Preliminary Considerations on
Ion Cyclotron Heating in ZEPHYR

J. Neuhauser

IPP 1/200 April 1982

Reprint of ZEPHYR-Report No. 22 of Oktober 1980.

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Summary

Ion cyclotron resonance heating (ICRH) in a ZEPHYR-type ignition experiment is briefly discussed on the basis of current theoretical and experimental knowledge.

The fast wave minority heating scheme is chosen for reference because of optimistic experimental results and because of its favourable scaling to ZEPHYR parameters. Second harmonic heating may become a serious contender, while the fast wave mode conversion regime seems to be of little interest for ZEPHYR. Slow wave heating via mode conversion to ion Berstein waves, proposed recently by Puri has not yet reached a status where it could be considered as a candidate on the ZEPHYR design time scale.

Preliminary studies for a fast wave ICRH system with poloidal loop coupling have shown its principal feasibility, the main problem being the appropriate antenna modul design. Wave guide coupling seems to be impossible in view of the small dimensions of ZEPHYR except for special scenarios, e.g. higher harmonic heating of a hydrogen minority or slow wave mode conversion which are not tested experimentally.

For the alternative HF-ZEPHYR (or the compressed standard ZEPHYR plasma, i.e. no major radius compression) a frequency range of 60 to 100 MHz is required for reasonable flexibility (e.g. helium-3 or deuterium minority heating or tritium second harmonic heating at full and reduced magnetic field strength). An extension to higher frequencies ($\lesssim$ 150 MHz) would allow for hydrogen minority and deuterium second harmonic heating.

Antenna moduls should be developed which fit into ZEPHYR ports without unfolding of loops in order to facilitate remote handling and repair. A periodic toroidal arrangement of 10 such antenna moduls in a 20 coil ZEPHYR may be sufficient, provided the power density can be increased by a factor of about two above present experiment values (the power per modul would be around 2 MW).

1D plasma simulations for ZEPHYR assuming a ICRH type heat deposition profile and currently discussed transport models show that a heating power of 10 to 15 MW deposited

in the plasma with a pulse length of about 1 second could heat it to ignition even if impurity sputtering is included. A pulse length of the order of the flat top time of the magnetic field is desired, however, in order to allow for high-Q driven operation or for "heating-down" the plasma without disruption.

Major radius compression is not required in connection with ICRH. If applied because of other reasons the main effect would be a decrease of the required frequency in proportion to the decreased magnetic field and, as a disadvantage, the loss of the α - particle contribution during heating. One should notice also that the antenna-plasma distance is critical for coupling and a plasma motion of several centimeters or more has to be avoided during heating.

In view of the reliability of the heating system required for ZEPHYR the present experimental status of ICRH does not yet justify a decision for ICRH as the only heating system. The antenna problem, the question of plasma boundary heating, induced transport and impurity resonances etc. requires still further investigation at an increased power level, far above the ohmic power, in order to clearly identify the effects. Such experiments are just starting and a rapid improvement of our knowledge is to be expected in the near future. A ICRH system could appreciably simplify the ZEPHYR design since no strong major radius compression is required, since the radiologic problems may be less severe and since - hopefully - the required technological effort is smaller than with neutral injection.

I. ZEPHYR references data

1. Present Design: Compression-Boosted Neutral Injection (/1/ and Fig. 2)

	before compression (after neutral injection)	after compression
Major radius R [m]	2.03	1.35
Minor radius a [m]	0.61	0.5
Magnetic field B [T]	6.1	9.1
Plasma current J [MA]	2.4	3.7
$\langle T \rangle$ [keV]	5 - 12	8 - 20
$\langle n_e \rangle$ [cm^{-3}]	2 - 1 x 10^{14}	4 - 2 x 10^{14}
τ_E [s]	250 ms	500 ms

($\langle \cdots \rangle$ = average value)

Before neutral injection, i.e. after the ohmic heating phase, the density is expected to be 1 - 2 x 10^{20} and the temperature T $\approx$ 1 keV. These are also the starting conditions for high-frequency (HF) heating in a ZEPHYR-type machine. The data given in the above table are representative of the densities and temperatures to be achieved. It should be noted that the peak temperature T is usually a factor of 2.5 higher than the average temperature $\langle T \rangle$, while the density profiles are expected to be flat or only moderately peaked in the case of gas puffing and recycling. They could be more peaked with pellet injection.

During an experimental programme of at least 5 years a large range of parameters will be covered. It is assumed that because of radiological implications operation will start with pure hydrogen (or possibly helium) and will then proceed to hydrogen/deuterium and deuterium/tritium mixtures (i.e. A_Z/Z = 1 - 2.5). The majority of the discharges will be done at reduced magnetic field strength, say 70 %. Central ion heating is desirable since the ions produce the fusion power, while the major loss channel may be through electrons even at high temperature (if the ripple is low enough). Ion heating is also a necessary condition for operation in the hot ion mode ($T_i > T_e$).

2. An Alternative Reference Data Set for ICRH Design Studies

ICRH does not need adiabatic compression in contrast to neutral injection with positive ion technology. Therefore, as a counterpart to the compressor, we defined a self-consistent data set with the following properties: no or weak compression, e.g. for burn control; ignition with circular plasma (Intor-Alcator scaling), but optionally weak ellipticity; space for cold-gas, cold-plasma, antennas etc. (partly in a high-ripple region) in the case of an ellipse or in the event that things work out better than at present assumed.

The most important data are given below together with Fig. 2. A more detailed description is given by Wilhelm in another ZEPHYR report No. 34.

$A = 3.5$

$a = 0.48$ m

$R = 1.68$ m

$b \lessapprox 0.62$ m

$\Delta_i = 0.12$ m

$\Delta_a = 0.36$ m

$\Delta_o \approx 0.24$ m

$B(R) = 9.74$ T

$W_{magn} \approx 0.9$ GJ

Number of coils $N = 20$

$R_a = 2.81$ m

$R_i = 0.79$ m

Toroidal pressure in neck : 170 MPa

Ripple at point ✱ : ± 0.75 %.

II. Status of ICRH

Several different heating scenarios are possible in the ion cyclotron range of frequencies. For a toroidal multicomponent tokamak plasma like that expected in ZEPHYR these are

a) fast wave minority heating

b) fast wave heating via linear mode conversion near the ion-ion-hybrid layer

c) fast wave second or higher harmonic heating

d) slow wave heating via linear mode conversion to ion Bernstein waves (Puri /2/)

Fast wave coupling requires $\tilde{E} \perp B_o$ (e.g. poloidal loops), while the slow wave polarization is $\tilde{E} \parallel B_o$. Slow wave coupling would be attractive in view of waveguide coupling, since narrow waveguides with the large dimension in poloidal direction could be used, fitting easily between adjacent toroidal field coil. In contrast, waveguide coupling to the fast wave requires large coil separation or the use of ridged waveguides with dielectric filling. Up to now waveguide coupling has not yet been tested experimentally and no relevant experiments are planned for the near future. Reasonable experience exists for loop coupling only.

The schemes a) and b) were successfully tested in PLT, TFR and other tokamaks up to about half a MW (e.g. /3,4/). Recently, second harmonic heating experiments on PLT at moderate power (~140 kW) have shown a bulk heating rate comparable to minority heating /3/. Because of the strong damping, explained by the presence of ion Bernstein waves, mode tracking does not seem to be necessary in contrast to earlier theoretical extimations. Slow wave heating via mode conversion to ion Bernstein waves at the plasma edge has not been tried up to now (only the mode conversion process was tested in a very small experiment /5/).

Meanwhile the source power is being increased into the MW range, e.g. 5 MW in PLT (~50 MHz) and 3 MW in TFR (50 ... 90 MHz).This power level is not far below that needed in ZEPHYR and the frequencies are not too different either. It is, however, still an open question whether this power can be transmitted to the plasma with high enough efficiency and without excessive boundary heating, but this may be answered in the near future. It is felt that a decision in favour of ICRH heating in ZEPHYR cannot be made until central plasma heating in the several MW range has been proved experimentally. This is true at least where ICRH is the primary heating system. If ICRH is only envisaged as a back-up to neutral injection, then the requirements may be less stringent and, furthermore, the decision on that system can be made later, when also more experimental knowledge is available.

Thus, in view of the planned ZEPHYR time schedule, a back-up ICRH system seems to be more realistic. But if the future experimental progress in ICRH should be as rapid as it was during the last year, then there is still a reasonable chance of an alternative RF ZEPHYR, like that described in Sec. 1.2.

An earlier review of the status of ICRH led us to the conclusion that the minority heating scheme would be the favourite for a ZEPHYR-type machine and recent theoretical and experimental results seem to support this decision. The following considerations are therefore based on minority heating. Nevertheless, since the frequencies and antennas are similar in these cases, it is possible to try other heating scenarios with the same high-frequency equipment.

Minority heating is compatible with coupling from the low-field side, but causes a hot ion population. In the case of hydrogen or helium as a minority, we get a pressure contribution which is useless with regard to fusion, but can be dangerous for the plasma towards the end of the heating pulse, where the plasma beta is usually close to the magnetohydrodynamic stability limit. The actual beta contribution can be estimated from the minority velocity distributions calculated in / 6 /. During heating it is necessarily higher than the minority density fraction and therefore usually small but not negligible. In the subsequent burning phase (temperature equilibrium) the minority contribution to beta corresponds to the density fraction, but it should be noted that helium-3 as minority contributes two electrons per ion in contrast to hydrogen. In the case of a deuterium minority there is some additional heating by fusion processes caused by the fast tail of the deuteron velocity distribution (in a hot plasma, the minority absorption process dominates even at a high minority fraction, e.g. 30 per cent). For ZEPHYR heating this contribution is of minor importance because the density is high and hence there is only a small temperature difference between deuterium and tritium. Nevertheless, deuterium "minority" heating may be the ultimate heating scheme in the D-T operation phase of ZEPHYR, especially if the beta limit turns out to be critical.

In the case of helium-3 minority fusion reactions also occur (fast ^{3}He ions on D), but their contribution to the RF heating power is always negligible in ZEPHYR.

In principle, the minority heating scheme offers several other operating scenarios, e.g. combination with neutral injection and selective heating of the injected hot particles. These have not yet been considered in detail.

III. Application of ICRH in ZEPHYR

1. Range of Frequencies

As mentioned, the minority heating scheme is taken as a reference. In addition, it is assumed that the magnetic field is frequently changed between 70 and 100 per cent of the peak value. Helium-3 is assumed as first choice since its content, e.g. in a D-T mixture, is much easier to control than that of a hydrogen minority and charge exchange losses should be less important. But deuterium "minority" heating, e.g. in a 30 : 70 D-T mixture, which is only slightly worse than a 50 : 50 mixture, should also be possible, at least near the maximum magnetic field. Because of the coincidence of ω_{He_3} and $2 \cdot \omega_T$ tritium second harmonic heating is also available alternatively to He^3 minority heating.

In Fig. 3 the cyclotron resonance frequency is shown for hydrogen and helium isotopes as a function of the magnetic field. With the above requirements and B_{max} = 9.74 tesla, (alternative HF-ZEPHYR) the minimum frequency span is about 60 to 100 MHz. Hydrogen minority or deuterium second-harmonic heating is then only possible at rather low magnetic field, while a variety of hybrid frequencies is accessible. Obviously an extension of the frequency band would offer more flexibility and is certainly desirable. For instance, if hydrogen minority or deuterium second harmonic heating is to be included at full magnetic field, then the upper end of the required frequency interval is shifted to $\lesssim$ 150 MHz.

If ICRH is applied to the present ZEPHYR compressor, then the required minimal frequency band depends on the plasma position during heating or, more precisely, on the magnetic field in the plasma centre. In the uncompressed state it would be only 35 ... 60 MHz. For the weak compression ratio case discussed below ($C \approx 1.1$ for burn control) we get roughly 50 ... 85 MHz.

2. Nonradioactive Operation Phase

The minority ion should have a smaller mass over charge ratio, A/Z, than the majority in order to have good access from the low-field side, where the antenna has to be located. Tritium as minority or hydrogen as majority should therefore be avoided (the experiments, however, are not yet conclusive with respect to this question).

This implies that non-radioactive operation may be difficult in hydrogen as majority, except if the heating mechanism is changed. The original minority heating scenario can only be kept if a hydrogen minority in helium or a helium-3 minority in helium-4 is used. In both cases the majority is helium and the discharge dynamics may be quite different from that with hydrogen (e.g. wall effects).

Since the heating system must be optimized for a D/T mixture, one cannot expect to solve all the plasma physics problems already in the non-radioactive phase, where deuterium and tritium must be avoided.

3. Heating Power and Pulse Length Necessary for Ignition

1D computer simulations of high frequency heating in ZEPHYR were made using the BALDUR code /7/. An Alcator-Intor type transport model was used, but a variety of other models was tested also. As a first approach, ICRH was simulated by a prescribed power deposition in a toroidal cylindrical shell with a thickness of 40 per cent of the plasma radius (Fig. 5) and electrons and ions were assumed to be equally heated. Most of the simulations were done for a plasma corresponding to that of ZEPHYR after compression (R = 1,35 m, a = 0.5 m, B_t = 9.14 T) in order to get a direct comparison with the standard neutral injection scenario. The density is increased during high frequency (HF) heating up to a final value of $\langle n \rangle = 3.5 \times 10^{20}\ \mathrm{m}^{-3}$. The corresponding heating profile after averaging over flux surfaces is shown in Fig. 4, compared to that with neutral injection (NI) for the same geometry and the final density and same total power.

In Fig. 5 the heating power required for ignition in a clean plasma is shown as function of the pulse duration τ_{HF}. The critical power decreases from 9 MW at $\tau_{HF} \approx 1$ s to an asymptotic value of about 3 MW at infinite pulse length. This is in contrast to NI heating of a precompressed plasma where an increased pulse length leads to saturation at a certain temperature.

The difference comes from the contribution of fusion α - particles which is substantial during heating in the compressed state but virtually negligible if heating occurs before compression. Because of economical reasons and since the total deposited energy (wall loading) increases with τ_{HF} (Fig. 5) it is reasonable to limit τ_{HF} to less than three energy confinement times resulting in a $P_{HF} \geqslant 6$ MW. The critical power increases slightly if a broader resonance layer is assumed or if more power goes to the electrons. Similar values are obtained for the alternative HF-ZEPHYR design.

If iron sputtering is included, then the critical heating power increases slightly, typically from 9 MW to 11 MW at a pulse length of $\tau_{HF} = 1$ s. A self-regulating, radiating cold plasma boundary layer is observed in these runs and the iron content saturates below 0.05 per cent, a level which is not critical with respect to ignition. Details concerning this radiating boundary layer are given in /8/. A comparison between high frequency heating and neutral injection is found in /9/.

One should notice that adiabatic compression is not necessary in connection with ICRH, but may be even a disadvantage, since the contribution of α- particles is lost, as mentioned above. Another point is that the plasma should be close to the antenna to allow for good coupling (the distance is however much less critical than with lower hybrid heating!) This means that it is not possible to have ICRH on during a strong adiabatic compression in contrast to the case with neutral injection. The compression speed would then be more critical ($\tau_{comp} \lesssim 50$ ms). Thus, a large compression ratio should be avoided. A small radial shift of the plasma may be required, however, for burn control, e.g. $C \approx 1.1$.

Several comments are still necessary with respect to the pulse length: A short pulse length of only several energy confinement times is desireable, in order to save flat top time for the subsequent burning phase. However, a driven mode of operation, which could be interesting because of various reasons, should be possible also. In that case, the pulse length should equal the flat top time, i.e. about 6 s. In addition, the boundary layer dynamics may require a finite pulse rise and fall time. RF heating could also be advantageous for other purposes, e.g. for"heating down" the plasma in a controlled manner, which should be possible with the same system.

4. Antenna and Transmitter

In spite of the fairly high frequency, it seems impossible to use waveguides because of the small dimensions of ZEPHYR, the radiological problems (dielectric filling!) and, last but not least, the lack of theoretical and experimental knowledge.

Sufficient experience exists only for coupling by poloidal loops. The power density obtained hitherto with loops ($\lesssim 600$ W/cm^2) is still somewhat too low.

In ZEPHYR one would expect an array of periodic antennas all around the torus. For practical reasons, one would prefer antenna modules which fit into appropriately shaped openings in order to facilitate remote handling. Such a module might also contain tuning elements etc. and could be driven by a single transmitter module. The transmitter does not require major development, though a lot of engineering work is still to be done.

It is the antenna which is the most critical point for ICRH in ZEPHYR. A more detailed study is under way.

5. Some Unsolved Physical Questions

There are still a lot of more or less severe physical problems to be solved. Some are mentioned here:

One open question is that of plasma boundary heating, which could occur through various mechanisms. For instance the strong and complicated near field of the antenna may couple to various surface waves or may drive nonlinear processes. Also, the theoretical understanding of cut-offs, resonances etc. in a hot, toroidal inhomogeneous plasma is rather incomplete, and the whole story is certainly more complicated than described in the currently used pictures of resonances and cut-offs. However, no strong surface heating is observed for the power densities in present experiments, but still no complete energy balances are available.

Another question is that of impurity resonances and their consequence. The diagram in Fig. 6 shows the cyclotron frequency and the harmonics for various ions. The abscissa corresponds to a normalized frequency or inverse magnetic field or major radius. In Fig. 7 we have drawn plasma cross-sections with aspect ratios relevant to ZEPHYR and PLT or TFR, compared to the location of fundamental cyclotron resonances of different ions (abscissa as above).

It is obvious that hydrogen minority heating is undisturbed by impurity resonances. Only harmonics occur in the plasma, which cause negligible damping compared with hydrogen. In contrast, deuterium minority heating in a D-T ZEPHYR plasma implies a lot of impurity resonances over half the plasma at the high-field side. A content of several per cent of low-Z impurities which is still compatible with ignition, can therefore cause appreciable RF absorption in this region. The partly ionized states only occur close to the boundary, while fully stripped ions are close to, or coincide with deuterium. The latter may simply enhance the central absorption, while partly stripped ions might cause surface heating. (Strong impurity diffusion may carry partly stripped ions far into the hot plasma). The impurity problem is less severe if some focusing of the wave energy is possible and especially if the absorption in one transit is nearly 100 per cent (see Fig. 6), as expected in large machines.

Figures 6, 7 are also useful to discuss the occurrence of several hydrogen-helium resonances and hybrid resonances in the plasma.

Take as an example helium-3 as minority. An aspect ratio A $>$ 3 is then required to avoid the deuterium and hydrogen resonances near the boundary. For coupling from the low-field side hydrogen is more dangerous and the hydrogen content should be kept low. The hybrid resonance connected with hydrogen is then not dangerous either. Certainly, these considerations are only indicative of what might happen and much more has to be done theoretically and experimentally.

The last question we mention here is that of the influence of RF fields on particle orbits and transport. In principle, the RF field is a coherent one and therefore should not cause diffusion like a random fluctuating field with the same amplitude, except for non-correlated decay processes, etc. It is not clear whether the RF field affects neoclassical transport, e.g. those processes which are connected with toroidal field ripple and which are already dangerous in ZEPHYR.

IV. Conclusions

In principle, ICRH seems to be close to an optimum heating method for large fusion experiments, though at present it is experimentally less advanced than neutral injection. However, because of the rapid experimental progress during the last few years and even months, ICRH is also a serious candidate for ZEPHYR, at least as a back-up system, but depending on the progress of the design, also as the primary heating system.

Exploratory considerations concerning ICRH on ZEPHYR have not revealed insurmountable difficulties, the main problem being that of an appropriately designed antenna module. A more detailed study of ICRH in ZEPHYR has to be done in order to identify the critical points and to get a more reliable basis for time and cost estimates, but also for the discussion about ZEPHYR alternatives without neutral injection and strong compression.

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Figure Captions

Fig. 1 Standard ZEPHYR compressor design.

Fig. 2 An alternative ZEPHYR design for ICRH without strong major radius compression.

Fig. 3 Ion cyclotron resonance frequency f_c for various ions as function of the magnetic field B. A reasonable frequency range allowing for He-3 and D minority heating or T second harmonic heating is indicated for $B_{max} \approx 10$ T.

Fig. 4 Comparison of the heating power density profile for idealized HF heating and a 160 keV neutral beam (60 : 20 : 20) perpendicularly injected. ($R = 1.35$ m, $a = 0.5$ m, $\langle n \rangle = 3.6 \times 10^{20}$ m^{-3}, $T_i = 8.8$ keV); normalized to a total power of 1 MW.

Fig. 5 HF heating power P and deposited energy W necessary for ignition ($R = 1.35$ m, $a = 0.5$ m, $\langle n \rangle = 3.5 \times 10^{20}$ m^{-3}). The assumed HF resonance layer is indicated.

Fig. 6 Ion cyclotron resonance frequency of hydrogen and helium isotopes and for impurity ions are shown in a plane Z/A versus a normalized major radius $R/R(\omega = \omega_H)$. (The abszissa may also be interpreted as ω/ω_H or $B(\omega = \omega_H)/B$).

In the bottom part we have sketched a toroidal plasma with aspect ratio $A = 2.7$ in such a way that the helium-3 resonance coincides with the plasma centre ("helium-3 minority heating"). It is seen that a lot of resonances occur inside the plasma (all the resonances between the two vertical lines).

Fig. 7 This figure is similar to Fig. 6, but only fundamental resonances are considered. Again the plasma cross section shown in the bottom part indicate, which resonance lies in the plasma region. For A = 4 and hydrogen minority only the hydrogen resonance occurs, while for A = 2.7 and deuterium minority heating a lot of other resonances are located inside the plasma.

Fig. 8 Idealized deuterium minority heating. If nearly 100 per cent of the HF-energy is absorbed in one transit, then the other resonances (tritium and impurities) located in the left part of the plasma are unimportant.

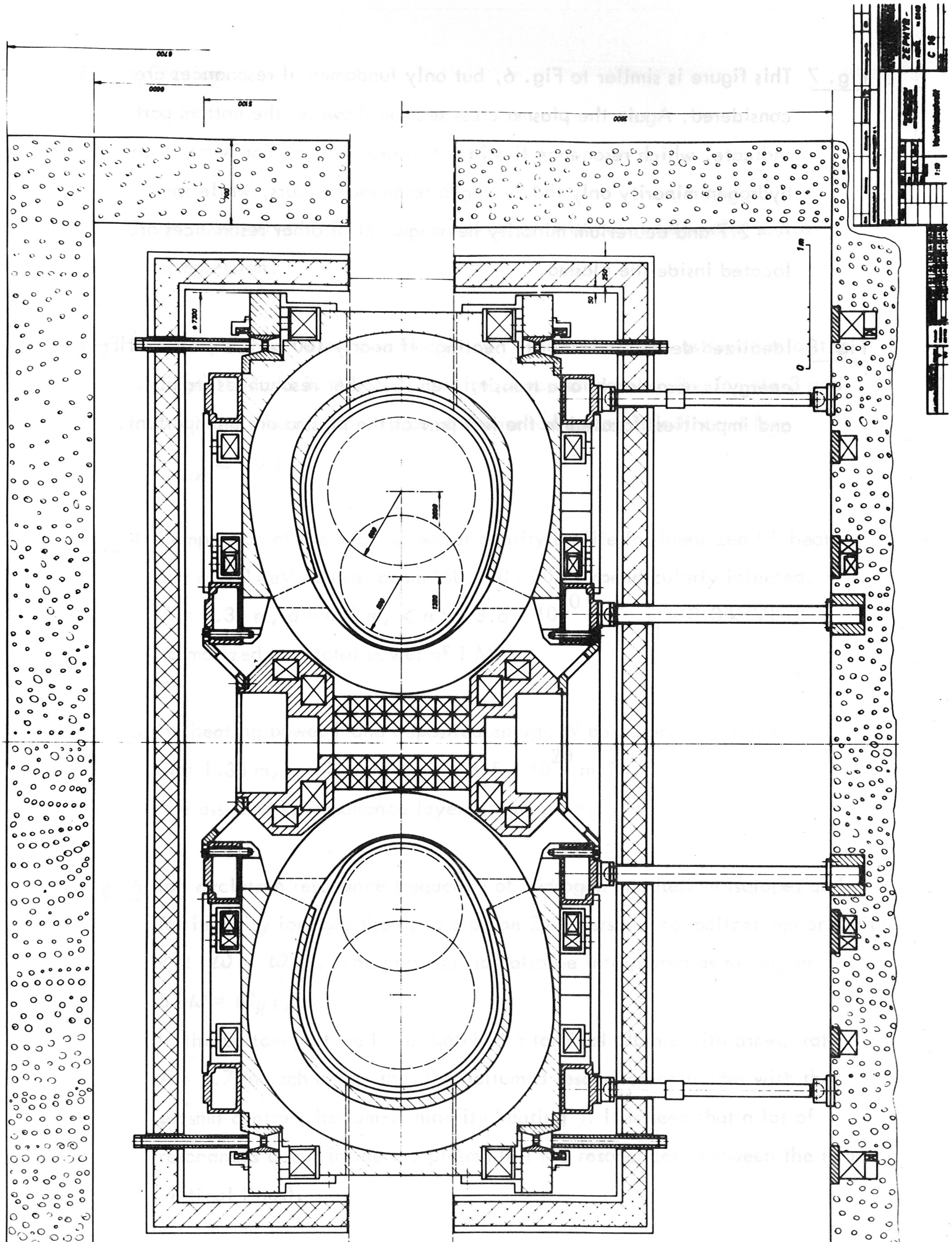


Fig. 1

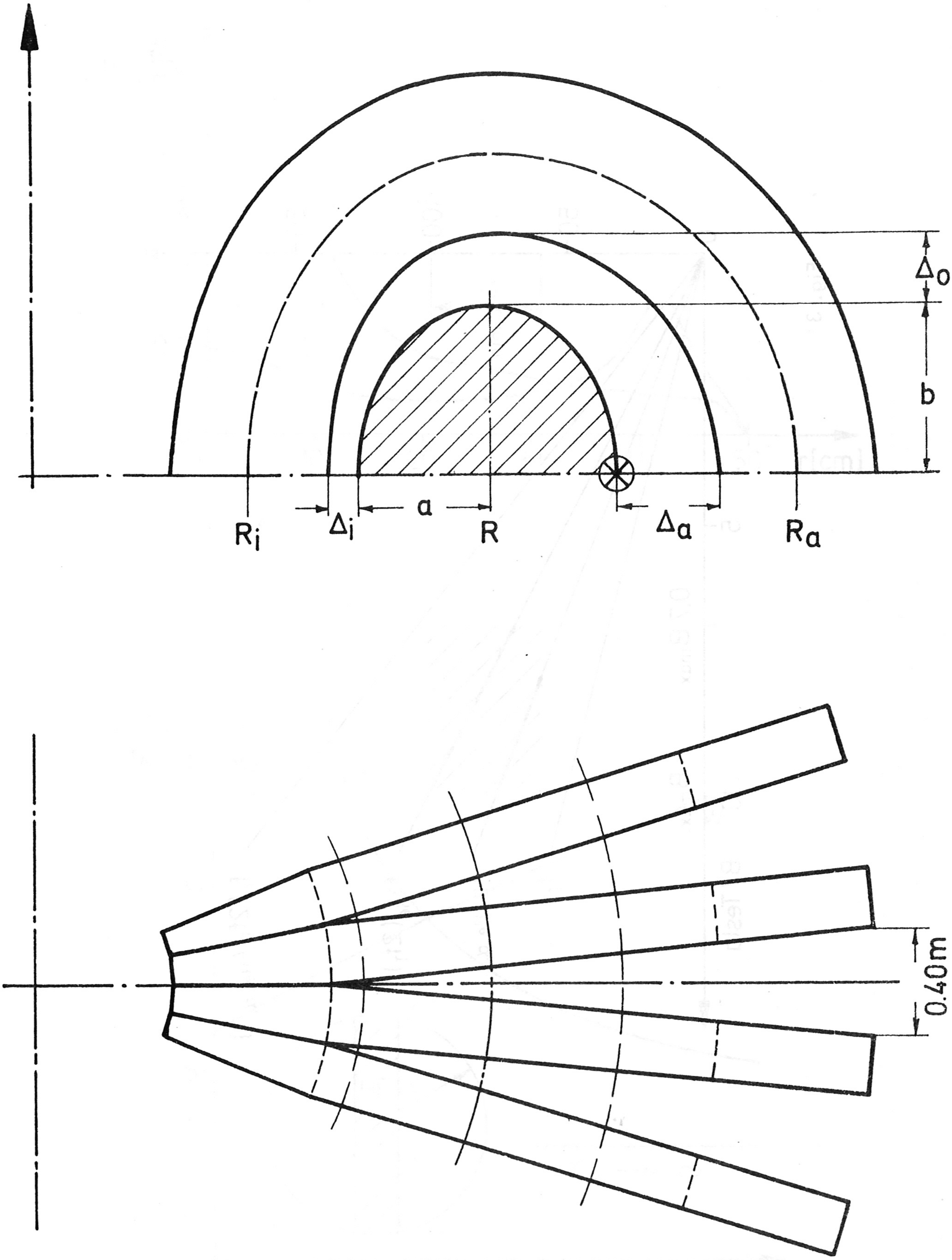


Fig. 2

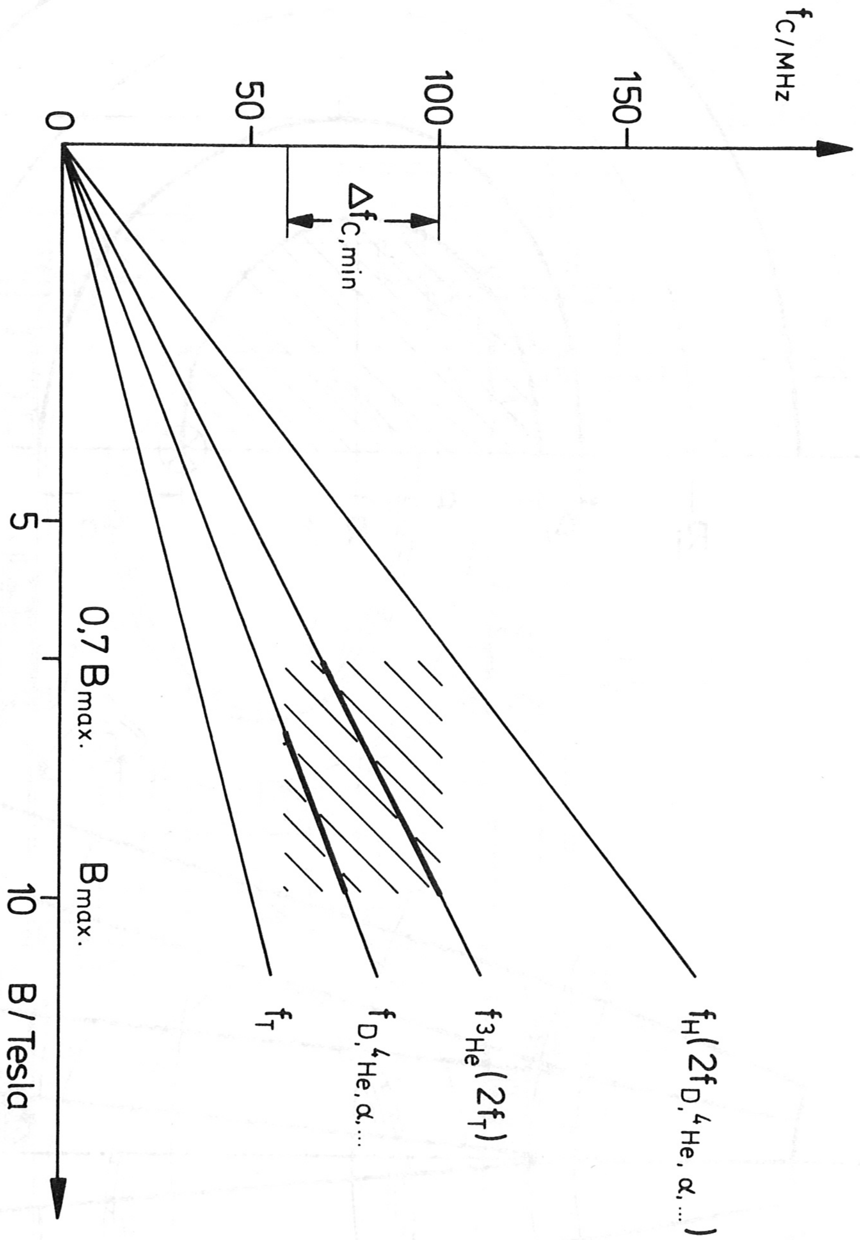

$f_{C/MHz}$
150
100
50
0
$\Delta f_{C,min}$
5
10
0,7 $B_{max.}$
$B_{max.}$
B/ Tesla
$f_H(2f_D, {}^4He, \alpha, ...)$
$f_{{}^3He}(2f_T)$
$f_{D, {}^4He, \alpha ...}$
f_T

Fig. 3

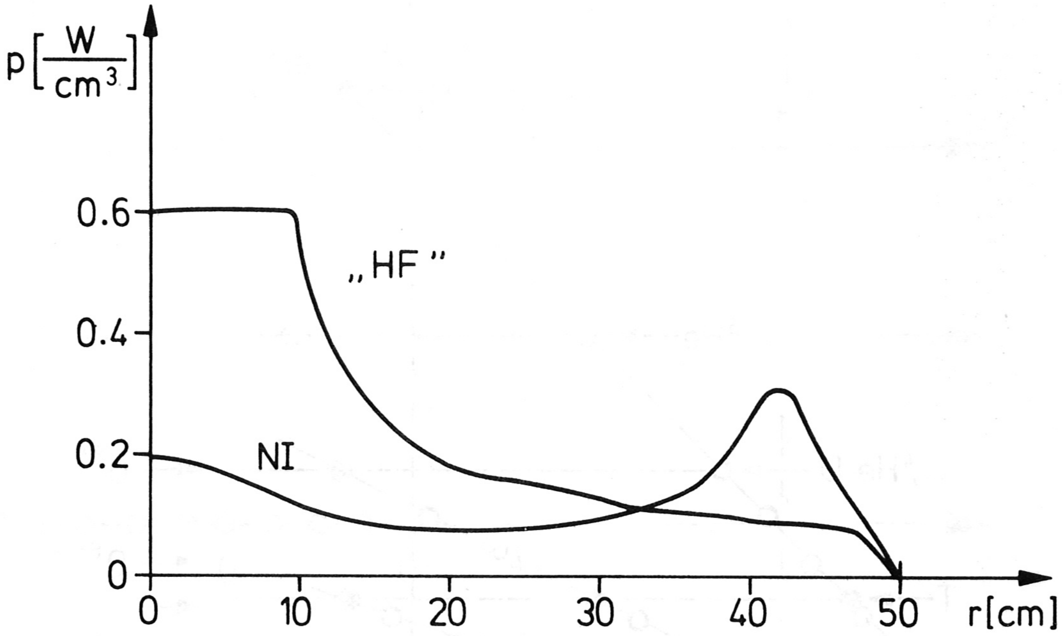

p [W/cm³]
0.6
0.4
0.2
0
„HF"
NI
0
10
20
30
40
50
r [cm]

Fig. 4

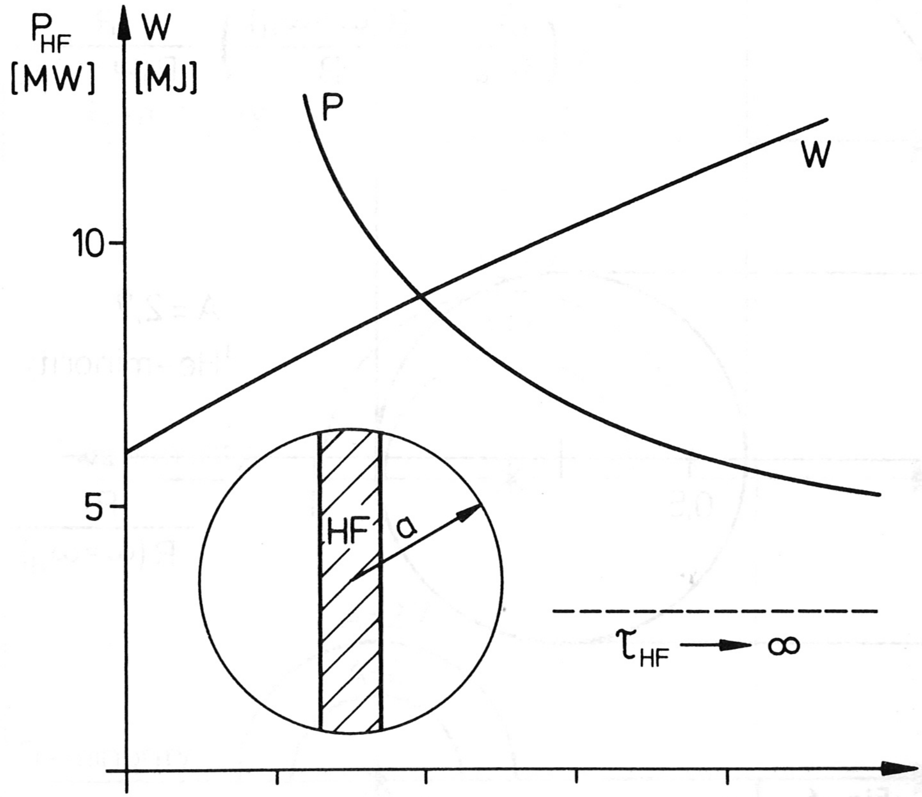

P_HF [MW]
W [MJ]
P
W
10
5
HF
a
τ_HF → ∞
0
1
2
τ_HF [s]

Fig. 5

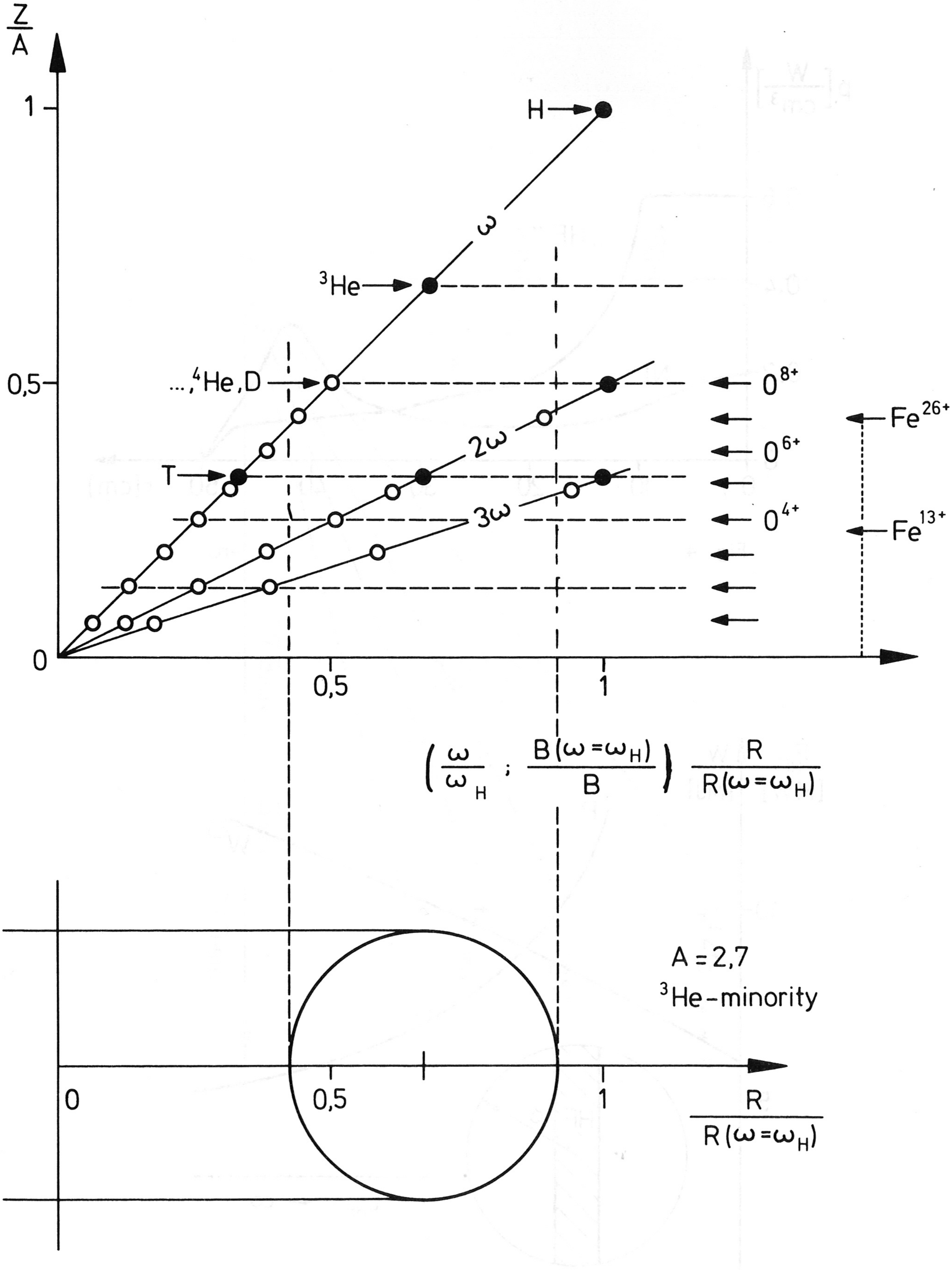
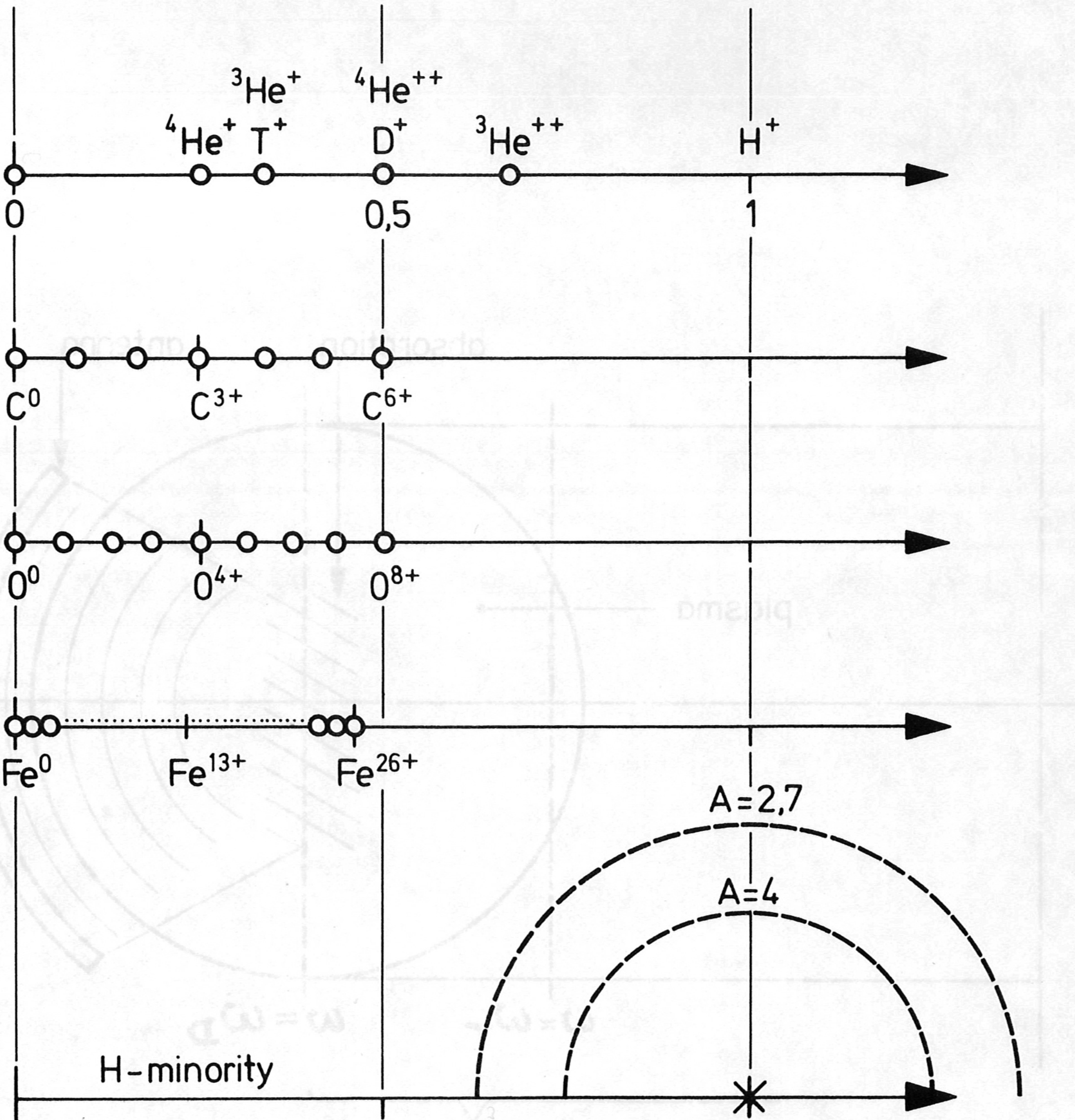

$\frac{Z}{A}$
1
0,5
0
H
ω
^{3}He
...,^{4}He,D
T
2ω
3ω
O^{8+}
O^{6+}
O^{4+}
Fe^{26+}
Fe^{13+}
0,5
1
$\left(\frac{\omega}{\omega_H} ; \frac{B(\omega=\omega_H)}{B}\right) \frac{R}{R(\omega=\omega_H)}$
A = 2,7
^{3}He-minority
0
0,5
1
$\frac{R}{R(\omega=\omega_H)}$

Fig. 6



$^3He^+$
$^4He^{++}$
$^4He^+$
T^+
D^+
$^3He^{++}$
H^+
0
0,5
1
C^0
C^{3+}
C^{6+}
O^0
O^{4+}
O^{8+}
Fe^0
Fe^{13+}
Fe^{26+}
A=2,7
A=4
H-minority
A=2,7
A=4
^{3}He-minority
A=2,7
A=4
D-minority
0
0,5
1
$R/R(\omega=\omega_H)$

Fig. 7

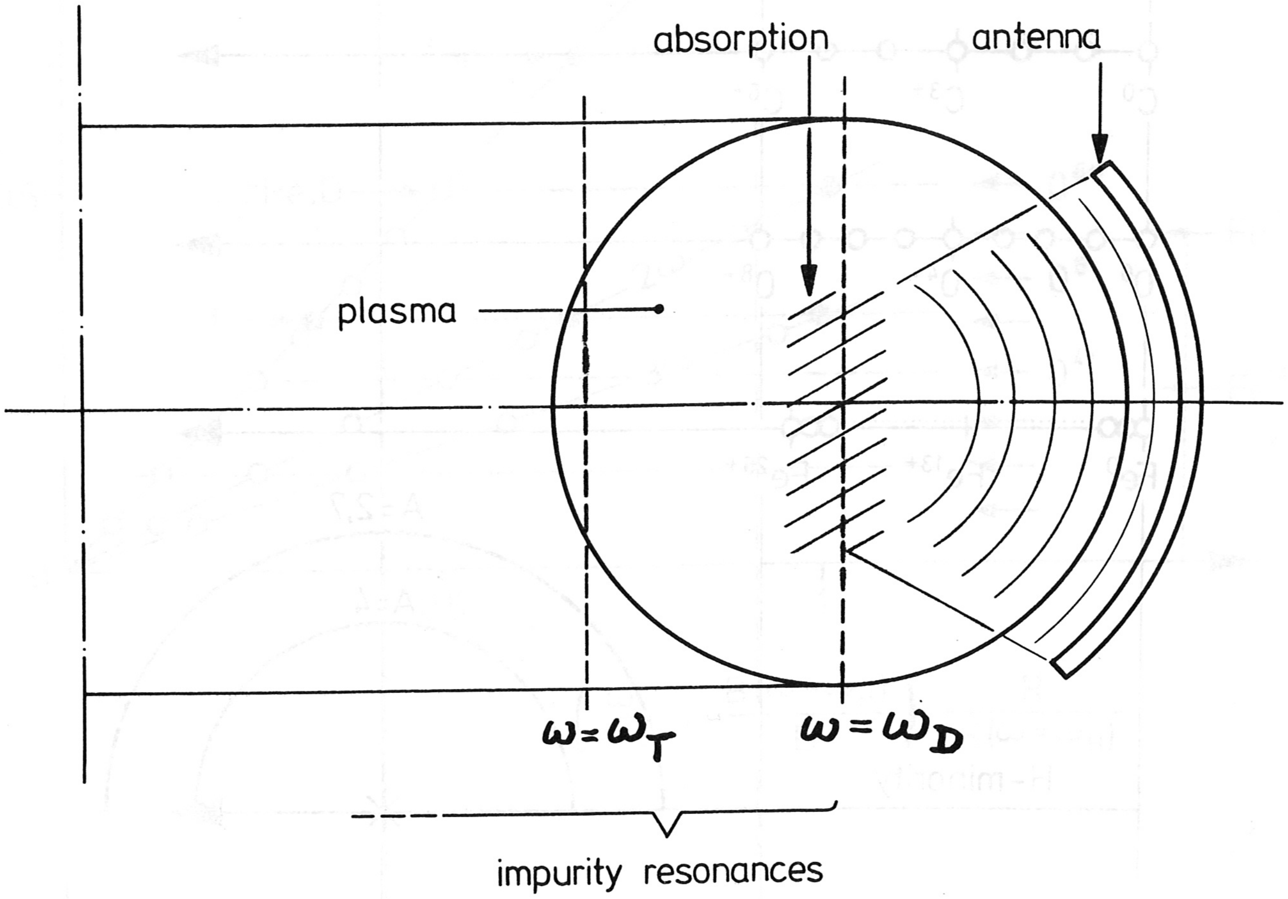

absorption
antenna
plasma
$\omega = \omega_T$
$\omega = \omega_D$
impurity resonances

Fig. 8

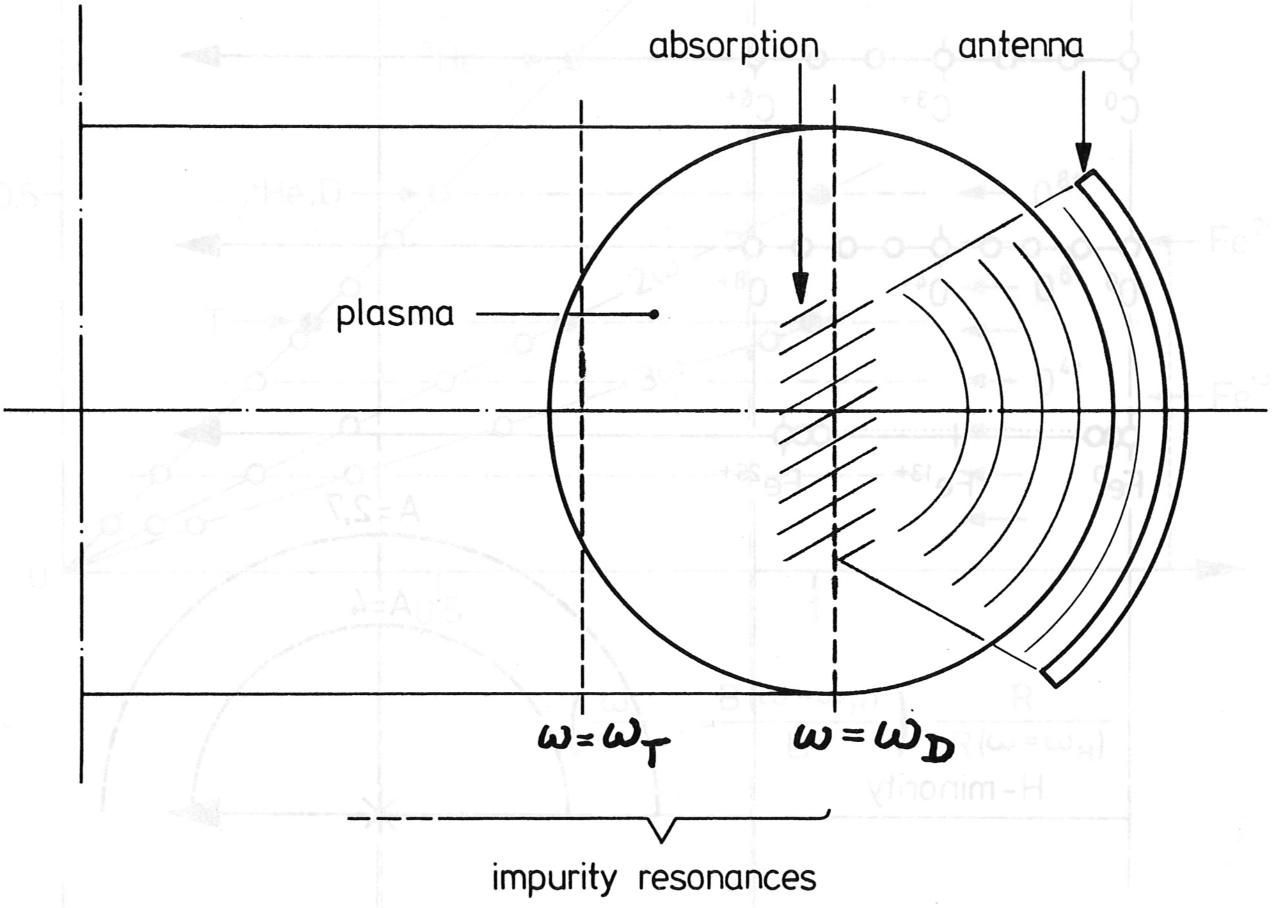


Fig. 8