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Progress of the Plasma Centerpost for the PROTO-SPHERA Spherical Tokamak

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Abstract: Plasma properties can be useful in a wide spectrum of applications. Experimental projects on controlled nuclear fusion are the most challenging of these applications and, at the same time, the best way to approach plasma science. Since nuclear fusion reactors can ensure a large-scale, safe, environmentally-friendly and virtually inexhaustible source of energy, several fusion-oriented megaprojects and innovative companies are appearing all over the world. PROTO-SPHERA (Spherical Plasma for HElicity Relaxation Assessment) is the first plasma project with a simply connected configuration, namely not requiring additional objects inside the plasma volume. This is obtained by a plasma arc, shaped as a screw pinch, acting as the centerpost of a spherical torus with minimal aspect ratio. Due to its intrinsic physical, engineering and economic advantages, this new approach is attractive also on an industrial scale and with several developments that still needs to be explored. This paper presents the PROTO-SPHERA basic principles, its first encouraging results and its expected and potential evolutions.

Keywords: nuclear fusion; pinch; plasma physics; power converters and inverters; power plants; power supply; spherical tokamak; sustainable energy sources

1. Introduction

Plasma is the most abundant form of matter in the Universe, estimated to account for more than 99% of the existing visible matter. It can be approximately described as an electrically neutral medium of unbound positive and negative particles, featuring a high conductivity and other special properties different from the other three fundamental states (solid, liquid, and gas). This can be exploited in a wide spectrum of possible applications: low energy lights, sources of radiation, destruction of harmful substances, superficial treatments, creation of new materials [1,2].

Controlled nuclear fusion is the most challenging and exciting application of plasma science [3–6]. In a proper plasma environment, atomic nuclei can collide at a very high speed and join to form a new nucleus. During this reaction, matter is converted to energy (heat) that could be exploited with many benefits. Nuclear fusion is also a very fundamental natural phenomenon in the Universe, being the working principle of Sun and other stars.

Power stations based on fusion would provide more energy for a given weight of fuel than any fuel-consuming energy source currently in use and the most used fuel (deuterium) is abundant on Earth. Moreover, the adopted technologies are supposed to be safe and with a limited waste impact, especially if compared to their nuclear fission counterparts. Not surprisingly, a debate is growing if nuclear fusion can be considered as a sustainable energy form and about its role in the energy perspectives [7–9].

Therefore, many different fusion approaches were proposed and investigated, but unfortunately they are not yet economically viable, as they produce less energy than that needed to initiate and contain the fusion reaction. Nevertheless, governments and international agencies are funding several fusion-oriented megaprojects, such as ITER (under construction in France [10]), JT-60SA (to be completed in 2019 in Japan [3,11]), Wendelstein 7-X (completed in October 2015 in Germany [12]) and the National Ignition Facility (the 500 TW laser based in California that recently announced an energy gain [13]). Furthermore, an increasing number of billionaire investors and major corporations are betting that small-scale fusion will be ready for market sooner than the big international projects [14–18], drawing attention even outside the scientific community [19,20]. The USA has at least six private-sector fusion projects underway [19], but innovative companies can be found all over the world (and the lists consider only the most rigorous approaches). This scenario is compliant with some recent theoretical achievements that showed that the energy gain achievable in a nuclear fusion device weakly depends on the device size, implying that useful performances can also be obtained in relatively small devices [21].

On the other hand, much of the knowledge of the plasma properties comes or could come from the activities in the nuclear fusion field. In addition, fusion research has involvement and outcomes in many areas, such as power supplies, superconductors, special materials, radiofrequency devices, real-time measurement and control, vacuum technologies, computational electromagnetics, and so on [4,22,23].

Currently, the most developed approach to nuclear fusion reactors consists in magnetic confinement devices, especially in the tokamak configuration [3,4]. Tokamaks are able to confine hot plasma for a sufficient period of time (a few seconds) so light nuclei (typically hydrogen) can overcome their natural repulsive forces. Moreover, they aim to operate at an energy density sufficient to become self-sustaining (ignition), namely to internally produce the conditions for further fusion reactions.

The most investigated magnetic plasma configurations (tokamak, reversed field pinch, stellarator) are not simply connected, namely the plasma cannot be sustained without inserting an external element (coil) in its volume. The viability of a simply connected magnetic configuration would remarkably simplify the design of a nuclear fusion reactor.

A step forward is expected by the Spherical Plasma for HElicity Relaxation Assessment (PROTO-SPHERA) project developed at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Frascati, the first plasma experiment with a simply connected configuration and closed flux surfaces. This can be achieved by triggering a sort of spherical tokamak through the self-organization of a plasma arc fed by electrodes (anode and cathode) [24–30]. Also considering the mentioned background, the project was conceived to be compact, flexible and cost-effective, even on an industrial scale.

Being simply connected, the plasma can be compressed to a very compact configuration up to the lowest possible aspect ratio. The relevance of this result for energy purposes was confirmed by the cited researches on the performance achievable by compact and small devices [21]. These devices may develop an alternative and faster path to fusion energy [14,31,32] and PROTO-SPHERA may be a milestone on such a path.

This paper describes the initial activities of the PROTO-SPHERA project, with emphasis on the tests and commissioning performed to implement the plasma central column. In order to investigate any possible crucial topic, the PROTO-SPHERA set-up was simplified and adapted to obtain an intermediated experimental phases. 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. More in general, it could contribute to the other fields related to fusion and plasma researches.

2. Advantages and Potential Developments of the PROTO-SPHERA Approach

This section introduces the theoretical and practical advantages inherent in the PROTO-SPHERA approach and its potential future developments. Some of the presented concepts will be explained in the subsequent sections of the paper.

Even though the physics of mainstream tokamaks (as ITER or JET (Joint European Torus) [33]) have been investigated for decades, some plasma instabilities are still unpredictable and unsolved. For instance, a fast disruption can extinguish the plasma in few milliseconds, even with damage to the tokamak structure. This phenomenon was also registered in the experiments closest to the nuclear fusion (deuterium-tritium plasmas). Maybe also for this reason, since 1994 only alternative configurations (especially spherical tokamaks) were built ex-novo in Europe and USA.

All the spherical/compact tokamak configurations can reach large toroidal plasma current I_p with a low value of the applied magnetic field [34,35]. The magnetic field needed to keep the plasma stable can be a factor of up to ten times less than in a conventional tokamak. The most important consequence consists in a reduction of the costs for the tokamak construction (materials and structure) and for the input electrical power to operate it [5].

Unfortunately, the development and diffusion of the spherical tokamaks may be limited by the engineering difficulties around the centerpost of the toroidal field [35–37]. While this region should be as small as possible, it is subject to heavy stresses due to high plasma power, magnetic fields (concentrated in that region) and neutron emissions (that would need a thick shield). Moreover, in this configuration the plasma needs to be sustained by a drive current that is particularly demanding due to the large toroidal plasma current and density and to the low value of the toroidal magnetic field. Also in conventional tokamaks, the inner part of the toroidal magnets and the ohmic transformer (solenoid) are crucial for any operation [4,11].

In PROTO-SPHERA the current I_p is driven by the electrode current I_e (screw pinch helicity injection). The resulting configuration is expected to provide an elongated spherical plasma with a minimal size (total diameter about 70 cm) and complexity. This structure would introduce several engineering advantages, as simpler manufacture and handling and improved reliability. Nevertheless, the magnetic configuration is quite robust [25].

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 centerpost.
- 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.

However, the results of the experimental project could also be relevant for the mainstream tokamak line. In fact:

- The PROTO-SPHERA toroidal plasma current and related magnetic fields would have the same characteristics of those induced in a conventional tokamak.
- The power density on the electrodes (about 20 $\mathrm{MW/m^2}$) could be used in the study of plasma sources for neutral beam injectors [22].
- The high power flux allows to assess the heat loads of materials in a fusion-relevant environment but without introducing all the tokamak complexity.
- The current on the electrodes (about 1 $\mathrm{MA/m^2}$) can support the investigation of high current vacuum arcs in presence of guiding magnetic fields.

From an industrial point of view, it is useful to stress that the arc mechanism is similar to a plasma torch [1,2], a device for generating a directed flow of plasma for waste disposal (but also material cutting and treatment). Also some well-known problems, such as anchoring, are common and could be addressed in the same way.

The availability of a laboratory plasma like that obtained in PROTO-SPHERA could provide useful information also on some astrophysical phenomena, like solar and protostellar flares. As a possible far-future development, it should be stressed that a simply connected configuration is particularly suitable for magnetic fusion space propulsion [38,39]. Finally, it is noteworthy that some recently announced machines can even be regarded as a sort of PROTO-SPHERA configuration with some fluctuating coils [18].

3. Physical Basis and Expected Plasma Evolution

The physical considerations summarized in this section are adapted to the scope of this paper and journal. The values in Table 1 are also reported only for quick reference as they depend on the configuration and settings (scenario) of the experiment. Extensive and rigorous approaches can be found in the referenced literature.

Table 1. Typical (approximate) parameters of relevant fusion devices.

		A	B_{T0}	I_p	β_{T0} (β)	q_{95}
Conventional	ITER [10]	$6.2/2 \approx 3.1$	5.3 T	15 MA	$\approx$3%	$2.6 \div 3$
	JET [33]	$3/1 \approx 3$	3.4 T	3.5 MA	$\approx$3%	$\approx$3
	JT-60SA [11]	$2.93/1.14 \approx 2.5$	2.3 T	5.5 MA	$\approx$4%	$\approx$3
	DTT [22]	$2.15/0.7 \approx 3.1$	6 T	6 MA	$\approx$3%	$\approx$2.8
Spherical	START [40]	$0.34/0.27 \approx 1.26$	0.3 T	250 kA	$\approx$40%	$\approx$5
	MAST [41]	$0.85/0.65 \approx 1.3$	0.6 T	1.3 MA	$\approx$40%	$\approx$5
	NSTX [42]	$0.85/0.67 \approx 1.27$	0.3 T	1.4 MA	$\approx$40%	>5
	PROTO-SPHERA	$0.2/0.16 \approx 1.25$	0.05 T	180 kA	$\approx$80% (β = 30%)	$\approx$3

The geometry of a fusion device can be characterized by its aspect ratio A, defined as the ratio of the plasma major radius to its minor radius:

$$A \triangleq \frac{R}{r} \tag{1}$$

Just to give some reference values, in a conventional tokamak $2.5 \leqslant A \leqslant 5$, while a torus can be considered spherical if $A < 2$ (see Table 1). Interestingly, the first fusion reactor patent [43] is classified as compact fusion, even if $A = 1.3/0.3 \approx 4.3$.

The stability of a plasma configuration can be assessed by the safety factor q, roughly corresponding to the ratio of the windings of the magnetic field along the toroidal direction to the windings in the orthogonal (poloidal) direction [4]. Plasmas that rotate around the torus in the poloidal direction about the same number of times as in the toroidal one are inherently less susceptible to instabilities. Since in some cases q may tend to infinity, a modified definition, known as q_{95}, is normally used.

The efficiency of a magnetic confinement reactor can be quantitatively estimated by the ratio of the plasma pressure to the magnetic pressure [4]:

$$\beta \triangleq \frac{\int p dV}{\int \frac{B^2}{2\mu_0} dV} \tag{2}$$

where p is the plasma pressure, V is its volume, B is the magnetic field and μ_0 is the free space permeability. Intuitively, β compares the force available against the nuclei repulsion with the electrical power necessary to produce it. Even though (2) is the rigorous definition, the experiments often adopt the free space field B_{T0} on the plasma axis:

$$\beta_{\mathrm{T0}} \triangleq 2\mu_0 \frac{\int p dV}{\int {B_{\mathrm{T0}}}^2 dV} \cong \frac{2\mu_0 n k_{\mathrm{B}} T}{{B_{\mathrm{T0}}}^2} \tag{3}$$

where n is the number density, k_{B} is the Boltzmann constant and T is the temperature. This parameter is often reported as a percentage. The difference between β and β_{T0} is usually negligible in conventional tokamaks, but may be significant for spherical tokamaks. The maximum registered β was $\beta \approx 40\%$ obtained by the pioneering Small Tight Aspect Ratio Tokamak (START), operated in Culham from 1991 to 1998 [40,44].

The most relevant performance for a fusion device to be employed as an energy reactor is the energy gain factor [4,13,21]:

$$Q \triangleq \frac{P_{\mathrm{fusion}}}{P_{\mathrm{in}}} \tag{4}$$

given by the ratio of the produced fusion power to the power required to maintain the plasma in steady state.

The simple consideration that ${B_{\mathrm{T0}}}^2$ is proportional to the input electrical power stresses a positive effect of β on the energy performance [5,21]. However, the estimation of the actual dependence of Q on β and on A [35] is an unresolved problem, even though operations at high β are considered clearly desirable [21].

Figure 1 summarizes the plasma evolution expected in PROTO-SPHERA [45,46]. The cylinder schematized in the Figure contains only plasma (simply connected configuration). 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.

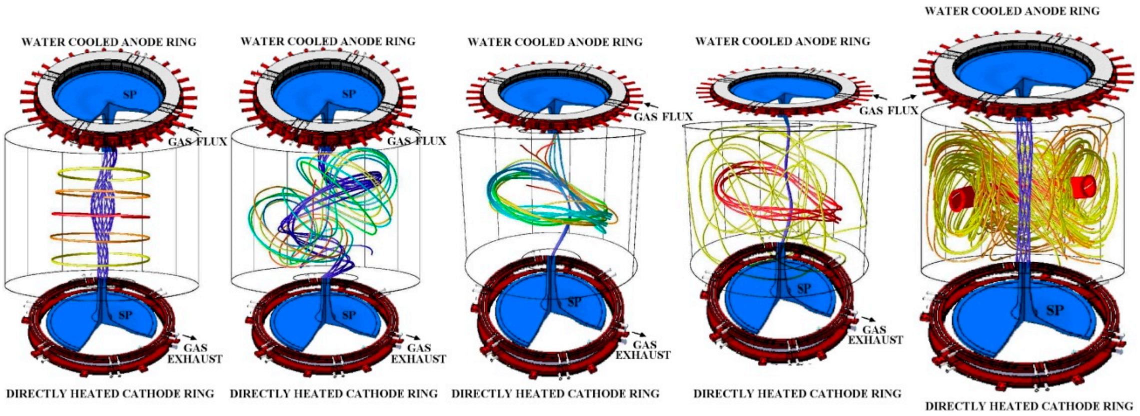


Figure 1. Formation and evolution of the PROTO-SPHERA central column and spherical torus plasma (developed from the three-dimensional simulations by García Martínez and Farengo [45,46]).

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 $q > 2$ [24,25]. Raising the electrode current up to 60 kA, the screw pinch will become unstable with $q << 1$. During the instability, the 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.

The creation of the spherical form around the plasma centerpost was experimentally demonstrated in 1993 in the TS-3 experiment at Tokyo University [47]. The TS-3 experiment sustained the spherical torus plasma for about 100 Alfvén times, but it could not assess its resilience up to a resistive timescale: this is one of the main PROTO-SPHERA goals.

The inductive flux that will be obtained from the PROTO-SPHERA compression coils at the time of the spherical torus formation will guarantee 120 kA of toroidal current. The ensuing increase to 240 kA depends on the efficiency of helicity injection at formation time. This is an unknown before the experiments, but it was estimated [24] from the data of the helicity sustainment of HIT-II [48] and from computational simulations [49,50].

PROTO-SPHERA aims to compress a spherical tokamak to the lowest possible A ($\approx$1.2 $\div$ 1.3) in a time of about 1800 Alfvén times ($\approx$1 ms) and to show that efficient helicity injection can sustain the spherical torus around the screw pinch for at least one resistive time ($\approx$70 ms). The edge safety factor resulting from the longitudinal current (60 kA) and from the toroidal current (120 $\div$ 240 kA) will be $q_{95} \approx 2.5 \div 3$. This would produce a plasma with a substantially high β, up to 30% [24,25].

Even though the evolution sketched in Figure 1 could appear surprising, it can be identified in several natural phenomena, as shown in the Figures 2–4. The analogy of what is attempted in a laboratory with natural phenomena has always been a very precious guide for scientific and technical developments. Nevertheless, most configurations introduced in magnetically controlled nuclear fusion experiments do not have a correspondence in Nature.

Figure 2. Two images of a beluga producing toroidal rings in water.

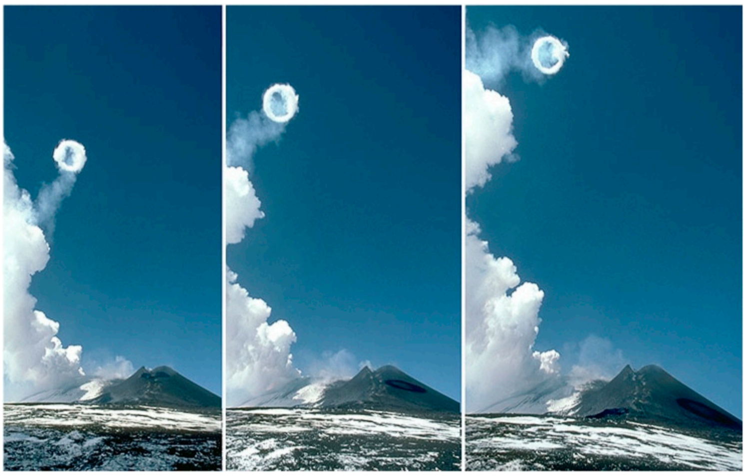


Figure 3. Smoke rings on the Etna volcano in Italy.

On the other hand, the PROTO-SPHERA research could be relevant for some astrophysical phenomena. In fact, in several astrophysical (gravity-confined) systems, unstable twisted magnetic flux tubes are able to produce helical twisted toroidal plasmoids through magnetic reconnection. The fate of these toroidal shapes is to expand and to be expelled from the generating gravity-confined parent systems. In this process the system is able to eject helicity and to shed a relevant magnetic flux, with a negligible loss of mass. The resulting formation mechanism is similar to PROTO-SPHERA, although the astrophysical phenomena occur at much larger magnetic Lundquist numbers and span a wide range of β values (β « 1 in the solar corona, $\beta \leqslant 1$ in collapsing magnetized clumps inside giant molecular clouds, β >> 1 in protostar magnetized accretion disks) [24].

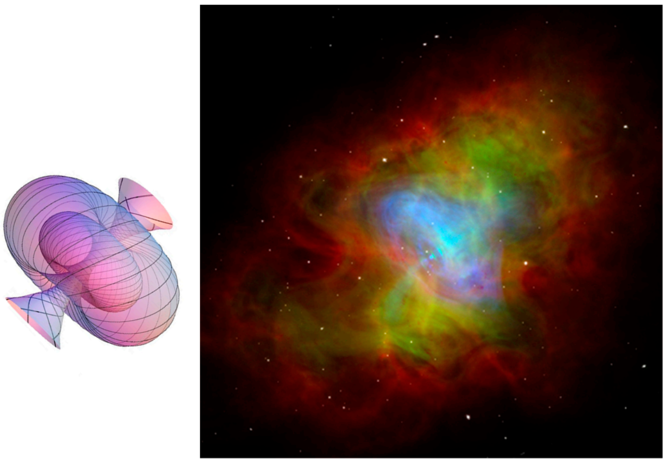


Figure 4. Comparison between the Hopf foliation (**left**) and a combined X-rays and infrared image of the Crab Nebula after a supernova explosion (**right**).

Finally, PROTO-SPHERA could sustain a Chandrasekhar-Kendall-Furth (CKF) magnetic configuration [39], which is a novel approach to magnetic confinement. CKF configurations are simply connected axisymmetric plasma equilibria containing a magnetic separatrix with ordinary X-points ($B \neq 0$), which divides a main spherical torus and two secondary tori (on top and bottom) surrounded by a spheromak discharge. Unrelaxed CKF equilibria are stable to all ideal MHD perturbations up to $\beta \approx 1$. Unrelaxed CKF fusion reactors with the right helicity injection would allow for an unimpeded outflow of a part of the high energy charged fusion products. These products would drift across the magnetic separatrix to the degenerated magnetic X-points ($B = 0$) on the top and bottom, allowing direct energy conversion to use the burner as a space thruster. The high β opens the possibility that plasma motions (radial electric fields) can sustain the magnetic field of CKF configurations.

4. Experimental Set-Up

4.1. Vessel and Poloidal Coils

The innovative PROTO-SPHERA design was validated on a prototype test-bench called PROTO-PINCH [51]. PROTO-PINCH had a Pyrex vacuum vessel with an anode-cathode distance of 0.75 m with eight copper conductors for the current return (see Figure 5). This set-up was able to produce hydrogen and helium arcs in the form of screw pinch discharges up to $I_e = 670$ A, stabilized by two poloidal field coils (PFCs) located outside the vacuum vessel. The PROTO-PINCH experience (and the initial PROTO-SPHERA experiments) are fundamental because electrodes and arcs are not used in tokamaks (including compact ones).

In order to compare the performances with those achievable with a metal central post at same geometrical size and plasma currents, the PROTO-SPHERA vacuum vessel was adapted from the spherical tokamak experiment START [40]. Within the framework of a collaboration between the corresponding Italian and the British associations, in 2004 the United Kingdom Atomic Energy Authority (UKAEA) donated to ENEA the START vacuum vessel (interestingly, this was already used for previous experiments). Figure 6 show the vessel arrival and its present location in the ENEA Research Center. The START vacuum vessel was lengthened by attaching two cylindrical appendixes on its top and bottom. 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. Inside or outside this vacuum vessel, there are three sets of PFCs, each composed by coils connected in series:

1. The first set of eight PFCs has the goal to shape the screw pinch with a current constant during the plasma evolution. This set is already assembled inside the vessel, as shown in Figure 7.
2. A second set of coils with variable current will be introduced (after the successful completion of the first experimental phases) inside the vessel to compress the spherical torus.
3. A further set of coils was inserted outside the vessel as described in Section 4.7.

Figure 5. The PROTO-PINCH vacuum vessel.

(**a**) (**b**)

Figure 6. (**a**) Arrival of the modified START vacuum vessel in Frascati in 2010; (**b**) Present aspect of the vessel in the ENEA Research Center.

The vessel and the PFC casings were designed to have independent and floating potentials. The effects of their potentials to the ground have been investigated through many experiments. Even though each PFC is in principle at a floating potential, it can be connected (through resistors) to the vessel, anode and cathode potentials, according to the experimental needs.

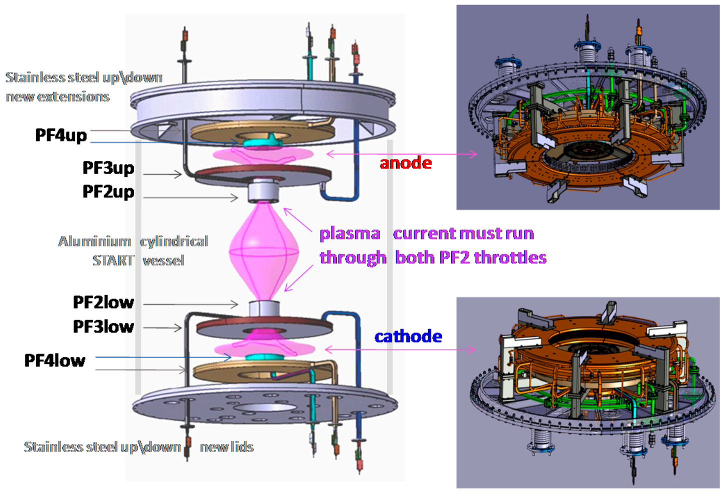


Figure 7. The eight PFCs in series inside the vacuum vessel.

4.2. Anode and Cathode Electrodes

Figure 8 schematizes the vacuum vessel with its electrodes. The anode and cathode electrodes supplying the pinch arc are placed on the vessel top and bottom, respectively. The plasma in the electrode regions is shaped to a "mushroom-like" profile by four PFCs internal to the cylindrical vacuum vessel, as shown in Figure 7. The arc current has a reclosing path outside the vacuum vessel through eight copper bars (see Figure 8).

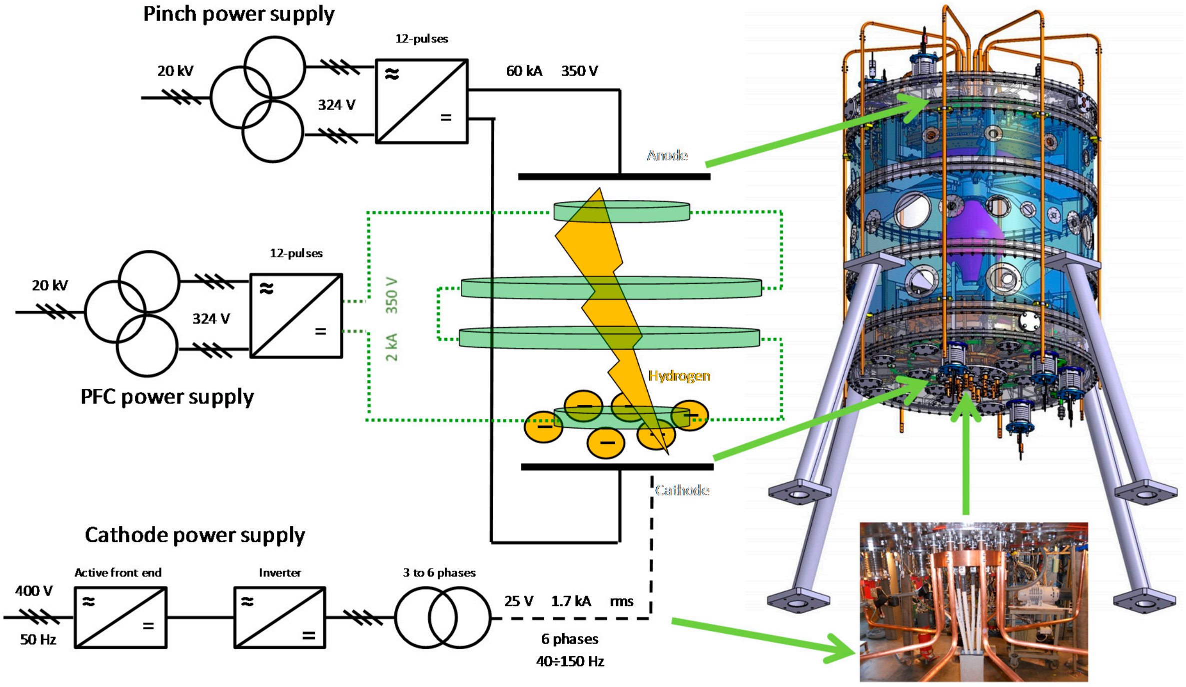


Figure 8. Summary of the PROTO-SPHERA vessel, electros and power supplies.

Figure 9 illustrates the working principle of the cathode electrode. The images on the right provide a detail view of a cathode module. Each module consists of three tungsten filaments used to emit the electrons by thermionic effect. As shown in Figure 9, the tungsten filaments were designed with a special conic-spiral shape (caduceus-like) selected to optimize the thermionic effect.

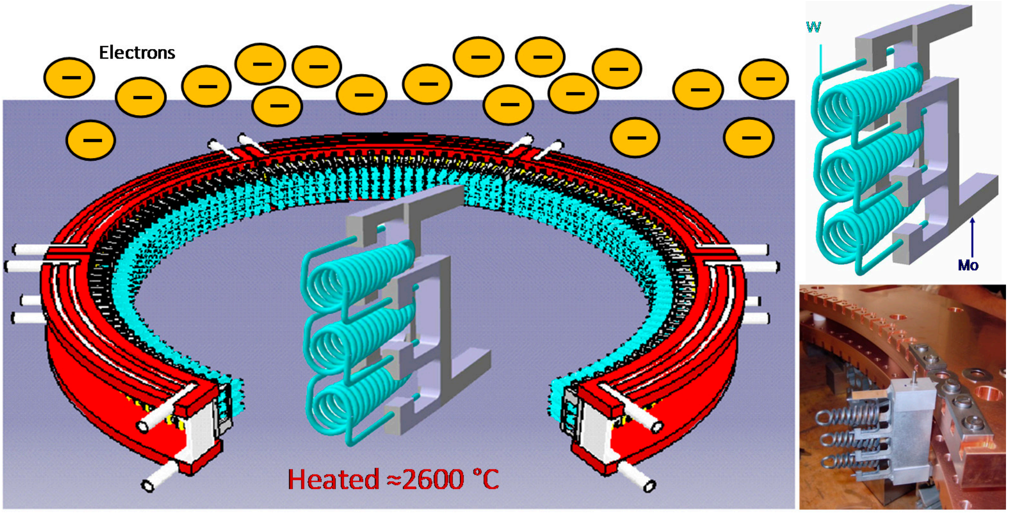


Figure 9. Scheme and working principle of the cathode electrode. Each cathode module contains three tungsten filaments used to emit the electrons by thermionic effect at about 2600 °C.

Moreover, since the filaments wind from one connector to the tip point and then unwind from the tip point to the other connector, they do not produce any relevant perturbation to the magnetic field. The cathode power supply is controlled to heat these filaments up to about 2600 °C (but experiments were performed up to almost 3000 °C). The electrons emitted by the filaments produce the required plasma by ionizing the gas 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 [51]. To ensure a high safety margin, the pinch power supply was designed to surpass 300 V. Nevertheless, this is a critical point and the first outcome expected during the first experiments, also because it is difficult to define an electrical model of the pinch formation and thus a strategy to manage it.

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 same inconvenient is often observed in arc discharges, as in arc welding and plasma torches. The excessive stress of such zones would be intolerable for the PROTO-SPHERA powers, even though both electrodes have an annular shape to handle the high plasma power and current density. In order to distribute the arc, the cathode power supply was implemented by a six-phase alternating current.

The power supplies schematized in Figure 8 are summarized in Table 2. Of course, the characteristics of the upgraded power supplies will be refined taking into account the result of the first experimental phases. The set-up was designed to allow an easy connection of each power supply to the vacuum vessel but also to specific dummy loads. The already built power supplies were designed to be reused in the final set-up. The idea is to obtain the pinch upgrade by superimposing a 50 kA generator to the existing one, while the new PFCs will be fed by another specific power supply. As introduced in Section 4.5, the use of technology based on supercapacitors (SCs) [52] can reduce the required input power, allowing to feed all the system from the 380 V grid.

Table 2. Summary of PROTO-SPHERA power supplies. The upgraded characteristics will be refined taking into account the first experimental results.

	Cathode		**Pinch**		**PFC**	
	Present	Upgrade	Present	Upgrade	Present	New
Current	1.7 kA rms	10 kA rms	10 kA	60 kA	2 kA	1200 V
Voltage	25 V rms		350 V		350 V	2 kV
Frequency	40–150 Hz	50 Hz	DC		DC	DC
Dummy load	6 star	6 or 3 star	15 mΩ	–	1 mH, 80 mΩ	–
Dummy load energy	>6800 kJ	–	>1.6 MJ	–	>300 kJ	–
Operating load	≈14 mΩ	≈2 mΩ	Arc		2 mH, 60 mΩ	–
Rise time	15–30 s		25 ms	1 ms	50 ms	1 ms
Operating time	15–31 s including ramp		≈1 s		≈1 s	
Duty cycle	≈30/600 s/s		≈1/600 s/s		≈1/600 s/s	
Control	Voltage		Current		Current	
Input voltage	400 V		20 kV	SCs	20 kV	SCs
Peak power	300 kVA	1.8 MVA	4.4 MVA	≈20 MVA	900 kVA	–

4.3. Dummy Loads

The power supplies were designed and optimized for the dummy load reported in Table 2 and in Figure 10. Since the resistance of the tungsten filaments is very variable during the heating, it was chosen to fix the dummy load at the resistance value estimated with the cathode at 2600 °C (≈14 mΩ).

(**a**) (**b**)

Figure 10. (**a**) Dummy load for the cathode power supply (6 star-connected resistors); (**b**) Dummy loads for the pinch (on the left) and PFC power supplies with their measurement shunts.

The design was particularly critical for the pinch power supply, as the actual load is very different from the resistive dummy load. However, a model of the plasma arc is not available. Also considering the PROTO-PINCH experience, in the final design, this power supply was regulated by a current feedback and by a proportional-integral-derivative (PID) controller. The effectiveness of such design was validated during the experimental phase.

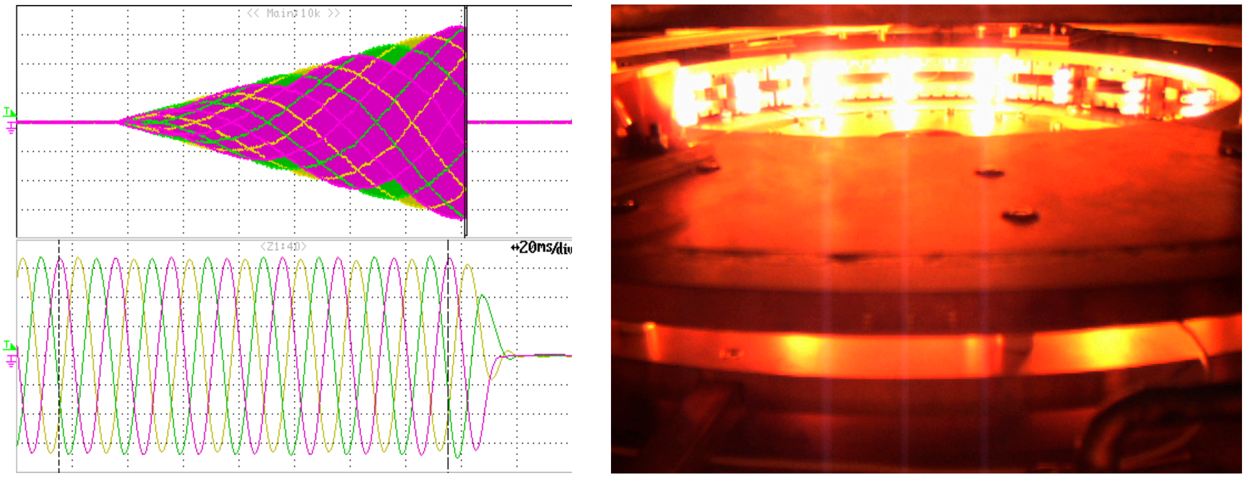
4.4. Cathode Heating Power Supply

The first stage of the six phase power supplies consists in an active front end (AFE) that rectifies a three-phase voltage at 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 three-phase/30 V six-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 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 also the effects of the different frequencies and rotation sequences in the cathode power supply.

Even though the cathode power supply is able to operate in continuous wave mode, 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 sine waves 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 triggers 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.

Figure 11a shows the voltage measured on the cathode power supply (only three phases are reported to simplify the graph) during a voltage ramp. The top graph shows the entire ramp-up phase (about 25 s), while the bottom graph shows a zoom of the final part of the flat-top (about 1 s). The fast decay of the inverter output voltage (especially in case of fault) was a design request in order to limit the stress on the filaments. The effect of the voltage ramp is shown in Figure 11b reporting an image taken on a cathode sector during the heating phase (before activating the pinch power supply).



(**a**) (**b**)

Figure 11. (**a**) Voltage measured in three phases of the cathode power supply during a voltage ramp; (**b**) Photo of the cathode taken during the heating phase.

4.5. Pinch Power Supply

The pinch and PFC power supply systems are located in a segregated cubicle of the PROTO-SPHERA hall, as shown in Figure 12. Both the systems are based on a 12-pulse AC/DC converter implemented by two parallel thyristor bridges fed by a 20 kV/324 V transformer with two secondary (delta and star) windings. The two converter transformers are dry-type for indoor installation.

The scope of the pinch power supply is to generate and maintain the arc between the electrodes. Its converter current controller is regulated to reach the desired flat-top in the minimum possible time. On the 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. In case this strategy would not be able to manage the breakdown, a possible design upgrade included a stabilization resistance in parallel to the pinch (a stabilization effect could be provided also by the voltage drop on the connection cables between the power supply and the vessel).

Figure 12. Power supply cubicle in the PROTO-SPHERA hall.

In the present configuration, the power supplies derive the power from dedicate connections from a 20 kV line fed by the ENEA 150 kV substation. This configuration is rather expensive and would not be possible in absence of a medium or high voltage distribution. However, as reported in Table 2, the duty cycle for these converters is relatively small, mainly due to the heat load on the PROTO-SPHERA copper and tungsten electrodes. This is a typical situation where SCs can be successfully used [52].

An alternative design based on SCs was already developed, based on a commercial bank having a total capacitance of 63 F and a maximum voltage of 125 V. The simulations performed on typical scenarios showed that the new scheme can produce the same current waveforms, even providing better performances (for example, reducing the current ripple by adjusting the carrier frequency). A SC-based scheme was also used to produce the current step from 10 kA to 60 kA in less than 1 ms, necessary for the following experimental phases [52].

It is worth noticing that the new SC-based power supplies could operate without any connection to the 20 kV substation and without the step-down transformers. These advantages are particularly relevant as the PROTO-SPHERA project was conceived to be cost-effective and replicable, even on an industrial scale.

4.6. PFC Power Supply

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

While in standard tokamaks the PFCs are supplied by separated circuits, in PROTO-SPHERA all the coils used in the present set-up are connected in series to the same power supply. Also the future set of coils will be connected in series to the same power supply with variable current.

Since all the undesired magnetic fields could affect the plasma and the electronics in the environment outside the vessel, special solutions were adopted for the connection cables in order to compensate the intense currents. As exemplified in Figure 13, the current from the power supplies flows in the outer conductor of a coaxial cable, has a special connection to each coil on the top and bottom of the vessel and is reclosed to the cable inner conductor. In particular, Figure 13b sketches the current path between the outer and the inner conductor at the last PFC.

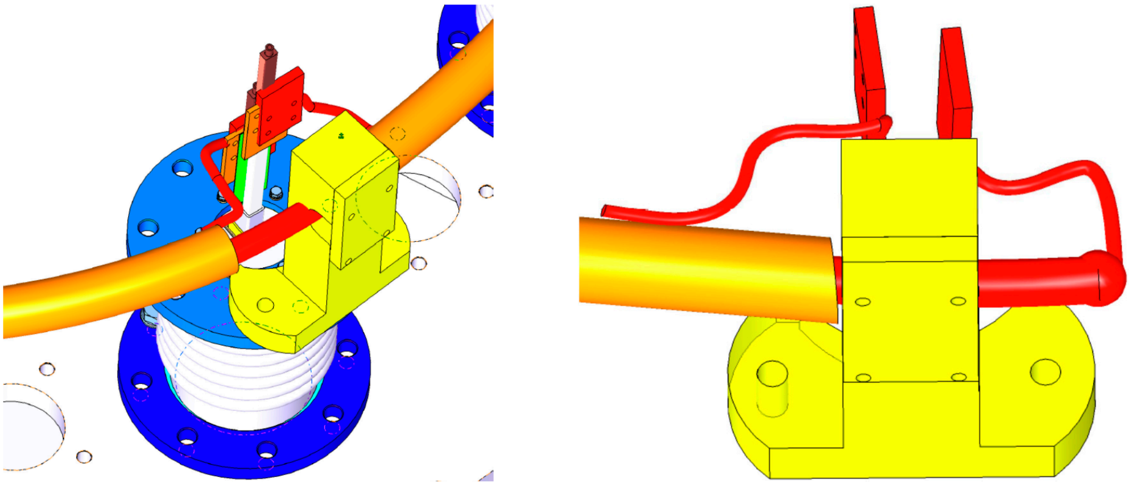

(**a**) (**b**)

Figure 13. (**a**) Connection of the cable to a PFC on the top of the vessel; (**b**) Closure of the current path at the last PFC to minimize the undesired magnetic fields.

4.7. Additional External PFCs

In order to analyze the magnetic fields produced by the coils and by the plasma current 72 magnetic probes were inserted inside the vacuum vessel.

The first experiments showed an undesired equatorial X-point ($B = 0$) inside the vessel that was removed by introducing four further external PFCs, as sketched in Figure 14.

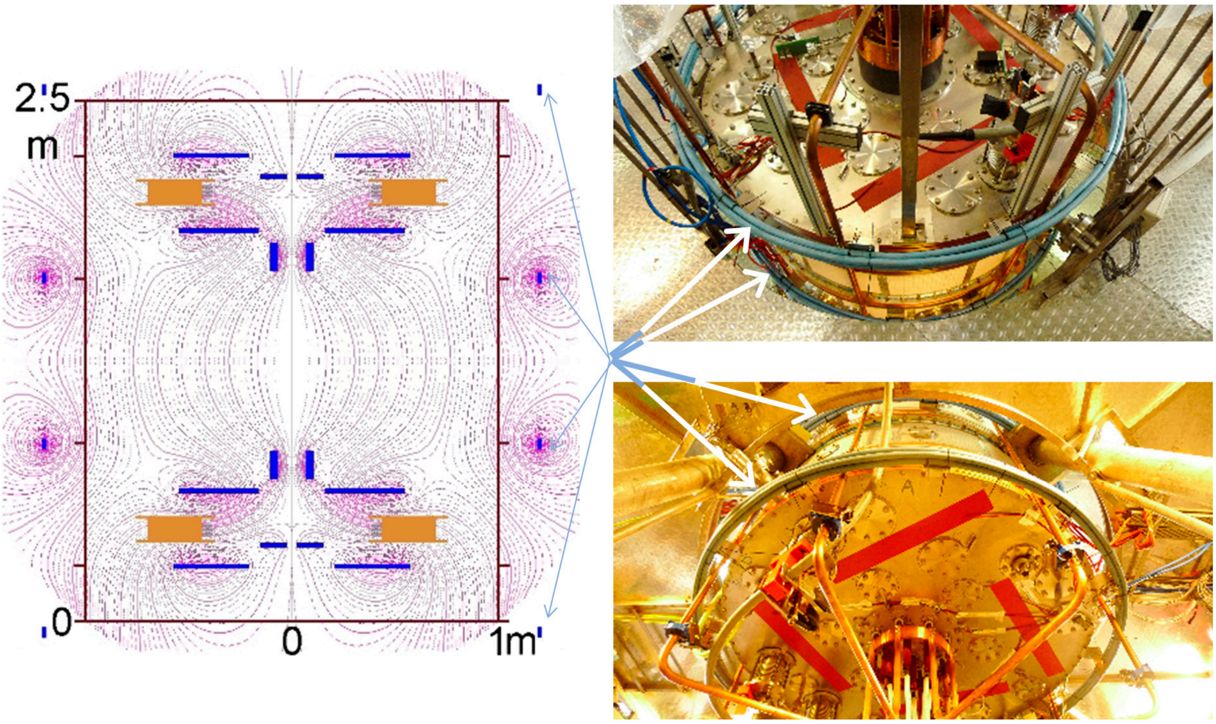


Figure 14. Location and impact on the magnetic fields of the additional external PFCs.

These coils were manufactured in a simple way from spare connection cable. Since the PFC power supply has a sufficient margin to sustain also this load, the external coils were connected in series with the internal PFCs. However, in order to allow the diffusion of skin current in aluminum vessel and stainless steel lids, the power supply sequence had to be modified by firing the plasma 0.75 s after the generation of the PFC current.

In the future upgrade, these coils will be fed by a specific power supply, presumably based on SCs, having a voltage of 50 V and a current up to 2000 A [53].

5. Experimental Results and Discussion

5.1. Aims of the first Experimental Phases

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 items and the plasma behavior before the formation of the spherical torus, the set-up was adapted to successive intermediated steps. The adaptions were designed to reuse in the final set-up as many components as possible.

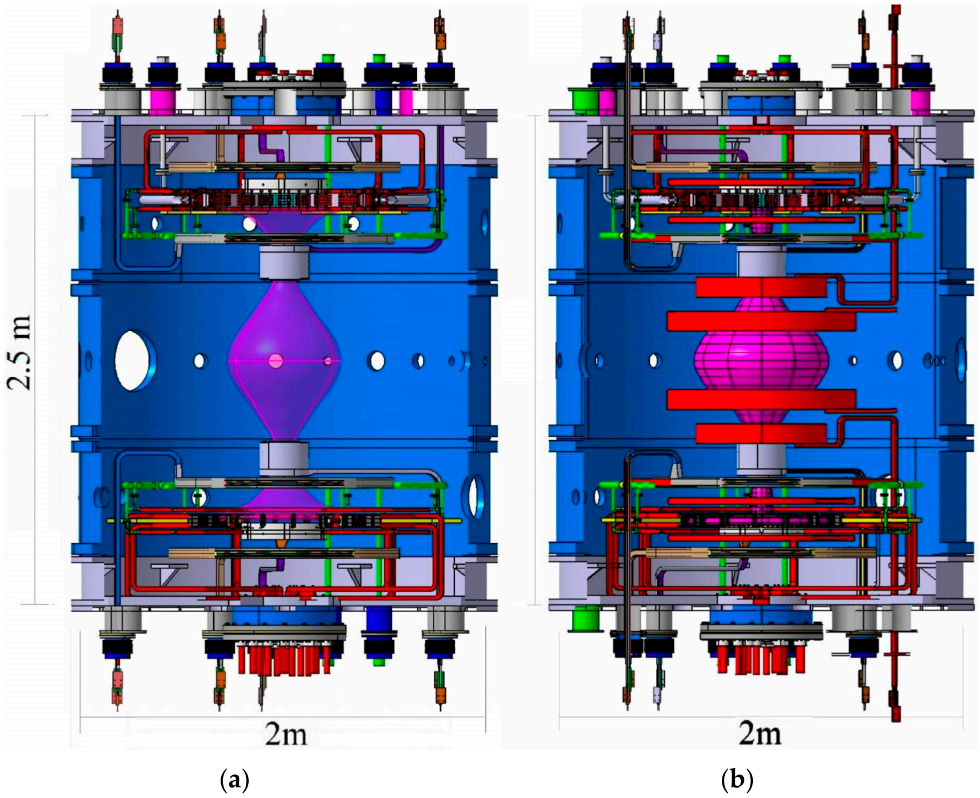
Therefore, the plasma centerpost was operated and monitored reproducing the conditions of the first phase of the discharge. In particular, the power supplies were modified as described in the following:

- The pinch (plasma) current was limited to 10 kA, but keeping the full voltage (350 V) to ensure and characterize the breakdown.
- The cathode was adapted and scaled for the same value of current, but each installed filament is heated by its nominal current (150 A) and current density (1 MA/m^2). This was implemented by using the final PROTO-SPHERA cathode, but only partially filled with the tungsten filaments (54 in 18 modules instead of 378 in 126 modules), and a cathode heating power supply of 1.7 kA rms per phase and nominal voltage (25 V rms).
- Only a PFC subset (the eight plasma shaping coils close to the electrodes) was installed and connected in series to the PFC power supply. This is necessary to give the arc the desired shape.

The resulting set-up is shown in Figure 15, where it is also compared with the expected final configuration (after successful completion of the present experiments). Some relevant (temporary) modifications were performed also on other aspects of the experiment:

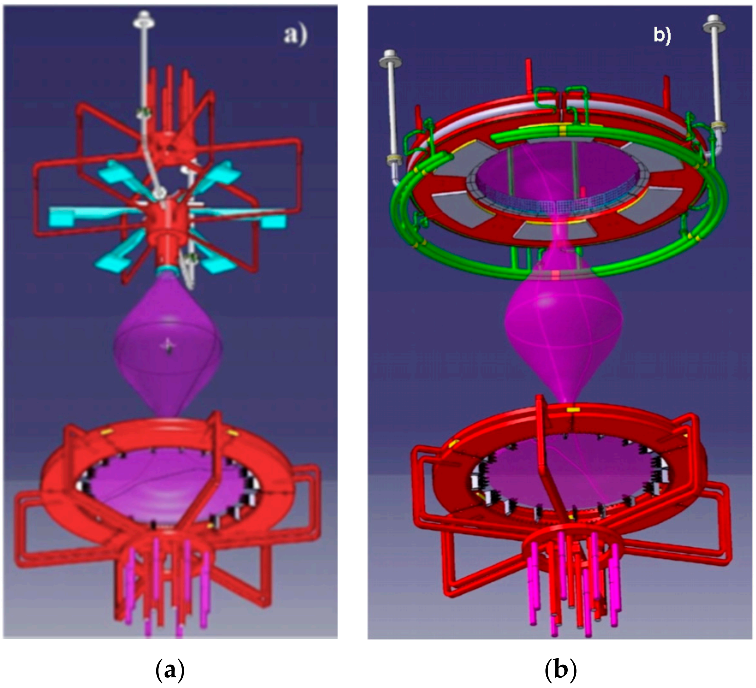
- Being afraid of anode anchoring, the annular anode was substituted only in the first experiments by a simple cylindrical anode, as sketched in Figure 16, resulting in a reduced distance of 1.4 m between anode and cathode.
- The additional external coils, as described in previous section, were inserted after the first experiments.
- Since the PROTO-SPHERA plasma configuration is novel and poorly known, especially with respect to the tokamak one, a thorough characterization of the plasma behavior is necessary before proceeding. For this reason, the hydrogen was substituted by the argon as filling gas. This reduced the voltage necessary for breakdown together with all the other voltages of the set-up.

The next experimental target will be to achieve the nominal current of 8.5 kA. This result requires patient learning of how to tailor boundary conditions (electrostatic potential of the PFC casings, magnetic field by additional coils external to the vessel).



(**a**) (**b**)

Figure 15. (**a**) Simplified set-up to investigate the plasma breakdown; (**b**) Complete set-up.



(**a**) (**b**)

Figure 16. (**a**) Cylindrical anode; (**b**) Annular anode.

5.2. Summary of Main Experimental Results

Figure 17 shows a meaningful comprehensive image captured by high resolution cameras during a PROTO-SPHERA operating sequence. The cathode filaments were heated by a 15 s voltage ramp to a 15 V flat-top. The current in the PFCs was that expected in the final configuration (1900 A). It is in interesting to recognize a plasma profile that could be useful for space propulsion (the authors would be happy to provide the full movies of the experiments upon request). Many useful conclusions can be summarized at this stage:

1. The PROTO-SPHERA experiments are regularly producing the plasma centerpost.
2. The plasma breakdown voltage is about 75 V in argon (see Figure 18) and about 200 V in hydrogen.
3. As expected, the breakdown was obtained in the range 170–200 V and with a stationary voltage of about 100–150 V at a hydrogen filling pressure of 10^{-3}–10^{-2} mbar. The pinch control strategy was validated without inserting any stabilization resistance.
4. The plasma column started on the proper path, through the poloidal field throttles at both the electrodes, and was shaped as predicted by the design calculations also near both the annular electrodes. A very good agreement was observed between the experimental data and the modeling projections (see Figure 19).
5. Even the expected triple X-points [25] on the top and bottom of the vessel were observed, as shown in Figure 20.
6. 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, are moved around and distributed.
7. Then, the major concern of anchoring has been already removed. Each PF coil is spontaneously and independently charged to an electric potential by the plasma discharge itself: luckily enough the ensuing electric field inside the machine produces an $E \times B$ drift which distributes smoothly the plasma on the annular hollow anode, with neither evidence of attachment nor of filamentation in the anode plasma region. This result is even more impressive as the plasma emerges from the directly heated annular cathode in 18 instead of 108 filaments of three superposed tungsten emitters. Evidently, the $E \times B$ drift eliminates the filamentation just as the plasma enters the anode region.
8. No deformations or other problems were observed on the cathode filaments after more of 500 heating cycles.
9. As shown in Figure 18, the current is limited to 3 kA (the target is 8.5 kA for some hundreds of milliseconds) by spurious plasma discharge paths near the vacuum vessel wall, which are driving half of the plasma current on the outboard of the main path.
10. The previous problem is being tackled by adding four additional PFCs, external to the vessel, having a constant current.
11. The plasma breakdown was easily achieved with both the cylindrical and the annular anodes. Even if the breakdown is easier with the cylindrical anode, this anode was just a source of troubles (also because the magnetic field configuration was designed for the annular anode).

Figure 17. Comprehensive representation of the PROTO-SPHERA plasma center post, obtained by merging three images captured during a typical experiment by high resolution cameras.

When the current during the experiment reaches the target value, the new power supply will extend this current up to 60 kA [52]. This current may appear extraordinary both in magnitude and in derivative, but they are usual for a standard tokamak [4,54]. Just for 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) switching unit for the plasma breakdown and ramp-up [55]. For further comparisons, the total installed power of a conventional tokamak power supplies ranges from 500 MVA (JET) to 2 GVA (ITER).

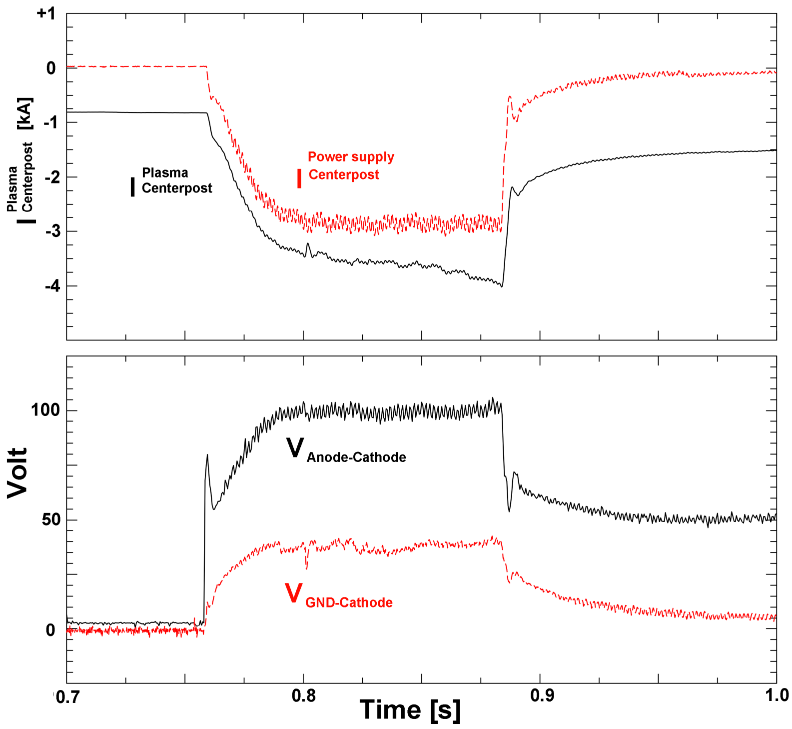


Figure 18. Currents and voltages measured during the scenario producing the images in Figure 17. The plasma centerpost current is that flowing through the PF2 coils (see Figure 7), measured by two Rogowski coils placed near the anode and cathode throttles.

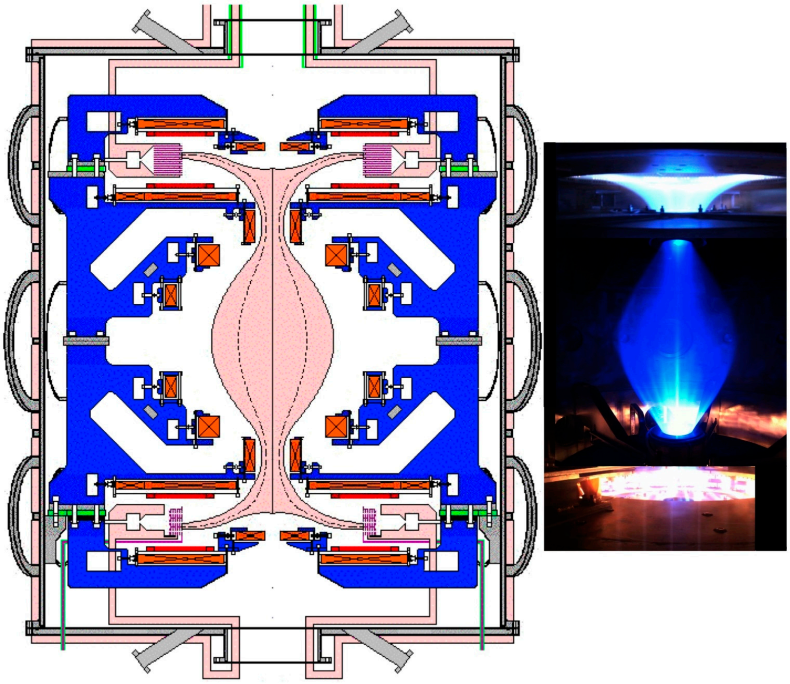


Figure 19. Comparison between the centerpost expected from the calculations and the shape obtained during the experiments (the slight differences are due the different perspectives and image superimpositions).

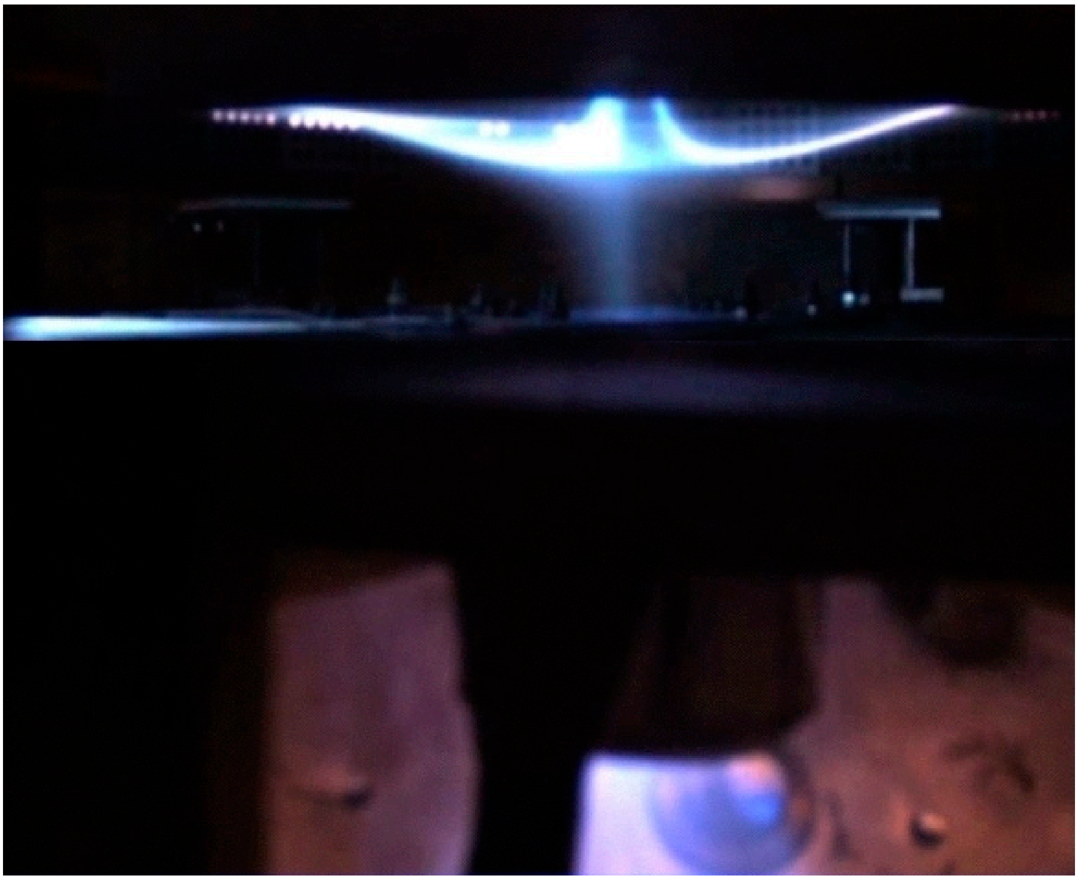


Figure 20. Triple X-point observed above the anode, as expected from calculations [25].

5.3. Future Plans and Expectations

The future plans and expectations of the PROTO-SPHERA program are summarized in the following. The speed in the implementation of the schedule will mainly depend on the funding availability.

1. Two polycarbonate flanges are being inserted in the vessel to improve the insulations among metallic parts.
2. The plasma centerpost should reach the design value (8.5 kA) or even the maximum value available from the power supplies (10 kA).
3. Such current should be sustained for at least 0.5 s up to 1 s (depending on the availability of the independent power supply for the additional external PFCs).
4. The set-up should be modified by inserting at least ten new internal PFCs. Since this should be done by a big mechanical manufacturer, this would require the most relevant investment (estimated more than 1 M€).
5. The maintenance operations and the vessel inspections during the successive experimental campaign (with the spherical torus) would be more complex (18 instead of 8 PFCs) and time consuming. Therefore, some modifications are expected during the same manufacturing to cope with the undesired phenomena. In particular, after verifying the actual level of metallization of the insulating flanges, further coils could be introduced to limit it.
6. The diagnostic tools and the plasma modeling should be improved. For instance, the lack of any anodic anchoring was a good surprise, but specific studies should be carried out to achieve an exhaustive explanation. In fact, the uniform plasma distribution in both the electrodes should

be kept with a sufficient level of confidence also in the upgraded configuration, especially considering the further PFCs.

7. The current centerpost should be increased up to 60 kA. The current amplitude is not expected to be critical due to the large amount of electrons coming from the 324 filaments. On the other hand, the plasma evolution would strongly depend on the generated waveforms and on the control strategies over short timescales (1 ms).
8. The real breakthroughs (or the new problems) are expected to be observed after the formation of the 120 kA in the spherical torus. The grade of success of the experiment would be determined by the actual amount of helicity injection in that phase.

6. Conclusions

The history of the PROTO-SPHERA project begun in 1995 when this "aggressive proposal" was presented [56]. The experimental activities had a boost in 2009 when the modified START vacuum vessel arrived at the ENEA laboratories. About twenty years after the first idea, PROTO-SPHERA is producing its first centerpost plasmas.

The obtained results have validated the design assumptions and theoretical calculations. The major concerns of the first experimental phases were overcome.

The program is only an intermediate stage, as PROTO-SPHERA aims to completely replace the metal centerpost of a spherical tokamak with a plasma column, demonstrating the feasibility of a simply connected magnetic configuration. Even though the confinement magnetic field would be simpler, this would reproduce many tokamak characteristics in an innovative way and introducing several advantages, in terms of plasma confinement and geometrical size but also in terms of handling and reliability.

Nuclear fusion could ensure a large-scale, safe, environmentally-friendly and virtually inexhaustible source of energy, but tokamaks and other fusion devices are very large, complex and expensive. PROTO-SPHERA can develop small-scale and medium-scale programs in the field of fusion and plasma science with a flexible set-up where it is easy to introduce new components or modifications. These programs can be realized at reasonable costs, especially if compared with typical costs of fusion machines under construction or design [22]. In fact, the total cost of the PROTO-SPHERA project, including past and expected future activities, is less than 4 M€. Of course, a direct cost comparison with other programs is not simple and could be misleading, as their principles and final goals are different. For instance, a mature reactor needs to face with several further problems related to burning plasmas.

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Author Contributions: Franco Alladio, Paolo Micozzi and Alessandro Mancuso conceived the experiment physics and designed the original set-up; Alessandro Lampasi and Giuseppe Maffia designed and tested the power supplies; Luca Boncagni, Edmondo Giovannozzi and Vincenzo Zanza developed the special diagnostics and software; Luigi Andrea Grosso, Valerio Piergotti, Giuliano Rocchi, Alessandro Sibio, Benedetto Tilia ("The Pool") manufactured and assembled all the vacuum, diagnostic and interface systems and performed the in-house works; Alessandro Lampasi wrote the paper with the fundamental contribution by Franco Alladio and Paolo Micozzi; all the authors participated to the experimental activities with equal dedication.

Conflicts of Interest: The authors declare no conflict of interest.

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