Scaling and Some Electrotechnical Parameters in Tokamak Fusion Reactors

A. Knobloch

IPP 4/105 November 1972

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Abstract

A certain scaling of the quasi-stationary Tokamak fusion reactor produced by fixing two absolute dimensions and two specific stress values is used to show the scaling of important electrotechnical parameters in the confinement and heating systems. The thermonuclear power range covered is 1 ÷ 2o GW_{th}. Economical considerations are not included.

Scaling and Some Electrotechnical Parameters in Tokamak Fusion Reactors

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Electrotechnical problems in fusion machines naturally are closely connected with the scaling of such machines. At present the scaling of fusion devices is one of the main points of interest in plasma research itself. Thus the consideration of electrotechnical problems is a part of more general studies on fusion reactors which have to follow the development of knowledge on plasma confinement.

As we are considering here stationary or quasi-stationary tokamaks, the electrotechnical problems are likely to be found along the following lines:

1. The magnetic energy of tokamak devices will be determined by the confinement configuration in the machine, namely the toroidal magnetic field B_t and, to a much smaller extent, by the poloidal field of the ring current B_p. Additional magnetic energy will be found in the vertical field for the compensation of the hoop force on the ring and in correction fields. In connection with these magnetic fields, problems of structural mechanics, materials technology, power supplies, and safety engineering, will occur. Further problems in magnetic fields arise in a magnetic divertor which has to scrape off the charged particles leaving the reacting plasma volume at the outer confinement boundary. Problems of magnetic divertors, however, are excluded here because their definition requires considerably more theoretical and experimental data than is available now. The magnetic fields required are determined by the specific parameters of the plasma to be confined, by its shape and dimensions. The specific plasma data includes also the conditions for equilibrium and stability. With quantitative numbers given, we can look at the possibilities of generating the necessary magnetic fields, taking into account some limiting factors which are of plasma-physical, topological, and technical nature.

2. Given the confinement configuration, we can further look at the plasma heating requirements for start-up. Since close to classical diffusion behaviour of plasmas gradually seems to be approached, relatively slow heating mechanisms and relatively low heating power levels can be expected. However, experimental knowledge e.g. of low frequency and injection heating remains still to be gained. We must rely on the application of some theoretical considerations on heating methods which can be applied to magnetically confined plasmas. High frequency heating will not be treated here.

3. Starting from energy balance considerations for charged particle heating, and including fuelling and fuel extraction etc., one can study the theoretical control performance of a fusion reactor. But as control of a reactor naturally would require at least command of the steady state behaviour of the plasma, this topic is beyond the scope of this paper.

Thus, in the following paragraphs we shall keep to the first two aspects in characterizing tokamak machines from the electrotechnical point of view. In doing this we shall completely omit economic considerations. They have been treated, for instance, for the toroidal superconducting magnet by Schmitter.[1] We shall try to give some quantitative figures for a selected series of possible reactor designs in order to assess technical requirements. In order to determine the parameter range of tokamak reactors to be considered here, we shall first evaluate possible magnetic fields and dimensions based on a scaling and optimization study by Ohta et. al.[2] Using their notation (essentially the same given by Carruthers' et. al. Report CLM-85) and geometry, we have the following items: (Fig. 1)

1. Plasma ring. Large radius R; Small radius a;
   Aspect ratio $A = \frac{R}{a}$

2. Interface plasma wall. $r_w - a = \text{constant}$

The interface will depend on vacuum conditions and should perhaps not scale.

3. Blanket and shield thickness. $t = \text{constant}$.

t depends on primary neutron energy and should not scale.

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(1) K.H. Schmitter. Lecture Int. School of Fusion Reactor Technology, Erice, Sept. 1972

(2) M. Ohta, H. Yamato, S. Mori, JAERI-Memo 4448 (unpublished) May 1971.

4. Toroidal coils: overall winding thickness s. s should scale with fixed average mechanical stress.

5. Transformer winding: minimum coil radius b. Dimensions s and b will be checked for maximum mean current density and flux swing respectively.

The toroidal magnetic flux density on the axis is B_{to}; its critical value at the radius (b + s) is B_{tc}.

The plasma pressure at uniform density $n = n_e = n_i$ and uniform temperature $T = T_e = T_i$ is relative to the toroidal and poloidal fields

$$\beta_t = \frac{4\mu_o nkT}{B_{to}^2} \qquad \beta_p = \frac{4\mu_o nkT}{B_p^2}$$

According to Shafranov $\beta_p = \xi A$

where $0 \leq \xi \leq 1$

If $\xi < 1$, that would considerably reduce the prospects for a tokamak reactor, as we shall see. Due to the Kruskal-Shafranov rule, we have $q = \frac{B_{to}}{B_p} \cdot \frac{1}{A}$

where $q \geq 1$

Our first aim is to evaluate possible reactor performance data. The thermonuclear specific power is

$$p_{th} = \frac{n^2}{4} <\sigma v> Q_{th}$$

where $<\sigma v> = f(T)$ is taken e.g. from (9)

Q_{th} = 17.6 MeV for D-T (22.4 MeV including Li reactions)

Using $$\beta_p = 4\mu_o nkT \frac{q^2 A^2}{B_{to}^2}$$

we have $$n = \frac{\beta_p}{2kT} \cdot \frac{B_{to}^2}{2\mu_o} \cdot \frac{1}{q^2 A^2}$$

and $$p_{th} = \frac{1}{4}\left(\frac{\beta_p}{2q^2}\right)^2 \left(\frac{B_{to}^2}{2\mu_o}\right)^2 \frac{<\sigma v>}{(kT)^2} Q_{th} \cdot \frac{1}{A^4}$$

The total thermonuclear power is determined by the plasma volume.

$$P_{th} = p_{th} \cdot 2\pi^2 A a^3$$

Together with the Shafranov condition we have

$$P_{th} = \frac{\xi^2 B_{to}^4 \pi^2 a^3}{32\mu_0^2 q^4 A} \cdot \frac{\langle\sigma v\rangle}{(\kappa T)^2} \cdot Q_{th}$$

This can be written

$$P_{th} = \left(\frac{\xi^2 \pi^2}{32\mu_0^2 q^4} \cdot \frac{\langle\sigma v\rangle}{(\kappa T)^2} Q_{th}\right) \cdot \left(\frac{B_{to}^4 \cdot a^3}{A}\right)$$

the first term depending on temperature and confinement achieved in the plasma, the second term restricted by the following conditions:

The critical flux density B_{tc} at the inner coil circumference is

$$B_{tc} = B_{to} \frac{R}{R-(a+c)} \quad \text{where } R = a+b+c+s \quad \text{(Fig. 1)}$$

The average mechanical stress in the toroidal magnet coils is approximately

$$\sigma_s = \frac{B_{to}^2}{2\mu_0} \cdot \frac{a+c}{s}$$

Since B_{to} will vary according to dimensional relationships and because of its 4th power influence we shall eliminate the toroidal flux density as follows:

B_{tc}-restriction:

$$B_{t_o}^4 = 4\mu_0^2 \sigma_s^2 \cdot \frac{B_{tc}^4}{4\mu_0^2 \sigma_s^2} \cdot \left(1 - \frac{a+c}{Aa}\right)^4$$

σ_c-restriction:

$$B_{t_o}^4 = 4\mu_0^2 \sigma_s^2 \cdot \left(\frac{Aa}{a+c} - 1 - \frac{b}{a+c}\right)^2$$

Now we leave the calculation of Ohta et. al.[2] and write:

$$P_{th} = \frac{\xi^2 \pi^2}{32\mu_0^2 q^4} \cdot \frac{\langle\sigma v\rangle}{(\kappa T)^2} Q_{th} \cdot 4\mu_0^2 \sigma_s^2 \cdot G$$

where G can have 2 values, the lower of which will be permitted:

$$G_B = \left(\frac{B_{tc}^2}{2\mu_0 \sigma_s}\right)^2 \frac{a^3}{A} \left(1 - \frac{a+c}{Aa}\right)^4$$

$$G_\sigma = \frac{a^3}{A} \left(\frac{Aa-b}{a+c} - 1\right)^2$$

In order to be able to draw the G-function vs a with A as a parameter, we derive the flux swing condition for the flux core radius b assuming that we need a time dependent magnetic flux for building up and maintaining the plasma current. Using the total flux density variation ΔB for producing the plasma current, and choosing a factor of $\eta \geq 1$, taking into account additional flux variation for maintaining the current, we have

$$\Delta B \pi b^2 = \eta \mu_o R \left(\ln A + \frac{1}{4} \right) \frac{B_p}{\mu_o} 2\pi a$$

In the inductance calculation we assume as usual that the leakage field contribution of the primary transformer winding is made very small by proper spatial distribution. This is required for minimization of leakage field disturbance in the plasma region: The plasma should see only its own poloidal field.
The mean value of ($\ln A + \frac{1}{4}$) for a range of possible interest $3.5 < A < 6$ is about 1.8. Thus we take

$$\Delta B \cdot b^2 \approx 3{,}6 \eta a^2 \frac{B_{to}}{q} \quad \text{or} \quad b = a \sqrt{3{,}6 \eta \frac{B_{to}}{q \Delta B}}$$

As a mean value we choose b = 2.5 x a, in order to be sure that ΔB will not exceed any technically reasonable value while the flux swing condition is fulfilled.

With

$$z = \sqrt{3{,}6 \eta \frac{B_{to}}{q \Delta B}}$$

we have

$$G_\sigma = \frac{a^3}{A} \left(\frac{Aa}{a+c} \cdot \frac{A-z}{A} - 1 \right)^2$$

It is convenient to plot

$$G_B \cdot \frac{A}{a^3} \quad \text{and} \quad G_\sigma \cdot \frac{A}{a^3} \quad \text{vs } a \qquad \text{(Fig. 2)}.$$

The curves incorporate the following fixed values:

$c = 200$ cm; $B_{tc} = 141$ kG; $\sigma_s = 9810$ Ncm^{-2}; $z = 2.5$

We get pairs of intersecting curves; the intersecting points define designs which fulfill both the B_{tc} and σ_s conditions. Going to larger a-values along the G_B curve reduces the average mechanical stress in the windings; smaller a-values along the G_σ curve reduce the maximum flux density. Both ΔB and the average current density $\bar{j}$ in the toroidal coil windings will have to be checked along with other specific data such as the apparent wall power loading p_W. The intersecting points of the $G \cdot A/a^3$ curves will be used for the evaluation of a series of possible reactor designs with a given function a = f(A). Using the equation for the thermonuclear power density

$$p_{th} = \frac{\xi^2 \pi^2}{32 \mu_o^2 q^4} \cdot \frac{\langle \sigma v \rangle}{(kT)^2} Q_{th} \cdot 4 \mu_o \sigma_s^2 \frac{1}{2\pi^2 A^2} \cdot G \frac{A}{a^3}$$

we see that the functions plotted in Fig. 2, together with q and ξ, fix the value of that power density. We take $\xi = 1$ and q between 2 and 2.5.
The apparent wall power flux is

$$p_W = p_{th} \cdot \frac{a^2}{2(a+c-t)} \cdot \frac{22,4}{17,6}$$

This power flux is the important quantity which determines the neutron and heat loads on the vacuum wall. The values for p_W will serve as a further means of checking the practical relevance of our calculation. Using the already known equation for the determination of the flux density swing ΔB, the plasma density, and the equation for the average current density in the B_t coil windings

$$\bar{j} = \frac{B_{to}}{\mu_o s}$$

we get the curves in Fig. 3,4,5. It turns out that conditions used and values fixed lead to a relatively satisfactory scaling in the sense that the essential specific values j, B_{to}, and ΔB, remain nearly constant vs A, though the total thermonuclear power range is more than an order of magnitude. The plasma density also stays within quite a usual region. The apparent wall power flux for a 5 GW(th) reactor is between 5.5 and 8 MW/m^2 which is again a value which may be possible. p_W scales here with the reactor size in a way that should be required for the gradual solution of the wall damage problem. It should be mentioned that we have assumed rectangular profiles of the density and temperature in the plasma column. The corresponding results for a bell-shaped distribution could, of course, be slightly different. The absolute values of $\bar{j}$ and ΔB suggest that b/a could possibly be lowered from 2.5 to 2, and that the average mechanical stress in the winding could be increased to about 15,000 Ncm^{-2}. With regard to ΔB it seems that an iron core could, in principle, be used if the constant dimensions $r_W - a$ = 50 cm (interface plasma-vacuum wall), t = 150 cm (blanket and shield thickness) must be kept and the low values mentioned of the apparent wall power flux remain valid, because then there is no need to go to higher ΔB.
The magnetic energy of the toroidal field (neglecting the energy in the winding volume) is

$$W_{Mt} = 2\pi^2 A a (a+c)^2 \frac{B_{to}^2}{2\mu_o}$$

It amounts to ~ 3o ÷ loo GJ.
The required plasma current is

$$J = \frac{B_{to}}{\mu_o q A} \cdot 2\pi a$$

which ranges between ~3 and lo MA,

and the magnetic energy associated with the plasma ring is

$$W_{MJ} = \frac{1}{2} L J^2 \quad (0{,}1 \div 1\ GJ)$$

where we apply the approximation formula

$$L = \mu_0 A a \left(\ln A + \frac{1}{4} \right)$$

already used for the rough evaluation of ΔB.
(It turns out that recalculation of ΔB using the L-formula yields the plotted values within about 5%). (Fig.5)
For comparison we plot also the plasma energy

$$W_p = 3nkT \cdot 2\pi^2 A a^3 \quad (0{,}2 \div 2\ GJ)$$

We find (Fig. 5) that the magnetic energy of the toroidal and poloidal fields differ by about 2 orders of magnitude. The variation of their scaling shows the geometrical effect of the constant blanket thickness at lower plasma radii.

One should not forget the restrictions caused by stationary vertical fields in a tokamak without a stabilizing shell. The considerable flux density required can be calculated according to Artsimovich(3)

$$B_V = \frac{J}{(A)} \cdot \frac{(cm)}{10 A a} \left(\ln A + \xi A + 0{,}83 \right) (G)$$

With $\xi = 1$ B_V turns out to be between 6.48 kG and 2.12 kG. Provided the vertical field winding cannot be placed inside the toroidal field coils with enough spacing for flux return, there will be considerable forces on the toroidal field coils and their structure additional to the forces generated by the toroidal field itself.
The torque, occurring between an externally generated vertical field and the N toroidal field coils, which tends to turn every individual coil toward the midplain of the torus can be roughly calculated by

$$M = \frac{\pi}{N} (a+c)^2 B_V \cdot 2\pi A a \frac{B_{to}}{\mu_0}$$

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(3) L.A. Artsimovich. Nucl. Fus. 12/1972, p. 218.

Assuming, for instance, that due to field ripple considerations, 32 individual toroidal field coils are required, the torque/coil will be

$$\frac{\pi^2}{16} A a (a+c)^2 \frac{B_v B_{to}}{\mu_0}$$

Using our data this amounts to

$$531\ \mathrm{MNm} \div 46\ \mathrm{MNm} \text{ per coil.}$$

We shall now look into the time scaling involved in our reactor series. Assuming Spitzer resistivity and a uniform current distribution in the plasma, the possible on-time per pulse can be estimated by calculating the time constant of the plasma ring.(4) Fig. 6 shows the plasma ring time constant for different temperatures. Especially when using an iron transformer core, as was already suggested by the ΔB values, it is very likely that pulse lengths of about 1000 sec can be achieved. As ΔB should be kept close to the value required for building up the current, the pulse length should not exceed some % of the plasma ring time constant. As can be seen from the curves for the plasma Joule losses at 1 keV (Fig. 6), at which temperature we have almost metallic conductivity, a normalconducting primary transformer winding, operating at the same current density as the plasma, is possible. It is questionable, however, that a normalconducting winding consuming up to about 1 % of the electrical reactor output at the 1 GW level could compete economically with a superconducting primary winding. Taking the plasma ring time constant at 100 eV as relevant for building up the current, (assuming that this initial temperature can be provided by a pre-discharge using e.g. capacitive storage), the primary winding would have to handle the flux density swing of 20-30 kG within about 1-5 sec. The apparent power

$$\frac{2W_{MJ}}{\tau_p}$$ at 100 eV is shown in Fig. 6 and amounts to about 6-20 % of the electrical reactor output (compare Fig. 3 thermo-dynamic cycle efficiency of 4o-5o%). This is a power level already considered as continuous rating for future AC generators with water-cooled rotors or, in the more distant future, for generators without any iron in the magnet flux path but with superconducting windings.(5) Fig. 7 shows the range of power ratings now being considered.(6)

(4) P. Hubert, Proc. Nucl. Fus. Reactor Conf. Culham 1969, p.23o

(5) Technische Rundschau 52/Dec. 1O, 1971, p. 27.

(6) B.E. Mulhall. Phys. Bull. Dec. 1971, p. 721.

One can derive from Fig. 7 that the energy storage in the rotor of such machines amounts to 1-50 GJ, which would be enough for current build-up in a tokamak reactor.

With regard to plasma heating, Mills [7] has made a calculation of ohmic heating by plasma current, assuming that the time for building up the current is very short compared to the heating time at a constant current. Assuming only bremsstrahlung as energy loss

$$p_b = 5{,}33 \cdot 10^{-31} \frac{n^2}{(cm^{-6})} \sqrt{\frac{kT}{(keV)}} \left(\frac{W}{cm^3} \right)$$

and Spitzer resistivity for the column, one gets the equation

$$\frac{J^2 R_p}{2\pi^2 A a^3} - p_b = 3n \frac{d(kT)}{dt}$$

with $R_p = \varrho_p \frac{A}{a}$ and $\varrho_p = 2{,}6 \cdot 10^{-6} \left(\frac{kT}{keV} \right)^{-\frac{3}{2}} (\Omega cm)$

which can be solved explicitly. It can be shown that the final temperature is reached only after very long heating periods. Therefore, according to Mills' calculation, we use ohmic heating only up to 1/2 of the final possible temperature:

$$kT_\Omega = 2.21 \cdot 10^{12} \frac{J}{(A)} \cdot \frac{(cm^2)(cm^{-3})}{\pi a^2 \; n} \; (keV)$$

The time needed to reach this temperature is

$$\tau_\Omega = 0.713 \cdot 10^{15} \frac{(cm^{-3})}{n} \sqrt[4]{\frac{kT_\Omega}{(keV)}} \; (s)$$

From Fig. 8 we can see that within times of 2-10 sec, temperatures in the range of about 1 kV can be reached by ohmic heating, provided the plasma diffusion is low enough.

Plasma diffusion has been included in the work of Canobbio [8], who considers magnetic pumping as an auxiliary heating method to ohmic heating. The minimum temperature needed to start magnetic pumping is

$$kT_{0\,TTMP} \geq \sqrt{1{,}78 \cdot 10^{-14} \, q \frac{a}{(cm)} A^{\frac{5}{2}} \frac{n}{(cm^{-3})} \ln \Lambda} \; (eV)$$

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(7) R.G. Mills. Lecture Notes, June 1, 1970.

(8) E. Canobbio, S. Guiffre. Report EUR-CEA-FC-601, Dec. 1971

with $\ln \Lambda \approx 16.$

We find the curves in Fig. 8 which intersect the kT_Ω curves. From the intersection points together with the relative scaling of kT_Ω and τ_Ω, one would conclude that, over the whole range, an ohmic heating time of about 5 sec would suffice to reach the temperature necessary for take-over by magnetic pumping.
Usually the power requirement for start-up is evaluated by using the following equation

$$p_h = \frac{3nkT}{\tau} + p_b - \frac{n^2}{4}\langle\sigma v\rangle Q_\alpha \quad (Q_\alpha = 3{,}52\ \mathrm{MeV})$$

Taking a revised Bohm diffusion time for τ we get an upper limit of specific heating power p_h from the maximum of the curves $p_h = f(kT)$. With the diffusion coefficient

$$D_{Bohm} = \frac{kT}{16eB} = \frac{10^8}{16}\frac{kT}{(keV)}\cdot\frac{(kG)}{B}\left(\frac{cm^2}{s}\right)$$

the Bohm diffusion time over the plasma radius a is

$$\tau_{Bohm} = \frac{a^2}{D_{Bohm}}$$

We have therefore,

$$p_h = \frac{3nkT}{\alpha\tau_{Bohm}} + p_b - \frac{n^2}{4}\langle\sigma v\rangle Q_\alpha$$

α is a factor usually taken for the quotient of confinement time and Bohm diffusion time. Assuming that the same ratio of confinement time to Bohm time holds during the heating process as it is calculated for the operating temperature according to the alpha particle heating condition with

$$\alpha = \frac{2.11\cdot 10^{22}}{\frac{n}{(cm^{-3})}\,\frac{a^2}{(cm^2)}\,\frac{B}{(kG)}} \quad \text{for } kT = 20\ \mathrm{keV}$$

we have

$$p_h = \frac{n^2}{(cm^{-6})}\cdot 10^{-31}\left\{1.42\left(\frac{kT}{keV}\right)^2 + 5.33\sqrt{\frac{kT}{keV}} - 0.4\frac{\langle\sigma v\rangle}{(cm^3 s^{-1})}\frac{Q_\alpha}{(keV)}\cdot 10^{-16}\right\}\left(\frac{W}{cm^3}\right)$$

The functions of $p_n(kT)$ are similar for all values of n. It can be shown that they have a maximum at about 5.7 keV and that, with this scaling, ignition would occur at about 10 keV. In order to evaluate the power requirements for heating up to ignition, we take the specific heating power at the maximum of p_h and assume that the heating methods would also suffice for the heating requirements below and above 5.7 keV where the heating power decreases. $p_{h_{max}}$ and also the total heating power P_h are plotted in Fig. 9. With our scaling, the required maximum heating power is a nearly constant fraction of the thermonuclear power of about 0.7 ‰. over the whole range.

Coming back to magnetic pumping, we can now evaluate t the necessary field modulation assuming a temperature of 5.7 keV and a constant density. With 4 coil periods along the circumference of the torus, we get the relative modulation of the toroidal field

$$\frac{\Delta B_t}{B_{to}} = 0.97 \sqrt{\frac{P_{h\,max}}{2.7\,nkT} \cdot Aa \sqrt{\frac{m_i}{2kT}}}$$

The magnetic pumping frequency is

$$\omega_{TTMP} = \frac{4}{Aa}\sqrt{\frac{2kT}{m_i}}$$

where the relative ion mass is taken to be 2.5. Fig. 9 shows the range for both quantities. The pumping frequency varies between 40-70 kHz, and the relative flux density amplitude lies between 1-2 ‰. As Cato et. al.[9] have pointed out, the problems of TTMP heating coil structures are mainly cooling problems because of Joule losses and nuclear heating, and insulation difficulties.

Each single-turn coil consisting of an array of parallel rings would have to carry a total current of about

$$J_c \approx \frac{\Delta B_t \pi a'^2}{L_c}$$

where a' = a + 25 cm.

For the evaluation of power and losses, we assume that the length of each of the 8 coils is equal to their actual distance, and that the radial distances from the plasma and the vacuum wall are 25 cm respectively. Furthermore, we assume image currents in the vacuum wall, having the same (uniform) spatial distribution as the coil currents and all current carrying surfaces to consist of niobium at 1300 K. Thus

$$L_c \approx \mu_o \frac{2\pi r_w (r_w - a)\cdot 16}{2\pi R}$$

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[9] Cato et. al. Nucl. Fus. 12/1972, p. 345.

The ohmic resistance is

$$R_c = 32 \varrho \frac{a'}{\delta R}$$

where

$$\delta = \sqrt{\frac{2\varrho}{\mu_0 \omega_{TTMP}}}$$

The coil voltage is about

$$U_c \approx \omega_{TTMP} L_c J_c$$

Fig. lo shows the current/coil, the coil voltage, and the total Joule loss power for TTMP heating which turns out to be about 3-5 % of the thermonuclear power. These extremely high loss values stress the necessity of subdividing the vacuum wall, in which case a reduction by about an order of magnitude appears possible.

RF heating methods working at higher frequency may scale up to the voltage and the joule loss, and increase the insulation difficulty and the thermal problem, the latter by adding the possibility of surface melting at the coils.

Neutral injection is another interesting heating possibility currently being studied. Theoretical considerations exist for the case of accelerating D^+ and injecting the neutrals produced into a deuterium plasma (lo). We shall apply these results to our reactor series. Fig. 11 shows the neutral beam energy for an effective plasma thickness of $\frac{na}{2}$ and the total injection current according to the heating power $P_{h_{max}}$ (Fig. 9). Depending on the total injection efficiency, the power required for injection heating will range from lo MW for a 1 GW(th) reactor (q = 2) to 1 GW for a 2o GW(th) reactor.

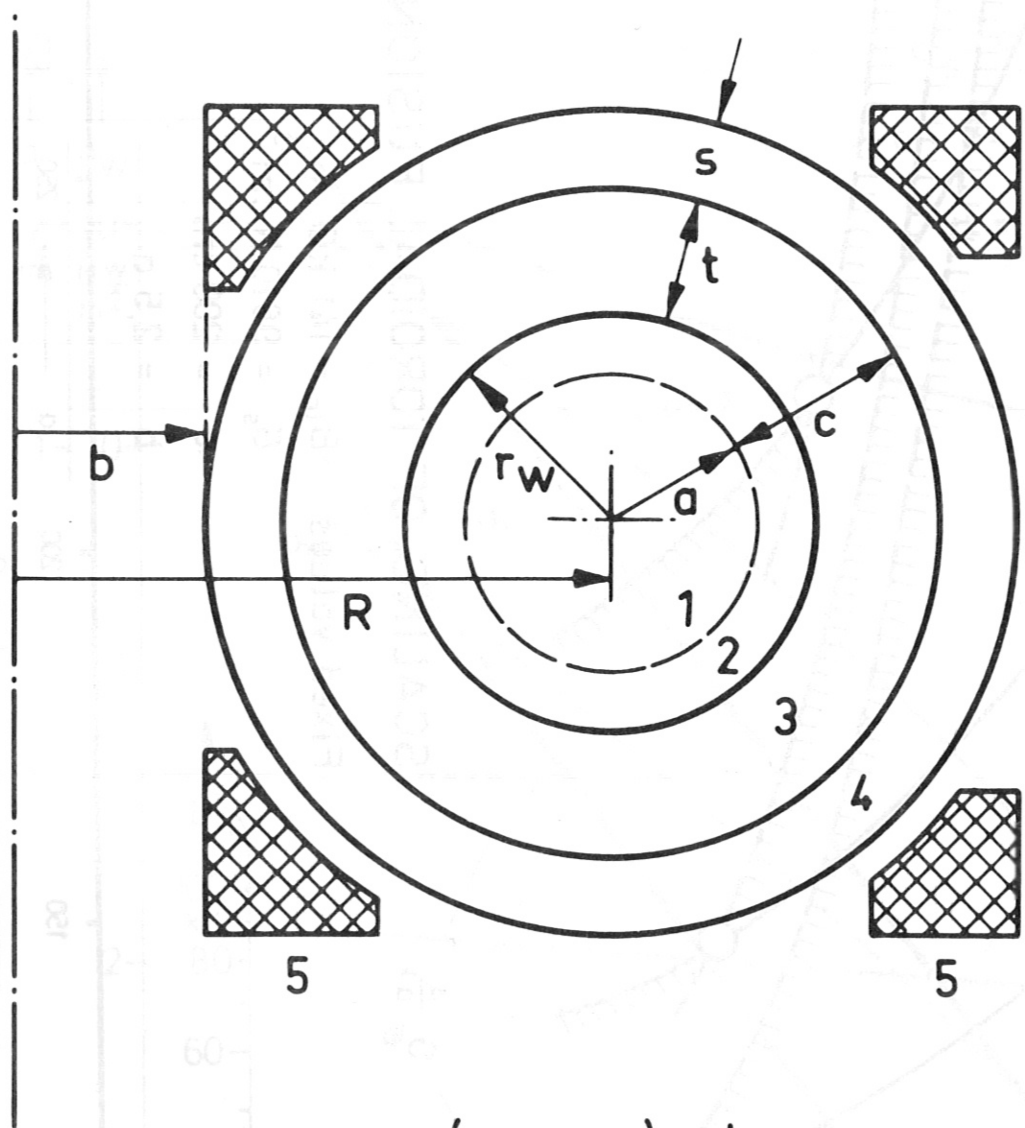
Concerning the heating times required, either for TTMP or injection heating, it is very likely that both will operate only for a few seconds/pulse, or even less thus enabling the design of part of the electrotechnical components to perform low-pulse duty.

These short and very rough remarks on scaling and some electrotechnical parameters seem to suggest that besides of the possibly economic 5 GW(th) reactors units also a ~1 GW prototype with its strongly reduced requirements should be considered. It would be important to intensify these studies also with respect to intermediate steps and to improve them with respect to accuracy and adaptation to an increasing knowledge of plasma behaviour.

(lo) Sweetman et. al. Report CLM-R112-1971.

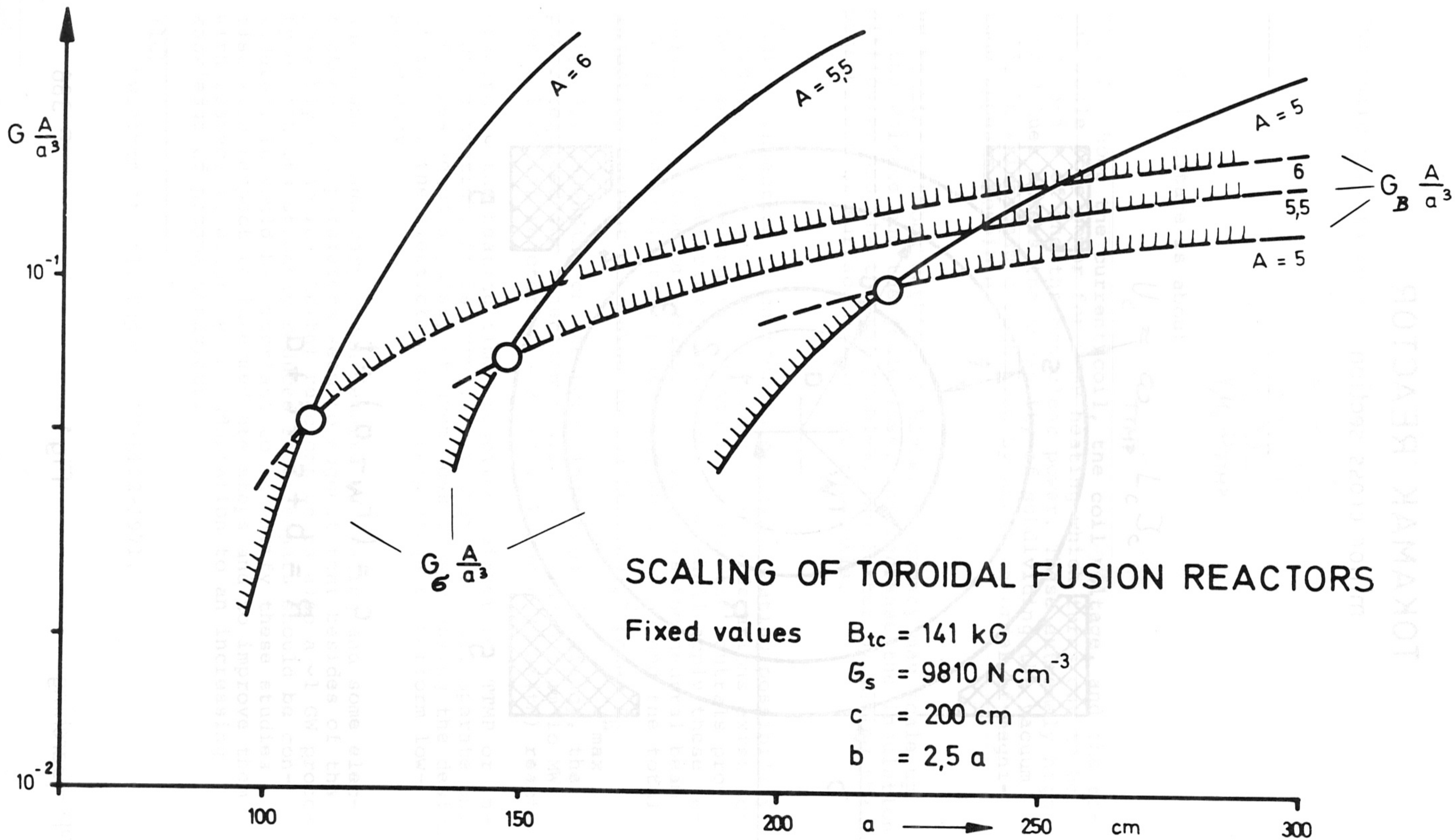
TOKAMAK REACTOR

minor cross section



$$c = (r_W - a) + t$$

$$R = b + s + c + a$$



IPP – Garching

Fig. 2

P 387

DT FUSION REACTOR DATA (1)

Tokamak

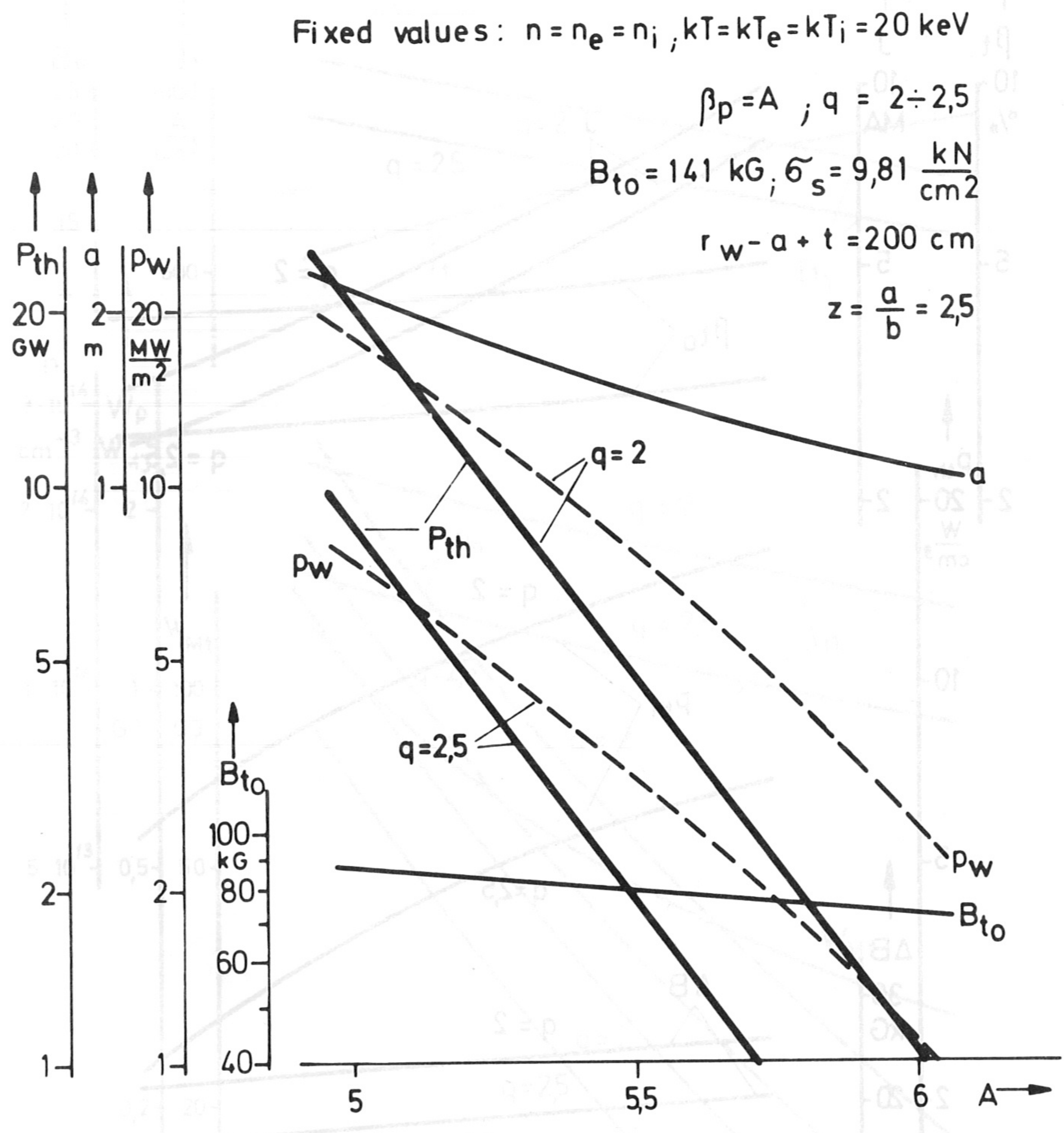


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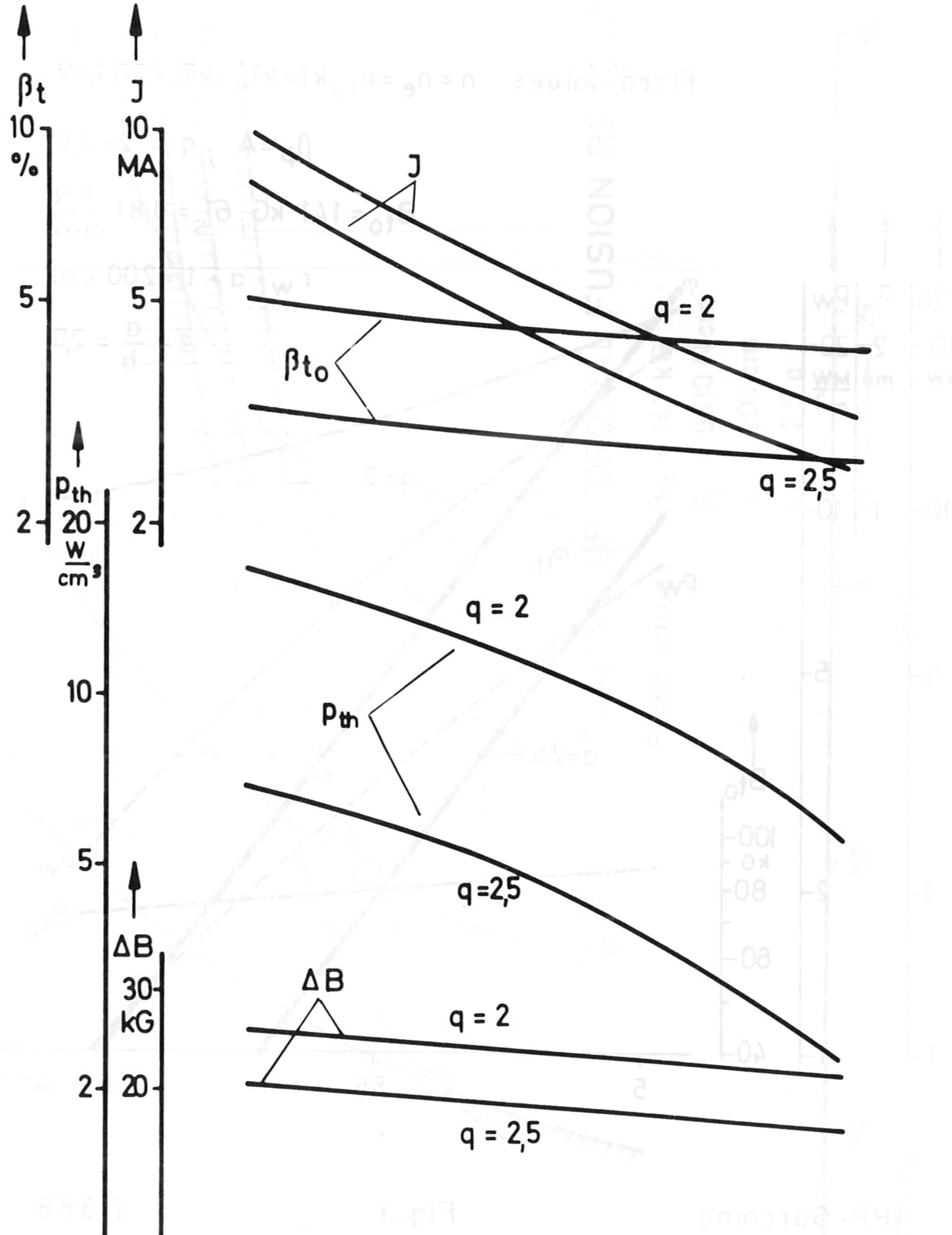
Fig. 3

P 388

DT FUSION REACTOR DATA (2)

Tokamak



DT FUSION REACTOR DATA (3)

Tokamak

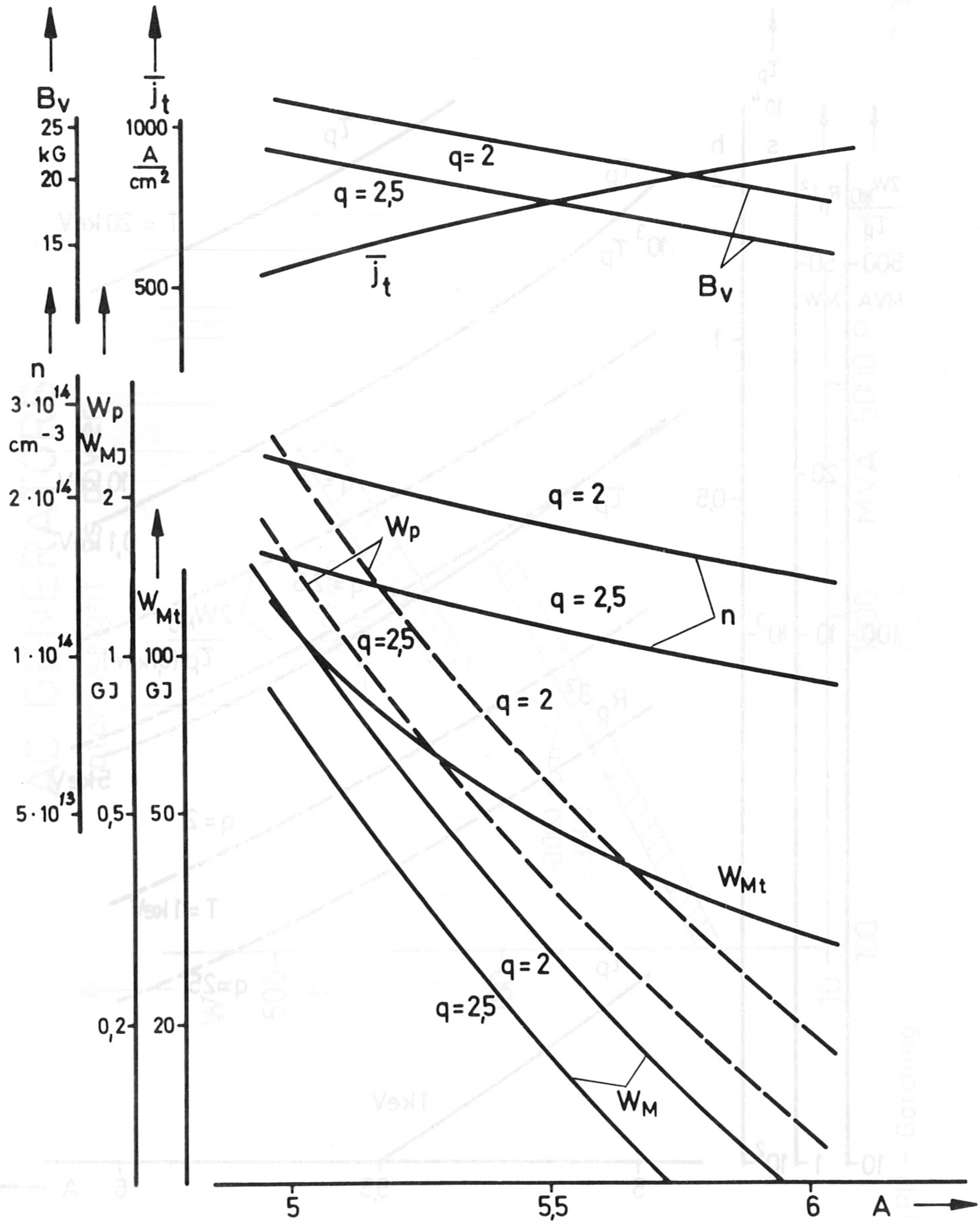


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Fig. 5

DT FUSION REACTOR DATA (4)

Tokamak

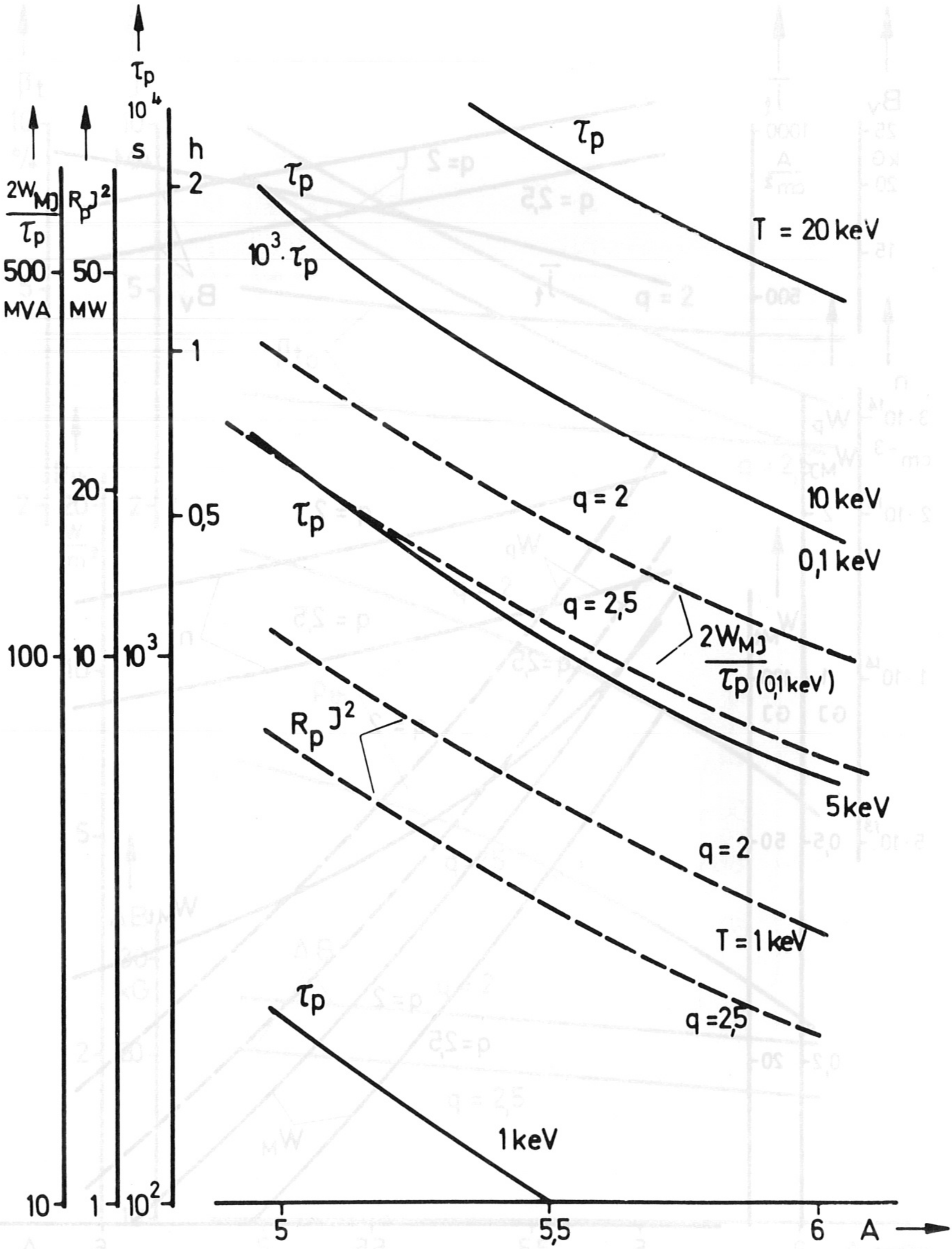


Fig. 6

AC GENERATORS

rotor weight vs power

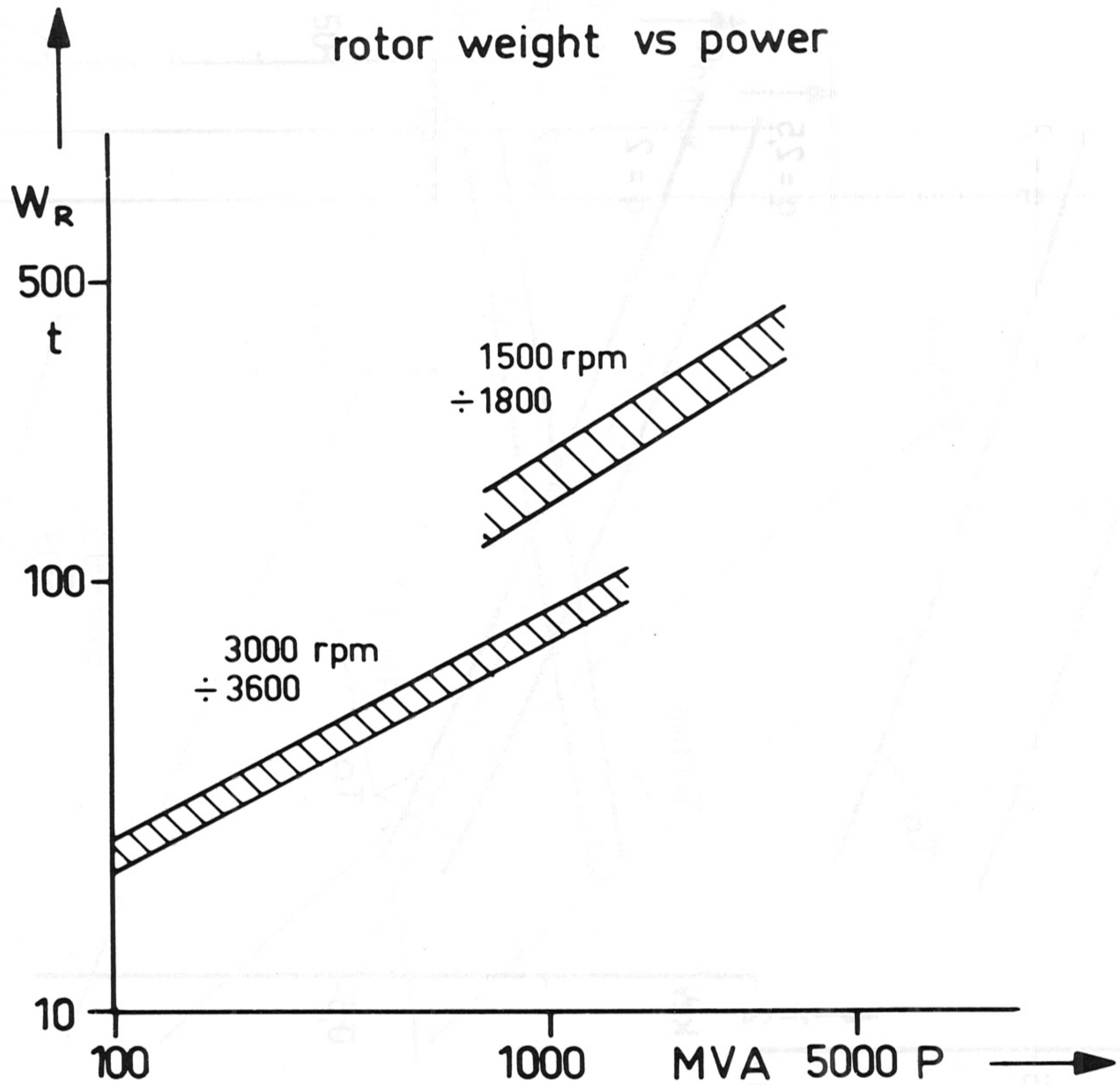
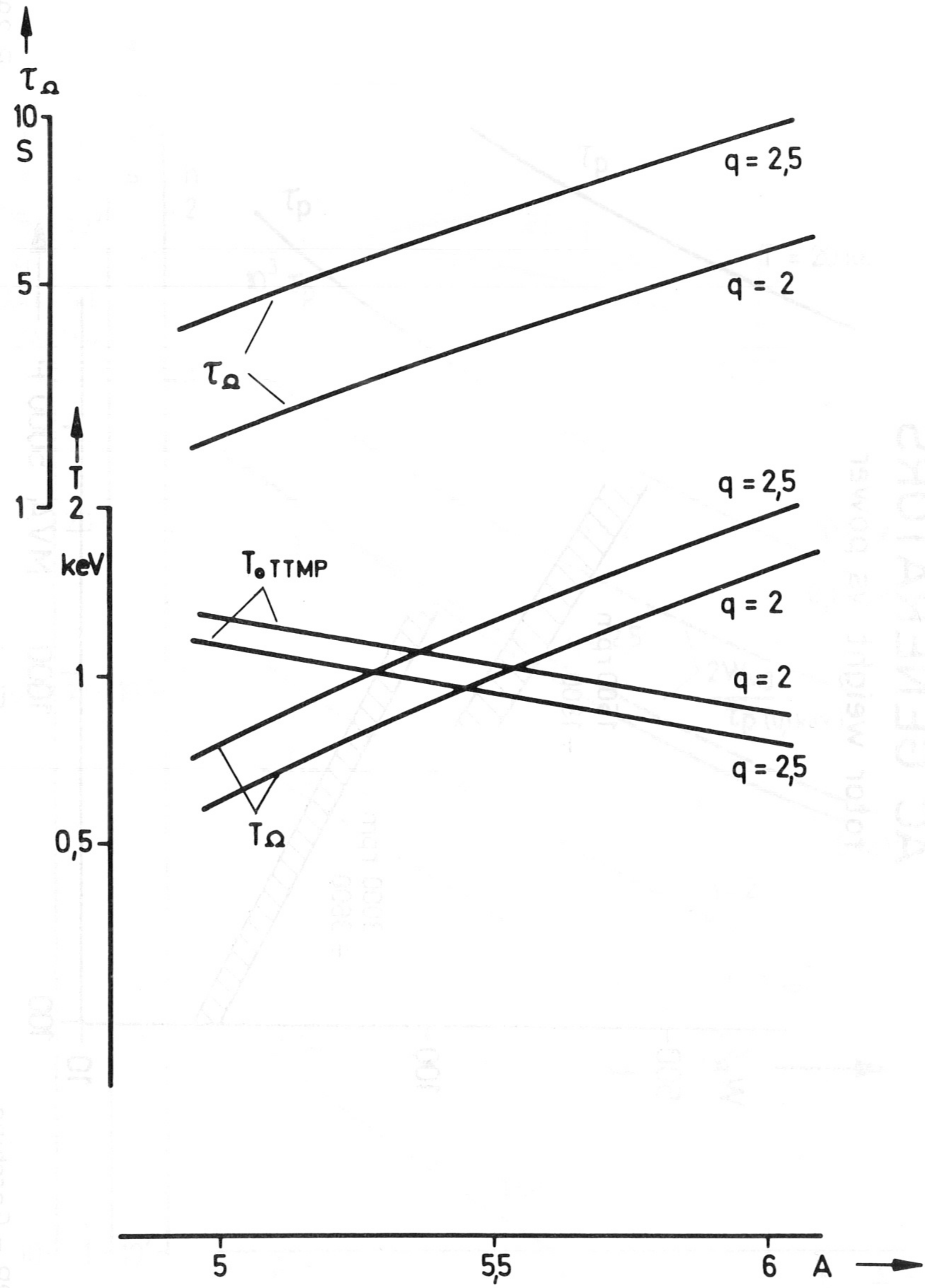


Fig. 7

DT FUSION REACTOR DATA (5)

Tokamak



DT FUSION REACTOR DATA (6)

Tokamak

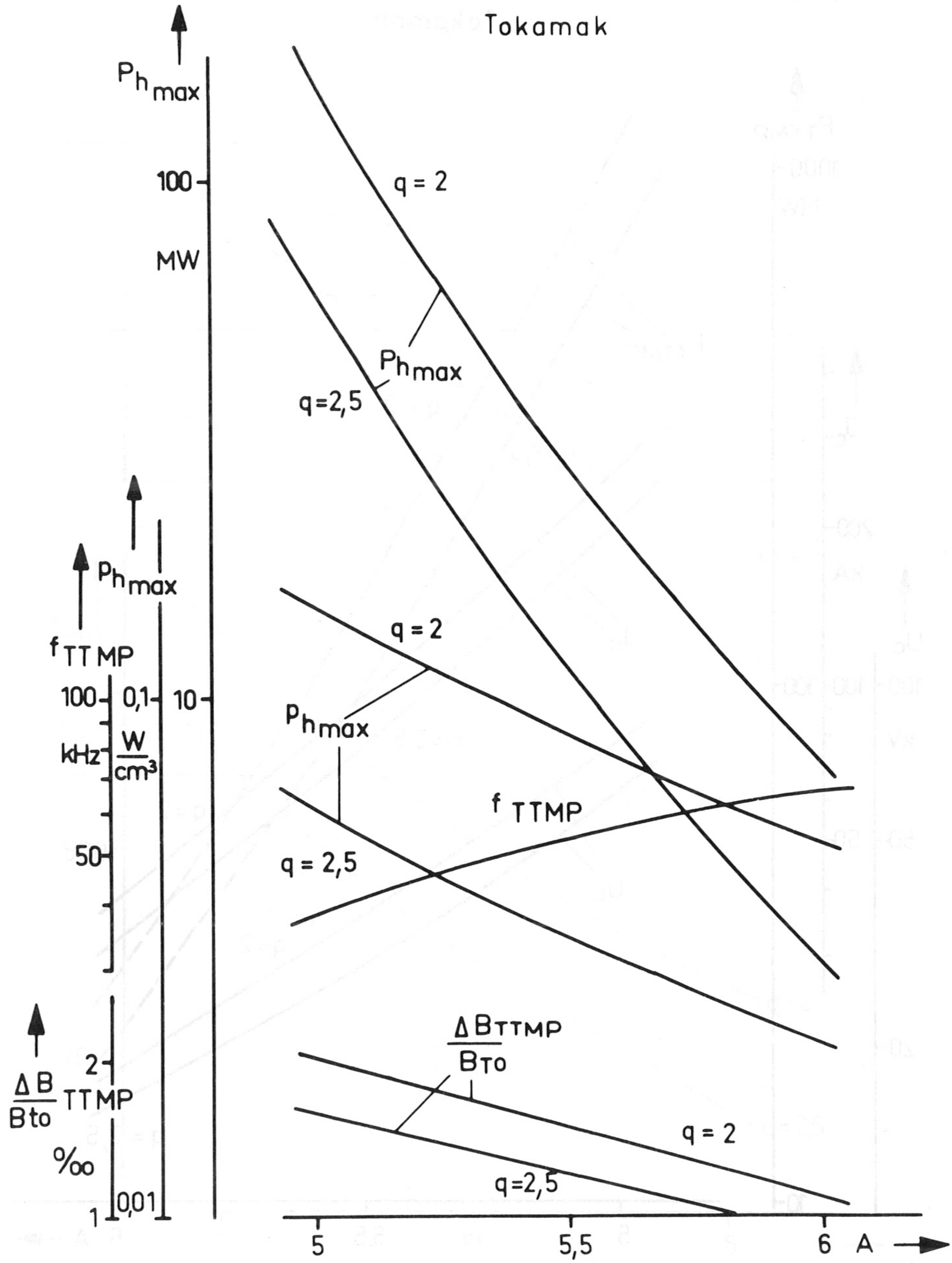
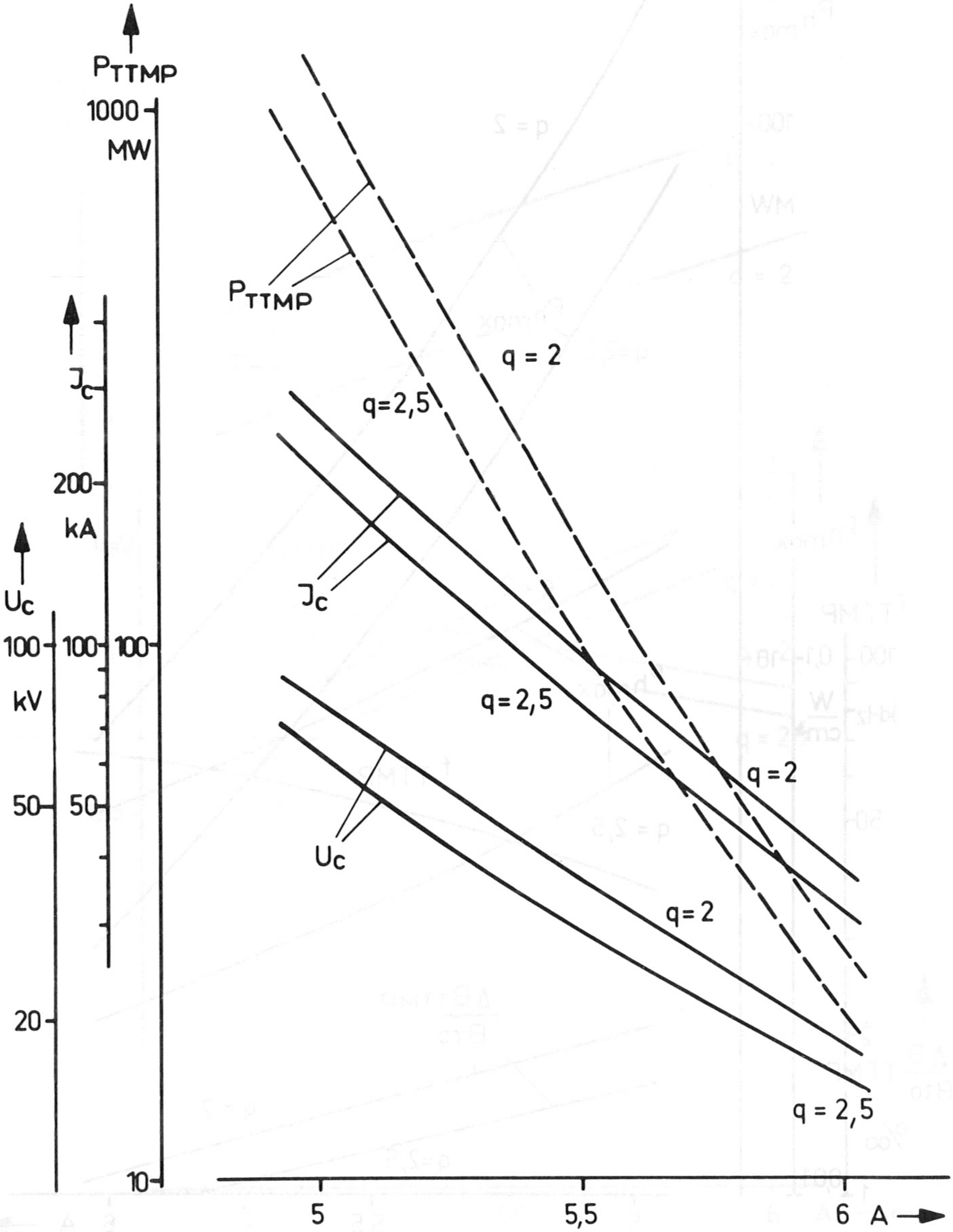


Fig. 9

DT FUSION REACTOR DATA (7)

Tokamak



DT FUSION REACTOR DATA (8)

Tokamak

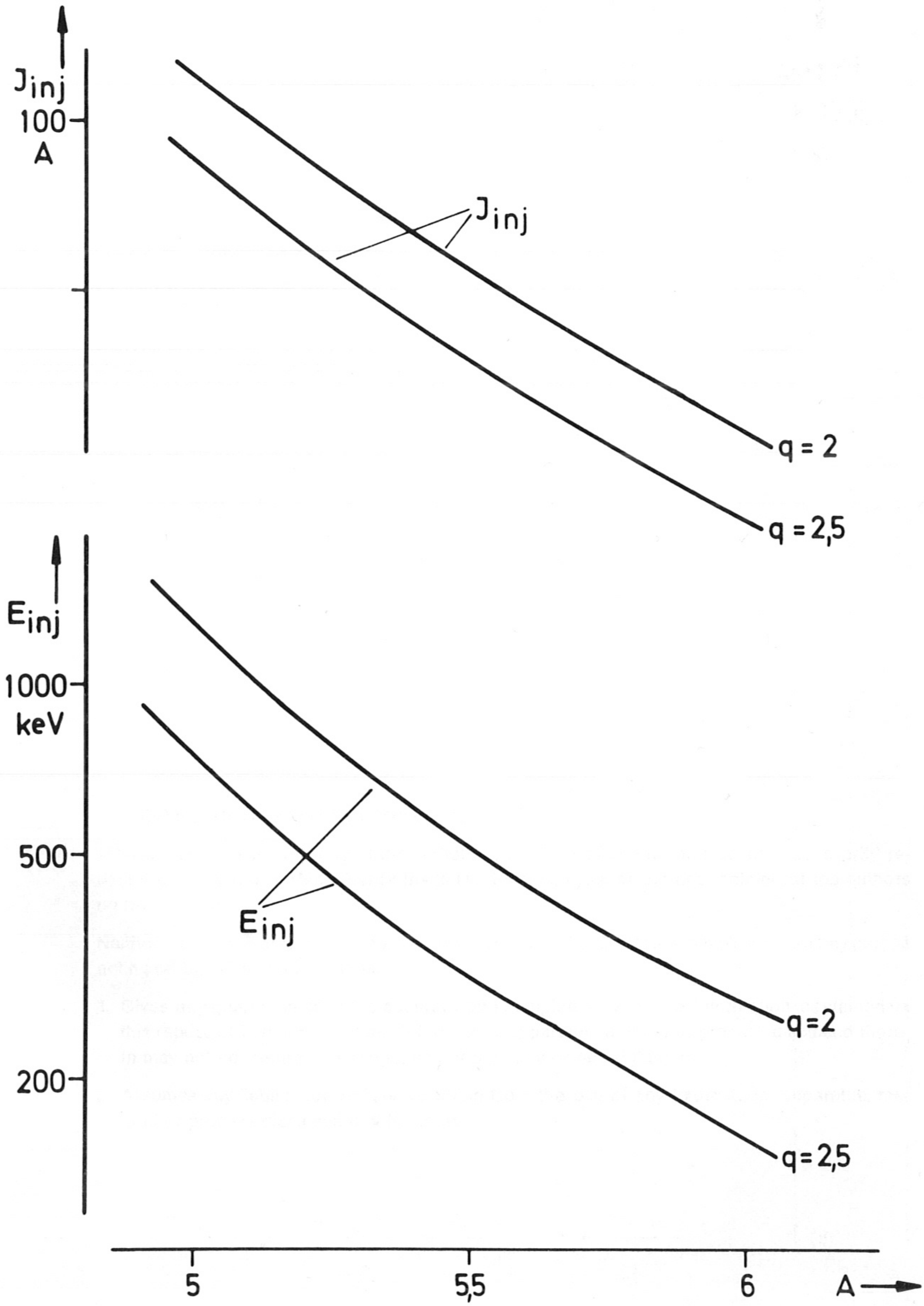


Fig. 11