Commissioning of the Plasma Central Column for the PROTO-SPHERA Spherical Tokamak

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***Abstract*—PROTO-SPHERA is the first plasma project with a simply connected configuration, namely not requiring other objects inside the plasma. This is obtained by a hydrogen plasma arc, shaped as a screw pinch, acting as the central column of a spherical torus with minimal aspect ratio. The reduced size and complexity of the configuration can lead to several physical and engineering advantages, providing relevant contributions to the magnetic plasma confinement methods. Moreover, due to the limited costs and requirements, the set-up is attractive for replication and developments also on an industrial scale with many potential applications. This paper describes the initial activities of the PROTO-SPHERA project, with emphasis on the electrical tests and commissioning performed to implement the plasma central column. In particular, an intermediated experiment classified as MULTI-PINCH was designed to investigate the breakdown conditions and the pinch stability.**

Keywords—AC/DC converter; nuclear fusion energy; power inverter; plasma physics; spherical tokamak; pinch

I. INTRODUCTION

The most investigated magnetic plasma configurations (tokamaks, reversed field pinch, stellarator) are not simply connected. In fact, the elements contained in the central post, as the inner part of the toroidal magnets and the ohmic transformer (solenoid), are crucial for the tokamak operations. The feasibility of a simply connected magnetic configuration would remarkably simplify the design of a nuclear fusion reactor [1-4].

A spherical tokamak would have the important advantage of allowing for large toroidal plasma current with a low value of the toroidal magnetic field [5, 6]. However, it would unfortunately concentrate most of its engineering difficulties around the toroidal field center stack [6, 7], where the magnetic fields and therefore the electromechanical stresses are the highest, and which, due to its slimness, cannot be shielded from neutrons. In the same way, the almost inexistent space allowable for a central makes it mandatory to sustain also a magnetic fusion configuration of this kind through current drive, which would become particularly demanding due to the large toroidal plasma current and density and to the low value of the toroidal magnetic field.

An intriguing possibility is to replace the central post current with the plasma current of a screw pinch driven by electrodes (anode and cathode). The PROTO-SPHERA (Spherical Plasma for HElicity Relaxation Assessment) project developed at ENEA Frascati aims to demonstrate the feasibility of a spherical torus triggered from a hydrogen plasma arc fed by the electrodes [1-4].

Moreover, PROTO-SPHERA is the first plasma experiment with a simply connected configuration and closed flux surfaces. The magnetic configuration is expected to provide an elongated spherical plasma with a minimal geometrical size (70 cm diameter). Anyway, the toroidal plasma current and related magnetic field would have the same characteristics of those induced in a standard tokamak.

The minimal size and complexity of the structure result in engineering advantages (simpler manufacture and handling, improved reliability) but several physical points (plasma confinement and stability) have to be assessed by the experiments. Even though the confinement magnetic field would be simpler, the helicity injection from the screw pinch to the toroidal plasma closed surfaces should be able to sustain the plasma current inside the torus through cyclic reconnection oscillations of the magnetic configuration.

The success of PROTO-SPHERA could provide relevant contributions in many plasma applications (fusion energy reactors, standard tokamaks, spherical tokamaks, spheromaks, reversed field configurations, material characterization, propulsion engines, astrophysical phenomena). In particular, the relevance of compact configurations was emphasized by recent studies showing that the energy gain achievable in a nuclear fusion device weakly depends on the device size, implying that useful performances can be obtained also in relatively small devices [8].

This paper describes the initial activities of the PROTO-SPHERA project, with emphasis on the electrical tests and commissioning performed to implement the plasma central column. The most critical items for the experiment start-up concern:

1. The plasma breakdown conditions.
2. The pinch stability in the starting phase of the discharge.

In order to investigate these crucial topics and to solve any possible arising problem, the PROTO-SPHERA set-up was simplified and adapted to obtain an intermediated experiment classified as MULTI-PINCH [1].

II. PROTO-SPHERA Physics and Engineering

A. Vessel Configuration and Commissioning

The innovative PROTO-SPHERA design was validated on a prototype test-bench called PROTO-PINCH [9].

In order to compare the plasma performances of PROTO-SPHERA with those of a spherical tokamak with metal central post, geometrical size and plasma currents very similar to the ones of the pioneering spherical tokamak experiment START, operated in Culham from 1991 to 1998, have been chosen. Within that framework of a collaboration between the Italian and the British associations, in 2004 UKAEA donated to ENEA the START vacuum vessel. This was adapted for the new experiments by ASG Superconductors (Genoa, Italy) and shipped to ENEA in 2010.

As shown in Fig. 1, the resulting PROTO-SPHERA load-assembly is contained in a cylindrical vacuum vessel having and height of 2.5 m and a diameter of 2.1 m. This vacuum vessel includes also two sets of poloidal field coils, each composed by coils connected in series. The first set of coils already built shapes the screw pinch and its current does not vary during the plasma evolution. A second set of coils which compress the spherical torus and whose currents vary during the plasma evolution will be built after the successful completion of the first phase of the experiment.

B. Functions of the Anode and Cathode Electrodes

The anode and cathode electrodes supplying the pinch arc are placed on the vessel top and bottom, respectively. The arc current has a reclosing path outside the vacuum vessel through eight copper bars (see Fig. 1).

The cathode consists of tungsten filaments having a special conic-spiral shape (shown in Fig. 2) designed to optimize the thermionic effect limiting the electromagnetic interferences. The cathode power supply is designed to heat these filament up to about 2600 °C. The electrons emitted by the filaments due to the thermionic effect produce the required plasma by ionizing the hydrogen injected from the top (in the anode region).

In this situation, an anode voltage in the order of 150 V should be sufficient to form the screw pinch. This value was estimated by scaling the corresponding value of about 100 V found in the PROTO-PINCH test-bench [9]. To ensure a high safety margin the pinch power supply presented in this paper was designed to overcome 300 V. Nevertheless, this is a critical point and the first outcome expected during the first experiments, also because it is difficult to determine a control strategy of the power supply based on an electrical model of the pinch formation.

In PROTO-PINCH the cathode was heated by direct current. However, an undesired phenomenon affected the experiments with direct current: the arc had a tendency to remain anchored in limited zones of the electrodes. The excessive stress of such zones would be intolerable for the PROTO-SPHERA powers. In order to distribute the arc, the cathode power supply was implemented by a six-phase alternating current, as described in Section IV.

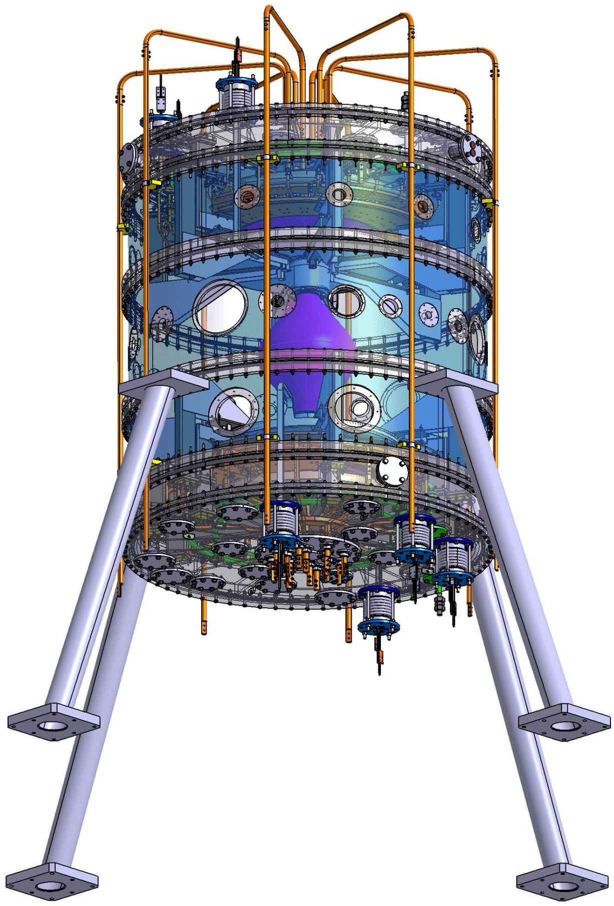


Fig. 1. Model of the PROTO-SPHERA (MULTI-PINCH) set-up, including a sketch of the plasma screw pinch.

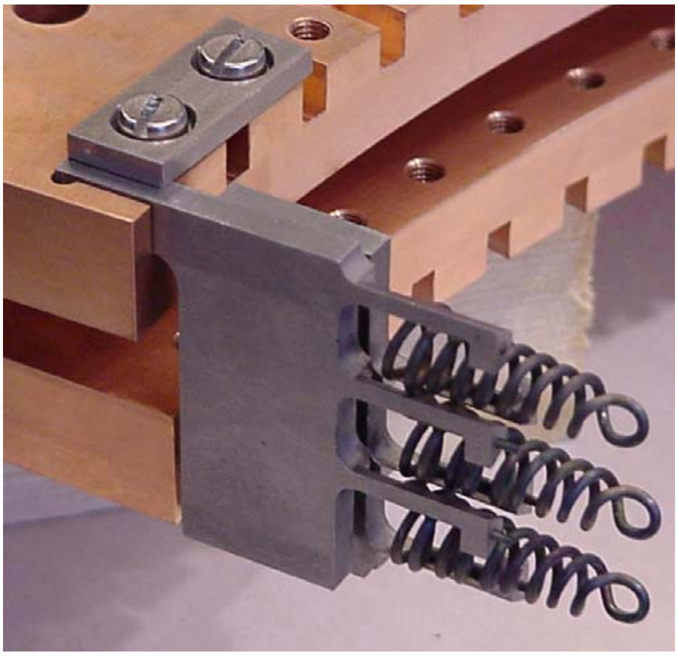


Fig. 2. Cathode module containing three tungsten filaments used to emit the electrons by thermionic effect.

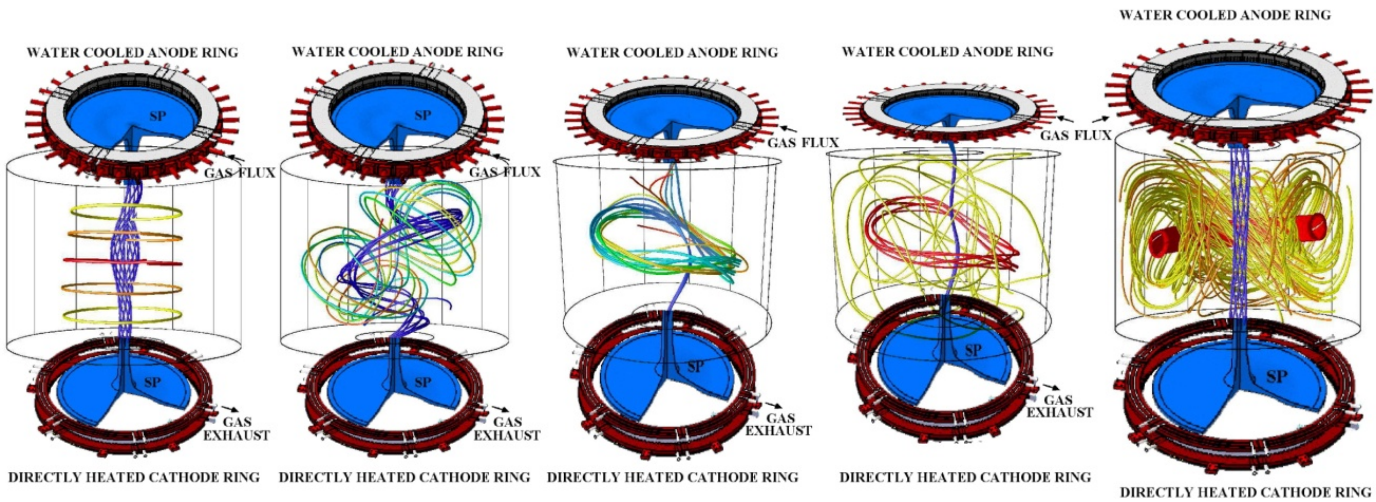


Fig. 3. Sketch of the formation and evolution of the PROTO-SPHERA central column and spherical torus plasma (developed from the 3D simulations by García Martínez and Farengo [10], [11]).

TABLE I. SUMMARY OF MULTI-PINCH POWER SUPPLIES.

Power Supply	Cathode	Pinch	Coils
Current	1.7 kA rms	10 kA	2 kA
Voltage	25 V rms	350 V	350 V
Frequency	40-150 Hz	Dc	dc
Dummy load	6 star 14 mΩ	15 mΩ	1 mH, 80 mΩ
Operating load	≈14 mΩ at 2600 °C	Arc	2 mH, 60 mΩ
Rise time	15-30 s	25 ms	50 ms
Operating time	15-31 s including ramp	≈1 s	≈1 s
Control	Voltage	Current	Current
Input voltage	380 V	20 kV	20 kV
Peak power	300 kVA	4.4 MVA	900 kVA

C. *Expected Plasma Evolution*

Fig. 3 summarizes the plasma evolution expected in PROTO-SPHERA [10], [11]. When the screw pinch acts as a central column, the resistive instabilities will drive magnetic reconnections, injecting magnetic helicity, poloidal flux and plasma current from the screw pinch into the torus and converting into plasma kinetic energy a fraction of the injected magnetic energy.

In presence of a hot cathode, the screw pinch is expected to be formed at an electrode current of about 8.5 kA, which guarantees magnetohydrodynamic (MHD) stability, as its winding number (safety factor) is $q>2$ [1, 2]. Raising the electrode current up to 60 kA, the screw pinch will become unstable with $q<<1$. During the instability the poloidal field compression coils will be pulsed and the spherical torus will be generated around the screw pinch, driven in part by the inductive flux and in part by the helicity injection.

PROTO-SPHERA aims to compress a spherical tokamak to the lowest possible aspect ratio (1.2÷1.3) in a time of about 1800 Alfvén times (≈1 ms) and to show that efficient helicity injection can sustain the spherical torus around the screw pinch for at least one resistive time (≈70 ms). The edge safety factor resulting from the longitudinal current (60 kA) and from the toroidal current (120÷240 kA) will be $q\approx2.5\div3$ [1, 2]. This will produce a substantial high β plasma, up to 30% [2].

The reported pinch currents may appear extraordinary both in magnitude and in derivative, but they are usual for a standard tokamak. Just to give a comparison, the central solenoid of JT-60SA (the most relevant tokamak being assembled nowadays) is divided in four independent modules, each supplied by a ±20 kA AC/DC converter together with a dedicated fast (<1 ms at 20 kA switching unit for the plasma breakdown and ramp-up [12].

III. MULTI-PINCH AND THE CENTRAL COLUMN

In order to investigate the plasma behavior before the formation of the spherical torus, the set-up was adapted to an intermediated step classified as MULTI-PINCH, designed to investigate the breakdown conditions and the pinch stability in this phase. To this aim, in MULTI-PINCH the central column was operated and monitored reproducing the conditions of the first phase of the PROTO-SPHERA discharge in absence of the spherical torus and precisely:

- The pinch current is limited to 10 kA, but keeping the full voltage (350 V) to ensure and characterize the breakdown.
- The cathode is adapted and scaled for the pinch (plasma) current. The cathode is the final PROTO-SPHERA cathode, but only partially filled with the tungsten filaments (54 in 18 modules instead of 378 in 126 modules). Each installed filament is heated by its nominal current (150 A) and current density (1 MA/m^2), requiring a cathode heating power supply at 1.7 kA rms and 25 V rms.

- Only a subset (the 8 plasma shaping coils close to the electrodes) of the poloidal field coils is installed. This is necessary to give the arc the desired shape. The used 8 coils are connected in series and supplied by a single AC/DC converter.

IV. Power Supply Scenario

The power supplies for the MULTI-PINCH experiment, summarized in Table I, were delivered to ENEA in 2013. The set-up was designed to allow an easy connection of each power supply to the vacuum vessel but also to specific dummy loads.

A. Cathode Heating Power Supply

The first stage of the six phase power supplies consists in an active front end (AFE) that rectifies a three phase 400 V rms at 50 Hz. The DC voltage at the AFE output is used as input of a three phase inverter. The further required three phases are introduced by a special 380 V 3-phase / 30 V 6-phase transformer at the inverter output. The resulting power supply can reach 25 V and 1.7 kA per phase at the flat-top.

The alternating six-phase configuration introduces a rotating magnetic field with a 60° displacement between phases. Such field is expected to move the pinch reducing the aforementioned arc anchoring effect. Moreover, the use of an inverter introduced a new degree of freedom with respect to PROTO-PINCH and to the initial PROTO-SPHERA design. In particular, the experiments will investigate the effect of the cathode frequency and rotation sequence.

Even though the cathode power supply is able to operate in continuous wave, its operations have to be limited to avoid stresses and deformations in the tungsten filaments. Several preliminary simulations and tests were performed to characterize heating of the filaments. This analysis suggested to heat them by sinewaves with peak voltage increasing at a constant rate. The desired flat-top (10-20 V rms) is reached after at least 15 s and is kept for about 1 s. The actual reaching of the cathode flat-top is detected to produce a trigger for the coil and pinch power supplies. Since the rise time of these power supplies is shorter than 50 ms, all the three systems operate simultaneously at their flat-tops. The cathode inverter is immediately turned off after the pinch completion.

B. Pinch Power Supply

The pinch power supply generates and keeps the arc between the electrodes. The pinch power supply consists of a 12-pulse AC/DC converter implemented by two thyristors bridges in parallel and fed by a 20 kV / 324 V transformer with two secondary (delta and star) windings.

The converter has a current feedback regulated by a PID controller to reach the desired flat-top in the minimum time. On a resistive dummy load the flat-top current can be generated in less than 25 ms and kept for more than 1 s with a 2% ripple at full scale. When connected to the electrodes, the controller perceives an open circuit and increases the voltage up to the value necessary for the breakdown. The attainment of the breakdown corresponds to a reduction of the impedance between the electrodes, resulting in a lower voltage.

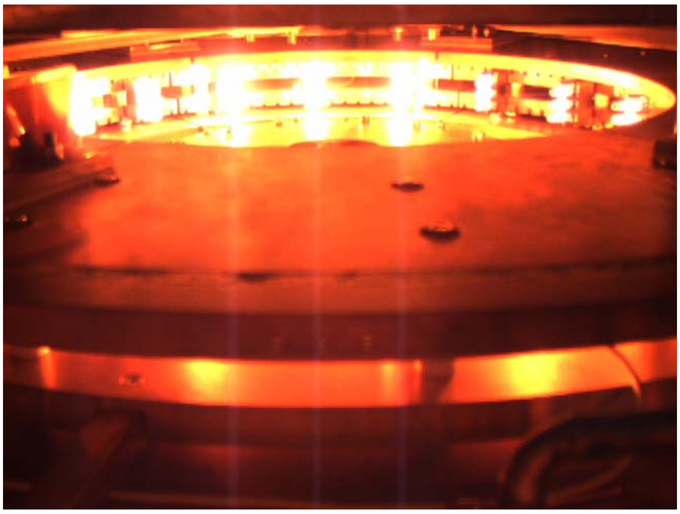


Fig. 4. Picture of the cathode taken during the heating phase.

C. Poloidal Field Coil Power Supply

The scheme of the coil power supply is very similar to that of the pinch power supply but with lower current. Moreover, since the load is inductive, no filter is used at the converter output.

While in standard tokamaks the poloidal coils are supplied by separated circuits, in PROTO-SPHERA all the coils are connected in series to the same power supply. Also further coils that could be inserted for future upgrades are designed to be connected to the same power supply.

V. Experimental Results and Discussion

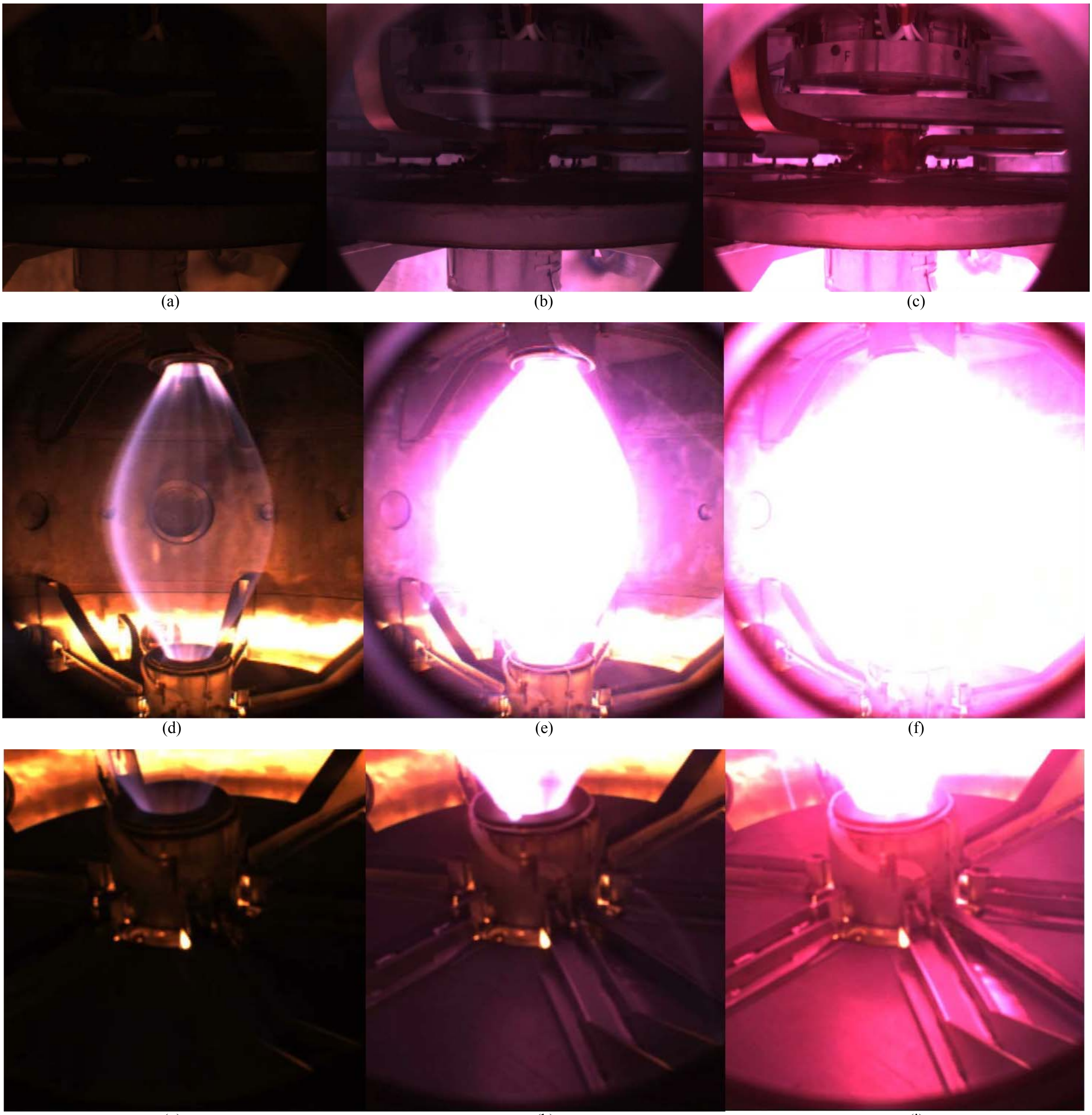
Fig. 4 and Fig. 5 show some meaningful images captured by cameras during an operating sequence of a MULTI-PINCH experiment. The cathode filaments are heated by a 15 s voltage ramp to a 15 V flat-top. The current in the poloidal coils was that expected in PROTO-SPHERA (1900 A).

The effect of the heating current on the cathode filaments on the bottom of the machine is shown in Fig. 4. No deformations or other problems were observed on these filaments after more of 350 heating cycles.

Fig. 5 describes the formation of the plasma central column. The plasma breakdown was obtained as expected in the range 170-200 V at a hydrogen filling pressure of 10^{-3}-10^{-2} mbar.

The plasma column started on the proper path, through the poloidal field throttles at both the electrodes. No anchoring phenomena were experienced. In fact, even with the limited camera resolution, it was possible to observe that the plasma local hot spots, when present (see Fig. 5d), are moved around and distributed by the cathode rotating field.

The central column was obtained with a simple provisional cylindrical anode. This specific anode was introduced to verify that the plasma breakdown was achievable over the distance of 1.4 m between anode and cathode, within the available power supply (maximum 350 V).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 5. Formation of the plasma central column. The status of three different zones are shown in three successive moments: plasma break-down, plasma current at 500 A (10 ms after breakdown), plasma current at 1500 A (20 ms after breakdown). The top row (a, b, c) was captured by a camera placed on the anode, the bottom row (g, h, i) present a detail of the plasma entering the cathode constriction coil. The images in the central row (d, e, f) are overexposed.

Since the magnetic field configuration was obviously designed for the annular anode, some undesired metallic discharges occurred from the cylindrical anode and the surrounding throttle with consequent spurious plasma discharges on the rear of anode and cathode. This limited to about 20 ms the sustainment of the central plasma column with the expected shape. Nevertheless, the compliance of the results with the targets of this experimental phase allows to proceed with the insertion of the annular anode. The new operations with this anode are supposed to sustain a plasma current of 8.5 kA for some hundreds of milliseconds. A future development would extend this current up to 60 kA [1, 13].

VI. Conclusions and Future Developments

PROTO-SPHERA is a relevant plasma experiment that reproduce many tokamak characteristic in an innovative way and introducing several advantages, in terms of plasma confinement but also in terms of handling and reliability.

The absence of components related to the central post reduces the fault probabilities, as, based on the FTU experience, they are among the most demanding and stressed elements in a tokamak.

From the point of view of the researches on magnetic fusion energy, the PROTO-SPHERA project could explore the connections between other well-known approaches and configurations:

- The described set-up can form and sustain a flux-core spheromak with a new technique.
- The safety factor profile is similar to those obtained in standard spherical tokamaks with the metal central post.
- The compression of the screw pinch, while decreasing the longitudinal pinch current, could even lead to the formation of a field reversed configuration with a new technique.
- PROTO-SPHERA could be relevant for the mainstream tokamak line to investigate biased divertors and plasma sources for NBI injectors and for high current vacuum arcs in presence of guiding magnetic fields.

As a possible far-future development, it is interesting to consider that a simply connected configuration is particularly suitable for magnetic fusion space propulsion [14].

The availability of a laboratory plasma like that obtained in PROTO-SPHERA could provide useful information also on some astrophysical phenomena, mainly solar and protostellar flares. In fact, as a matter of fact, in several astrophysical (gravity-confined) systems, unstable twisted magnetic flux tubes are able to produce, through magnetic reconnection, helical twisted toroidal plasmoids.

This paper presented the set-up and the commissioning of the first phases of the PROTO-SPHERA project. The obtained results validated the design assumptions and theoretical calculations. In fact:

1. The vessel conditions and the electrode voltage were demonstrated to be suitable for the plasma breakdown. In particular, this was obtained with an initial voltage of about 170-200 V and with a stationary voltage of about 100-150 V, in good agreement with the expectations.
2. The pinch stability in the starting phase of the discharge was analyzed.

The compliance of the experimental activities with the targets of these first phases allows to proceed with the successive steps of the project, including the upgrade of the pinch and cathode power supplies.

Acknowledgments

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