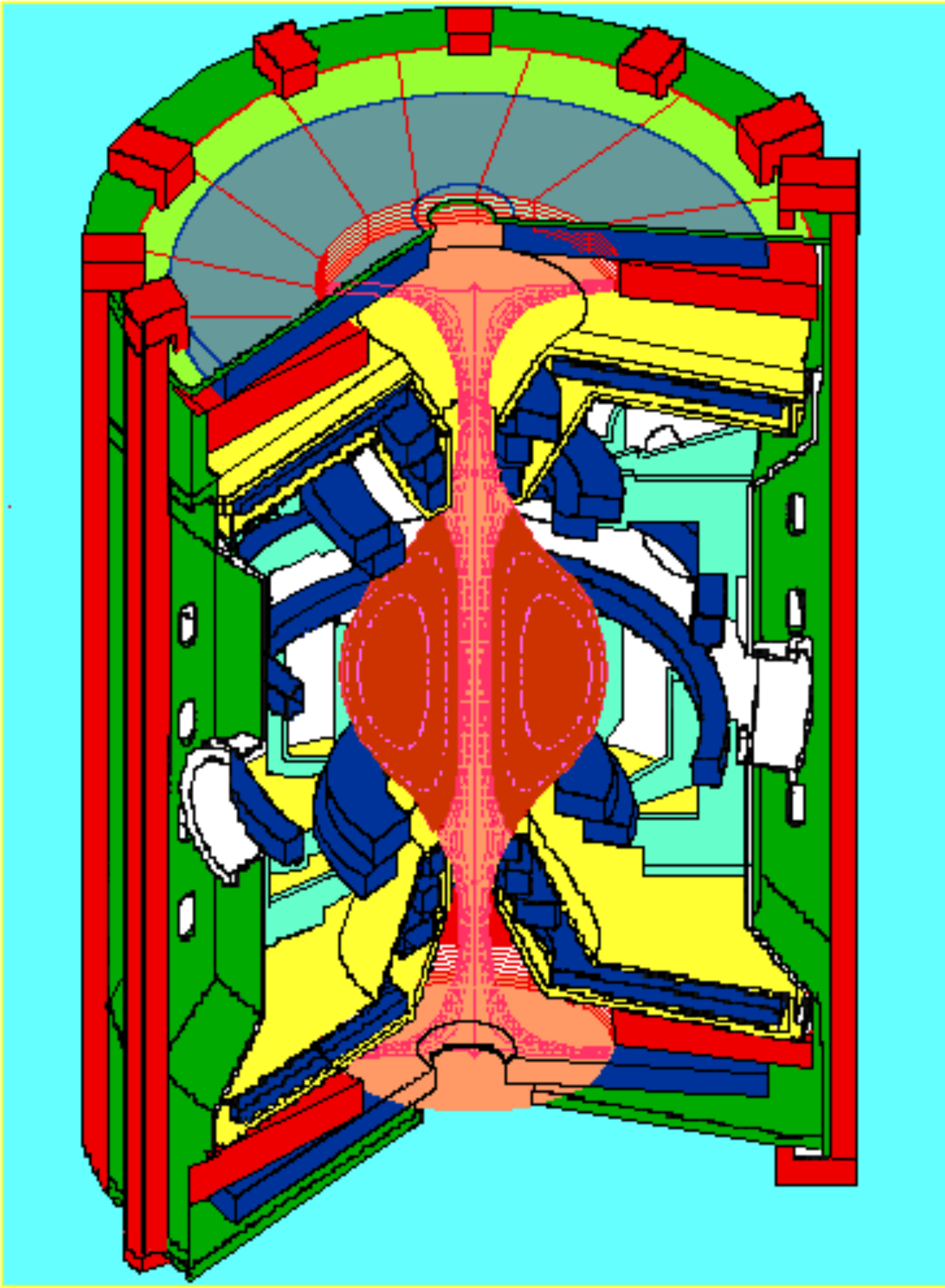
SPHERA:

Spherical Plasma for HElicity Relaxation Assessment



F. Alladio, C. Gourlan, S. Mantovani,
P. Micozzi, L. Pieroni , V. Zanza

Associazione EURATOM ENEA
Centro Ricerche Frascati (Rome), Italy

INNOVATIVE CONFINEMENT CONCEPT WORKSHOP, Marina del Rey, March, 3-6, 1997

Low Aspect Ratio Tokamak (LART, $A \leq 2$)

Main problems of a **LART** reactor:

- Central conductor of toroidal magnet unshielded
- Is then bombarded by neutrons
  (under small solid angle, but must be replaced)
- Cannot be built by super conducting materials
- Energy dissipation large compared to fusion power

Ultra Low Aspect Ratio Tokamak (ULART, $A \leq 1.3$)

Ratio between the current in the central conductor I_{tf}
and the toroidal plasma current I_p, for aspect ratios $A < 2$:

[Yamada, M., Pomphrey, N., Morita, A., Ono, Y., Katsurai, M., Nucl. Fus. '96]

$$\mathbf{I_{tf}/I_p = \pi^2 q_\psi (A-1)^2 / (2\kappa^2)}$$

At $q_\psi \sim 4$, an **ULART** with aspect ratio $A \sim 1.2$ and elongation $\kappa \sim 3$, can have a ratio as low as $I_{tf}/I_p \sim 0.10$

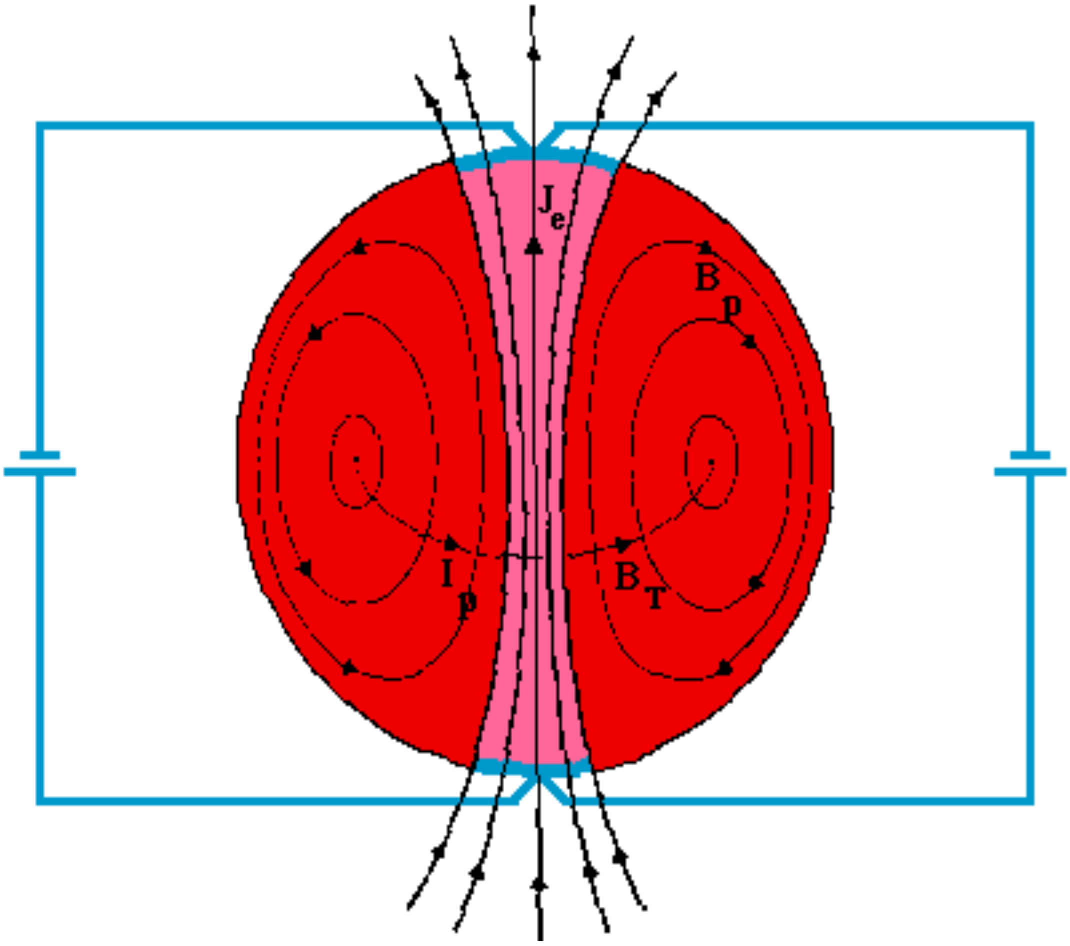
Main problems of an **ULART** reactor:

- The **ULART** leaves no space for an ohmic transformer and requires non inductive Current Drive methods
- The **ULART** does not solve the problem of the neutron damaging of the central conductor

THE SPHERA PROPOSAL

The SPHERA experiment proposal aimed to test an
ULART, where the central rod is substituted by a current carrying plasma

This Plasma is a force-free Screw Pinch fed by two "polar caps" electrodes placed along the expansions of the ULART internal divertor regions



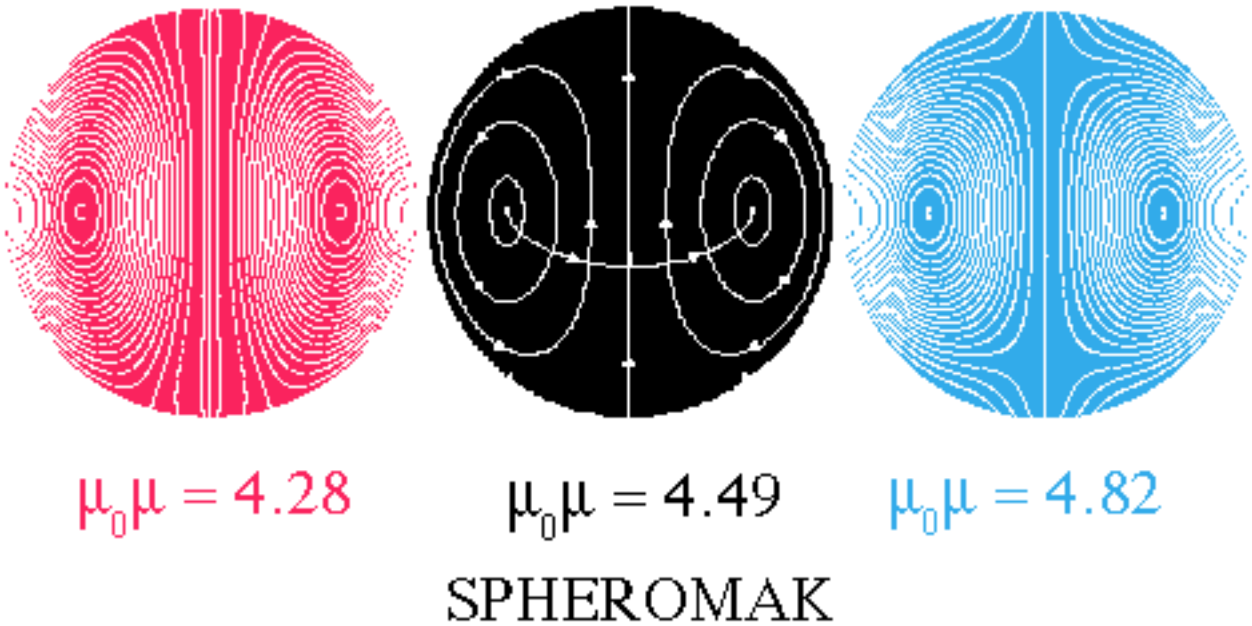
This configuration has been investigated under the name "Bumpy Z-Pinch" [Jensen and Chu, J.Pl.Phys, '81] **, "Flux Core Spheromak"** [Turner, Phys. Fluids '84] [Taylor, Nucl. Fus. '89]

SPHERA tries to avoid the neutron damaging of the central conductor
SPHERA tries to sustain the ULART configuration through DC Helicity Injection, by driving the Plasma current I_e along the lines of force of the central Screw Pinch

Equilibrium of a completely relaxed state, $\nabla \wedge \mathbf{B} = \mu_0 \mu \mathbf{B}$, with μ constant everywhere, enclosed within a perfectly conducting portion of sphere, with radius R_{sph}, fed by two electrodes upon the polar caps

If $\mu_0 \mu R_{sph} = 4.49$ well known **Spheromak** solution

If **$\mu_0 \mu R_{sph} < 4.49$ a plasma current flows within the hole of the spherical torus**. Taylor's theory predicts these configurations to be **ideal MHD stable**



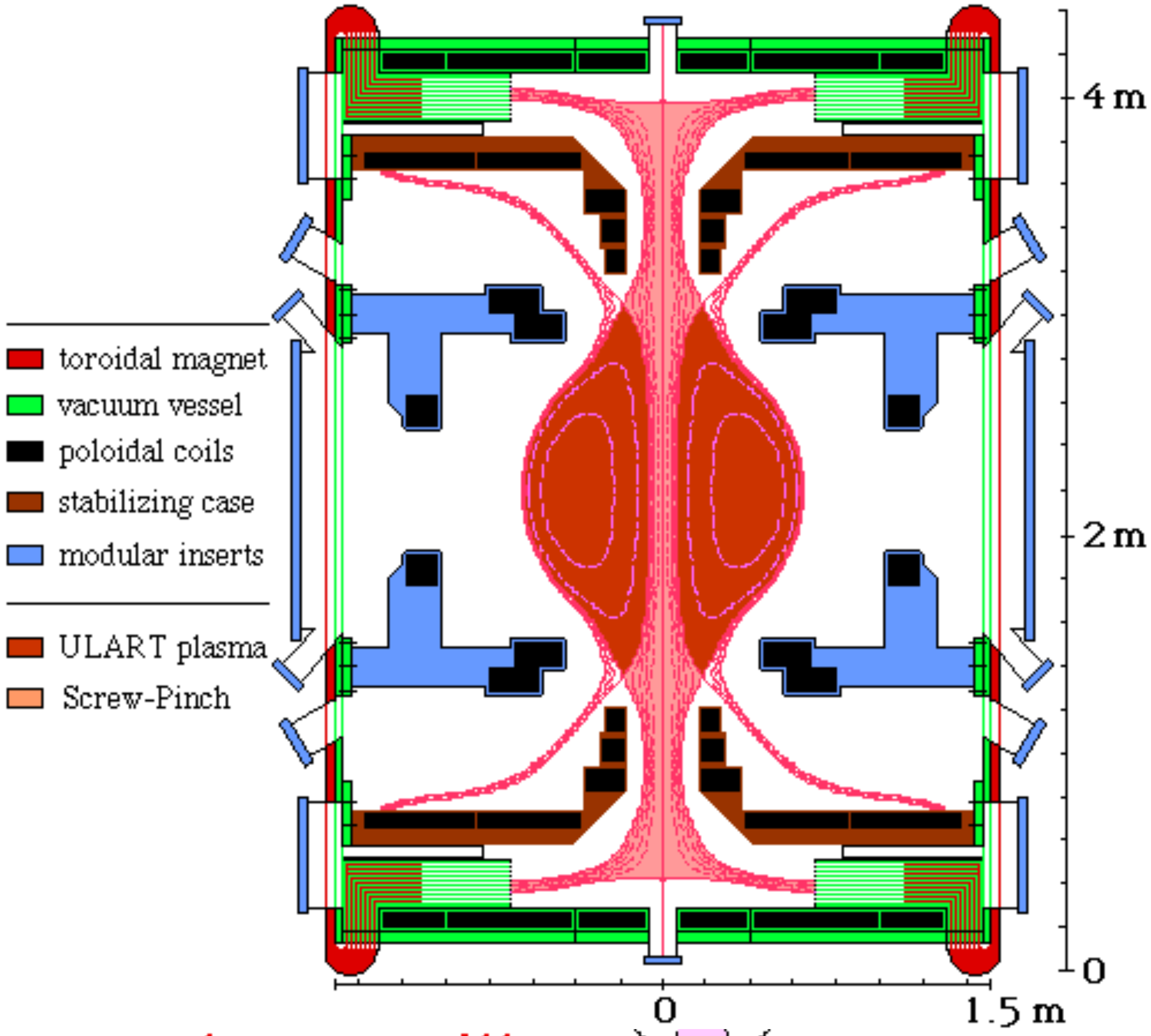
If **$\mu_0 \mu R_{sph} > 4.49$ a plasma current flows around the spherical torus**. These configurations are **ideal MHD unstable**

PARAMETERS OF THE PROPOSAL

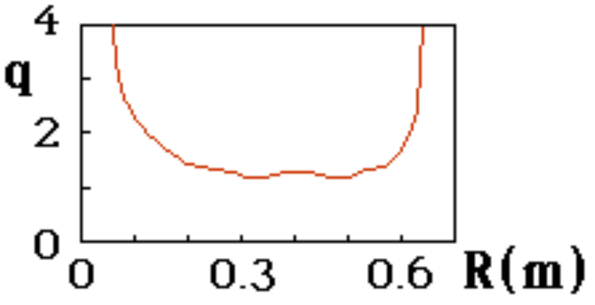
Radius of the Sphere	R_{sph}=0.63 m
Minimum Plasma radius:	$\rho_{Pinch} \leq 0.06$ m
Length of Screw Pinch	L_{Pinch}=3.6 m
Major radius of ULART	R_{ULART}=0.35
Minor radius of ULART	a_{ULART}=0.29
Aspect ratio	A=1.21
Elongation with DN divertor	κ=3.0
Maximal plasma current(q_ψ=2-3)	I_p= 2.7 MA
Current in central Screw Pinch	I_e= 0.365 MA
...which means (at R=0.36 m)	B_{T0}=0.2 T
...including paramagnetism	B_T =0.9 T

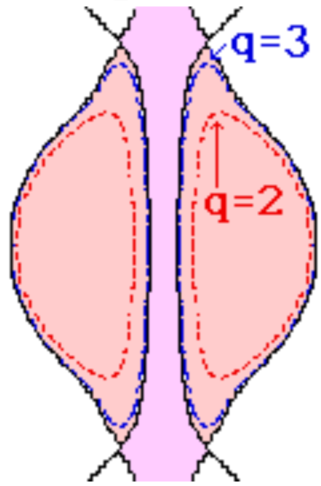
EQUILIBRIUM & STABILITY

Combined Equilibrium: **Force-Free Pinch** **(I_ϕ^{Pinch}=1.9 MA)**
+ ULART **(I_ϕ^{ULART}=2.7 MA)**



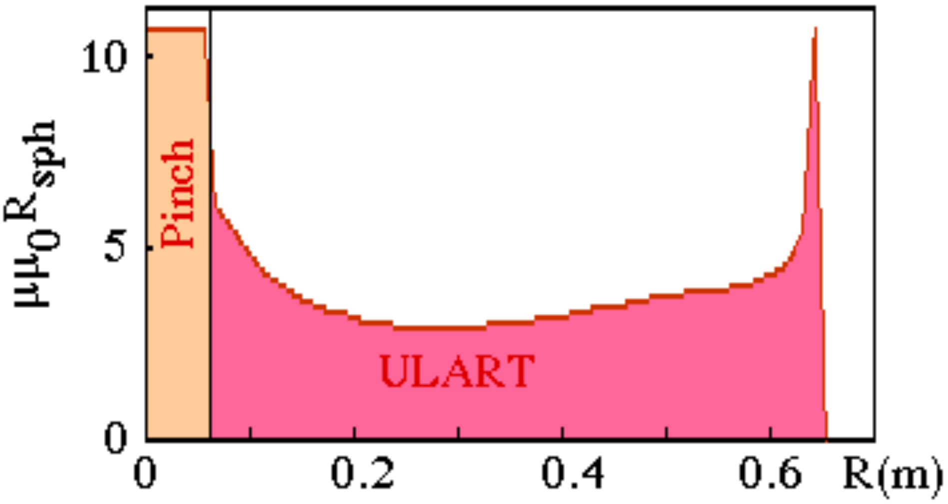
q values are still Tokamak-like





Simple calculation of MHD stability
gives stability to rigid Vertical/Shift and Tilt modes

The ULART of SPHERA could show a tendency toward a force-free quasi relaxed state, i.e. with $\mu_0\mu = \mathbf{j}\cdot\mathbf{B}/B^2$ almost constant upon the plasma

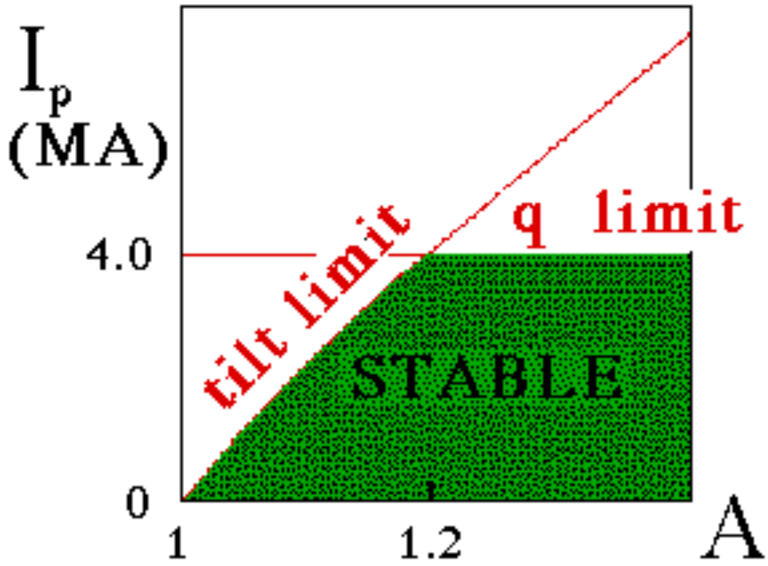


To reduce ohmic dissipation in the Screw-Pinch
⇒ reduce A at fixed $j_{Pinch}(0) = 3.2\ 10^7$ A/m^2, ...but...

$$I_p \le j_{Pinch}(0) 2\kappa^2 a^2/(\pi\, q_\psi) \qquad q_\psi \text{ limit}$$
$$I_p \le j_{Pinch}(0) \pi \kappa^{3/2} a^2 (A-1)/2A^{1/2} \qquad \text{tilt}$$

[Yamada, M., Pomphrey, N., Morita, A., Ono, Y., Katsurai, M., Nucl. Fus. '96]

With q_ψ=4.0, κ=3, vertical field C_L=0.65 and n*=0.07



COMPRESSION

Reduction of A & increase of $I_p \Rightarrow$ increase of I_ϕ^{Pinch}

Compression to A=1.1 with I_p=5.0 MA, I_e=0.365 MA

Combined Equilibrium: Force-Free Pinch (I_ϕ^{Pinch}=3.1 MA)

+ULART (I_ϕ^{ULART}=5.0 MA)

unstable to rigid Tilt modes

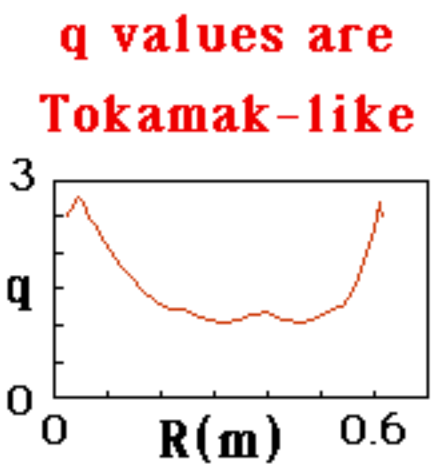
To reduce ohmic dissipation in the Screw-Pinch

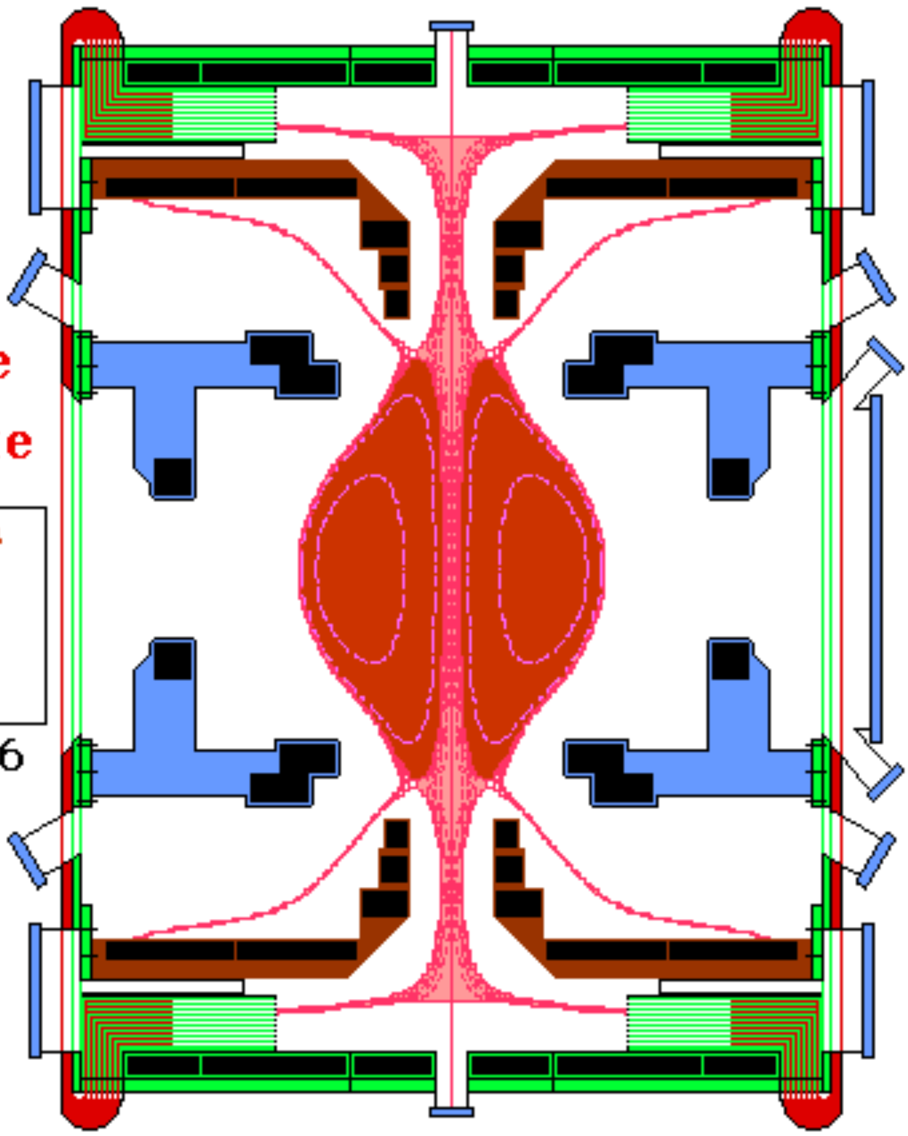
Compression to A=1.1 with I_p=2.7 MA, I_e=0.091 MA

Combined Equilibrium: Force-Free Pinch (I_ϕ^{Pinch}=0.4 MA)

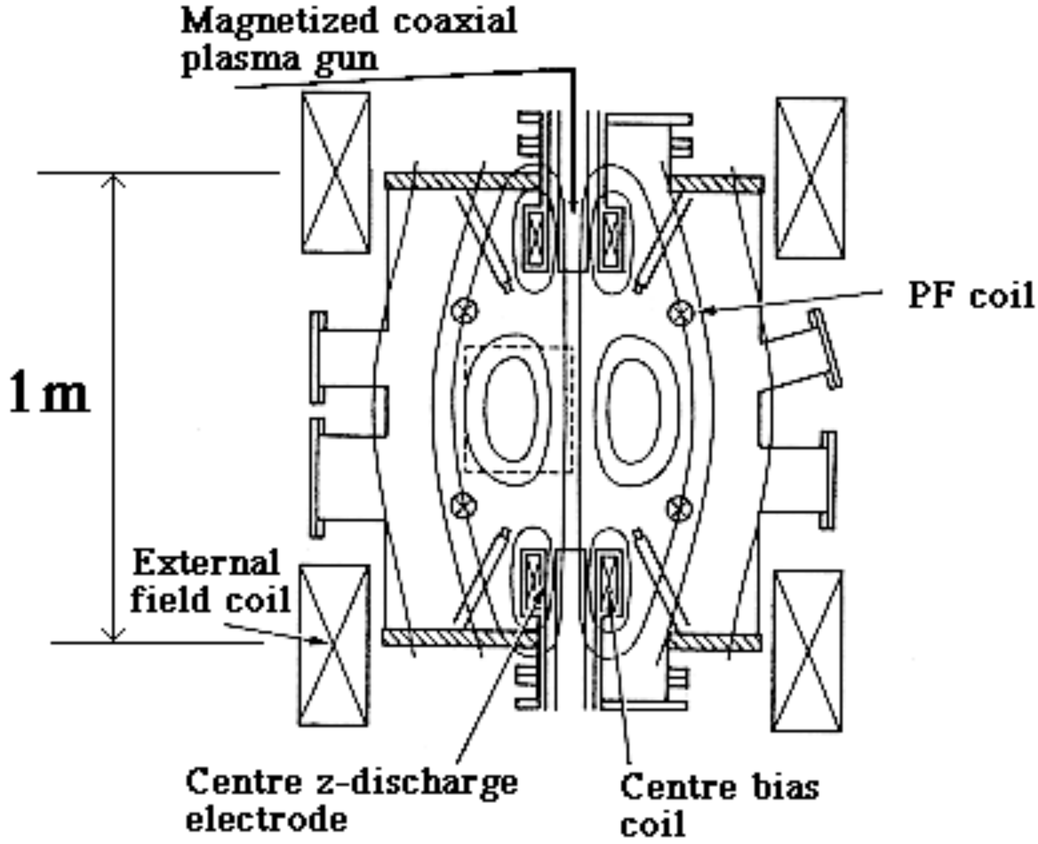
+ULART (I_ϕ^{ULART}=2.7 MA)

stable to rigid Vertical/Shift and Tilt modes

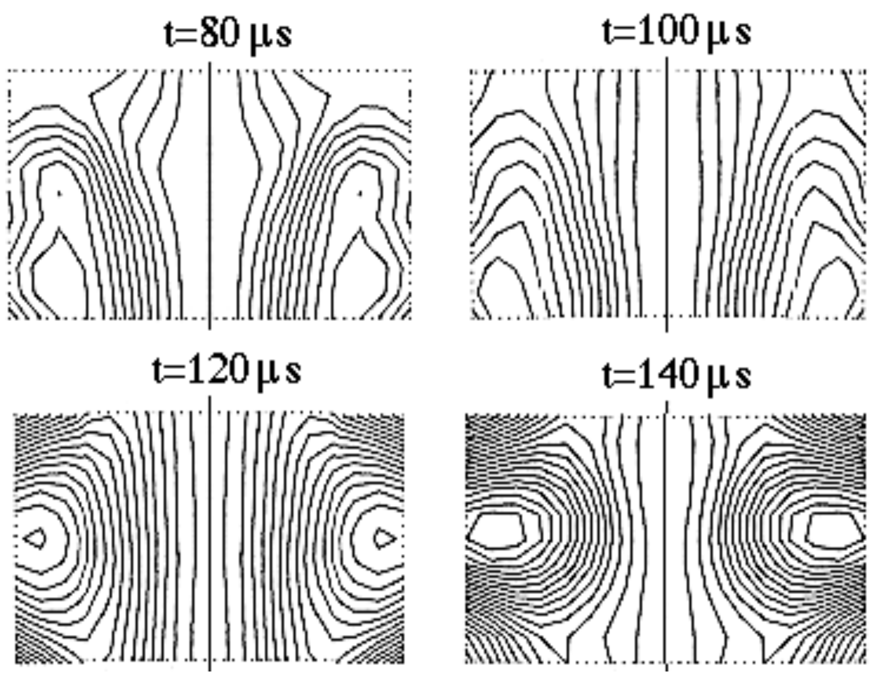




Stable (tens of τ_A) similar configuration produced & compressed in TS-3 (Tokyo University) [Amemiya, JPSJ '93]



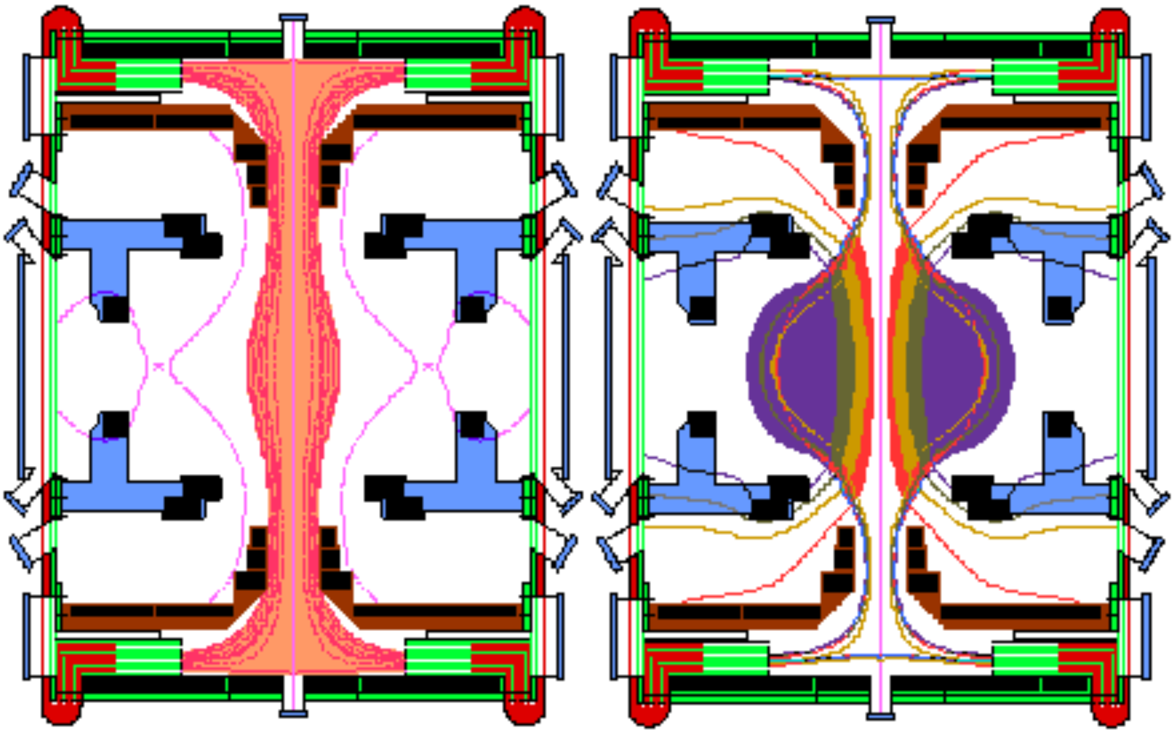
ULART produced by Helicity Injection, from the unstable Screw Pinch obtained between the plasma guns.
Compression: the tilt stability limit is $q_\psi \geq 2$-3



FORMATION

The idea of the SPHERA experiment is to drive the plasma, through a particular formation and compression scheme, toward a stable state with $\mu_0\mu R_{sph} < 4.49$, starting from tokamak-like configuration

Double breakdown in the same vacuum vessel is one of the main difficulties, but also a point of interest of SPHERA



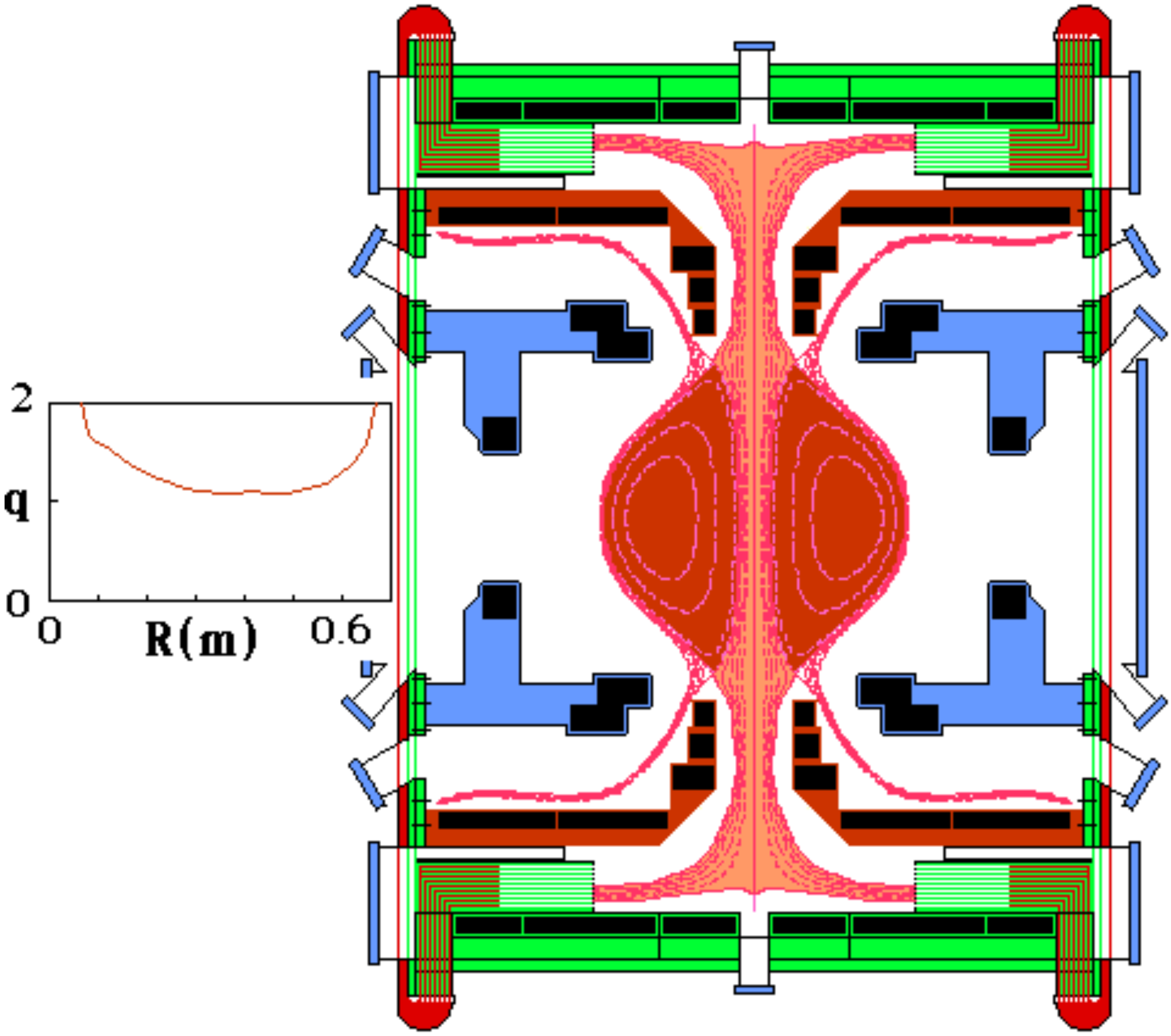
Pinch Breakdown
Preionisation140 Ghz
(2.5 T at Z=±0.6, ±1.2 m)
I_e=365 kA-3 msec
q_{Pinch}>2
τ_{Skin} (50 eV)=20 msec

Tokamak Breakdown
Preionisation 2.45 GHz
(0.09 T at R=0.83 m)
Compression to 0.7 MA-24 msec
q_{ULART}=2.5-3.0
Flux for $n_e=n_{eGreenwald}$

To avoid rigid Vertical & Tilt/Shift instability during the compression the secondary vacuum vessel **is a stabilising shell for a few tens of ms**

VERSATILITY

secondary vacuum vessel and electrodes movable by 20 cm to obtain variable elongation down to κ=1.8



κ=2 configuration is more stable to rigid Vertical & Tilt/Shift during the compression even without the stabilising shell

κ=2 configuration has safety factor more similar to a Spheromak

KEY-POINTS OF SPHERA

- **obtaining and sustaining the Pinch-ULART configuration**
- **controlling the Helicity Injection and the Magnetic Relaxation**
- **exploring the resulting confinement and β limits**

If the operation of the central Screw Pinch as an Helicity Injector is successful and requires a moderate power level, the SPHERA Experiment could be run for a few seconds

Greenwald density limit $\langle n_e^{max} \rangle = 1 \cdot 10^{21}\ m^{-3}$ at $I_p = 2.7$ MA
$\langle n_e^{max} \rangle = 4 \cdot 10^{20}\ m^{-3}$ at $I_p = 1.0$ MA

Assuming efficiency of Helicity Injection ε=0.4 and
Lackner-Gottardi energy confinement scaling,
the power necessary for the Helicity Injection:
$P_{HI} \leq 3.4$ MW (at the Greenwald density limit)
$P_{HI} > P_{Hmode}^{ASDEX}$ (at all densities)

SPHERA κ=2

I_p (MA)	$\langle n_e \rangle$ 10^{20} m^{-3}	P_{HI} (MW)	$H \cdot \tau_E^{LG}$ (ms)	$\langle T_e \rangle$ (eV)	$\langle \beta \rangle$ %	β_{pol}	t_{plasma} (s)
2.7	10.	3.4	H•60	H•384	H•21	H•0.24	Steady
2.7	1.0	0.9	H•53	H•898	H•5	H•0.06	Steady
1.0	4.0	0.7	H•87	H•290	H•23	H•0.50	Steady
1.0	0.4	0.2	H•74	H•700	H•6	H•0.12	Steady

Paramagnetism 150% κ=2.3 I_p=1 MA
450% ! κ=2.3 I_p=2.7 MA
300% ! κ=3.0 I_p=2.7 MA

13

SCREW PINCH

Simple model for the Screw Pinch, assumes constant plasma temperature along the field lines and negligible radial losses:
$T_{Pinch} \approx 50$ eV, $n_{Pinch} \approx 1 \cdot 10^{20}$ m^{-3}

Ohmic dissipation inside the Pinch:

$P_{ohPinch} = 17\ Z_{eff}$ MW with $\rho_{Pinch} = 0.06$ m (A = 1.2)

Allowing for variations of ρ_{Pinch} (A < 1.2)

$P_{ohPinch} = 17\ (\rho_{Pinch}/0.06)^2\ Z_{eff}$ MW

(P_{HI} independent upon ρ_{Pinch})

So lowering A can reduce the ohmic dissipation in the Screw Pinch if κ=3 ULART is stable to Tilt modes

Russian experiments on stabilised and sustained Screw Pinches more than 30 years ago [Golovin, IAEA '62]:

- Experiment in quartz cylinders 70 cm long
  $0 < B_z < 2.7$ T
- Plane and hemispherical Fe and Cu electrodes with diameters of 4 to 17 cm
- Currents in the range $3 < I_e < 300$ kA for 2 msec (AC)
- The filling Deuterium pressure $5\ 10^{-3} < p_D < 5$ Torr
- **j** aligned to **B** (quasi force-free)
- MHD stable for 2 ms (AC) if $q_{Pinch} > 2$
- Temperatures $10 < T_e < 100$ eV
- Ionisation degree 20% < x < 100%

ELECTRODES

Minimise damages and impurity influx

"Hollow Cathodes" [Lidsky, Journ. Appl. Phys. '62]

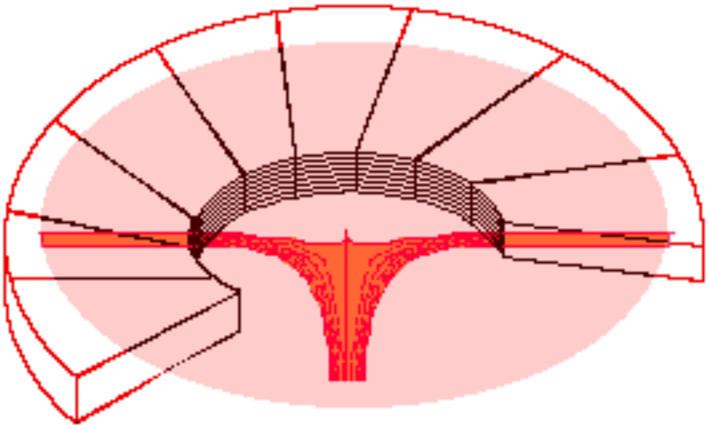
- **Extended emission surface of refractory metal**
- **Heating by impact of positive ions from anode**
- **Positive space charge-efficient electron extraction**
- **Electrons confined in the hollow geometry $B_{||}$ & $E^{\sim}$**
  Positive ions will recombine and reionise many times before escaping as neutrals at the rear-strong ion density gradient

"Hollow Anodes" [Gibbons, Proc. V Int. Conf. Ion. Phenom. in Gases '61]

- **Arc discharges run for many hours without deterioration of electrodes**
  1-3 m long, 1 cm^2 cross section, 4 Torr·l/sec,
  0.7 T stabilising field, I_e=150 A at V_e<100 Volt
- **Able to withstand high heat fluxes (15 kW/cm^2) at the entrance of the tubes**
- **Able to sustain 150 A/cm^2 at the entrance of the tubes**
- **Plasma parameters: $n_e=10^{20}$ m^{-3}, T_e=50 eV,**
  impurity level < 0.1%
- **Positive ions recombined & reionised several times by gas injection from the end of the anode**

Large number of elementary tubes of refractory metal (hollow cathodes and hollow anodes)

The lines of force can be made horizontally straight

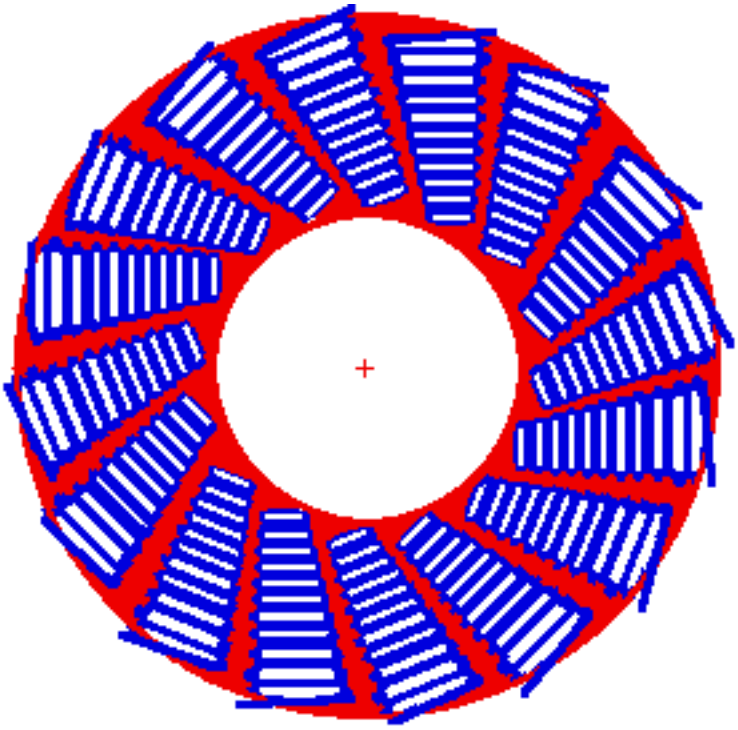


Side view of hollow anode/cathode electrodes

Radius of electrodes at the entrance: 70 cm
Width of plasma at the entrance: 6 cm

I_e^{max} = 400 kA (with 150 A/cm^2)

P_e^{max} = 40 MW (with 15 kW/cm^2)



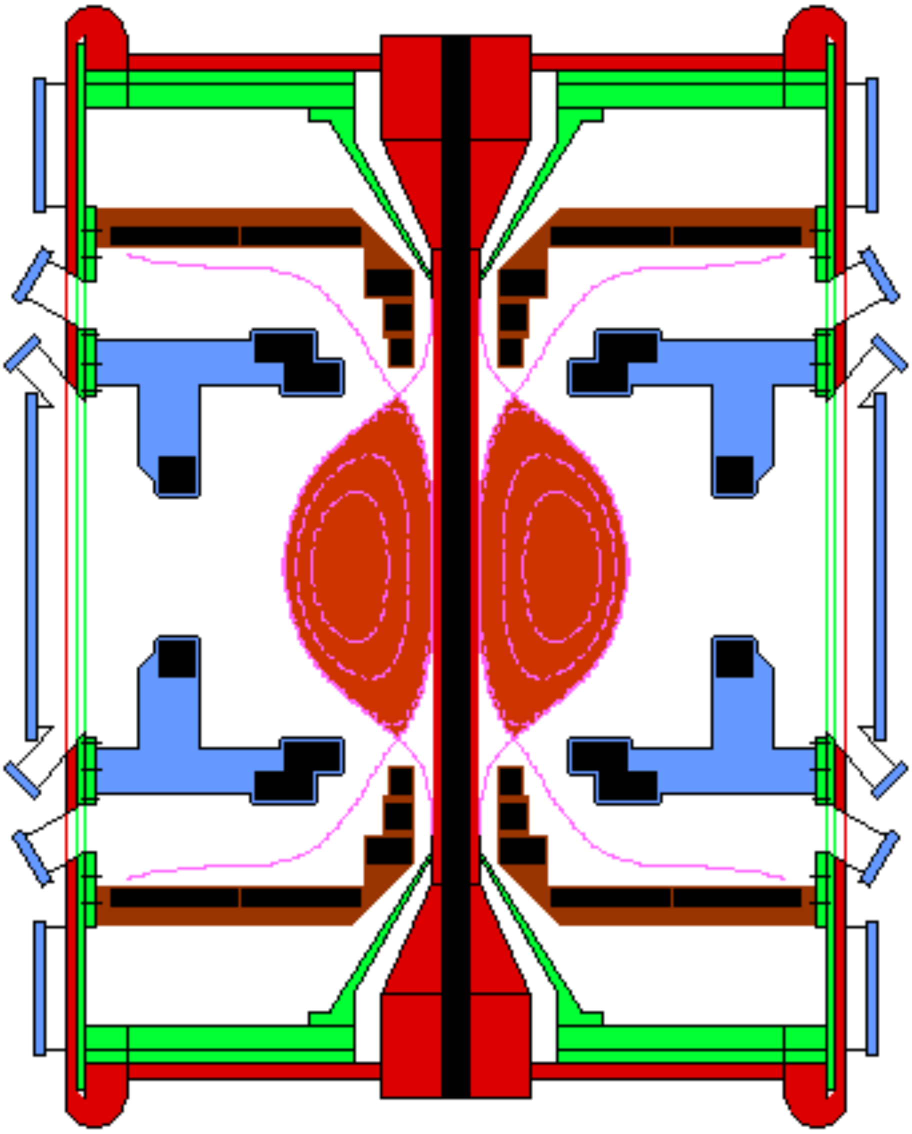
Top view of resistive tubes tight wound coil to obtain collector depressing & dissipate most of the energy in volume Joule heating

Gas removal from rear of the cathode requires high pumping speed
SPHERA with the central Screw Pinch has to be prepared through preliminary simpler experiments, in which a central rod is present:

SPHERA-OH

Central rod, ohmic solenoid (130 mWb) and NBI (4 MW)
B_{T0}=0.5 T, B_T=0.7 T at R=0.36m (I_{tf}=891 kA),
I_p=1 MA, $q_\psi \approx 5$, R=0.39 m, a=0.30 m, A=1.3

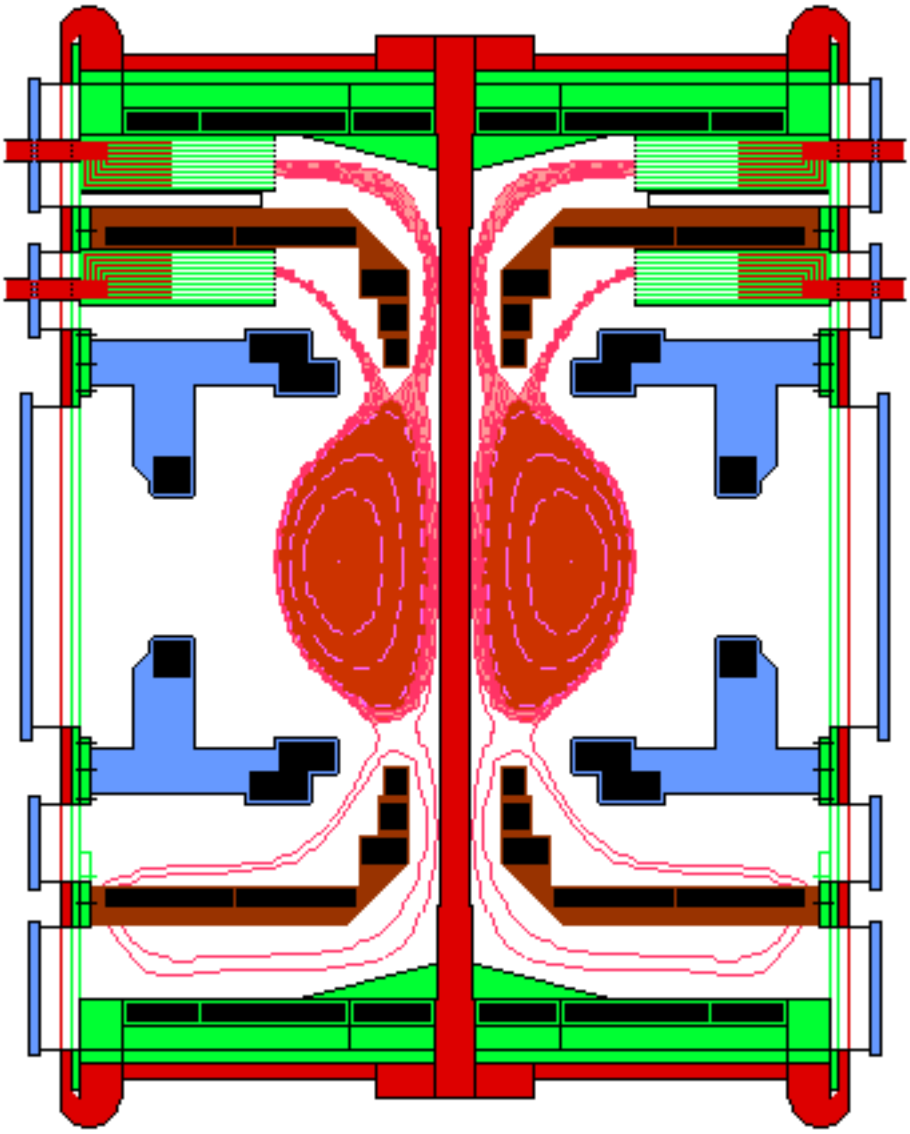
Main purpose:
- to work out the formation/compression scheme
- to establish a ohmic/NBI reference plasma



SPHERA-HI

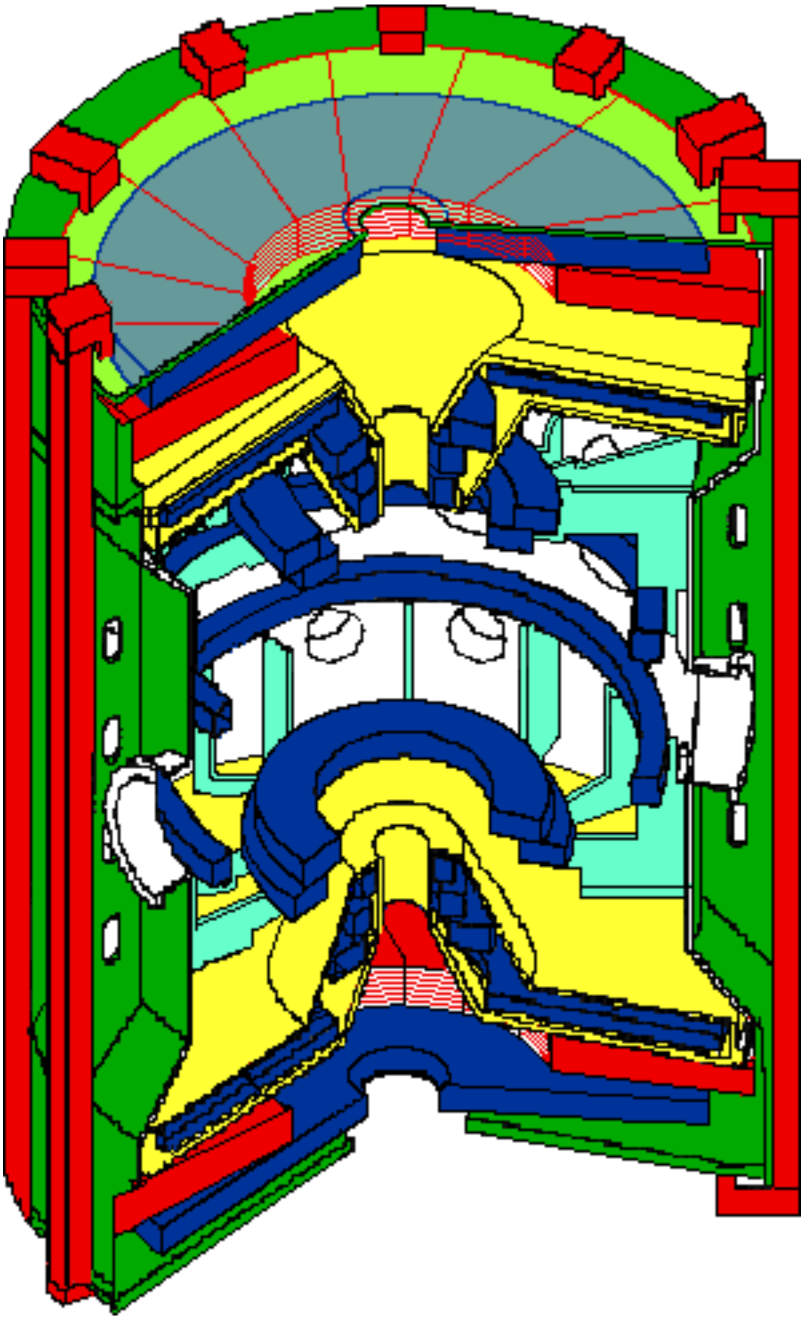
Central rod B_{T0}=0.33 T at R=0.36m (I_{tf}=0.6 MA)
R=0.385 m, a=0.295 m, A=1.30, I_p=1 MA, $q_\psi \approx 3$

Main purpose:
- to test the HICD with hollow anode/cathode electrodes
- to prepare the Pinch scenario



LOAD ASSEMBLY

- Vacuum vessel: cylinder with two enclosures
- 12 inserts sustain the poloidal field coils
- Toroidal magnet return coils (modulus 12) and hollow anode/cathode electrodes
- Divertor poloidal field coils contained inside a Secondary vacuum vessels acting as a stabilising shell
- Secondary vacuum vessel and electrodes movable by 20 cm to obtain variable elongation κ=1.8-3



STRESS ON THE CENTRAL CONDUCTOR

In case of a non-axisymmetric tilt disruption → net force on the central conductor

Preliminary conservative assessment:
need of lowering the clamping of the central conductor in SPHERA-OH → no internal divertor branch

POLOIDAL FIELD COILS: NO STRESS PROBLEMS!

POWER SUPPLY WITH CENTRAL CONDUCTOR (OH-HI)

Existing power supply and feeders are adequate

POWER SUPPLY FOR SPHERA WITH CENTRAL PINCH

- Existing commutation systems to be upgraded
- New commutations systems to be built
- 1-4 MW power feeders to be built
- Power for the Pinch extracted from the grid (40 MW)

COSTS

Load assembly	⇒ 13 M$
NBI system	⇒ 7 M$
Power supply	⇒ 6 M$
Total	⇒ 26 M$