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Design Basis Elements
for a Tokamak at Q=5
Tome 1 / 2 : main document

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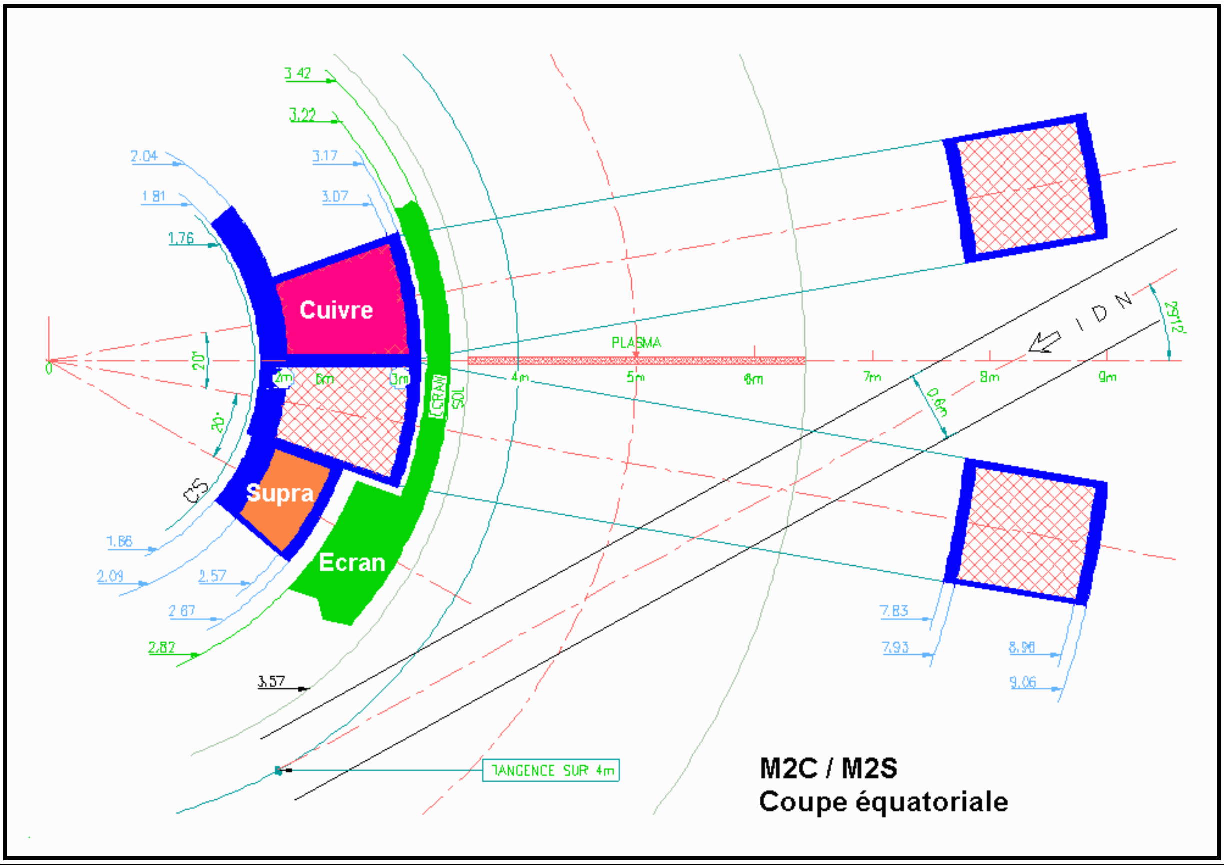

Warning :

This report is presented in 2 tomes :

- *Tome 1 : Main document (reference DRFC/EPDIM/99-016)*
- *Tome 2 : Appendices - in French - (reference DRFC/EPDIM/99-015)*

The original issue of Tome 1 is in French :
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0. Abstract

This report presents the results of a study conducted from September 1998 to May 1999 to complete the work performed in 1997 [1]. This initial work had outlined the program of an M2 machine which had been considered in case the ITER program were abandoned or delayed for a long time. The main aim of this new stage : **the study of plasma physics in a reactor perspective**, was confirmed. Compared to the ITER objectives, the M2 machine does not aim to reach ignition and no irradiation program for materials at high fluence is foreseen. This allows the technical requirements to be reduced, in particular those linked to the consequences of irradiation of structural materials and magnets.

In inductive operation, the amplification factor Q (= $P_{fusion}/P_{injected}$) was chosen to be equal to 5, a minimum value which allows a significant heating power by the α particles. The duration of the current plateau will be of roughly 500s. Under these conditions, and in view of a cumulated operating time of 700 hours in D-T regime, an optimization of the machine parameters was made, by assuming the magnets were superconducting. The design criteria, both physical and technological, are those of ITER-FDR, since they are widely acknowledged by the scientific community.

Defined in this context, the design basis of M2 (R=5m ; a=1.43m ; k_{95}=1.63 ; B_T=5.4T and I_P=9MA) results in a machine with a moderate fusion power of roughly 200MW, a neutronic flux at the wall of 500kW/m^2 and additional heating power of 40MW.

From a technological point of view, this machine, less ambitious than ITER, should not raise any particular problem. Its cost has been estimated at 1.7 billion Euros, which should be compatible with the European budget possibilities.

In parallel, a version of the machine with copper magnets has been studied, for identical plasma parameters. The data base for steady-state copper magnets is much less extensive than that for superconducting magnets. Nevertheless, after having explored the thermohydraulic, mechanical, neutronic and energetic aspects, there does not seem to be any impossibility in using copper. The total cost could be slightly less for this copper machine. However, studies have to be continued to obtain the same level of confidence as for that of a superconducting machine which is entirely based on the studies and developments made for ITER.

This report therefore shows that for an investment of less than 2 billion Euros, it is possible to envisage a machine with a fusion power of 200MW of which the main program would be the study of plasma physics in a reactor perspective. This machine could be superconducting or in copper, without any significant incidence on the program and on the cost.

It is to be reminded that such a machine would be part of a multi-stage strategy which would lead, according to the conclusions of the SWG ITER (1998, Task 2), to significantly increasing the global cost and the time frame to obtain a demonstration reactor, compared to the ITER-type strategy.

1. Framework of the study

End of 1996, the French Euratom-CEA Association was asked by Mrs Césarsky, Director of the DSM (« Direction des Sciences de la Matière »), to examine possible scenarii for the fusion program in relation with, in particular, the decision on whether or not to build ITER.

In 1997, while a " long term " group analyzed the reactor studies, a " design basis " group, made up of fifteen members of the Association, performed the preliminary design basis of 2 machines [1] :

- Machine M1, in the case ITER were to be built outside of Europe.

- Machine M2, in the case ITER were to be delayed for a long time.

Machine M1 is both a support for ITER and an additional program in the DEMO perspective. It is a non-nuclear machine (no Tritium), with a size comparable to Tore Supra, but with a high ellipticity, mainly aimed at studying stationary plasmas. The main technical options chosen are those of Tore Supra, both in an approach of continuity and to make its installation easier in the Tore Supra hall, where it will re-use part of the equipment. More details can be found in Appendix 7.1.

Machine M2, then under consideration, was part of a new multi-machine fusion strategy. It had a stated nuclear vocation with a Q (= $P_{fusion}/P_{injected}$) of 5, which would have allowed the study, under good conditions, of the internal heating by the α particles.

Since the beginning of 1998, which was the year of the publication of the Final Design Report of ITER (ITER-FDR), the international situation around the project has significantly changed :

- Concern on the financing possibilities of ITER-FDR, by the partners.

- Creation of a Special Work Group, SWG, in charge of both making proposals for an ITER project with reduced objectives and costs, and providing new bases for a strategy of fusion as a source of energy.

- ITER project abandoned by the Americans.

This context obviously led us **to continue to study the possibility of a machine of type M2**. Its design basis will be restricted by a limited European budget and its objectives will be carefully chosen to ensure maximum interest within the framework of a strategy still oriented on reactors.

This study will not propose a precise design, but will provide design bases in order to reach that goal and, in addition, some useful tools. It will analyze some possible technological options, for example copper or superconducting magnets with the corresponding fields of use. It will also show the effect of neutronic fluence on the thickness of the shielding and the consequence on the cost.

2. Objectives of the next stage

We are considering a machine of type M2 on the assumption that ITER, whatever its version (ITER-FDR or RTO/RC ITER), might definitely be abandoned or delayed for a long time. To not build ITER would mean, from the view point of those who decide, that the JET➔ITER➔DEMO➔"PROTO" strategy is questioned. This strategy, as was unanimously re-affirmed by the last SWG (Task 2), is that it would allow to reach, with a minimum of steps, an electricity-producing reactor, thus in a minimum time frame and global cost. It is obvious that, for the SWG, ITER can only be built within an international framework. Europe is presently committed to the ITER project as a logical follow up to JET. If the international context cannot be continued and if ITER is put into question, the SWG would have to foresee other alternatives in a new context.

It would therefore be timely, in Europe, to define a **multi-stage strategy** before DEMO, however longer timewise in the respect to the ITER strategy. This strategy would aim at reducing the scientific and technical risks, both by reduced extrapolations and objectives assigned to each machine. The prediction of the physical performances of the tokamaks is indeed based on statistical laws (confinement time of the energy,...), which are very sensitive to the geometrical parameters of the plasma, such as the aspect ratio A, the elongation k and the triangularity δ. This prediction would then be completed stage by stage.

The next stage would have as its **main vocation the study of plasma physics in a " reactor " perspective**, namely :

- **The physics of alpha particles** : barely explored in TFTR and JET, it should, in this machine, reach a power of that of the injected power, in other terms a **Q of 5 in inductive**, mainly depending on the operating modes (operation in current generation or not, density and temperature profiling,...).

- **The control and maintaining in stationary discharges**, with an operation at thermal equilibrium versus all the profile diffusion times (temperature and current density). This results in a **length of impulsion from 500 to 1000 seconds**.

- The validation of **non-inductive current generation concepts**, which play a fundamental part in the control of stationary discharges.

- The **study of the edge plasma** namely concerning the operation of the divertor and the pumping of He.

- The exploration of advanced tokamak concepts.

However, compared to the ITER objectives, this « next stage » would give up the ignition and some of the technological objectives, more particularly the neutronic irradiation tests of the materials. From this point of view, **no objectives in terms of fluence would be specified.** This « next stage » would then mostly use tested and reliable technologies. In this modified approach towards DEMO, the qualification of the materials under large neutronic fluences would no longer be urgent. This would allow, if the plasma conditions are similar, a reduction of the construction costs, obtained by less restrictive choices of the materials and significant reductions on the dimensions and the magnetic energy stored.

Therefore the investment costs for M2 could be restricted enough to be compatible with the **European Fusion Program budget**.

This machine would also provide, for the public and the decision makers, the proof of the feasibility of fusion by the validation of :

- the availability of Fusion energy at a significant power level (several hundreds of Megawatts) with an acceptable efficiency and clearly being seen as worthy of improvements.

- the safety conditions.

As far as its operation is concerned, this next machine would be experimental, D-T shot campaigns being performed after parameters are adjusted in D-D operation. If we assume 1000 shots of 500 seconds per year for 15 years, with 1/3 of the shots in D-T, and a neutronic flux at the wall of 0.5 MW/m^2, we would obtain a fluence of 0.04 $MW.y/m^2$, much less than that foreseen for the different versions of ITER. The cumulated operating time would then be of 2000 hours, of which 700 hours in D-T.

The studies already conducted in the previous years allow us to predict a range of parameters summarized in Table 2-1.

Parameter	Value
Major Radius, R (m)	4.2 - 5.2
Minor Radius, a (m)	1.4 - 1.5
Aspect ratio, A	3 - 3.5
Ellipticity, k	1.6 - 1.8
Triangularity, δ	0.3 - 0.35
Toroïdal field at R, B_t (T)	4 - 6
Plasma current, Ip (MA)	9 - 11
βn	2.5
Additional heatings, P_{AH} (MW)	40 - 60
Fusion Power, P_F (MW)	200 - 300
Neutron flux at the wall, Γn (MW/m^2)	< 0.5

Table 2-1 : range of parameters for machine M2

Table 2.2 on the next page, summarizes the positioning of M2 versus the existing machines, RTO/RC-ITER and ITER-FDR. The number in each box indicates the validation level acquired or predicted (from 0 : not-explored to 4 : complete validation). For the machine M2, some boxes show a clear difference between copper and supra machine.

Fusion program issues			Today Experiments	M2 Copper / Supra	RTO/RC ITER	ITER FDR
	Q		0.5	5	10	Ignition
Physics	Confinement and stability		2	3	4	4
	Power removal		1-2	3	4	4
	Alpha particle physics	Alpha heating	2	3	3-4	4
		Alpha confinement	1	3	3-4	4
		Plasma stability	1	4	4	4
	Particle control	ash removal	1	3-4	4	4
		burn control	1	3	3	4
	Steady state operation		1-2	3	3	3
	integration		1-2	2	4	4
Technology	Plasma facing components		2	2-3	3-4	3-4
	Additionnal heatings		3	4	4	4
	Fuelling technology		2	2-3	3-4	3-4
	Super-conducting magnets		3	0 3	4	4
	Neutron Fluence		0	0	1	2
	Tritium production		1	1	2	2
	low activation materials		0.5	0	0	1
	Remote handling		1-2	2 3	4	4
	Tritium handling		2	3	4	4
Integration (physics + technology)			1	1 2	3	3
Safety			1-2	3	3	3
Reliability (/ reactor)			0-1	1-2	1-2	1-2
Availability (/ reactor)			0	1	1	1
Electrical power generation			0	0	0	0

Table 2-2 : Comparison table

3. Design Basis and performances.

3.1 Choice of the aspect ratio and dimensions within the framework of a superconducting machine.

3.1.1 Optimization of dimensions for a given aspect ratio.

In the following paragraphs, we describe the way to get to the smallest machine generating a plasma in mode H with ELMs and satisfying the objectives hereunder :

- amplification factor **Q = 5** ;

- length of plateau of 500 seconds ;

- current (out of bootstrap) inductively generated, by imposing $q_{\Psi 95} = 3$;

with the following boundaries, close to those taken for the design basis of ITER :

- density equal to 90% in the limit of Greenwald ;

- conductive power P_{con} arriving on the last closed magnetic surface exceeding by at least 20% the $P_{H\text{-}L}$ power corresponding to the H-L transition ;

- bêta normalized inferior or equal to 2.5 ;

We also assume that the current ramp-up is made inductively.

The other assumptions on the shape of the plasma, the impurity contents, the scale law for the energy lifetime, the profiles , the calculation of plasma current and the current generation are detailed in Appendix 7.2. The bases for the magnet design are explained in Appendix 7.5.

- For a given aspect ratio (A = 3.5 for example) we take a tentative plasma size (R = 4.6 m for example). For a magnetic field B_t too weak on the axis (5 T for example), we note that the curve Q = 5 in the plane (n, T) is located entirely above the line $n/n_{Gr} = 0.9$. We then increase the magnetic field and the corresponding current (with $q_{\psi 95} = 3$) until the curve Q=5 becomes the tangent to the line $n/n_{Gr} = 0.9$. If the corresponding operating point meets the requirements $P_{con}/P_{HL} \geq 1.2$ and $\beta_N \leq 2.5$, we keep the magnetic field ; otherwise, we increase it until we obtain an operating point simultaneously meeting the requirements of these two restrictions (in practice, the point obtained corresponds to $P_{con}/P_{HL} = 1.2$ and $\beta_N < 2.5$).

- For the plasma field obtained, we calculate the field $B_{t,max}$ in the superconducting coiling corresponding to the plasma considered by taking into account the ripple. Then we calculate the thickness of the toroïdal coil, for the maximum current density authorized by $B_{t,max}$, which allows the generation of the field $B_{t,max}$ while meeting the mechanical constraints. The dimensions of the external leg are then calculated to ensure the constraint of maximum ripple outside the plasma.

- Having thus obtained the available radius for the central solenoid, we can then design the poloïdal coils and calculate the maximum reserve for the poloïdal flux. After subtracting the flux necessary for the current ramp-up, we can calculate the duration of the plateau corresponding to the operating point determined in the preceding stage.

- If this duration is inferior to 500 seconds, we can choose a larger dimension and repeat the algorithm above until we obtain a plateau of 500 seconds.

The machine thus obtained is therefore the smallest machine meeting the imposed physical and technological requirements.

In Figure 3.1.1, the values of Bt and $B_{t,max}$ are represented as well as the duration of the plateau versus plasma size, for a fixed aspect ratio A = 3.5. When R < 4.51 m (red zone) the ESCORT code cannot calculate a toroïdal magnet meeting the mechanical stresses. For 4.51 < R < 4.72 m (yellow zone), this magnet exists, but the poloïdal flux available provides only part of the current ramp-up. For R > 4.72 m (white zone), the plateau exists and becomes equal to 500 seconds for R=5.00 m.

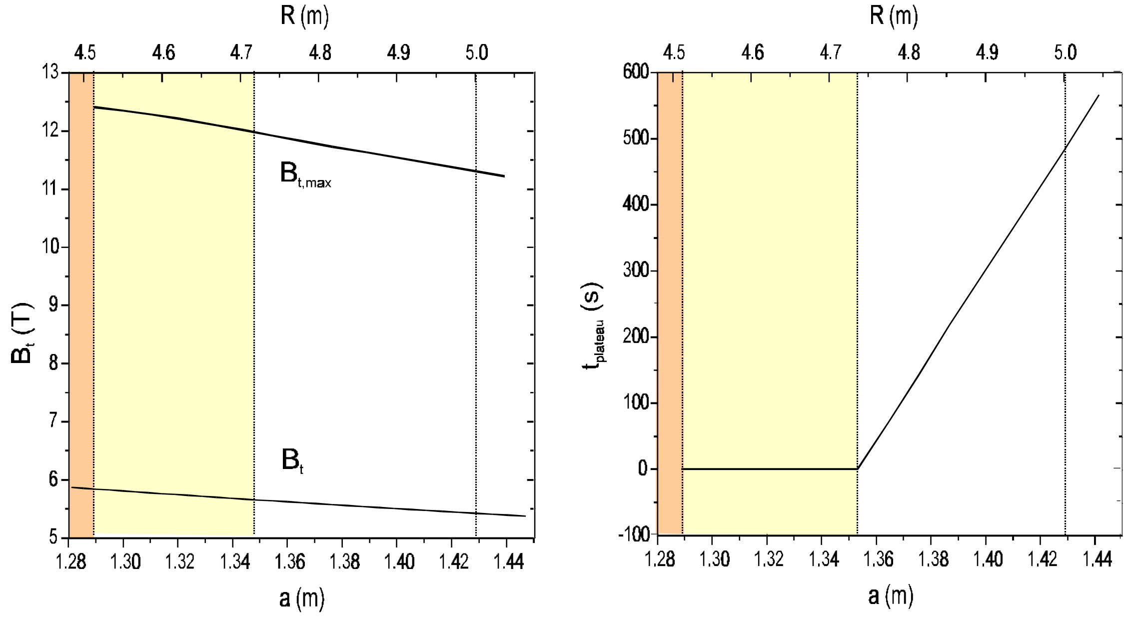


Figure 3.1.1: Magnetic field in the plasma, in the superconductor and duration of current plateau corresponding to machines of increasing dimensions, for A=3.5, obtained by the optimization algorithm.

3.1.2 Comparison of machines obtained for aspect ratios 3, 3.5 and 4.

In Appendix 7.2, in Figures 7.2.1, 7.2.2, 7.2.3 and in Table 7.2.1, the characteristics of the inductive operating point corresponding to the optimized machine are represented for aspect ratios 3, 3.5 and 4.

In this first approach, we have neglected the radiated power at the edge of the plasma inside the separatrix (which corresponds to the case where the temperature pedestal in mode-H is high enough so that the light impurities no longer radiate and where heavy impurities are not injected). The values indicated in Table 7.2.1 correspond to the maximum thermal flux on the divertor plates (by neglecting the radiated power in the scrape-off layer and the divertor). They were obtained by taking a value of the ratio S_{div}/R (1.23 m) identical to that chosen in ITER FDR.

Finally, in Table 7.2.2 the characteristics of the operating point, in current generation with an advanced scenario, are given for each optimized machine. The point considered is located on the curve $n/n_{Gr} = 0.9$ in the plane (n, P_{CD}) and it corresponds to an amplification factor Q equal to 5, with the constraint $\beta_N \leq 2.5$.

In view of these results, the following statements can be made :

- the operating window is reduced when the aspect ratio increases ;

- in inductive operation, the average thermal flux (maximum) on the divertor plates increases when the aspect ratio increases ;

- the amplification factor in current generation significantly increases (from 5 to 8) when the aspect ratio goes from 3 to 4 (mainly due to the increase in the bootstrap fraction).

Finally, it is to be reminded that the discharges corresponding to an aspect ratio of 4 are not well documented in the data base used to establish the scaling law of the energy lifetime.

On account of these elements, we are inclined to favor the machine with an intermediate aspect ratio : A = 3.5.

3.2 Principle of possible machines.

In view of the operating modes considered in Chapter 2 and of the neutronic shielding needs (cf. Appendix 7.4), it is possible to consider two options for the toroïdal magnet of the machine corresponding to the plasma parameters determined in the above chapter.

- superconducting magnet for which the shielding is designed to limit the thermal load on the conductor (optimization made in this context in Chapter 3.1).

- copper magnet for which the shielding is designed to limit the cumulated irradiation on the insulation.

While keeping the same plasma parameters, the radial dimensions for a toroïdal magnet in superconductor and in copper are summarized below, in Table 3.2-1 :

	Element	**M2S** Supra Machine (cm)	**M2C** Copper Machine (cm)	color on figure 3.2-2
	Plasma			
1	Scrap off layer	15	15	
2	Blanket + VV	60	20	
3	Vacuum gap	15	5	
4	Internal casing	10	10	
5	Winding	48	103	
6	Thick casing	23	23	
7	Vacuum gap	10	5	
	Total	181	181	
	Δ_{int} (1+2+3+4)	**100**	**50**	
	Shielding (2+4)	**70**	**30**	
	Δ_{ext}	150	150	

Table 3.2-1 : Radial design basis of Supra and Copper machines

The radial thickness of the winding obviously depends on the solenation, that is, on the product B_T*R. The values given in the previous table correspond to solenations of 150MA which lead to acceptable current densities in the supra and the copper conductors respectively (see Appendix 7.6). The value of Δ_{ext} is designed so as to reduce the spatial fluctuations of the magnetic field (" ripple ") and is thus independent from the type of conductor. The figure on the cover page and Figure 3.2-2 on the next page illustrate the construction in the case of a machine with a major radius R=5 and a minor radius a = 1.43 m.

Concerning the poloïdal coils, the 2 options, Copper or Supra may also be considered. The 3 following concepts are possible :

- Coils completely made of copper, as the JET or Asdex.

- Coils completely made of superconductor, as ITER, which implies the presence of a large cryostat simultaneously housing the toroïdal and poloïdal magnets.

- « Mixed machine », with superconducting toroïdal coils and copper poloïdal coils, of which the best example is obviously, Tore-Supra. In such a machine, the global cryostat is no longer necessary.

In the next chapter, three machines are presented and their performances compared. They should not be considered as fully optimized projects but as guidelines for a machine meeting the stated demands.

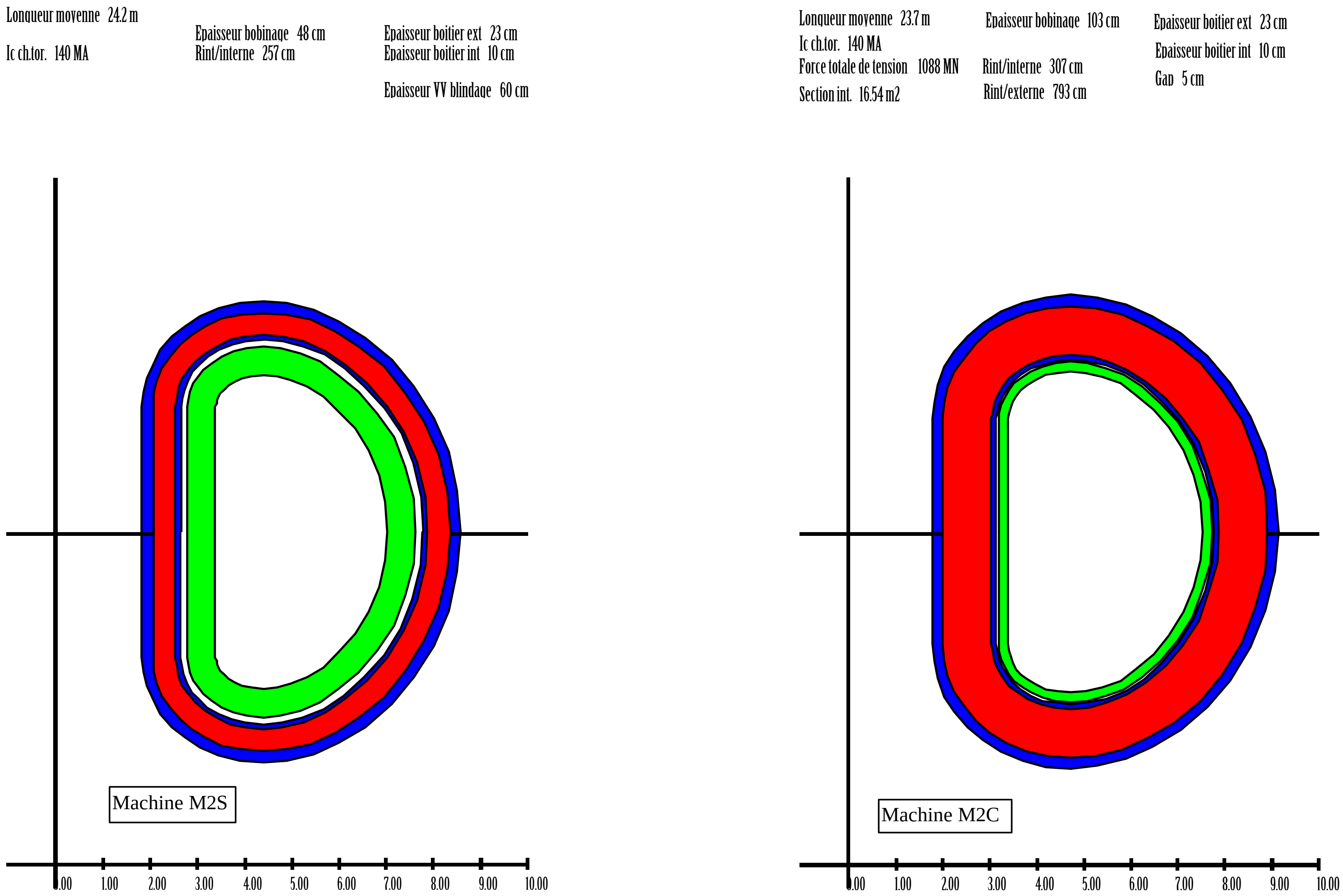

Longueur moyenne 24.2 m
Ic ch.tor. 140 MA
Epaisseur bobinage 48 cm
Rint/interne 257 cm
Epaisseur boitier ext 23 cm
Epaisseur boitier int 10 cm
Epaisseur VV blindage 60 cm
Machine M2S
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Longueur moyenne 23.7 m
Ic ch.tor. 140 MA
Force totale de tension 1088 MN
Section int. 16.54 m2
Epaisseur bobinage 103 cm
Rint/interne 307 cm
Rint/externe 793 cm
Epaisseur boitier ext 23 cm
Epaisseur boitier int 10 cm
Gap 5 cm
Machine M2C
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00

Figure 3.2-2

3.3 Compared performances of several machines.

Table 3.3-1 below summarizes the performances and dimensions of 3 machines :

- M2S : Supra machine optimized using the principle described in Chapter 3.1.

- M2C : copper machine with plasma characteristics identical to the M2S machine and built using the radial design described in Chapter 3.2.

- MPHR : copper machine proposed by PH Rebut with performances close to those of M2S and M2C, but based on a slightly different technological and physical design.

	M2S	M2C(4)	MPHR (C9 19/03/99)
R (m)	5	5	4.6
a (m)	1.43	1.43	1.43
A	3.5	3.5	3.22
k_{95}	1.63	1.63	1.75
δ_{95}	0.35	0.35	0.28
Bt (T)	5.43	5.43	4.78
Ip (MA)	9	9	10
q_{psi}	3	3	3 [1] / 2.81 [2]
Q	5	5	5
Pfus (MW)	210	210	220
Flux (MW/m^2)	0.40	0.40	
Available radius for the central solenoid (m)	1.76	1.76	1.65

[1] : value calculated by PH Rebut.
[2] : value calculated with the usual methods (Cf appendix 7.8).

Table 3.3-1 : performances and dimensions of several machines

4. Technical description of different machines.

4.1 M2S, fully superconducting machine

The optimization of a Superconducting machine was made in Chapter 3.1 taking into account both the objectives and the technological restrictions. In the present chapter the main technical lines of the machine are defined.

The main choices for the magnetic system of M2S are as follows :

- The vault concept is chosen for the toroïdal field system.

- The toroïdal field system is made of double pancakes stacked without plates.

- The central CS solenoid is independent from the toroïdal field system. The quantity of steel is very dependent on the number of cycles in the life of the Tokamak.

- All the conductors are circular cables inserted in a square steel jacket.

- The CS and the Toroidal magnet are made of Nb_3Sn (with a margin of 1 K) and the poloidal system is made of NbTi (with a margin of 2 K)

4.1.1 Toroïdal field system

The shape of the cable is that selected for ITER : 6 petals around a central hole which allows helium to circulate with a low pressure drop.

The toroïdal field system is composed of 18 coils. Under these conditions, the access available for the neutral beam is of 0.65 m, which seems to be enough.

The protection system intervenes in the design. In the case of ITER, the magnetic energy was so high, that at 10 kV of discharge voltage, and with one protection system per coil, the time constant required was long : 20s, which meant a lot of copper in the conductor. For MS2 the current is taken as equal to 40 kA and the discharge voltage as 9 kV. We can consider one protection system per 2 coils, which gives a discharge time constant of 12 s, sufficiently high versus the delay in detection (2s). Thus only 9 pairs of current leads are needed instead of 18. In a first approach, we consider a limitation at 250 K for the adiabatic hot point, by only taking into account the strands for the increase in temperature. This criterion is equivalent to the classic criterion of 150 K by taking into account the helium and steel of the conductor, which is realistic.

Number of pancakes in a coil	16
Length of a pancake	400 m
Number of turns	188
Total inductance of the toroïdal field system	27.2 H
Magnetic energy of the toroïdal field system	19.7 GJ
Thickness of the vault	0.23 m
Weight of copper strands (one coil)	1.6 t
Weight of superconducting strands (one coil)	15 t
Weight of conductor (one coil)	19 t
Weight of casing	34 t
Total weight (one coil)	96 t

Table 4.1.1-1 : Characteristics of a magnet of the TF system

From a mechanical point of view, the explosion force is partly taken up by the conductor jacket and partly by the casing. The centering force is transmitted through the conductor jacket to the inner nose of the coils, so that the 18 coils make up a vault. The design Tresca constraint is of 600 Mpa for the conductor and of 700 Mpa for the vault. The magnets do not have the perfect shape of D. The external part of the D closes to ensure a « ripple » of 1% at the edge of the plasma.

The distance of one meter between the edge of the plasma and the conductor is lower than for ITER. It implies an increase in temperature of the superconductor of 1 K during a plasma shot at full power. This distance needs to be optimized in relation to the cost of the machine and its mode of use.

4.1.2 Poloïdal field system

The M2S machine is optimized for a plasma of 500 seconds. In order to do this the maximum field on the conductor of the Central Solenoid (CS), made of Nb3Sn, is 13.5 T. The CS system is independent from the TF system and thus is submitted to a mechanical cycling. The design of the steel structural materials takes this into account.

The large coils of the poloïdal field system are made of NbTi and produce a low X point and an equilibrium field necessary to control the 9 MA plasma current, which gives 0.59 T corresponding to $\beta p+li/2=1.46$.

Flux of CS (air) :	156 Wb
Contribution of vertical field :	33 Wb
Total flux available :	189 Wb
Inductive consumption for the flux increase :	93 Wb
Resistive consumption for the flux increase :	25 Wb
Total consumption for the flux increase :	138 Wb
Flux available for the plateau :	52 Wb

Table 4.1.2-1 :Evaluation of poloïdal flux.

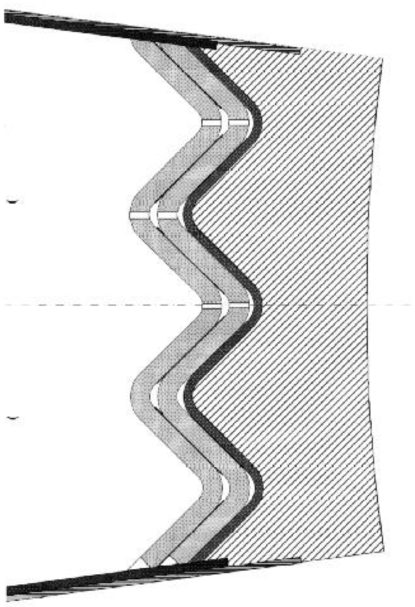
4.2 MPHR, all Copper machine

This chapter describes the copper machine proposed by PH Rebut.

4.2.1 Principle

All the coils are made of copper. Forced fluid circulation keeps the toroïdal coils in thermal steady state all along the 500s plasma plateau. The expected advantages of such a solution would be a gain of room by limiting the necessary shielding, an easier intervention on the machine and a limitation of the number of interfaces.

4.2.2 General structure



Concerning the toroïdal field coils, the use of mineral insulators would authorize the decrease of the thickness of the shielding, on the high field side, to a value of 0.2 to 0.3 m. In view of the high level of irradiation, no impregnation under vacuum with resins would be envisaged. Moreover, the coils would not be cooled by water but by organic fluids.

The conductor of the toroïdal field coil would be made of copper sheets with the same azimuthal width as the coil. This conductor would not be flat but of corrugated shape. The insulation between the layers would be made by discontinuous flat elements.

Figure 4.2.2-1 : TF coil section of MPHR.

The coolant would flow across the layers through holes (cooling of Bitter type), without any hydraulic insulation between layers.

To take up the hoop forces, the layers are tightly fit into each other and finally supported by a thick steel belt which is placed all around the coil.

This belt includes on its internal face a corrugation enabling the fitting together and the blocking of all the layers. The whole coil is included in a " thin " casing. The overturning moment created by the action of the poloïdal field would be taken up by the corrugated belt, via the insulators which experience only compression stresses.

The belts of each TF coil could be welded to each other in order to achieve a complete structure which would provide rigidity for the whole assembly and would be vacuum tight.

The main centripetal force would be taken up by the internal part of this belt to which a central bucking cylinder could be added if necessary.

Forces among poloïdal field coils would be taken up by on purpose vertical elements.

A more thorough study could be carried out after the mechanical structure being drawn and measured. In particular, special attention will have to be paid to :

- the global organization of the machine.
- the support structure of the poloïdal coils.
- the impact of the ports on the mechanical behavior.

The analysis of the stresses could then be made using a simplified global model integrated by complete details of the critical parts of different elements to evaluate the stresses and the necessary local thickness.

4.2.3 Some options .

The neutronic shield can be thicker on the outside in order to allow access to the workers in this zone.

The TF coils can be larger on the outside in order to reduce the electrical resistance and the associated power dissipation.

The belt could then have a reduced thickness in the center to spare room for the Central Solenoid which create the flux swing.

4.2.4 Some design basis elements

Number of Toroïdal Field coils :	24
Current by conductor :	≈ 100 kA
Thickness of copper conductor :	≈ 8 mm
Thickness of insulating wedges :	≈ 1 mm
Weight of toroïdal field system :	≈ 1675 t (for copper)
Weight of poloïdal field system	≈ 1300 t (for copper)
Estimated average stress in the toroïdal magnet :	152 MPa (Tresca stress)
Electrical consumption for the toroïdal field system:	650MW

4.3 Considerations on a mixed solution (TF Supra, PF Copper)

A Tore-Supra like mixed solution is possible.

The main advantage is a very easy access to the vacuum vessel without breaking the cryogenic vacuum thus by maintaining the TF system cold. This solution is particularly interesting in the non-nuclear phase of the machine.

The CS flux could be slightly penalized by the reduction in room due to the external cryostat, but the same flux is likely to be still created in the available space.

During the plateau of 500 s, we can assume a resistive power of 300 MW for the PF system. The resistive consumption is roughly of 200 MW for the CS system at maximum current. During the 500 seconds plateau, the CS current is at more than 50% from the maximum current.

4.4 Estimate of electrical power for the 3 options

Concerning the toroïdal magnet, the electrical power can be considered as nil in the case of superconducting coils. This is not the case for the poloïdal circuit because of the need to control the field to ensure equilibrium and stability. A power of 400 MW can be estimated to perform this function.

Table 4.4-1 below summarizes the electrical power in MW for the 3 options

Function	all supra machine	all copper machine	mixed machine
Toroïdal (including reserve for the field ramp-up, non-simultaneous with the heatings)	0	900 150	0
Poloïdal : resistive losses	0	500	500
Poloïdal : control	400	400	400
Additional heatings	150	150	150
Simultaneous total	**550**	**1800**	**1050**

Table 4.4-1 : Electrical power consumed by the machines.

The impact on the network is significant especially in the case of the all copper machine. It is likely that this machine could be built only in a few specially selected sites. Preliminary contacts with EdF (Electricité de France) have shown that a supply of 2 GW would be marginally possible at Cadarache if the 400kV Boutre-Carros loop were build.

5. Cost Estimate

5.1 Investment

A first investment cost estimate was made based on the design basis of a M2S all supra machine and a M2C all copper machine as described in Chapter 3.2, with identical plasmas. The costs are presented in the same way as in the report [1]. In Appendix 7.7, are the details on the cost analysis, which are summarized in Table 5.1 below :

Objets		M2S (MF96)	M2C (MF96)	Parameters of main costs
1.1	Toroidal magnets (18 coils)	2 370	1 460	Type and length of supra section, total mass (copper)
1.2	Poloidal magnets	1 130	700	% of TF
2	Buildings	1 500	1 600	R, a , k, etc...
3.1	Divertor + 1st wall	735	735	
3.2	Blanket and vacuum chamber	700	215	
3.3	Cryostat	110	0	
4.1	TF : Power Supplies + protection	100	360	0.4MF/MW
4.2	PF : Power Supplies + protection	240	360	0.4MF/MW
4.3	HV distribution	300	720	
5	Assembly & maintenance tools	830	735	% of cost (out of 10)
6.1	Machine cooling	400	400	fusion power
6.2	Magnet cooling	0	290	0.23 MF/MW
7	Control and diagnostics	500	500	estimate */ ITER
8	Tritium, fueling and pumping	900	900	Plasma volume, density
9	Cryogenic system	300	0	Cryogenic power
10	Additional Heatings (45MW)	880	880	Power and type of heatings
	Total cost (without 10)	10 115	8 975	
	Total cost(with 10)	**10 995**	**9 855**	
	Total cost(in MEuros)	**1 675**	**1 500**	

in red : items favorable to copper machine
in blue : items favorable to supra machine

Table 5.1-1 : Cost estimate (in MF)

5.2 Operation (cost of electricity for the Toroïdal magnet)

In this paragraph, we will limit ourselves to the comparison of the operating cost of the toroidal field system, for the 2 options, copper and supra.

5.2.1 Copper option

In the copper option, the toroidal field is only established at the time of the plasma pulses and the electrical consumption is independent from the operating mode (D-D or D-T). For a consumed power of 750 MW and an average electrical cost of 0.25 F/kWh, valid for a facility in France [2], the operating cost of one hour is of 190 kF. If we consider a cumulated operating time of 2000 hours (see Chapter 2), we obtain an electrical consumption of **380 MF** for the lifetime of the machine, in other terms **58 MEuros**.

5.2.2 Superconducting option

In the supra option, the electrical consumption is that of the cryogenic refrigerator, but the operating modes are more numerous, because of the several kinds of losses :

- P1 : Thermal losses by radiation / conduction (as soon as the magnet is cold).

- P2 : Joule losses in the conductors and connections (as soon as the field is established).

- P3 : Eddy current losses (in the presence of plasma).

- P4 : Losses by neutronic heating (in the presence of D-T plasma)

Powers P3 and P4 are averaged over operation cycle with a ratio of 1/10.

The table below gives the estimates for the different powers at the temperature of 4.5K.

P1 (kW)	P2 (kW)	P3 (kW)	P4 (kW)
11	1	1.5	6.5

From an investment point of view, the refrigerator will be designed for the sum of these 4 values, in other terms 20kW.

The table below gives an estimate of the electrical energy consumed depending on the duration of each operating mode. An efficiency of 1/400 between the power at 4.5 K and the total electrical power consumed is taken into account.

Mode	power (MW)	time	energy (MW.h)
Cold magnet	4.4	2/3 of 15 years	385 400
Field established	0.4	25 000 hours	10 000
Plasma	0.6	2 000 hours	1 200
Plasma in D-T	2.6	700 hours	1 800
TOTAL	8		~ 400 000

It is to be noted that because of the operating program of the machine, most of the electrical consumption is due to the thermal losses by radiation / conduction. By again taking 0.25 F/kWh, we obtain an electrical consumption of **100 MF** in other terms **15 MEuros** for the lifetime of the machine.

6. State of research on the comparison between copper and supra machines

This comparison is made with plasma (R, a, k, δ, B_T) and the available radius for the central solenoid unchanged in both options.
The neutron flux is of ≤ 0.5 MW/m2.

6.1 Design basis of the toroïdal field system

Superconducting coils :

This solution benefits from the experience of the Euratom-CEA Association, acquired on Tore-Supra and during the R&D actions for the definition of the ITER superconducting coils.

In the case of the present project, the M2S coils must be protected by a neutronic shield with a total thickness of more than 0.7 m, to limit the neutronic power on the superconductor and on the coil casing. The lower limit of 0.7 m is acceptable in view of a cyclic ratio of 1/10 for the plasma shots, which limits the average load on the refrigerator at low temperature. This operation is compatible with the considered use of the machine. The construction of coils is compatible with the mechanical stresses on the magnet.

The access available ($0.6 * 0.9\ m^2$) for a neutral beam, as that projected on ITER-FDR and ITER-RC (33 MW of neutrals from negative ions), is compatible with the sizes of the coils and the shield thickness of 0.7 m. This beam is tangent to the radius 4m.

Copper coils :

The neutronic shield can be significantly lightened. The design basis factors for the shield are the doses on the insulators and in the copper. The design basis factors for the copper section are the mechanical stresses and the dissipated electrical power, which must be supplied by the network.

The mechanical stresses, which are the most critical, lead to a copper thickness not less than 0.9 to 1 m. Consequently, the design of a copper machine, with a plasma identical to that of the reference superconducting machine, results in neutronic shields not exceeding roughly 0.3 m. Sum of traction and compression stresses is 140 ÷ 160 MPa, (which is still acceptable for copper with an ultimate tensile strength of 250 Mpa, such as the OFHC doped with Ag (cf. Appendix 7.3)).

The current density in the copper is roughly of 14 A/mm^2 and that in the section occupied by the winding of 10 A/mm^2. Consequently, the total mass of copper for the toroïdal magnet is roughly of 2000 tons and the dissipated electrical power is roughly of 750 MW, for solenations of 150 MAt.

For the irradiation time considered (700 h) and a shield thickness of 0.3 m, doses on the conductor are of 10^8 Gy, corresponding to roughly 10^{-3} dpa. The mechanical and electrical properties of copper are therefore not modified by irradiation. The maximum acceptable irradiation dose on the insulating materials depends on their type. The irradiation dose ranges between 6 and $10 * 10^7$ Gy, which requires the use of mineral insulators.

The access available ($0.6 * 0.9\ m^2$) for a neutral beam, as that projected on ITER-FDR and ITER-RC (33 MW of neutrals from negative ions), is compatible with the sizes of the coils and the thickness of the shield of 0.3 m. This beam is tangent to the radius 4m.

6.2 Design basis of Central Solenoid (CS)

(this section has been slightly modified with regard to the French original one)

When using the same available surface, which is the case for both solutions M2S and M2C, the central copper solenoid supplies the same flux as that of the superconductor.

Superconducting CS :

The limitation of B on the conductor ($B < 13 \div 14$ T) sets the upper limit of the available flux. The average current density $< j >$ depends on B_{max} and the radial thickness of the CS.

In practice, in machines of the size of M2- ITER, $< j >$ is between 11 and 14 A/mm^2.

In M2S, with $B \sim 13$ T, we obtain a magnetic flux swing of roughly 140 Wb, with a solenoid of 1.7 m in external radius, 0.8 m in radial thickness and an average current density of 13 A/mm^2.

Copper CS :

With the same average current density as in the superconducting CS, the local current density in copper is 18.5 A/mm^2. It is within the range used for the toroïdal magnet and its cooling. Obviously, the magnetic flux swing is the same for both solutions.

The mechanical stresses (azimutal traction and axial compression) are around 200 Mpa, which requires the use of copper alloys with an ultimate tensile strength greater than 350 Mpa (Cu/Be and Cu/Cr/Zr).

In M2C, the same solenoid as in the superconducting solution would have a mass of 400 t and would dissipate 300 MW for the same flux and same <j>.

By taking into account the flux needed for the creation and ramp-up of the plasma current (~120 Wb) and the contribution of the other poloïdal coils (~30 Wb), a current plateau of ~500s is possible with a plasma loop voltage of 100 mV, for both superconducting and copper central solenoid.

6.3 Comparison of costs

The cost estimates are presented in Chapter 5.1. If a significant gain is seen on the cost of magnets (of roughly 40 % lower for copper compared to the supra) and on the cost of shielding (3 times less) for the copper machine, this trend is greatly reduced when considering also the cost of the power supplies (more than twice as much for the copper machine) and that of all the identical items for the 2 machines.

In the end, the copper machine appears slightly less costly in investments than the supra machine. The difference is not completely absorbed by the over-consumption of electricity of the copper toroïdal field system.

6.4 Conclusions

The conclusions are preliminary ; they must be verified by detailed analyses on the actual structure of the toroïdal coil and of the central solenoid. Numerical calculations concerning all the mechanical stresses exerted on the coils are needed, if we want to be thorough in understanding the problems linked to the use of copper magnets. The cost estimate must also be deeply analyzed.

At present, we could say that it seems possible to build all the copper magnets without changing the plasma nor the available magnetic flux.

With 18 coils, the access for an ITER type neutral beam seems possible in both cases, all the while ensuring the neutronic protection of the coils.

As for the costs, according to this preliminary work, there seems to be a slight advantage for the copper version, which should not be taken as a deciding factor in the choice of one technology over another.

7. Appendices (see Tome 2 - DRFC/EPDIM/99-015 - in french)

7.1 Résumé des études précédentes sur une machine « M1 » :

Summary of previous studies on a « M1 » machine
Bernard Turck.

7.2 Choix du rapport d'aspect : méthode de dimensionnement, exemple sur une machine Supraconductrice :

Choice of an aspect ratio : design basis method, example on a superconducting machine
Ferran Albajar-Vinas, Jean-Luc Duchateau, Jean Johner.

7.3 Propriétés des alliages de cuivre et influence de l'irradiation sur les propriétés des matériaux des aimants :

Properties of copper alloys and influence of irradiation on the properties of the magnet materials
Patrick Hertout.

7.4 Critères de dimensionnement du blindage neutronique :

Design Basis criteria for neutronic shielding
Franco Bottiglioni, Mohamed Eid, Gabriel Marbach.

7.5 Aspects techniques du dimensionnement d'un système d'aimants supraconducteurs :

Technical aspects of design basis of a superconducting magnet system
Jean-Luc Duchateau.

7.6 Aspects techniques du dimensionnement d'un système d'aimants en Cuivre :

Technical aspects of the design basis of copper magnet system
Jean-Michel Bottereau, Franco Bottiglioni.

7.7 Détermination des coûts :

Cost determination
Jean-Michel Bottereau, Philippe Magaud.

7.8 Etude des équilibres MHD avec le code « CHEASE » :

Study of MHD equilibria using the " CHEASE " code
Maxime Zabiégo.

8. References

[1] DRFC / Etudes prospectives . Groupe de dimensionnement, Rapport d’activité 1997. Rapport DRFC/DIR 98/045

[2] DRFC / Etudes PIAC (Projet ITER à Cadarache). 1995-1996.

More detailed references can be found in the appendices