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IGNITION BY TTMP HEATING IN THE FUTURE EUROPEAN TOKAMAK +

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M.Bernard, G.Briffod, F.Parlange.

INTRODUCTION

As a first step three skeleton Tokamaks are now studied by the Joint Tokamak Working Group.

The possibility to reach ignition in these three Tokamaks by neutral injection has been studied by Girard, Rebut, Sweetman. In the same context we establish the required conditions in order to obtain ignition by TTMP heating. The R-F modulation rate, heating time, heating power and dissipated power are evaluated for the three machines.

+ This paper has been presented at the 3rd meeting of the Joint Tokamak Working Group, Culham the 10-11th of October 1972.

RESUME

Dans un premier temps, trois avant projets ont été retenus et mis à l'étude par le "Joint Tokamak Working Group" dans le but de définir la conception du futur Tokamak Européen. Nous examinons dans ce papier les possibilités de chauffage par TTMP. Il en ressort que, par ce moyen de chauffage, l'ignition peut être atteinte dans chacun des trois types de projet avec un taux de modulation HF du champ magnétique toroïdal de l'ordre de 1 à 2 x 10^{-3}. Nous calculons les puissances correspondantes que devraient fournir les oscillateurs et les puissances dissipées dans les bobinages HF. L'ordre de grandeur des résultats montre que la mise en oeuvre du chauffage par TTMP pour atteindre l'ignition, ne pose que le problème technologique de l'isolation des bobinages HF par rapport au plasma.

SUMMARY

In a first step, three preliminary designs,for the possible concept of a future European Tokamak, have been retained for study by the "Joint Tokamak Working Group". We examine in this paper the feasibility of TTMP heating. It comes out that ignition can be reached by the means of TTMP heating for each of the three skeleton Tokamaks. The necessary RF modulation rate of the toroidal magnetic field is about 1 to 2.10^{-3}. We calculate the corresponding power which must be delivered by the oscillators and the power dissipated in the RF coils. The results show that setting TTMP heating in order to reach ignition asks only the technological question of insulating the R-F coils from the plasma column.

I. NUMERICAL COMPUTATIONS.

In order to get more precise information on the plasma heating by Transit Time Magnetic Pumping, we use a numerical code owing to which electron and ion temperatures are computed in function of time by integrating the two species energy balance equations.

The particle density is assumed to be constant ($n_i = n_e = n$) and we consider a 50% - 50% Deuterium-Tritium ion mixture. The ion atomic mass is taken 2.5 in such a way that only one ion-energy balance equation has to be written.

The heat conductivity losses are given by a term : nT/τ_E , $\tau_E^{-1} = \gamma \frac{\chi_\perp}{a^2}$

$\chi_\perp$ is the heat conductivity coefficient, a the plasma radius and γ a numerical coefficient taking into account the radial temperature gradient.

The values of this γ coefficient are adjusted referring to experimental results which have been obtained up to now on large Tokamaks.

Due to the order of magnitude of the parameters of the 3 skeleton Tokamaks $\chi_\perp$ will be the heat conductivity coefficient in the trapped particle regime.

The ohmic heating and equipartition terms are classical :

$$P_{Ohm} = 3.3 10^{15} \frac{\text{Log}\Lambda \ I^2}{T_e^{3/2} \ a^4}$$

I , amp
a , cm
T_e , eV

$$\tau_{\substack{\text{equipartition}\\ \text{second}}} = 3.14 \ 10^{8} \ \frac{T_e^{3/2}}{n \ \text{Log}\Lambda}$$

n, cm^{-3}

The Bremsstrahlung losses are taken as :

$$P_{Brems.} = 1.06 \ 10^{-13} \ n^2 \ T_e^{1/2}$$

eV x cm^{-3} x s^{-1}

and the cyclotron radiation losses are written by Rosenbluth (Nucl. Fus., 10, 3, 1970 p. 340) :

$$P_{cycl.} = 0.4.10^{+2} \ \frac{B^{5/2}}{R^{1/2}} \ n^{1/2} \ T_e^2$$

eV x cm^{-3} x s^{-1}

B, Tesla
R , cm

It is besides assumed that the energy of the α particles produced by the D-T reaction is transferred for the most important part to the electrons.

The energy per unit time carried by these α particles is :

$$P = 8.75\ 10^5\ n^2 \langle \overline{\sigma v} \rangle_{DT} = 3.22\ 10^{-4}\ n^2\ T_i^{-2/3} \exp\left[-\frac{199}{T_i^{1/3}}\right]$$

$eV \times cm^{-3} \times s^{-1}$

The TTMP heating terms have been calculated by E.Canobbio :

$$P_{TTMP} = \frac{V_{TH}}{R}\ b^2\ n\ T\ Q_L \quad \text{when} \quad n < n_{critical}$$

$$P_{TTMP} = \frac{n^2}{T}\ V_{TH}\ b^{1/2}\ Q_{NL} \quad \text{when} \quad n > n_{critical}$$

with $n_{critical} = \dfrac{b^{3/2}\ T^2}{R \operatorname{Log}\Lambda}\ \dfrac{Q_L}{Q_{NL}}$

In these formulas $b \sim \dfrac{B_1}{B_0}$, V_{TH} is the thermal velocity, Q_L and Q_{NL} are coefficients which depend on $\dfrac{T_e}{T_i}$ and $X = \dfrac{V_{PHASE}}{V_{TH}} = \dfrac{\omega}{k V_{TH}}$

The numerical code first compute the equilibrium point without TTMP heating then, starting from this point performs the time integration of the two energy-balance equations when TTMP heating is applied.

The ignition condition is defined by :

$P_\alpha >$ Heat conductivity losses + cyclotron radiation losses + Bremsstrahlung losses.

Typical results are represented on the Fig. 1 and 2 for the 10.0 Tesla Tokamak, onf the Fig. 2 and 3 for the 6.0 Tesla Tokamak and on Fig. 4 and 5 for the 3.6 Tesla Tokamak.

II. COMMENTS.

1. General remarks

We first remember that the 3 skeleton Tokamaks have been planed to work at q = 3, 3 MA and with the aspect ratio $\frac{R}{a}$ = 3.33. These three conditions need that the product a B is constant and equal to 6.10^4 Tesla x cm.

When these relations are taken into account the terms of the energy balance equations can be rewritten as :

Ohmic heating : $P_{Ohm} = 3.5 \ 10^{18} \frac{B^4}{T_e^{3/2}}$ B, Tesla; Te, Ti eV

Bremsstrahlung Losses : $P_{Brem.} = P_B = 1.06 \ 10^{-13} \ n^2 \ T_e^{1/2}$ n, cm^{-3}

Cyclotron radiation Losses :

$$P_{Cycl.} = P_C = 0.89 \ n^{1/2} \ T_e^2 \ B^3$$

Heat conductivity ion Losses :

$$\frac{nTi}{\tau_{Ei}} = P_D = 3.4 \ 10^{-14} \ \gamma \ T_i^{1/2} \ n^2$$

α-particles heating : $P_\alpha = 3.22 \ 10^{-4} \ n^2 \ T_i^{-2/3} \ \exp\left[-\frac{199}{T_i^{1/3}}\right]$

We must remak that if the coefficient γ is equal to 3, the two terms P_B and P_D are equal for $T_i = T_e$

We consider now the sums $\frac{P_{Ohm} + P_\alpha}{n^2}$ and $\frac{P_{Brem} + P_{Cycl.} + P_D}{n^2}$

These two quantities which depend only on the parameter $\frac{n}{B^2}$ are plotted versus T_e on Fig. 7, 8,9 for different values of $\frac{n}{B^2}$

(i.e. $\frac{n}{B^2}$ = 1,4 10^{12} , $\frac{n}{B^2}$ = 2.10^{12} , $\frac{n}{B^2}$ = 2.8 10^{12})

and for $T_e = T_i$

The two curves intersect in a point $T = T_{eQ}$ which is the equilibrium point for the Tokamak without additional heating.

If $\frac{n}{B^2}$ is sufficiently high - which is the case on the three figures - there is a second intersection point for $T = T_{IGN}$. This temperature T_{IGN} is the ignition temperature : when $T > T_{IGN}$ the plasma temperature is self-sustaining or increasing due to the α-particles heating, which makes the energy balance to be positive.

The ion and electron temperatures have been assumed to be equal because the equipartition time. for energy exchange between ions and electrons is less than the confinement times of the three skeleton Tokamaks.

A second reason is the following: if we assume $T_i > Te$, due to the additional heating which is applied preferentially to the ions, the P_α term will be higher than the previous one evaluated for $T_i = T_e$. Thus the second intersection point of the two curves will happen for a lower value of T_{IGN}. But if we stop there the additional heating, the ions will be cooled and the electrons heated by energy exchange between the two species. This thus involved that P_α decreases and the loss terms increase so that the energy balance becomes negative and the D-T reaction rapidly slows down.

Referring to the Fig. 7, 8, 9, we can consider the minimum practical value of $\frac{n}{B^2}$ is 2. 10^{12} (cm^{-3} x $Tesla^{-2}$) . The corresponding values of the starting equilibrium point and of the ignition temperature are :

$T_{EQ} \sim$ 2 KeV

$T_{IGN} \sim$ 8 KeV

with the following plasma densities :

Tokamak 3.6 Tesla : $n = 0.26 \times 10^{14}$ cm^{-3}

Tokamak 6.0 Tesla : $n = 0.72 \times 10^{14}$ cm^{-3}

tokamak 10.0 Tesla: $n = 2.0 \times 10^{14}$ cm^{-3}

2. TTMP characteristics, modulation rate .

In the regime where $n < n_{critical}$, which is the most interesting one, the TTMP heating term for the ions can be rewritten as :

$$P_{TTMP} = 1.12 \; 10^{+3} \; B \; T_i^{3/2} \; b^2 \; n$$
$$eV \times cm^{-3} \times s^{-1}$$

As the TTMP term is an increasing function of T_i we can write that the minimum TTMP heating leading to ignition has to make zero the energy balance at T = 3 keV. We can see on the Fig. 8 that the energy balance at a temperature of 3 keV is $\Delta P = 8.5\ 10^{-12}\ n^2$. Thus :

$$|\Delta P| = 8.5\ 10^{-12}\ n^2 = 1.84\ 10^8\ B\ b^2\ n$$

or

$$b = 3.4\ 10^{-4}\ B$$

and for the three skeleton Tokamaks :

$B = 3.6$ Tesla $\quad b = 0.64\ 10^{-3}$

$B = 6.0$ Tesla $\quad b = 0.83\ 10^{-3}$

$B = 10.0$ Tesla $\quad b = 1.07\ 10^{-3}$

The minimum practical value of b necessary to get ignition must fulfil a supplementary condition : the heating time must be of the order of the confinement time of the machine.

If the practical mean value of $\frac{dTi}{dt}$ is taken as 1 keV/second we can write the energy balance for T_i = 3 keV.

$$\frac{dTi}{dt} = 10^3 = \frac{P_{TTMP} - \Delta P}{2\ n} = 0.92\ 10^8\ Bb^2 - 4.2 10^{-12}\ n$$

or

$$b^2 = \frac{1 + 4.2\ 10^{15}\ n}{0.92\ 10^5\ B}$$

and for the three Tokamaks with $\frac{n}{B^2} = 2.10^{12}$

3.6	Tesla	$n = 2.6\ 10^{13}$	$b = 1.8\ 10^{-3}$
6.0	Tesla	$n = 7.2\ 10^{13}$	$b = 1.5\ 10^{-3}$
10.0	Tesla	$n = 2.\ 10^{14}$	$b = 1.4\ 10^{-3}$

These calculations have been done in the TTMP "linear regime" $n < n_{critical}$ or $T < T_{critical}$

The value of the critical temperature can be written as :

$$T^2_{critical} \sim 2.0\ 10^{-13}\ \frac{n}{B^2}\ \frac{R}{a}\ (aB)\ b^{-3/2}\ B \qquad \text{B, Tesla}$$

$$\sim 8\ \ 10^2\ b^{-3/2}\ B \qquad \text{a, cm}$$

or for the three Tokamaks :

$T^{(3.6\ T)}_{crit.} \sim 6.2$ keV

$T_{Crit.}^{(6.0\ T)}$ ~ 9.2 keV

$T_{Crit.}^{(10.T)}$ ~ 12.4 keV

In the non linear TTMP regime, when $n > n_{crit.}$ or $T > T_{crit.}$, the P_{TTMP} term decreases as $T^{-1/2}$ which is a quite slow dependence on the temperature.

The minimum b necessary for ignition as calculated previously is thus not seriously changed provided that the critical temperature is higher than 4 or 5 keV.

III. RF POWER NEEDED FOR TTMP HEATING

The power which must be supplied by the RF generator can be divided in 3 parts : power necessary to compensate the plasma losses, power necessary to heat the plasma without losses and power dissipated in the RF coils and eventually in the copper shell or any metallic vessel surrounding the coils.

1. Power necessary to compensate the plasma energy losses.

The plasma energy losses are given by the energy balance calculated previously in absence of TTMP heating. Its mean value is taken as $\frac{2}{3} \times \Delta P_{Max}$ where ΔP_{Max} is the maximum absolute value of the negative energy balance. We obtain from Fig. 7, 8, 9 :

$\frac{n}{B^2}$ cm^{-3}, Tesla^{-2}	$1.4\ 10^{12}$	2.10^{12}	$2.8\ 10^{12}$
$\frac{\Delta P_{Max}}{n^2}$ eV cm^3/sec	$1.4\ 10^{-11}$	$1.2.10^{-11}$	$1.1\ 10^{-11}$

Choosing $\frac{n}{B^2} = 2.10^{12}$ the mean energy losses are for the three machines.

B Tesla	3.6	6.0	10.0
n cm^{-3}	2.6×10^{13}	7.2×10^{13}	$2. \times 10^{14}$
P_{Losses} w/cm3	$1.0\ 10^{-3}$	$6.6\ 10^{-3}$	$4.7\ 10^{-2}$
Plasma Volume cm^3	$3\ 05 \times 10^6$	66×10^6	$14.2\ 10^6$
Total energy Losses MW	0.30	0.44	0.67

2. RF Power needed for heating the plasma.

From the previous results we can evaluate the RF power which is necessary to heat the plasma in absence of losses. The heating energy can be written as :

$$E_H = n\ V \left[(T_{i\ (Ignition)} - T_{io}) + T_{e\ (Ignition)} - T_{eo} \right]$$

V is the plasma volume

and the related RF power

$$P_H = \frac{E_H}{\tau_H}$$, τ_H being the time necessary to reach ignition conditions when TTMP is applied.

The numerical values are presented on the next table :

	n cm^{-3}	b	E_H (MJ)	P_H (MW)
Tokamak 10 Tesla	10^{14}	10^{-3}	4.7	1.0
	2.10^{14}	2.10^{-3}	4.4	3.7
Tokamak 6 Tesla	5.10^{13}	10^{-3}	6.8	0.96
	7.10^{13}	2.10^{-3}	6.9	3.8
Tokamak 3-6 Tesla	2.10^{13}	10^{-3}	10.7	0.97
	5.10^{13}	2.10^{-3}	24.9	4.2

3. RF Power dissipated in the heating coils and in a copper shell.

The power dissipated in the RF coils and in a closed copper shell surrounding both the plasma and the RF coils has been calculated by T.K.N'Guyen, using a cylindrical model in which the heating coils are simulated by a continuous current sheet the density of which is $J = J \cos Kz + J_3 \cos 3\, Kz + J_5 \cos 5\, Kz$... K is the wave number along the torus : $K = \frac{N}{2R}$

N being the number of coils.

In a first attempt we choose to put 8 coils in each machine and to apply TTMP heating with a constant RF frequency corresponding to a ratio $X = \frac{\text{wave phase velocity}}{\text{ion thermal velocity}}$ equal to 1.12 for $T_i = 5$ keV

The modulation rate is $b = 1.4\ 10^{-3}$ and we know that the voltage per turn, the total ampere x turn number and the dissipated power are respectively proportional to b, b and b^2 .

For each machine the coils will be made with elliptical cross section copper wire. The length, l, of a coil is defined by the relation $K_z l = \frac{Nl}{2R} \simeq 1$

or $l = \frac{2R}{N}$ where N is the number of turns and R the major radius of the torus

The minor diameter of the copper wire is 1 cm, and the major diameter is optimized in order to get less dissipation owing to the relation.

Major diameter = $\beta \frac{l}{N}$ with $\beta \simeq 0.7$

The calculations are made with and without copper shell.

The results are summarized in the following table, the number of turns of the RF coils varying from 1 to 4.

	10 Tesla		6 Tesla		3.6 Tesla	
	Without shell	with shell	Without shell	with shell	Without shell	With shell
ajor radius of the torus (m)	2.00	2.00	3.33	3.33	5.55	5.55
lasma radius (m)	0.60	0.60	1.00	1.00	1.67	1.67
at I = 3 MA	3	3	3	3	3	3
iner outer radius (m)	0.62	0.62	1.02	1.02	1.69	1.69
hell inner radius (m)	-	0.78	-	1.23	-	1.98
ax. coil radius (m)	0.63	0.63	1.03	1.03	1.70	1.70
ength of the coil (m)	0.50	0.50	0.83	0.83	1.39	1.39
inor diameter of the pper wire (cm)	1.0	1.0	1.0	1.0	1.0	1.0
ajor diameter of the opper wire (cm) : . 1 turn . 2 turns . 3 turns . 4 turns	 35. 17.5 11.7 8.7	 35. 17.5 11.7 8.7	 58.3 29.2 19.4 14.6	 58.3 29.2 19.4 14.6	 97.3 48.7 32.4 24.3	 97.3 48.7 32.4 24.3
F frequency khz	221.	221.	133.	133.	79.8	79.8
F Magnetic field (Gauss)	140.	140.	84.	84.	50.4	50.4
oltage per turn (kV)	33.7	37.4	32.4	36.6	30.1	36.2
otal amp x turns (kA)	17.9	33.9	17.6	38.5	17.4	43.1
ower dissipated in the opper shell	-	1.42	-	1.69	-	1.85
otal power dissipated shell + coils) : . 1 turn coils MW) . 2 turns coils . 3 turns coils . 4 turns coils	 2.28 2.22 2.16 2.11	 9.5 9.3 9.1 8.9	 1.69 1.67 1.64 1.62	 9.8 9.6 9.5 9.4	 1.28 1.27 1.26 1.25	 9.7 9.6 9.5 9.4

CONCLUSION

It appears from this work that we can reach ignition in the three skeleton Tokamaks by TTMP heating. The RF power needed do not lead to technological difficulties. However the cost of the RF equipments as well as the question of general environment of the RF coils have to be more investigated.

These problems are now under study at smaller scale on the experimental device "PETULA" which is to be built at the GRENOBLE's Laboratory.

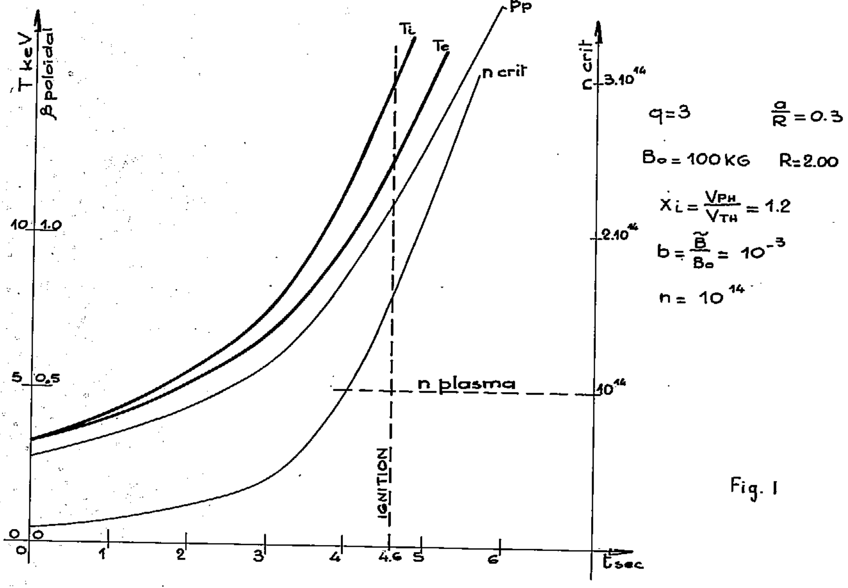
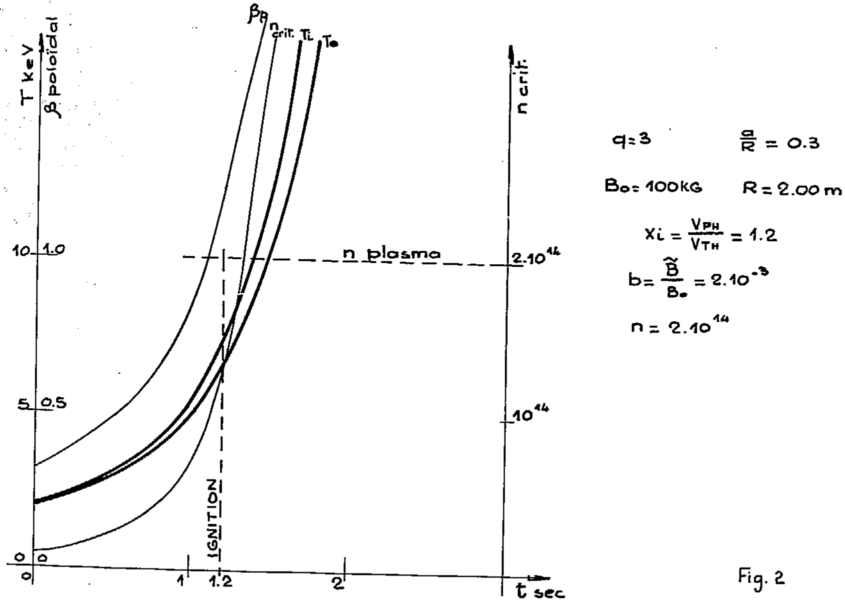
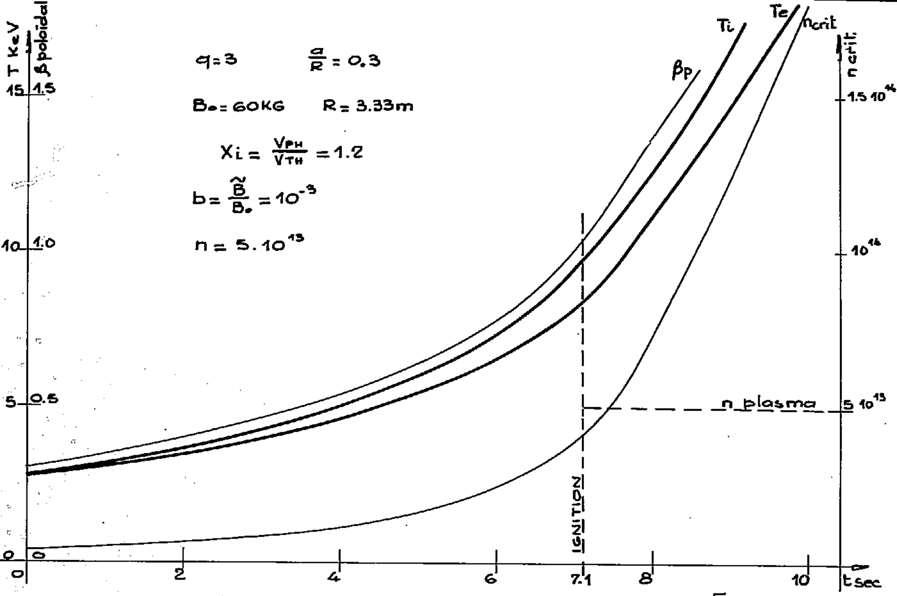

T keV
β poloidal
10 1.0
5 0,5
0 0
Ti
Te
βp
n crit
n crit
3.10^14
2.10^14
10^14
n plasma
IGNITION
0 1 2 3 4 4.6 5 6
t sec
q=3
a/R = 0.3
Bo = 100 KG
R=2.00
Xi = VPH/VTH = 1.2
b = B̃/Bo = 10^-3
n = 10^14

Fig. 1



T keV
β poloïdal
n crit.
β_θ
n crit.
T_i
T_e
10
1.0
5
0.5
0
0
n plasma
2.10^{14}
10^{14}
IGNITION
1
1.2
2
t sec
q = 3
$\frac{a}{R}$ = 0.3
B_o = 100KG
R = 2.00 m
$X_i = \frac{V_{PH}}{V_{TH}} = 1.2$
$b = \frac{\tilde{B}}{B_o} = 2.10^{-3}$
$n = 2.10^{14}$

Fig. 2



T KeV
β poloidal
q = 3
a/R = 0.3
B₀ = 60KG
R = 3.33m
Xi = VPH/VTH = 1.2
b = B̃/B₀ = 10⁻³
n = 5.10¹³
βp
Ti
Te
ncrit
n crit
1.5 10¹⁴
10¹⁴
5 10¹³
n plasma
IGNITION
15
1.5
10
1.0
5
0.5
0
0
2
4
6
7.1
8
10
t sec

Fig. 3

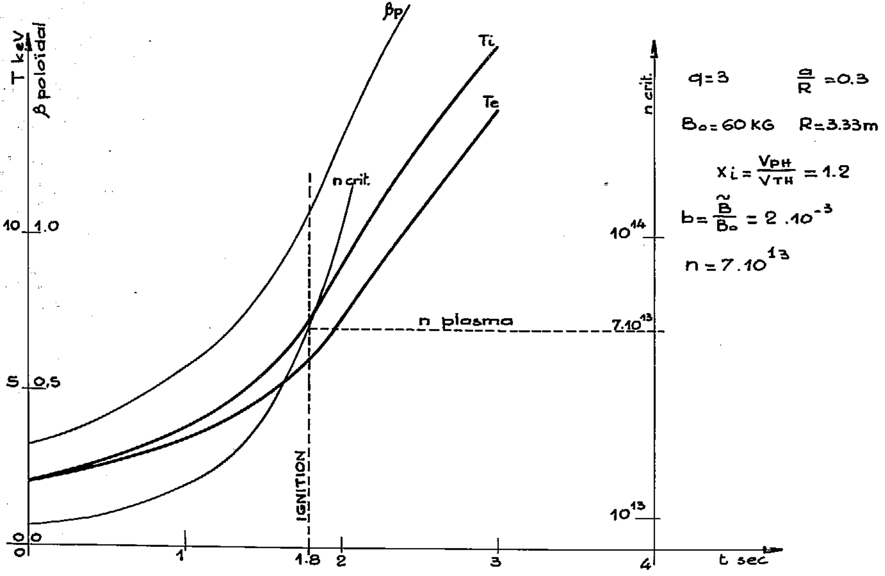
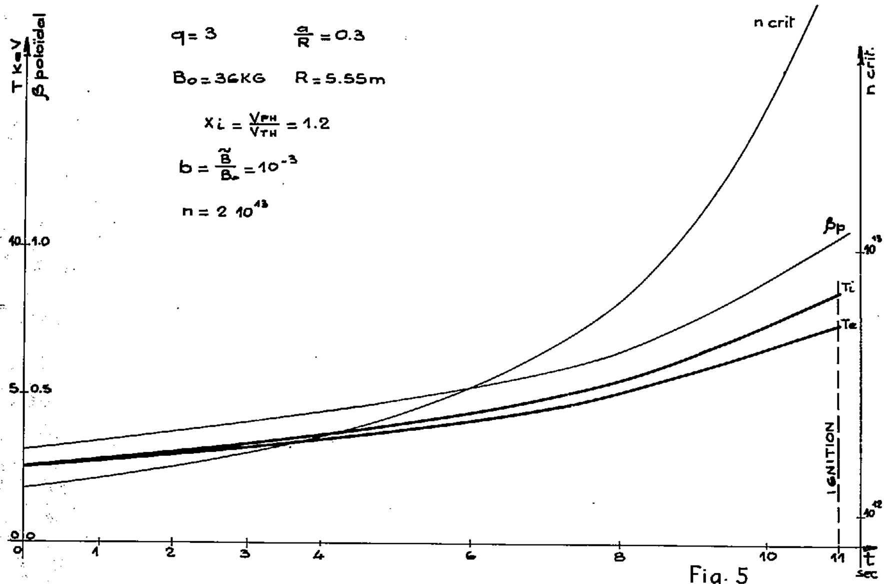
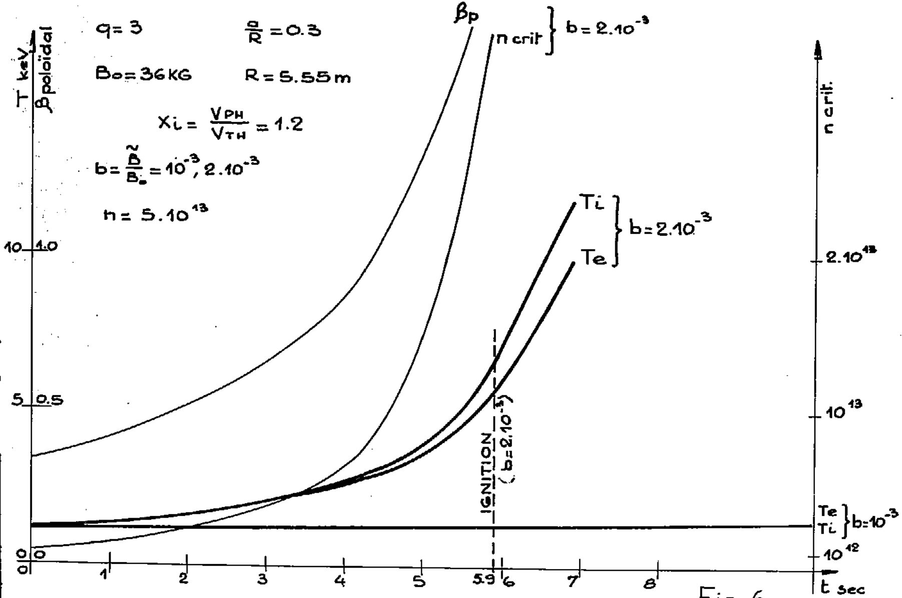

T keV
β poloïdal
βp
Ti
Te
n crit.
n crit.
q=3
a/R =0.3
Bo=60 KG
R=3.33m
Xi = VPH/VTH = 1.2
b = B̃/Bo = 2 .10^-3
n = 7.10^13
10
1.0
5
0,5
0
0
10^14
7.10^13
10^13
n plasma
IGNITION
1
1.8
2
3
4
t sec

Fig. 4



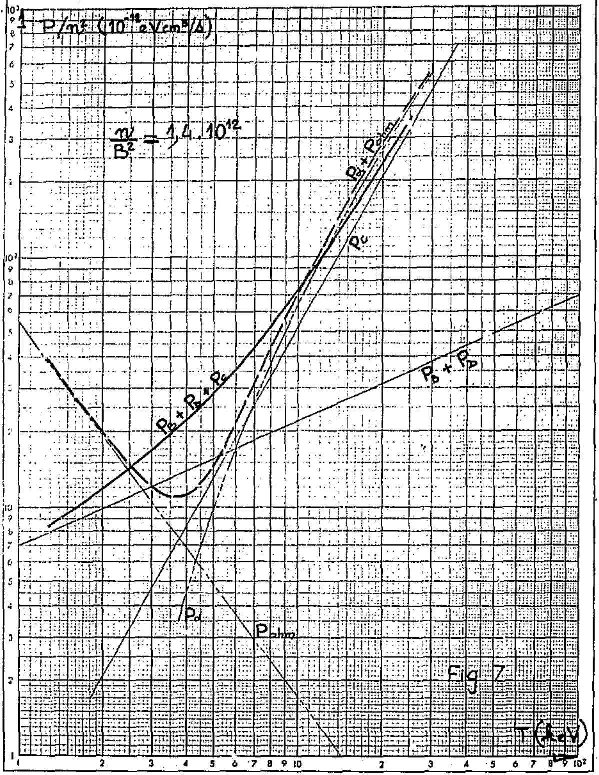
T KeV
β poloïdal
n crit
q = 3
a/R = 0.3
Bo = 36KG
R = 5.55m
Xi = VPH/VTH = 1.2
b = B̃/Bo = 10-3
n = 2 1013
βp
Ti
Te
IGNITION
10 1.0
5 0.5
0 0
1013
1012
0
1
2
3
4
6
8
10
11
t
sec

Fig. 5



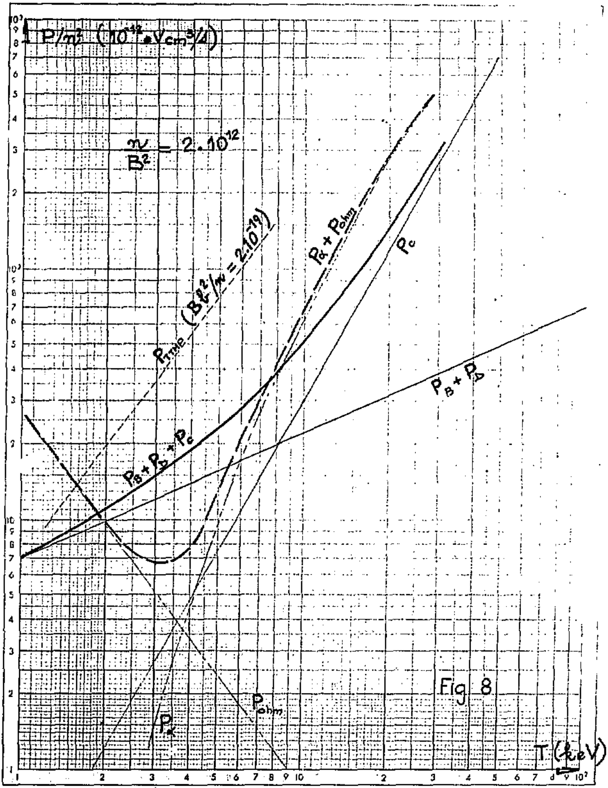
q= 3
a/R = 0.3
Bo = 36 KG
R = 5.55 m
Xi = VPH / VTH = 1.2
b = B̃/Bo = 10^-3, 2.10^-3
n = 5.10^13
βp
n crit } b = 2.10^-3
T keV
β poloidal
n crit.
Ti
Te
} b = 2.10^-3
2.10^13
10^13
10^12
Te
Ti
} b=10^-3
IGNITION (b=2.10^-3)
10
1.0
5
0.5
0
0
1
2
3
4
5
5.9
6
7
8
t sec

Fig. 6



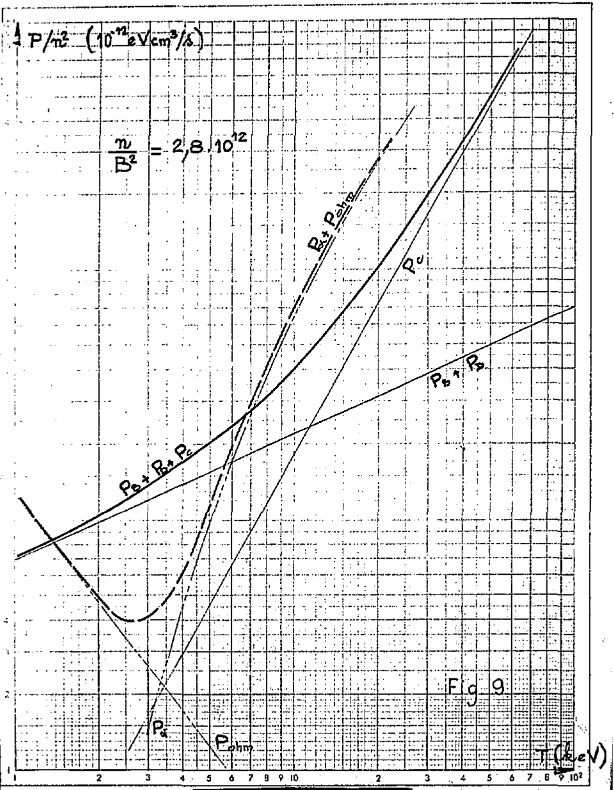
P/n² (10⁻¹² eV cm³/s)
n/B² = 1,4.10¹²
P_B + P_ohm
P_c
P_B + P_A + P_c
P_B + P_A
P_d
P_ohm
T (keV)

Fig 7



P/n² (10⁻¹²·V cm³/s)
n/B² = 2.10¹²
P_TME (Bℓ²/n = 2.10⁻¹⁹)
Pα + P_ohm
P_c
P_B + P_Δ
P_B + P_Δ + P_c
P_ohm
Pα
T (keV)

Fig 8



P/n² (10⁻¹² eV cm³/s)
n/B² = 2,8.10¹²
Pα + Pohm
Pc
Pb + Pβ
Pβ + Pb + Pc
Pα
Pohm
T (keV)
1
2
3
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
10²

Fig 9.