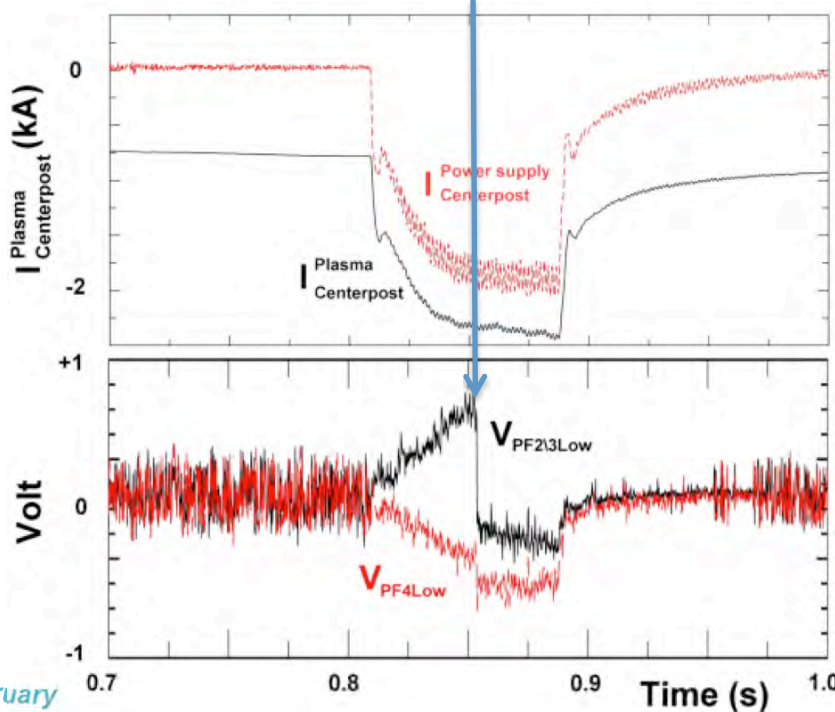
Straighter grounding of lower PF coils and better filling of cathode flowing current only in the two external PF coils nearer to equator

Argon discharge at 2 kA Shot 227



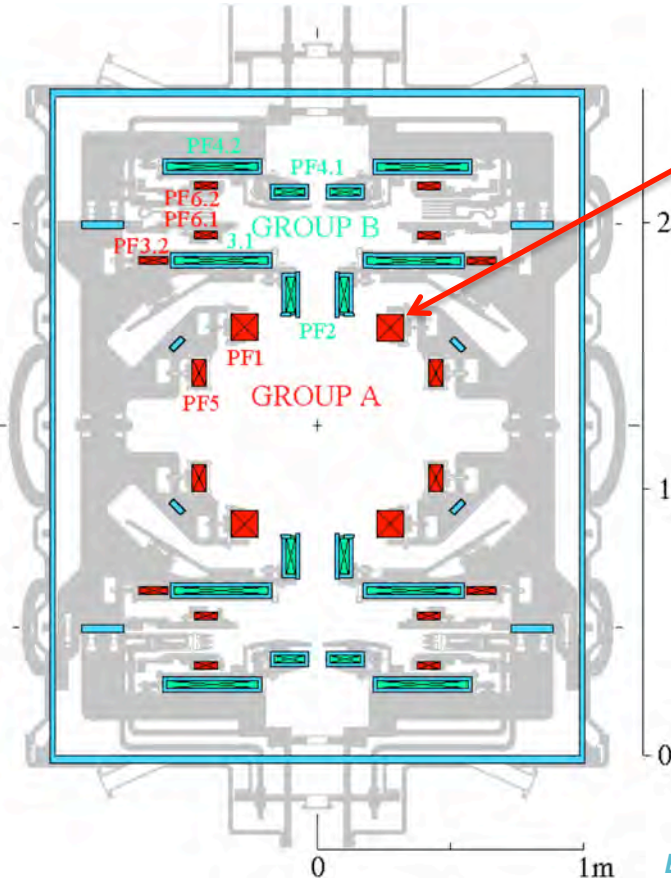
voltage spikes have been eliminated on PF2/3low,
after 1 V amplitude jump even small sparks vanish

voltage jump does not lose plasma current
very quiet plasma at 2 kA after voltage jump



*To be build after 10 kA
plasma centerpost achieved*

- Spherical Torus Compression PF Coils
- 324 W filaments (full filling of cathode)
- Final Power supplies



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)

Replica of existing (all replaced) cost ~ 0.2 M€

Final Power Supplies for:

- | | |
|--|--------------------|
| 1) Group A PF coils | cost ~ 0.1 M€ |
| 2) Cathode (I_{cath} 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

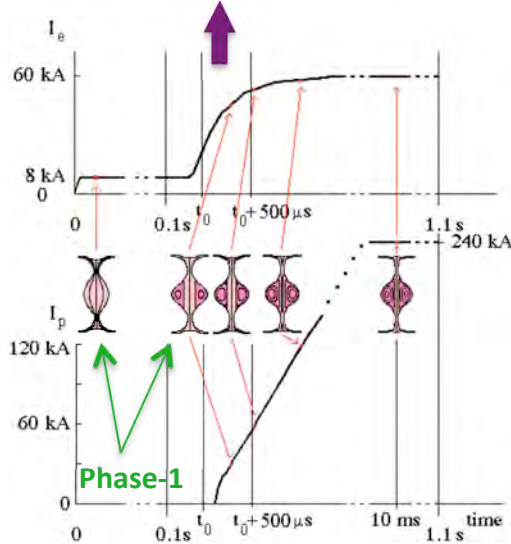
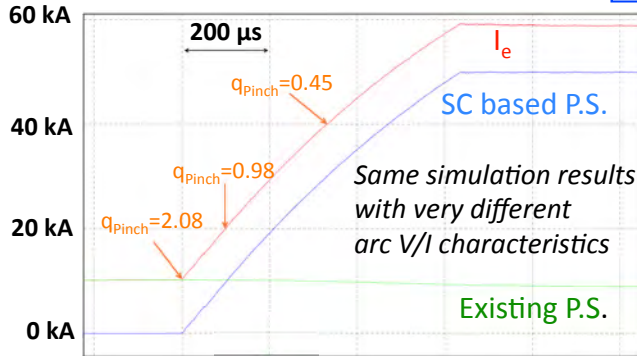
Cost up to now ~ 2.0 M€

Cost for final stage of experiment ~ 1.6 M€

PROTO-SPHERA power supplies: SuperCapacitors will be used

G. Maffia et al., IEEEIC 2015, Rome

Screw Pinch



Cost $\approx$ 0.6M\$

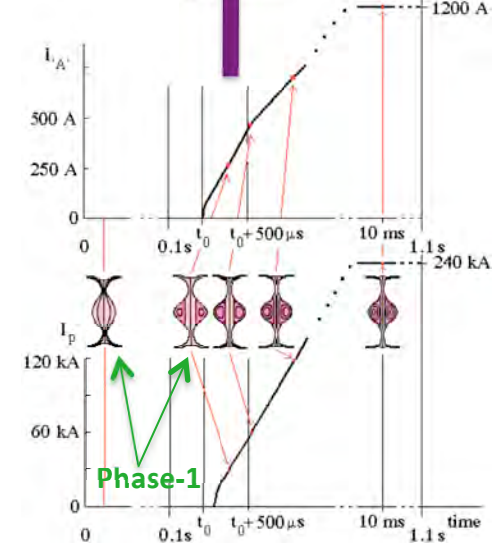
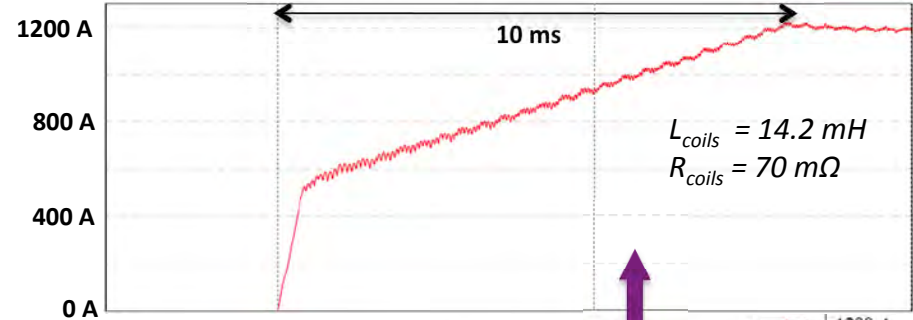
Maxwel Technologies SC (C=63 F, V=125 V)

Advantages:

- No connection to 20 kV substation and no step-down transformers
- Standard SCR Controller (no thyristor bridges)
- Very reduced cost!

For the "PF coils A" P.S. a small conventional capacitor bank (Ducati) must be added

PF coils 'A'



Cost: less than 0.1M\$

20 years after 2nd ST Workshop – Princeton (1995) the “aggressive proposal” PROTO-SPHERA is producing its first centerpost plasmas ...*better late than never!*

Hollow anode surprise, no anode arc attachment (electrostatic potential, $E \wedge B$ plasma rotation)

(1/3) of the due current (10 kA) achieved, 3 kA sustained in Argon plasma

To achieve full current of 10 kA requires patient learning of how to tailor boundary conditions:

- electrostatic potential by connecting PF coils casings, built floating with respect to the vessel
- magnetic field by additional coils external to the vessel
- new Anode/Cathode “feed through” flanges in Polycarbonate, *now in progress*

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 only an appetizer for the production of the Spherical Torus

...放龙入海!

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

PROTO-SPHERA will assess a new magnetic confinement configuration

- simply connected (easier construction & maintenance)
- with high plasma beta (minimal geometrical size)
- sustained by helicity injection

PROTO-SPHERA can develop this program:

at very modest costs ($\sim 1.6\text{M€}$); in a flexible way (new components can be easily added)

Final PROTO-SPHERA will be much more demanding in manpower and effort than the present phase-1 of PROTO-SPHERA with Centerpost plasma only

Will be an experiment even more challenging than START was for Culham

- ***with sophisticated control requests (very fast rise of currents for Torus formation)***
- ***with demanding diagnostic requests***
- ***challenging physicists, engineers and technologists creativity with its adaptability***

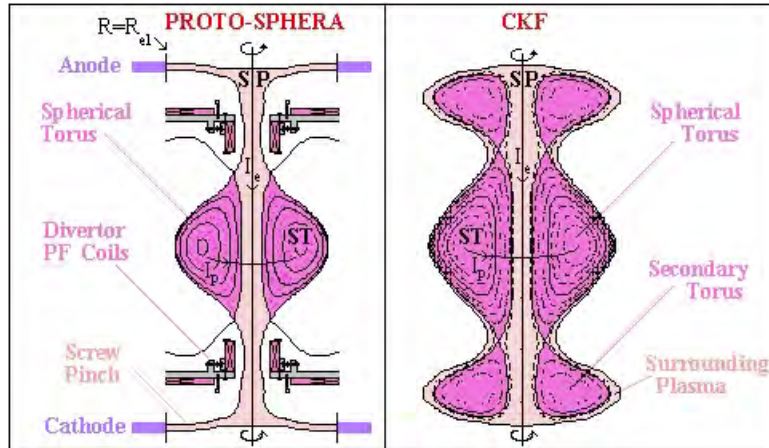
CKF configuration: a possible evolution of PROTO-SPHERA

Degenerate X-point on PROTO-SPHERA anode is a nozzle?



2015 experiment

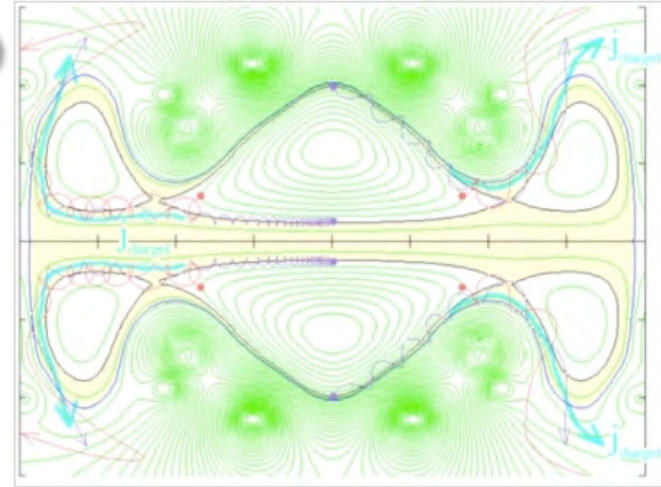
CKF found to be ideally MHD stable up to $\beta=1$
...promising for future fusion space thrusters?



PROTO-SPHERA: a CKF whose *Surrounding Plasma* terminates upon electrodes and whose *Secondary Tori* are substituted by PF2/3 poloidal field coils



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

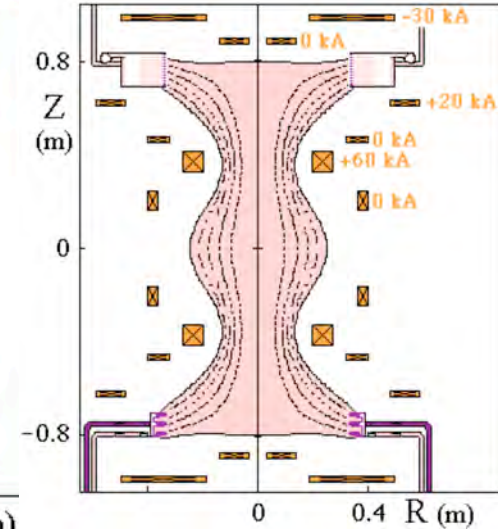
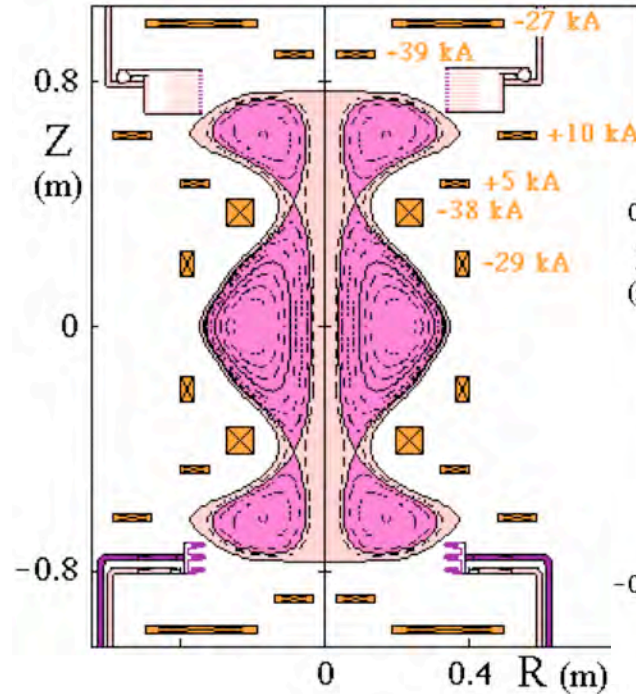
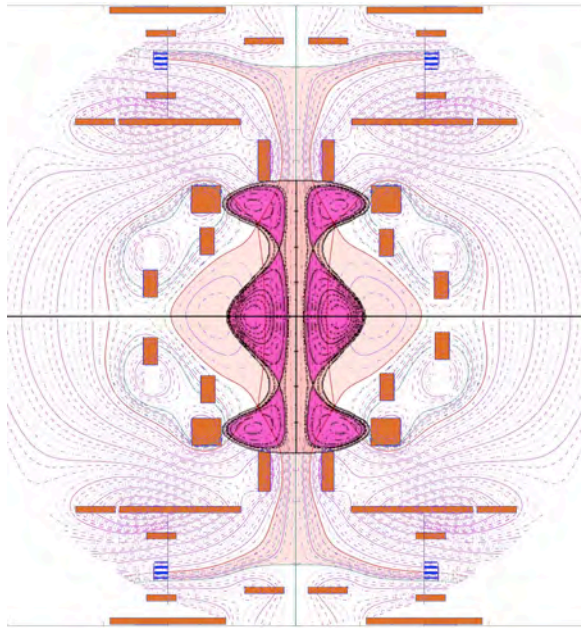


How to drive the ST current?
In a D-He₃ reactor the co- & counter-circulation of charged fusion products could produce the sustainment current of the surrounding plasma...

CKF configuration: a possible evolution of PROTO-SPHERA

(CONTINUE...)

PROTO-SPHERA load assembly could in principle accommodate a CKF, with some changes, in order to investigate formation, stability and β level before the resistive decay



**A pair of new coils, same electrodes:
smaller but hotter?**

**Same coils, new electrodes:
bigger but colder?**

Having produced a plasma, albeit only the centerpost one, we finally got our star at the 2015 Princeton International Spherical Torus Workshop!

