Perspectives of the PROTO-SPHERA experiment

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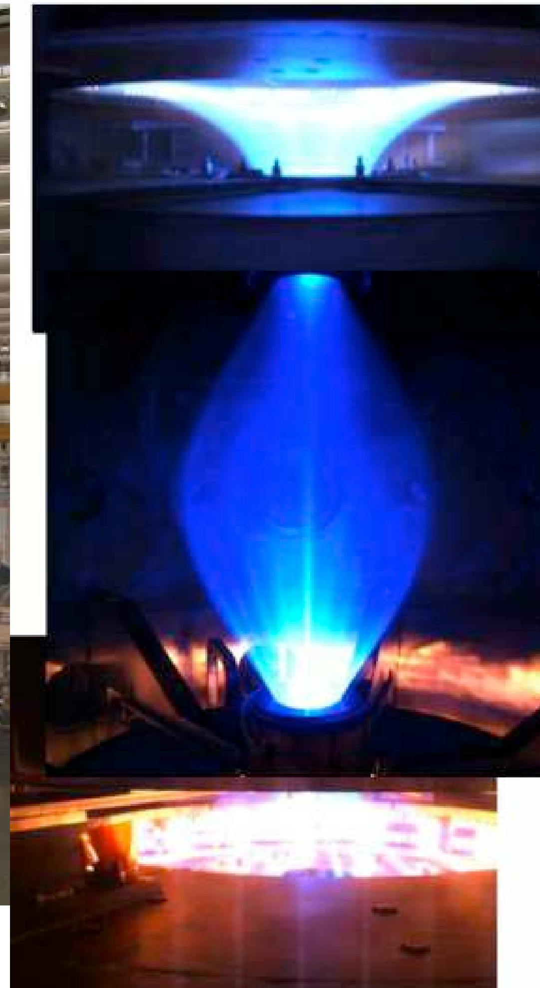
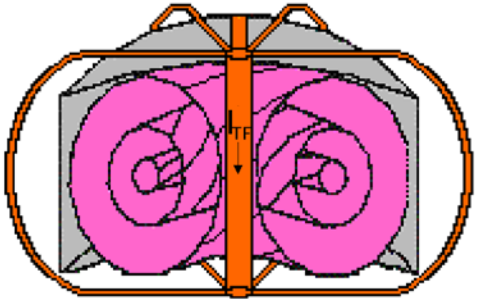




Spherical Tokamaks allow to obtain:

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

But, for a reactor/CTF extrapolation:

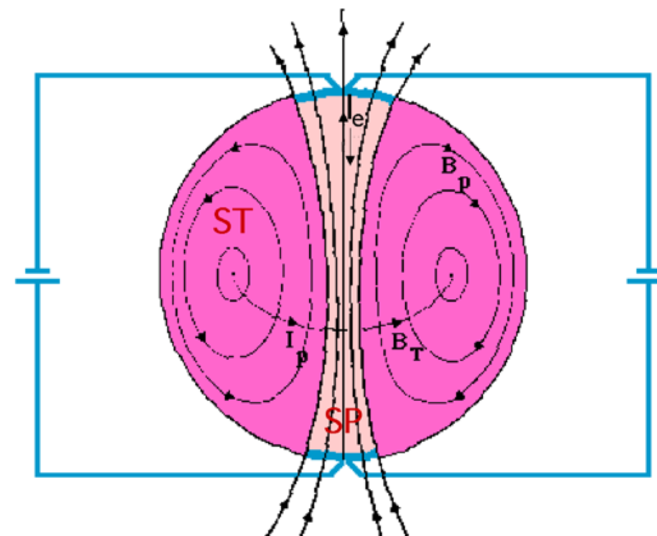
- No space for central solenoid (Current Drive requirement more severe)
- No neutrons shield for central stack (no superconductor/high dissipation)

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

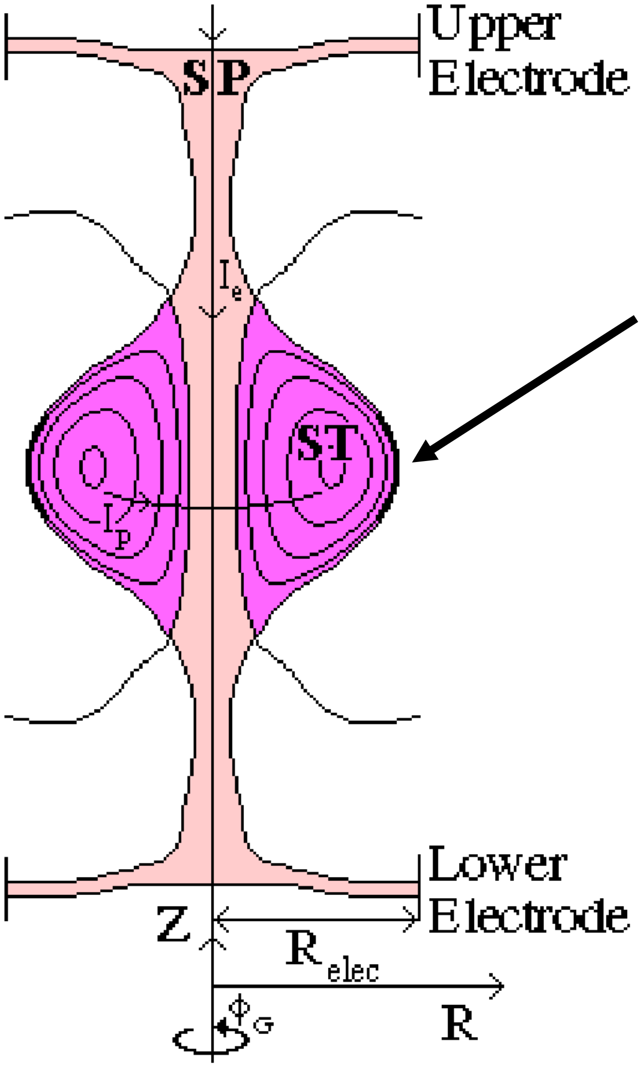
Potentially two problems solved:

- 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≤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≥1.2, κ=b/a~2.3) to get a Tokamak-like safety factor (q_0≥1, q_{edge}~3)

SP electrode current	I_e=60 kA
ST toroidal current	I_p=120÷240 kA
ST diameter	R_{sph}=0.7 m

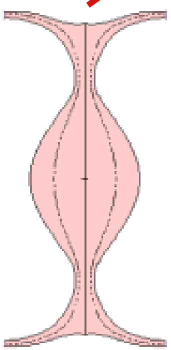
⇓

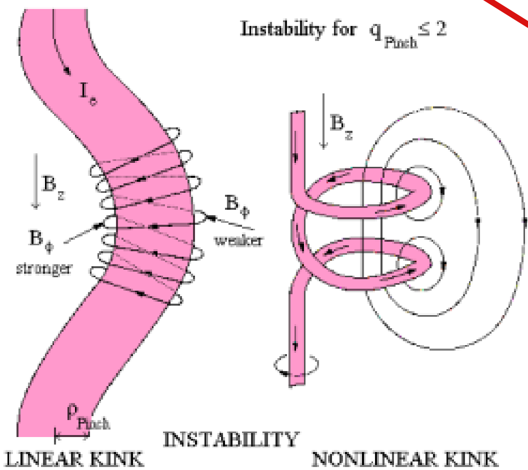
Stability should be improved and helicity drive may be less disruptive than in conventional Flux-Core-Spheromak

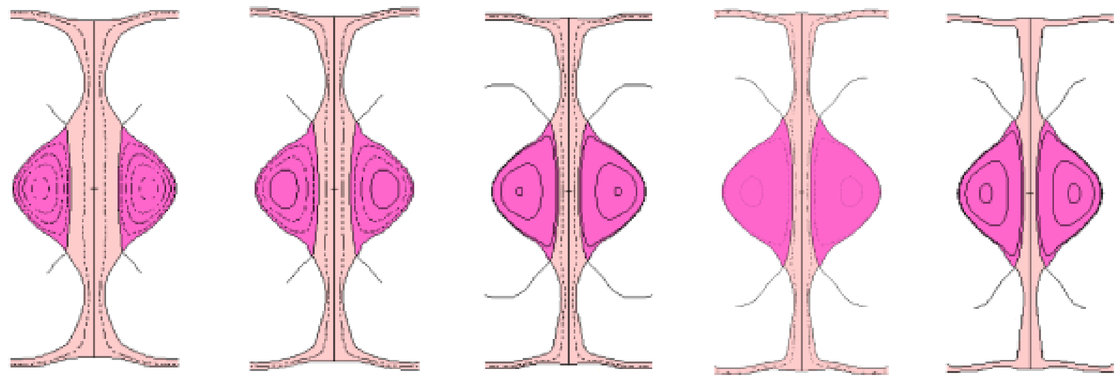
PROTO-SPHERA formation follows TS-3 scheme (SP kink instability)

Tunnelling (ST formation)

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







T0
I_e=8.5 kA

I_e 8.5→60 kA

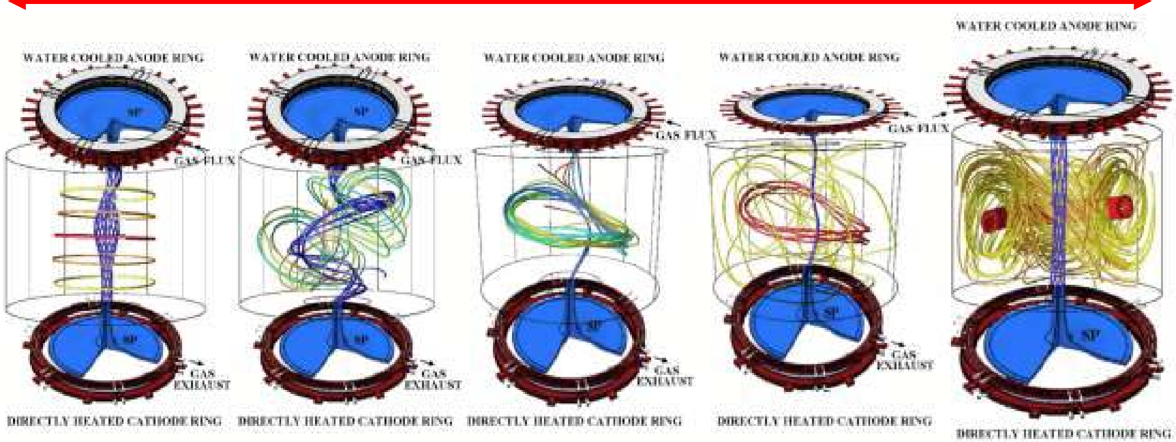
T3
I_p=30 kA
A=1.8

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 τ_A~ 0.5 µs

Resistive diffusion time τ_R~ 70 ms

$(\tau_R \tau_A)^{1/2}$~ 1 ms for I_{ST}=120 kA (2xI_e)

Courtesy by Farengo
(ISTW2008 - Frascati)

Smoke-ring-like formation

Key points of PROTO-SPHERA design

• Stable Screw Pinch formed at Tokamak pressures ($10^{-3} \div 10^{-2}$ mbar) and 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
monotonic
as well as
reversal safety factor profiles

⇓

magnetic configutation is quite robust

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 analisys to assess I_p/I_e & β limits

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

⇓

• **Stable at β 21÷26% for I_p/I_e=0.5, down to 14÷16% for I_p/I_e=4**
Comparing with the conventional Spherical Tokamak with central rod:
β_{T0}=28 ÷29% for I_p/I_e=0.5 to β_{T0}=72 ÷84% for I_p/I_e=4

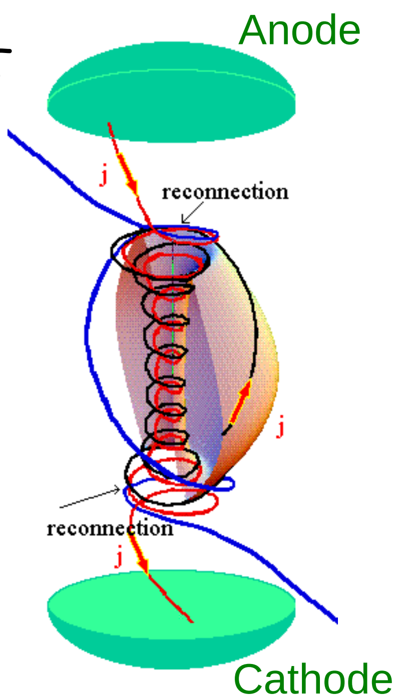
• **Spherical Torus elongation κ plays a key role in increasing I_p/I_e**

• **Comparison with TS-3 experimental results:**
disk-shaped SP plasma important for the configuration stability

Critical points of PROTO-SPHERA

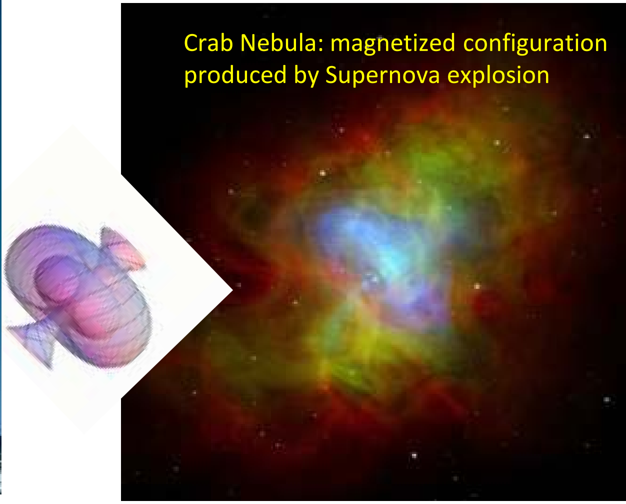
Helicity Injection to sustain the plasma torus:
driven relaxation of Plasma Central Column forms & sustains the ST

- electrode plasma - open field lines - has $\vec{\mathbf{j}} \;//\; \vec{\mathbf{B}}$
- the open field lines also wind toroidally
- magnetic reconnections convert open $\vec{\mathbf{j}}, \vec{\mathbf{B}}$ lines into closed $\vec{\mathbf{j}}, \vec{\mathbf{B}}$ lines winding on a spherical torus



- **I_{ST}= 240 kA ($4xI_e$) really achievable?**
- **Can it be sustained by H.I. for at least τ_R~ 70 ms?**
- **Resistive MHD stability & confinement?**

"Smoke-ring like self-organization"



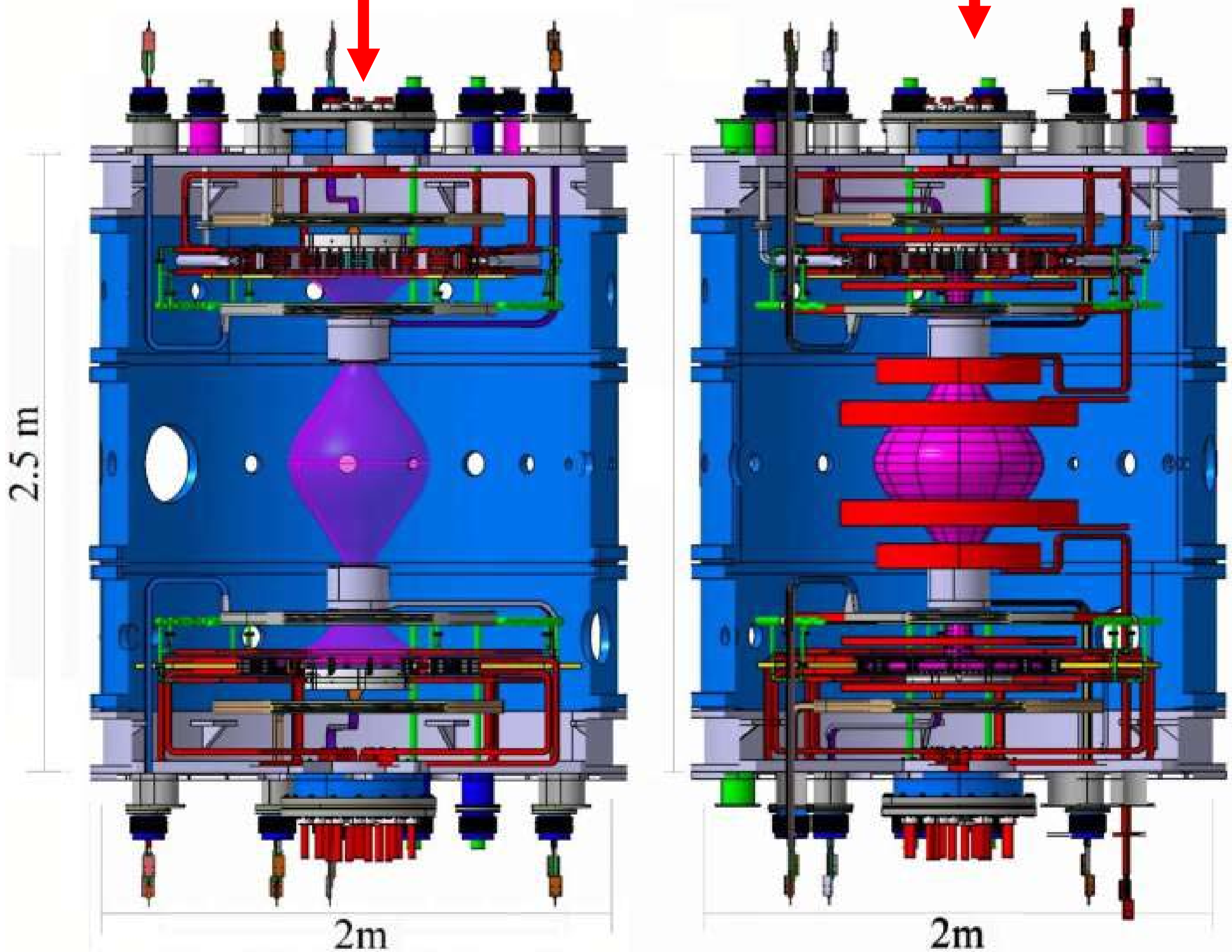
Proto-Sphera Phase1 (Multi-Pinch)

Aims:

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

Proto-Sphera

(All parts will be reused)

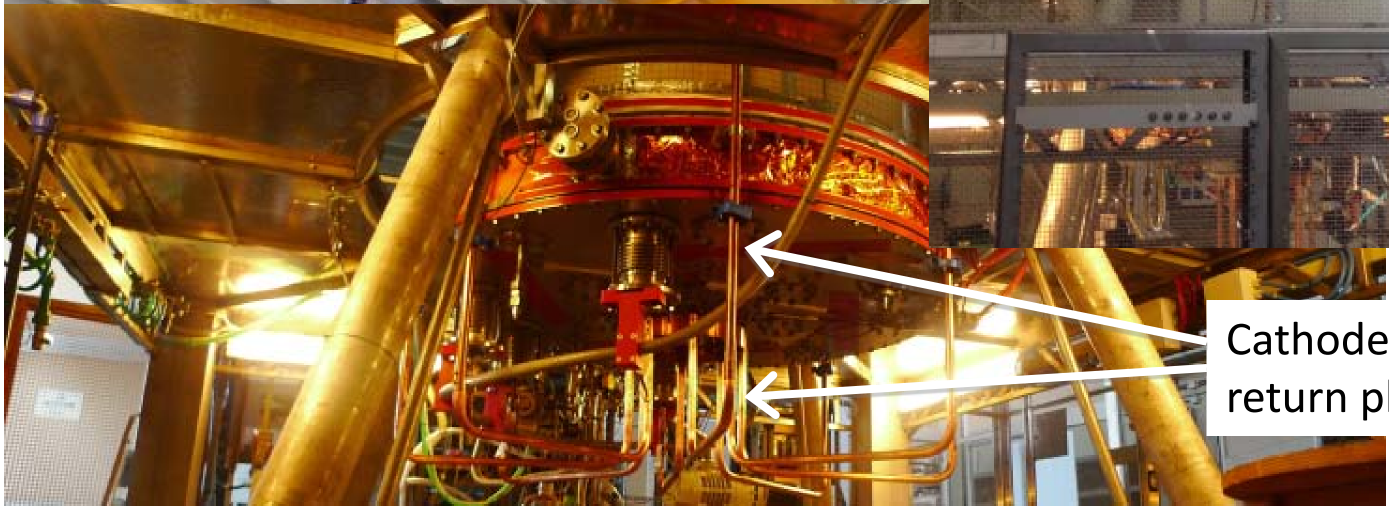


By adding:

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

Assembly of the anular anode on the machine (May 2015)

ENEA
ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT



Cathode feeder bars and return plasma current rods

Proto-Sphera Phase1 preliminary results

(*Much more details on F. Alladio presentation*)

Anodic plasma

Plasma Central column

Cathodic plasma

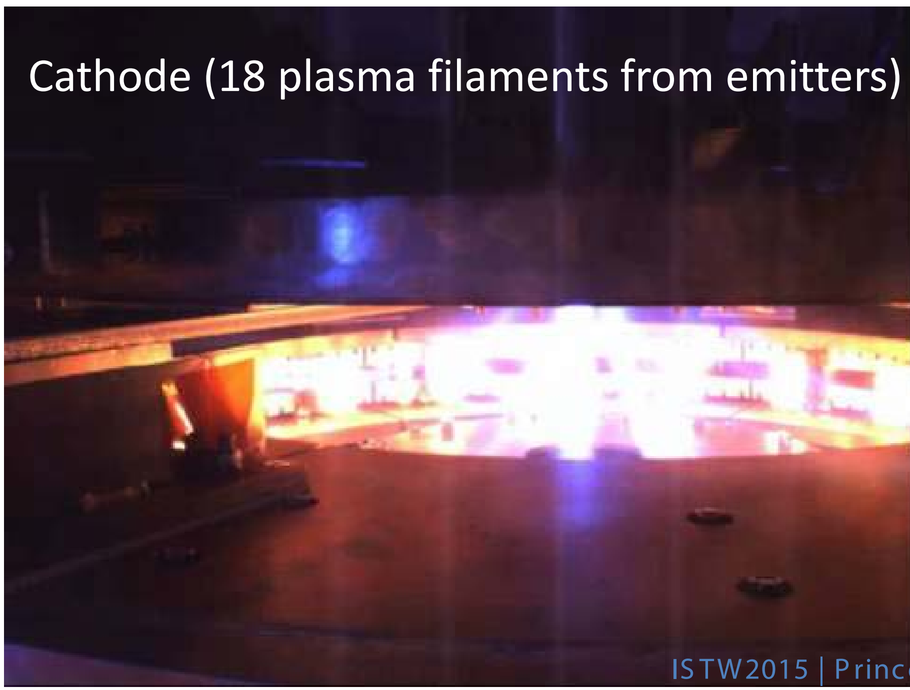
- $I_e \approx$ 3 kA for about 300 ms
- More than 500 shots without any damage on cathode W filaments

But there is a problem… wrong path on the external part of vacuum vessel

Proto-Sphera Phase1 preliminary results

(*See F. Alladio presentation*)

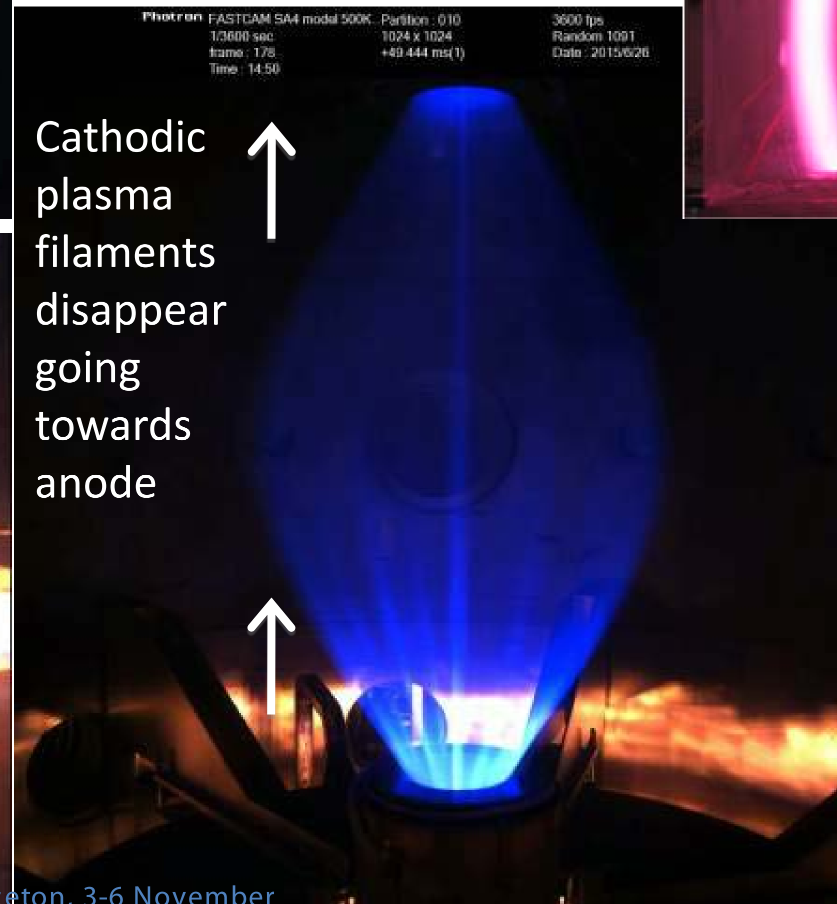

Anode (no plasma filaments)


Cathode (18 plasma filaments from emitters)

The major risk...

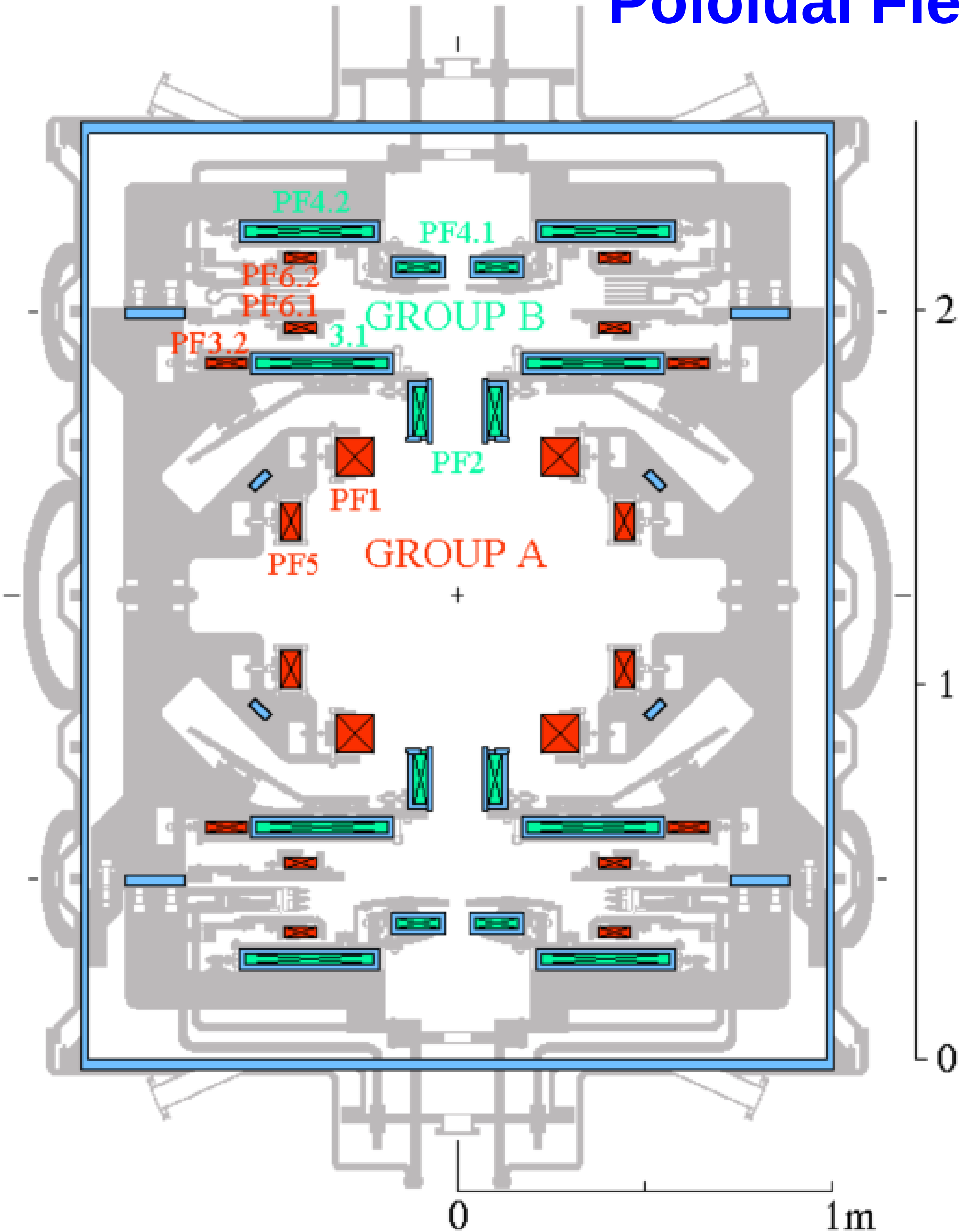
Anodic anchoring of arc discharges

On the contrary in PROTO-SPHERA... due to favourable **E x B** effect...



Cathodic plasma filaments disappear going towards anode

PROTO-SPHERA
Poloidal Field coils



Group A: ST compression coils (connected in series)
Not installed on Multi-Pinch

Characteristics:
- High voltage (~20 kV) insulation
- Thin Inconel casings to allow for fast **B** diffusion

Cost ≈ 0.5M$

Group B: SP shaping coils (connected in series)
Already installed on Multi-Pinch

Three new Power Supplies:

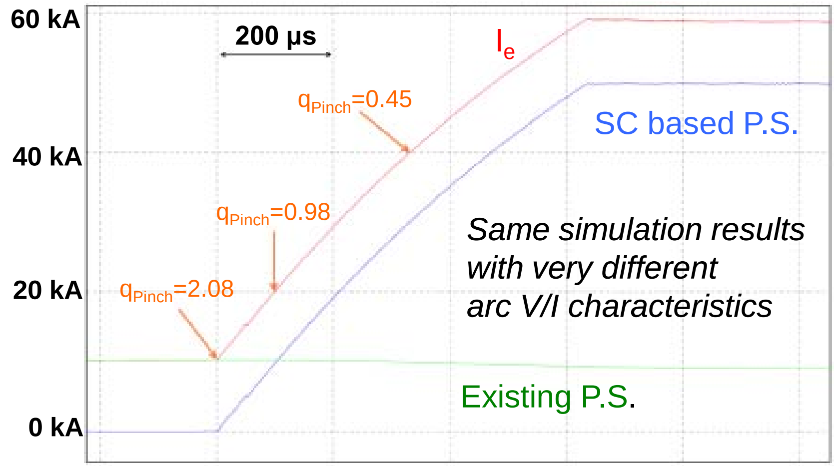
1)"Group A" (no on Multi-Pinch)

2)"Cathode" (reduced on Multi-Pinch)
implementation cost ≈ 0.2M$

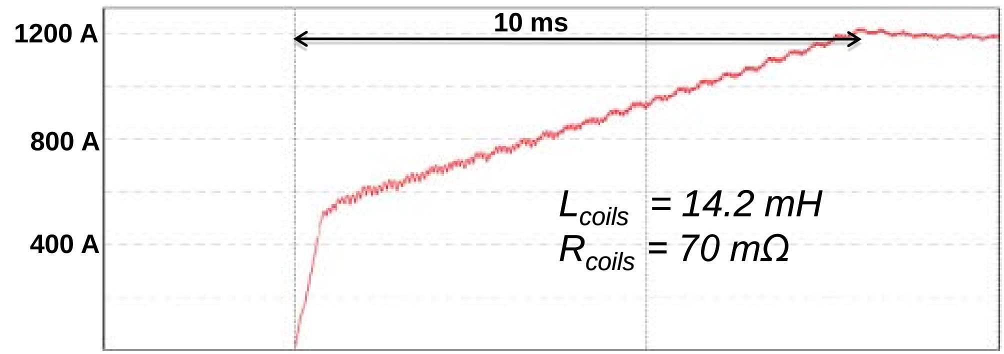
3)"Screw Pinch" (reduced on Multi-Pinch)

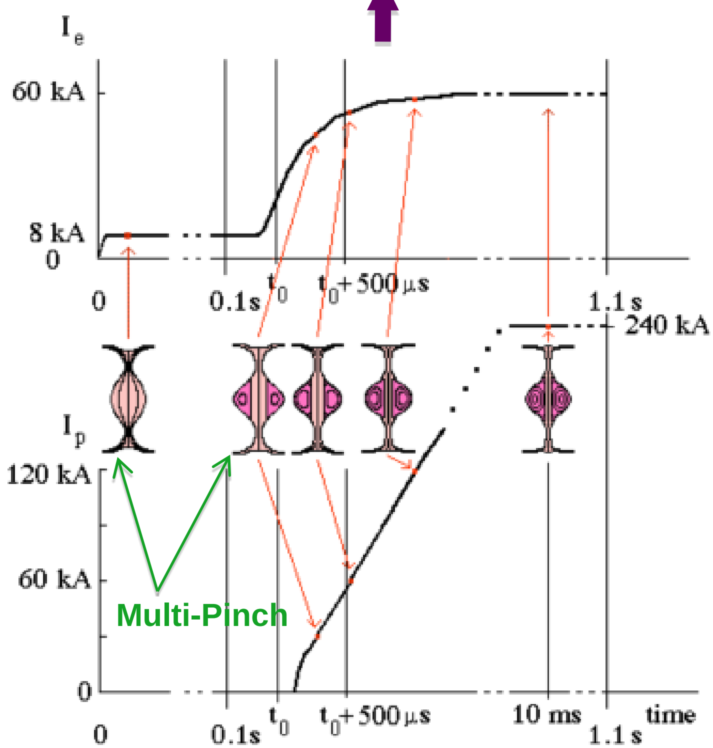
Proto-Sphera power supplies: *SuperCapacitors will be used*

Screw Pinch



PF coils 'A'





Cost ≈ 0.6M$

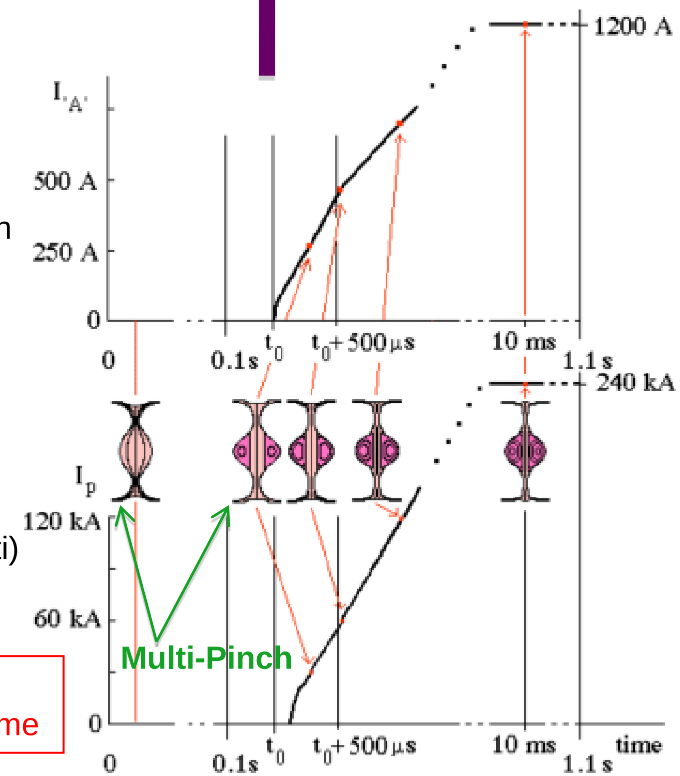
Maxwel Technologies SC (C=63 F , V=125 V)

Advantages:

- No connection to 20 kV substation and no the 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

Reference:
G. Maffia et al., EEEIC 2015, Rome



Cost: less than 0.1M$

Conclusions

Proto-Sphera Phase1 already solved the major concern: no anode arc anchoring!

The progress in SuperCondenser solves the major "technological" concern

If Central plasma column & Spherical Torus formation are successful

Proto-Sphera will allow to assess if magnetic configurations

- simply connected (construction advantages!)
- with high plasma beta (minimal geometrical size)
- sustained by helicity injection

can have further developments…

Proto-Sphera can develop this program:

at very modest costs (≈1.5M$);

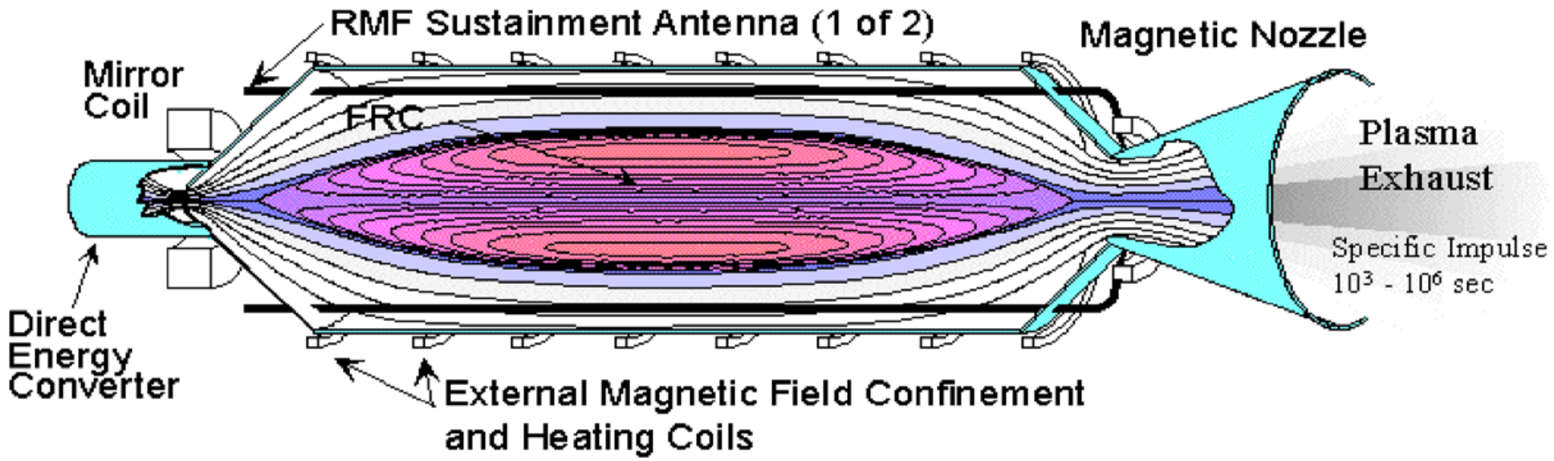
in a flexible way (easy to add-up new machine components)

Further developments…

"Open" structure of the magnetic field & simply connected configurations:

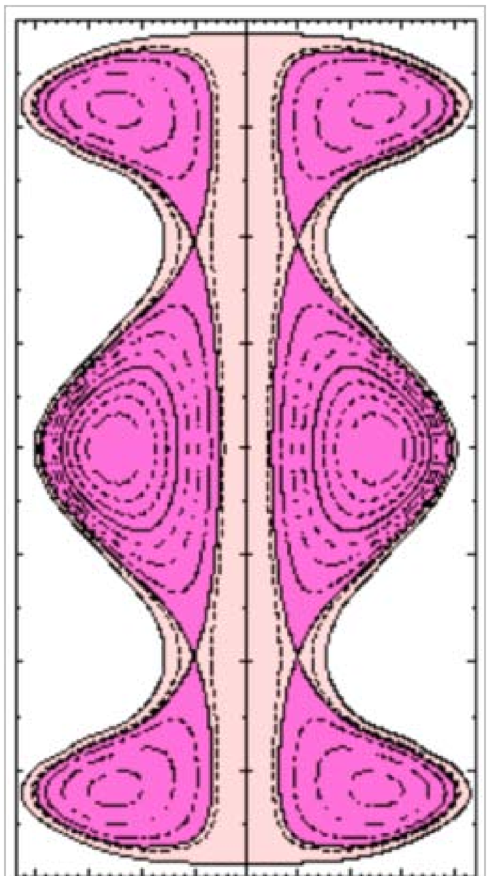
- Magnetic well inside the plasma at $\beta \approx 1$
- Confinement system with two "ends" : easy refueling/exhausting of plasma
- Emerging field lines ease the control of the electric potential within the plasma
- Recover from disruptions (plasma rebuilds from the open ends if there are electrodes)

A simply connected configuration is also more suitable for channeling particle jets and transforming fusion power into propulsive power (for space thrusters)



From University of Washington Star Thrust Experiment (STX)

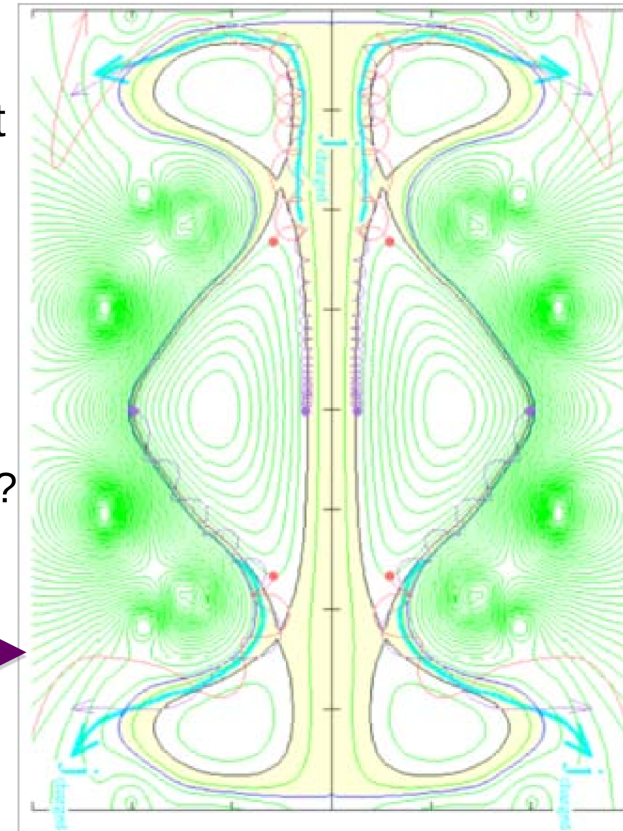
Further developments…



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

It has found to be
ideally MHD stable up to β=1
(same code of Proto-Sphera)
…promising for space thrusters

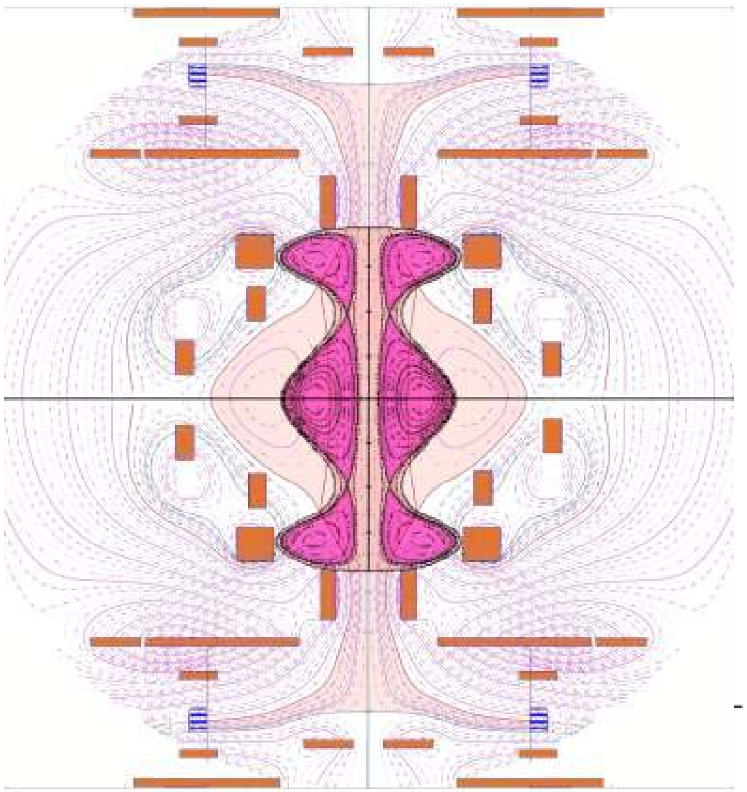
But how to drive the ST current?
In a D-He_3 reactor the fast
particle losses could produce
the "right" current on the
surrounding discharge…

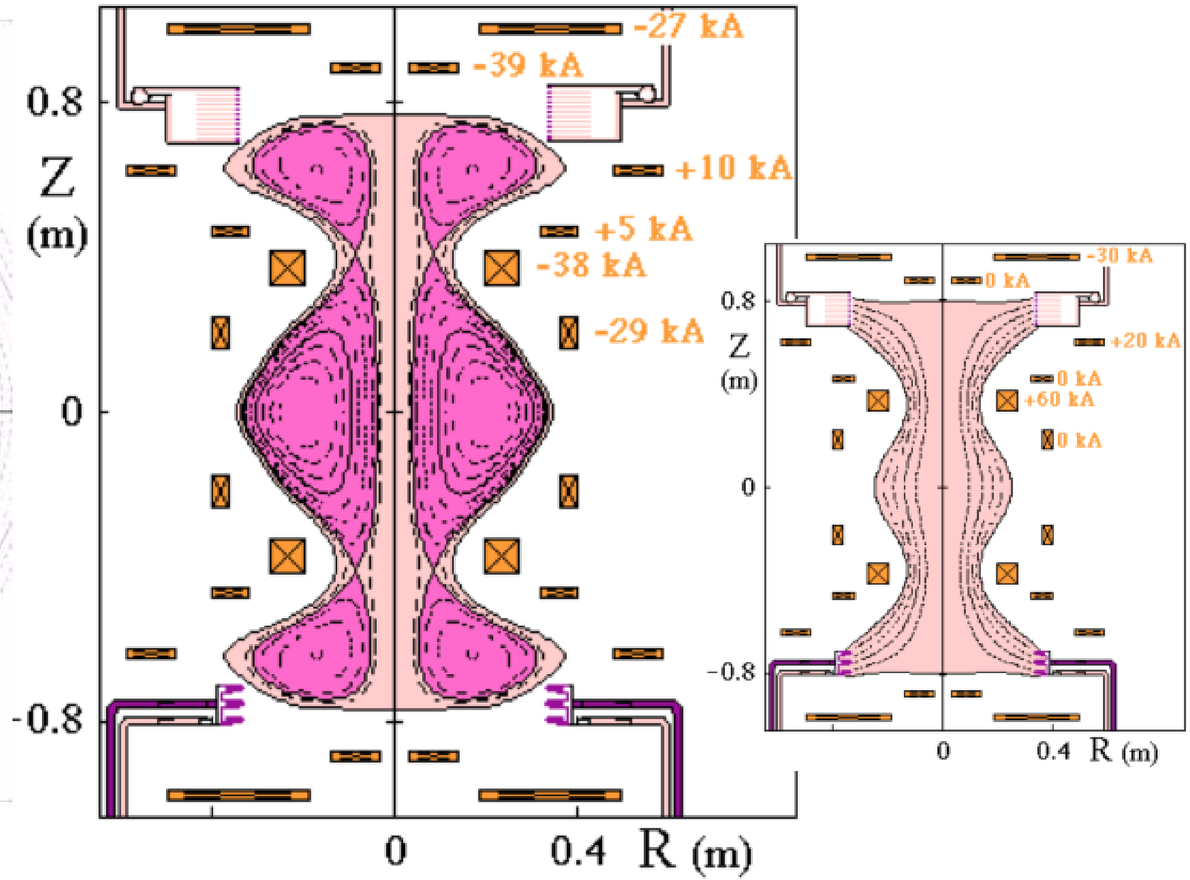


This mechanism could also help
in producing the SP current (I_e)
in a D-T reactor based upon the
"standard" Proto-Sphera configuration (β≈0.2):
SP dissipation is a crucial point…

Further developments…

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?