Crossing of resonances and particle losses in the Garching electron-ring accelerator

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Abstract

During compression of the ring blow-up and particle losses are observed, which lead to a reduction in holding power. Because of the low particle number collective instabilities are not very likely and comparison of the Landau damping coefficients with the experimental results excludes the radial and axial transverse resistive wall instability. The loss curves are in agreement with the crossing of single particle resonances. It seems that in the present geometry field perturbations are below the level, which causes observable particle losses at n = 0.36 and n = 0.25. Losses in these cases are due to the Walkinshaw-resonance (at n = 0.2), which does not need a field perturbation. Ring blow-up at n = 0.25 could be produced by adding field perturbations close to the resonance region. Discrimination between the n = 0.25 and the n = 0.2 resonance was possible by adding metal cylinders around axis with such a shape that the field index n = 0.2 was not crossed. Field index contours have been obtained by computer calculation.

INTRODUCTION

The experimental arrangement and the first experiments with the Garching plasma-ring compressor have been described at different places [1)2)3)]. The holding power achieved after compression of the ring to a large radius of 3 cm was below the desired value by at least two orders of magnitude. Different reasons are responsible for this result: 1) The current injected through the snout into the compressor is not sufficient. 2) The inflection process might not yet be optimised. 3) Instabilities during the compression cycle may lead to beam blow up and particle losses. Investigations about this third point are the subject of this report.

There were different hints for particle losses and instabilities during compression of the ring. Some were connected with the presence of Faraday cups (FC), some were not. By the radial FC instabilities are detected only if they lead to losses of particles or to an enlarged radial dimension. But even if the instabilities cause a blow up of the ring in axial direction only without remarkable losses, this is highly unwanted because of the reduced holding power. The axial dimension of the ring after compression could be investigated by studying the synchrotron light emitted by the rotating electrons. It was found [3)] that part of the electrons had an axial betatron amplitude of more than 8 mm. Assuming linear betatron theory and adiabatic compression this corresponds to an amplitude of more than 3.6 cm at a radius of 18 cm. According to the acceptance of the injection snout maximum axial amplitudes after injection of $\approx$1.9 cm can be expected. There are therefore processes active during compression which lead to a blow up of the beam in axial direction, if not to losses, because 3.5 cm is about the maximum amplitude possible inside the inflection system.

Main origins for the beam blow up could be unstable collective modes or single particle resonances (nonlinear betatron motions).

Among the <u>single particle resonances</u> the main instabilities in question are the ones at n = 0.36, n = 0.25; and n = 0.2.

In the n = 0.36 resonance[4] different radial and axial modes couple with each other; the most severe coupling is supposed to be the sum resonance $\nu_R + 2\nu_z = 2$. It needs a disturbance of the field in order to grow and the growth rate depends on the amplitude of the sinusoidal second harmonic disturbance. Because this is unknown, we cannot give the growth rates here.

At n = 0.36 a coupling is possible, which leads to exchange of radial and axial oscillation energy and does not need a driving term: $3\nu_R - 4\nu_z = 0$. But this is a coupling of relatively high harmonics and is therefore anticipated to be not very dangerous.

At n = 0.25 a purely axial mode is growing if a field perturbation is present. The betatron tune here is 1/2 and each second turn the particle sees a disturbance with the same phase. Again growth rates and instability stop bands depend on the size of the disturbance.

For n = 0.2 a coupling of two low order modes leads to exchange of radial and axial oscillation energy without the presence of an external perturbation: $\nu_R - 2\nu_z = 0$; there ν_R is just twice as big as ν_z. Growth rates for this so-called Walkinskow resonance have been calculated by L.J. Lasslett[5]. The maximum growth rate is estimated to be:

$$\mu_{max} = \frac{|K| \cdot |A_x|}{\nu_R}$$

with $K = \frac{1}{2} \frac{\partial^2 B_z}{\partial R^2}$ and $A_x = \frac{A_R}{R}$
where A_R is the radial betatron amplitude. The instability stop band extends between n_1 and n_2, which are given by:

$$n_{1/2} = 0{,}2 \pm 0{,}8 \, |K A_x|$$

The total growth of axial amplitude, which is supposed to be small at the beginning, after crossing the instability zone is calculated to be:

$$G = 3{,}83 \, \frac{K^2 A_x^2}{|dn/d\tau|}$$ decades per revolution,

here $dn/d\tau$ is the change of n per revolution.

The collective modes in question have been investigated theoretically[6]. Because these modes depend on the kind and position of walls around the ring, growth rates are not easily calculated. Energy spread in the beam causes a kind of Landau damping, whose magnitude - the Landau damping coefficient - has been calculated by L.J.Lasslett[7]. The coefficients are given by:

$$D_{R/M} = \frac{1}{\beta^2}\left[(M_R - \nu_R)\cdot\left(\frac{1}{1-n} - \frac{1}{\gamma^2}\right) - \frac{\tau \, dn/d\tau}{2(1-n)\cdot\nu_R}\right]$$

and

$$D_{z/M} = \frac{1}{\beta^2}\left[(M_z - \nu_z)\cdot\left(\frac{1}{1-n} - \frac{1}{\gamma^2}\right) + \frac{\tau \, dn/d\tau}{2\cdot(1-n)\cdot\nu_z}\right]$$

$M_{R,z}$ are integers, $v_{R,z}$ the betatron tunes. When these damping coefficients get small for one mode or the other this collective mode might get unstable. The frequencies connected with these instabilities are given by:

$$\omega = (M - \nu_{R/z}) \cdot \omega_c$$

These damping coefficients have been calculated for geometries used and the results have been compared with the experiments. Independent on this damping there exists a treshold for the density below which no growth occurs. Corresponding to some preliminary calculations of Möhl and Garren[8] the treshold for collective modes might be crossed in our experiment.

A. Investigation of the losses and discussion of collective modes

Losses of particles from the ring after injection and inflection could go in three ways: radially outward, radially inward and axially. Faraday cups inserted from outside to a radius a few millimeters less than the injection snout showed decreasing losses of particles during the first 300 nsec or 75 turns after injection. These losses, shortly after injection and probably connected with the inflection process, do not seem to be very severe and are not the subject of this report. At later times during compression no losses directed radially outward were detected. Losses going radially inward would be detected by the inner FC. Particles appearing at the inner FC would normally be counted as particles belonging to the ring. At least at larger radii the current to the FC starts at rather early times. Whether this has to be attributed to large energy spread or poor inflection or to instabilities occuring shortly after injection, cannot be decided from the FC signals alone.

In order to find out whether there are axial losses, an L-shaped FC was built (Fig. 1). The radial FC was about 5 cm long and at a z-position of about 2.5 cm from midplane. With this FC axial losses could be detected and in the same shot the number of electrons remaining in the ring could be measured. Three typical examples - although in some respect irritating and special as will be explained later - are shown for different ignition times of coil pair 2 (TB 2) in Fig. 2. The oscillogrammes in the upper line show the current to the radial FC at R = 9 cm. The end of those peaks appears at times, which correspond to the calculated compression time of the particles with the highest energy without betatron oscillations. It seems that most of the particles have a radial betatron amplitude, which is not very small (probably according to the process of inflection). The number of electrons in the ring is only a few times 10^{11} in this case. The signals in the second line show the losses to the axial FC at z = 2,5 cm, extending from R = 9 cm to R = 14,5 cm. For the ignition times of coil 2: TB2 = 2.6 and 2.75 μs (injection time is 2,5 μs) four different peaks can be separated. The first lasts some hundred ns after injection and is attributed to the earlier mentioned starting losses. The both next peaks are the losses under investigation here. The small forth peak belongs to electrons which are scattered when striking the radial FC. For TB2 = 3.75 μs the starting losses extend to 3.75 μs and go abruptly to zero, when the second coil pair is fired. The losses in this case appear to be smaller than in the other cases, although the ring current is much less. The reason for this is that the losses in that case occur at even larger radii than 14.5 cm, as can be seen when the FC is moved outward.

The surprising and irritating result is the double loss peak, which seems to indicate losses at different resonances. But because of the large energy spread in the beam and therefore large spread of closed orbits over field index this explanation seemed to be highly unrealistic. It turned out that this double peak was due to collector oscillations in the third coil pair. When the frequency of these oscillations was changed, the appearance and distance of these peaks changed too. When the oscillations were critically damped, the double peak disappeared and was replaced by a broader single loss peak, as shown on Fig. 3 for the three ignition times. (In this case the losses were detected by measuring the x-rays originating on a Cu-wire at z = 2.5 cm extending from R = 7 cm to R = 17 cm). A probable explanation of the appearance of the double peak is given in the appendix.

All the further experiments described here have been performed with critically damped oscillations or even without a collector connected to coil 3.

On Fig. 4 the both lowest frequency modes of the so-called Landau damping coefficients of the radial and axial collective instabilities are plotted together with the loss curves. If the damping gets small, collective modes could be possible. A comparison of the loss curves with the damping curves shows that axial collective modes very probably are not excited in our compressor. Only the damping coefficient of the second radial mode assumes low values. Losses caused by this mode would be expected to occur predominantly in radial direction. With other geometries described later (Fig.14) very low values of DR2 are present without any indication of axial losses. We therefore conclude that collective modes are not the origin for the detected axial losses. It therefore has to be checked whether single particle resonances could be made responsible for the blow up of the ring.

On Fig. 5 the calculated and measured compression curves and the calculated field index curves are drawn. As an insert on the same time scale the losses to a Cu-wire are plotted in arbitrary units and normalized. The experimental compression seems to be a little bit faster than the calculated one and indicates large energy spread and/or radial betatron amplitudes. R and n-curves are drawn for 1.9 and 1.8 MeV. The actual energy spread might be even larger, electrons with 1.7 MeV could be present. The losses exist at a time when the ring with its large spread of closed orbits crosses the single particle resonances at n = 0.25 and n = 0.2.

Very good information cannot be obtained from these experiments because the calculation did not take into account that the field could penetrate into the thick third coil pair during the compression time. This would increase the field index a little bit. Because of the stop band around the resonance, which depends on the amplitude A_R/R, the instability could go even as far below the resonance value as 0.16. But because the growth rate is rather high and because of the finite effect of the n = 0.2 resonance one would not expect to find losses at these low n-values after the beam had gone through the resonance.

Nevertheless the losses last even if the highest energy particles have gone through the resonance. For the case with TB2 = 3.75 μs this is partly explainable by the fast reduction of n and the herewith connected increase in axial amplitude. Not explainable in this case is the duration of the losses after ignition of the 2nd coil pair. Also with TB2 = 2.6 μs and TB2 = 2.75 μs the losses last somewhat longer than corresponds to the calculated stop band. But besides that effect (which might be because of field penetration into coil 3) losses are compatible with the n = 0.25 and n = 0.2 resonance. In order to be able to distinguish between these both resonances, a couple of other experiments has been performed.

B. <u>Experiments to distinguish between the different possible resonances</u>

Different arrangements have been tested in order to exclude one or the other resonance. The difficulty with these geometry variations is that the growth rates of the remaining resonances are changed too because of a change of $\partial^2 B_z / \partial R^2$ and/or $dn/d\tau$. By watching these shifts and calculating the growth rates it was hoped that we were able to avoid misinterpretations.

<u>1. Variation in geometry:</u> The first variation tested was the case with thick coil pair 3 replaced by a 3 mm thin coil pair with an inner radius of 8 cm in order to eliminate the penetration effect.

The growth rates at the $n = 0.2$ resonance for this case are given in the following table:

TB2 = 2.6 μs

E	R	t	A_x	dn/dt	τ	K	G
1.9	9.2	4.65	0.1	5.5×10^4	1.93×10^{-9}	0.085	2.6
1.8	9.5	4.23	0.1	6.6×10^4	2×10^{-9}	0.093	2.5

(Here E is the injection energy in MeV, R and t radius and time in cm and μs for crossing $n = 0.2$, A_x ratio of radial betatron amplitude to radius, dn/dt change of n with t at $n = 0.2$, τ revolution time, K is defined in the introduction, G total growth in decades).
The total growth rates are very large for those cases.

From the experimental result (on Fig. 6) it is seen that there are no losses when the beam crosses the $n = 0.36$ resonance. This is true for all the following geometry variations. The radii of the ring for this resonance are between 14 and 12 cm, i.e. fairly large. Apparently the disturbance introduced by the snout at these radii is not large enough to drive this resonance. The loss region covers the resonances at $n = 0.25$ and $n = 0.2$. When the highest energy particles have crossed the $n = 0.2$ resonance, the losses disappear. The loss could be explained by the $n = 0.2$ resonance alone. Particles with $E = 1.7$ MeV at injection would enter the stop band at times when the losses start. But an effect of the $n = 0.25$ resonance cannot be excluded.

The losses and the current to the FC at R = 8 cm depend on the position of the Cu-wire in axial direction. Fig. 7 shows the time diagram. If the wire is at z = 3 cm, no losses appear. The current to the FC starts at early times corresponding to the energy spread and/or radial betatron amplitudes. If the z-position of the wire is reduced, axial losses appear at early times continuing the longer, the less the distance of the wire is. At the same time the current to the FC starts the later, the less the distance of the wire is. Apparently there is a strong coupling between radial and axial betatron amplitudes, which is in good agreement with what one would expect from the n = 0.2 resonance, whereas the n = 0.25 resonance should not have an effect depending on the radial amplitude.

If the second coil is fired later (TB2 = 4.75 μs) one gets the picture of Fig. 8.

The growth rates are given in table 2:

TB2 = 4.75 μs

E	R	t	A_x	dn/dt	τ	K	G
1.9	14.31	3.75	0.1	10^5	$3x10^{-9}$	0.233	7.1
1.8	14.3	3.35	0.1	$1.1x10^5$	$3x10^{-9}$	0.234	6.4

The losses don't fit to the n = 0.36 resonance, but they cover the region of n = 0.25 and n = 0.2. Again, when the highest energy particles - a lot of which have probably fairly large amplitudes - have crossed the stop band for the n = 0.2 resonance, the losses disappear.

<u>2. Variation in geometry:</u> "Dosenrings" removed. The resonances n = 0.25 and 0.20 are crossed at smaller radii. If disturbances are necessary, their effect should be reduced at smaller radii.

Injection time is 2.25 μs now. With coil pair 2 fired immediately after injection, we get the compression scheme at Fig. 9. Fig. 10 shows compression and losses for later ignition times of coil pair 2 (TB2 = 2.8 μs and TB2 = 4.75 μs). The table 3 gives the relevant growth rates for:

E	R	t	A_x	dn/dt	τ	K	G
TB2 = 2.3 μs							
1.9	10	3.87	0.1	$7,5\times10^4$	$2,08\times10^{-9}$	0.127	3.36
1.8	1o.34	3.49	0.1	9×10^4	2.17×10^{-9}	0.142	3.94
1.7	10.69	3.22	0.1	9×10^4	2.24×10^{-9}	0.159	4.8
TB2 = 2.8 μs							
1.9	10.56	3.97	0.1	7×10^4	2.21×10^{-9}	0.153	5.8
1.8	15.21	2.61	0.1	1.5×10^5	3.18×10^{-9}	0.229	4.2
1.8	14.1	2.9	0.1	2.1×10^5	3.1×10^{-9}	0.223	2.95
1.8	11.37	3.49	0.1	1.2×10^5	2.38×10^{-9}	0.186	4.64
1.7	15.18	2.43	0.1	1.65×10^5	3.18×10^{-9}	0.228	3.8
TB2 = 4.75 μs							
1.9	15.21	2.93	0.1	1.4×10^5	3.18×10^{-9}	0.229	4.53
1.8	15.21	2.618	0.1	1.5×10^5	3.18×10^{-9}	0.229	4.2
1.7	15.18	2.43	0.1	1.65×10^5	3.18×10^{-9}	0.228	3.8

Again 0.25 and 0.2 resonances are crossed. But when the highest energy particles have gone through the 0.2 resonance, the main losses ended. Some weak losses continue, which is explained by the fact that the axial dimension of the ring is not compressed until coil 2 is fired. More interesting is the case with

TB2 = 2.8 μs (Fig.10). In the beginning we get the losses as in the case with TB2=4.75 μs.But when coil 2 is fired, the losses stop in agreement with the increased field index. But as soon as the field index crosses the n = 0.2 resonance again, the electrons which had not exchanged their transverse energy during their first approach to n = 0.2 do so now and are lost. Again, when the highest energy electrons have crossed the n = 0.2 resonance, the losses disappear.

Here we should point to an interesting fact, which is in agreement with the theoretical treatments of the Walkinshaw resonance: Although the resonance in some cases (e.g. for TB2 = 4.75 μs) is crossed more than twice as fast than in other cases (e.g. for TB2 = 2.3 μs), the losses are not influenced, as has to be expected by the nearly equal growth rates, calculated for those cases.

3. Variation in geometry: A "Faßl" (little barrel) was inserted, which was shaped parabolically in such a form that the field index at the surface had the value n = 0.3. With TB2 = 2.6 μs the resonances at 0.25 and 0.2 are not crossed. The experiment shows that no losses occur, besides the losses at the very beginning.

The calculations for TB2 = 3.75 μs show that for 1.9 and 1.8 MeV the n = 0.2 resonance should not be crossed. But electrons with slightly lower energy and large amplitudes would see the instability band. From the losses detected experimentally in that case it cannot be concluded that they have to be attributed to the n = 0.25 resonance (Fig. 11).

4. Variation in geometry: The short circuited "Faßl" of the 3rd geometry variation was slitted. An inner collector was mounted to the slit, in order to reduce the penetration of the field through the slit. The n = 0.2 resonance is crossed only by the low energy particles and with TB2 = 3.75 μs:

E	R	t	A_x	dn/dt	τ	K	G
1.8	14.2	3.37	0.1	10^5	2.98×10^{-9}	0.199	5.1

Fig. 12 and 13 show compression and n-diagram together with the loss curves for TB2 = 2.6 μs and TB2 = 3.75 μs. The losses at this arrangement are rather interesting. With TB2 = 2.6 μs the n = 0.2 resonance is not crossed. In this case the losses have to be due to the n = 0.25 resonance. The same resonance is crossed a little bit later again. An instability at this later time would not have been detected because it occurs at radii below 7 cm, the endpoint of the Cu-wire.

The n = 0.25 resonance leads to an instability only in the presence of a perturbation. Apparently a rather big perturbation has been introduced by the slit. Possibly only when this slit perturbation is present and the ring is not too far away from it - here 2 to 5 cm -, the n = 0.25 resonance grows.

At TB2 = 3.75 μs the first crossing of the n = 0.25 resonance may not lead to an instability because the corresponding radii are fairly large and far away from the slit. Here probably the n = 0.2 resonance is responsible for the two loss peaks at 3.5 and 4.5 μs. But the third peak at 6.4 μs seems clearly caused by the n = 0.25 resonance. These losses occur - in agreement with the calculations - at radii between 7 and 8 cm, as can be proved by moving the Cu-wire radially outward. Accordingly the losses of the second peak disappear gradually, if the wire is further withdrawn to about 11 cm.

In order to check that only in the case with a slit the perturbation is big enough to drive a remarkable n = 0.25 instability, one more geometry variation has been tested, in which n = 0.25 is crossed and n = 0.2 is avoided.

5. Variation in geometry: The "Faßl" was replaced by an unslitted one with n = 0.218 on the surface. The value n = 0.25 was crossed under these circumstances with TB2 = 2.6 μs at radii not far away from the "Faßl" surface, but far enough that large radial betatron amplitudes are possible at n = 0.25. No losses are seen. Fig. 14 gives the compression, n-diagram and Landau damping coefficients. As we can see from Fig. 14, the Landau damping coefficient for the first radial mode goes through zero. From the fact that no losses appear we conclude that our losses detected in other geometries are not due to the radial collective mode instability.
With TB2 = 3.75 μs low level losses are seen just before ignition of coil pair 2. At that time electrons with only 1.7 MeV original energy cross the n = 0.2 resonance. Their growth rate is extremely small. See the following table for TB2 = 3.75 μs and TB2 = 12 μs.

E	R	t	A_x	dn/dt	τ	K	G
1.9	12.5	4.475	0.1	3×10^4	2.61×10^{-9}	0.011	0.059
1.7	12.5	3.675	0.1	4×10^4	2.61×10^{-9}	0.012	0.053

Also in the case with TB2 = 12 μs losses are seen for a long time during which electrons with an energy between 1.9 MeV and 1.7 MeV are close to n = 0.2. Loss curves together with n- und R-diagrams are given in Fig. 15. It is very surprising that this very low growth rate leads to blow up of the beam. It would be highly interesting to check the calculation of the growth rates by following a single particle during compression in the region of n = 0.2.

Discussion of the results

Instabilities during the fast compression of the Garching compressor have been detected by measuring axial losses, which occur during beam blow up. The instability area is not consistent with the area of low Landau damping coefficients. It therefore seems to be excluded that the instability in question is of the collective type. The beam blow up is best explained by single particle resonances. In most cases - with no extra field perturbation - the only resonance causing the losses seems to be the so-called Walkinshaw-resonance at n = 0.2. With a field perturbation introduced by slits in the "Faßl", very clearly a resonance at n = 0.25 was seen. In all other cases it seems to be justified to say that the accuracy of the field in our experiment is high enough to avoid large growth rates for n = 0.25 and n = 0.36 resonances.

The effect of the n = 0.2 resonance has still to be considered. It was initially said that axial amplitudes are limited to about twice the radial amplitude. It seems to be verified[9] that $4A_R^2 + A_z^2$ = const. With adiabatic compression the axial and radial amplitudes at n = 0.2 are given by:

$$A_R^2 = A_{R0}^2 \frac{B_0 \sqrt{1-n_0}}{B \sqrt{1-n}}$$

$$A_z^2 = A_{z0}^2 \frac{B_0 \sqrt{n_0}}{B \sqrt{n}}$$

If we assume that during the instability the whole radial oscillation energy has been transformed to axial energy, we find:

$$A_{zi}^2 = A_{z0}^2 \frac{B_0 \sqrt{n_0}}{B \sqrt{n}} + 4 A_{R0}^2 \frac{B_0 \sqrt{1-n_0}}{B \sqrt{1-n}}$$

and

$$\frac{A_{zi}^2}{A_z^2} = 1 + \frac{4 A_{R0}^2}{A_{z0}^2} \frac{\sqrt{1-n_0} \cdot \sqrt{n}}{\sqrt{1-n} \sqrt{n_0}}$$

with $n_0 = 0.5$ and $n = 0.2$ one finds:

$$\frac{A_{zi}^2}{A_z^2} = 1 + \frac{2 A_{R0}^2}{A_{z0}^2}$$

for $A_{R0} = A_{z0}$ we get a blow up of about 70 %.

For a ring which has a twice as large radial as axial dimension - as could be because of the radial inflection process - it looks even worse: The axial dimension changes by a factor of about 3. Therefore under no circumstances the effect of the n = 0.2 resonance is negligible. The bad point is that even in cases with very low calculated growth rates the blow up appears to be effective. The question is whether another choice of the field index at time of injection would reduce the effect of the n = 0.2 resonance. Especially it seems to be worthwhile to consider a scheme of compression, with injection and compression always below n = 0.2. But there has to be a compromise, because of the lower threshold for collective modes in case of low field index.

The other way of avoiding the effect of the n = 0.2 resonance - reducing K - does not seem to be very promising. Not even with G of the order 10^{-4} the resonance losses disappeared.

APPENDIX

By measurement and calculation it was shown that the field index did not change enough during the oscillations, that the ring with its large energy spread was carried out of the instability zone. But it still could be possible that the growth rate became very small, as might be when dn/dt gets very large or/and $\partial^2 B/\partial R^2$ very small. It turned out, however, that the losses disappeared when dn/dt was very small and the second derivative of B was not. Therefore, growth rates are rather large and this does not explain directly why losses are reduced during one half period of oscillation.

But having in mind that the Walkinshaw resonance is accompanied by growth to a finite axial amplitude only, we see that large growth rates in connection with the dependence of the axial amplitude on the field index can explain the reduced loss. Looking at Fig. 16 we see that the time derivative of n changes with the collector frequency. dn/dt is small or positive when the losses are reduced, and is rather large and negative when the losses have their maximum value. But even in this last case the growth rates are rather large. Now then, when electrons enter the stop band, they very soon exchange their radial oscillation energy into axial one during the time dn/dt at the location of the electron is negative. During the time dn/dt is about zero or even positive, no new particles enter the instability zone and the losses cease. Only when electrons have been just at the border line of the instability band, the growth rate might have been small and the particle might not have achieved its final amplitude. Under these circumstances the amplitude could continue to grow, but with small growth rates only. But even here losses would barely be seen, because for dn/dt $\geq$ 0 the axial amplitude is fast compressed according to adiabatic theory. For the case on Fig. 16 the compression of the axial amplitude at $t = 3.22\,\mu s$ and $z = 3$ cm is close to 10^6 cm/s. Only for large growth rates the ring blow up is faster. Therefore in case of the Walkinshaw resonance the reduction of the losses is explainable. If the $n = 0.25$ resonance is driving the instability, the loss reduction could be explained, if the growth rates are small and adiabatic compression is fast compared with the ring blow up.

References

1 C. Andelfinger et al., Contribution to the 3rd Work Meeting on Electron Ring Accelerators, Kernforschungszentrum Karlsruhe, ext. Report 3/69-30.

2 C. Andelfinger et al., Proceedings of the 4th Work Meeting on Electron Ring Accelerators, IPP-Report 0/3, 1971.

3 C. Andelfinger et al., Proceedings of the 1971 Particle Accelerator Conference, Chicago, USA, Nuclear Science Vol. 18, No. 3, page 505.

4 L.J. Laslett, ERAN 74 + 139, Electron Ring Accelerator Group, Berkeley.

5 L.J. Laslett, ERAN 71, Electron Ring Accelerator Group, Berkeley.

6 L.J. Laslett, V. Kelvin Neil, A.M. Sessler, Rev.Sci.Instr. 36, 436, 1965

7 L.J. Laslett, ERAN 121, Electron Ring Accelerator Group, Berkeley.

8 Möhl, Garren, Private communication.

9 W. Perkins, ERAN 141, Electron Ring Accelerator Group, Berkeley.

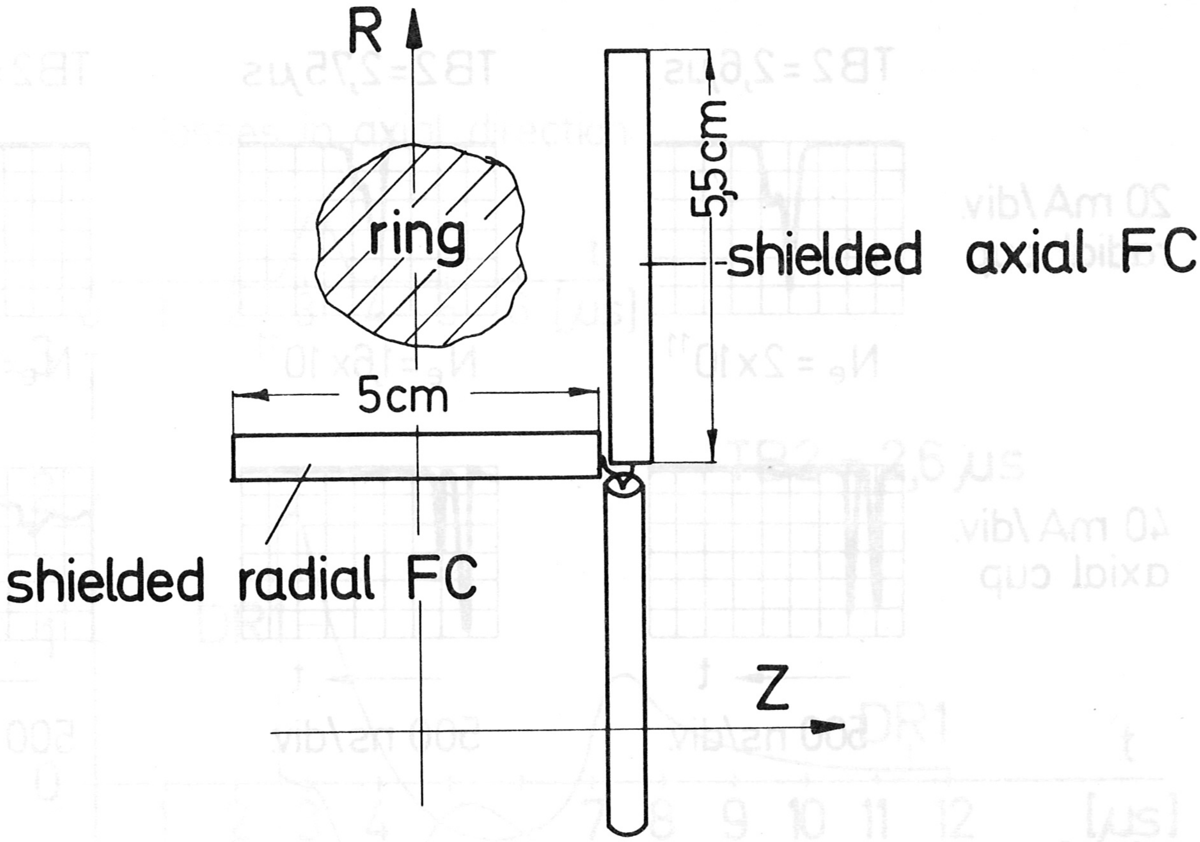


fig.1 L-shaped FC (movable in radial direction)

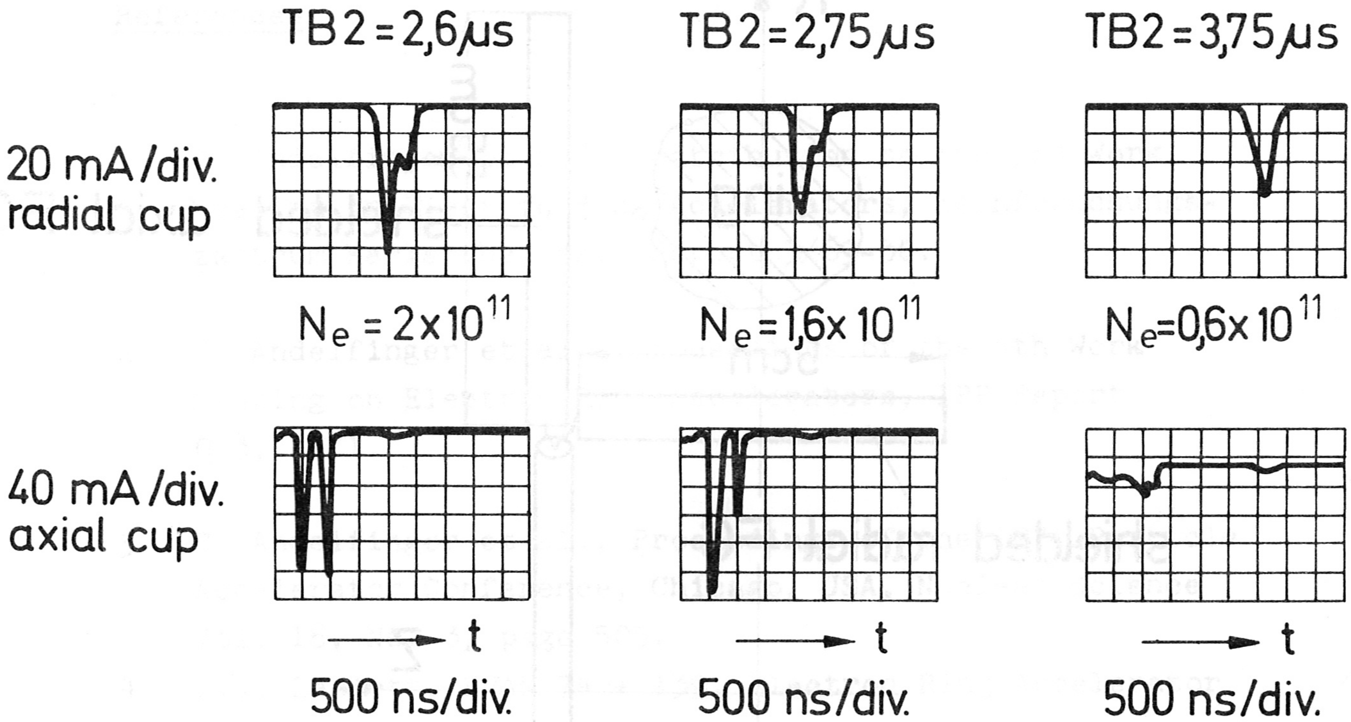


fig.2 currents to axial cup and radial cup at r = 9 cm

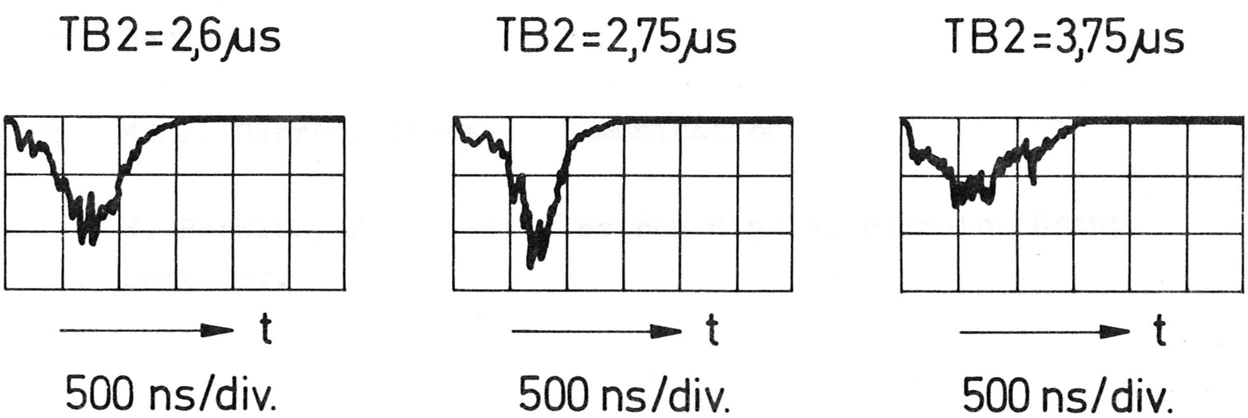


fig. 3 γ-signal from a cu-wire at z = 2,5 cm with critically damped collector oscillations

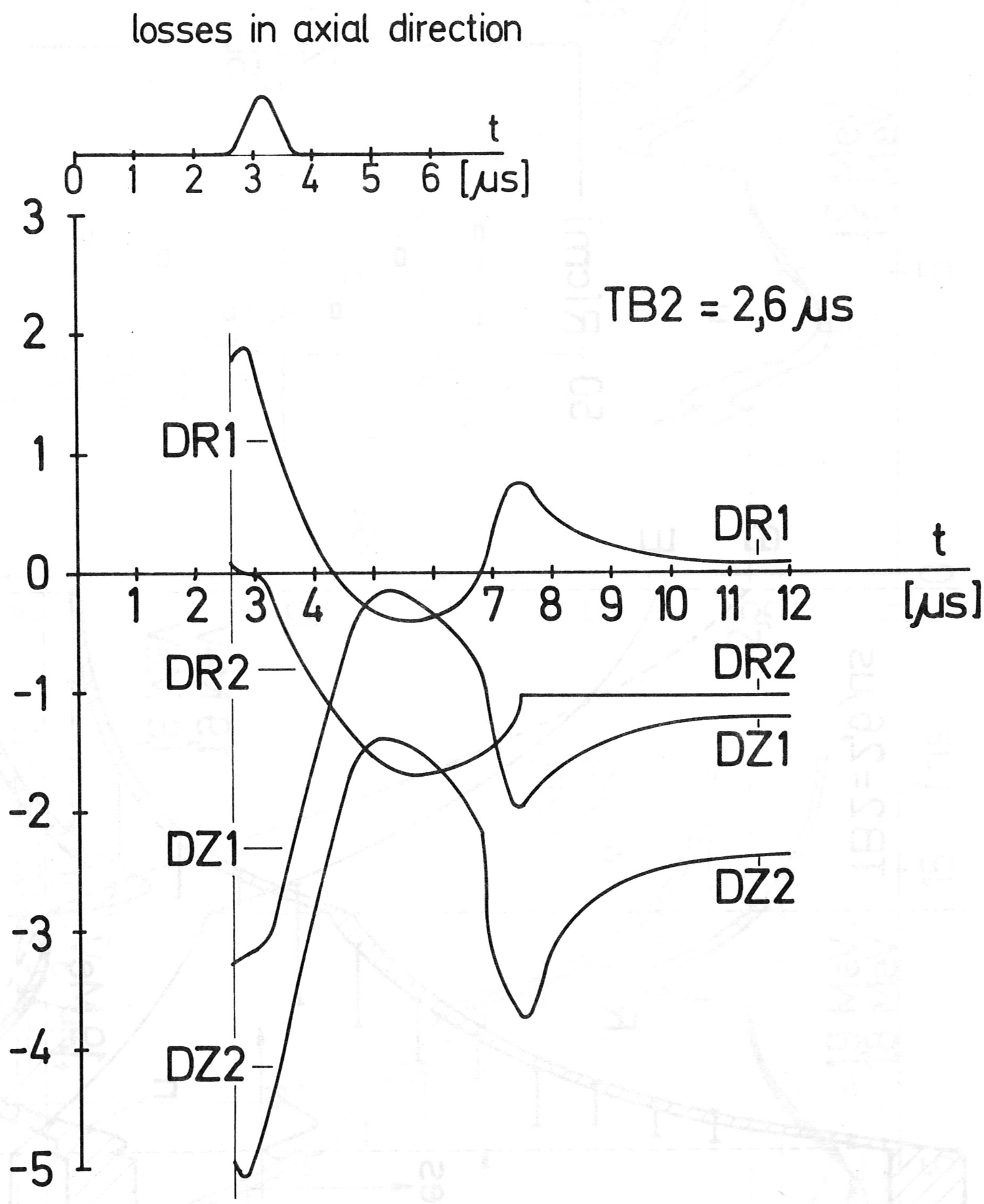


fig.4 time behaviour of Landau damping coefficients and losses

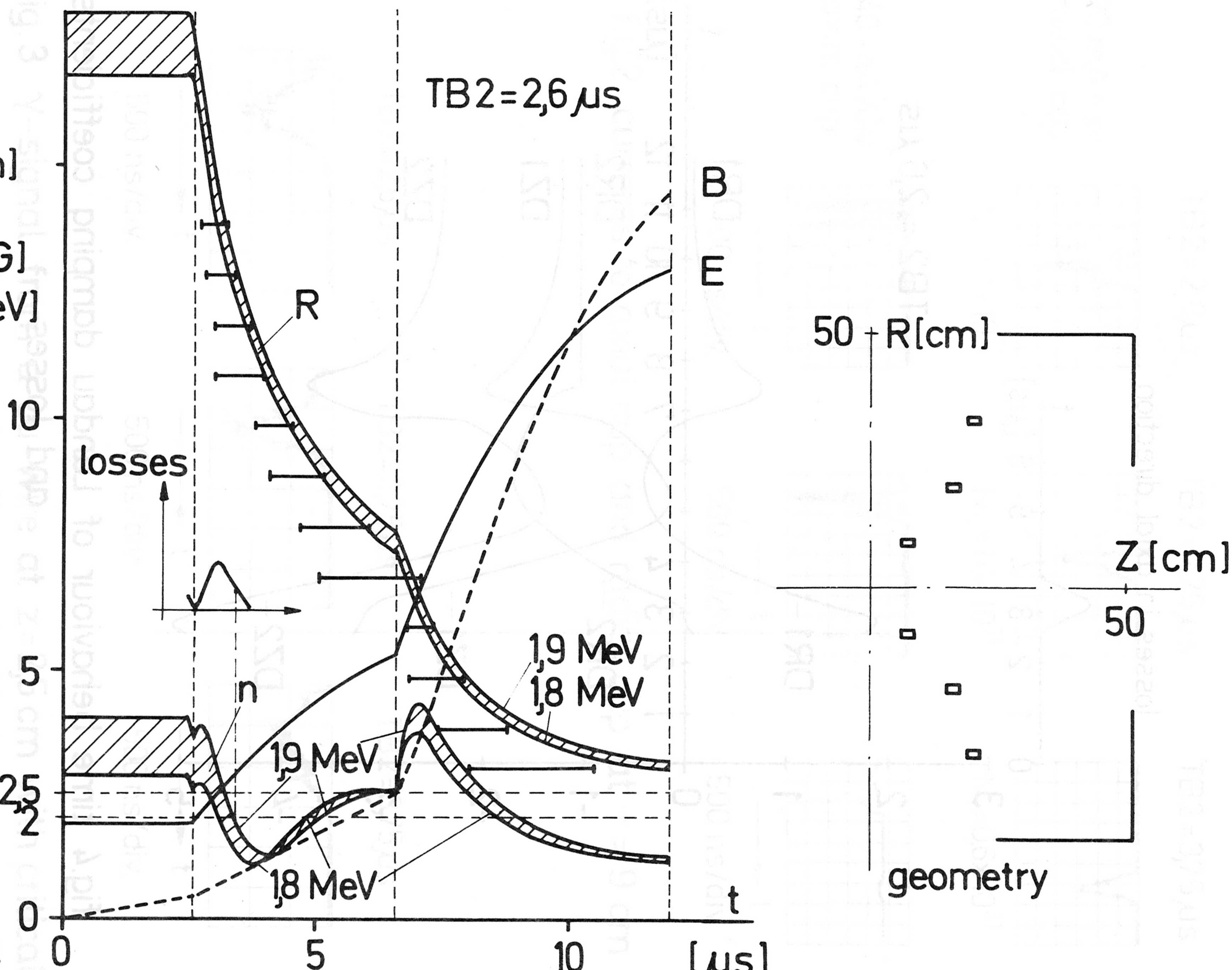
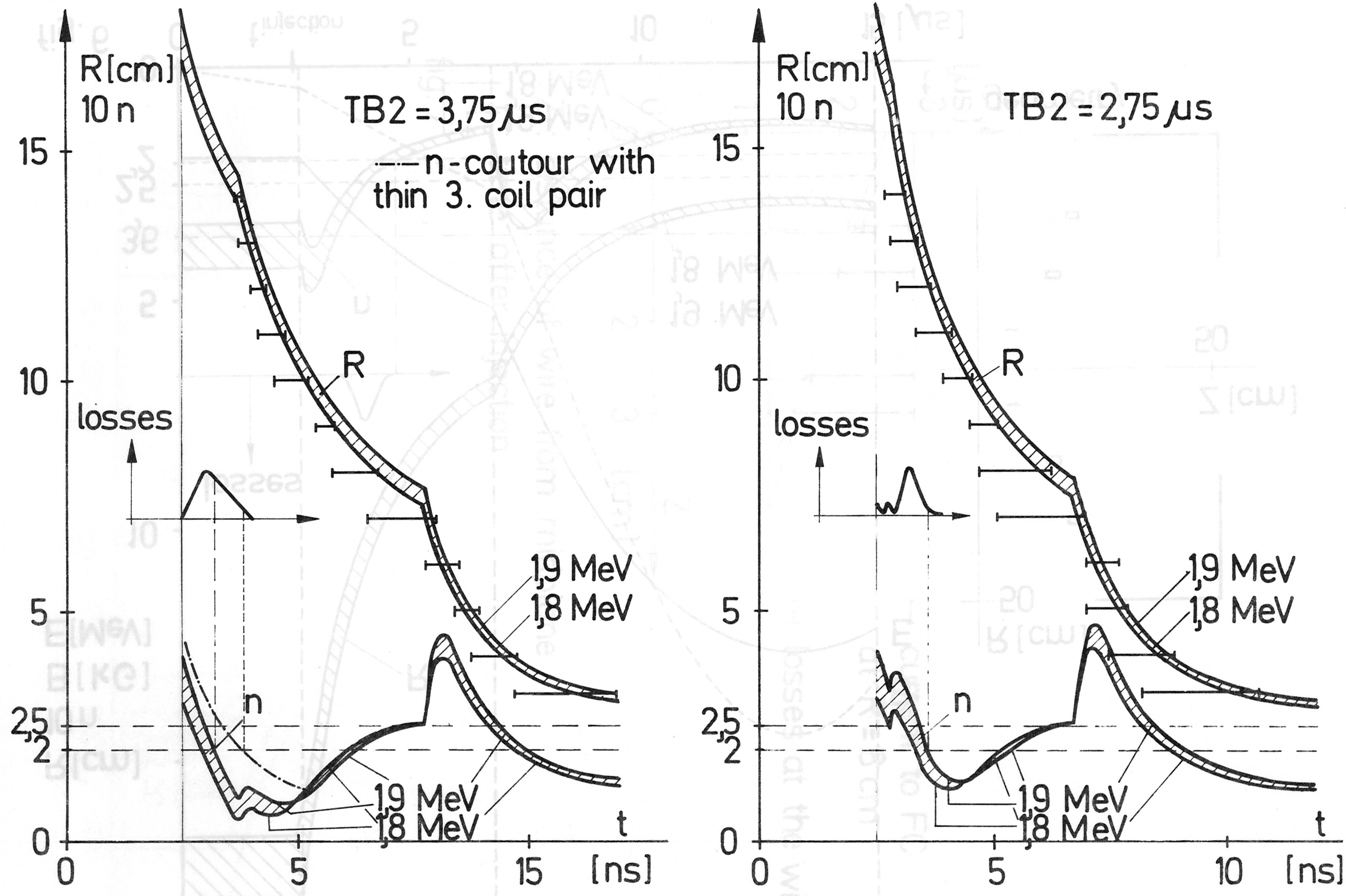

TB2=2,6 µs
R[cm]
10n
B[kG]
E[MeV]
10
5
2,5
2
0
losses
R
n
B
E
1,9 MeV
1,8 MeV
1,9 MeV
1,8 MeV
t
[µs]
0
5
10
50
R[cm]
Z[cm]
50
geometry

fig.5a


R[cm]
10 n
TB2 = 3,75 μs
—·— n-coutour with
thin 3. coil pair
losses
R
n
1,9 MeV
1,8 MeV
1,9 MeV
1,8 MeV
t
[ns]
R[cm]
10 n
TB2 = 2,75 μs
losses
R
n
1,9 MeV
1,8 MeV
1,9 MeV
1,8 MeV
t
[ns]
fig. 5b

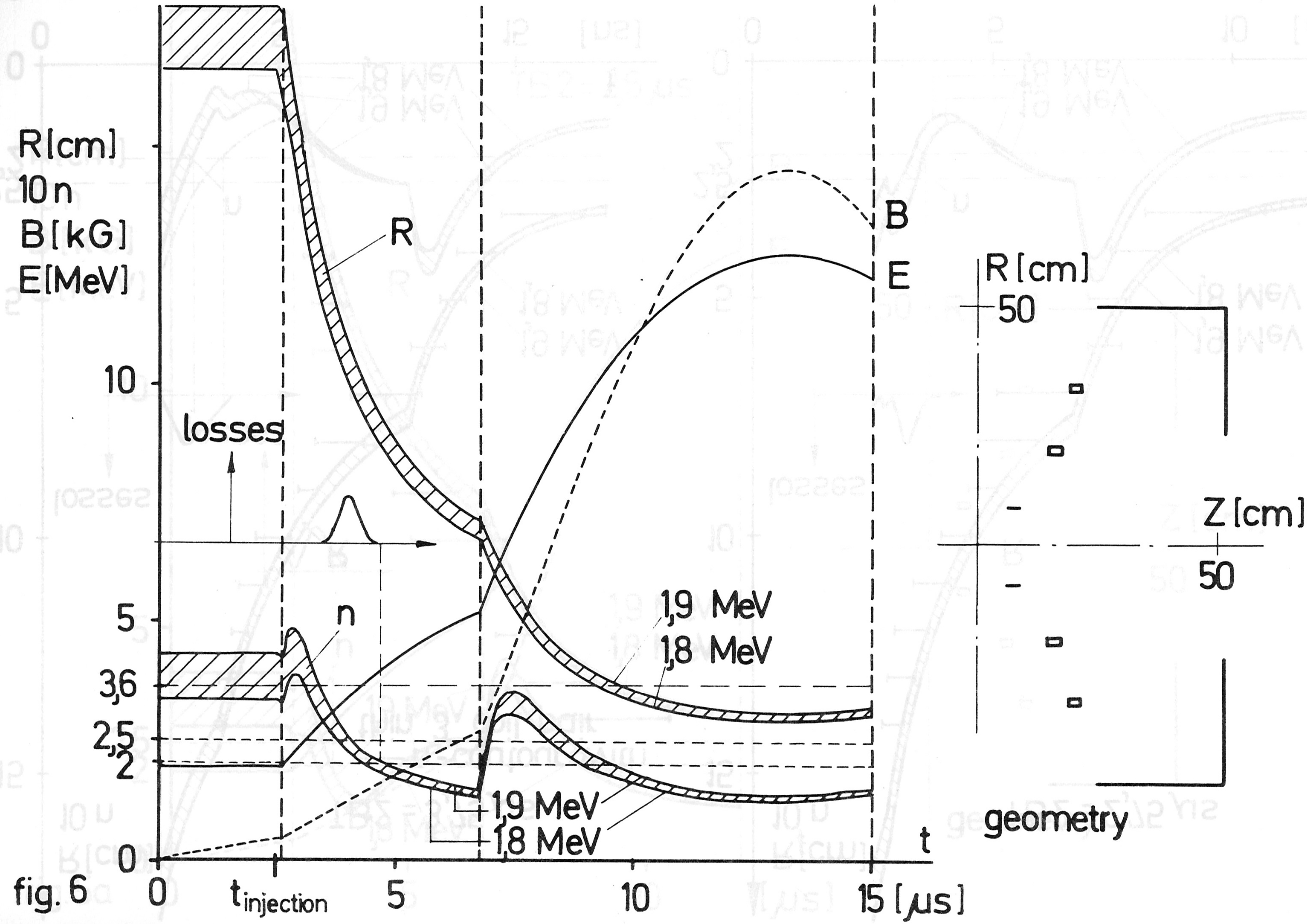
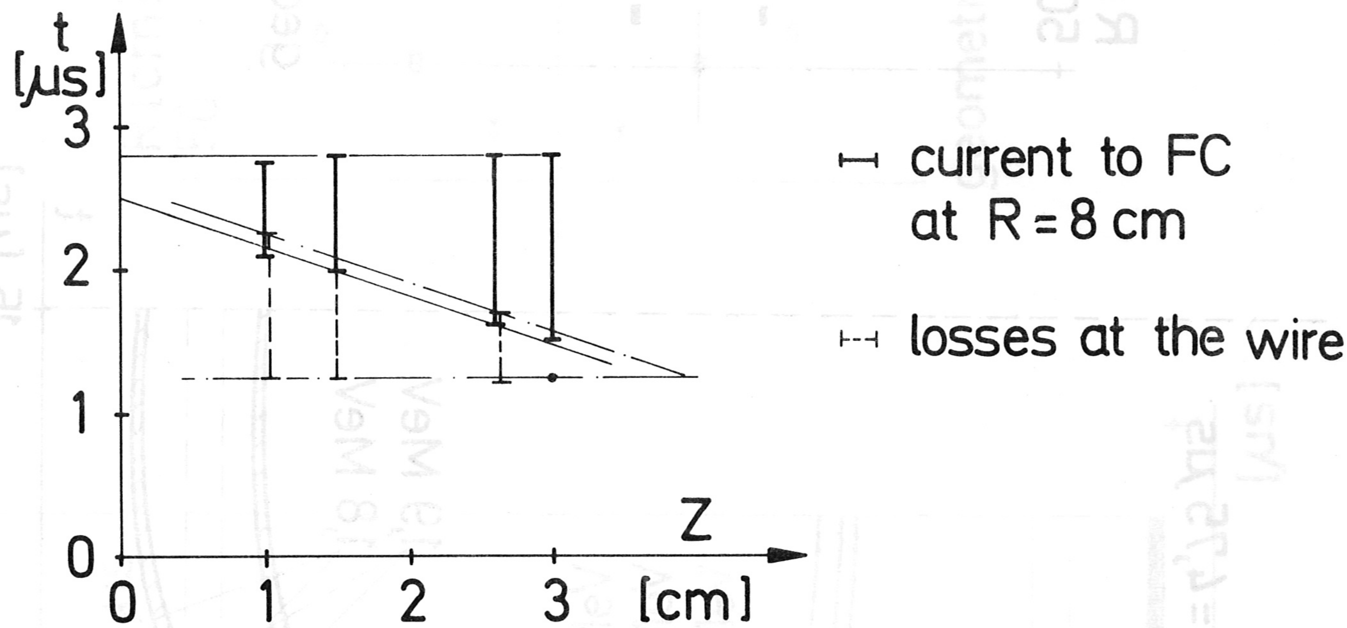
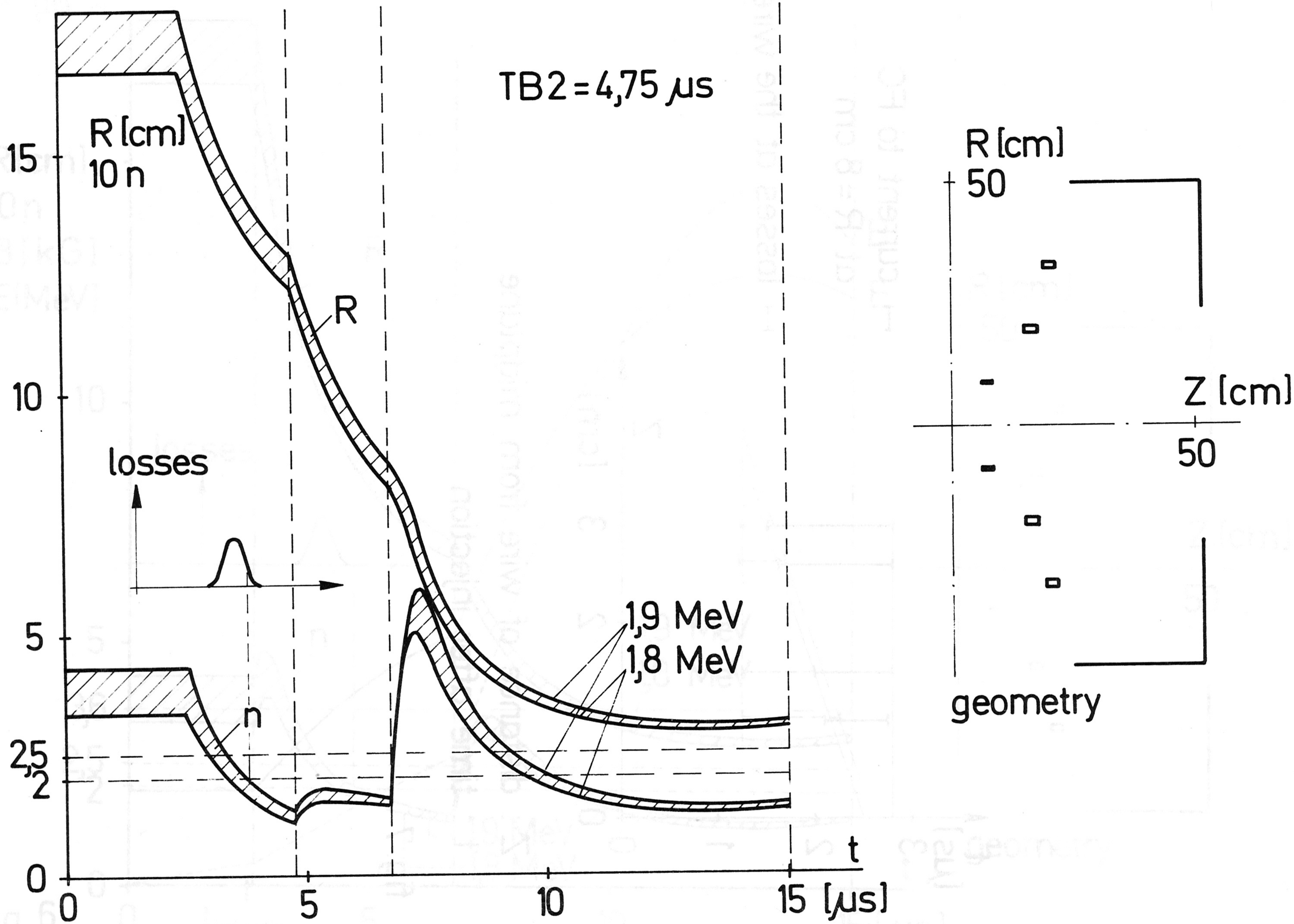

R [cm]
10 n
B [kG]
E [MeV]
10
5
3,6
2,5
2
0
0
t_injection
5
10
15 [μs]
t
losses
R
n
B
E
1,9 MeV
1,8 MeV
1,9 MeV
1,8 MeV
R [cm]
50
Z [cm]
50
geometry

fig. 6



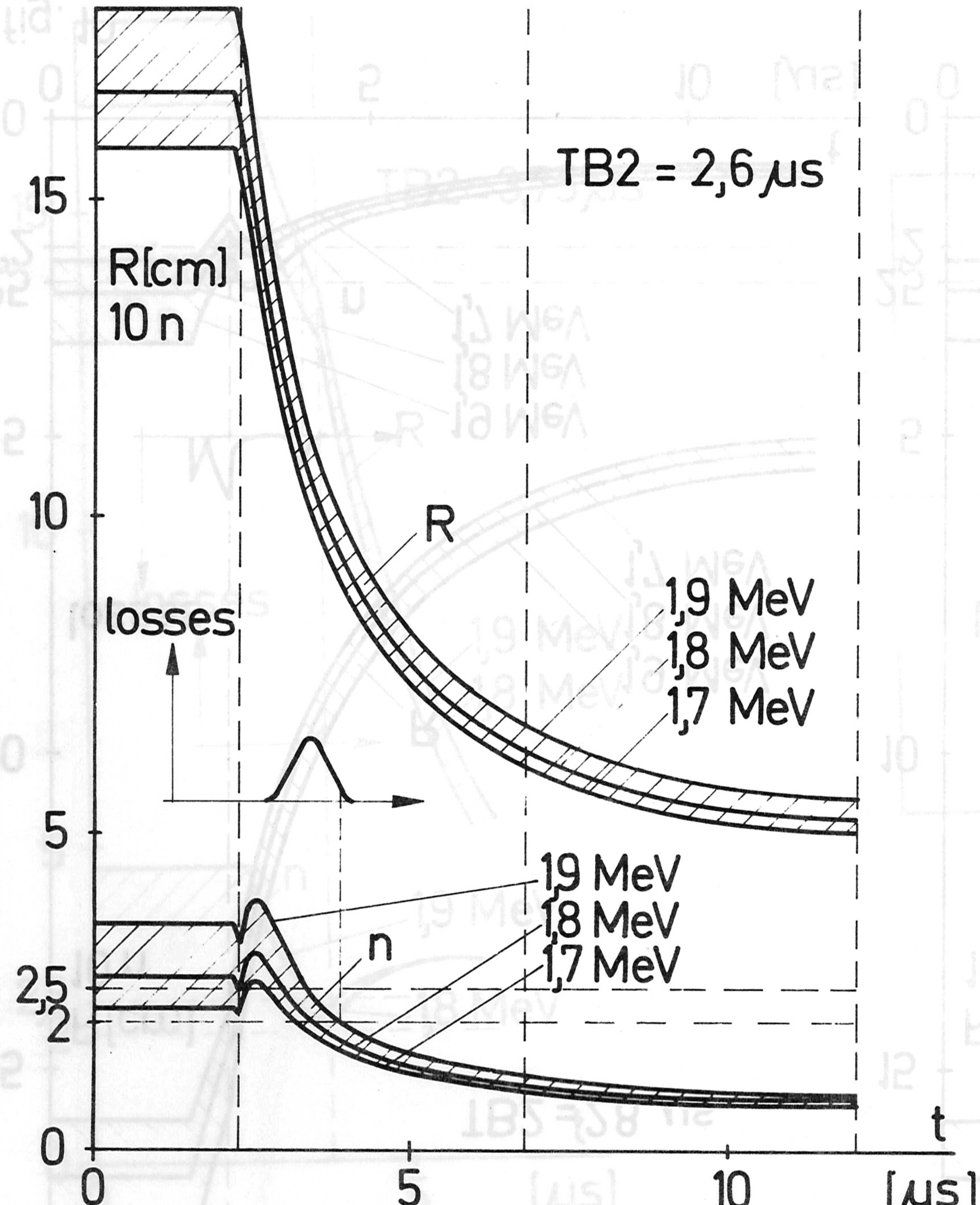
Z : distance of wire from midplane
t : time after injection

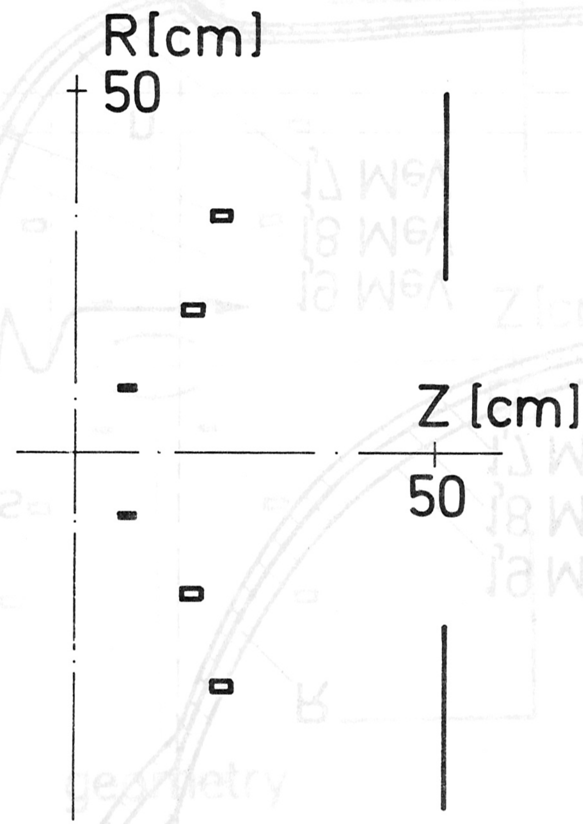
fig. 7



TB2 = 4,75 μs
R [cm]
10 n
15
10
5
2,5
2
0
losses
R
n
1,9 MeV
1,8 MeV
t
0
5
10
15 [μs]
R [cm]
50
Z [cm]
50
geometry

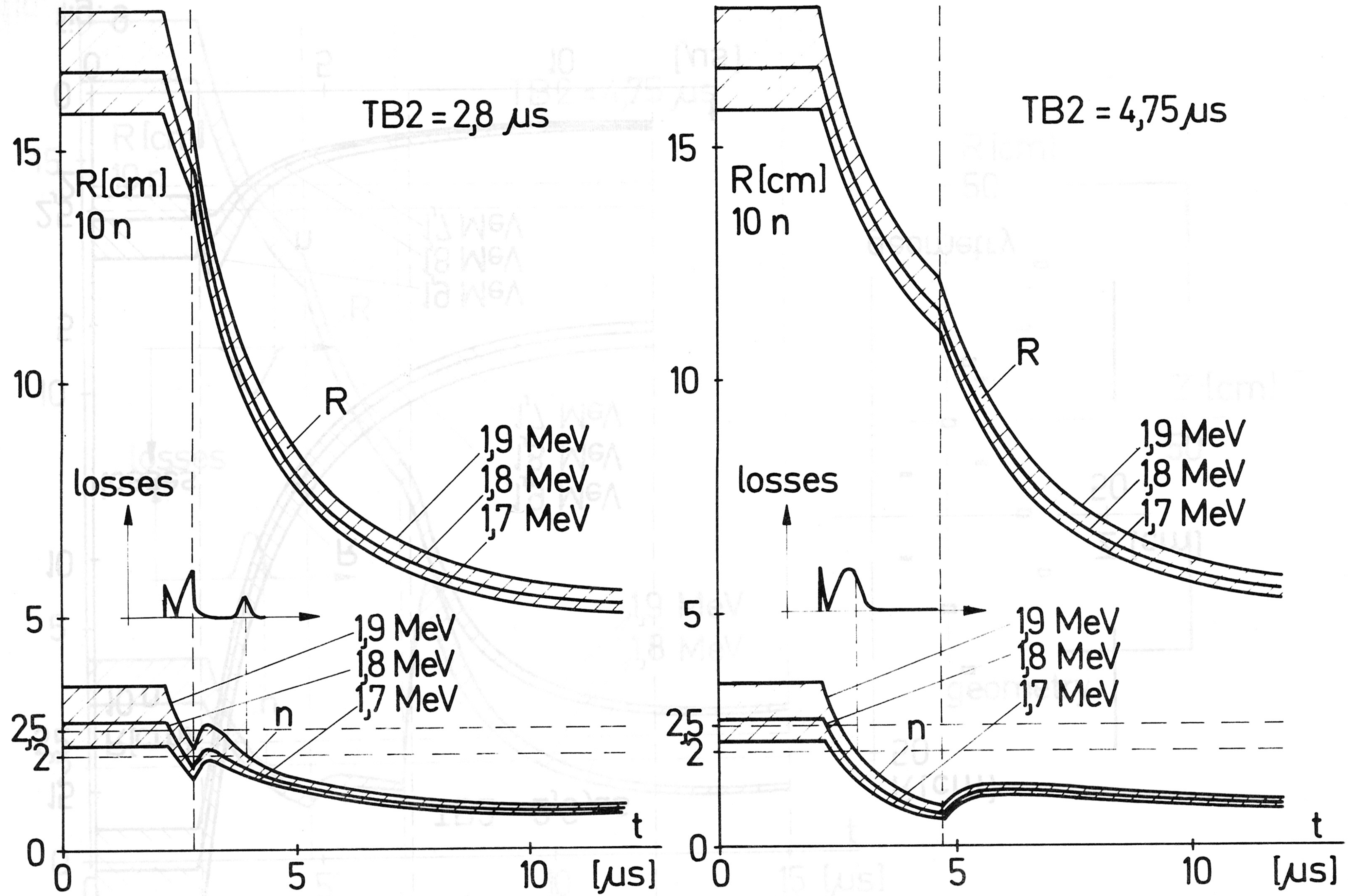
fig. 8





geometry

fig. 9


TB2 = 2,8 μs
R[cm]
10 n
losses
R
1,9 MeV
1,8 MeV
1,7 MeV
n
1,9 MeV
1,8 MeV
1,7 MeV
t
[μs]
TB2 = 4,75 μs
R[cm]
10 n
losses
R
1,9 MeV
1,8 MeV
1,7 MeV
n
1,9 MeV
1,8 MeV
1,7 MeV
t
[μs]
fig. 10

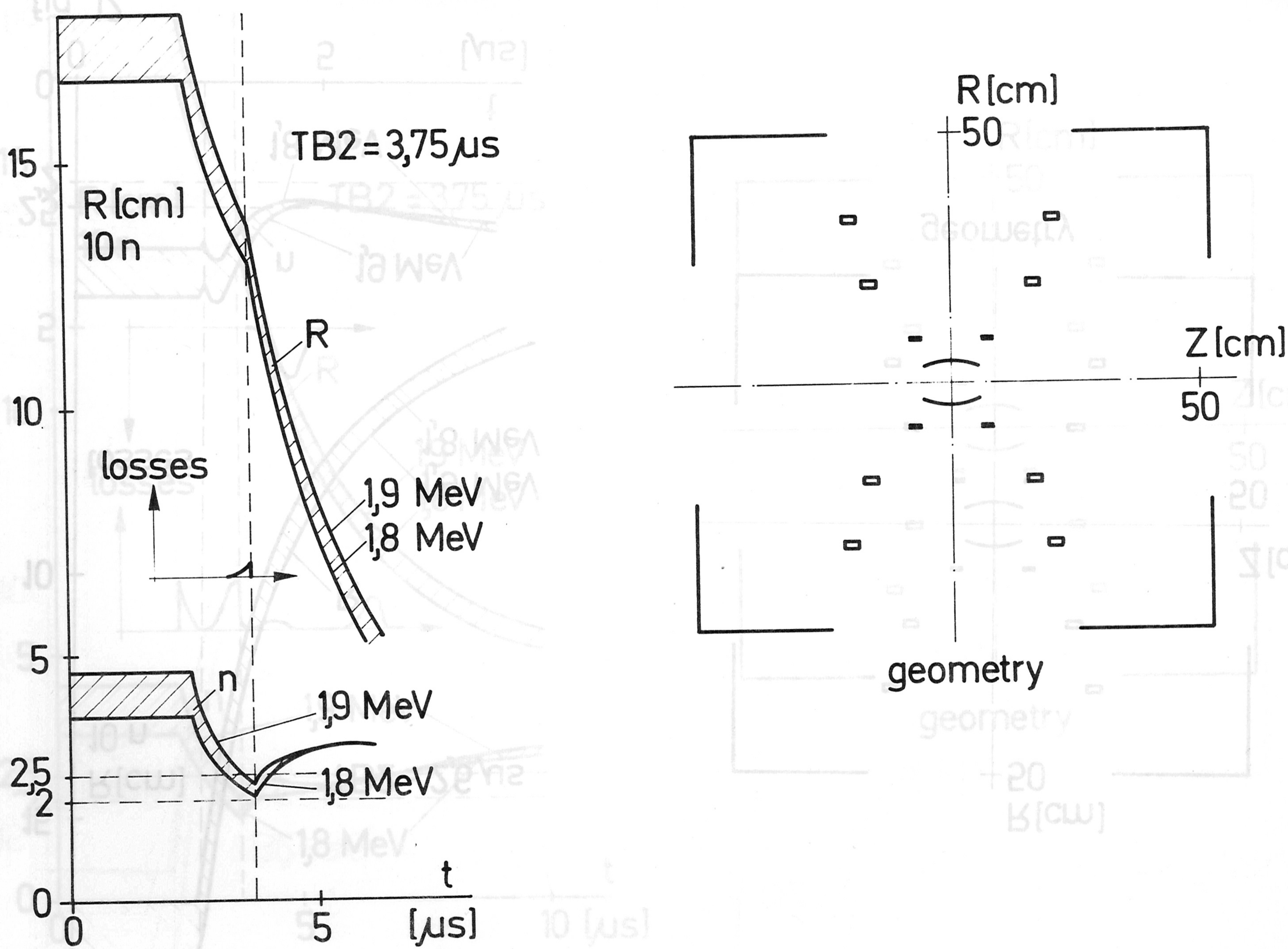

TB2 = 3,75 µs
R [cm]
10 n
losses
R
n
1,9 MeV
1,8 MeV
1,9 MeV
1,8 MeV
15
10
5
2,5
2
0
0
5
t
[µs]
R [cm]
50
Z [cm]
50
geometry

fig. 11

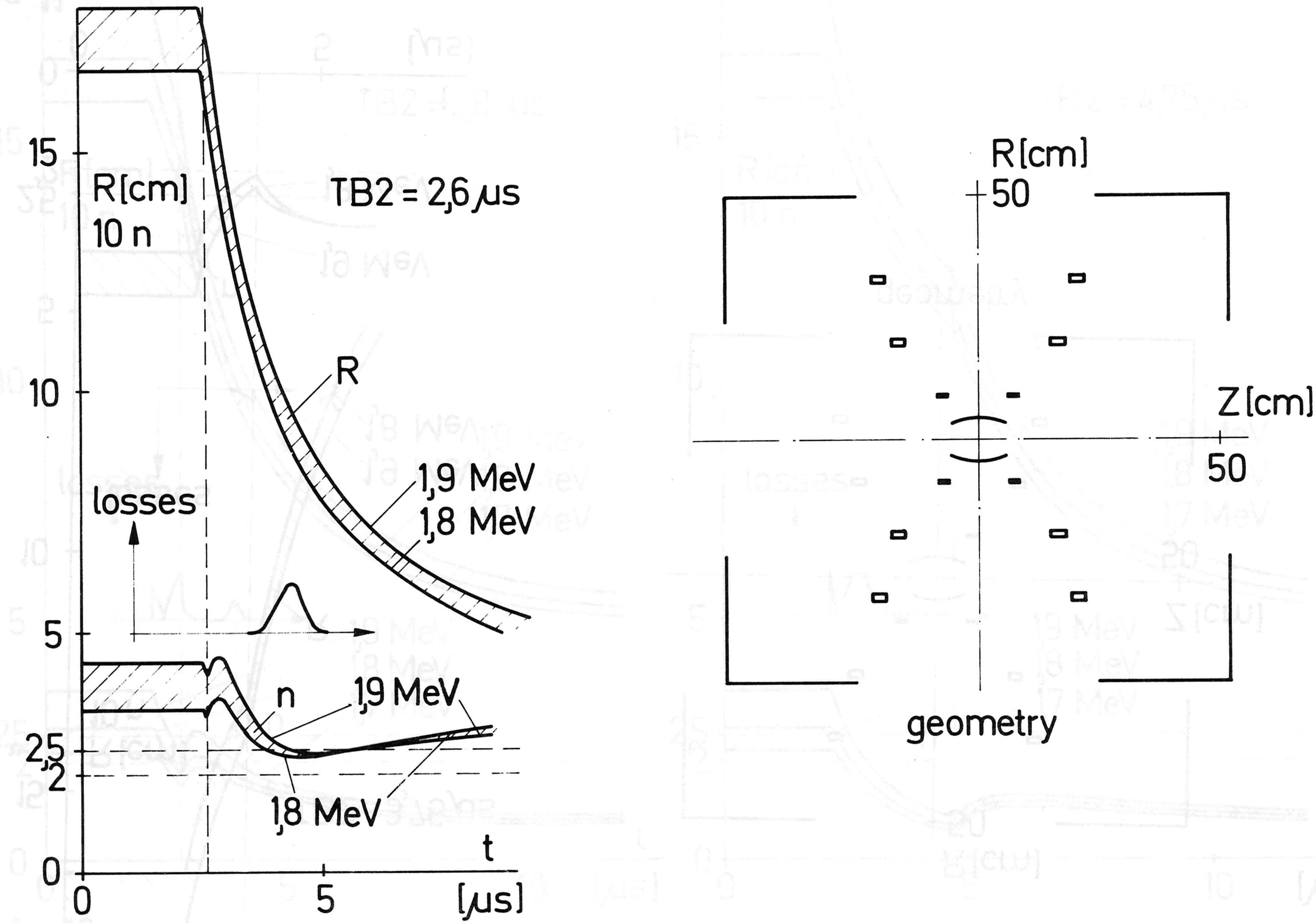

R[cm]
10 n
TB2 = 2,6 μs
15
10
5
2,5
2
0
R
losses
1,9 MeV
1,8 MeV
n
1,9 MeV
1,8 MeV
t
0
5
[μs]
R[cm]
50
Z[cm]
50
geometry

fig. 12

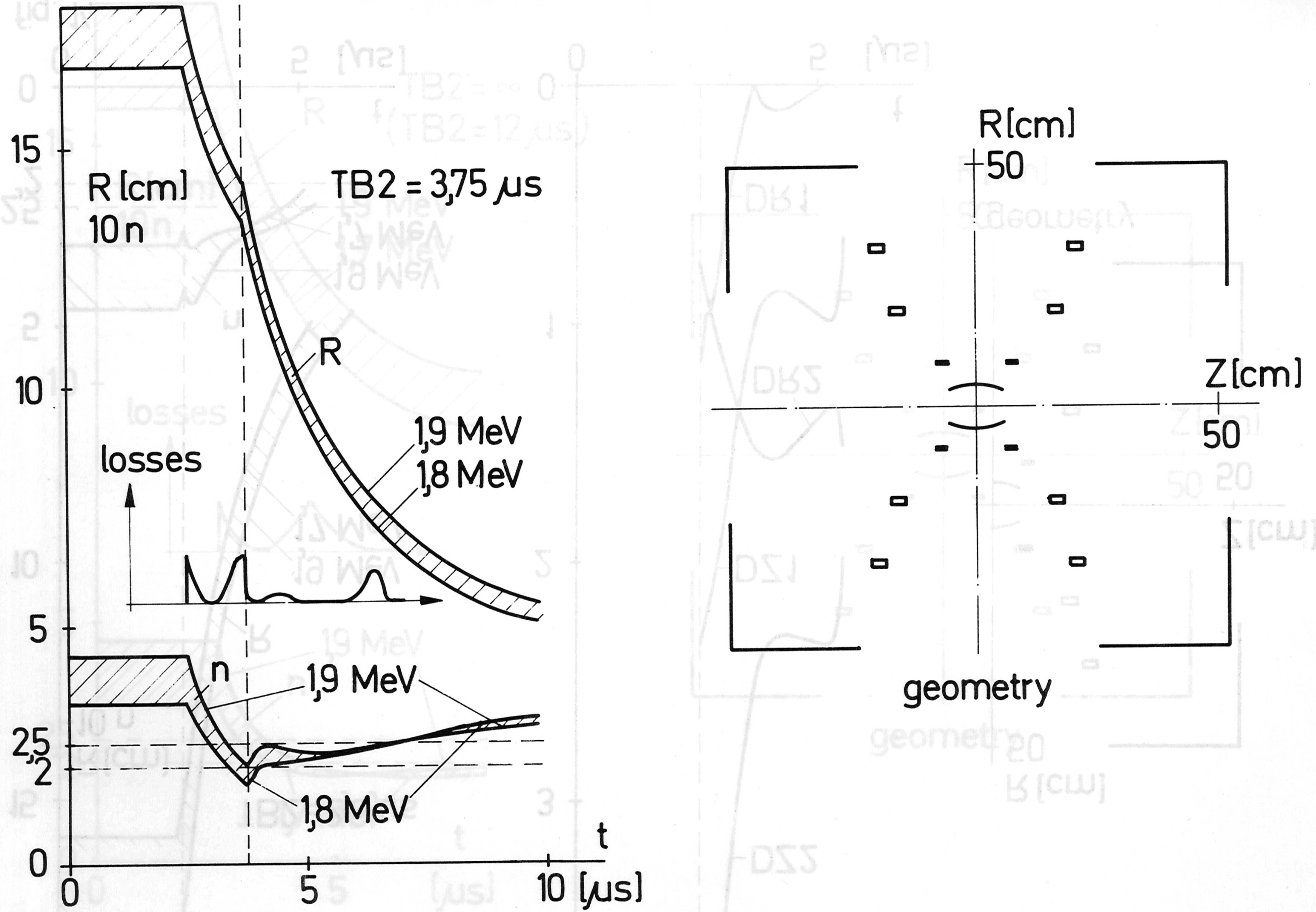

R [cm]
10 n
TB2 = 3,75 µs
R
1,9 MeV
1,8 MeV
losses
n
1,9 MeV
1,8 MeV
15
10
5
2,5
2
0
0
5
10 [µs]
t
R [cm]
50
Z [cm]
50
geometry

fig. 13

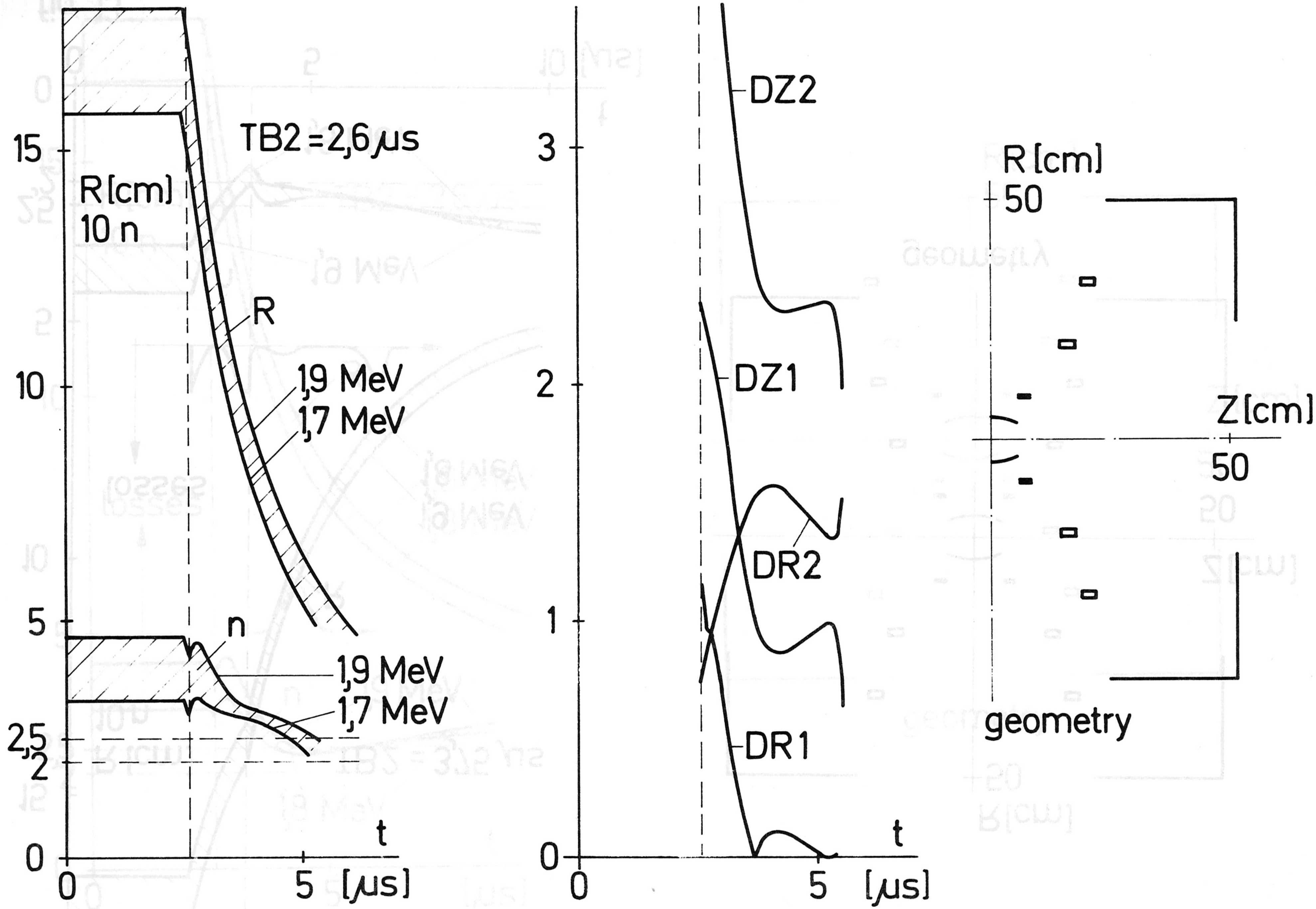
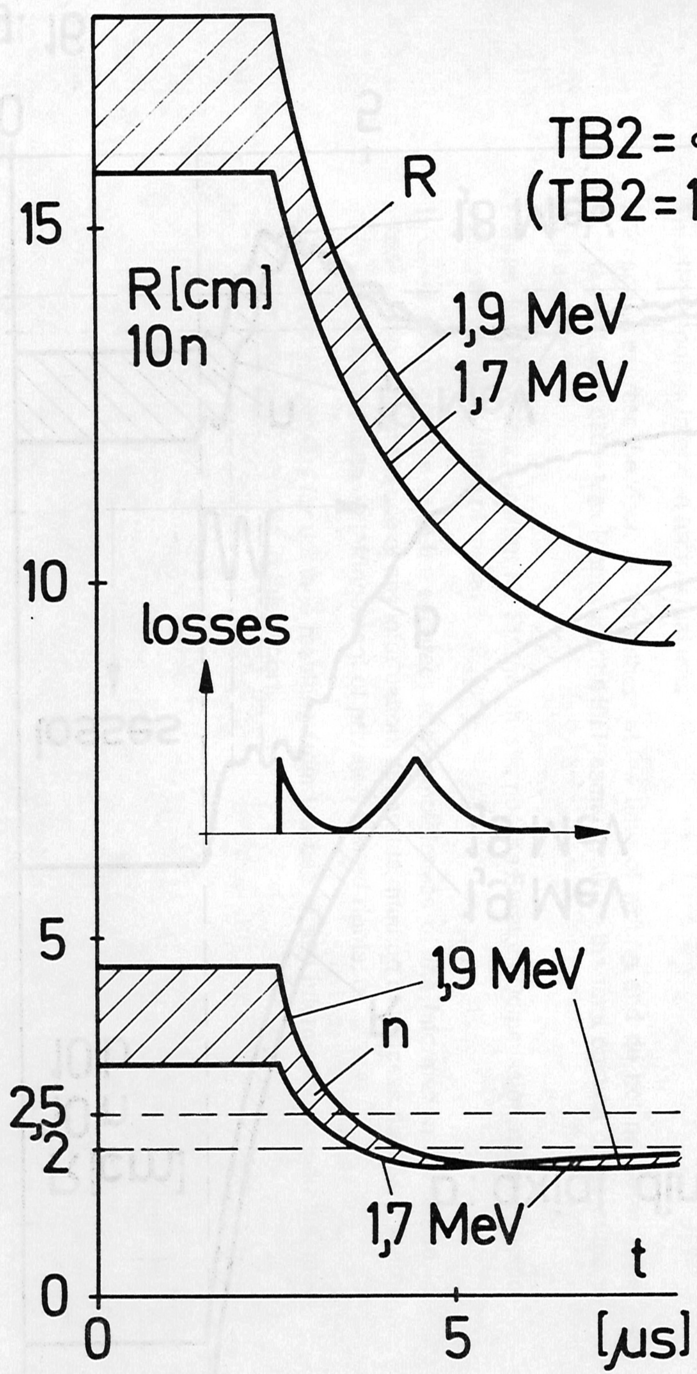
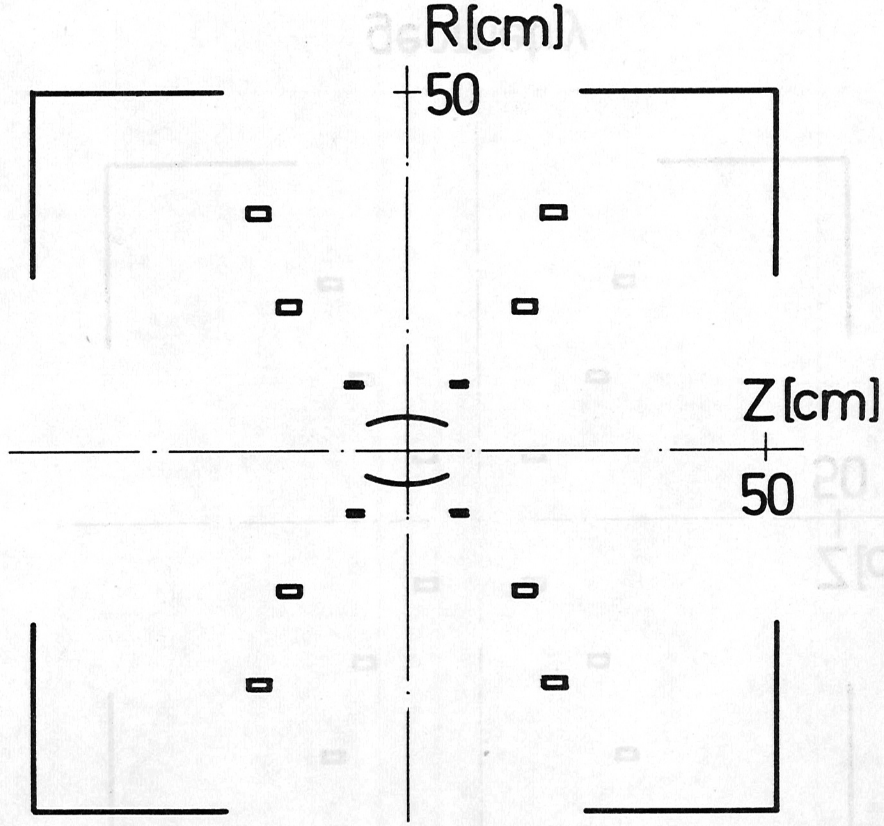

TB2 = 2,6 μs
R [cm]
10 n
R
1,9 MeV
1,7 MeV
n
1,9 MeV
1,7 MeV
t
[μs]
DZ2
DZ1
DR2
DR1
t
[μs]
R [cm]
Z [cm]
geometry

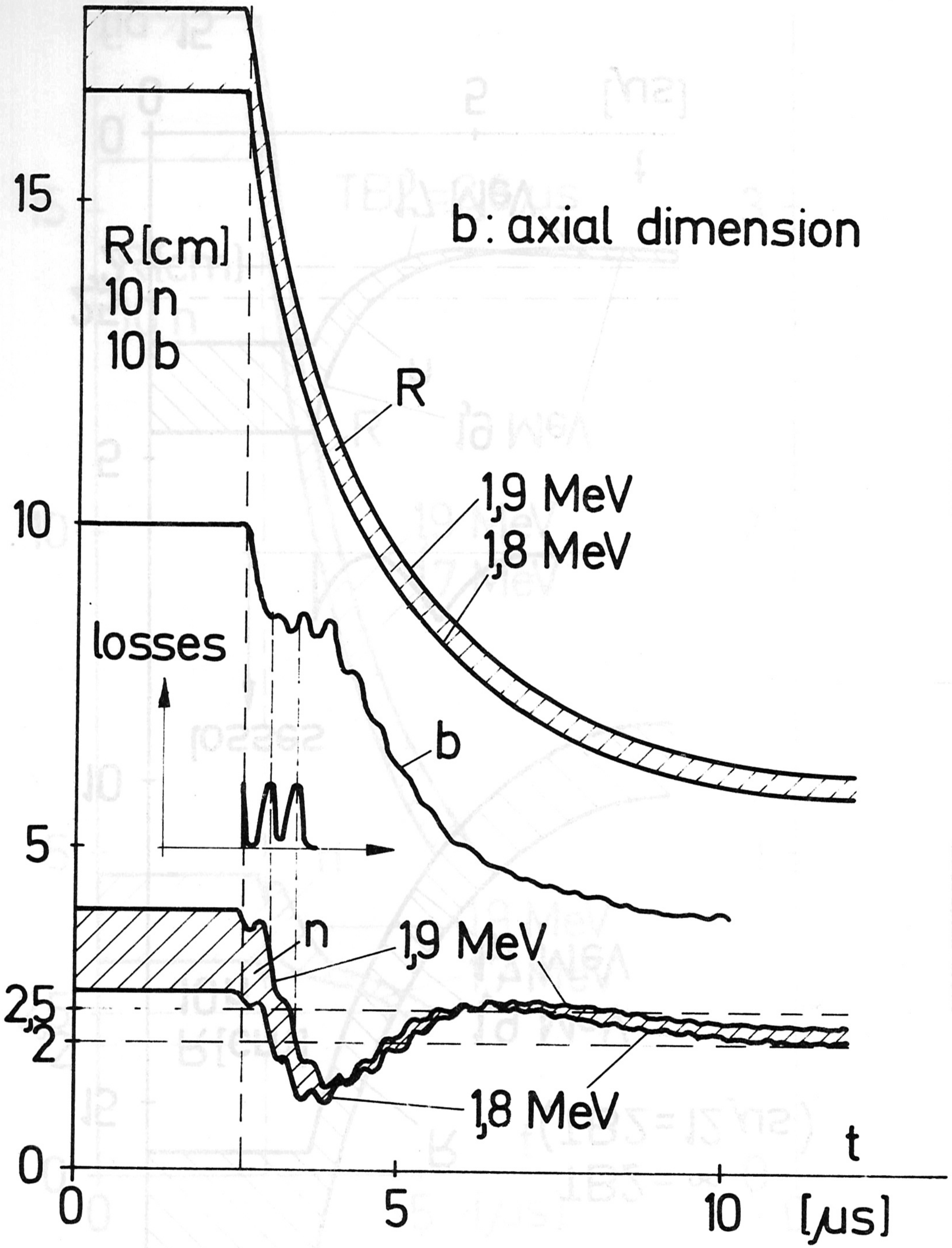
fig. 14





geometry

fig. 15


15
10
5
2,5
2
0
R [cm]
10 n
10 b
b: axial dimension
R
1,9 MeV
1,8 MeV
losses
b
n
1,9 MeV
1,8 MeV
t
0
5
10
[μs]

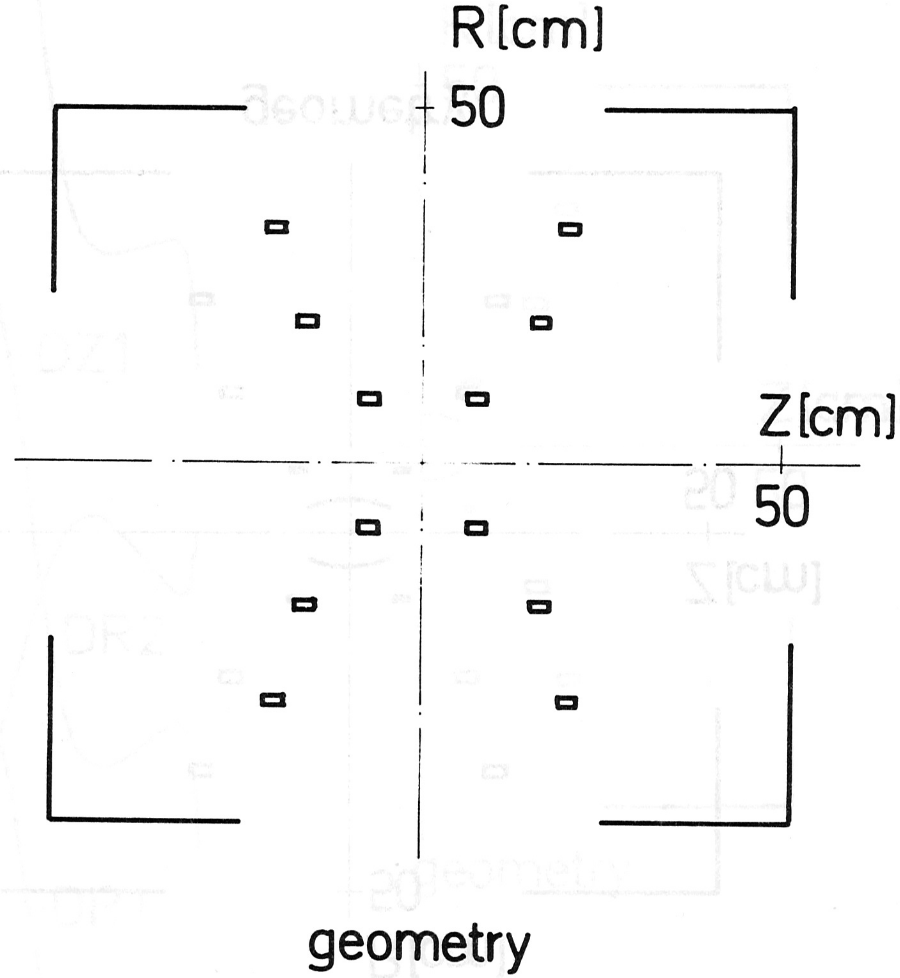

R [cm]
50
Z [cm]
50
geometry

fig. 16