

7. MECHANICAL ENGINEERING

The PROTO-SPHERA machine consists of the following components: the vacuum vessel (VV), poloidal field (PF) coil system, the internal support, the anode and cathode and the machine support (MS), see Fig. 7.1. In addition a number of screening plates protect the coils from the hot anode and cathode. Stabilizing limiters, divertor protection plates and reflection rings are also required. The main parameters of the machine are given in Tab. 7.1.

Spherical Torus (ST) diameter	0.7 m
Longitudinal Screw Pinch current	60 kA
Toroidal ST current	120÷240 kA
Plasma pulse duration	1 s
Minimum time between two pulses	5 min.
Maximum heat loads on first wall components in divertor region	$\sim 2 \text{ MW/m}^2$
Maximum heat loads on rest of first wall	3 MW/m^2 , for 0.5 ms
Maximum current density on the plasma-electrode interface	0.8 MA/m^2

Table 7.1. Machine Parameters.

The basic principle of the mechanical engineering of PROTO-SPHERA is for a substantial VV, which provides both the ultra-high vacuum enclosure and contains the PF coils, the anode, the cathode and the other components. The PF coils are located very close to the plasma and therefore must be positioned inside the VV. In order to achieve the required ultra high vacuum conditions ($\sim 10^{-8}$ mbar), each coil will be enclosed in a vacuum tight metal case.

The plasma arc inside the machine is produced by two electrodes, anode and cathode, which are (particularly the cathode) the most unconventional and technologically demanding components.

The primary aim is to produce a design as simple as possible, easily assembled, with good access, particularly to anode and cathode, which are critical components and may require frequent maintenance/repair. Considering the experience in PROTO-PINCH, no major problems are also expected with the electrodes, the only unconventional components.

In order to enhance the reliability and maintainability, all connections for the PF coils are external to the VV. All the feeds come from the top and bottom flanges, leaving space for diagnostic ports in the main body of the VV. Each coil has a separate feed connected to the access flange by a flexible bellows arrangement, in order to adjust its position. Provisions will be made in the design to minimize the stray magnetic field, particularly in region near the spherical torus.

Particular care has been exercised to maintain the appropriate potential in each component, to avoid hot spots (circa 90°C) in the coils and to accommodate the electromagnetic stresses during plasma disruptions. Insulation plates have been used where appropriate, while no coil can see directly the cathode.

The PF coil system, the anode and the cathode will be pre-assembled outside the VV to check and adjust their relative positions. They will then be installed inside the VV, which will be closed by the top and bottom flanges.

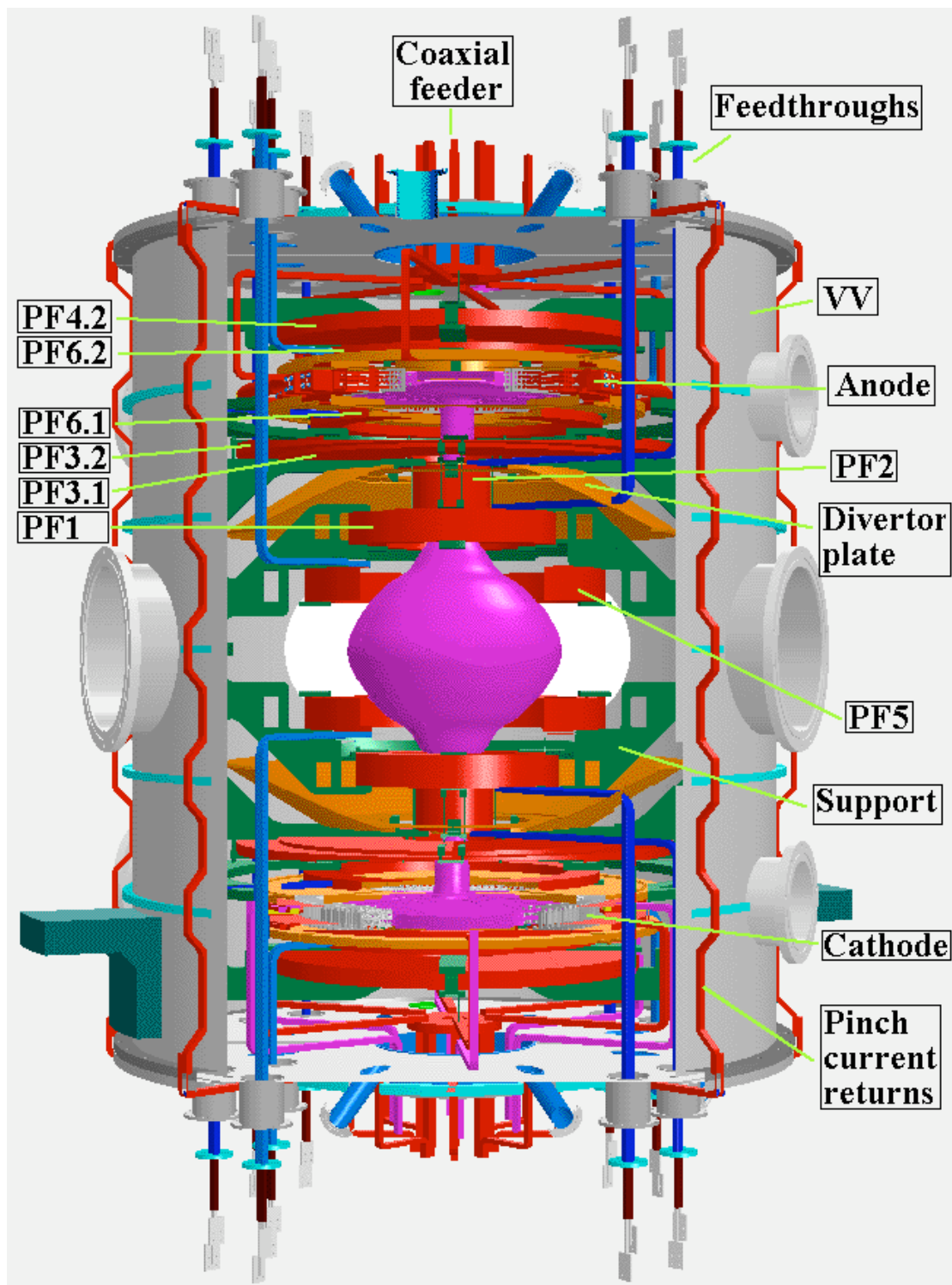


Fig. 7.1. 3D outline of PROTO-SPHERA, showing the main machine components.

7.1. Vacuum Vessel

Figure 7.2 gives the basic machine geometry. The VV is a non-magnetic Stainless Steel (AISI 304L) vessel, 2 m in diameter and ~2.5 m in height. The thickness of the VV will be ~18 mm while the flat top and bottom flanges will be ~30 mm, in order to resist effectively the vacuum forces (~300 kN per flange). Flat flanges (albeit with increased thickness with respect to the VV cylinder) have been chosen to generate space for the coil feedthroughs, and facilitate interfaces.

The VV has a large number of ports for diagnostic purposes and vacuum pumping. Eight 500 mm and eight 250 mm ports are foreseen in total. In order to accommodate the vacuum forces and avoid distortion (ovality) of the ports, stiffening ribs will be incorporated as required. Note that in the top and bottom flanges, viewing ports will be employed to check the condition and operation of anode and cathode, see Fig. 7.2. During normal conditions the VV will be at room temperature (20 °C) with a vacuum of $\sim 10^{-8}$ mbar. However provision will be made to bake the machine up to 80-90 °C. Such a baking temperatures are effective in removing water vapor. They allow for the use of Viton O-rings and simplify the flange design. Finally they avoid any control of the PF coil insulation, which should be maintained always lower than 100 °C, in order not to run any risk of damage due to excessive temperatures. In addition the choice of a relatively low baking temperature of 80-90 °C will also result in a lower total cost for the machine. The predicted total outgassing rate by the O rings and the VV Stainless Steel is $\sim 3 \cdot 10^{-5}$ mbar·l/s. Such an outgassing rate, together with that of anode and cathode, can be easily accommodated by turbomolecular pumps, considering the port areas present in the VV.

The baking temperature will be reached by electrical heating tapes located on the external surface of the VV and of the top and bottoms flanges. The size of the machine requires a supply of ~25 kW for baking, which will take about 3÷4 hours to heat the assembly. Note that in order to speed up the baking cycle, avoid hot spots (dangerous for the coils) inside the machine, minimize thermal gradients and avoid relying only on conduction and radiation to heat the internal components, contact dry Nitrogen gas at ~1 mbar will be used during the temperature ramp-up phase. At this filling pressure convection starts to become effective. Thermal insulating material outside the VV would reduce losses to the environment and speed up also the baking cycle.

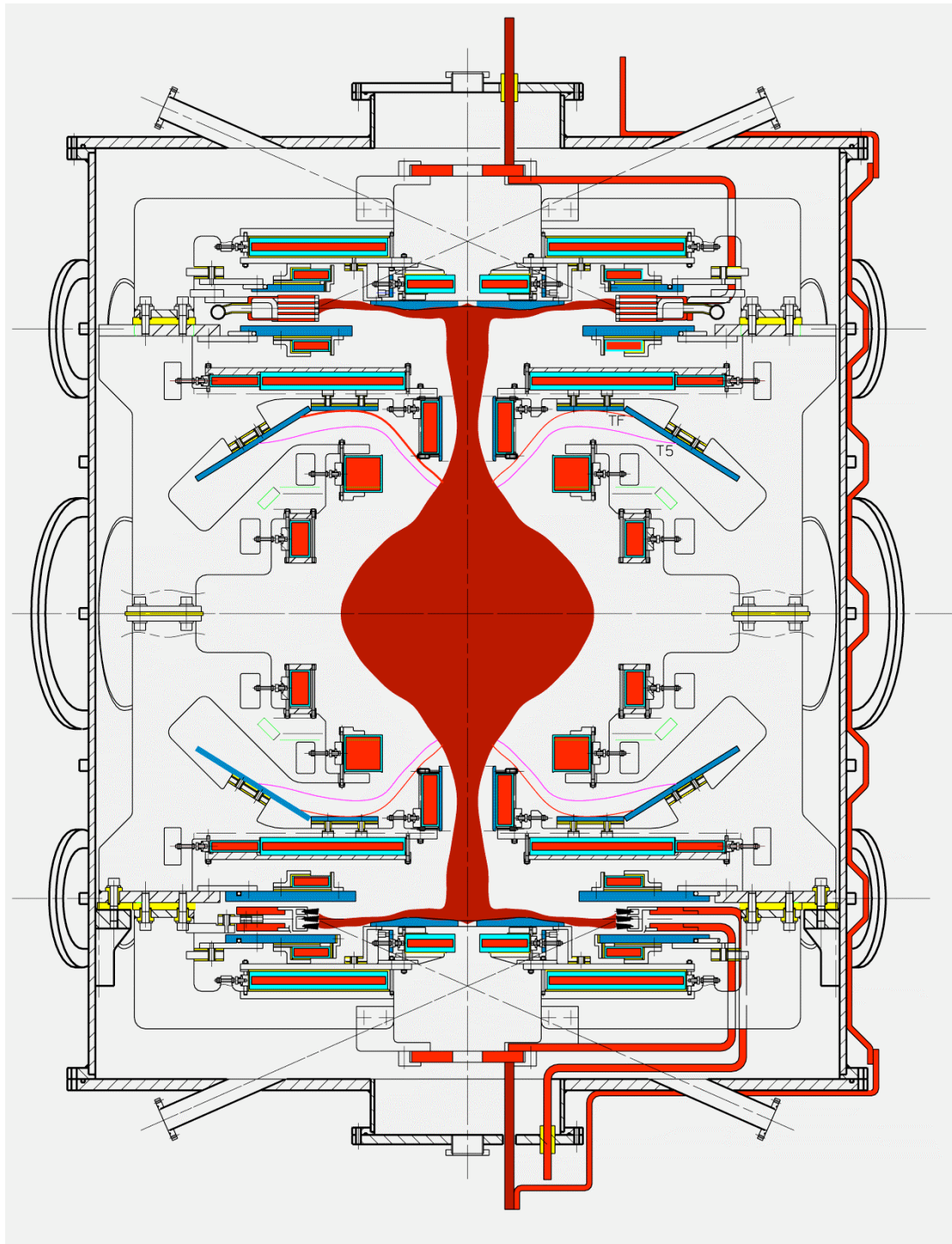


Fig. 7.2. Basic machine geometry as a cross-section outline.

In Fig. 7.2 the internal coil support structure is also shown. This supports mainly the PF coils, anode and cathode and consists of a rigid mechanical framework in which toroidal eddy currents are limited. The structure is divided vertically into 4 parts, which can be connected at different levels of potential. The 3 upper parts are electrically insulated from each other and from the VV. Alumina or other suitable material will be adopted for the insulation. The coil support structure will have to withstand the electromagnetic forces generated during normal operation and plasma

formation and will incorporate suitable mechanical system to adjust to the required alignments. Figure 7.3 shows the support of the VV, which has to accommodate thermal expansions during baking, in addition to the ~110 kN weight of the machine. It will be made from non-magnetic Stainless Steel (AISI 304L) to limit the stray field in the plasma region. This support arrangement provides also space for access to remove the top and bottom flanges, as required for the anode/cathode maintenance.

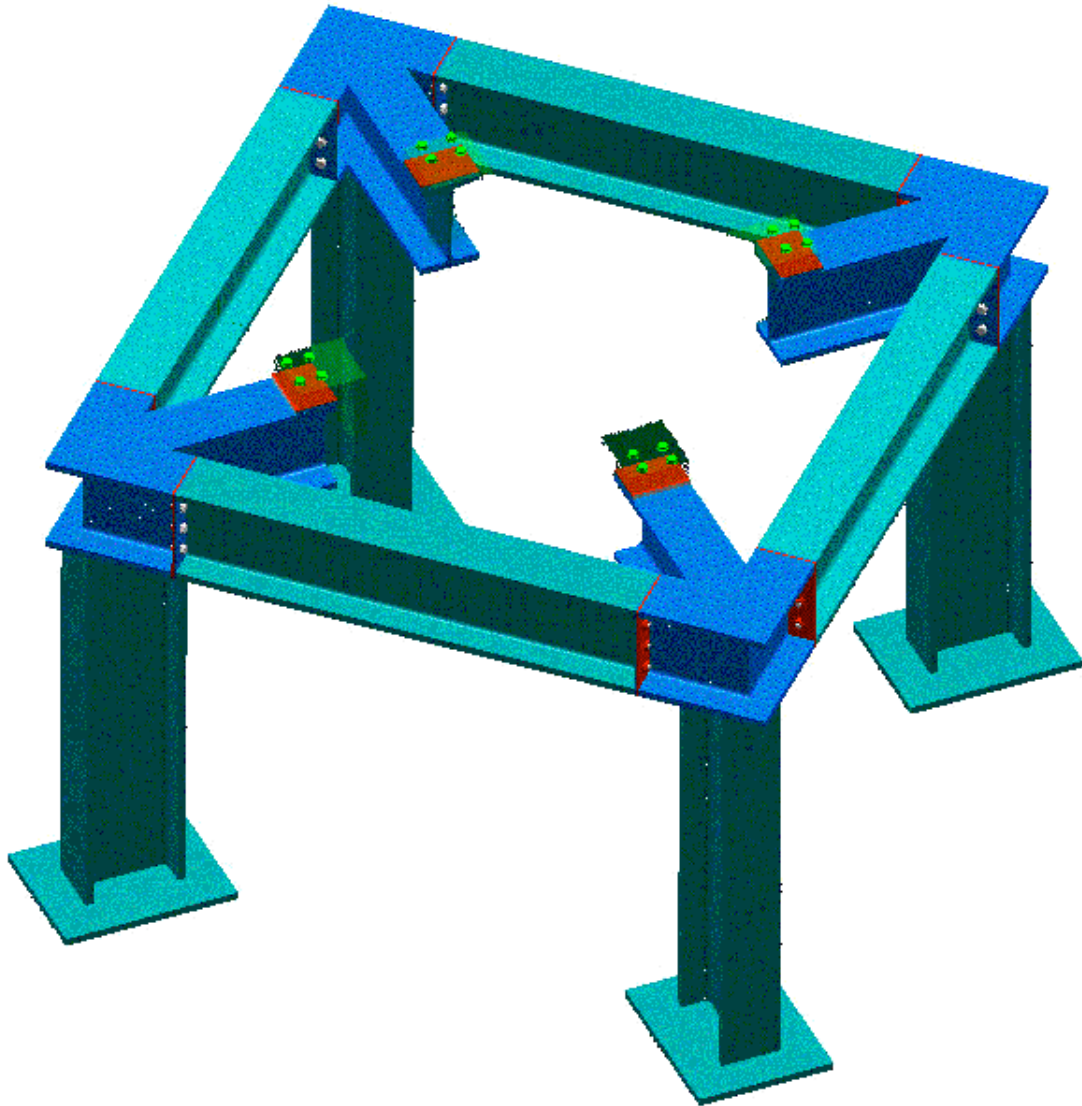


Fig. 7.3. Support structure of the vacuum vessel.

The VV will be designed in detail and manufactured according to pressure vessel requirements (ASME), with limited weld radiography where possible. Where not possible, welder qualifications will suffice. Good ultra high vacuum practice (no blind holes, clean conditions, etc) will be naturally employed, while all components will be vacuum baked to at least 150 °C prior to final installation.

7.2. Poloidal Field Coils

There will be two sets of poloidal field coils in PROTO-SPHERA, see Fig. 7.4: type 'B', the set of coils which shape the screw pinch and whose currents do not vary during the plasma evolution; type 'A', the set of coils which compress the ST and whose currents vary during the plasma evolution. As the formation time of the configuration will be 1 ms, the coils whose variable currents compress the ST will be shielded inside thin metal cases (time constant $\sim 200 \mu\text{s}$). On the other hand the coils with constant current will have to be enclosed inside thick conductors (time constant $> 2 \text{ ms}$) in order to stabilize the formation phase. As a consequence the type 'A', PF coils will be enclosed in an Inconel case of 1.5 mm thickness, while the type 'B' coils in a Stainless Steel (AISI 304L) case of $\sim 10 \text{ mm}$ thickness. Note that the two PF2 coils, Fig. 7.4, require an additional cylindrical shield facing the plasma to reach the required time constant of 2 ms. This will be made from Copper-Tungsten alloy and, due to space restrictions, can act also as a first wall protection for the coil.

All coils at present are designed considering normal operating conditions, i.e. using PF current waveforms consistent with the proposed plasma current and shape (see Section 8). This is due to the fact that the time variations of PF current waveforms during the plasma formation result in flux variations similar to those occurring in tokamak disruptions. Fault conditions will however be considered in detail in future design stages.

The coils are arranged coaxially and sustained by the support structure, Fig. 7.4. The coils and their supports are designed to withstand electromagnetic forces during normal and fault conditions. They can also accommodate thermal expansion during baking and normal operation.

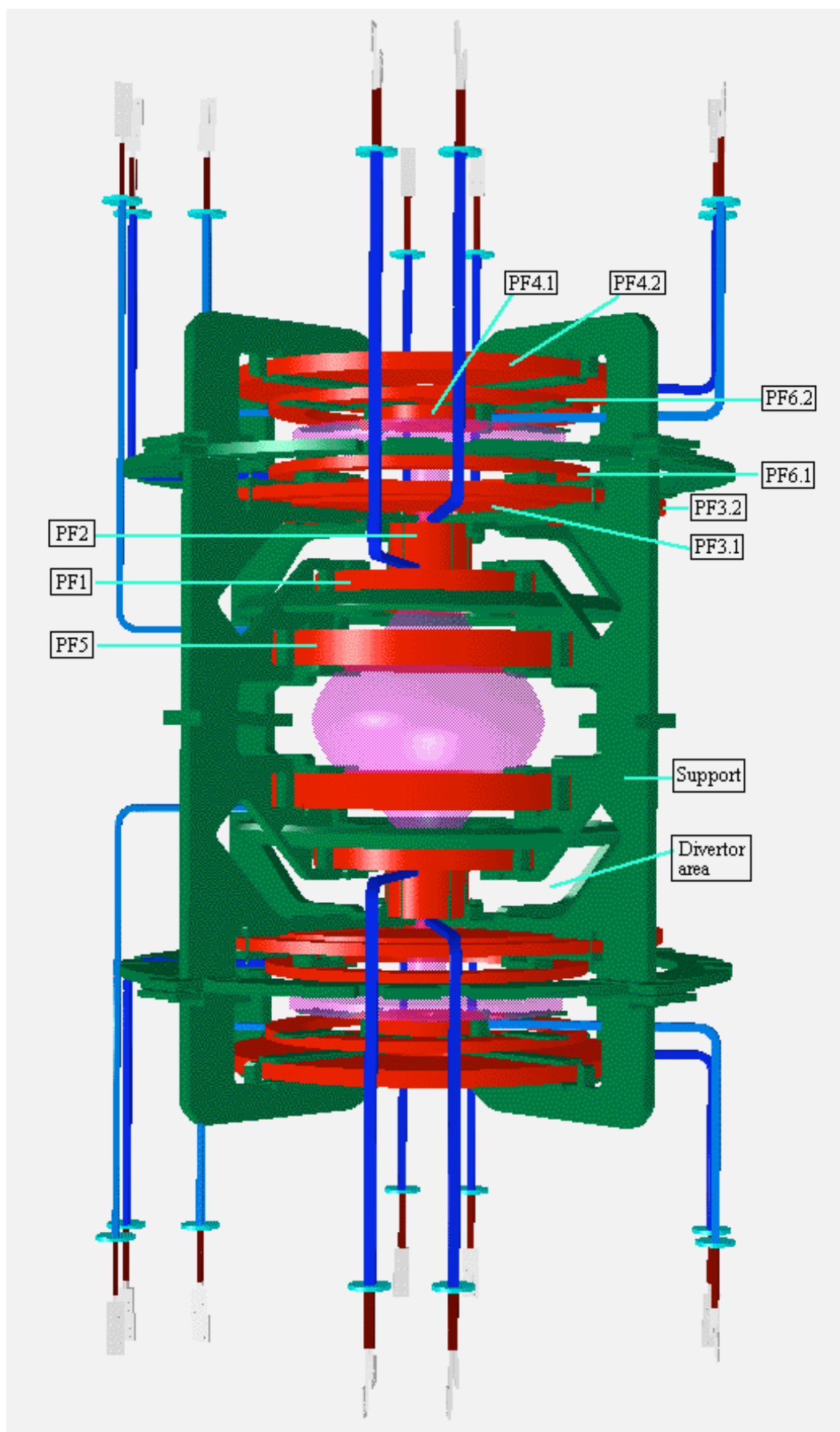


Fig. 7.4. Poloidal field coil arrangement and support structure.

All the coils will be made from hollow OFHC Cu water-cooled conductors, insulated with glass fiber and Kapton tapes, vacuum impregnated with epoxy resin within the metal cases. Coils PF1, PF2 and PF5 are of a helical winding type while the rest are of pancake type to accommodate geometrical requirements. The PF coil system will be fed by two power supplies (see Section 8). One will feed PF1, PF3.2, PF5, PF6.1 and PF6.2 in series, while the other power supply will feed the other coils, also in series. In order to simplify the construction and reduce the costs in the pancake coils, dummy turns with no current will be introduced (Fig. 7.5).

The metal cases of all PF coils will be kept individually floating.

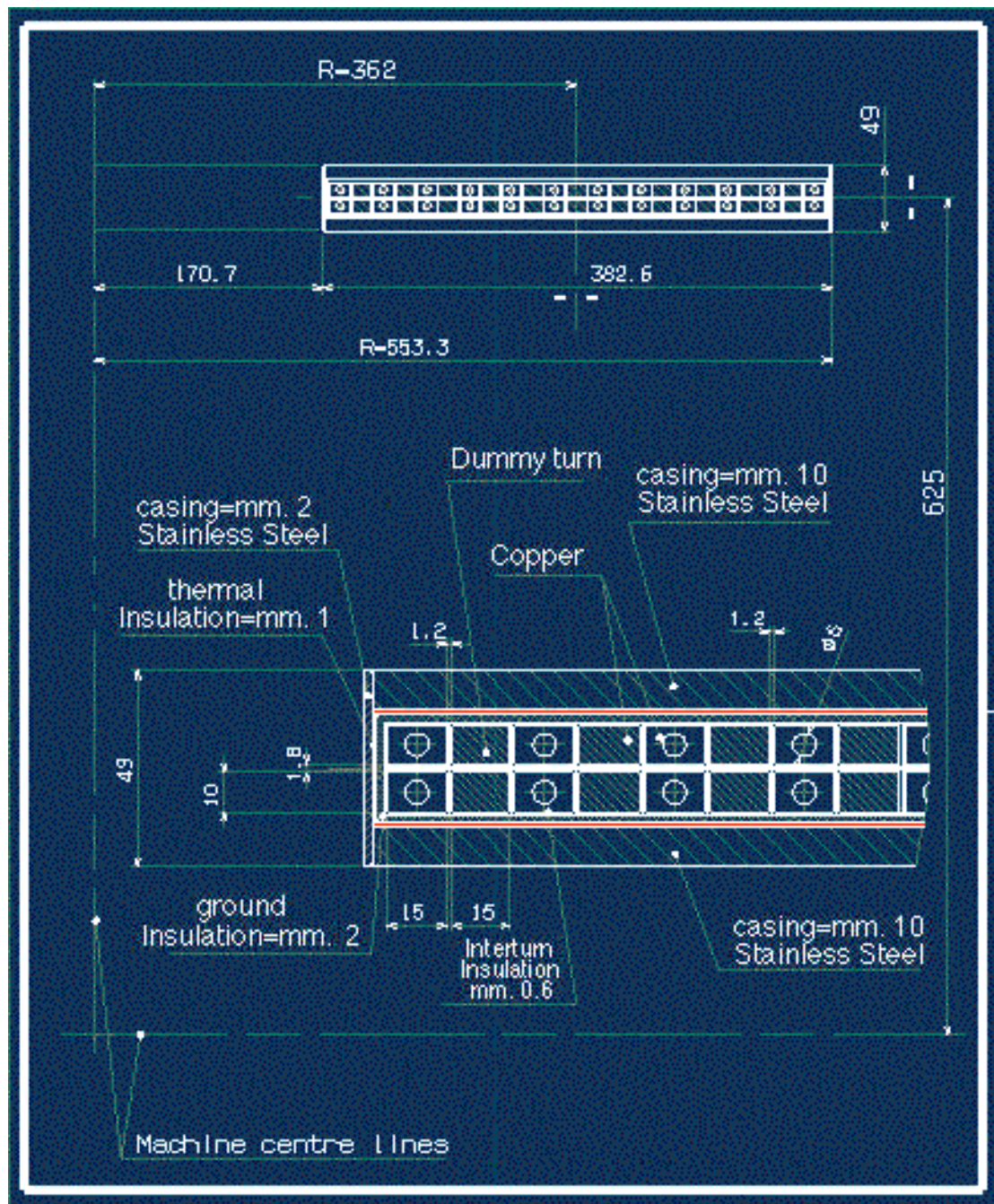


Fig. 7.5. PF3.1 as an example of a group 'B' poloidal field coil.

Table 7.2 gives the electrical, geometrical and thermal coil characteristics. The coils need to be cooled between pulses within ~ 5 min. A maximum ΔT after a pulse of ~ 35 °C has been predicted in the PF2 coil with pessimistic assumptions; this ΔT is generated from the coil current (Joule effect), from the plasma, which is at close proximity, and from the anode or cathode. Water has been chosen as coolant in order to limit the pressure drop ΔP , which was too high in case of gas cooling (He or N₂). With water and a 6-mm hollow conductor, the ΔP will be limited to a few bar (≤ 4 bar).

Coil	N° of turns	Maximum Current per turn [A]	Mean Radius [mm]	Coil z* location [mm]	Coil size $\Delta r \cdot \Delta z$ [mm ²]	Approx. Coil Weight [N]	Current density [A/mm ²]	Total Coil ΔT [°C]
PF 1	64	1156	280	375	98.92	530	11.56	3
PF 3.2	10	1156	625	625	129.26	440	4.59	25
PF 5	32	1156	450	200	51.94	450	11.56	3
PF 2	48	1875	100	500	43.138	295	25.51	35
PF 3.1	24	1875	362	625	383.26	1480	5.21	25
PF 4.1	18	1875	100	885	138.26	200	11.16	25
PF 4.2	18	1875	400	985	365.26	1565	3.72	25
PF 6.1	8	1156	420	720 ₍₇₁₀₎	93.21	332	6.8	2
PF 6.2	8	1156	420	910	93.21	332	6.8	2

* vertical distance from machine center line

Table 7.2. PF coil characteristics.

Table 7.3 gives a preliminary estimate of the coil vertical electromagnetic forces generated during normal operation. These forces would be accommodated by the support systems. A preliminary assessment of the hoop stresses generated in the Cu conductors gives a value of only a few MPa.

COILS	without Plasma	with Plasma
PF1+PF5	-8.2	-1.6
PF2+PF3.1+PF3.2	6.9	0
PF4.1+PF4.2	-2.7	0

Table 7.3. Coil electromagnetic forces [kN] during operation; see Fig. 7.4.

Figures 7.5 and 7.6 show typical coil details. Each coil turn is wrapped with half-lapped glass fiber and Kapton tape up to 0.6 mm, where necessary to meet the voltage requirements. The inter-layer insulation will be made from the same material, but 1.8 mm thick.

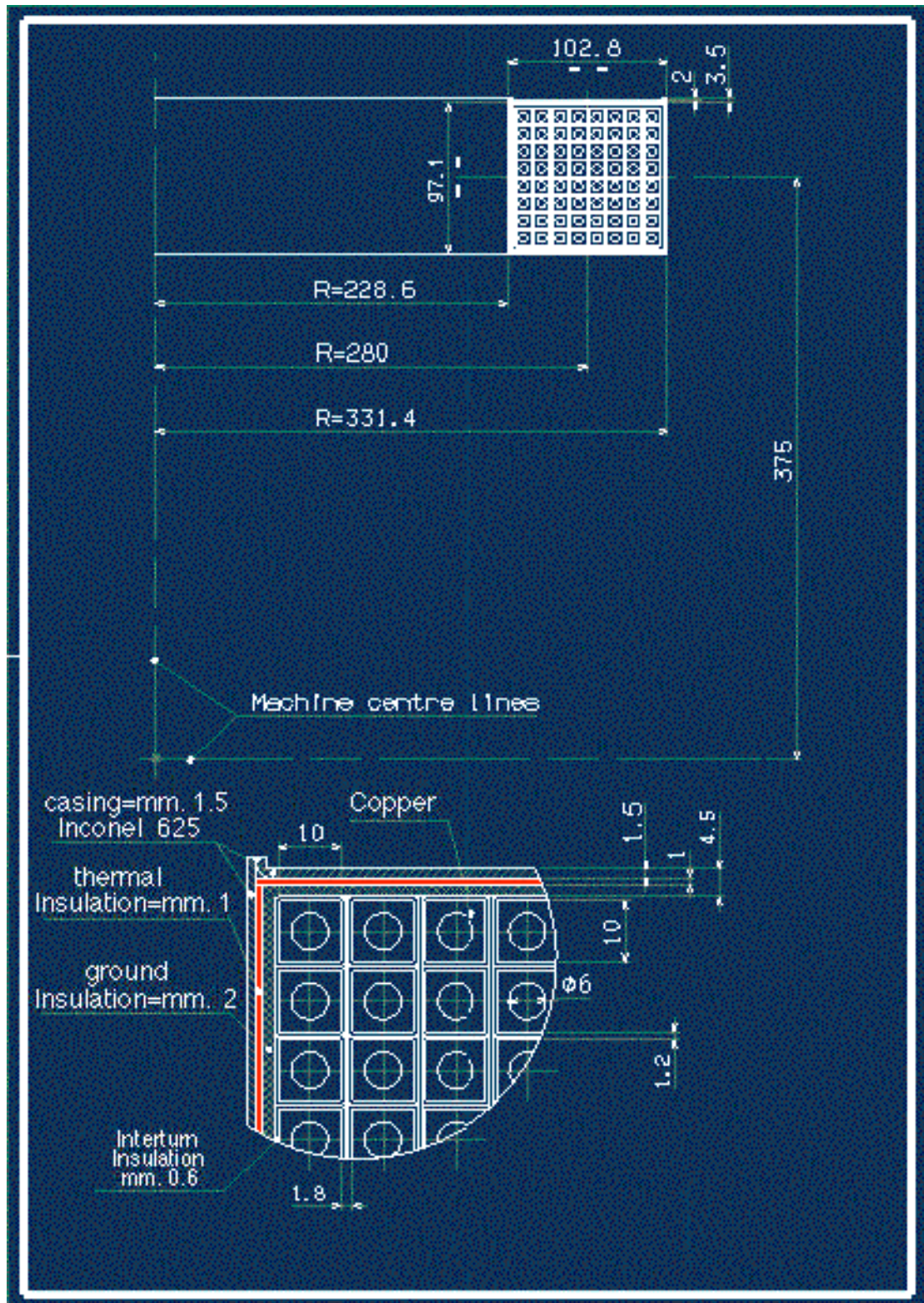


Fig. 7.6. PF1 as an example of a group 'A' poloidal field coil.

The ground insulation will be up to 2 mm thick. Figure 7.7 gives details of the coil feedthroughs and the associated bellows arrangement to accommodate coil alignment requirements and thermal movements. An electrical break, vacuum-sealed, assures the electrical insulation between the VV and the coil metal cases. The coils after the manufacture of interturn and interlayer insulation will be vacuum impregnated with

epoxy resin prior to casing. Then the ground insulation will be made and the coils will be positioned inside their cases, and a thick layer of high temperature thermal insulation will be placed between the case and the coil. The final welding is done in a lap joint of the metal case to avoid damage in the insulation. The whole assembly is then evacuated and vacuum impregnated with epoxy resin.

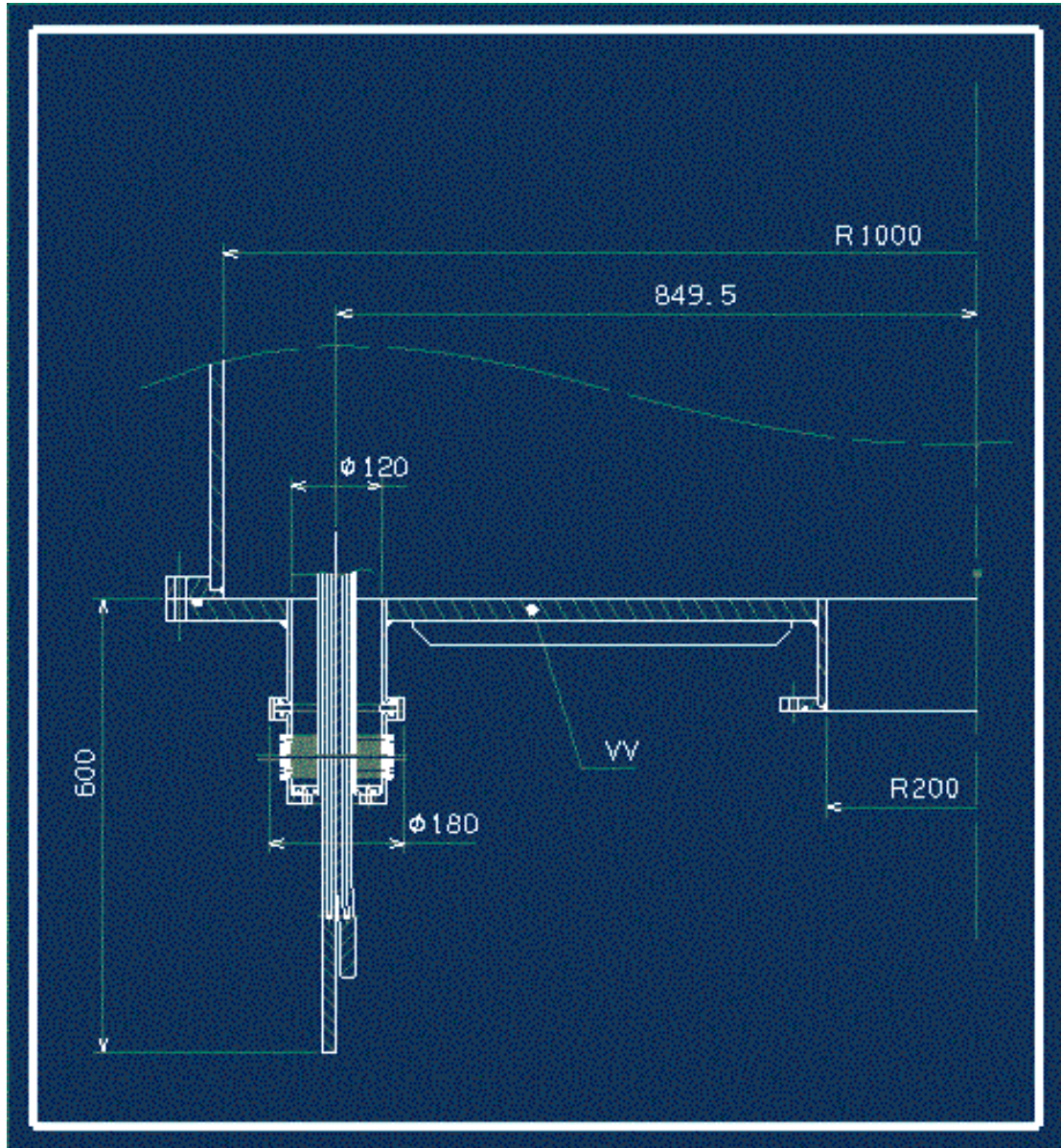


Fig. 7.7. Detail of the feedthrough of a poloidal field coil.

Note that stray fields can be generated in the plasma region. Stray fields can be due to induced currents in the VV, support structure and coil metal cases, to misaligned position of the coils, to the detailed geometry of the turns, to the electrical feeders and to the presence of ferromagnetic materials. The significance of such error fields is being assessed and suitable provisions are being adopted: a precise alignment procedure has been studied. The effect of induced currents will be computed and an ad hoc insulation will be introduced, if required. The joggles in the PF coil turns will be localized if necessary in order to compensate, as much as possible, the vertical component of the current in the helical winding type coils. The two electrical feeders

of each coil will be maintained very close to each other and will be connected to the coil as far away as possible from the plasma region. Finally non-magnetic materials will be used.

The coil metal cases and the support structure need to be protected from the plasma heat loads. A max power density of $\sim 2 \text{ MW/m}^2$ for $\sim 1 \text{ s}$ is expected in the divertor region (Figs. 4.16 and 4.17), and significantly lower heat loads elsewhere in the machine. Such a power can be accommodated with conventional AISI 304L tiles. For a very short time ($\sim 0.5 \text{ ms}$) during the plasma start-up phase (Figs. 4.5, 4.14 and 4.15), a thermal load of 3 MW/m^2 has been estimated on the cylindrical shields of the PF2 coils.

7.3. Electrodes

The anode and cathode, the two electrodes for producing the screw pinch plasma that characterizes the machine, are perhaps the most technologically demanding components. Fig. 7.8 and Tab. 7.4 show the main characteristics and a preliminary design of the anode. This cylindrical component is formed by six 60° sectors, each with 5 modules. Each module is made from OFHC Cu, with its surface, exposed to the plasma arc, protected by an alloy of W-Cu(5%) to resist excessive transient temperatures ($\sim 1000^\circ \text{C}$). Gas puff in each individual module, summing up to $30 \text{ mbar}\cdot\text{l/s}$, is performed through 20, 10-mm diameter holes, see Fig. 7.8, to spread the arc energy and avoid melting. The modular design of the anode permits replacement of each module individually.

Main Sectors:	6	Total Module Number:	30
Module Material:	Cu	Total Anode Holes:	600
Nuts & Bolts:	Inconel or Ta	Energy for each hole 1 sec:	6.7 kJ
Modules per Sector:	5	Total Arc Current:	60 kA
Protection Tile Material:	W-Cu (5%)	Arc Voltage:	100 V
Tile Max. Temperature:	$\sim 1000^\circ \text{C}$	Arc duration:	1 s
Module Hole Number:	20	Energy Distribution: Anode	2/3
Hole Diameter:	10 mm	Energy Deposition:	4 MJ
Module-Plasma Surface:	H 85mm • L 70mm		

Table 7.4. Anode main features.

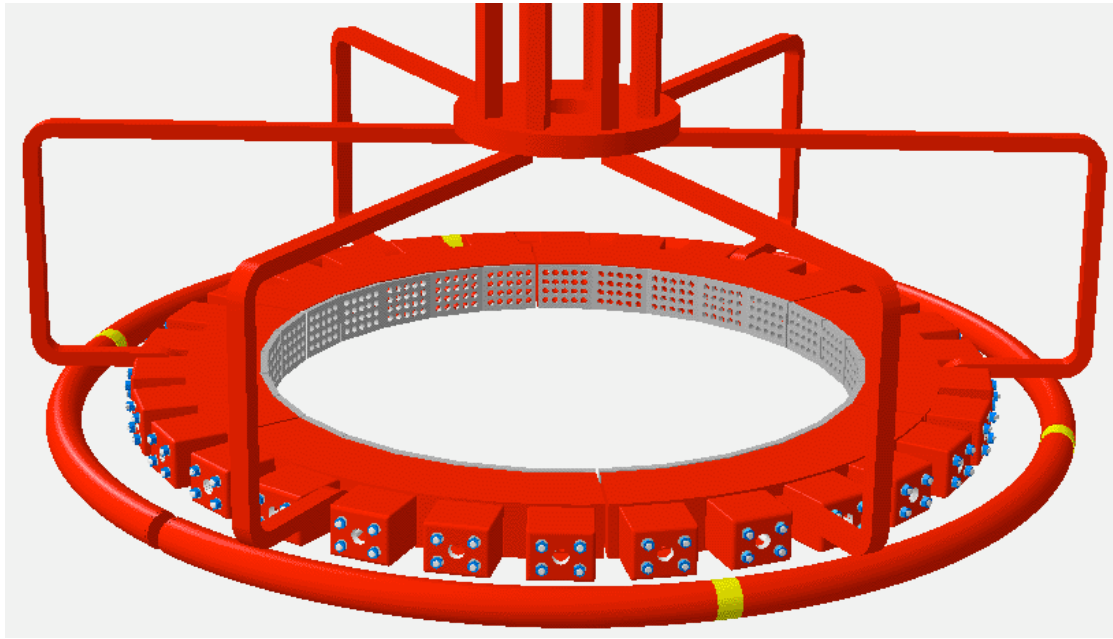


Fig. 7.8. Outline of the anode. Tubes (non-indicated) will connect each anode module to the gas distribution torus.

Figure 7.9 gives a view of the anode and the top part of the machine load-assembly.

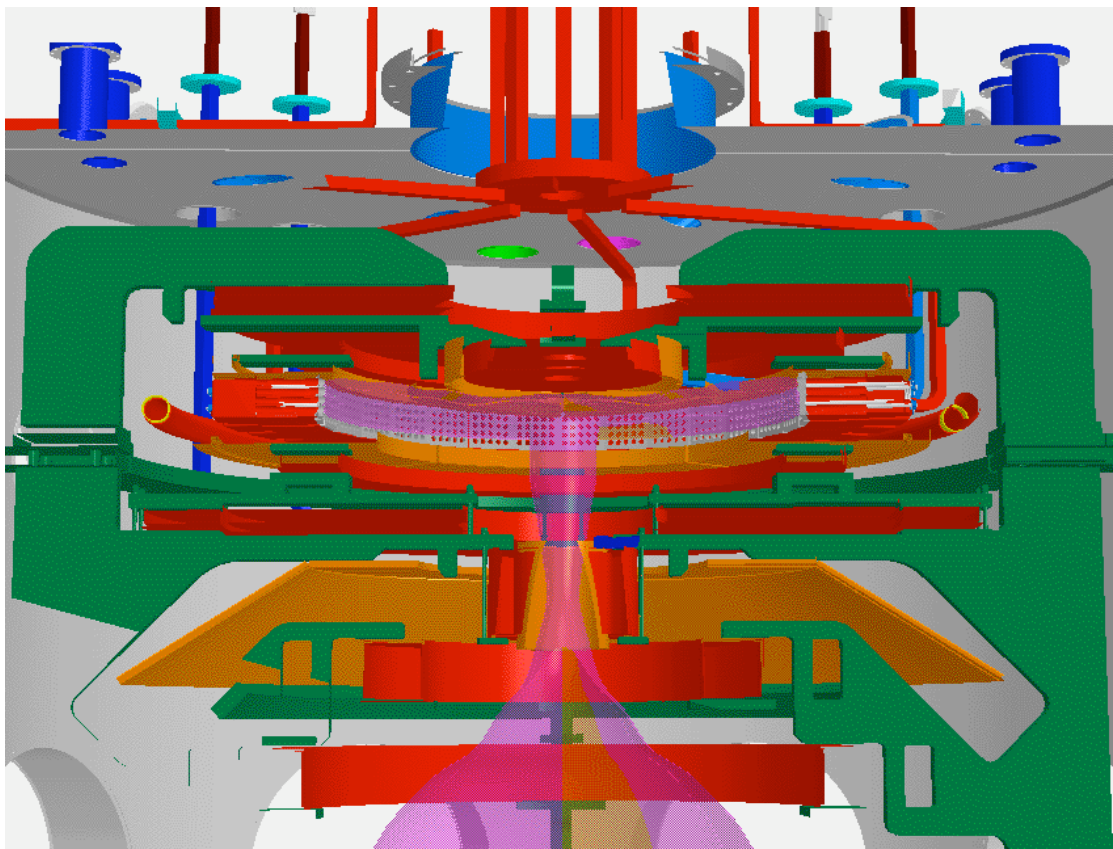


Fig. 7.9. 3D view of the anode inside the PROTO-SPHERA anode chamber.

Figure 7.10 and Tab. 7.5 show the main features and a preliminary design of the cathode.

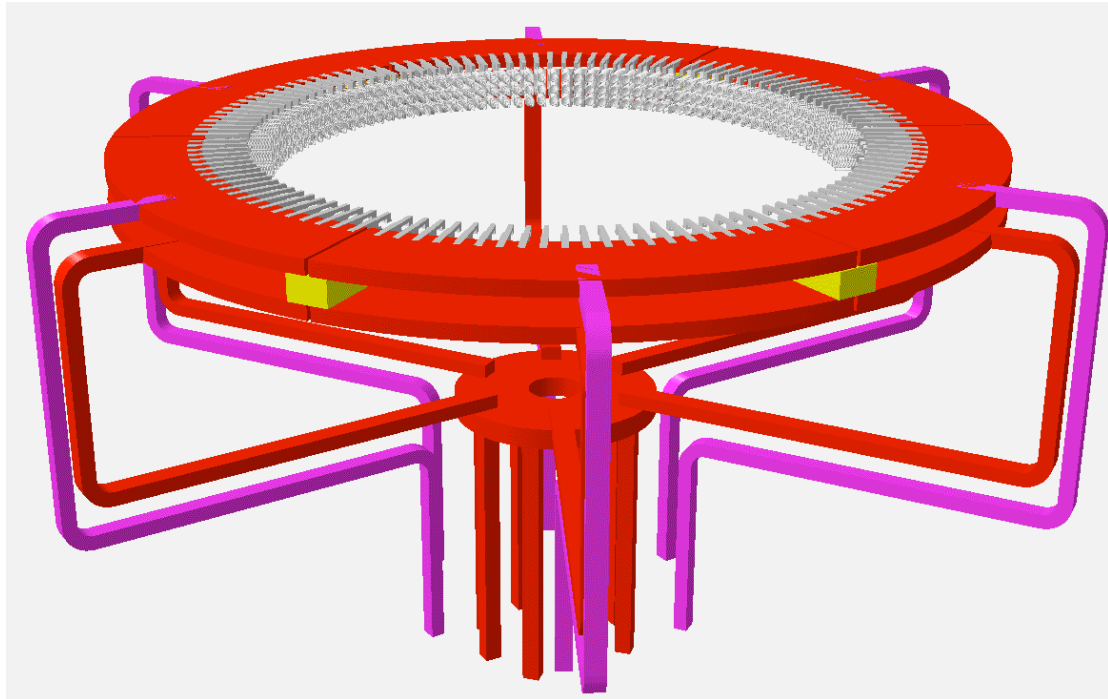


Fig. 7.10. Outline of the cathode.

Main Sectors:	6	Wire Length:	40 cm
Dispenser Material:	Mo	Coil Surface:	25 cm ²
Nuts & Bolts:	Tantalum	Total Coil Number:	378
Insulators:	Alumina	Electron Emission Density:	6 Amp/cm ²
Dispenser per Sector:	24	Emission for each coil:	150 A
Coils per Dispenser:	3	Max electron Emission:	64.8 kA
Coil Material:	W	Voltage Power Supply:	15 V
Coil Work. Temper.	2750 °C	Total Cathode Current:	60 kA
Turns Number:	8	Heating Time:	15 sec
Wire Diameter:	2 mm	Est. Heating Energy:	8 MJ
Coil Diameter:	14 mm	Est. Arc Energy Deposition:	2 MJ
Coil Length:	50 mm		

Table 7.5. Cathode main features.

The cylindrical component is made from 378 coils supported by a dispenser assembly, see Figs. 7.11 and 7.12, which also feeds the current to the W coils. The dispensers are made from Mo to resist to high temperatures, which in the coils can reach up to 2750 °C. The cathode is composed from 6 sectors, each powered by a six-phased AC power supply. 24 dispensers form each sector, each carrying 3 coils of null field type, see Figs. 7.10, 7.11 and 7.12.

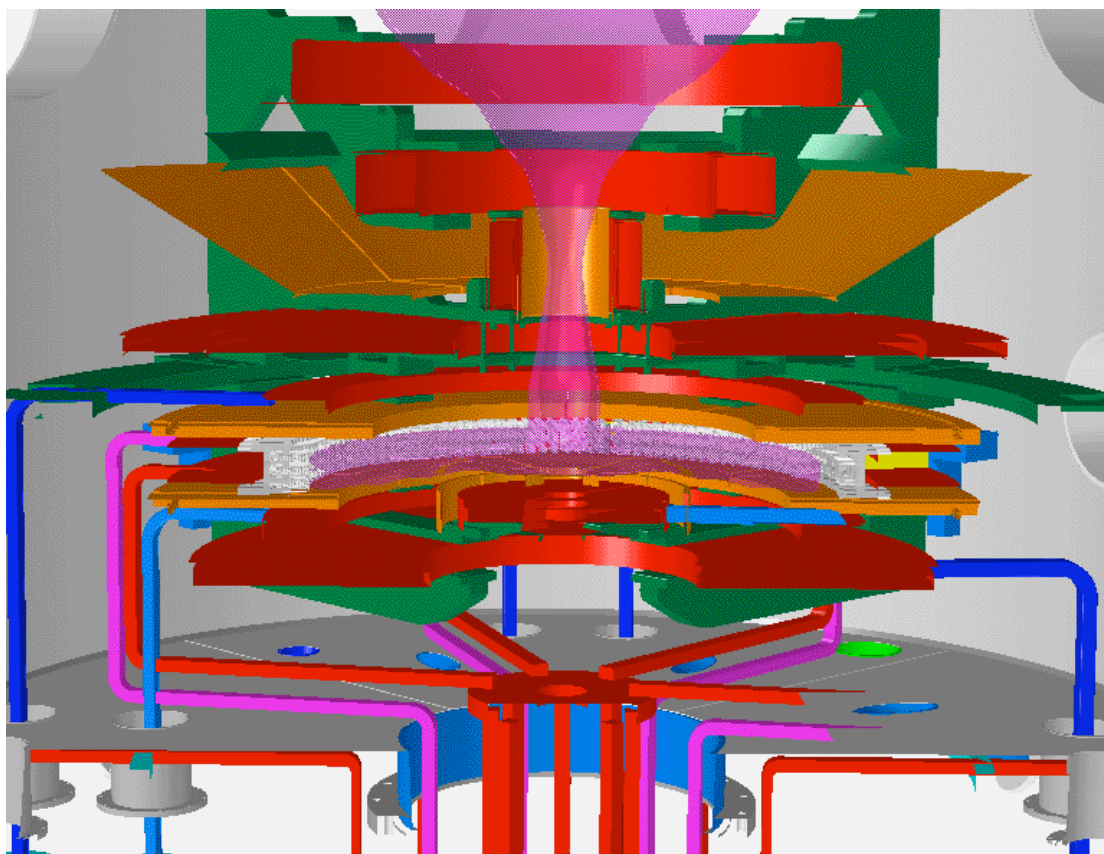


Fig. 7.11. 3D view of the cathode inside the PROTO-SPHERA cathode chamber.

The design is such that each dispenser can be individually replaceable. The six-phased AC power supply gives 8 MJ to the cathode. The heating time to the working temperature (2600 °C) of the coil wires is 15 s. As soon as the screw pinch plasma breaks down, the coil temperature increases to a maximum of 2750 °C.

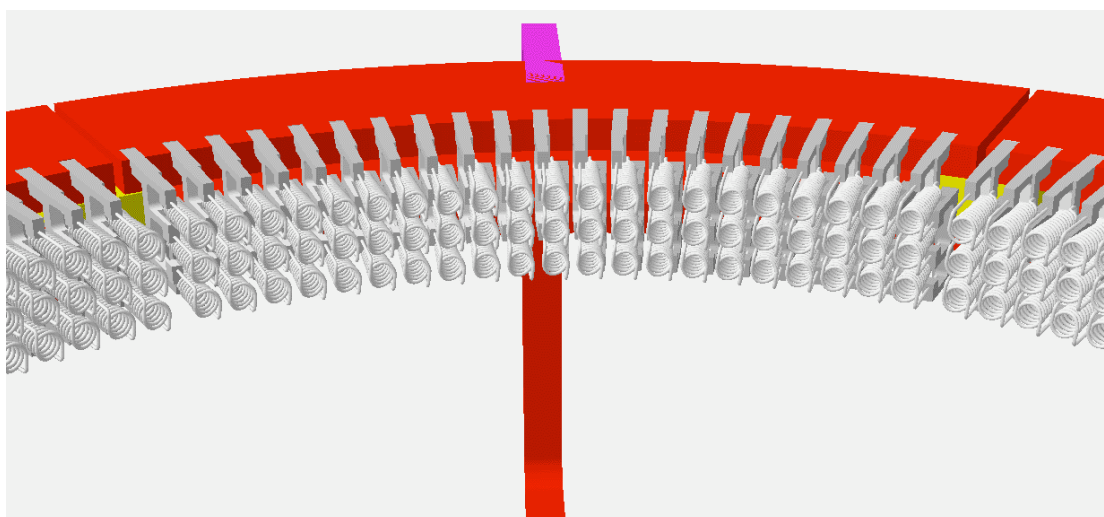


Fig. 7.12. 3D front view of the cathode.

Concerning the reliability of the W filaments that operate at high temperatures, preliminary analytical and experimental work indicates no significant problems. The

predicted stresses are much less than the ultimate W strength at 2750 °C (circa 40 MPa) and result also in no creep at these temperatures for several thousand pulses. The machine duty cycle will be determined by the cooling time of the electrodes. The interpulse cooling of the anode and cathode will be mainly done by radiation. In order to achieve a machine duty cycle of 5 min, the global temperature (after a few successive pulses) must be 380 °C for the anode and 450 °C for the cathode. To facilitate the radiation cooling, the electrodes will be plasma-sprayed (where possible) by $\text{Al}_2\text{O}_3+\text{TiO}_2$, in order to enhance their radiation emissivity. Also the conduction cooling, via the electrodes supports and the copper conductors, although not yet quantified, would significantly facilitates the cooling.

Note that optical diagnostics are used to view directly most of the anode and cathode from the top and bottom flanges, in order to monitor any degradation. The design of the electrodes is modular so that local replacements can be done at minimum cost.

7.4. Divertor

Among the coils of the poloidal system of PROTO-SPHERA, some are very near and in direct view of the plasma and thus can be subjected to thermal loads. In addition the double X-point configuration requires target plates, where the thermal power diverted from the spherical torus can be dumped. Only the "normal" operation is considered here, while the problems that could arise in pathological events are only indicated.

The thermal flux impinging upon the divertor plates in the steady-state phase of the discharge is first evaluated, assuming that the spherical torus can be sustained for 1 s. Based on the calculated equilibrium configurations, the position of the divertor protection plates have been chosen, as indicated in Fig. 7.13. The rationale of this choice is to provide a large enough separation from the plasma to the divertor plates and to allow for the positioning of the target at a sufficiently small angle with the projection of the separatrix on the poloidal cross-section.

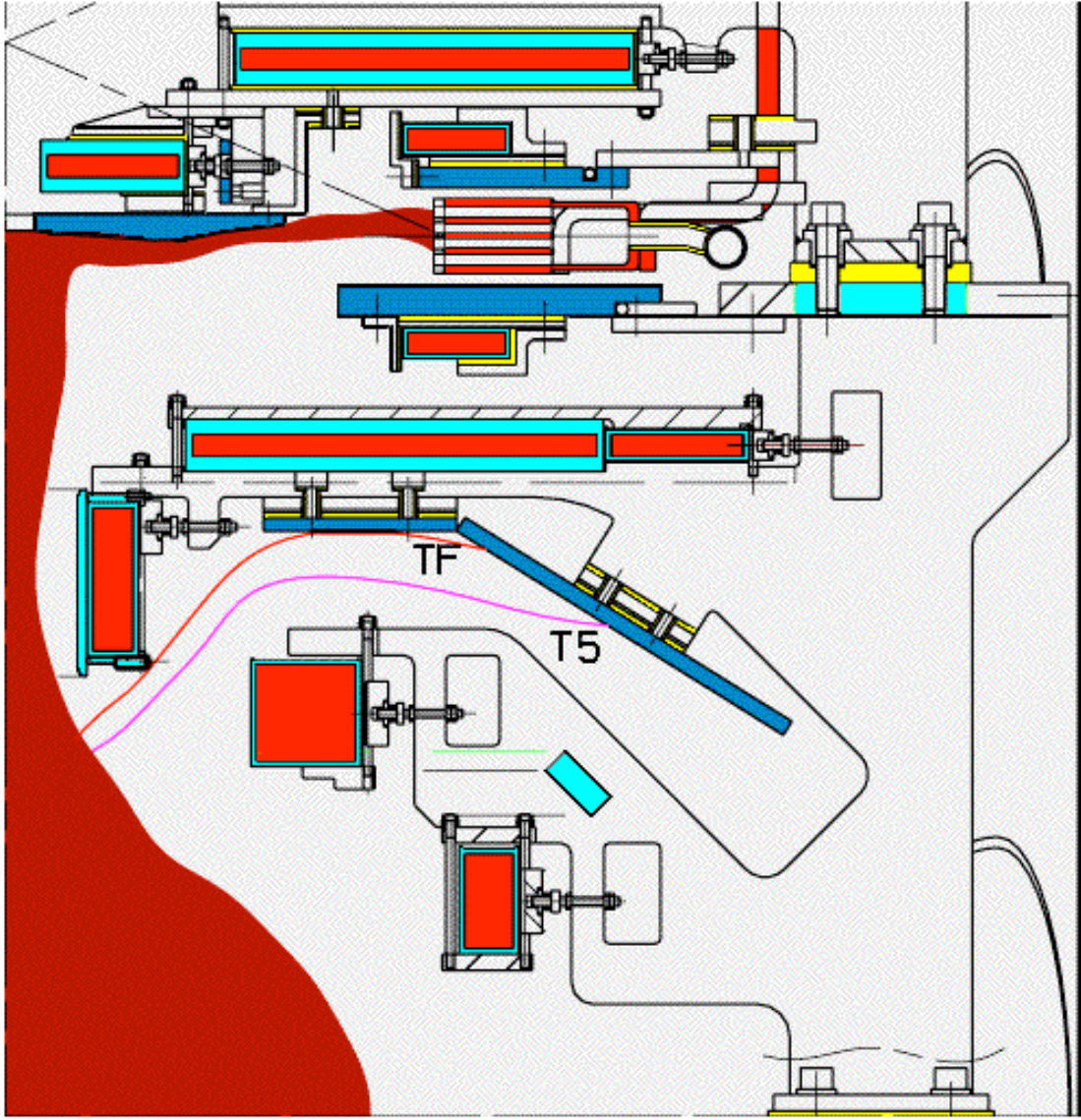


Fig. 7.13. Position of the divertor protection plates.

The total power required by the helicity injection through the X-points amounts to $P_{OH} \sim 0.58$ MW. A fraction of 50% of this power is assumed to be lost by radiation, due to the impurity content of the plasma. The remaining power is conducted/convected to the two (top and bottom) target plates through the scrape-off-layer (SOL). A further assumption is that all this power goes to the outer leg of the separatrix.

The total target surface wetted by the SOL plasma is given by

$$S_t = 2 \cdot 2\pi R \cdot \lambda_E \cdot e_{flux} \cdot 1/\sin\phi ,$$

where R is the distance from the axis of the separatrix strike point on the target, λ_E is the energy decay length at the ST midplane, e_{flux} is the magnetic flux expansion at this distance, and ϕ the poloidal angle between the separatrix and the target surface. At the stated position, the following numbers are plugged into the equation:

$R = 0.45$ m, $e_{flux} = 2.5$ and $\phi = 20^\circ$, λ_E is taken as 1 cm, which is typical for the energy decay length at the midplane of a conventional tokamak. Thus the average thermal flux on the divertor plates is $P_{OH}/S_t = 0.7$ MW/m². One could expect that the corresponding peak thermal flux would be larger than this value by a factor of 3.

This thermal flux is easily manageable by any material we can think for the divertor plates, so that the choice of this material can be based on other issues. The most convenient one would be Stainless Steel. It is to be noted that the divertor plates configuration just described is rather unconventional with respect to tokamak experiments, and it could offer some advantages:

- The wetted surface is quite far away from the plasma, so that the impurity flux to the plasma, due to generation at the plates, could be lower than in more conventional configurations.
- Also the recycling should be quite different: neutrals emitted from the target can reenter the plasma only after recirculation through the vacuum chamber volume. This could result into a very diffuse refueling and into an effective recycling coefficient substantially smaller than 1.
- The target plates are accessible for optical, bolometric and thermographic diagnostics.

The target tiles have to be properly aligned in order to avoid formation of hot spots due to exposed edges. A possible problem to be examined is the abnormal behavior in presence of runaway electrons and disruptions.

The PF2 coils are situated in the private region of the ST divertor and are quite near to the screw pinch discharge. The contribution of the thermal flux due to the screw pinch can be evaluated by considering that the power loss due to transport across the magnetic field of the pinch can be approximated by: $Q_{per} = n_e \chi_{eff} (T_e + T_i) / a_{Pinch}$,

where n_e is the pinch electron density, χ_{eff} the conductivity coefficient, T_e and T_i the peak electron and ion temperature in the screw pinch plasma, and a_{pinch} the pinch radius at the PF2 position. Assuming radial transport of the Bohm type, $T_i = T_e \sim 30$ eV and a magnetic field of 0.25 T, we have $\chi_{eff} \sim 35$ m²/s, and for a pinch density $n_e = 1.5 \cdot 10^{19}$ m⁻³:

$Q_{per} \sim 0.1$ MW/m², which can be considered negligible.

The thermal load impinging upon the surfaces of the coils, due to heat transport in the private region of the divertor, is quite difficult to evaluate. Anyway, on the basis of the data from conventional tokamaks, taking into account the distance from the separatrix, we can estimate that only a few percent of the power flowing in the SOL will impinge on the PF2 surface. Thus this heat flux would be of the same order of magnitude as that delivered by the screw pinch discharge.

Finally the PF1 coil intercepts the separatrix during the first millisecond of the ST formation (see Fig. 7.14 and 4.15). Even if in this case a power flux of ~ 3 MW/m² can hit the surface of the PF1 metal case, the total energy deposited there will be insufficient to increase its temperature by more than a few °C.

7.5. Protection Components

7.5.1. Coil Screening Plates

The coil screening plates, Fig. 7.14, are made out of copper. Their task is to contain the temperature increase of the coils that can see directly the cathode or anode to much less than 100 °C. The cathode can radiate up to 3 MW/m² when it reaches its maximum temperature. With this power density the metal cases of the coils, if directly exposed to the radiation, could reach locally temperatures well in excess of 100 °C in less than 1 sec. Such temperatures are dangerous for the insulation, which should not rise to more than 90 °C.

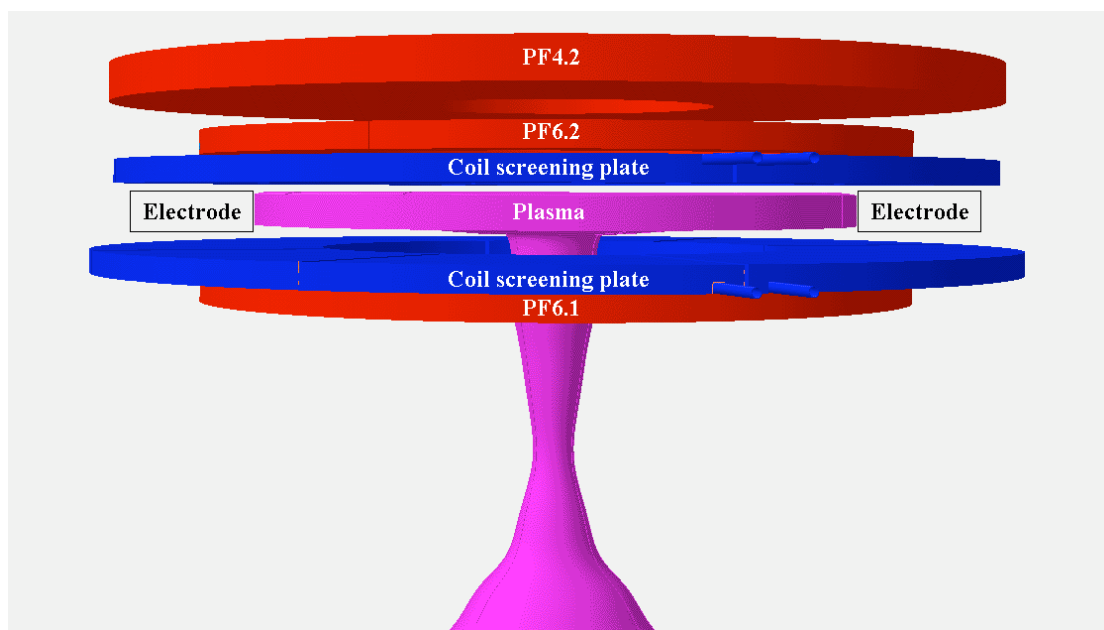


Fig. 7.14. Outline of the upper PF6 coils screening plates.

The coil screening plates are designed so that the electrodes viewing factors towards the coils is eliminated and their thermal mass is such that the maximum operating temperature is always less than 100 °C. Furthermore the plates are water-cooled in between pulses. In the 10-mm cooling pipes, a pressure drop Δp of less than 2 bar is expected for a flow velocity of about 4 m/sec. The conduction and convection resistances of the plates permit a cooling capacity of at least 20 kW, which allows for cooling within 5 min.

The surfaces of the screening plates will be plasma sprayed wherever possible. This will facilitate the total energy collection (about 16 MJ) at known resilient components and the radiation cooling, which will reach 1 kW/m², adding up at least 2 kW to the 20 kW cooling of the water circuit.

In order to avoid axisymmetric eddy currents, all the coil screening plates are subdivided in four 90° sectors. A pessimistic estimate of $B = 500$ G and of $dB/dt = 50$ T/s, provides maximum stresses not exceeding 100 MPa, even neglecting skin effects. Due to the high copper electrical conductivity and small formation time (~ 1 ms), skin effects will however be significant and would reduce the generated moments and stresses significantly.

Finally the PF2 coil is also screened by 10-mm thick collar made of W-Cu, Fig. 7.15. This component must also operate at less than 100 °C. Thus the maximum power density and energy it can accept are about 2 MW/m² and 120 kJ, respectively. It should be thermo-coupled, to avoid energy accumulation after a few successive pulses, since its maximum cooling capacity is limited to about 40 W.

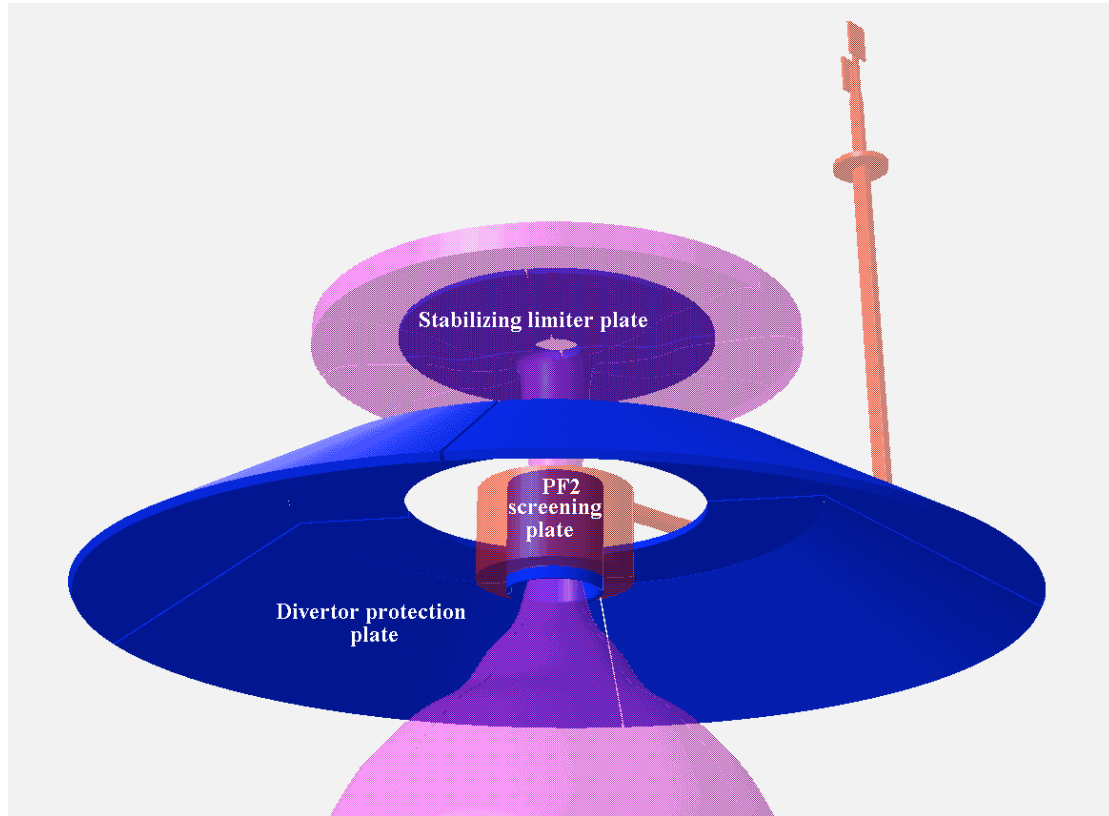


Fig. 7.15. Outline of the upper divertor protection plate, upper PF2 screening plate and upper stabilizing limiter plate.

7.5.2. Stabilizing Limiter Plates

The stabilizing limiter plates, shown in Fig. 7.15, are made from Cu with W plasma sprayed black and their plasma surface is profiled to follow the evolving plasma shape. They can absorb up to 1 MJ of heat, without endangering the coil PF4.1, radiating from about 100 °C. Thus their maximum radiation cooling capacity will be 600 W/m² (120 W). Also the stabilizing limiter plates should be thermo-coupled in order to avoid energy accumulation after a few successive pulses. Finally these components will also be subdivided in four 90° sectors, in order to avoid axisymmetric eddy currents.

7.5.3. Divertor Protection Plates

The divertor protection plates are made from 10 mm AISI 304L and have a mass of about 30 kg and 100 kg, see Fig. 7.15. As the maximum power density impinging upon them will be 2 MW/m^2 for 1 sec, a maximum temperature increase of 120°C is expected locally in the front surface. The maximum bulk temperature raise is only 60°C . Under this condition, the maximum radiation capacity is about 300 W/m^2 . To avoid energy accumulation, blackening of the rear surfaces of these plates ($\text{Al}_2\text{O}_3+\text{TiO}_2$) may be used to raise the radiation capacity to 700 W/m^2 . In addition thermo-couples may be also employed to monitor the temperature.

7.5.4. Reflection Rings

Two reflecting rings will be incorporated around the coils PF4.1, to protect them from the hot anode and cathode. They will be silver-plated in the outer surface, to reflect the radiated energy from the anode and cathode. Their dimensions are such that their operating temperature, considering solid view-angle from the electrodes, is less than 100°C .

7.6 Allowable and Permitted Stresses

The maximum eddy current stresses during disruptions are designed to be in all component less than 100 MPa. In addition in the divertor protection plates, a power density of 2 MW/m^2 , 1 s could give significant local thermal stresses of up to 320 MPa.

For AISI 304L plate, according to ASMEIII-NB3221, the allowable stress is 200 MPa for 100°C (min. of $1/3$ of ultimate strength or of $2/3$ of yield strength). According to this code, the eddy current stresses (100 MPa) must be less than $200 \cdot 1.5 = 300 \text{ MPa}$. The sum of all (including thermal) stresses ($100+320=420 \text{ MPa}$) must be less than $200 \cdot 3 = 600 \text{ MPa}$. It is clear therefore that significant safety factors are incorporated in the design.

Concerning the low temperature Cu components, an allowable of more than 70 MPa at 100°C is required to accommodate the eddy current stresses of less than 100 MPa. Therefore Cu slightly hardened with a yield strength more than 115 MPa and ultimate strength more than 230 MPa at 20°C is required.

Finally care requires to be exercised for the electrode Cu, where high strength at relatively high temperature may be required.

7.7. Machine Services

Figures 7.16 and 7.17 show the top and bottom flanges of the machine with the ports dedicated for the services. The water requirements are $2 \div 3 \text{ kg/s}$ per flange with a pressure drop of $4 \div 5 \text{ bar}$. The relatively high pressure drop is determined by the hydraulic resistance of the coils which, even with this pressure drop, have a flow velocity of about 1 m/s ($\text{Re}=6000$), the minimum acceptable.

Top View

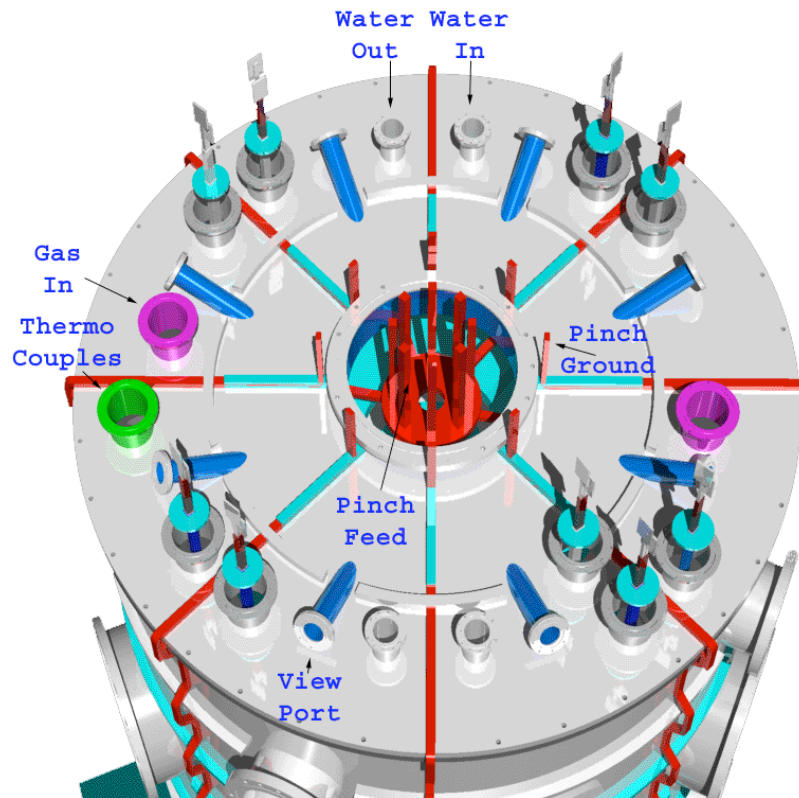


Fig. 7.16. Top flange of the PROTO-SPHERA machine.

Bottom View

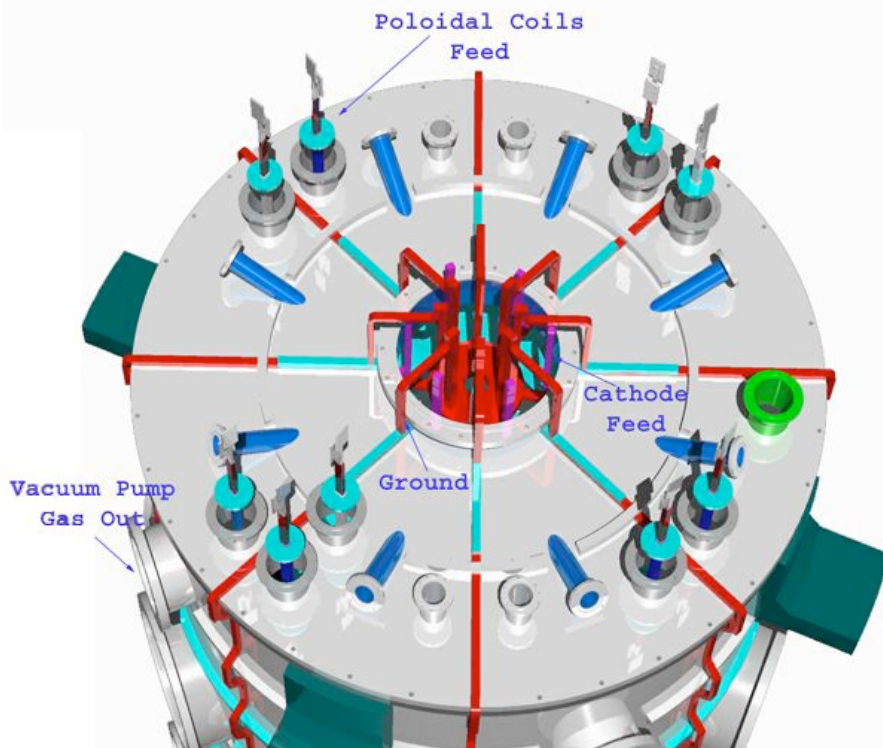


Fig. 7.17. Bottom flange of the PROTO-SPHERA machine.

Gas flow needs are 30 mbar·l/sec through the two flanges shown in Fig. 7.16. Electric services are composed by eighteen feedthroughs for poloidal coils (nine for each main flange), eight insulated flanges and eight return ground connectors in the top main flange and six insulated connector in the bottom main flange (for more details about anode and cathode insulated connectors through the top and bottom flanges, see Fig. 7.2). For the voltage and current requirements for electric services, see Section 8.

7.8. Assembly and Maintenance

To facilitate the assembly and maintenance, the machine services are routed through ports at the bottom and top flat flanges. Thus no internal, to the vacuum, connections to the services are needed. Furthermore the design of the coil feedthrough and of the other services is such as to avoid any cutting and re-welding when the machine is partially dismantled for access to the electrodes, see Fig. 7.7.

The PF coils, anode, cathode and their support structure will be pre-assembled on a customized jig outside the VV. The relative position of the coils will be adjusted to guarantee the accuracy of the magnetic field. The magnetic field will be measured with a magnetic probe system, which would record the value and direction of the field. In addition the position of the probe(s) in relation to datum points together with these of anode, cathode and PF Coil system will also be carefully measured. Then the PF coils, anode, cathode and their supports will be installed inside the VV, which will be closed by the top and bottom flanges. These flanges can be removed in situ for repair of the anode/cathode as required.