Investigations on Preionization for Toroidal High-Beta-Experiments

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Abstract

Preionization is achieved in toroidal geometry by induced azimuthal currents. Favourable breakdown properties down to filling pressures of 3 mTorr D_2 and suitable preionization plasmas were established by application of a rf-predischarge and superposition of small magnetic fields with only 10 kVolts potential difference around the 200 cm long torus circumference. Detailed studies have been performed on the effectiveness of the rf-oscillations, e.g. as to their frequency and to their amplitude, and on the achievement of a stable and clean preionization plasma with only neglegible amounts of plasma currents present.

A systematic investigation on toroidal preionization covering filling pressures between about 5 and 50 mTorr has been carried out by Ellis and Firth (1) for the "Toroidal High-Beta-Experiment" under preparation at the Culham Laboratory. It was demonstrated that preionization of deuterium gas in a torus with about 2 meter circumference length could be attained in a relatively simple way by induced azimuthal currents with and without superimposed azimuthal magnetic fields in the kGauss range. A 1.5 kJoule bank with a maximum charging voltage of 60 kVolts and a risetime of 2 µsec has been applied in this case to provide the primary currents in the torus shell.

In the present studies achievement of suitable toroidal preionization was intended principally along the same lines (2). In order to reduce the danger of adverse coupling of the preionization circuit to subsequent discharge circuits great importance was attached to the application of low charging voltages for the bank providing the primary currents. In addition, among some other practical problems, the usefulness of a preceding rf-predischarge was tested to investigate the possibilities of achieving proper breakdown conditions at very low filling pressures.

Experimental Design

A sketch of the experimental setup is shown on fig.1. The torus vessel had a major diameter of 2R = 60 cm and a minor diameter of 2r = 10.5 cm. It was surrounded by a 1 mm thick copper shell in order to simulate the current leads in case of a toroidal high energy experiment (time for penetration of alternating magnetic fields in the 1 mm thick copper shell is about 10^{-4} sec). The preionization of the gas was achieved by azimuthal currents, which were induced inside the torus vessel by primary currents (I_z-currents) in two current belts. These two belts encircled the circumference of the torus outside the copper shell on the outer and the inner major radius, respectively. Short-circuiting of induced currents in the copper shell was prevented by corresponding slits. In their construction particular care was taken that the two adjoining parts of the copper shell overlapped for 2 cm, being separated by insulating foils and leaving a space of about 0.1 cm for the slit.

The primary I_z-currents in the belts were supplied by a bank having a capacity of 46 µF and a maximum charging voltage of 16 kVolts, which corresponds to 10 kVolts potential difference along the 200 cm long belts around the torus. This relatively low value was chosen to meet the requirement of reducing the danger of adverse coupling of the preionization circuit to the subsequent discharge circuits. Correspondingly the quarter period used was relatively long. It had a value of 10 µsec and enabled breakdown in the same quarter period with delaytimes of up to 7 µsec. The I_z-current circuit was furnished with crowbar switches to allow for shortcircuiting at will the primary currents in the belts at any moment within the first quarter period. In addition, for one set of experiments the 46 µF bank was devided into two separate banks of 23 µF each. The first 23 µF bank was used as before to provide the I_z-currents in the belts for achievement of breakdown and toroidal preionization in the deuterium filling gas. In this case the quarter period had a value of 8 µsec only and the 16 kVolts charging voltage of the bank corresponded to merely 6.7 kVolts potential difference along the 200 cm long belts around the torus. Some time after breakdown inside the torus a second 23 µF bank was used to cancel the I_z-currents from the first discharge. The second bank was charged to the same voltage as the first 23 µF bank (e.g. 16 kVolts) but was then connected to the belts in opposite direction.

In addition to the induced currents azimuthal magnetic fields of up to 5 kGauss could be generated inside the torus by separate meridional windings with a corresponding B_z-bank. This slowly varying magnetic field had a risetime of 23 µsec.

Finally, it was possible to investigate the breakdown behaviour of deuterium in the presence of a preceding rf-discharge ringing at frequencies between 4 and 17 MHz. Its electrical circuit, which was designed basically according to a proposal of R.Wilhelm (3), is sketched in fig.2. Up to 8 pairs of loops around the smaller diameter of the torus vessel - two of which are shown in the sketch - were equidistantly distributed along the circumference of the vessel. Together with the toroidal copper shell they formed the capacity (about 10 pF each) of the rf-oscillatory circuit, while the secondary windings of a non-linear transformer together with some additional windings for adjustment of the frequency constituted the inductance (1 to 10 µHy). The ringing of this circuit was restarted every 4 µsec by the zero-passages of the current in a small primary oscillatory circuit as demonstrated in fig. 2. The average peak to peak voltage of these rf-oscillations was adjustable up to about 10 kVolts by altering the coupling between the primary and the secondary windings of the transformer.

Breakdown Properties of the Toroidal Discharges

Before discussing the breakdown properties of the deuterium gas in the toroidal arrangement the distribution of the electric fields inside the torus vessel before breakdown is briefly considered. It corresponds to the equivalent situation in the theta pinch geometry which has been discussed in the past by several authors, for instance by Chodura (4), by Allen and Segre (5), and by Malesani and coworkers (6,7). This initial distribution of the electric field inside the torus results from the superposition of two contributions, namely of the curl-field, which is due to the increasing I_z-currents in the belts and which is in the azimuthal direction of the torus, and of the electric potential field from charges on the surface of the electric lead outside the torus vessel, which in the present arrangement is the copper shell rather than the current belts. The superposition of these two contributions in the very initial phases results in a total electric field which has normal components only at the surface of the conductive shell and which concentrates in the vicinity of the slits which are introduced to prevent short-circuiting of induced currents in the copper shell. In this early phase charge carriers initially formed hit the inner walls of the vessel following a relatively short path without a great chance for further ionization collisions with the deuterium molecules in the torus volume. By corresponding accumulation of such charge carriers on the inner vessel surface the potential field is progressively shielded and the electric field inside the torus becomes more and more governed by the curl-field contribution. This azimuthal electric field then provides a longer path for the charge carriers inside the torus with correspondingly more ionization collisions and a rapid increase of the density of charge carriers can develop.

In the experiment the breakdown properties of the deuterium gas were observed in the presence of different superimposed magnetic fields. For this purpose the breakdown characteristics are defined as the relationship between the deuterium filling pressure p_o(mTorr) and the delaytime Δt (μsec) between start of the I_z-currents and the moment of breakdown.

Some of the results are shown on fig.3. They refer to the case of a charging voltage of $U_{o,Iz}$ = 16 kVolts and a capacity of C = 46 μF of the bank for the I_z-currents. In this diagram every breakdown characteristic at a particular superimposed azimuthal magnetic field $B_{o,z}$(kGauss) is tentatively summarized by a hyperbolic relationship between p_o and Δt:

$$p_o \times \Delta t = \text{const.}$$

The plotted values connected by the solid line refer to the case where no rf-predischarge was applied. They indicate:

(i) The approximation of the breakdown characteristics by the hyperbolic relationship gives a suitable representation of the results, which were obtained for deuterium filling pressures from 50 mTorr on downwards and which fit the respective values within the error brackets shown.

(ii) At complete absence of superimposed azimuthal magnetic fields breakdown with delaytimes $\Delta t \leq 7$ µsec could only be achieved for filling pressures $p_o > 20$ mTorr, if no rf-predischarge was used.

(iii) Application of small $B_{o,z}$-fields improved the breakdown behaviour considerably: At $B_{o,z} = 700$ Gauss breakdown occured down to filling pressures of $p_o \approx 3$ mTorr. This can be understood from an extended path of accellerated charge carriers inside the torus volume before they are lost for ionization processes through wall contact.

(iv) At higher $B_{o,z}$-fields the breakdown behaviour worsened again. This is attributed to the fact that screening of the electric potential field on the inner vessel surface by charge carriers is increasingly impeded by the higher azimthal $B_{o,z}$-fields. (Larmor radius for deuterons: $r_{L,D} \approx 200 \cdot W_{\perp}^{1/2} \cdot B^{-1}$ cm ($W_{\perp}$ in eV, B in Gauss)).

Also shown in the diagram by the open circles are some results where the discharge was preceded by an rf-predischarge. The frequency of the rf-oscillatory circuit was adjusted to 8 MHz in this case and 8 pairs of loops around the smaller diameter of the torus were used. A substantial improvement of the breakdown behaviour was observed in this situation. This is further demonstrated in fig.4. Here the breakdown characteristics in the absence of azimuthal $B_{o,z}$-fields, at 46 µF bank capacity and at $U_{o,I_z} = 16$ kVolts charging voltage for the I_z-currents are compared for the cases with and without rf-predischarge. With the preceding 8-MHz-rf breakdown did occur for deuterium filling pressures down to 5 mTorr. As is also indicated by this diagram the duration of the rf-oscillations when longer than 2 µsec had only a minor effect on this improvement.

The simple hyperbolic relationship cited, however, is no longer valid: At higher filling pressures breakdown occured together with the start of the I_z-currents, whereas at low filling pressures breakdown rapidly failed. This feature was indicated in the foregoing fig. 3 by the large error brackets in the ($B_{o,z}$ = 0 Gauss)-case which only considered experimental ($p_o \times \Delta t$)-values for deuterium filling pressures below p_o = 10 mTorr. Nevertheless, for the sake of transparency average ($p_o \times \Delta t$)-values only are incorporated by open circles in fig.3 and in some of the following figures in order to indicate the improvement in the breakdown properties by the preceding rf-predischarge.

It has been verified experimentally that only very minor alterations in the breakdown characteristics resulted from an addition of about 2 % of oxygen, nitrogen or carbon (introduced by an admixture of methane) to the deuterium filling gas. Since only impurities of the order of 0.1 % were found liberated by the rf-predischarge the observed improvement in the breakdown properties is interpreted as an enhanced screening of the electric potential field by additional charges produced in the rf-oscillations, rather than by the formation of a slight ionization of the filling gas throughout in the torus volume.

In fig. 5 the results of some further studies on the breakdown behaviour are summarized. In addition to the findings in the former fig.3 the situation here is concerned with smaller charging voltages U_{o,I_z}, though at the same capacity of C = 46 µF of the bank for the I_z- currents. As may be noticed from the plotted curves no breakdown occured at values of the charging voltage below U_{o,I_z} = 6 kVolts, when neither a magnetic field was superimposed nor an rf-predischarge was used. Due to the application alone of the preceding 8-MHz-oscillations of 5 µsec duration (open circles in fig.5) could breakdown readily be achieved. This occurence was found down to filling pressures of $p_o \approx 5$ mTorr even in the case of U_{o,I_z} = 4 kVolts charging voltage for the I_z-current bank.

In order to obtain more comprehensive information on the prospects of the rf-predischarge in practical situations its effectiveness was investigated as a function of the number of the capacity loops along the 200 cm long circumference of the torus, the ringing frequency, and the amplitude of the rf-oscillations.

These measurements were performed with only half of the total bank capacity available for the I_z-currents (C = 23 µF), but with U_{o,I_z} = 16 kVolts charging voltage. Under these conditions a potential difference of 6.7 kVolts occured along the 200 cm long current belts around the torus as for the case of full bank capacity C = 46 µF, but with U_{o,I_z} = 10 Volts charging voltage. The rf-predischarge was always started 5 µsec before the I_z-current bank.

In fig. 6 the experimental results for the breakdown behaviour are presented under the above outlined conditions and at varying numbers of capacity loops. The individual breakdown characteristics are again summarized by average ($p_o \times \Delta t$)-values and are plotted as functions of the superimposed $B_{o,z}$-fields. The frequency of the rf-oscillations was adjusted to 8 MHz during this set of experiments and their average peak to peak amplitude was about 10 kVolts. For comparison the situation observed in the absence of the rf-predischarge is also incorporated in the diagram.

The results in fig. 6 reveal an improvement of the breakdown behaviour by the preceding rf-oscillations which at higher superimposed $B_{o,z}$-fields was independent of the number of pairs of rf-loops. At low $B_{o,z}$-values, however, this improvement reduced as the distance between the individual loops increased, and the preceding rf became nearly ineffective if the superimposed $B_{o,z}$-field was absent at all and if there were less than about 1 loop per meter. These findings are to be expected from the comments made before: With no $B_{o,z}$-fields the reach of the additional charges from the rf-oscillations is restricted primarily to the vicinity of the loop location. The charges are guided further around the torus, however, when superimposed magnetic fields are present and are then eventually able to screen the electric potential field everywhere along the inner vessel surface.

The breakdown characteristics revealed complete screening of the potential field after 5 µsec (at 20 mTorr filling pressure) if the loops are 100 cm apart and a $B_{o,z}$-field of 400 Gauss was applied. A kinetic energy of the order of 100 eV must then be attributed to deuterons formed by the rf-oscillations. In agreement with this is the fact that the Larmor radius of such charge carriers then just coincided with the minor torus radius.

Further information about the effectiveness of the rf-predischarge was obtained by varying the frequency and the peak-to-peak amplitude of the rf-oscillations. Both investigations have been performed without superimposed $B_{o,z}$-fields and with only two pairs of capacity loops around the torus. The results are shown in fig.7 for the frequency dependence (at constant amplitude U_{rf} = 8 kVolts), and in fig. 8, for the variation of the peak to peak voltage U_{rf} (at constant frequency ν_{rf} = 8 MHz) of the rf-oscillations. Considering also the value obtained without rf-predischarge ($(p_o \times \Delta t) = 240$ (mTorr x µsec)) gave an exponential frequency dependence which could be expressed numerically by:

$$(p_o \times \Delta t) = 240 \cdot \exp\left(-\frac{\nu_{rf}\,(\mathrm{MHz})}{6}\right) \quad (\mathrm{mTorr} \times \mu\mathrm{sec})$$

for the present experimental conditions. For the variation of the rf-amplitude U_{rf} a representation depending on the rf-output (U_{rf}^2):

$$(p_o \times \Delta t) = 240 \cdot \left[1 + 0.033(U_{rf}(\mathrm{kVolts}))^2\right]^{-1} \quad (\mathrm{mTorr} \times \mu\mathrm{sec})$$

provided a slightly better fit to the experimental data than an exponential slope such as:

$$(p_o \times \Delta t) = 240 \cdot \exp\left(-\frac{U_{rf}\,(\mathrm{kVolts})}{7}\right) \quad (\mathrm{mTorr} \times \mu\mathrm{sec}).$$

An additional set of experiments was concerned with the question of whether the breakdown behaviour could be improved by varying the number of insulated slits in the toroidal copper shell. It was felt that some deconcentration of the electric potential field should be a consequence of multiplication of these slits. As can be seen from fig. 9 the experimental results confirmed this supposition. The number of equidistant slits around the torus circumference was varied from 1 up to 8 with the consequence that a decrease in the $(p_o \times \Delta t)$-values by a factor of about three was indicated by the experimental findings. In these studies the complete I_z-current bank (C = 46 uF) has been used at U_{o,I_z} = 16 kVolts charging voltage but with no rf-predischarge and no superimposed $B_{o,z}$-field.

Properties of the Toroidal Preionization Plasmas

The present investigation was also concerned with the properties of the preionization plasmas achieved after breakdown.

Some of the experimental results are presented in fig. 10 for the case of p_o = 50 mTorr deuterium filling pressure and U_{o,I_z} = 16 kVolts charging voltage for the bank of the I_z-currents, with no azimuthal magnetic bias field and no rf-predischarge. In this case breakdown occured at about 3 µsec after start of the I_z-currents. The current in the plasma then rapidly exceeded values of I_{plasma} = 20 kAmperes, whereas the plasma itself was compressed within 2 µsec to a current channel of about 2 cm diameter, as illustrated in fig. 10 by the radial distribution of the meridional magnetic field B_θ.After this time the toroidal plasma column became unstable, as indicated for instance by some irreproducible peaks in the intensity of the Dβ(4860)-line and the impurity level then rapidly exceeded values of 1 %.

In order to counteract this undesired behaviour of the plasma two measures have been taken:

(i) A crowbar in the primary I_z-current circuit 1 µsec after breakdown provided a limitation of the rapidly increasing plasma current to values between 15 and 20 Amperes.

(ii) As indicated a stable equilibrium position of the toroidal preionization plasma was sought by superposition of azimuthal magnetic fields.

The success of these measures in one typical case is demonstrated in fig. 11. Again a capacity of C = 46 µF and a charging voltage of U_{o,I_z} = 16 kVolts for the I_z-current bank was chosen, but with a deuterium filling pressure of p_o = 15 mTorr. An azimuthal magnetic bias field of only $B_{o,z}$ = 400 Gauss was applied. The crowbaring of the I_z-currents 1 µsec after breakdown yielded a limitation of the plasma currents to values of about I_{plasma} = 15 kAmperes. The smooth slope of the intensity of the Dβ (4860)-line after the early peak -which was due to the heating and the compression in the initial phase of the discharge - indicated a quiet toroidal plasma column without noticeable instabilites. This stable plasma behaviour was also observed by probe measurements of the B_θ - and B_z-fields in the plasma. They showed - for example at 2 μsec after breakdown as shown in fig.11 - that the plasma current flowed fairly homogeneously across about 2/3 of the diameter of the discharge vessel with the result that the copper wall could support stabilization of the toroidal plasma column.

The ionization degree achieved in this case was derived from the Dβ (4860)- line profile and was found to be about 50 % at 15 μsec after breakdown. It agrees with former calculations of Köppendörfer (8) which predicted ionization degrees close to unity under the prevailing experimental conditions when the plasma current exceeds values of 15 kAmperes. The impurity level was only of the order of 0.1 %. These findings were not altered by the application of a preceding 8-MHz-rf-predischarge, except that the impurity level increased to about 0.2 % at 5 μsec rf-duration and to about 0.8 % at 20 μsec rf-duration.

It is further apparent from fig. 11, however, that due to the crowbar of the I_z-currents in the belts the plasma current decayed only very slowly because of the high plasma conductivity produced. In fact, the plasma current still could be traced after 100 μsec and together with it the intensity of the Dβ (4860)-line occured distinctly. This may not be an adverse feature for subsequent toroidal high energy experiments when plasma currents are to be generated in order to produce the desired confinement configuration, i.e. the screw-pinch. For some other toroidal investigations, such as high-β stellarator experiments, such plasma currents may be unwanted. Some effort has therefore been spent in finding proper means of eliminating the plasma currents in reasonably short periods of time.

A successful technique for eliminating the currents uses a second I_z-current pulse in the belts opposing the preionizing one some time after breakdown. In principle this idea could possibly be realized by a single period of ringing I_z-currents in the belts, if breakdown occurs together with the start of the I_z-currents. This was shown feasible at least above 10 mTorr filling pressure with use of a proper rf-predischarge. With the present experimental arrangement the subsequent cancellation of the plasma currents could easily be attained in the follwing way:

One half of the I_z-current bank (C = 23 uF) was chosen to achieve breakdown and preionization as outlined before. Instead of applying the crowbar of the I_z-currents some time after breakdown the second half of the I_z-current bank was applied in the opposite direction. The crowbar in both I_z-current circuits was then applied closely before the position of zero-passage of the plasma current.

The success of such a programmed preionization cycle is to be seen from fig.12. Both halves of the I_z-current bank were charged up to 16 kVolts in this case. A $B_{o,z}$-field of 300 Gauss was superimposed. The filling pressure was chosen to 15 mTorr. No rf-predischarge was applied.

In the upper part of fig. 12 the time behaviour of the potential difference in the I_z-current belts around the torus circumference, of the plasma current, and of the Dβ (4860)-line intensity in relative units is reproduced. The moments of starting the opposing I_z-current bank and the crowbar are indicated. The result was that 10 μsec after breakdown the plasma current had been indeed cancelled, within the experimental errors of less than about 1 kAmpere. The Dβ (4860)-line intensity reduced more gradually indicating a decaying preionization plasma in the superimposed magnetic field.

The indication of the stable behaviour of the preionization plasma at 2 μsec after breakdown and of the cancellation of the plasma currents at 10 μsec was supplied by probe measurements of the B_θ- and B_z-fields. They are represented in the lower part of fig.12 for the two moments of time in question. The slopes referring to the time 2 μsec, which is immediately before the start of the opposing I_z-current bank call attention to the results in fig.11. These slopes differ only in a somewhat broader plasma current distribution and in magnitude, reflecting merely the fact that a capacity of 23 μF instead of 46 μF for the I_z-current bank was applied. The corresponding ionization degree achieved was only $\alpha \approx 0.3$ which was derived from the profiles of the Dβ (4860)-line. At 10 μsec the probes indicated only very small B_θ-field components in the outer regions of the plasma, whereas the B_z-field had nearly attained a 1/R-slope similar to the vacuum case. From the Dβ(4860)-line profiles the ionization degree was determined to be $\alpha \approx 0.15$ at this time.

It has been attempted to further improve the ionization degree with applied cancellation of the plasma current. This can obviously be reached by a retarded start of the opposing I_z-current bank, thus producing higher plasma currents. Inspection of the corresponding experimental results made apparent that together with an improved ionization the subsequent cancellation of the plasma currents within a reasonably short time became increasingly difficult. If, for example, the plasma current was allowed to rise to 15 kAmperes by starting the opposing I_z-current bank at 2.5 µsec instead of 1.5 µsec the existence of the plasma current was still clearly detectable after 30 µsec corresponding to an increase of the ionization degree to $\alpha \approx 0{,}5$ at 2,5 µsec after breakdown. This is due to an enhanced conductivity of the plasma which prevents a relatively quick extinction of the initial plasma current by the inverted one which is induced after application of the opposing I_z-current bank.

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Figure Captions:

Fig. 1: Experimental setup for toroidal preionization

Fig. 2: Electrical circuit of rf-predischarge

Fig. 3: Breakdown behaviour in the torus ($p_o \times \Delta t$) for various $B_{o,z}$-fields with (open circles) and without (full circles) applied 8-MHz-rf-predischarge at $U_{o,I_z} = 16$ kVolts

Fig. 4: Breakdown characteristics ($\Delta t - p_o$) at $B_{o,z} = 0$ Gauss and $U_{o,I_z} = 16$ kVolts with and without 8-MHz-rf-predischarge

Fig. 5: Breakdown behaviour in the torus for various $B_{o,z}$-fields and values of U_{o,I_z} with and without rf-predischarge

Fig. 6: Breakdown behaviour at various $B_{o,z}$-fields as functions of the number of rf-loops

Fig. 7: Breakdown behaviour in dependency of the rf-frequency ν_{rf}

Fig. 8: Breakdown behaviour as a function of the rf-amplitude U_{rf}

Fig. 9: Influence of the number of insulated slits in the torus copper shell on the breakdown behaviour

Fig.10: Properties of the preionization plasma without $B_{o,z}$-field and I_z-current crowbar at $p_o = 50$ mTorr, $U_{o,I_z} = 16$ kVolts and C = 46 µF for the I_z-current bank

Fig.11: Properties of the preionization plasma with $B_{o,z} = 400$ Gauss and C = 46 µF for the I_z-current bank

Fig.12: Properties of the preionization plasma with applied plasma current cancellation. Experimental conditions: $B_{o,z} =$ 300 Gauss, $U_{o,I_z} = 16$ kVolts and C = 23 µF for the I_z-current bank

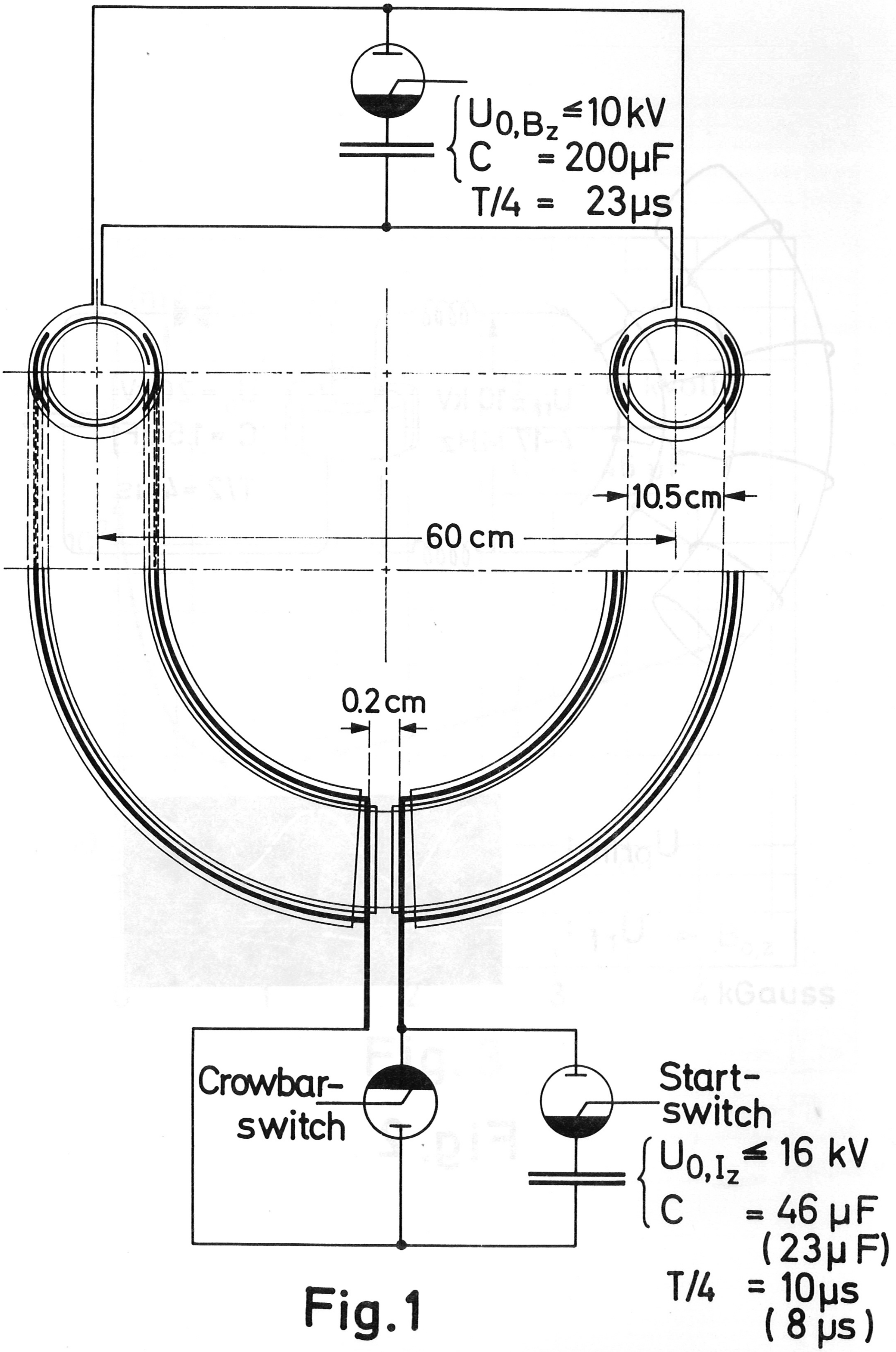

$U_{0,B_z} \leq 10\,kV$
$C = 200\,\mu F$
$T/4 = 23\,\mu s$
10.5 cm
60 cm
0.2 cm
Crowbar-switch
Start-switch
$U_{0,I_z} \leq 16\,kV$
$C = 46\,\mu F$
$(23\,\mu F)$
$T/4 = 10\,\mu s$
$(8\,\mu s)$

Fig.1

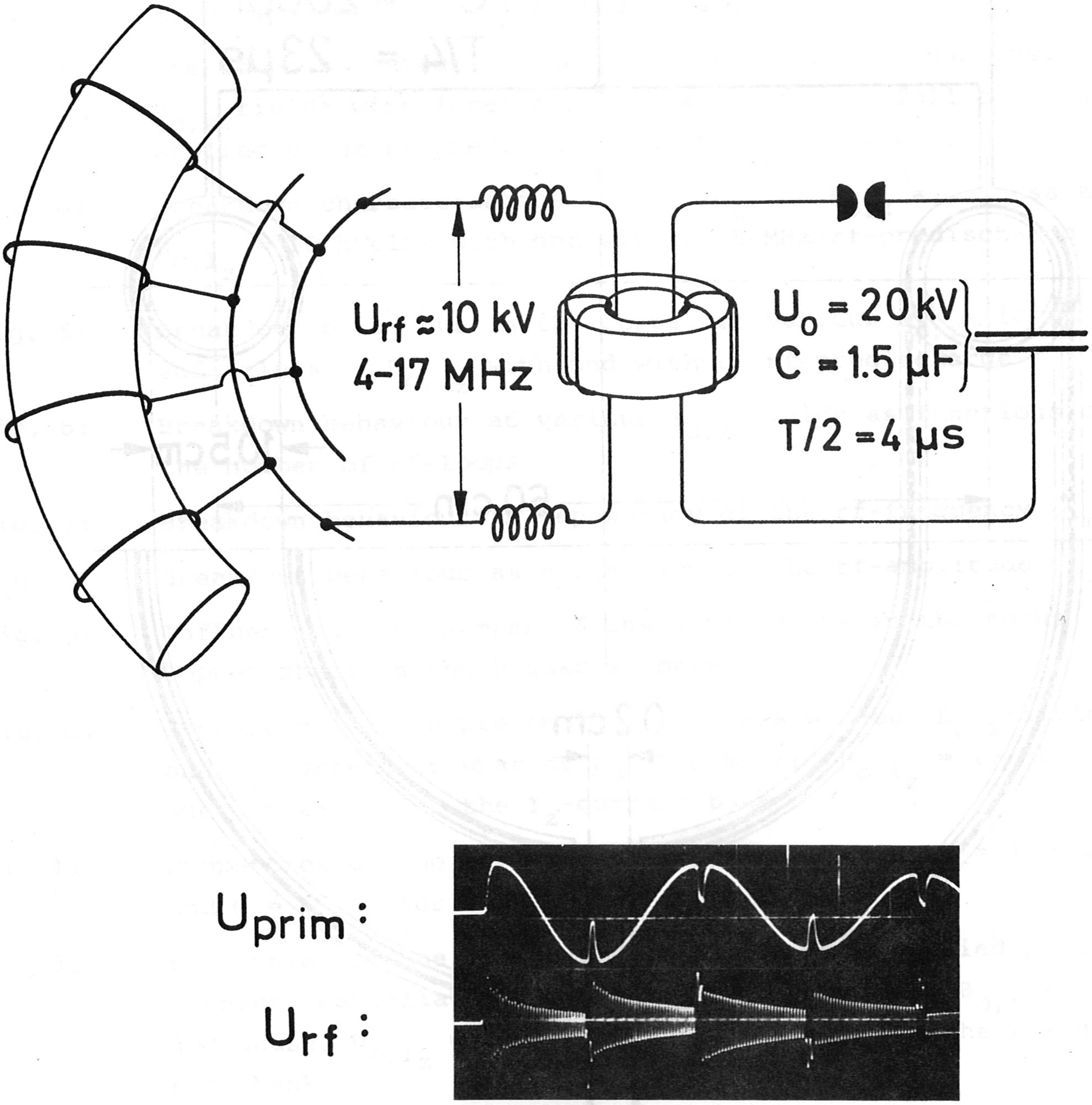


Fig. 2

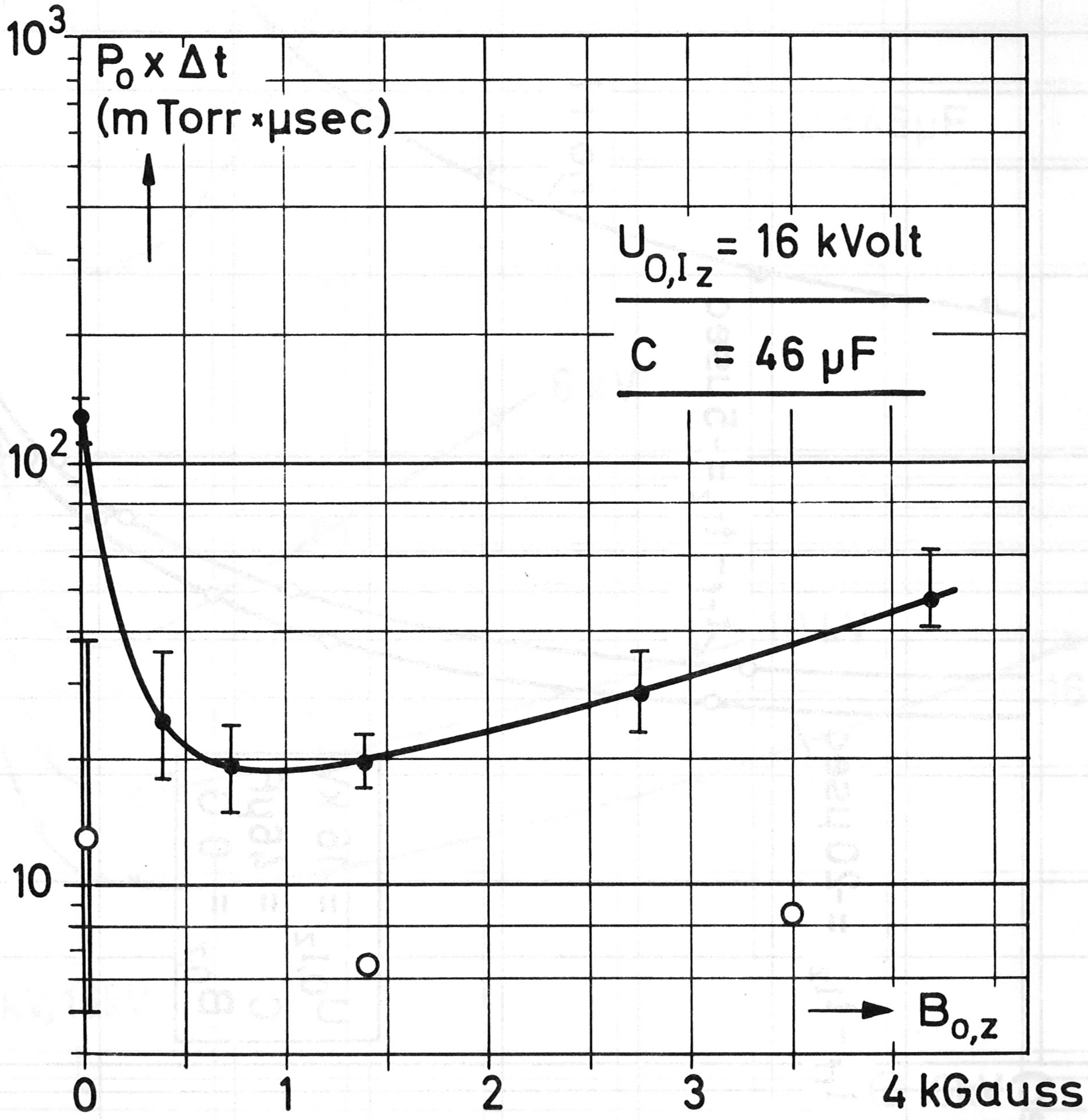

10^3
$P_0 \times \Delta t$
(m Torr × µsec)
U_{0,I_z} = 16 kVolt
C = 46 µF
10^2
10
$B_{0,z}$
0
1
2
3
4 kGauss

Fig. 3

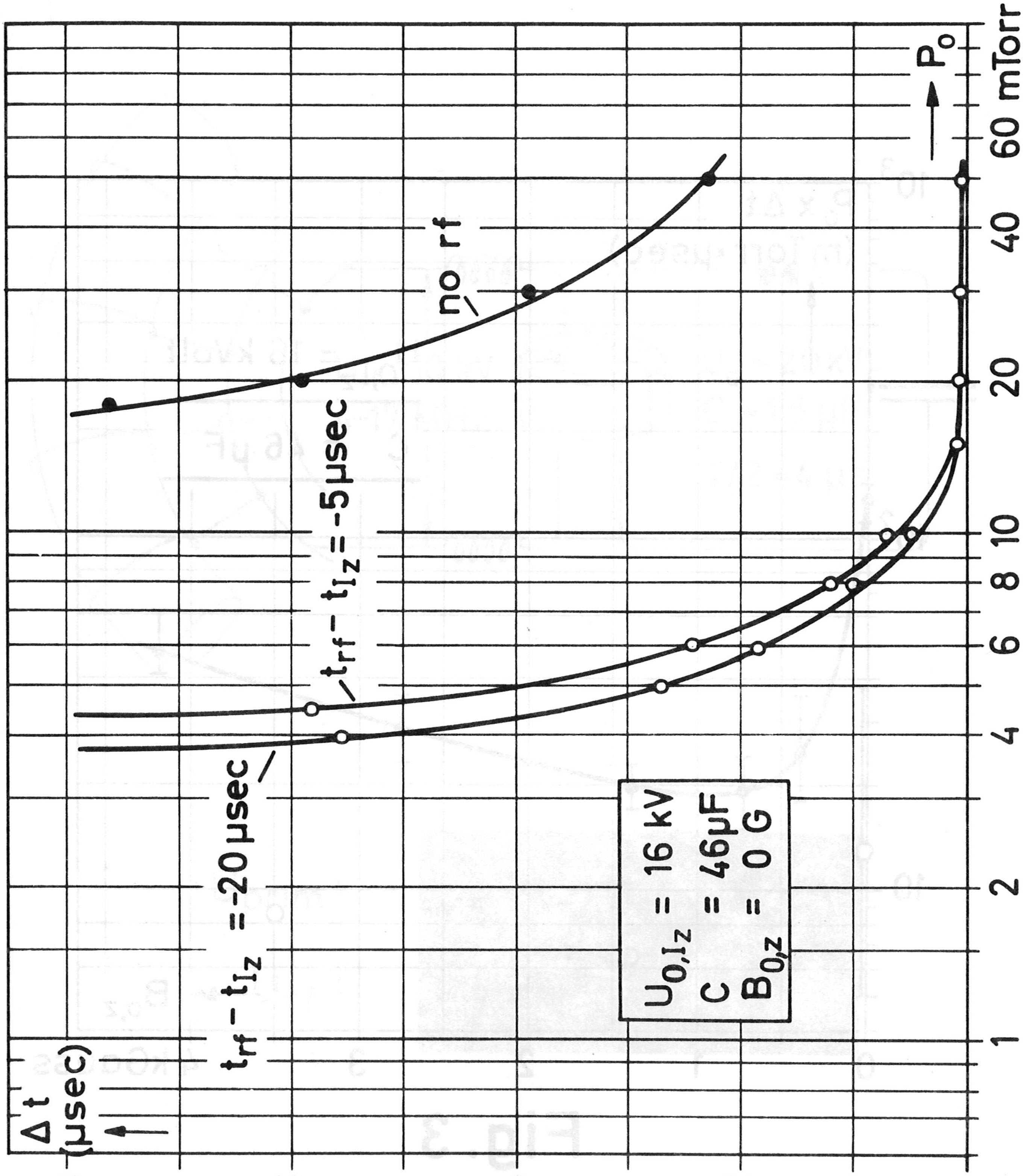
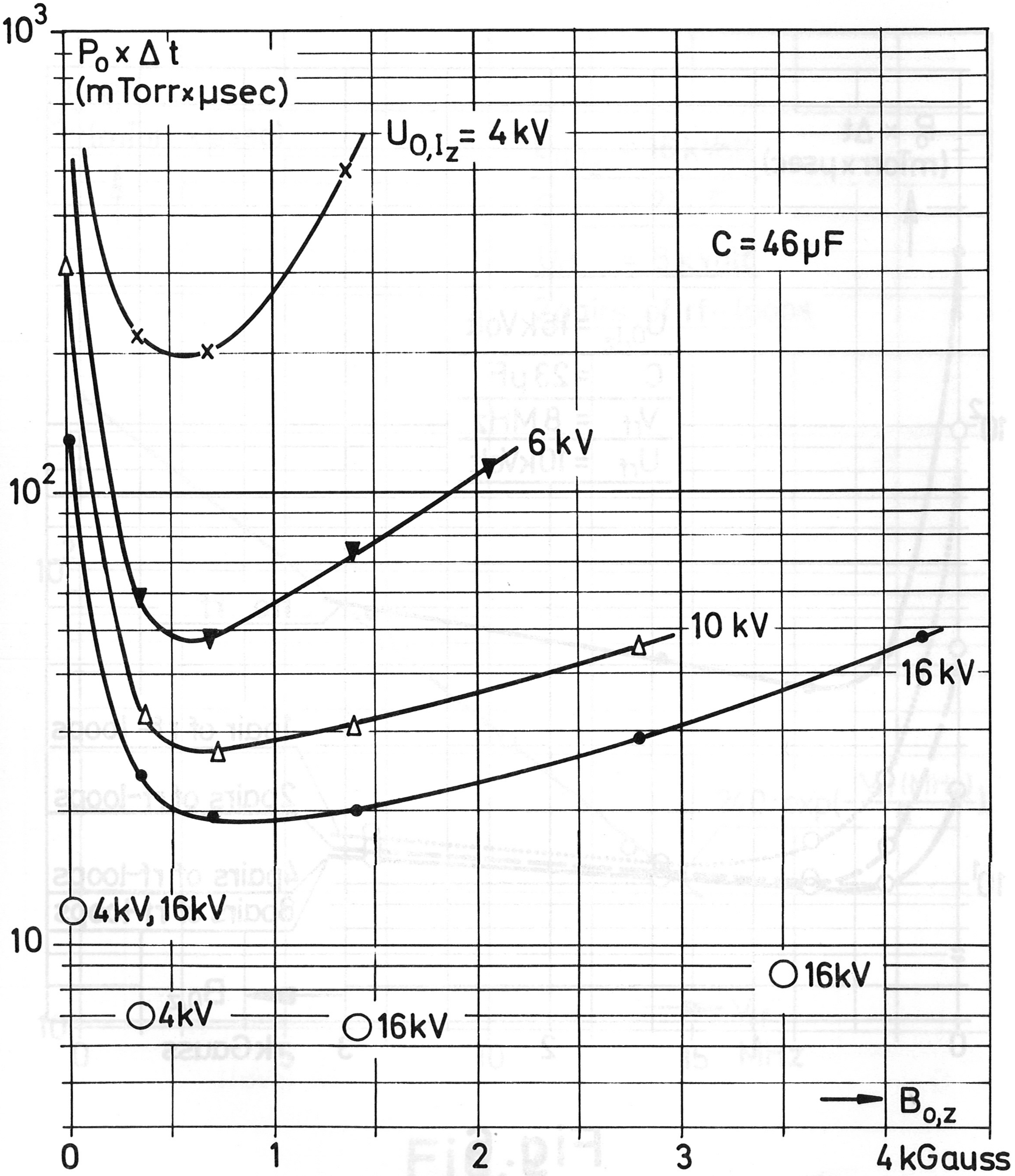
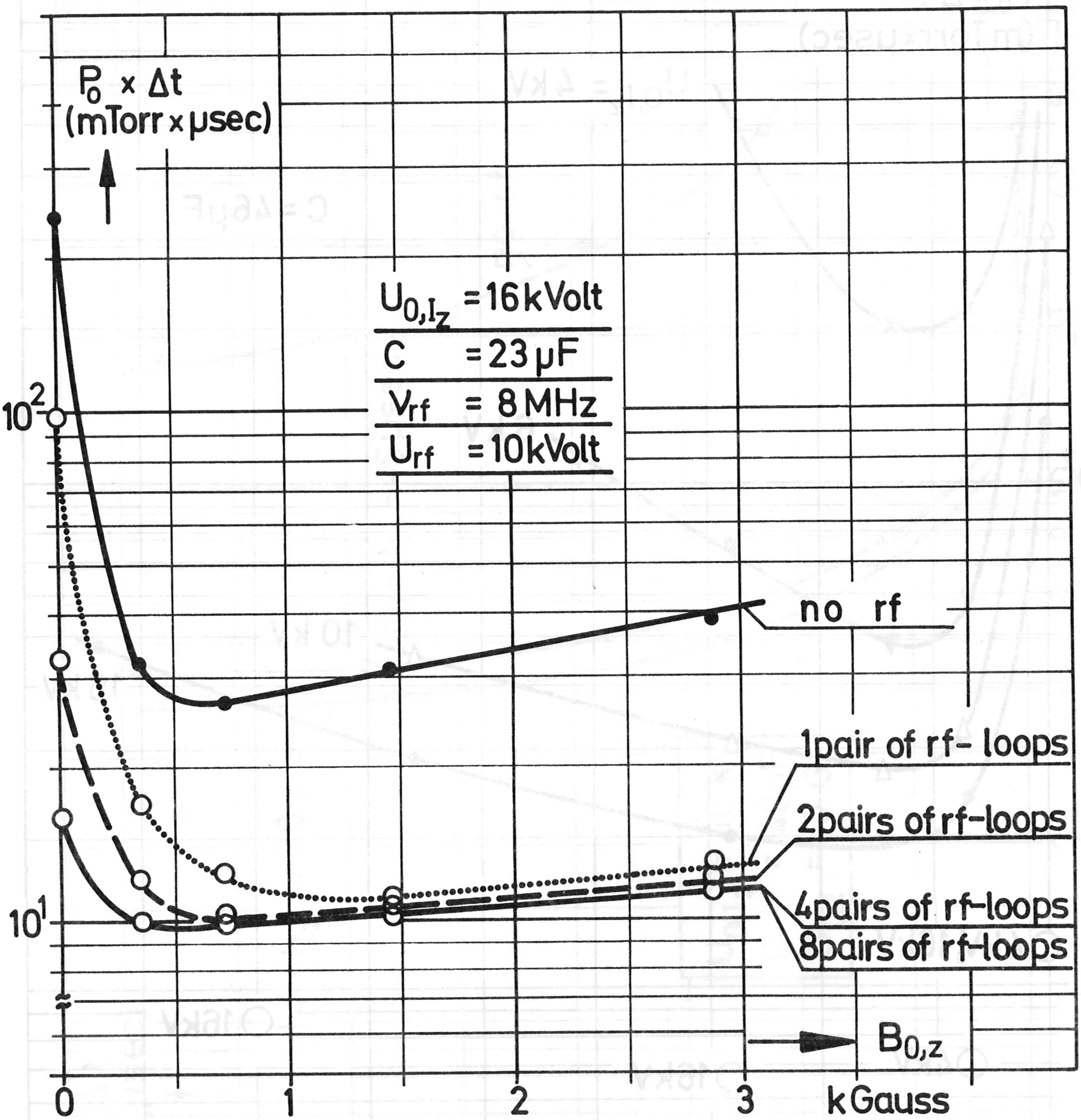

Δt (μsec)
8
6
4
2
0
1
2
4
6
8
10
20
40
60 mTorr
→ P₀
no rf
t_rf − t_Iz = −5 μsec
t_rf − t_Iz = −20 μsec
U_0,Iz = 16 kV
C = 46μF
B_0,z = 0 G

Fig. 4



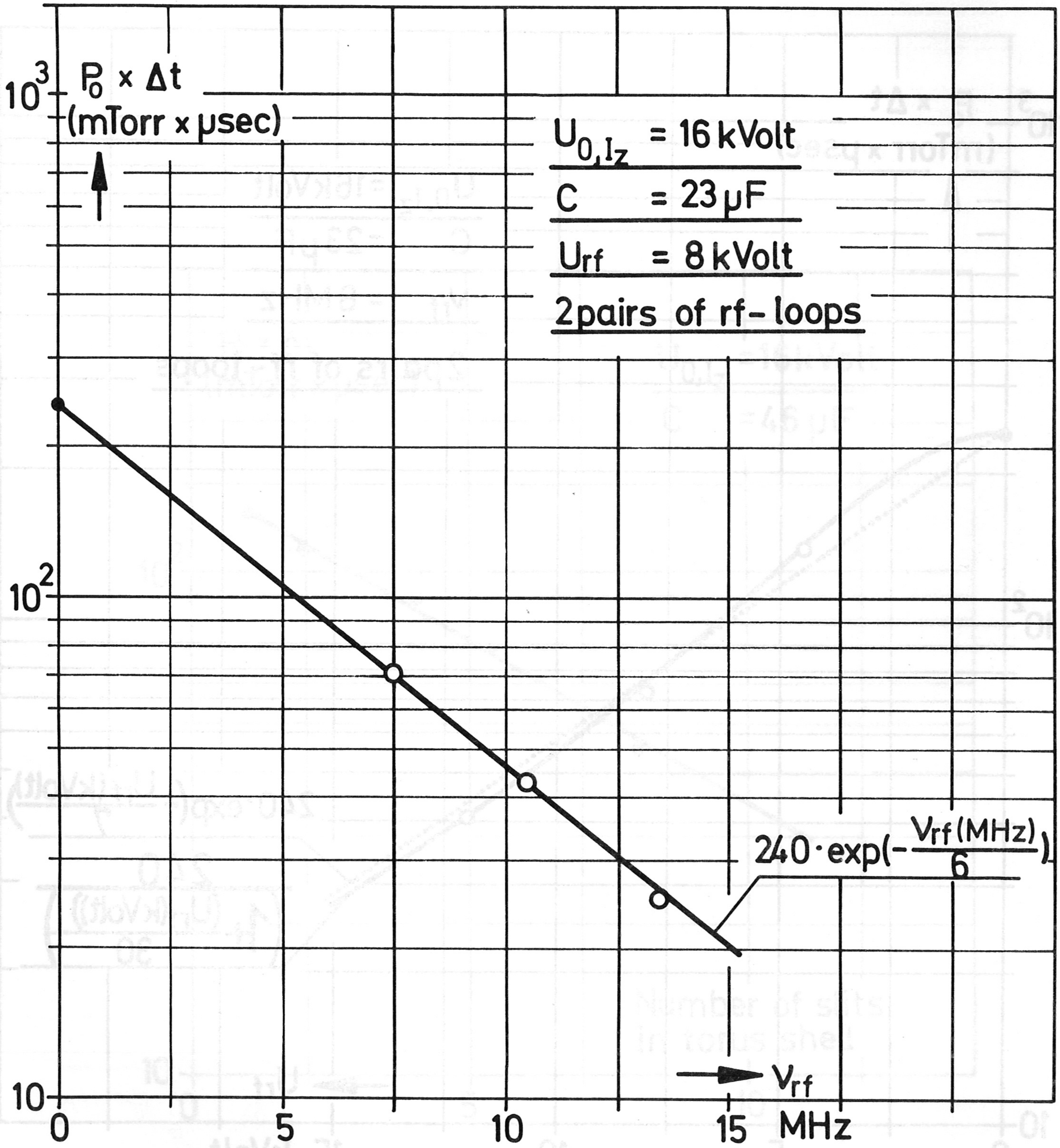
10³
P₀ × Δt
(mTorr × μsec)
U₀,Iz = 4 kV
C = 46 μF
6 kV
10²
10 kV
16 kV
○ 4kV, 16kV
10
○ 16kV
○ 4kV
○ 16kV
→ B₀,z
0
1
2
3
4 kGauss

Fig. 5



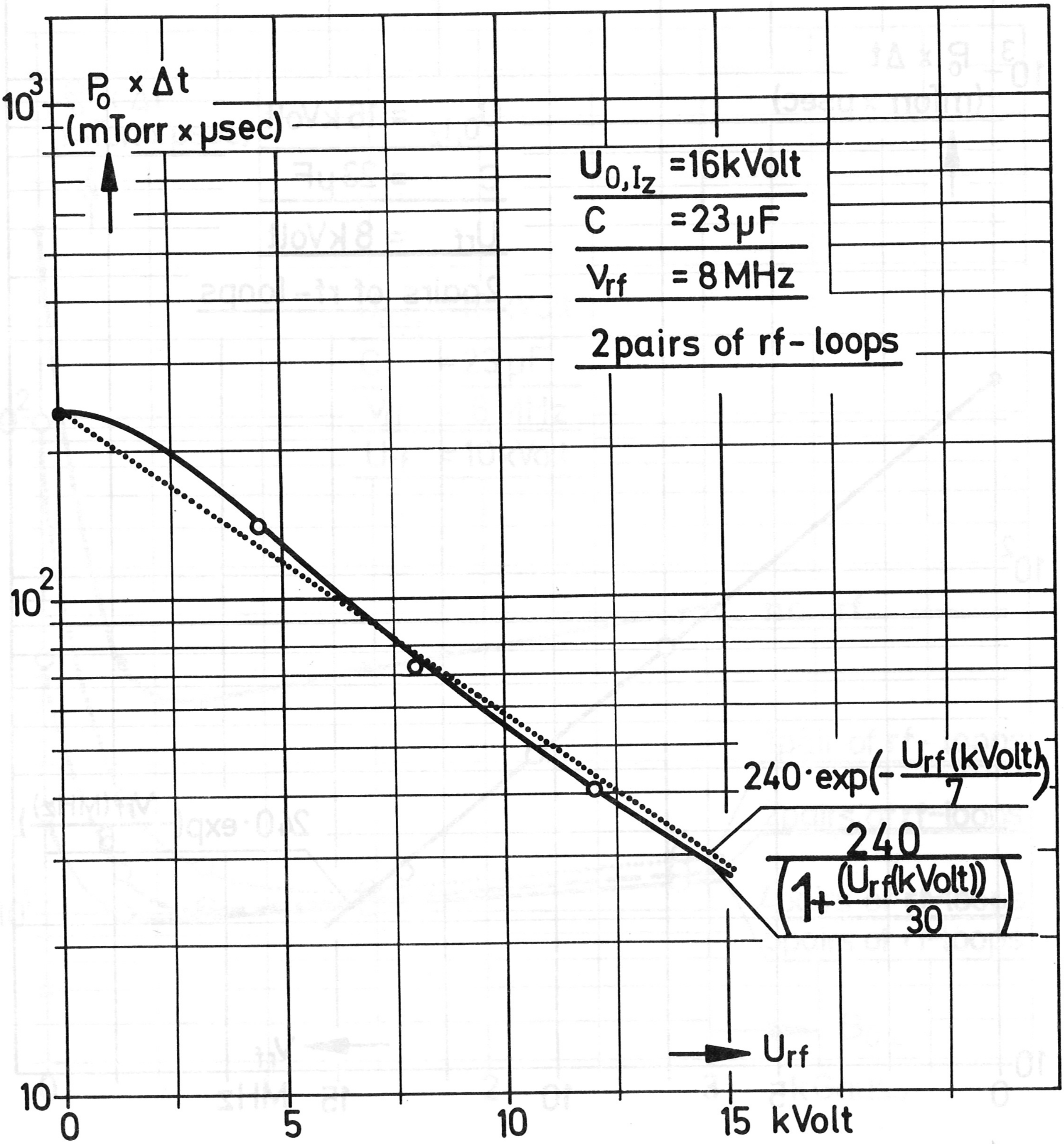
$P_0 \times \Delta t$
(mTorr x μsec)
U_{0,I_z} = 16 kVolt
C = 23 μF
ν_{rf} = 8 MHz
U_{rf} = 10 kVolt
no rf
1pair of rf- loops
2pairs of rf-loops
4pairs of rf-loops
8pairs of rf-loops
10^2
10^1
$B_{0,z}$
0
1
2
3
kGauss

Fig. 6



10^3
$P_0 \times \Delta t$
(mTorr x μsec)
10^2
10
U_{0,I_z} = 16 kVolt
C = 23 μF
U_{rf} = 8 kVolt
2 pairs of rf-loops
$240 \cdot \exp(-\frac{V_{rf}(\mathrm{MHz})}{6})$
V_{rf}
0
5
10
15
MHz

Fig. 7



10^3
$P_0 \times \Delta t$
(mTorr x µsec)
10^2
10
U_{0,I_z} =16kVolt
C =23µF
V_{rf} = 8MHz
2pairs of rf-loops
$240 \cdot \exp(-\frac{U_{rf}(kVolt)}{7})$
$\frac{240}{\left(1+\frac{(U_{rf}(kVolt))}{30}\right)}$
U_{rf}
0
5
10
15 kVolt

Fig. 8

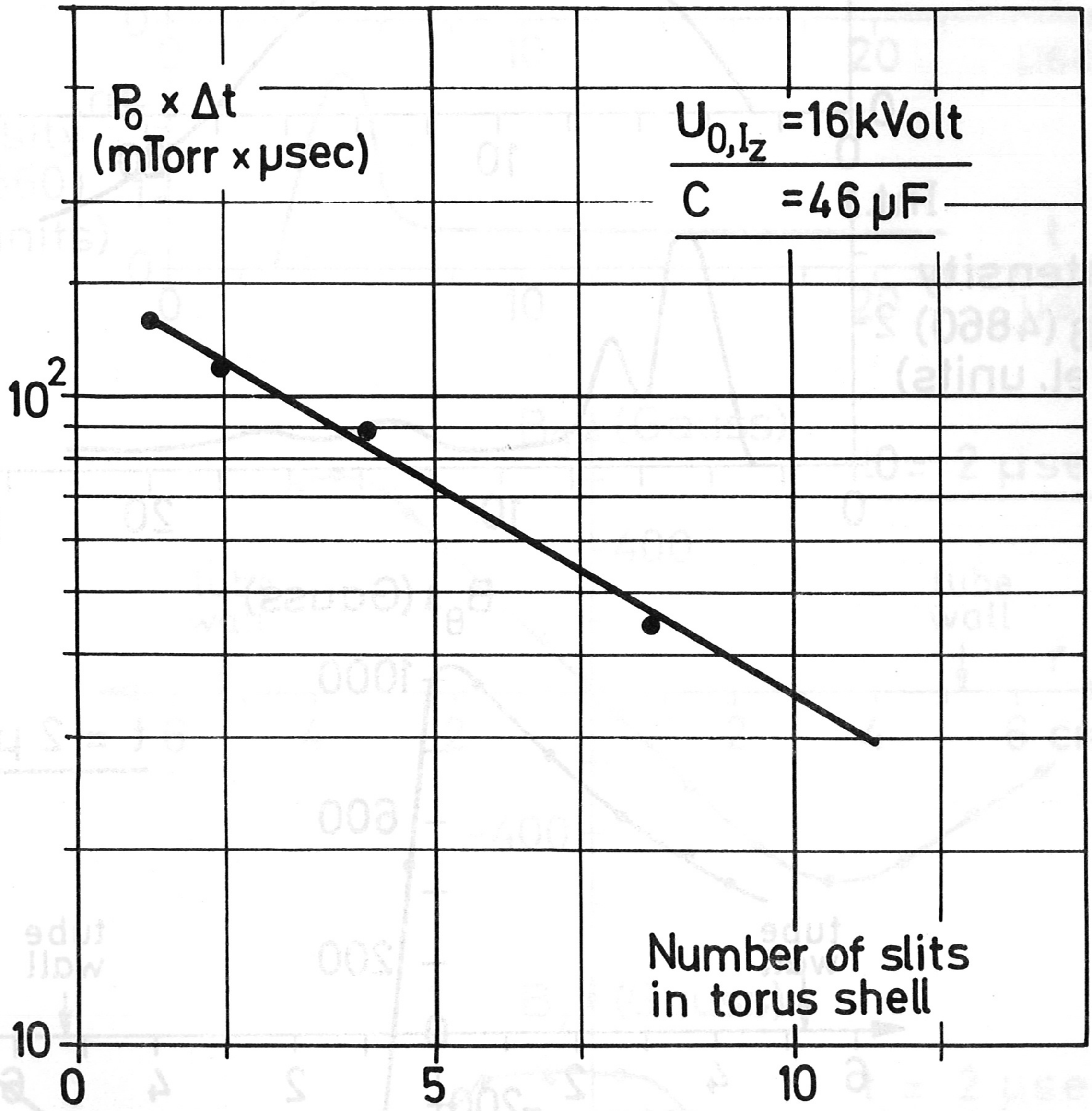
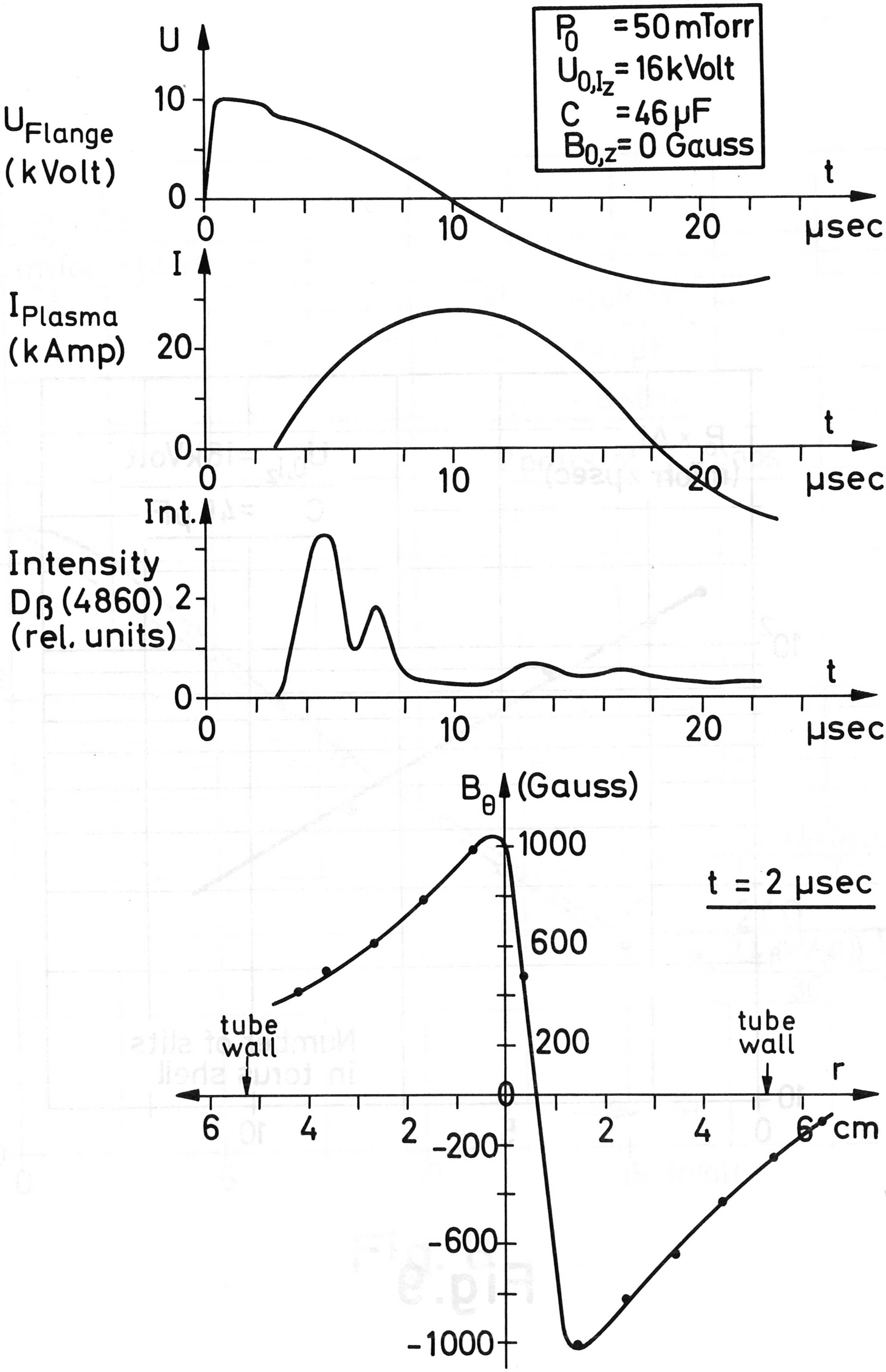
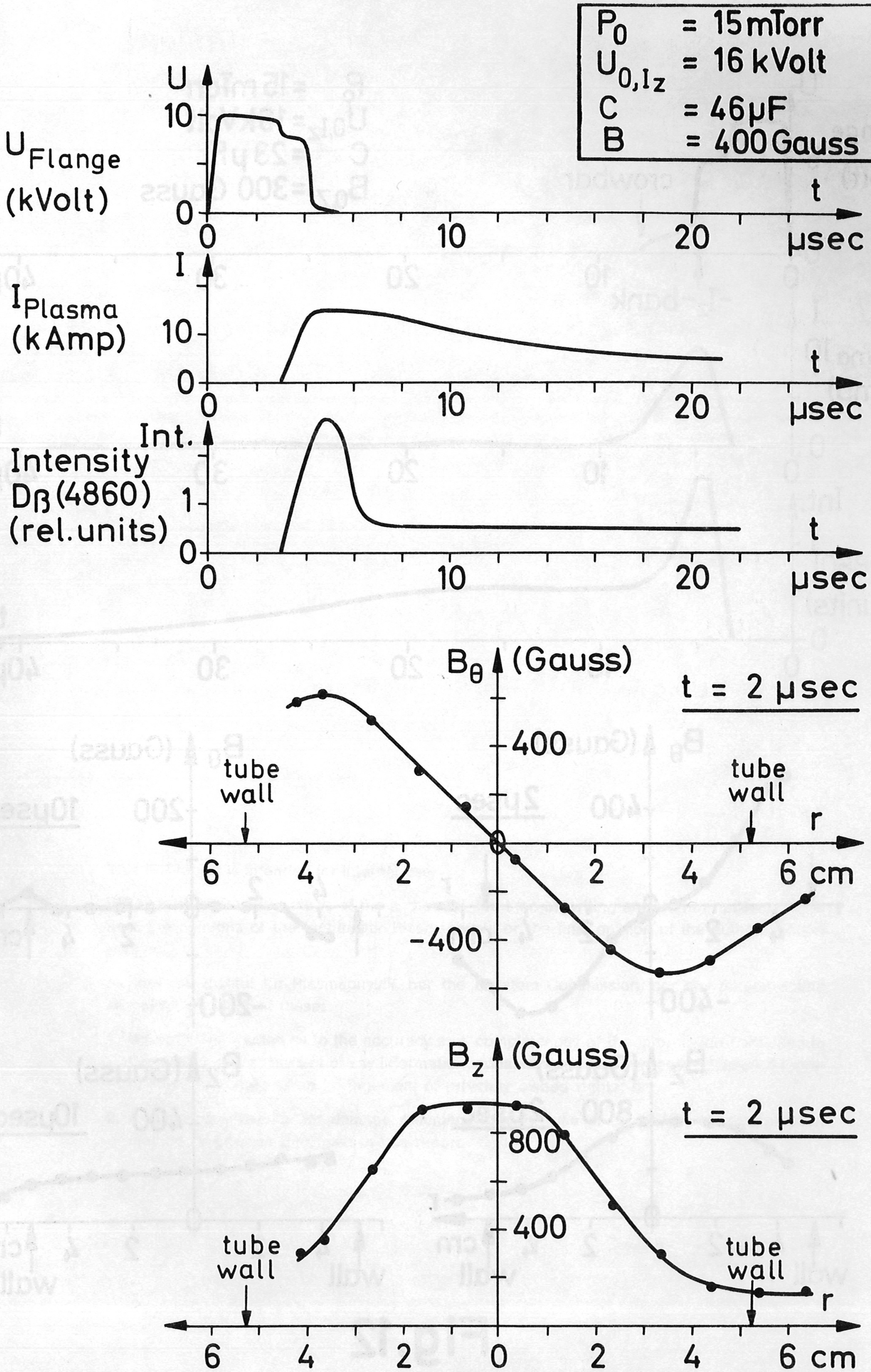

$P_0 \times \Delta t$
(mTorr x μsec)
U_{0,I_z} =16kVolt
C =46 μF
10^2
10
0
5
10
Number of slits in torus shell

Fig. 9



P_0 = 50 mTorr
U_{0,I_z} = 16 kVolt
C = 46 µF
$B_{0,z}$ = 0 Gauss
U
U_{Flange} (kVolt)
10
0
t
0
10
20
µsec
I
I_{Plasma} (kAmp)
20
0
t
0
10
20
µsec
Int.
Intensity Dβ (4860) (rel. units)
2
0
t
0
10
20
µsec
B_θ (Gauss)
1000
600
200
0
-200
-600
-1000
t = 2 µsec
tube wall
tube wall
r
6
4
2
2
4
6
cm

Fig. 10



P_0 = 15 mTorr
U_0,Iz = 16 kVolt
C = 46 µF
B = 400 Gauss
U
U_Flange (kVolt)
10
0
t
0
10
20
µsec
I
I_Plasma (kAmp)
10
0
t
0
10
20
µsec
Int.
Intensity Dβ (4860) (rel. units)
1
0
t
0
10
20
µsec
B_θ (Gauss)
t = 2 µsec
400
-400
tube wall
tube wall
r
6
4
2
0
2
4
6 cm
B_z (Gauss)
t = 2 µsec
800
400
tube wall
tube wall
r
6
4
2
0
2
4
6 cm

Fig. 11

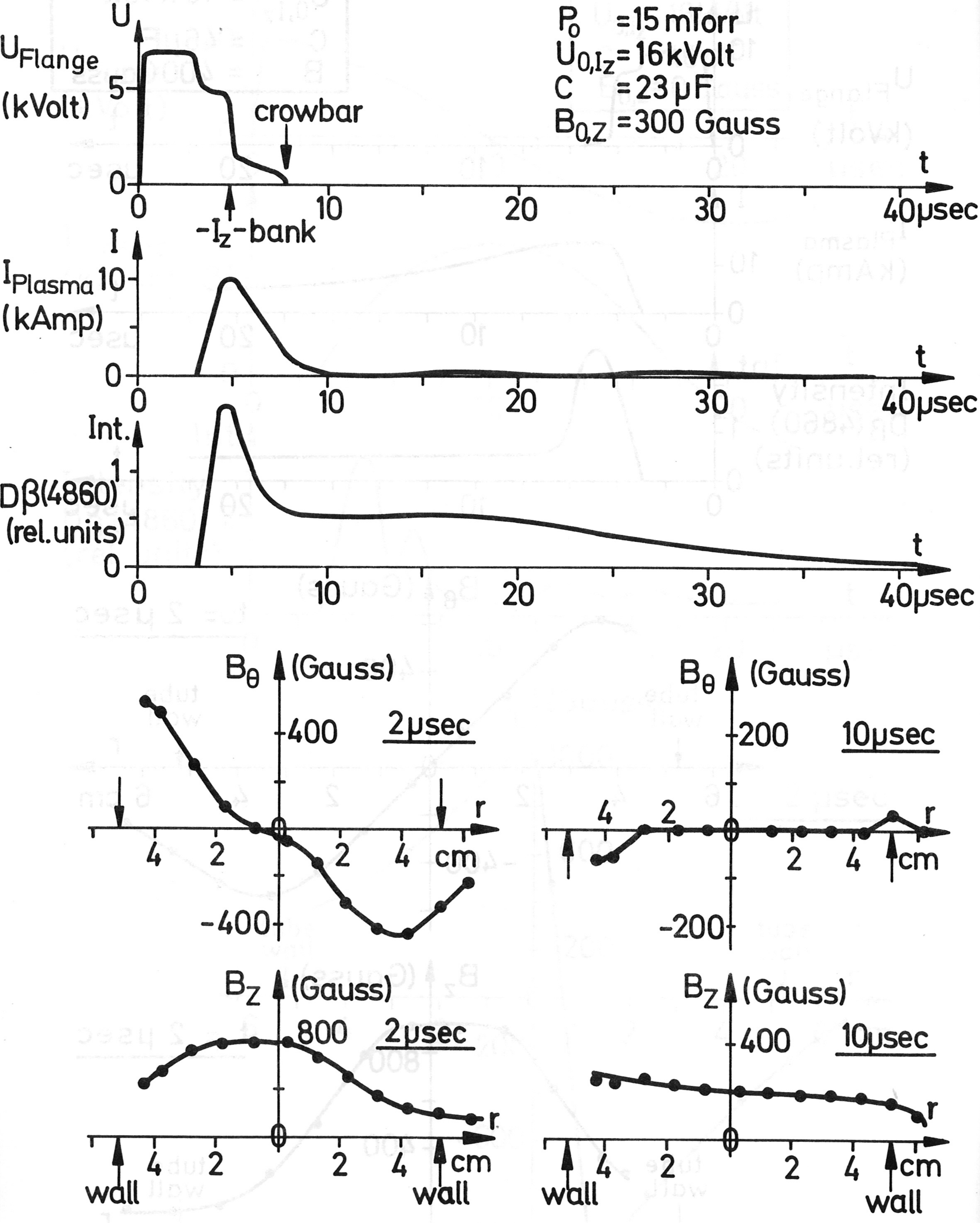

P_0 = 15 mTorr
U_{0,I_z} = 16 kVolt
C = 23 μF
$B_{0,Z}$ = 300 Gauss
U
U_{Flange}
(kVolt)
5
0
crowbar
t
0
10
20
30
40μsec
$-I_z$-bank
I
I_{Plasma}
(kAmp)
10
0
t
0
10
20
30
40μsec
Int.
Dβ(4860)
(rel.units)
1
0
t
0
10
20
30
40μsec
B_θ (Gauss)
400
2μsec
r
4
2
0
2
4
cm
-400
B_θ (Gauss)
200
10μsec
r
4
2
0
2
4
cm
-200
B_Z (Gauss)
800
2μsec
r
4
2
0
2
4
cm
wall
wall
B_Z (Gauss)
400
10μsec
r
4
2
0
2
4
cm
wall
wall

Fig. 12