

PROTO-SPHERA: Formare e sostenere un toro di plasma con un'iniezione di elicita' quasi-continua

Franco Alladio, Paolo Micozzi, Alessandro Mancuso





Le tre presentazioni di oggi:

Le motivazioni:

Questa presentazione

La modellizzazione (**Paolo Micozzi**):

Ideal MHD Stability boundary of Proto-Sphera

La costruzione meccanica della macchina (**Alessandro Mancuso**):

Proto-Sphera Load Assembly

Sommario di questa presentazione:

La configurazione – un toro sferico formato da una ‘colonna centrale’ di plasma

Formare e sostenere la configurazione

Formare e sagomare in modo adeguato la colonna centrale (Multi-Pinch)

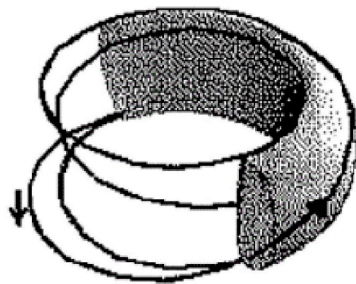
Tempi e costi del progetto

Oltre all’interesse di fisica del plasma, ha rilevanza per la fusione controllata?



The Spherical Tokamak (ST) is a magnetic confinement configuration that provides plasma β much higher than conventional tokamaks
The advantage stems from the nearly-geodesic lines of force in ST

Conventional Tokamak



High

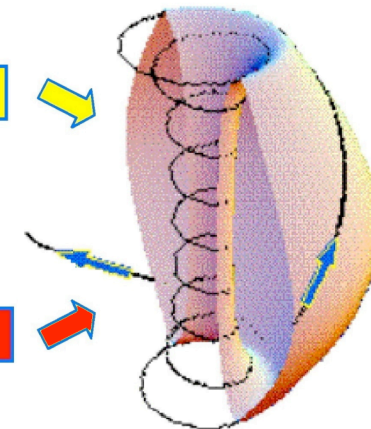
Low

Field in bad
Curvature region
&
Geodesic curvature

Plasma beta

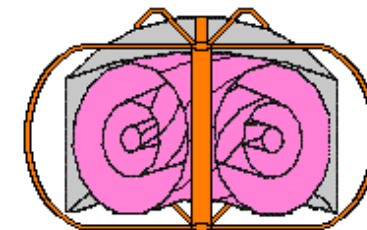
$$\beta = \frac{2\mu_0 p}{B^2}$$

Spherical Tokamak



Low

High

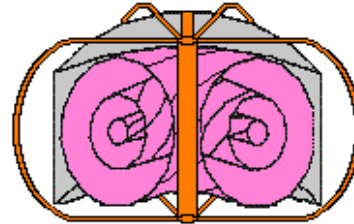


Severe space constraints for material center column:

- No space for central solenoid
- No neutrons shielding (no superconductor - high dissipation)

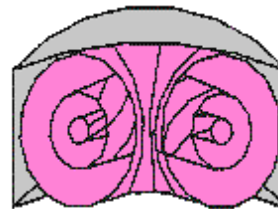


The most investigated magnetic fusion configurations are not simply connected:

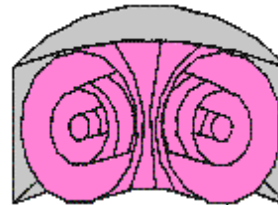


Compact Tori yield simply connected plasma configurations: Spheromaks and FRC's

Spheromak



FRC



Simply connected magnetic configuration strongly simplify the design of a reactor:

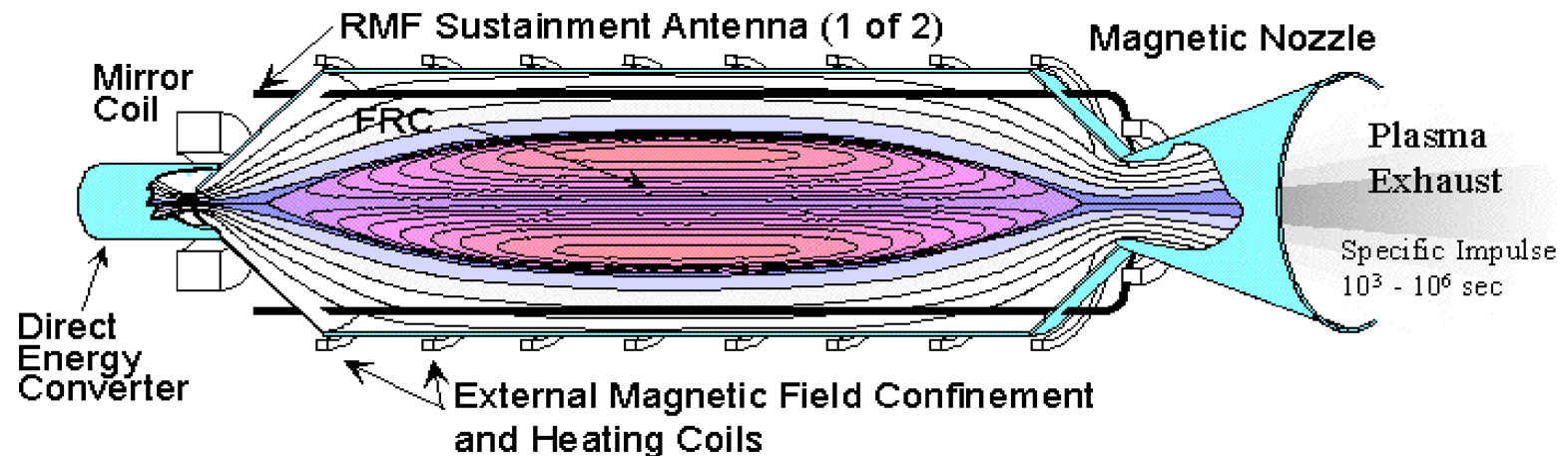
- Confining magnetic field (cylindrical solenoid)
- No damage and no maintenance of the critical central post
- Easy access to a cylindrical reactor chamber



"Open" structure of the magnetic field:

- Magnetic well inside the plasma ($\beta \approx 1$)
- Confinement system with two "ends" \ easy refueling/exhausting of plasma
- Emerging field lines ease the control of the electric potential within the plasma

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



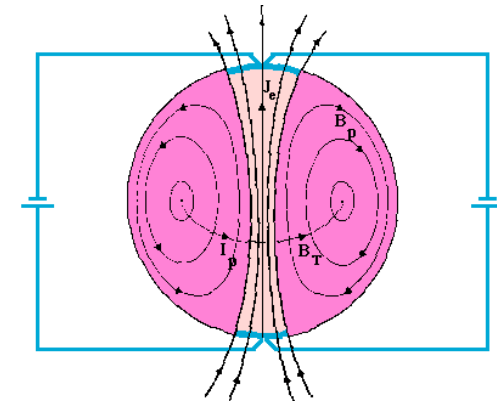
From University of Washington Star Thrust Experiment (STX)



PROTO-SPHERA¹: a plasma central column (ST-PCC)² Requires electrodes and plasma self-organization!

¹ F. Alladio, et al, NF 46 S613 (2006)

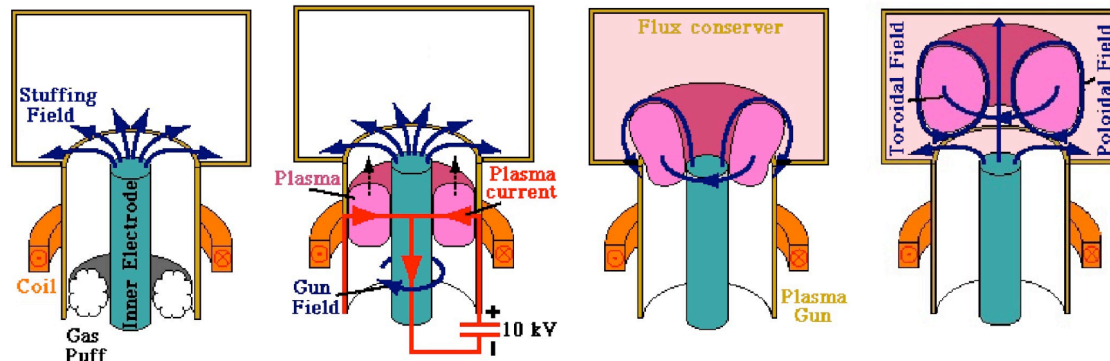
² S.C. Hsu and X.Z. Tang, J. Fus En. (2006) Complementary proposal- LANL



Plasma Central Column (PCC) FLUX-CORE-SPHEROMAKS

- injected by plasma guns,
- kV voltage on electrodes
- high pressure prefilling

have MHD safety factor $q \leq 1$



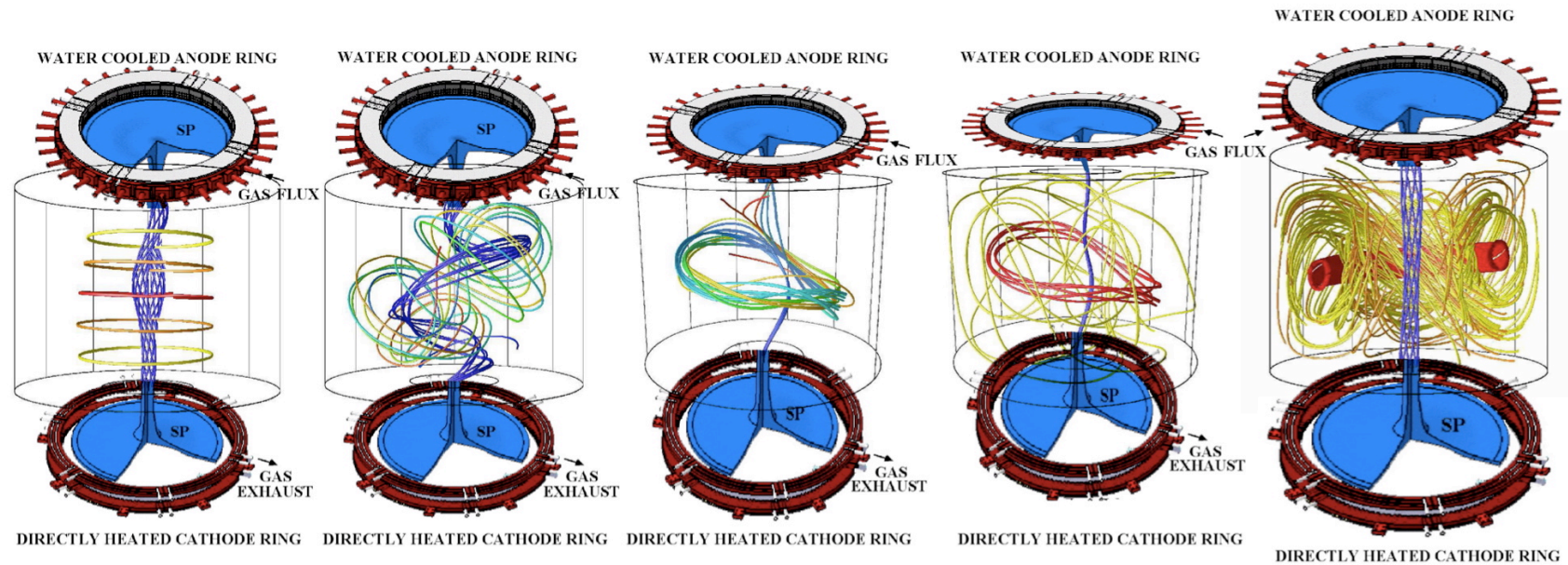
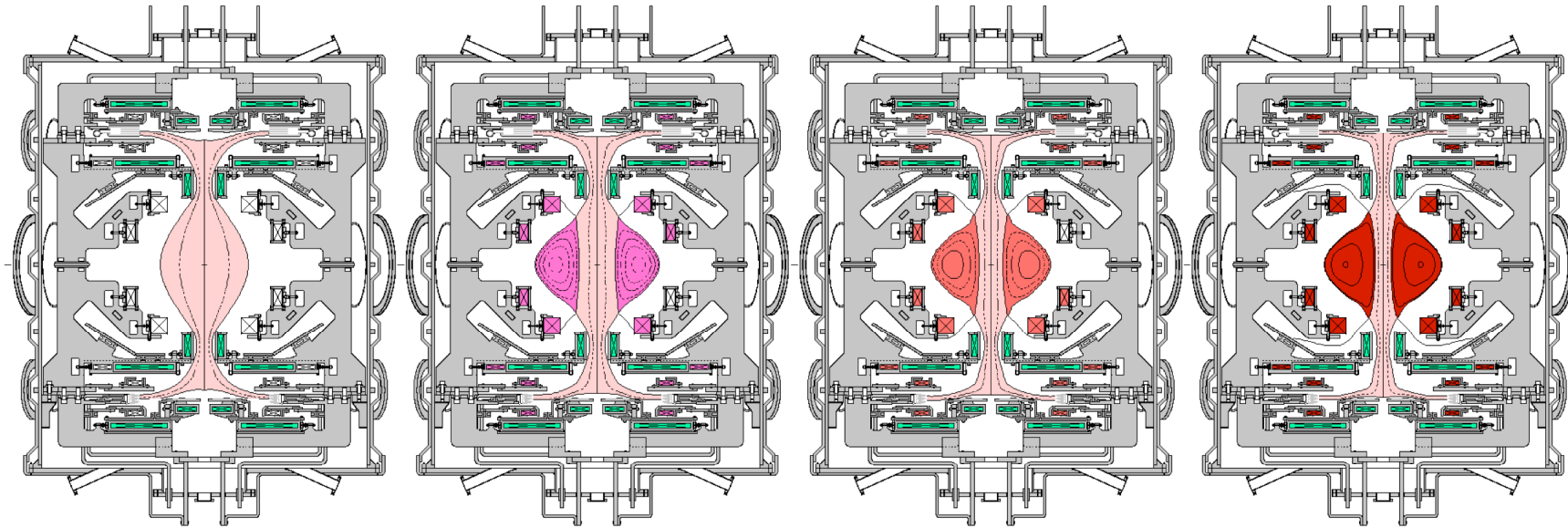
Breakdown in small spaces, with extremely high filling pressures and kV voltages

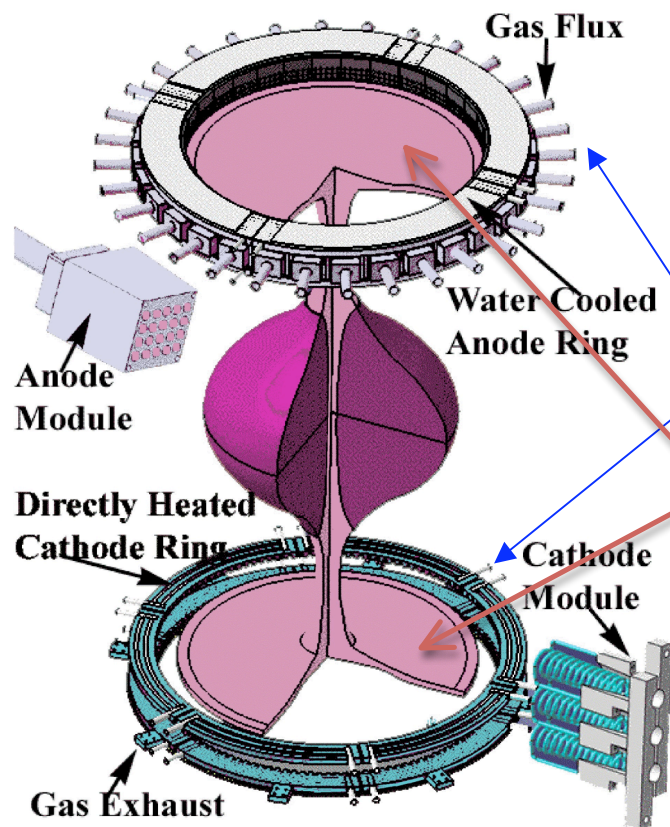
- Neutrals and impurities are released from the gun

After the formation, the Spheromak is accelerated and expanded into a flux conserver

- Field errors already present in the gun are amplified

**PROTO-SPHERA will form instead at tokamak-like densities,
with very low voltages (~ 100 V) and will not undergo any expansion**





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

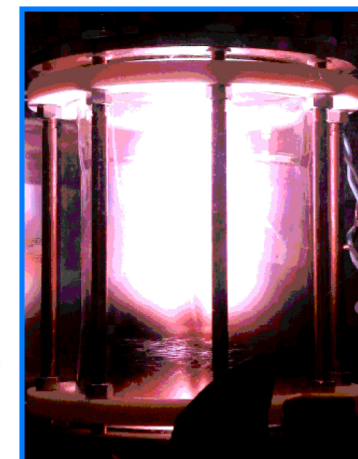
Emissive modular annular electrodes:

- gas puffed hollow anodes
- directly heated cathode W

• PCC disc-shaped, at interface:

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

obtained on (axial) electrode modules
for >thousand-1s discharges
on PROTO-PINCH testbench (2000)

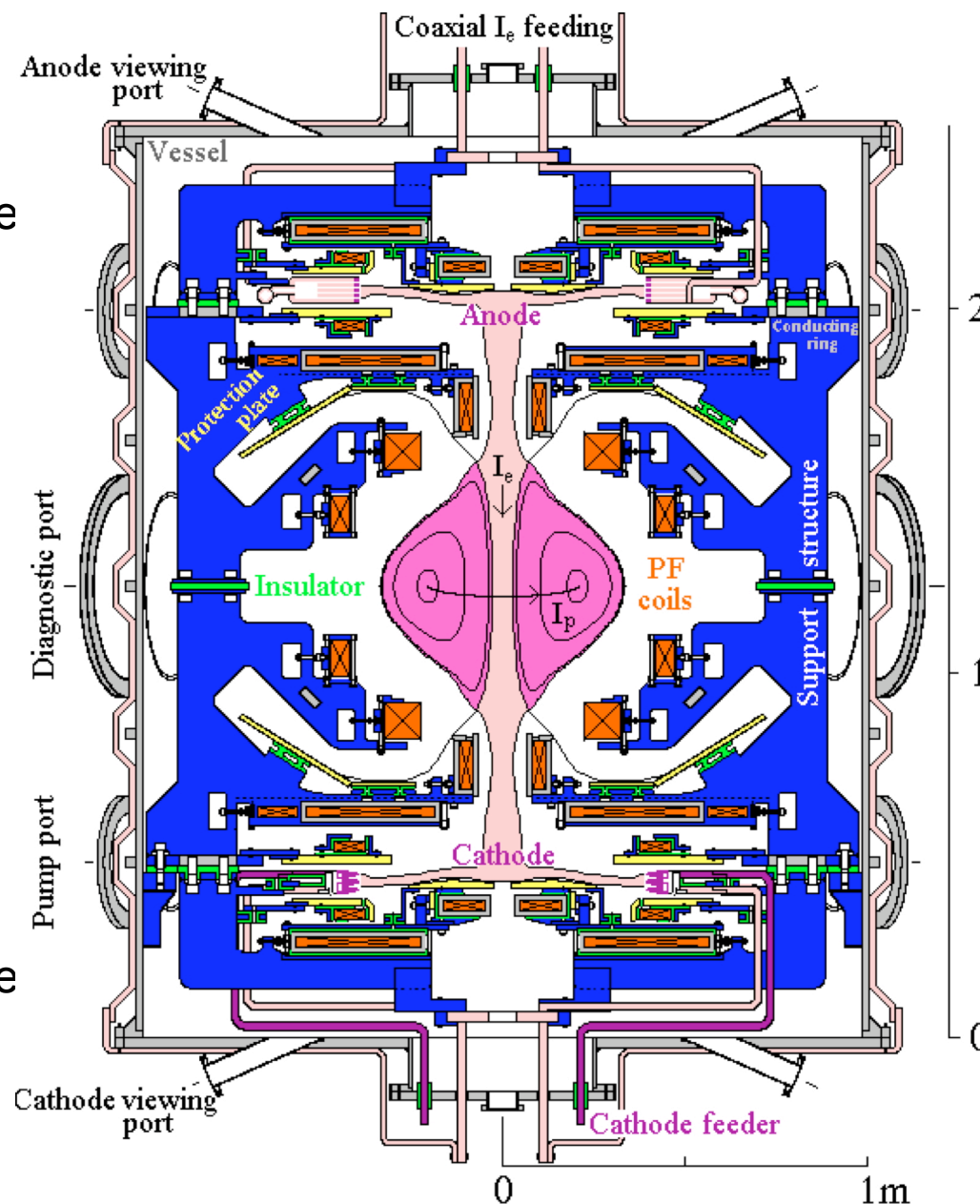




Separate chambe
for anode

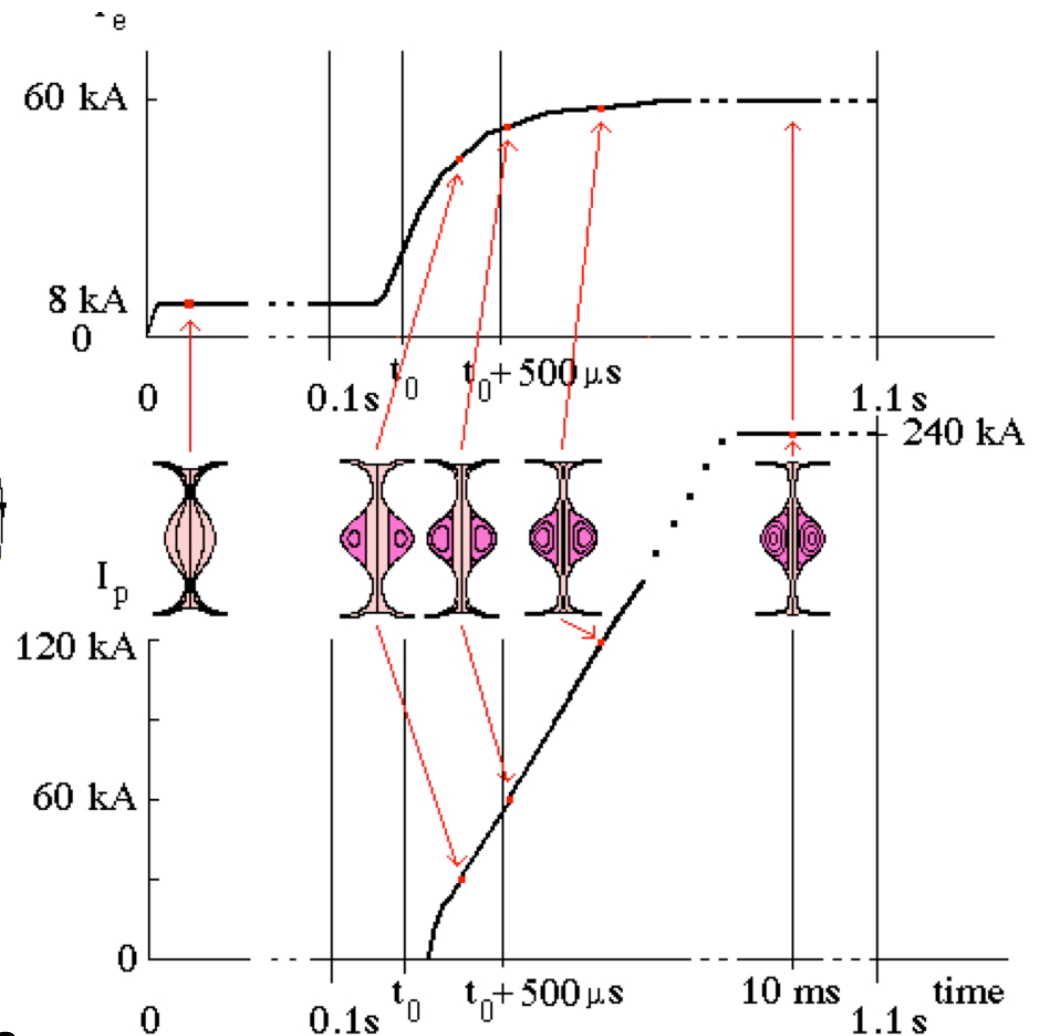
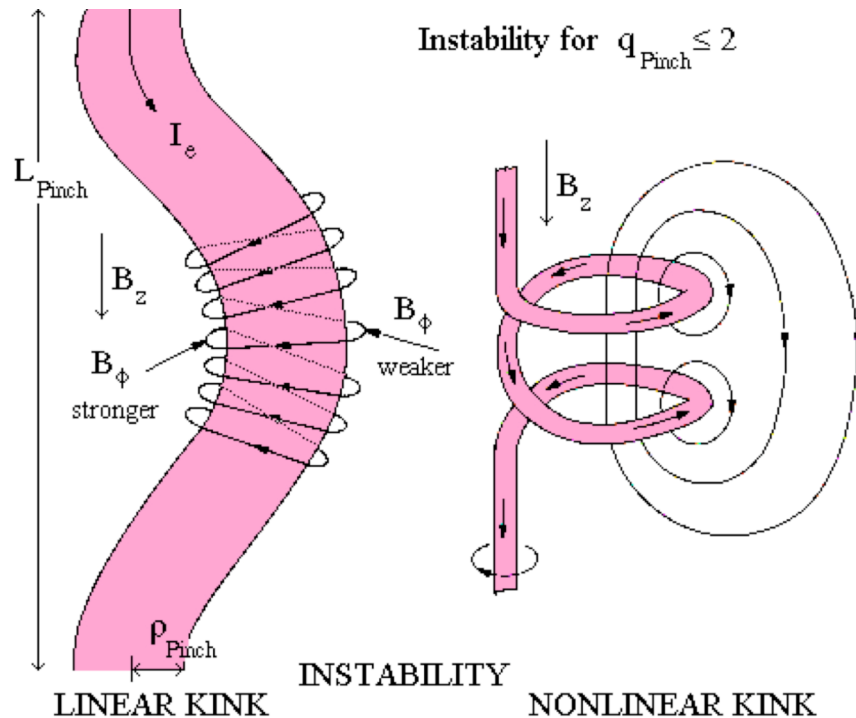
Main torus
chamber

Separate chambe
for cathode



Electrodes are
separated from
the main plasma

Formation time-scale



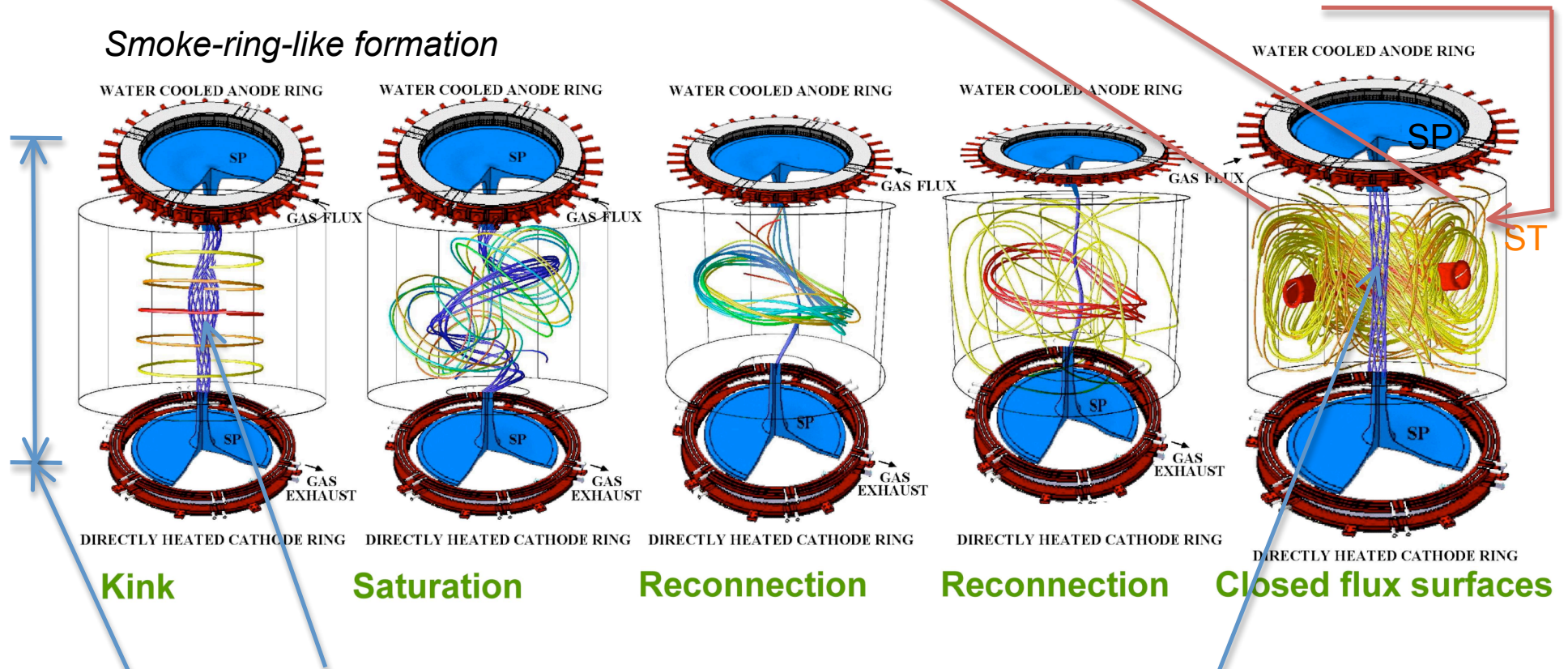
Alfvén MHD growth time: $\tau_A \sim 0.5 \mu\text{s}$

Resistive diffusion time: $\tau_R \sim 70 \text{ ms}$

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

- A **spherical torus (ST)**, with external diameter $2 \cdot R_{\text{sph}} = 0.7 \text{ m}$, with closed flux surfaces and toroidal plasma current $I_{\text{ST}} \leq 240 \text{ kA}$

Smoke-ring-like formation

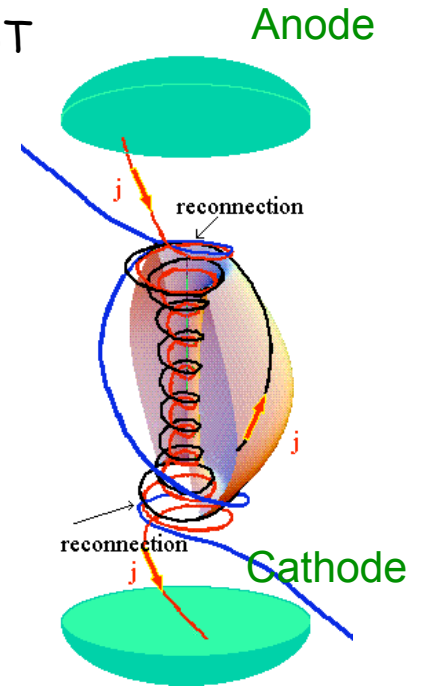


- A **Hydrogen plasma arc fed** by annular electrodes ($r_{\text{Electrode}} = 0.40 \text{ m}$, $\Delta z_{\text{Electrode}} = 0.04 \text{ m}$), taking the form of a **screw pinch: SP**, with length $L_{\text{Pinch}} \approx 2 \text{ m}$ and midplane diameter $2 \cdot r_{\text{Pinch}} \approx 0.08 \text{ m}$, with open flux surfaces and plasma electrode current $I_{\text{Electrode}} = 60 \text{ kA}$

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

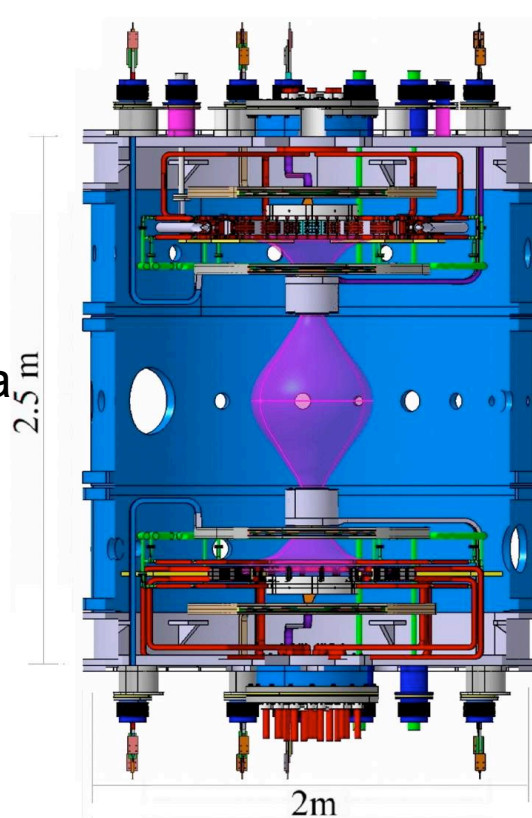
- electrode plasma - open field lines - has $\vec{j} \parallel \vec{B}$
- the open field lines also wind toroidally
- magnetic reconnections convert open $\vec{j}, \vec{B}$ lines into closed $\vec{j}, \vec{B}$ lines winding on a spherical torus

- $I_{ST} = 240 \text{ kA}$ ($4 \times I_e$) really achievable?
- Can it be sustained for $\tau_R \sim 70 \text{ ms}$?
- Resistive MHD stability & confinement?

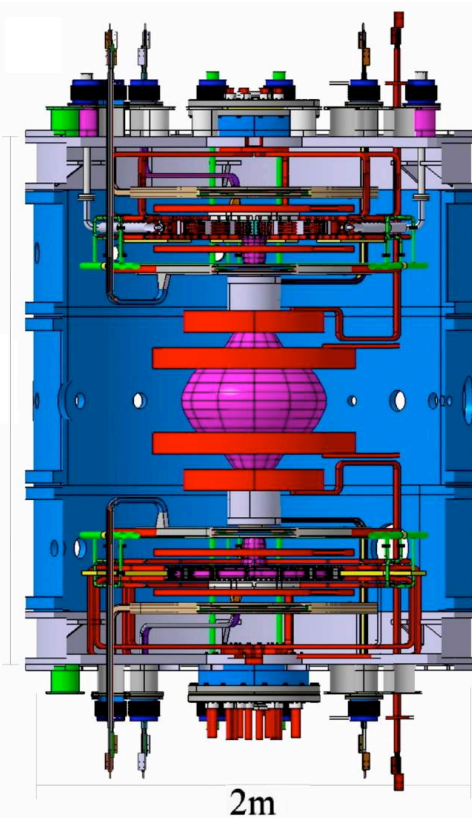


In order to clarify the breakdown conditions and the pinch stability before the formation of the Spherical Torus, the MULTI-PINCH test-bench has been designed as a reduced setup of the PROTO-SPHERA experiment.

Multi-Pinch
Proto-Sphera
Part 1

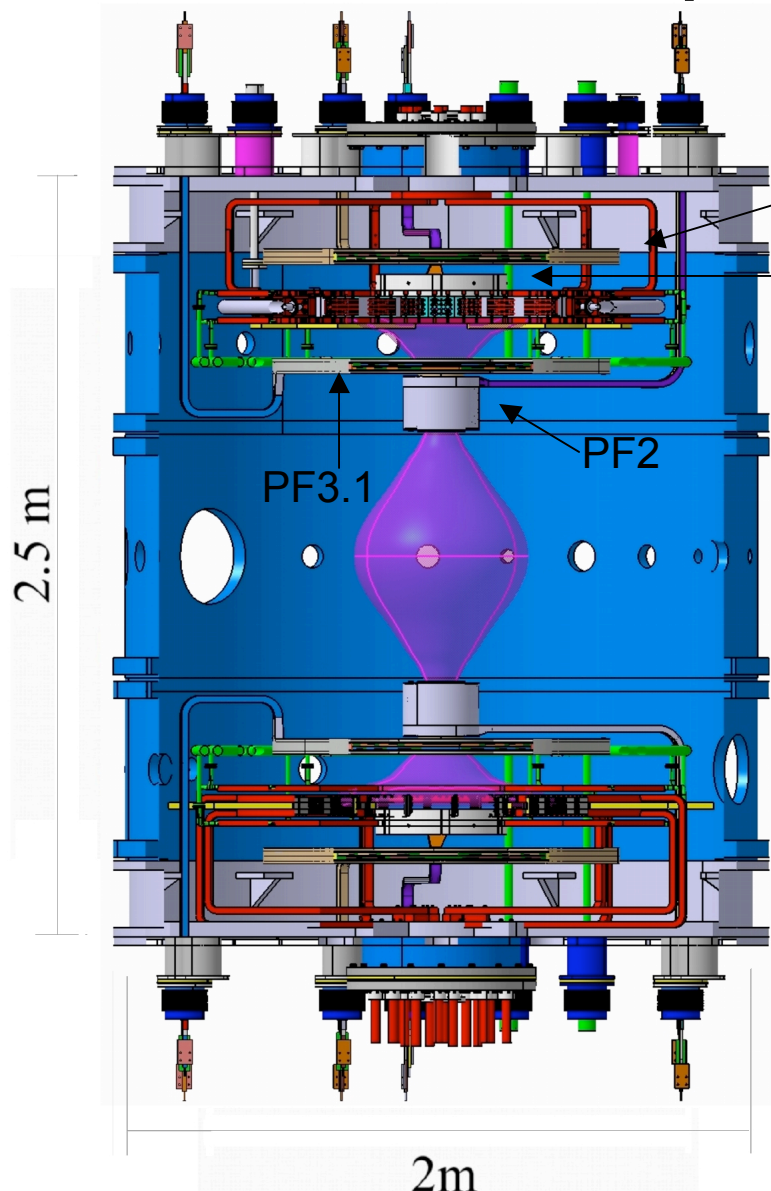


Proto-Sphera



- MULTI-PINCH explores the first phase of the PROTO-SPHERA discharge ($I_{\text{Electrode}} \leq 10 \text{ kA}$), in presence of the **shaping subset of the poloidal field coils alone and therefore in absence of the spherical torus**.
- The MULTI-PINCH cathode is the final PROTO-SPHERA cathode, only partially filled with Tungsten filament modules (54 Vs. 378); each filament will deliver its maximum plasma current (150 A).
- The screw pinch amplifier will be limited to the first unit ($I_{\text{Electrode}} \leq 10 \text{ kA}$) and also the cathode heating power supply will be a 1/6 of the final one (10 kA and 25 V AC).

Multi-Pinch Experiment (Proto-Sphera Part 1)



Aims:

- 1) Breakdown
- 2) Stable formation of plasma ‘mushrooms’
- 3) Stable (≈ 1 s) achievement of $I_e = 8.5$ kA
- 4) Resilience of electrodes to 1000 discharges

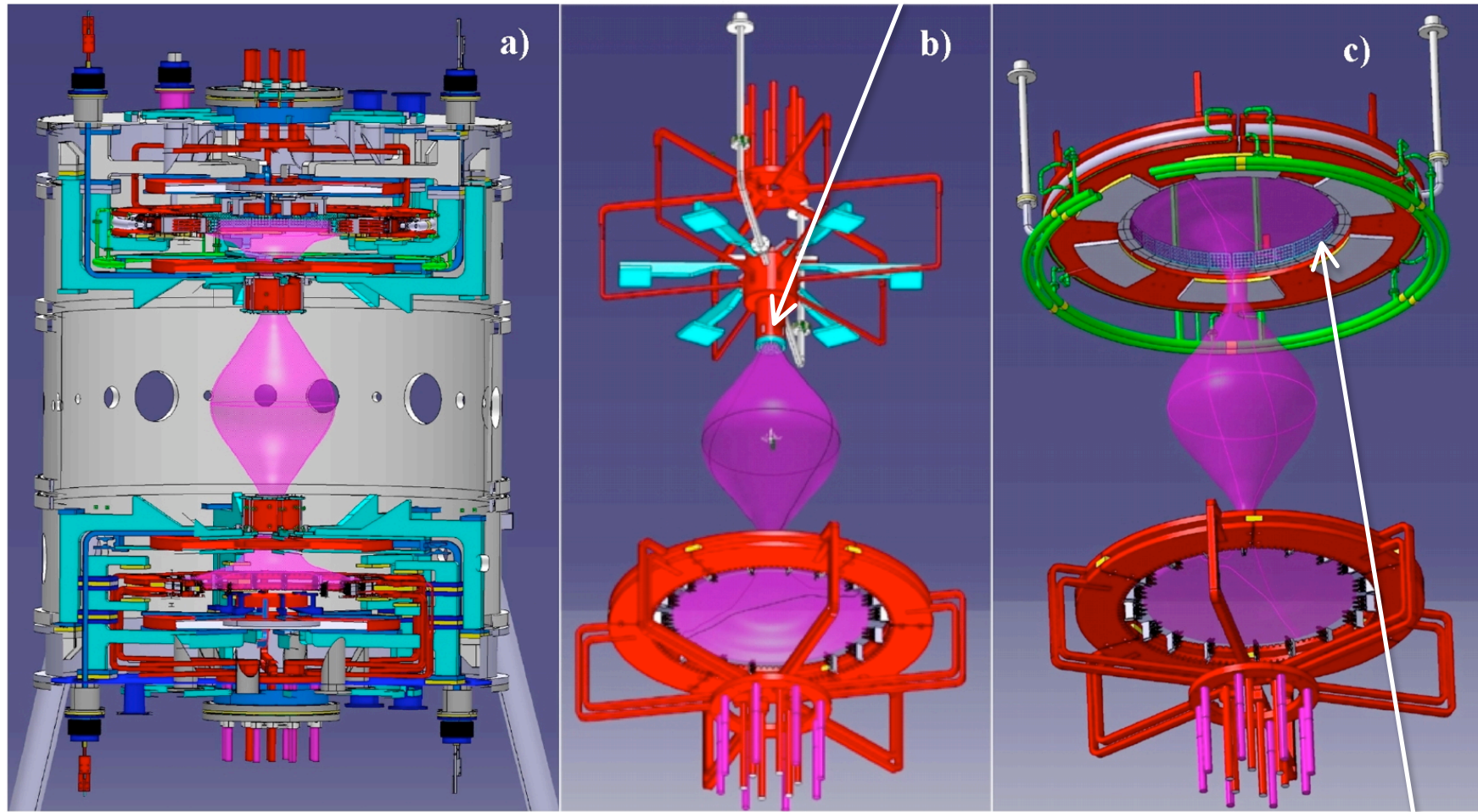
Then Proto-Sphera:

adding up PF coils and power supplies

All parts will be reused in Proto-Sphera

- START vacuum vessel
(in Frascati since May 2004)
- Partial PF coils (constant current):
only the “Pinch shaping coils”
(built since 2007)
- Definitive Anode & Cathode (built 2009)

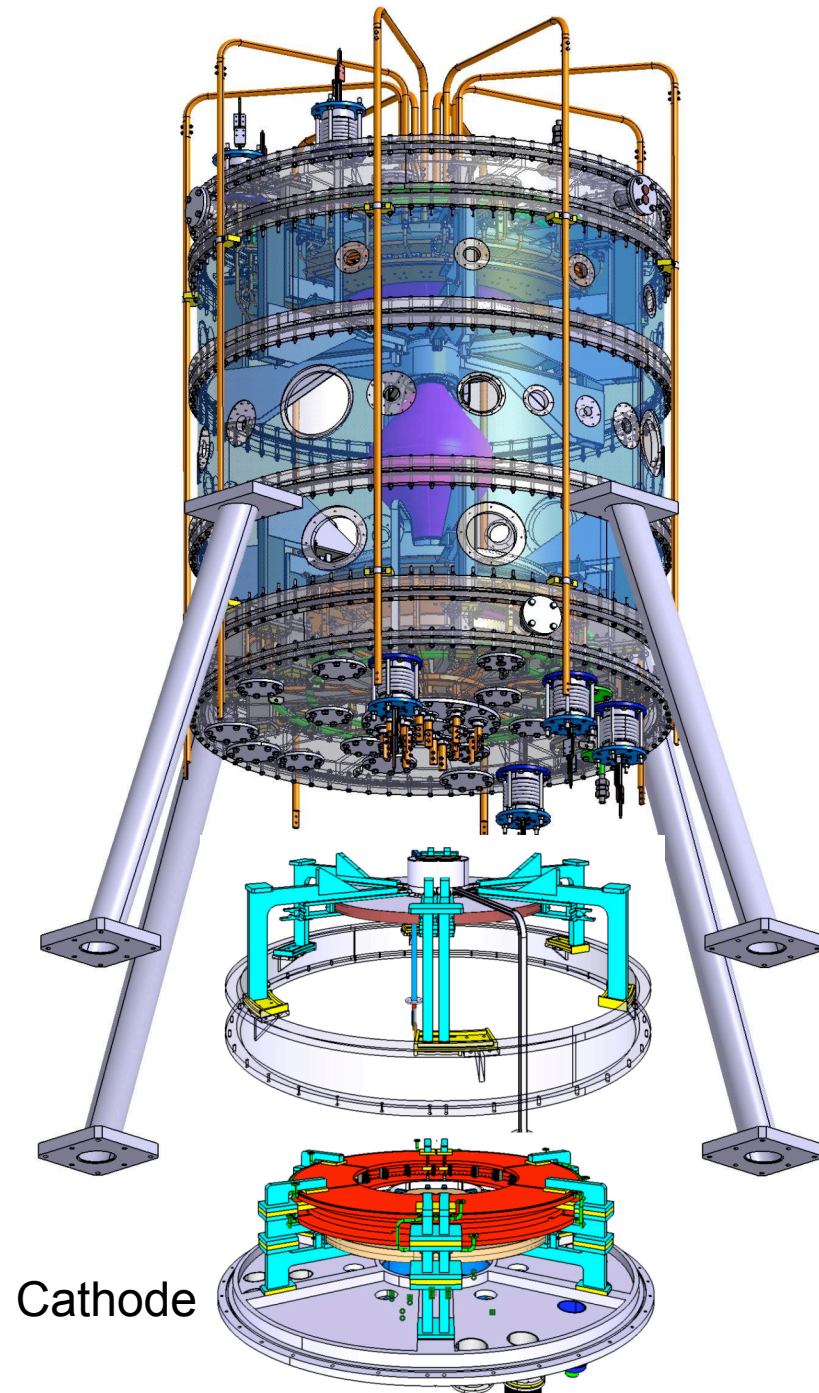
Multi-Pinch Phase 1: annular cathode, cylindrical anode



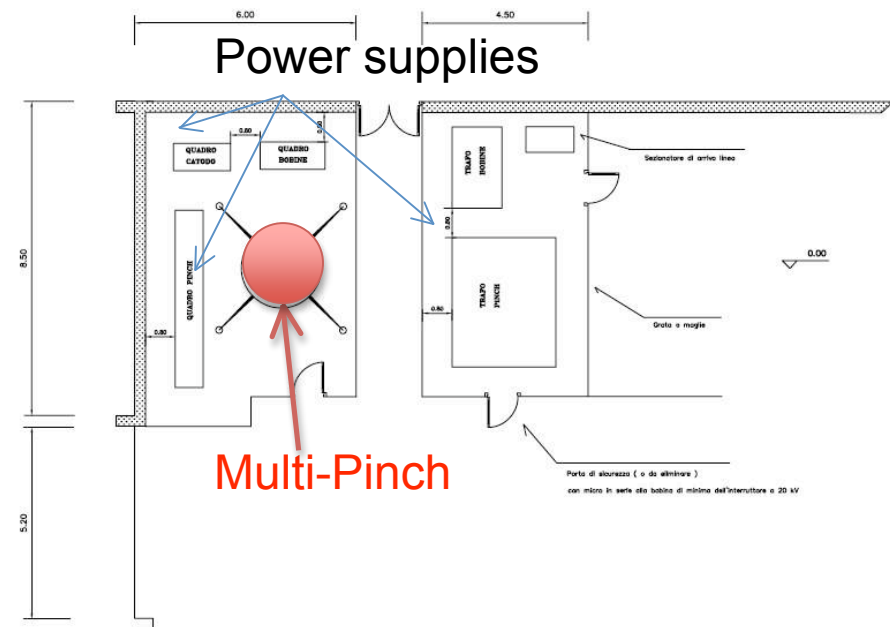
Multi-Pinch Phase 2: annular cathode, annular anode

MULTI-PINCH will be relevant for the main tokamak line

- for exploring biased divertors and plasma sources for NBI injectors ($P_{\text{Electrode}} \approx 20 \text{ MW/m}^2$)
- and for high current vacuum arcs ($j_{\text{Electrode}} \approx 1 \text{ MA/m}^2$) in presence of guiding magnetic fields



Multi-Pinch experiment will be positioned inside FTU assembly-hall, as low voltage and no toroidal plasma mean no X-rays.



“Easy” disassembly of cathode (bottom) and anode (top) – 4 extended legs.

Proto-Sphera toroidal plasma will require a new positioning, due to X-rays hazard (old FT torus hall?)



SCHEDULE

PF COILS		Design	Contract	Tender	Construction		Check
----------	--	--------	----------	--------	--------------	--	-------

| 2005 | 2006 | 2007

	TOTALS	Year 1		Year 2			Year 3		Year 4		
LOAD ASSEMBLY		Design	Contract	Tender	Construction	Check	Assembly			Final check	Guarantee
ASSEMBLY WORK					Tender	Orders	Work		Final check		
PUMP,GAS,CNTRL					Tender	Orders	Assembly		Final check		

| 2007 | 2008 | 2009 | 2010

POWER SUPPLY		Design		Tender	Construction	Check	Check	Assembly	Final check	Guarantee	
ELECTRICAL WRK		Design		Tender	Work				Final check	Guarantee	

| 2009 | 2010 | 2011

LOAD ASSEMBLY BUDGET

Costs as in 2001 Report:

Real costs

Poloidal field coils , including:		
feedthroughs and cooling system	620,000 Euro	
Design contract	77,500 Euro	
Subtotal	697,500 Euro	160,000 €
Vessel , including: tiles, supports,		
baking system and base	570,000 Euro	
Design contract	77,500 Euro	
Subtotal	647,500 Euro	730,000 €
Anode and Cathode , including		(including internal
feedthroughs and cooling system	230,000 Euro	measurements)
Design contract	50,000 Euro	
Subtotal	280,000 Euro	50,000 €
Assembly contract	90,000 Euro	
Pumping, gas feeding & cntrl.sys.	180,000 Euro	10,000 €
<u>TOTAL</u>	<u>1,895,000 Euro</u>	<u>950,000 €</u>

Presumable costs for upgrading to final Proto-Sphera
(PF coils group A + modifications + layouts)

400,000 €



POWER SUPPLY BUDGET

Costs as in 2001 Report:

“Real” costs

Power supply:	
Pinch feeder ‘P’	825,000 Euro
Cathode feeder ‘K’	102,000 Euro
PF feeder ‘A’	181,000 Euro
PF feeder ‘B’	92,000 Euro
Subtotal	1200,000 Euro
Electrical work contract	140,000 Euro
<u>TOTAL</u>	<u>1,340,000 Euro</u>

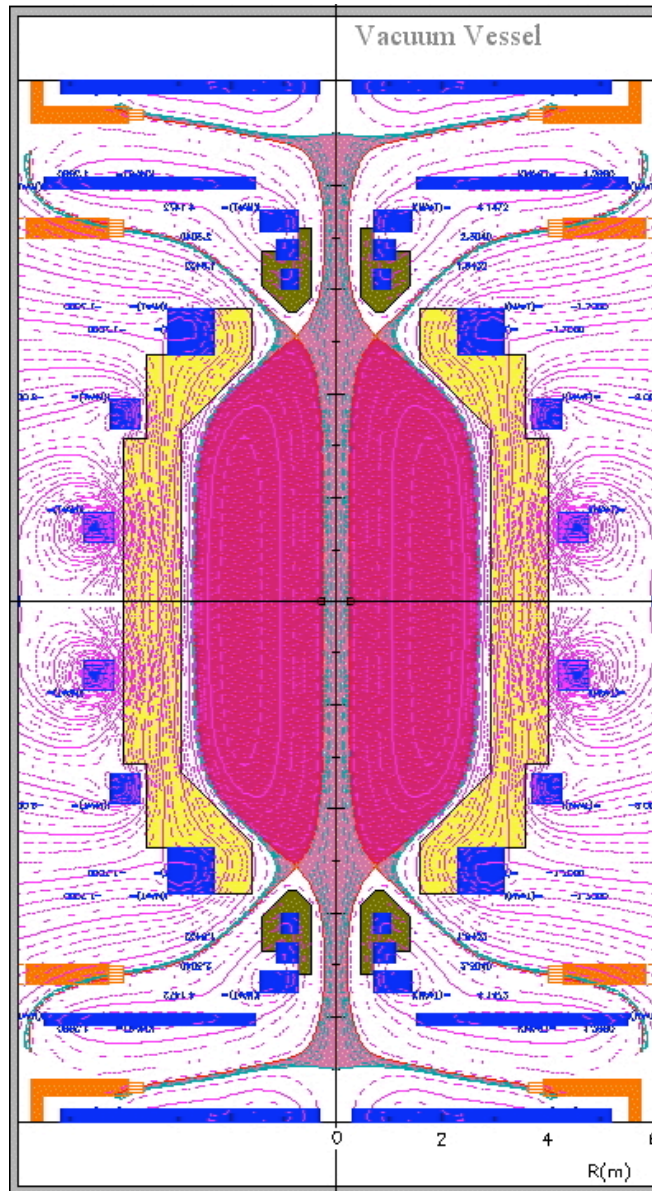
For Multi-Pinch
700,000 €
(including layouts)

Presumable costs for upgrading to final Proto-Sphera

1,000,000 €

Reactor extrapolation:

1) a configuration initiated and sustained by electrodes



Although at very high elongation $\kappa > 4$, large dimension (10 m high) and huge plasma currents $I_p \approx 40$ MA an extrapolation can be sketched, with a recirculating power of 20% but...

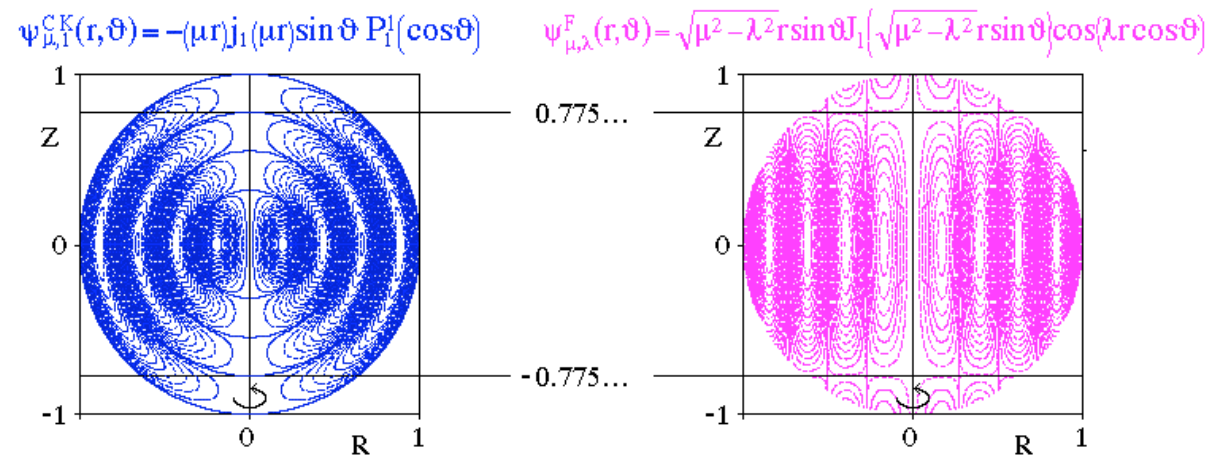
a remarkable breakthrough in technology would be required, such as to produce long time resilient electrodes

A favourable point is that the electrodes would be screened from neutrons

Reactor extrapolation:

2) a configuration initiated by electrodes but then detached from electrodes

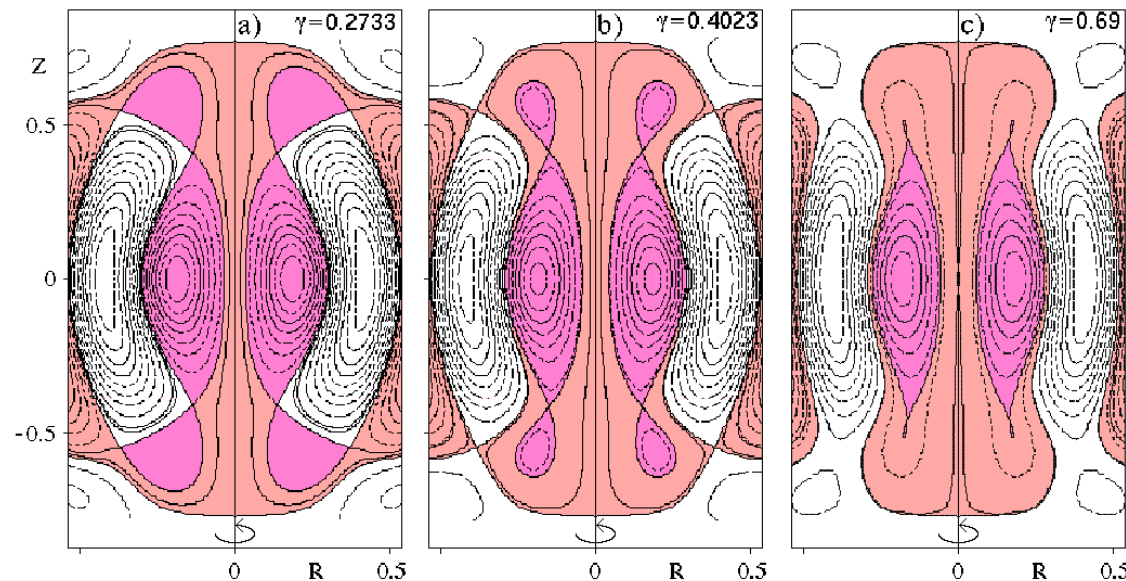
A step beyond the classical Chandrasekhar-Kendall spheromak



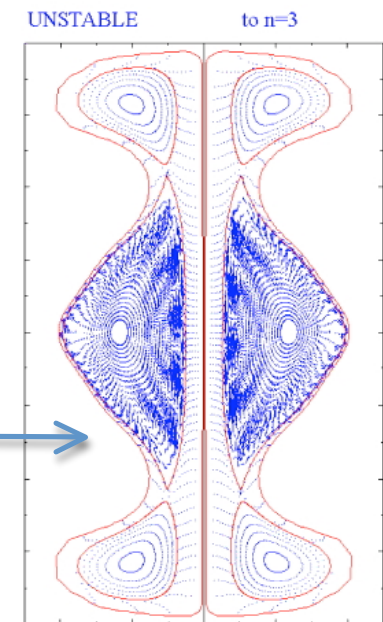
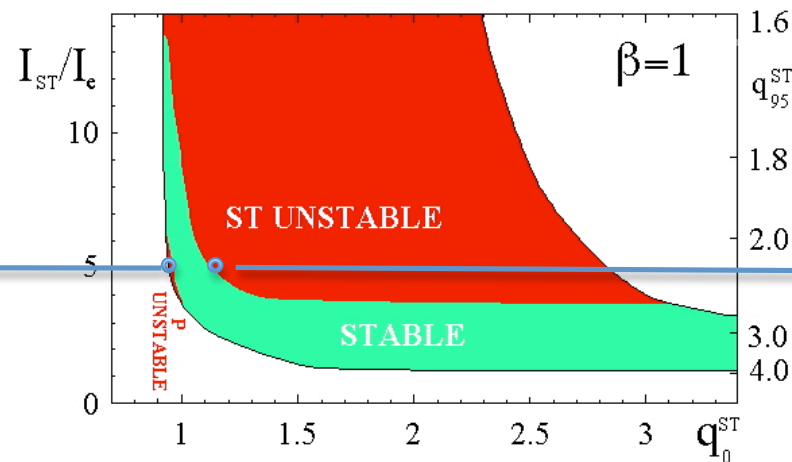
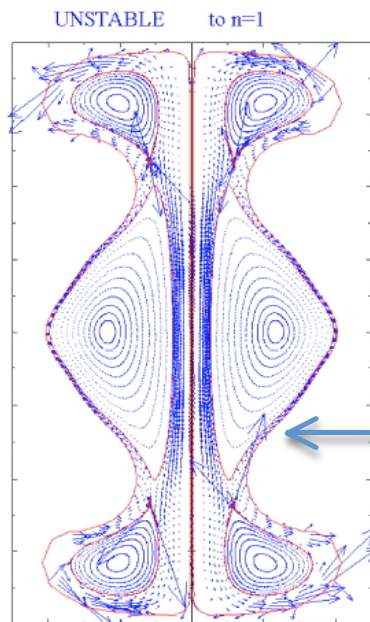
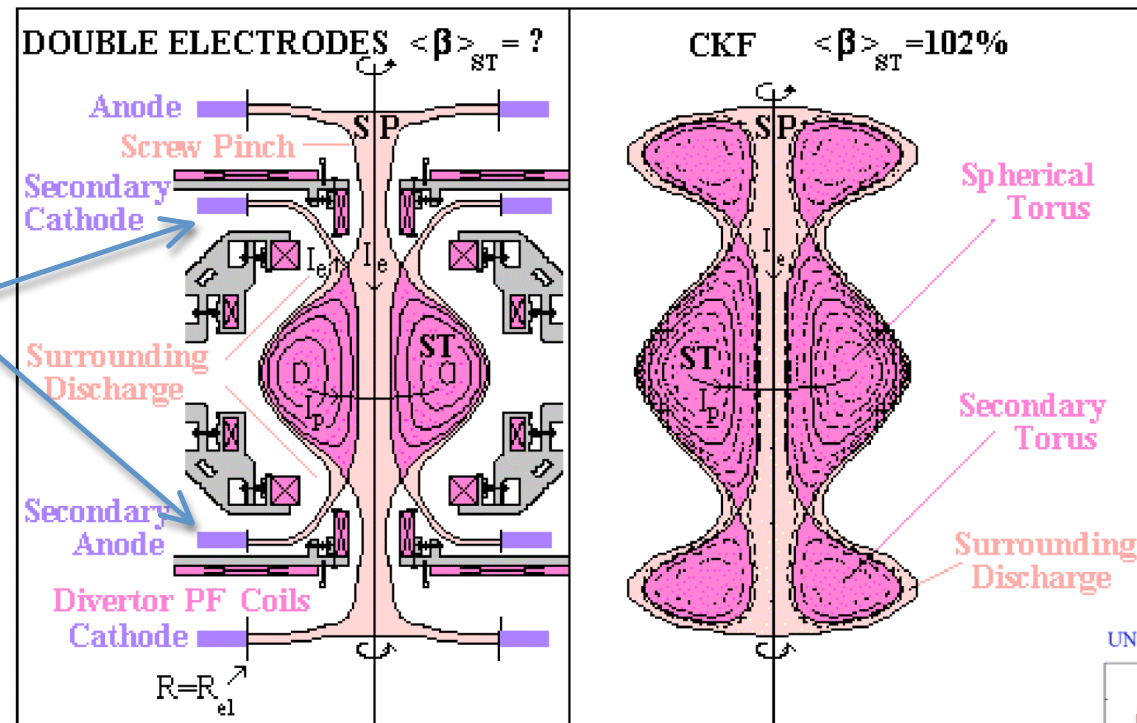
The superposition of the two force-free fields is: $\psi(r, \vartheta) = \psi_{\mu 1}^{CK} + \gamma \psi_{\mu \lambda}^F$

For $\gamma \geq 0.402...$ in a simply connected region the toroidal current density j_ϕ has same sign:

Chandrasekhar-Kendall-Furth force-free field (CKF) $\bar{\nabla} \wedge \bar{\mathbf{B}} = \mu \bar{\mathbf{B}}$, $\mu = \mu_0 \bar{\mathbf{j}} \cdot \bar{\mathbf{B}} / B^2 = \text{constant}$, $\bar{\nabla} p = 0$



Proto-Sphera can have further bias of 'divertor plates' to drive a surrounding discharge also in the torus outboard



Ideal Stability at $\beta=1$ in absence of any conducting shell around the plasma

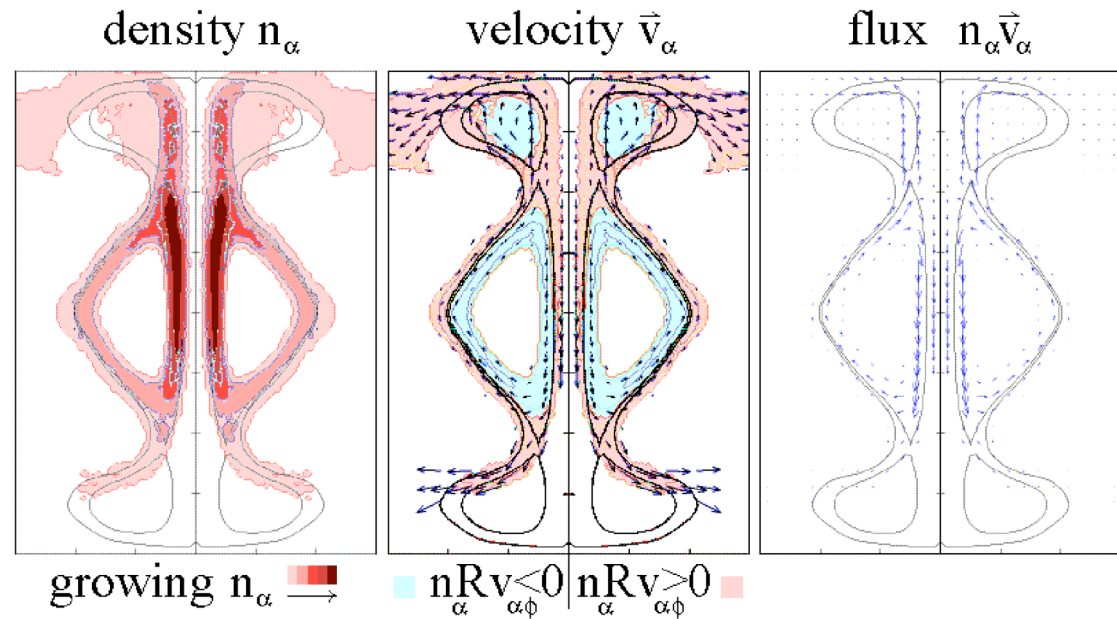
Arrow plots of global unstable modes at $\beta=1$, $I_{ST}/I_e=5$

CKF configurations: closed flux surface variant - ideal MHD stable at $\beta=1$

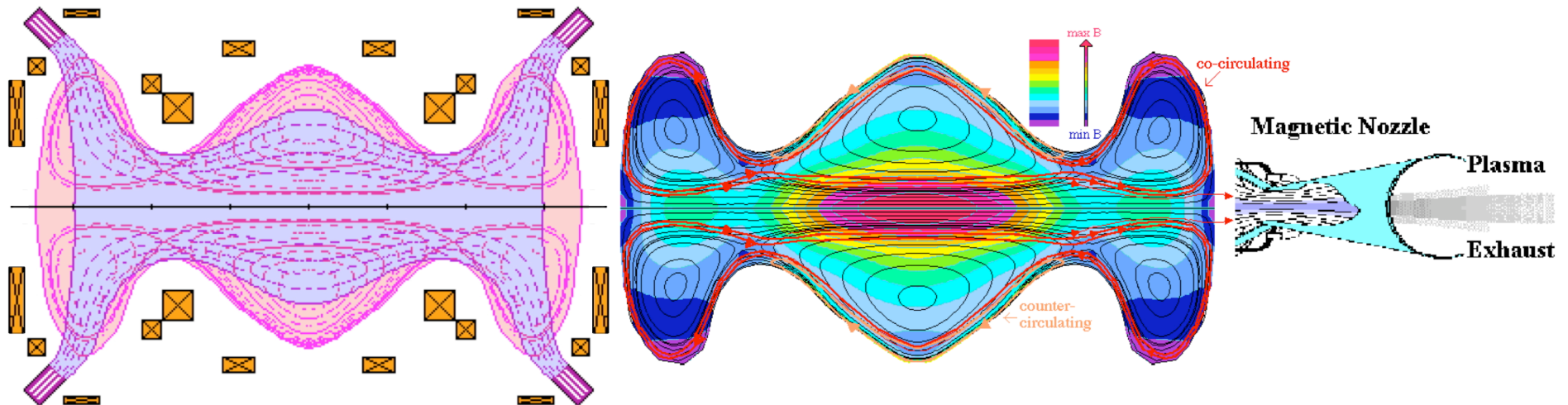
"Very imaginative" development:
 $\beta=1$ mandatory in thrusters³:
 (weight of coils forbids large B)

CKF-like configurations channel
 promptly lost (15%) charged fusion
 products: direct energy conversion
 and propulsive power

³ NASA/TM-2005-213559 (2005)



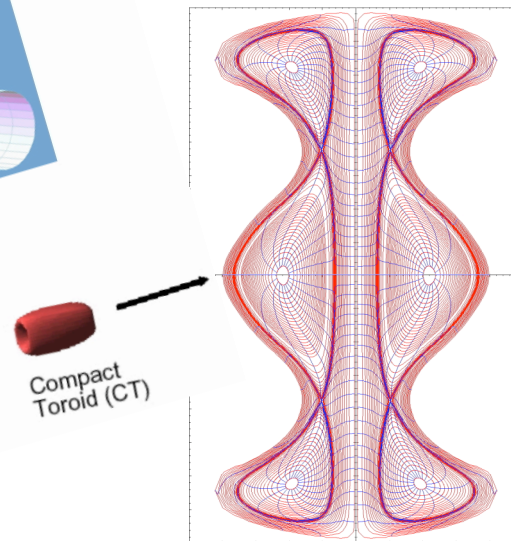
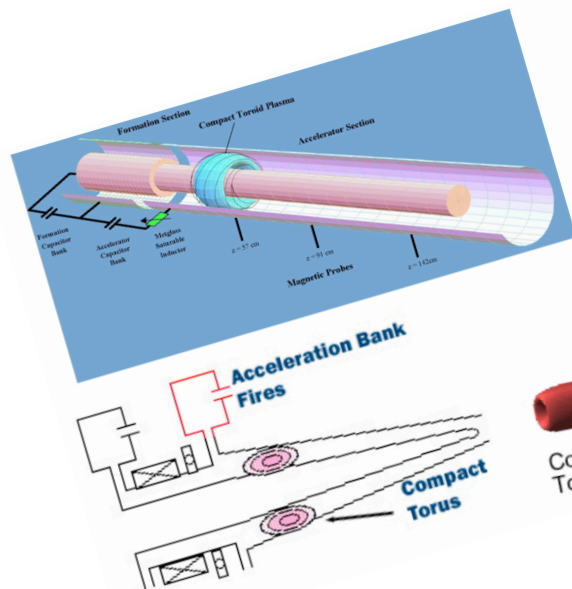
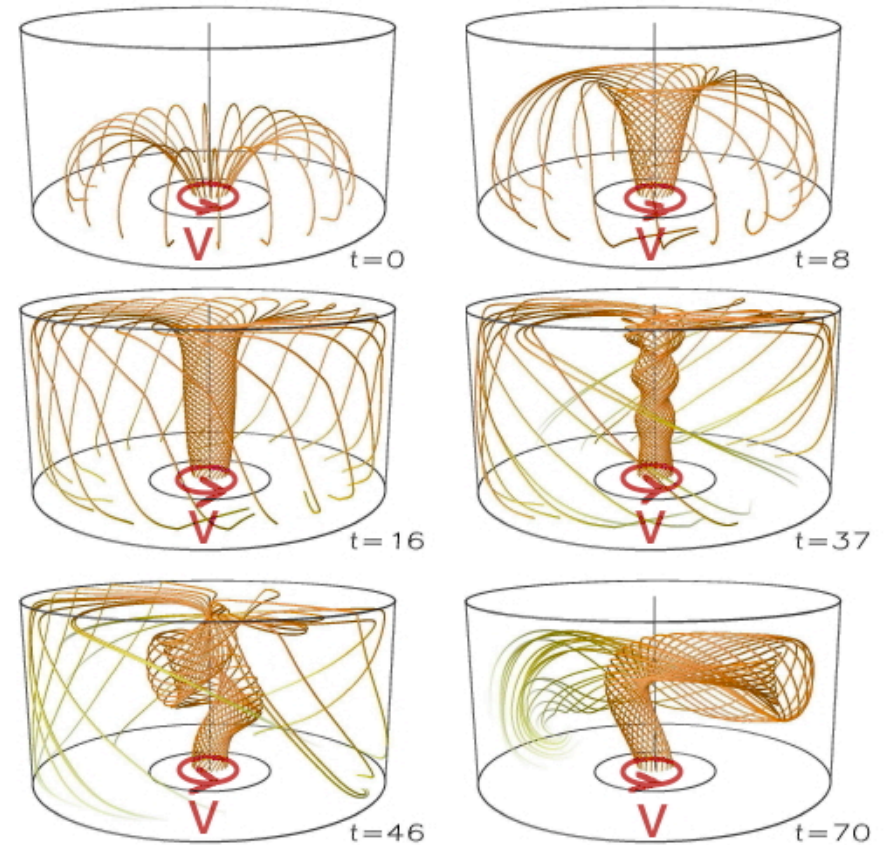
But how to form them?



But how to sustain them?

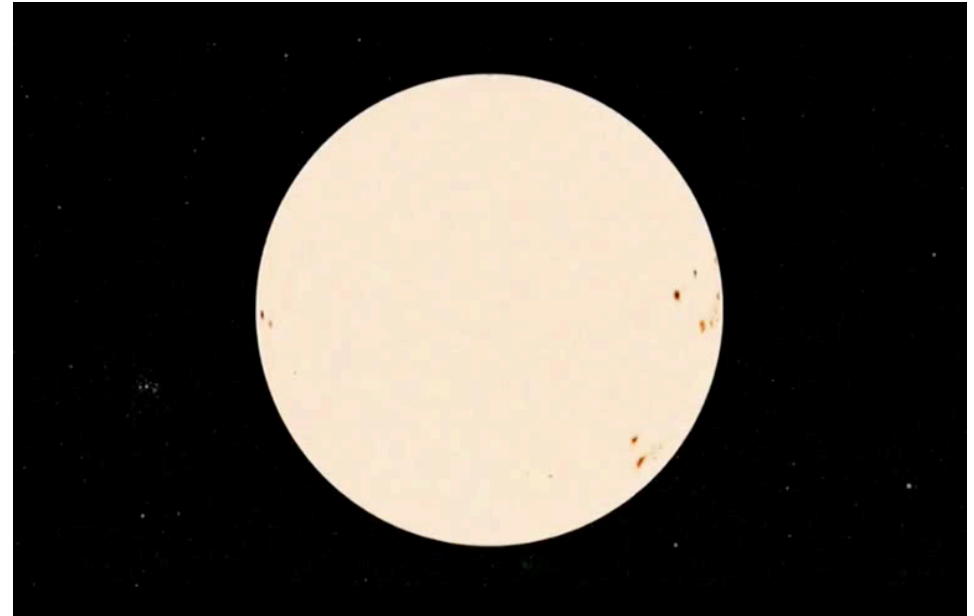
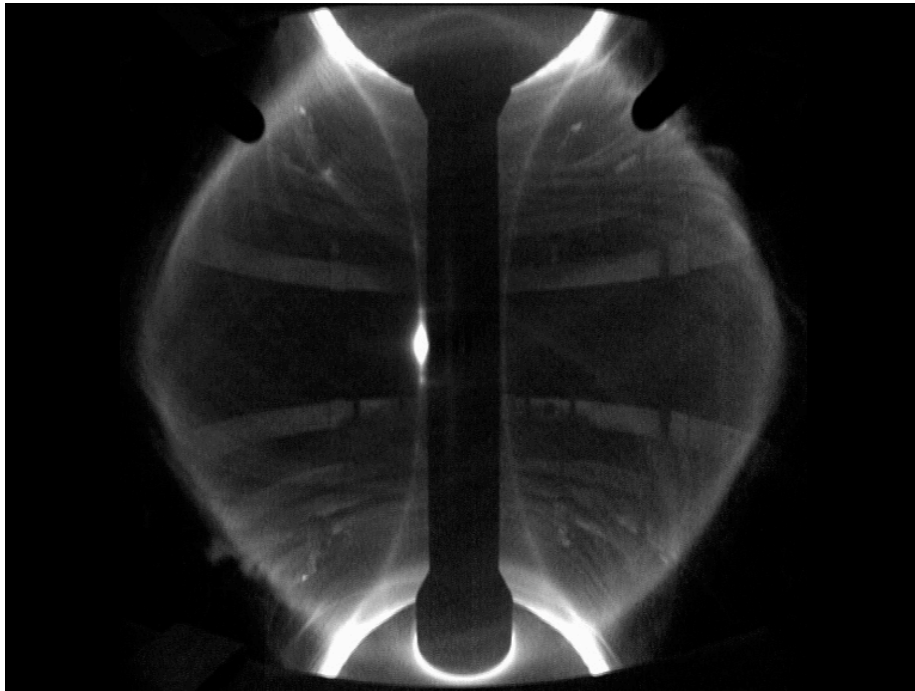
Sheared rotation of central column⁴
is in principle able to inject helicity and to
sustain the spherical torus

⁴ Farengo PoP (2010)



Tangential injection of
Compact Toroids to provide
sheared rotation at the edge
- and in the central column

After reconnection rotating filaments
in the surrounding discharge



Ejection of current carrying filaments from the edge of a rapidly rotating plasma (velocity shear layer with the larger speed on the inside)

Can the reverse, i.e. creation of a velocity shear layer at the edge – by CT injection – be used to create a velocity shear layer (larger speed in the surrounding discharge), in order to inject velocity and magnetic field inside the confinement region?

Conclusioni

Se i vari passi si riveleranno fattibili (Scarica centrale, Toro sferico, CKF)

Proto-Sphera porterà a valutare se configurazioni magnetiche

- semplicemente connesse (semplicità costruttiva)
- a beta unitario (minime dimensioni geometriche)
- capaci di emettere i prodotti carichi di fusione in modo direzionale (spinta)
- sostenute dall'iniezione (ripetitiva) di velocità tramite plasma guns

sono un candidato plausibile per qualcosa di più impegnativo....

Ma soprattutto Proto-Sphera può svolgere questo programma

in modo poco costoso,

in modo flessibile (facile aggiungere nuovi componenti alla macchina)

in modo rapido rispetto alla scala temporale a cui ci siamo purtroppo assuefatti