6. ELECTRODE EXPERIMENT

The purpose of this Section is to illustrate how the electrodes for PROTO-SPHERA have been developed. They were the most unconventional items and among the major concerns, when the design of PROTO-SPHERA was started. It was not clear that a feasible solution did exist, allowing for almost steady-state (1 second) emission from a cathode at a plasma current density level of 1 MA/m^2 at the plasma-cathode interface. Neither was it clear that a working solution did exist for an anode able to withstand 20÷30 MW/m^2 for the same discharge duration. Other concerns were about the endurance to many hundred discharges and about the contamination of the plasma. A final concern was the breakdown voltage, which could cause insulation problems in the PROTO-SPHERA load assembly.

In order to investigate these points the PROTO-PINCH benchmark of one anode and one cathode module has been built. It is similar to PROTO-SPHERA in physical dimensions and in the strength of the magnetic fields near the electrodes. 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. Following a trial and error procedure about 3 anode prototypes and 10 cathode prototypes have been tested on PROTO-PINCH from October 1998 to April 2001. The technical solutions are a W-Cu(5%) hollow anode and an AC directly heated cathode, composed by pure Tungsten helical filaments. The W-Th alloy, normally used in cathode where high current emission is required, has been substituted by pure W. As a matter of fact, the temperature of the filaments rises to about 2700 °C, as soon as the arc starts, and exceeds by far the Thorium melting point (1730 °C). The anode and cathode prototypes can work as they increase the effective plasma-electrode interaction area by a factor of about 16, reducing the effective loads to the level of 6A/cm^2 for the current density and of 1.4÷2 MW/m^2 for the power density.

The final result is that a cathode and an anode module, able to withstand the required current and power densities, have been built and have survived to many hundreds plasma shots. A further remarkable result is that the produced Hydrogen plasma has turned out to be almost free of impurities. The final relevant result is that the breakdown is produced at a low voltage (~100 V) in the same filling pressure range of a standard tokamak discharge ($\sim10^{-3}\div10^{-2}$ mbar).

6.1. PROTO-PINCH

Before building PROTO-SPHERA, the electrodes' benchmark PROTO-PINCH (see scheme in Fig. 6.1) has been built and operated, with the goal of testing modular units of the cathode and of the anode of PROTO-SPHERA.

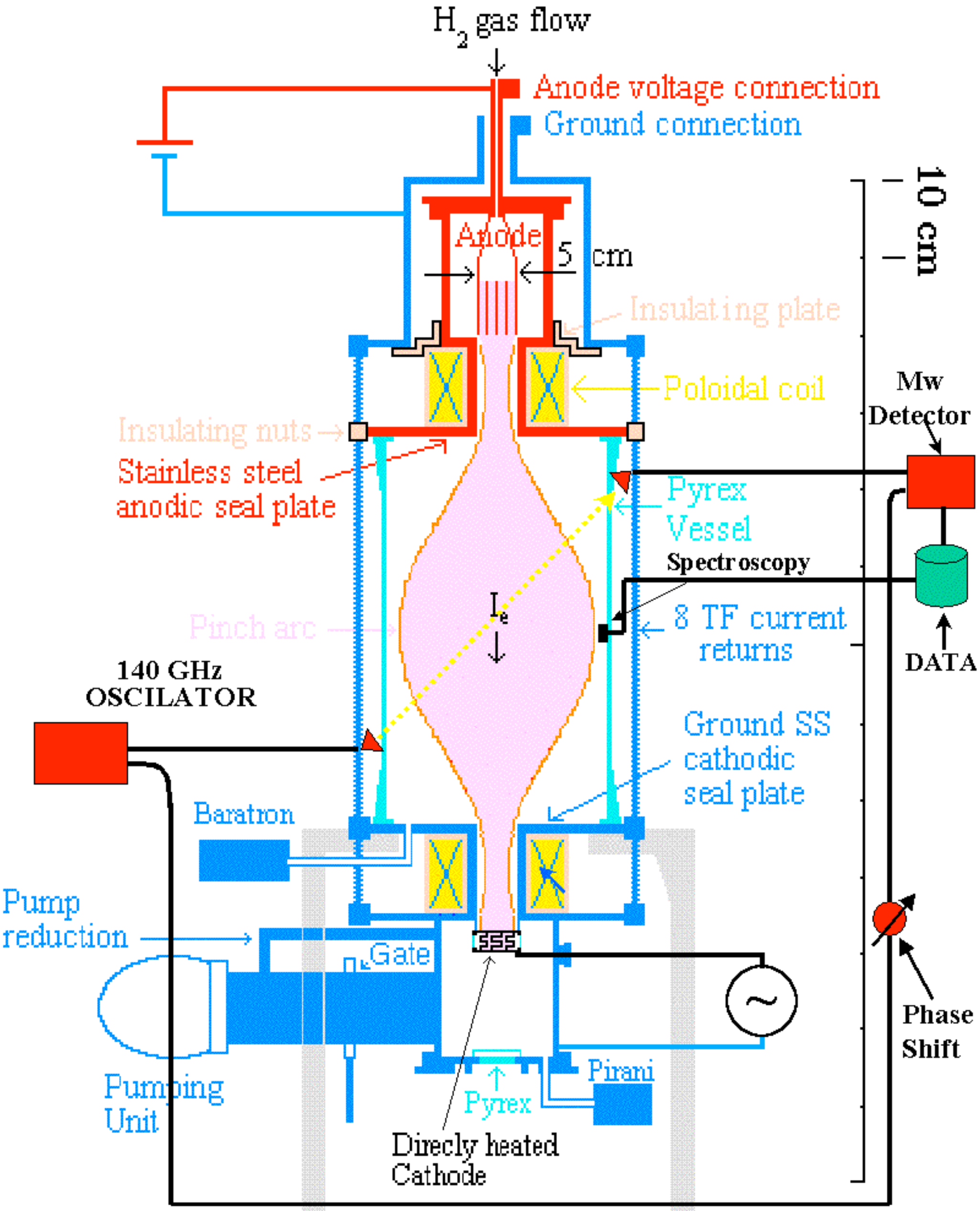

Fig. 6.1. **Scheme of the electrode testbench PROTO-PINCH, showing the main diagnostics: 140 GHz interferometer and spectroscopy.**

PROTO-PINCH, with an anode-cathode distance of 0.75 m and a stabilizing magnetic field up to B=1.0 kG, has a current capability of I_e=0.67 kA, (with a safety factor $q_{Pinch} \geq 2$). PROTO-PINCH has a Pyrex vacuum vessel, is stabilized by two poloidal field coils located outside the vacuum, has a coaxial I_e feeding structure and 8 copper conductors for the I_e current return (Fig. 6.2).

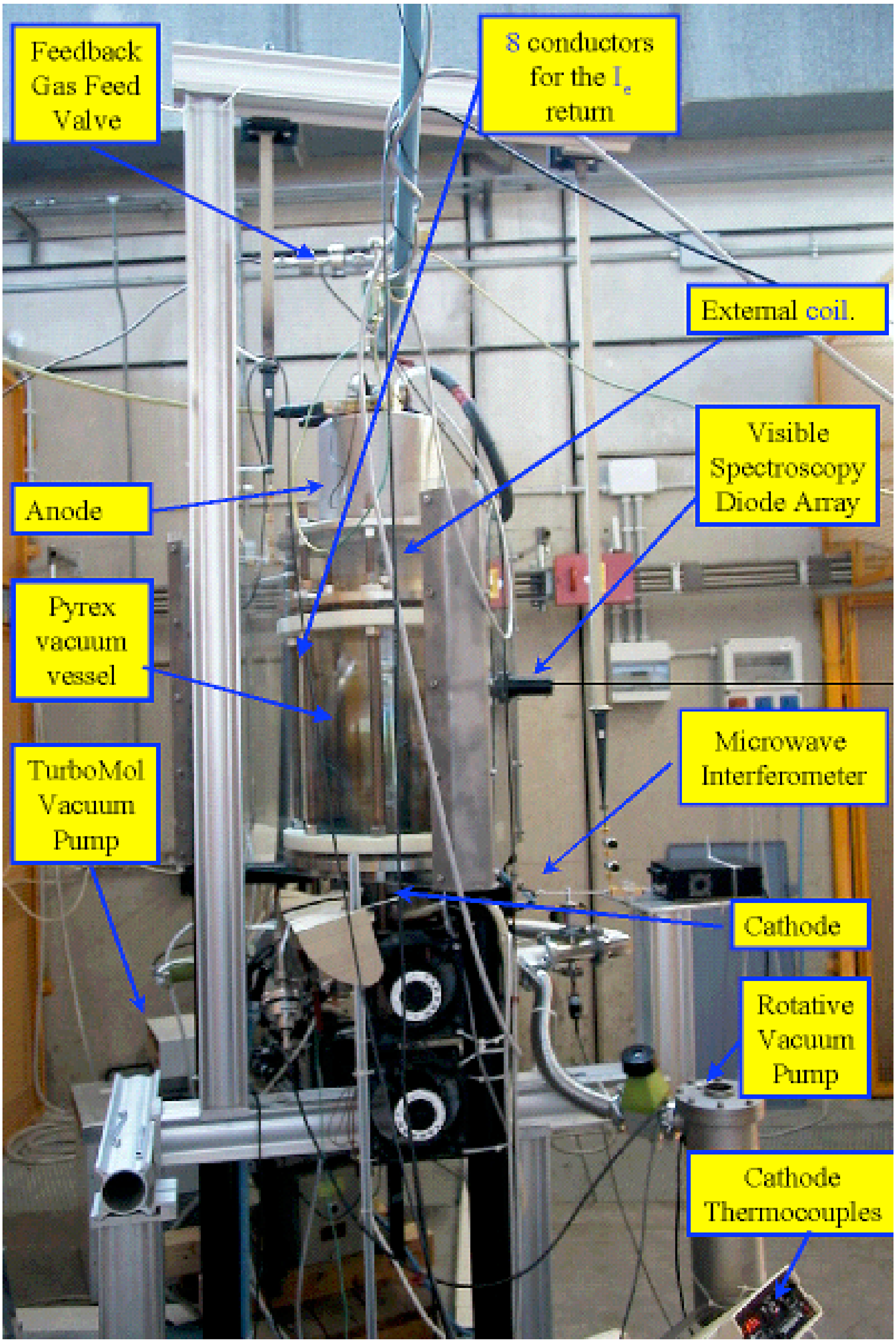

Fig. 6.2. **Photograph of the electrode testbench PROTO-PINCH, showing the main diagnostics: 140 GHz interferometer and spectroscopy.**

PROTO-PINCH has produced Hydrogen (see Fig. 6.3) and Helium arcs in the form of screw pinch discharges.

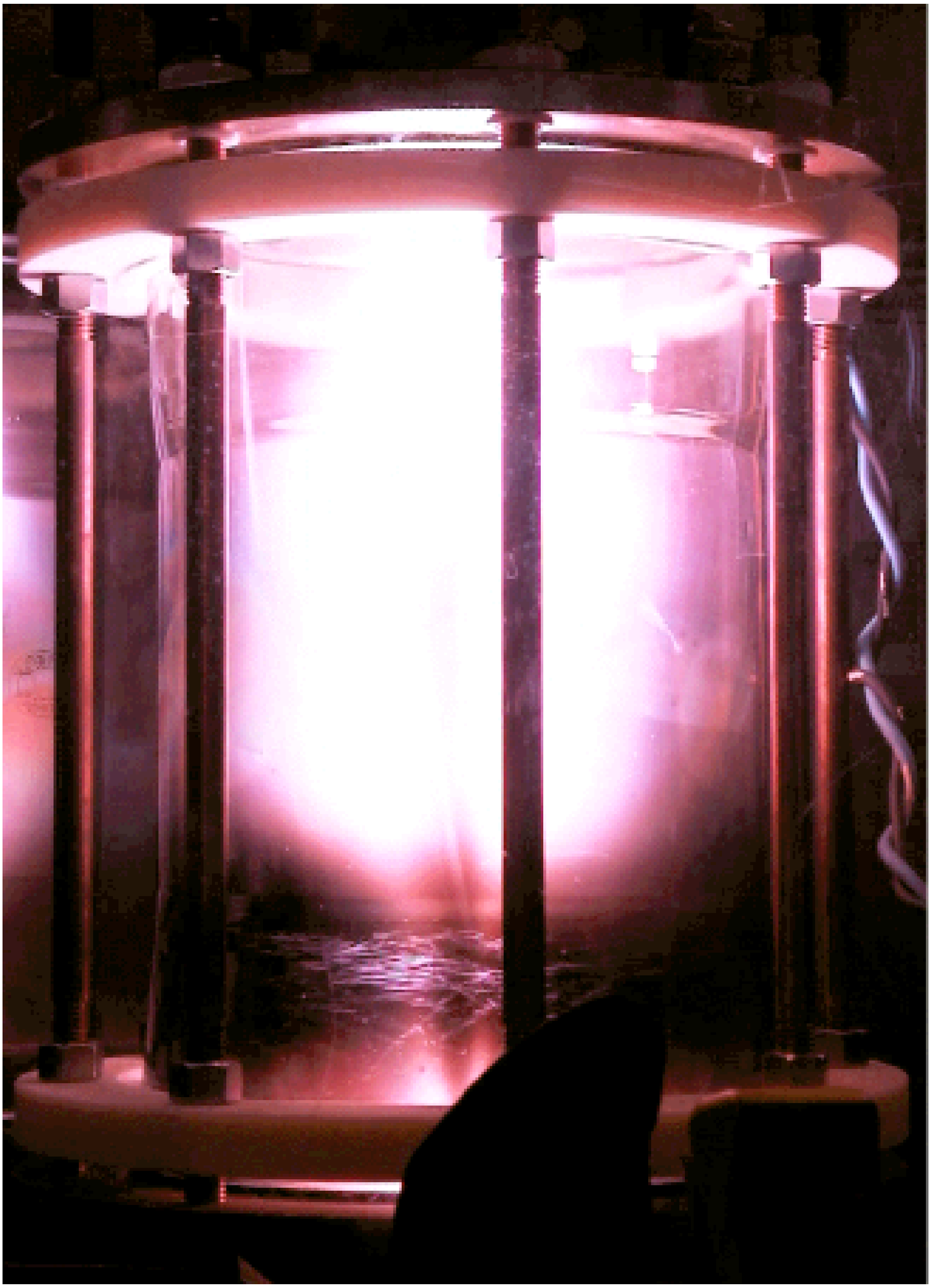

Fig. 6.3. Image of PROTO-PINCH Hydrogen plasma with I_e=600 A, B=1 kG.

Following a trial and error procedure 3 anode prototypes and 10 cathode prototypes have been tested on PROTO-PINCH from October 1998 to April 2001 (see Fig. 6.4).

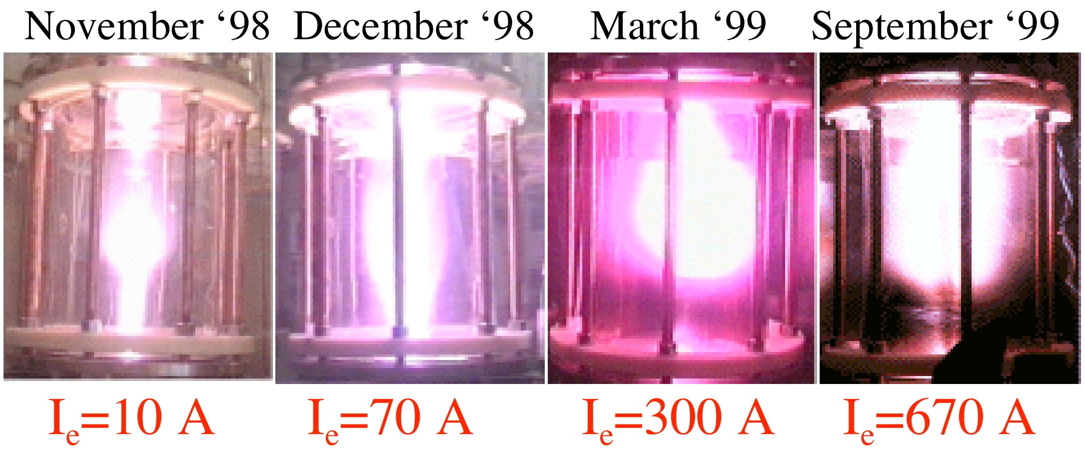

Fig. 6.4. Progress of the PROTO-PINCH experiment.

The main results of the PROTO-PINCH testbench are:

- The technical solution for the 5-cm diameter electrodes are: a directly heated (AC) Tungsten 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 $p_H=10^{-3}\div10^{-2}$ mbar, which is the same of a standard tokamak discharge.

- The pinch breakdown voltage is $V_e\leq100$ V, which means that the insulation problems in PROTO-SPHERA should be quite easy to deal with.

- The typical duration of a plasma pulse at I_e=600 A is 2÷5 s, limited by thermo-mechanical properties of the W cathode, 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 only at the lowest filling pressures ($p_H=1\div2\cdot10^{-3}$ mbar).

- The final anode and cathode prototypes have withstood 400 discharges at the current and the power densities required for PROTO-SPHERA.

6.2. Cathode

The directly heated (AC) cathode is composed (see Fig. 6.5) by two Molybdenum plates connected by Tantalum columns embedded in insulating Alumina.

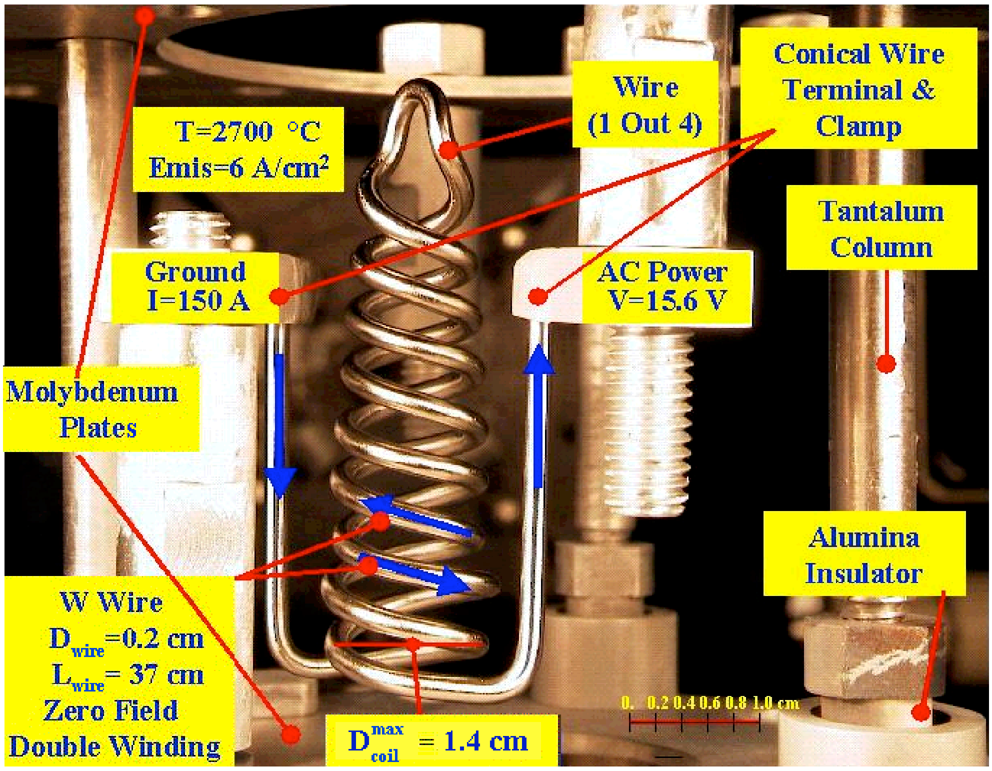

Fig. 6.5. **Scheme of the directly heated (AC) cathode of PROTO-PINCH, with the final version of the Tungsten filament.**

Four helical filaments of pure Tungsten, fixed by Tantalum nuts and bolts, connect in parallel the two plates (see Fig. 6.6).

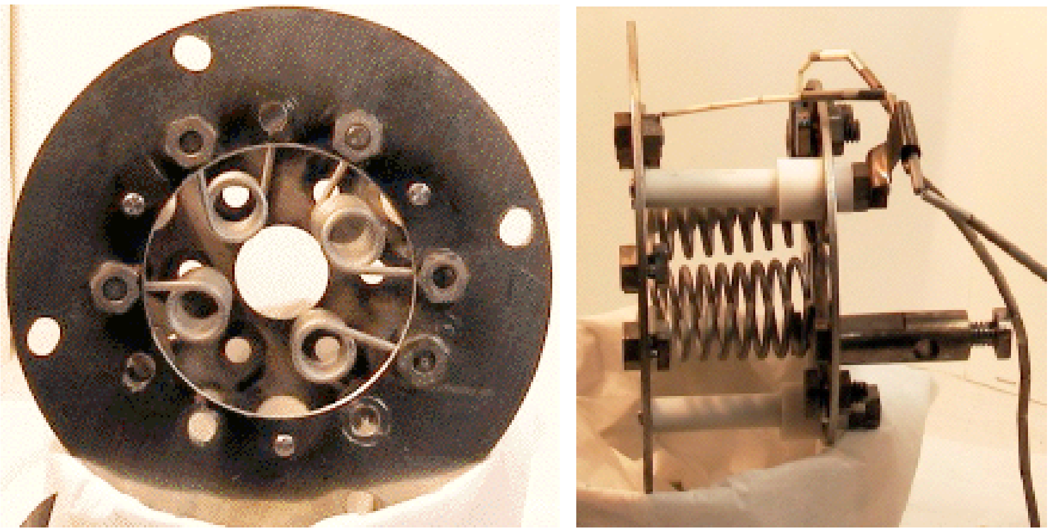

Fig. 6.6. **Pictures (plasma facing view and side view) of the directly heated (AC) cathode of PROTO-PINCH, with an earlier version of the filament.**

The wire diameter is D_{wire}= 2.0 mm, the total length of each filament is L_{wire}=370 mm and the maximum diameter of each filament is D^{max}_{coil} = 14 mm. These parameters have been chosen in order to guarantee the emission of 150 A of plasma current from each filament, while assuring enough mechanical resilience at the working temperature of 2700 °C.
Each of the four filaments has an effective emitting surface of 20 cm^2. They are heated up to 2600 °C, by a total AC current I_{cath}=590 A (rms). During the arc discharge the temperature rises up to 2750 °C. Pinch discharges have been obtained with B=0.8 kG, I_e=600÷700 A and V_e=70÷120 V. So the filament surface emissivity is about 8 A/cm^2. The cross-section emissivity of each spiral filament along its axis, i.e. in the direction of the impinging plasma, is about 100 A/cm^2.

A number of cathode treats and recipes are required to achieve this result:

- An AC current must be used for the direct heating of the cathode, in order to spread the ion plasma current over the filaments. DC heated cathodes did work but were prone to systematic damages at their most negative voltage point.
- The time required for heating up the cathode before the plasma shot is about 15 s.
- The AC current is switched off as soon as the Hydrogen arc breaks down.
- The AC heating current required for emitting I_e=600÷700 A of plasma current is I_{cath}=550÷590 A (rms.) at a voltage V_{cath}=14.5 V (rms). So the reference ratio between the emitted plasma current and the AC cathode heating current is, for each filament, I_e/I_{cath}~1.
- A cathode heating power $P_{cathode}$~8.5 kW allows to inject into the screw pinch plasma a total power P_e~50÷85 kW.

The PROTO-SPHERA cathode will be equivalent to 100 modules similar to the PROTO-PINCH cathode, connected in parallel in six groups (six-phased power supply): I_e = 60 kA = 100 modules • 600 A. Then the extrapolation to the PROTO-SPHERA cathode is:

1. The overall AC current required to heat the cathode will be $I_{cathode}$=60 kA (rms.) at $V_{cathode}$<20 V (rms.); it could be composed by a six-phased power supply able to deliver 10 kA per phase.

2. The overall cathode heating power will be $P_{cathode}$~850 kW. This peak power will be required only for about 1 s before the arc breakdown. As a matter of fact, during the 15 seconds, required for bringing the temperature of the filament to 2600 °C, the heating power will be growing almost linearly toward 850 kW.

3. The total power required by the PROTO-SPHERA screw pinch can be estimated in two different ways. The rougher estimate is just to scale, by a factor 100, the power injected into PROTO-PINCH: P_e=100 modules • 50÷85 kW~5.0÷8.5 MW. A more refined, but non less uncertain, estimate will be detailed in Section 6.5 and shows that the power injected into the PROTO-SPHERA electrode sheaths will be P^{el}_{Pinch}≤4.6 MW. The ohmic input P^{Ω}_{Pinch}≤5.4 MW (see Section 4.9) and the helicity injection power, required for sustaining the spherical torus, P_{HI}~0.6 MW (see Section 4.8) will have to be added, summing up to a total power P_e≤10.6 MW. A screw pinch power supply able to deliver 60 kA at 300 V will be adequate with both estimates (see Section 8.4).

Fig. 6.7 shows the waveforms of I_e and V_e obtained in PROTO-PINCH; the rise time of the pinch current is limited to 600 A/0.4 s by the characteristics of the power supply, which was originally the feeder of a klystron filament.

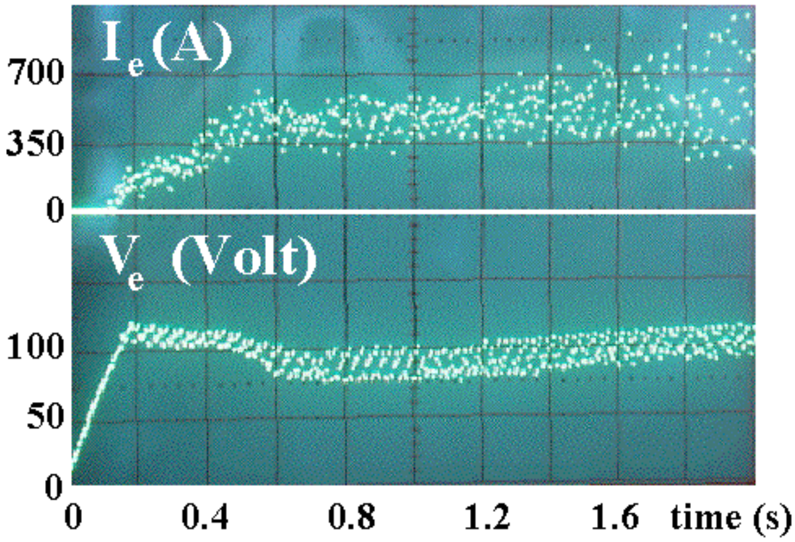

Fig. 6.7. **Waveform of I_e and V_e in PROTO-PINCH. The ripples are modulations due to the AC cathode heating.**

6.3. Anode

The PROTO-PINCH anode is a cylinder of Copper with 7 passing holes, of diameter 9 mm, drilled into it. Seven inserts of W95% -Cu5% protect the tips of the holes, on the plasma facing side. Scheme and pictures of the anode are shown in Fig. 6.8.

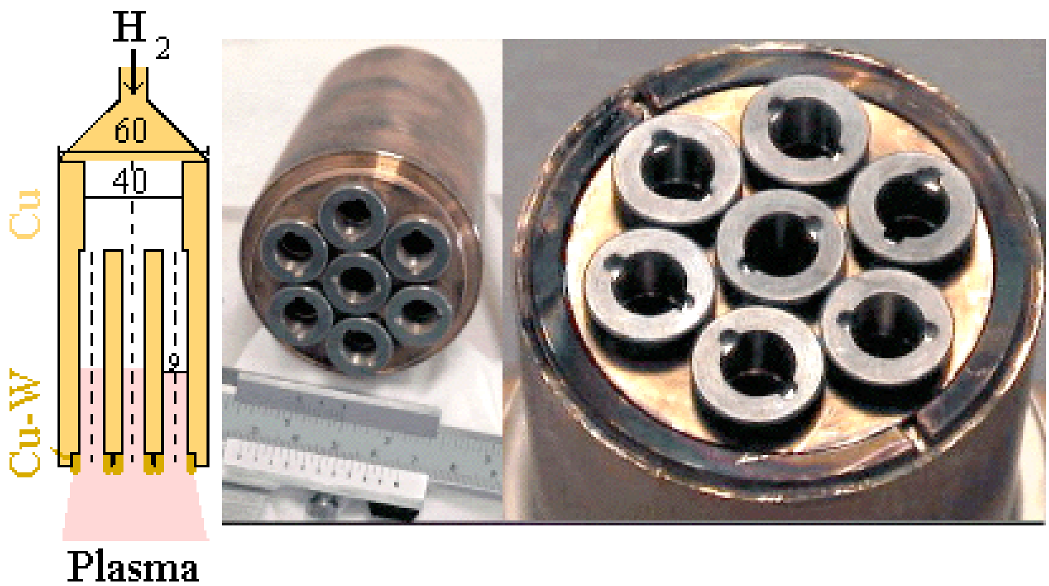

Fig. 6.8. **Scheme and pictures of the PROTO-PINCH anode.**

The PROTO-PINCH anode results can be so summarized:

- A feedback controlled system puffs gas at the rear of the holes and the emerging gas acts as a virtual anode for the plasma.
- The gas feedback system keeps p_H=constant inside the vacuum vessel.
- The PROTO-PINCH anode has not suffered any damage after more than 1000 plasma discharges.

While the cathode was DC heated there was sometimes evidence of anode arc anchoring (Fig. 6.9), where only one hole tip was emitting plasma. This dangerous phenomenon has disappeared after switching to AC cathode heating.

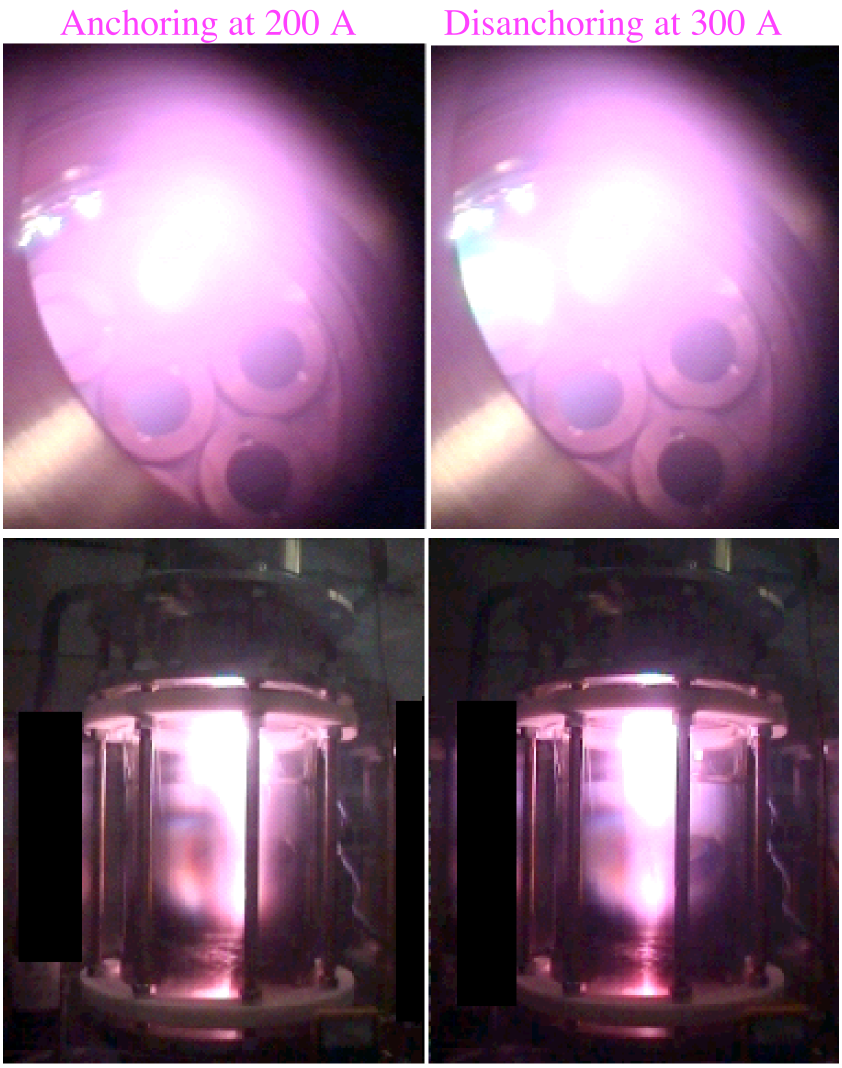

Fig. 6.9. Anode arc anchoring in PROTO-PINCH, while the cathode was DC heated.

Saddle coils near the PROTO-SPHERA electrodes could however be inserted, in order to provide a rotating magnetic field able to contrast arc anchoring, should this phenomenon reappear in PROTO-SPHERA. Four saddle coils, able to inject a torsional Alfvén wave with toroidal number n=2, could be placed below and above the anode and the cathode, respectively. The rotation frequency (of about 500 kHz) should be comparable to the Alfvén transit time in the plasma disk near the electrodes.

6.4. Diagnostics

The visible light emitted by the plasma of PROTO-PINCH has been collected on the equatorial plane by a telescope and focused onto 1-mm diameter optical fiber (see Fig. 6.1 and 6.2). An intensified diode array with 1024 pixels and spectral resolution of 3 A°/pixel has been used as detector. Visible spectroscopy of the Hydrogen plasma shows a single (unidentified) line near the H_γ ($\lambda \approx 4303$ Å) at a count level of about 10^{-2} of the largest H_α line counts. (Fig. 6.10 and 6.11).

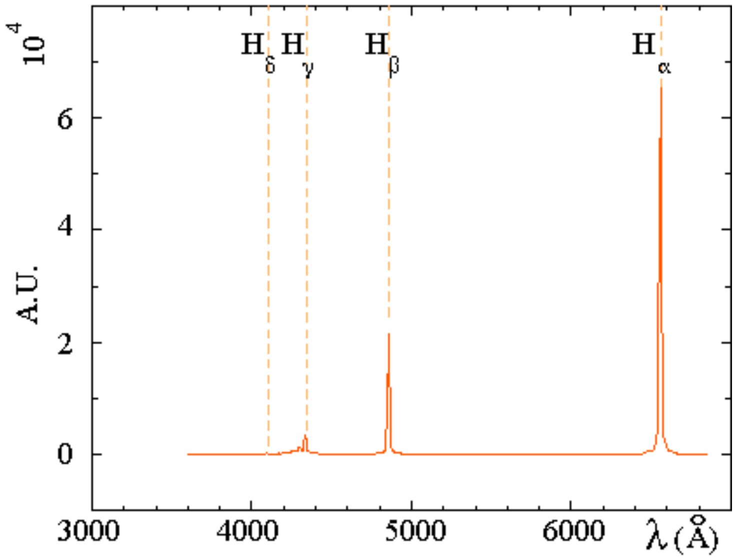

Fig. 6.10. Hydrogen plasma visible spectrum in PROTO-PINCH.

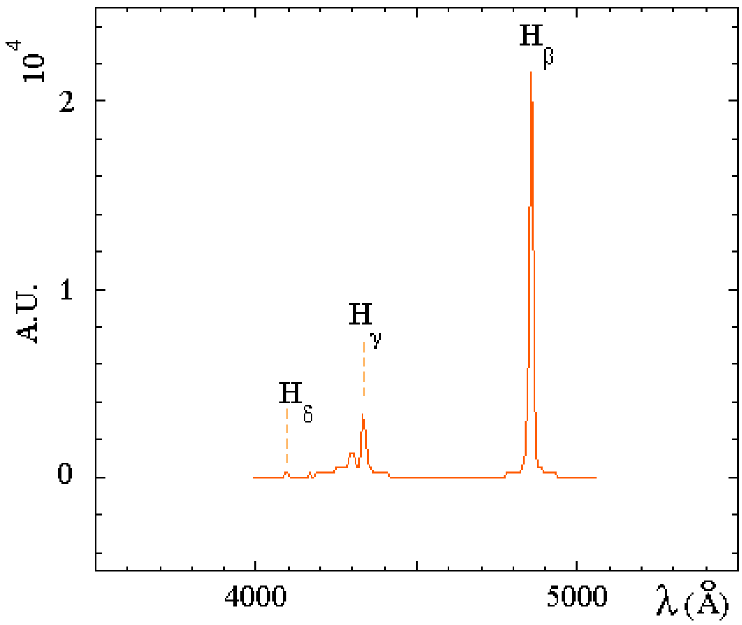

Fig. 6.11. Enlarged Hydrogen plasma visible spectrum in PROTO-PINCH. An unidentified line near the H_γ ($\lambda \approx 4303$ Å) appears.

Even when 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 Helium line counts (see Fig. 6.12)

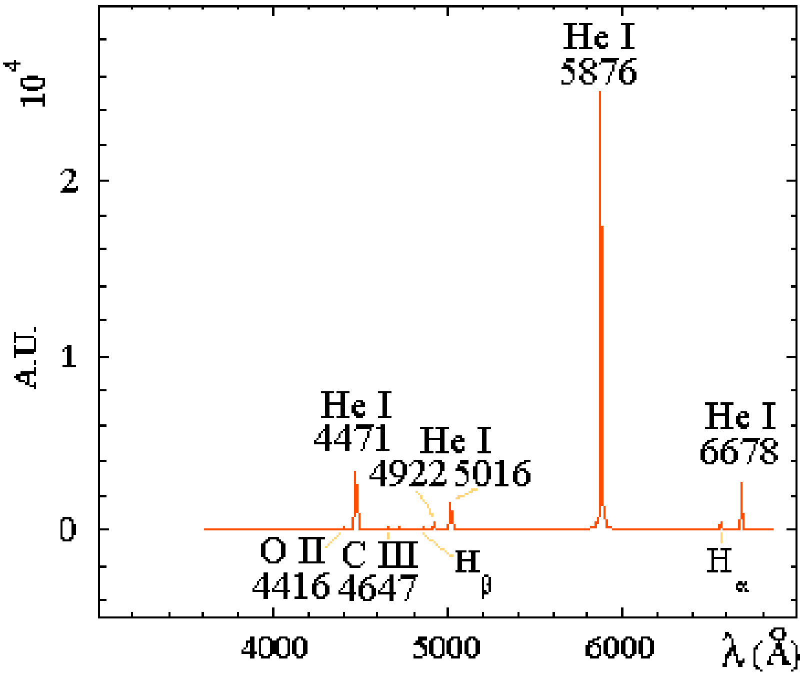

Fig. 6.12. **Helium plasma spectrum in PROTO-PINCH at low filling density, showing the presence of impurity lines O II (λ≈4416 Å) and C III (λ≈4647 Å). Hydrogen lines are still present.**

Density measurements has been done by means of a 2 mm microwave interferometer, whose scheme is shown in Fig. 6.1 and 6.2, using a 140 GHz oscillator. The density measurements have been successful only in Helium discharges at low arc currents (I_e<200 A). They indicate that the line-averaged electron density of Helium discharges increases linearly with the current I_e, see Fig. 6.13. With a filling pressure $p_{He}=4{\cdot}10^{-3}$ mbar, at I_e=200 A the Helium ionization degree is about 16%.

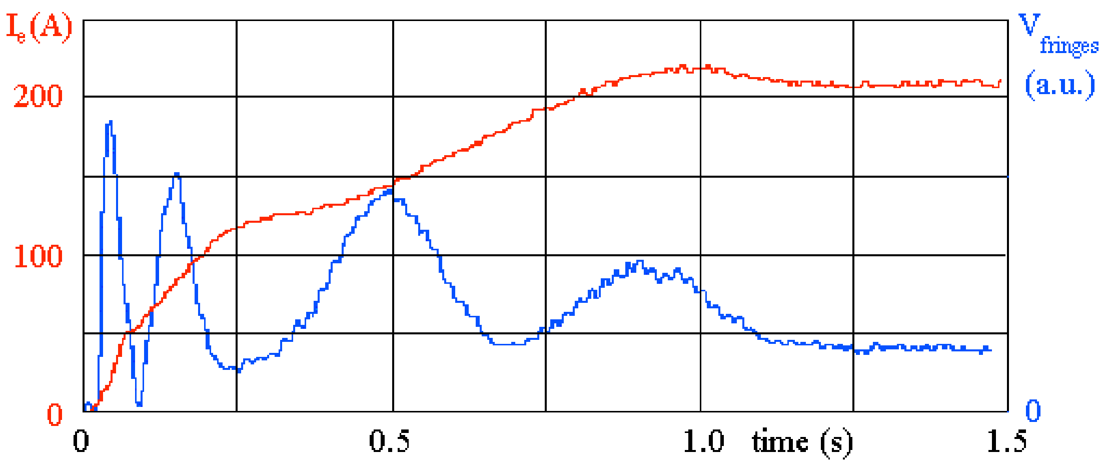

Fig. 6.13. **Waveform of I_e and of the analogue signal of 2-mm interferometer fringes in a Helium discharge of PROTO-PINCH.**

6.5. Screw Pinch Modeling and Extrapolation to PROTO-SPHERA

The PROTO-PINCH discharge at I_e=600 A is modeled as a straight cylinder of radius $<\rho_{Pinch}>$=0.10 m. Since the magnetic field lines are helices and the pinch safety factor at B=1 kG is q_{Pinch}~2, the connection length (i.e. the length of a field line from one electrode to the other) is taken as $1.33 \bullet L_{Pinch}$ (~1.0 m). Under the assumption of constant electrical conductivity in the screw pinch, σ=constant, one obtains for the ohmic power input:

$$P^{\Omega}_{Pinch} = \pi <j_{Pinch}>^2 <\rho_{Pinch}>^2 1.33 \bullet L_{Pinch} / \sigma \quad ,$$

where $<j_{Pinch}>=1.9 \bullet 10^4$ A/m^2 and $\sigma = 2 \bullet 10^2 \ln\Lambda T_e^{3/2}/Z_{eff}$.
In the main body of the discharge, neglecting the radiation losses, the convected flux due to the electron flow toward the anode is the main loss:
$P^{an}_{Pinch} = (5/2)<j_{Pinch}>T_e \pi<\rho^2_{Pinch}>$.
Balancing the two terms:
$(5/2) <j_{Pinch}> T_e \pi<\rho_{Pinch}>^2 = \pi<j_{Pinch}>^2 <\rho_{Pinch}>^2 1.33 \bullet L_{Pinch} Z_{eff} / (2 \bullet 10^2 \ln\Lambda T_e^{3/2})$.

Substituting the values L_{Pinch}=0.75 m, $<j_{Pinch}>=1.9 \bullet 10^4$ A/m^2, lnΛ= 8, Z_{eff}=2, the temperature of the main body of the PROTO-PINCH discharge is obtained: T_e=2.45 eV. This temperature is roughly in agreement with the spectroscopic estimate $1 \le T_e \le 3$ eV.

Assuming that at I_e=600 A the plasma is 50% ionized, a filling pressure $p_H = 8 \bullet 10^{-3}$ mbar of H_2 corresponds to an electron density $n_e = 2.15 \bullet 10^{20}$ m^{-3} in the main body of the plasma.

However the total ohmic power injected into the main body of the discharge turns out to be only $P^{\Omega}_{Pinch} = \pi<j_{Pinch}>^2 <\rho_{Pinch}>^2 1.33 \bullet L_{Pinch} Z_{eff} / (2 \bullet 10^2 \ln\Lambda T_e^{3/2})$~4 kW, whereas the total power injected through the electrodes is much larger, P_{Pinch}~50 kW. This means that most of the power in PROTO-PINCH is injected into the electrode plasma sheaths, P^{el}_{Pinch}~46 kW.

The power injected into the electrode plasma sheaths can be written as:
$P^{el}_{Pinch} = 1.6 \bullet 10^{-19} \bullet S_{el} \bullet \gamma k_s \bullet n_{el} \bullet T_{el}^{3/2}$ Watt, where γ is the energy transmission factor through the sheath (γ~8) and k_s the numerical coefficient for the sound velocity ($k_s = 9.78 \bullet 10^3/A^{1/2}$ m/s, A being the mass number of the incident ion). The electron temperature and density T_{el}, n_{el} near the electrodes can be guessed from this formula, by assuming furthermore that the electron pressure is constant and the same at the electrodes as well as in the body of the pinch. Accounting for the electron flow at a distance from the sheaths: $2n_{el} \bullet T_{el} = n_e \bullet T_e = 5.3 \bullet 10^{20}$ eV/m^3.
A total effective electrode area S_{el}=0.02 m^2 is used, composed by 100 cm^2 of cathode filaments (see Section 6.2) and by 100 cm^2 of anode plasma wetted surface (see Section 6.3). The prescription that $4.6 \bullet 10^4 = 1.6 \bullet 10^{-19} \bullet 0.02 \bullet \gamma k_s \bullet n_{el} \bullet T_{el}^{3/2}$ Watt, means $n_{el} \bullet T_{el}^{3/2} = 1.85 \bullet 10^{20}$, which together with $2n_{el} \bullet T_{el} = 5.3 \bullet 10^{20}$, gives: T_{el}=0.49 eV, of the same order as the temperature of the cathode filaments, and $n_{el} = 5.4 \bullet 10^{20}$ m^{-3}.

Intersecting the cross-section of both electrodes can perform an independent evaluation of the power injected into the electrode plasma sheaths. This gives a much smaller surface S_{el}=3.9•10^{-3} m^2, but using the parameters of the main body pinch discharge: n_e=2.15•10^{20} m^{-3}, T_e=2.45 eV, the estimate becomes P^{el}_{Pinch}=40 kW. This is in reasonable agreement with P^{el}_{Pinch}=46 kW, found using the electrode plasma parameters.

For the extrapolation to PROTO-SPHERA, one can assume that the plasma parameters near the electrodes will be the same as in PROTO-PINCH. This seems reasonable as the electrode modules will be almost the same and as the current and power densities at the electrode-plasma interface will also be the same. The plasma of PROTO-SPHERA shown in Fig. 4.8 (I_p=180 kA, I_e=60 kA, $\rho_{Pinch}(0)$=0.04 m), with T_{el}=0.49 eV and n_{el}=5.4•10^{20} m^{-3}, will have a temperature in the main body of the pinch discharge T_e=36 eV (see Section 4.9). Using $2n_{el}\cdot T_{el}=n_e\cdot T_e$=5.3•10^{20} eV/m^3, the result is that n_e=1.5•10^{19} m^{-3}, i.e. the main body of the PROTO-SPHERA screw pinch discharge will have an electron density much lower than PROTO-PINCH.
In PROTO-SPHERA the effective electrode surface will be 100 times the one of PROTO-PINCH: S_{el}=2 m^2. Therefore the power injected into the electrode plasma sheaths will be: $P^{el}_{Pinch}=1.6\cdot 10^{-19}\cdot 2\cdot\gamma k_s\cdot n_{el}\cdot T_{el}^{3/2}$=4.6 MW, which is obviously 100 times the one of PROTO-PINCH.

As a matter of fact, the radiative losses have been neglected in the analysis of the data of PROTO-PINCH; their proper accounting could reduce the estimate of the power injected into the PROTO-PINCH electrode plasma sheaths even by a factor of two. That would reduce the power required for PROTO-SPHERA, whose central screw pinch is predicted to work at a plasma density much lower with respect to PROTO-PINCH, with negligible radiation losses (0.1 MW). Therefore the estimate of the total power required for the screw pinch of PROTO-SPHERA, consisting of P^{Ω}_{Pinch}=5.4 MW, P^{el}_{Pinch}=4.6 MW, P^{HI}_{Pinch}=0.6 MW and summing up to P_e=10.6 MW, must be considered as a conservative upper bound.

The power injected into the electrode plasma sheaths can be considered to be constant P^{el}_{Pinch}=4.6 MW during all the toroidal plasma formation at I_e=60 kA. It will be instead much lower during the stable pinch formation at I_e=8.5 kA (see Section 4.4), where P^{el}_{Pinch}=0.65 MW, along with the ohmic power input P^{Ω}_{Pinch}~0.1 MW.

The power density impinging on the electrodes of PROTO-PINCH, considering the sum of the cross-section of both electrodes, is:
P_e/S_{el}=50÷85 kW /3.9•10^{-3} m^2=13÷22 MW/ m^2.

The same figure for PROTO-SPHERA, that has a sum of the cross-section of both electrodes S_{el}=3.5•10^{-1} m^2, is:
P_e/S_{el}=5÷10 MW /3.5•10^{-1} m^2=14÷28 MW/ m^2.