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Results of Proto-Pinch Testbench for the Proto-Sphera experiment

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I - Introduction

The Proto-Sphera experiment (Spherical Plasma for HElicity Relaxation Assessment), which will be built at Frascati, will be devoted to demonstrate the feasibility of a Spherical Torus (ST) where a Hydrogen plasma arc (a screw pinch fed by electrodes) replaces the central conductor. The screw pinch will be formed at a current I_e=8 kA, which guarantees MHD stability, as the safety factor of the pinch will be q_{Pinch}~2. Rising the electrode current up to I_e=60 kA, the screw pinch will become unstable, because q_{Pinch}«1. During the instability the poloidal compression coils will be pulsed and the ST will be generated around the screw pinch.

The main goals of the Proto-Sphera experiment will be to compress the ST to the lowest possible aspect ratio, in a time of about 1500 AlfvØn times, and to show that efficient helicity injection can maintain a stable configuration for at least one resistive time (50 ms).

The benchmark Proto-Pinch has been built and operated, with the goal of testing modular units of the cathode and of the anode. Proto-Pinch has produced, within a Pyrex vacuum vessel, Hydrogen and Helium arcs in the form of screw pinch discharges, stabilized by two poloidal field coils located outside the vacuum. Proto-Pinch, with an anode-cathode distance of 0.75 m and a stabilizing magnetic field up to B=1.5 kG, has a current capability of I_e=1 kA, (with a safety factor q_e ~ 2 The extrapolation to the 100 cathode modules required for Proto-Sphera, shows that the cathode will be heated by a total AC current I_{cath}=60 kA (rms), with a total heating power P_{cath}=850 kW.

II - Toroidal Plasma Formation and the TS-3 Experiment

The formation of the ST is obtained by the kink destabilization of a screw pinch, through an increase of the longitudinal arc current, as demonstrated on the TS-3 experiment (University of Tokyo). Figure 1 sketches the linear and nonlinear phase of a kink unstable screw pinch, with longitudinal field B_Z and toroidal field B , that means a pinch winding number $q_{Pinch} = 2\pi\, \rho_{Pinch}\, B_Z / L_{Pinch}\, B_\phi$..

The Proto-Sphera experiment aims at sustaining the toroidal plasma, after the formation, through DC helicity injection. Resistive MHD instabilities convert, through magnetic reconnections, open current/field lines into closed current/field lines winding on the closed magnetic flux surfaces. Magnetic reconnections necessarily break, through helical perturbations, the axial symmetry, as per Cowling s anti-dynamo theorem [2].

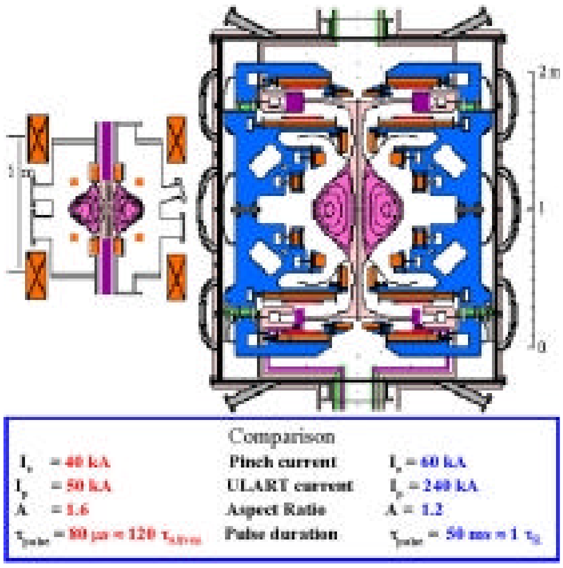

Fig. 1. TS3 and Proto-Sphera Comparison.

III - Proto-Sphera : μR_{sph}<4.49, not Spheromak solution

The literature has considered the equilibrium of a completely relaxed state, $\nabla \wedge B = \mu B$, with μ constant all over the plasma, enclosed within a perfectly conducting portion of sphere, with radius R_{sph}, fed by two electrodes upon the polar caps.

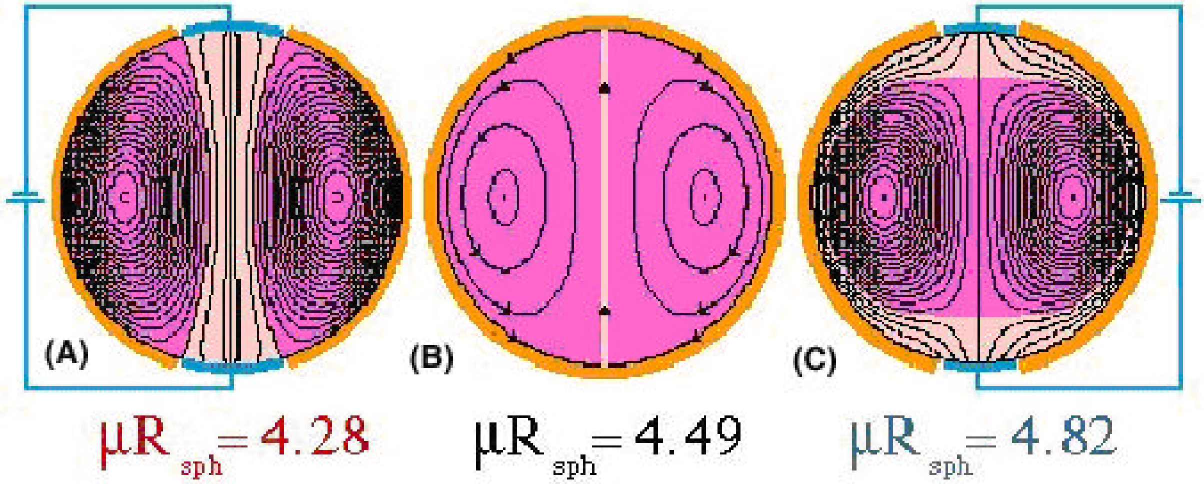

Fig. 2. Flux-core spheromak configurations with different relaxation parameter μR_{sph}.

If μR_{sph}=4.49 the well known spheromak solution [3] (see Fig. 3B), with B n=0 all over the sphere is obtained. However the spheromak configuration is very unstable, mainly due to the low value of the safety factor (q_ψ~0.6, q_{axis}~0.9) and it is prone to rotations and translations of the symmetry axis. For values μR_{sph}>4.49 a plasma current flows around the spherical torus. The result of an equilibrium calculation by Taylor and Turner with μR_{sph}=4.82 is shown in Fig. 3C. The Taylor's helicity injection theory [4] predicts that the configurations with μR_{sph}>4.49 are ideal MHD unstable. When μR_{sph}<4.49 a solution similar to Proto-Sphera is obtained.

A plasma current flows within the hole of the spherical torus (screw pinch). The result of an equilibrium calculation by Taylor and Turner with μR_{sph}=4.28 is shown in Fig. 3A. The Taylor's helicity injection theory [4] predicts that the configurations with μR_{sph}<4.49 are ideal MHD stable.

The overall plasma of Proto-Sphera could show a tendency toward a force-free quasi relaxed state, i.e. with $\mu = \mu_0 j\, B/B^2$ almost constant everywhere. The idea of the Proto-Sphera experiment is to drive the plasma, through a formation and compression scheme, toward a stable state with μR_{sph}<4.49, by increasing the value of μ, but maintaining in the spherical torus safety factor values (q_0~1, q_ψ~3-4) typical of a tokamak, with the aim of controlling the magnetic helicity flow toward the toroidal magnetic axis and of avoiding the complete relaxation of the system.

IV - Cathode the most unconventional item.

The main constraints in the physical design of Proto-Sphera have been the current densities, both in the plasma as well as in the poloidal field coils:

At the plasma-cathode interface: the maximum current density experimentally demonstrated on the electrode's testbench PROTO-PINCH as been j_e 100 A/cm^2, when the cross section of a single emitting filament is considered. This figure limits the total pinch current I_e, emerging

from the plasma-cathode interface, which has the shape of a ribbon with radius R_{el}=0.4 m and $I_e=2\pi R_{el}\Delta Z$ 100A/cm^2 60 kA.
The electrodes are the most unconventional items of Proto-Sphera. They are designed as modular (~120 modules) and are composed by a large number of elementary tubes and wires (~400). The electrodes are made out of refractory metal (directly heated cathodes and hollow gas puffed anodes) and pressed radially in a disk. Fig. 3 shows Proto-sphera cathode.

Proto Sphera Cathode	Module for Sector :21	Total Module : 126
Coils for module : 3	Total Coils : 378	Emission for coil : 170 A
Total Current : 63882 A		Main Sectors 6

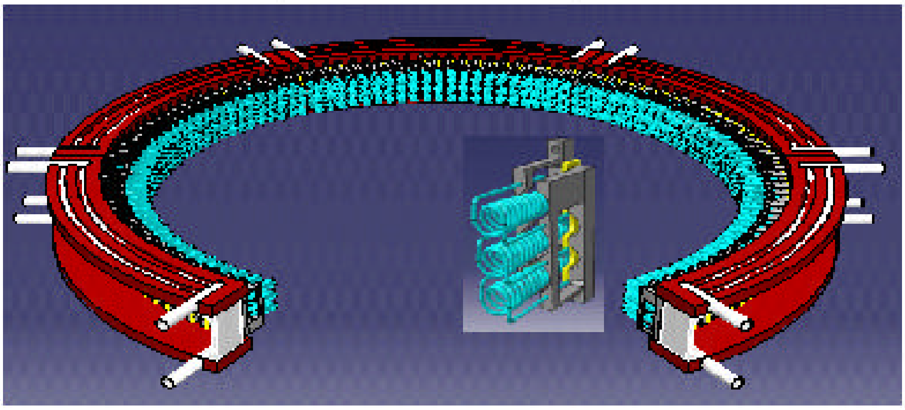

Fig. 3. Drawing and main features of Proto-Sphera Cathode

V - Proto-Pinch Experiment

Before building Proto-Sphera, the electrodes   benchmark Proto-Pinch (see scheme in Fig. 4) has been built and operated, with the goal of testing modular units of the cathode and of the anode of Proto-Sphera.

Main Results of Proto-Pinch experiment:

- Directly heated (AC) W-Th(2%) cathode and a Cu-W hollow anode, with H_2 (or He) puffed through it.
- The Hydrogen pinch breakdown occurs in the filling pressure range p_H=1 10^{-3}÷ 1 10^{-2} mbar, which is the same of a standard Tokamak discharge.
- The pinch breakdown voltage is $V_e \approx 100$ V, which means no insulation problems in PROTO-SPHERA
- The typical duration of a plasma pulse at I_e=600 A is 2÷ 5 s, limited by heating of Pyrex, rubber seals, etc
- The arc plasma is very clean: a few barely measurable impurity lines appear in Hydrogen and in Helium discharges at lowest filling pressures (1÷ 2 10^{-3} mbar).
- Anode and cathode have withstood 400 discharges with the current and the power densities required for Proto-Sphera

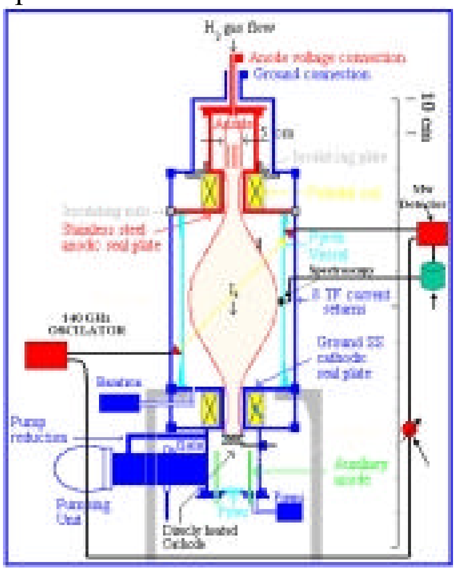

Fig. 4. Proto-Pinch scheme.

VI - Proto-Pinch Progress

Proto-Pinch has produced Hydrogen and Helium arcs in the form of screw pinch discharges. Following a trial and error procedure about 3 anode prototypes and 10 cathode prototypes have been tested on Proto-Pinch from October 1998 to September 1999 (see Fig. 4).

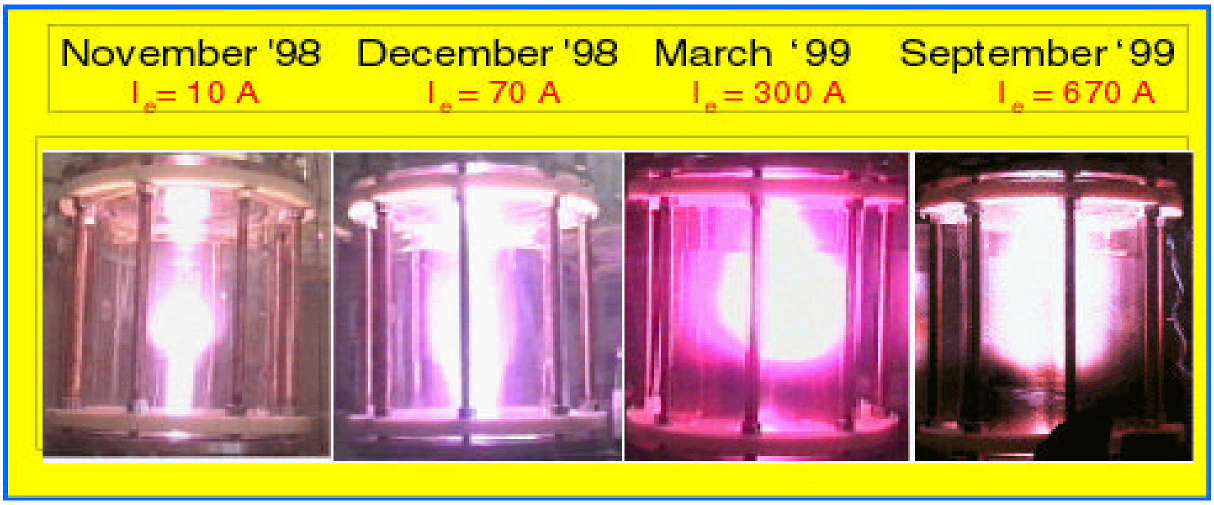

Fig. 4. Progress of Proto-Pinch experiment.

VII - Impurities and Density Diagnostics

The plasma visible light is collected by a telescope and focused onto 1 mm diameter fiber optics : linear dispersion 13 nm/mm. The detector is an intensified diode array with 1024 pixels and spectral resolution of 3 A° /pixel

H_2 and Helium plasma discharges were run, the spectroscopic measurements did show barely perceptible impurity lines at a count level of about 10^{-2} of the largest line counts. (see Fig. 5) Spectroscopy measurements fix $1eV<T_e<3.5eV$.

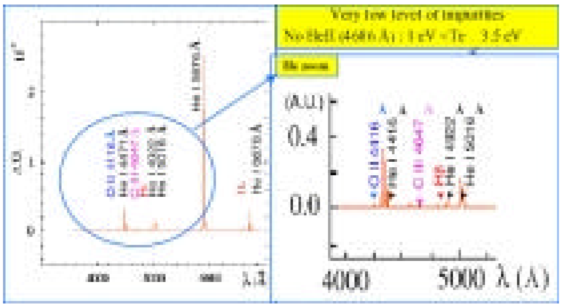

Fig. 5. Impurities in He Discharge

Density measurements has been done by means of a microwave interferometer with a 140 GHz generator. Up to now measurements have been done with He gas, line integrated density, as shown in Fig. 6, is $D = 1.4\ 10^{19}\ m^{-3}$.

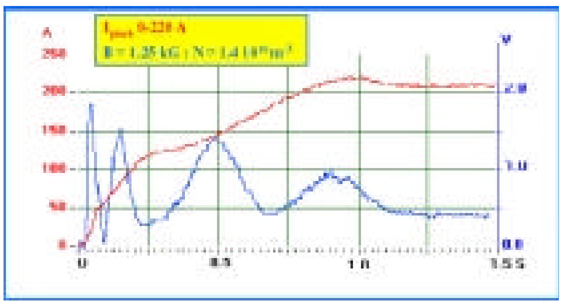

Fig. 6. Density measurement in He Discharge

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