Note PS/LPI/87-36 28 September 1987

BEAM LOADING MEASUREMENTS IN EPA

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1. INTRODUCTION

Fast growing beam instabilities have been observed in EPA, depending on RF cavity voltage and tuning angle.

Although the nominal performances of the machine are not affected by these instabilities, as far as the operation of the LEP injector chain is concerned, a study of beam loading effects seemed worthwhile, for 3 main reasons:

i) it might be necessary to accumulate up to 300 mA (i.e. 4 times the nominal intensity) for LEP injection[1].

ii) it was foreseen [2] to reduce the cavity voltage for better bunch matching at the injection to the PS. In that case the beam loading becomes a serious limitation.

iii) owing to the rather unconventional design of the RF cavity [3], there was some suspicion that the beam-cavity interaction would not behave as Robinson's criterion predicts.

In this note a collection of measurements taken in 1986 is presented. They refer to various values of the RF cavity voltage and tuning angle, and have been taken under various conditions, where, due to the presence of AVC and tuning loops, Robinson's criterion is no longer valid.

The observed intensity limits are reported in some important cases. They are sometimes different from those predicted by a simple model of the RF cavity: no possible explanation is given here. An attempt to fully understand these effects, requiring a more complicated model of the RF cavity, is still in progress.

2. REVIEW OF ROBINSON'S THEORY FOR BEAM CAVITY INTERACTION

The formalism is that used by Pedersen [4]: the cavity is schematized by a parallel RCL resonant circuit fed by 2 current generators (Fig. 1). The meaning of the symbols is the following:

$\tilde{I}_B = 2\, I_B^{dc}$ is the fundamental component of the beam current.

$\tilde{I}_G$ is the fundamental component of the plate current of the power tube, transformed to the gap.

$\tilde{I}_T = \tilde{I}_G + \tilde{I}_B$ is the total current at 19 MHz flowing into the cavity.

$\tilde{V}_C$ is the total gap voltage

$\tilde{I}_0$ is the shunt resistor current = $\tilde{V}_C/R_S$, where R_S is the shunt impedance of the cavity.

ϕ_S is the synchronous phase angle (in EPA $90^\circ < \phi_S < 180^\circ$ for stability)

ϕ_Z is the argument of the cavity impedance (= tuning angle)

ϕ_L is the argument of the cavity load plus the beam (= loading angle).

These parameters are shown in the usual phasor diagram of Fig. 2.

From the geometry the following steady state relations are derived:

$$\tan\phi_L = \frac{\tan\phi_Z + \dfrac{I_B}{I_0}\cos\phi_S}{1 + \dfrac{I_B}{I_0}\sin\phi_S} \qquad (1) \quad \text{and}$$

$$I_G = \frac{I_0 + I_B \sin\phi_S}{\cos\phi_L} \qquad (2)$$

It follows that in a storage ring ϕ_L and I_G are determined if I_B, V_C, ϕ_S and ϕ_Z are specified. The stability of this system was first studied by Robinson [5], who considered the propagation of small amplitude and phase modulations of the vectors $\tilde{I}_G$ and $\tilde{I}_B$. He derived a system of 4 linear differential equations of the 1st order relating amplitude and phase of cavity voltage and beam current to the other relevant parameters. After having written *the characteristic equation for this system, he tested it for roots with negative real part (Routh - Hurwitz criterion), which is the condition for stability. This was found to be (above the transition energy):*

$$0 < \sin 2\phi_Z < \frac{-2 I_0 \cos \phi_S}{I_B} \qquad (3)$$

The left side of (3) simply means that the cavity must be detuned off resonance, since $\tan \phi_Z = 2 Q_L \dfrac{\omega - \omega_0}{\omega_0}$, *where* ω_0 *is the cavity resonant frequency,* ω *is the beam frequency close to* ω_0 *and* Q_L *is the loaded Q of the cavity.*

This is the standard precaution against coherent dipole oscillations (lines n = 0, m = 1 in the beam spectrum), which have in general very fast growth rates, due to the high impedance of the cavity.

The right side is a sort of upper limit on the maximum current that can be stored in the ring. We expect, however, the beam to become unstable below this limit, which is not exactly a threshold in the common sense. In EPA 2 feedback loops controlling RF amplitude and cavity tuning were implemented since the start of the commissioning in June 1986. The amplitude control loop (AVC) keeps the gap voltage constant in amplitude at a preset value, independent of beam loading, tuning angle and temperature drifts in the cavity. It acts on the grid voltage of the RF tetrode. The tuning loop keeps the tetrode current (grid voltage) in phase with the gap voltage by acting on two mechanical tuners located on the cavity [3].

In most machines the tuning loop is used for reactive compensation of beam loading, by keeping the loading angle ϕ_L *constant around 0° and minimizing in this way the generator current (see eq. 2). In EPA there is no limitation on the available RF power even in the presence of high beam current at the lowest operating gap voltage of 10 kV. The maximum RF power is limited by the tetrode plate dissipation, which cannot exceed 30 kW for air cooling and 50 kW for water cooling (our case). The maximum generator current is easily found, by observing that the total tetrode power* P_T *must be equal to the power dissipated on the plate W plus the total generator power* [6] P_G:

$$P_T = P_G + W, \text{ but } P_T = V_{DC} \cdot I_G \cdot \frac{2}{\pi} \text{ and } P_G = \frac{V_C}{\tau} \frac{I_G \cos\phi_L}{2}$$

where τ is the voltage step-up (transformation ratio) between the tube anode and the accelerating gap, V_{DC} = 10 kV is the d.c. plate voltage, and the factor 2/π comes from the fact that I_G is the fundamental (Fourier) component of the plate current. Hence

$$I_G^{max} = \frac{W}{V_{DC} \cdot \frac{2}{\pi} - \frac{V_C}{\tau} \frac{\cos\phi_L}{2}} \cdot \frac{1}{\tau} \qquad (4)$$

is the maximum available generator current transformed to the gap (i.e. multiplied by 1/τ). By combining eqs. (2) and (4) the limits on the beam current imposed by the RF tube can be calculated. The results are shown together with Robinsons's limits in figs. 3,4 for V_C= 50 kV and V_C=10 kV respectively. The value of the shunt impedance, although higher than the measured value, is not unrealistic (anyway the picture improves more and more with a lower R_S). In the case V_c = 50 kV neither Robinson's criterion nor RF power impose serious limitations, while in the case V_C =10 kV (remember that the energy loss per turn due to synchrotron radiation is 7.2 keV at 600 MeV) the instability limit at low ϕ_L becomes severe and one has to go to higher ϕ_L where the tube limits become also tight (even for W = 50 kW). So it seems as if only in the extreme and until now unlikely case of very high current (> 300 mA) and reduced voltage the tube limit was approached.

On the other hand the limit imposed by beam loading instabilities seems more serious although it cannot be expressed in the simple form of eq. (3), owing to the presence of the AVC and tuning loops. Pedersen [4] made a thorough stability analysis of the beam and RF cavity system in various limiting cases. For the case AVC + tuning a dependence on the ϕ_L angle is foreseen, according to the bandwidth of the two loops. So it was of particular interest to us to measure the instability limits in all these conditions, both for a better understanding of the cavity behaviour and to see whether beam loading could really limit the EPA performances.

3. MEASUREMENTS IN THE CASE OF NO LOOPS

The measurable quantities are the average beam current (by the intensity monitor MIME), the cavity voltage (through a peak voltage detector, calibrated with X-rays) and the loading angle (through a phase discriminator). Some calibration errors should be taken into account for the intensity and gap voltage measurements, (to 5% for MIME and 2% for the probe looking at the gap), while the accuracy of the measurement of the absolute phase between the grid voltage (reference) and the gap voltage depends (to some $\pm$ 2°) on the choice of the 0° as the top of the resonance curve. Also, a phase shift ($\pm$ 1/2° over 10°) error is introduced as the amplitudes of the input signals change [7].

Since the corrections to apply are not evident, only the raw data are presented here.

The cavity V_C and the loading phase angle ϕ_L have been recorded as functions of the beam current I_B^{dc} using a HP chart recorder. To get the maximum intensity, 8 bunches were accumulated in EPA. Two examples of such measurements are shown in figs. 5 and 6, for ϕ_L (I_B^{dc}) and V_C (I_B^{dc}) respectively. Both refer to the case of no loops, where Robinson's criterion is valid. The cavity voltage was 30 kV at resonance, then the initial loading angle (which is equal to the tuning angle ϕ_Z at zero beam loading) was lowered to 23° for the mid curve and 35° for the lower curve. The upper curve is not considered here because its corresponding V_C (I_B^{dc}) curve was not recorded (fig. 6).

In fig. 5 the corresponding values of the cavity voltage at these 2 tuning angles are also shown. Since the accumulation into EPA is quite slow and the cavity is in stationary conditions (this means that the cavity filling time is much shorter than the Linac period and longer than the bunch distance in EPA), the steady state equation (1) can be applied. Using the measured values for V_C and ϕ_Z and the theoretical values for ϕ_S (ϕ_S = arcsin U_0/V_C where U_0=3.48 keV at E = 500 MeV and varies very little with the intensity), the loading angle ϕ_L is computed for 3 different values of the cavity shunt impedance R_S. The results are shown in fig. 7 and are compatible with R_S between 80 and 90 kΩ. This R_S includes also the tube internal impedance (plate resistance) R_p which is introduced to take into account the variation of the plate current versus the plate voltage at constant grid voltage.

This impedance (transformed to the gap) has to be added in parallel to the cavity 'cold' shunt resistance R to get the true shunt impedance as seen by the beam, so that $R_S = R//R_p$. We have: $R = \frac{r}{Q} \cdot Q_L$ where $\frac{r}{Q}$ is the characteristic impedance of the cavity (= 41 Ω) and Q_L is the loaded Q (≃ 3940 from measurements), so that R ≃ 162 kΩ. The plate resistance R_p depends on the voltage and on the phase angle of the impedance seen by the tube. An estimate can be extracted from the tube (SIEMENS RS1084C) characteristics by an interpolation program (VALVO) written by A. Susini and R. Giannini. Typical values are between 4.7 and 11 kΩ. The voltage step-up is about 6.5 and is calculated by a simple program which considers a more sophisticated model of the cavity. Further details about these calculations will be given in a subsequent note. With R_p = 4.7 kΩ we get eventually R_S = 89 kΩ which seems to agree with the experiment.

In figs. 5,6 the limits on the beam intensity are also shown. The observed instabilities display a non-oscillatory, pure exponential growth and produce an abrupt loss of most part of the beam. The ring is continuously filled in this experiment, so the curves $\phi_L(I_B^{dc})$ and $V_C(I_B^{dc})$ are reproduced several times in figs. 5,6. The observed limits occur repeatedly at $I_B^{dc} \simeq 3.3 \cdot 10^{11}$ and $I_B^{dc} \simeq 4.0 \cdot 10^{11}$ electrons in the ring. If the equation (3) is now evaluated with the experimental values for ϕ_Z and V_C and for R_S = 90 kΩ, the theoretical limits are found to be $I_B^{th} = 7.16 \cdot 10^{11}$ and $I_B^{th} = 7.87 \cdot 10^{11}\ e^-$, respectively. So the instability occurs at least a factor 2 below the expected upper limit. Moreover, we should expect the limit to be higher for $\phi_Z = \phi_L^0 = 23°$ than for $\phi_Z = 35°$, as predicted by equation (3). The opposite instead is observed. All the measurements made under these conditions agree with this observation. Even if an error on the measured ϕ_L and V_C is assumed, it will never give a satisfactory explanation of these effects. Perhaps this suggests that the simple RCL circuit model is not sufficient to describe the behaviour of our RF system with beam loading and the presence of the amplifier cavity is to be taken into account.*

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* ($10^{11}\ e^-$ = 38 mA in EPA)

4. MEASUREMENTS WITH FEEDBACK LOOPS

The cavity voltage was measured versus the beam current in the case of tuning loop only. An example is shown in fig. 8. In this experiment the sampling of the phase error occurs about every 32 ms, i.e. the tuning loop is almost 30 times faster than in the normal operation. Furthermore the accumulation was quite slow, in order to allow the tuners to keep the loading angle almost constant. The instability takes place at reduced cavity voltage (8 kV) and with about $3 \cdot 10^{11}$ particles in the ring. This limit seems quite reasonable, because if the eq. 1 is applied, assuming ϕ_L constant at the measured initial value of 34°, the final ϕ_Z turns out to be ~ 75° and with this value the instability criterion (3) gives $I_B^{th} = 4.2 \cdot 10^{11}$. Pedersen has shown that the stability criterion for tuning loop only approaches Robinson's formula (3), provided the bandwidth of the tuning loop is sufficiently small. It is difficult to come to any conclusion from these data and the data with no loops.

The beam-cavity interaction was measured with the AVC loop which is the most interesting case, since it corresponds to the normal operating conditions. An example of such measurements is shown in fig. 9. The loading angle ϕ_L is recorded against the beam current for various initial tuning angles. The accumulation is now higher (40 mA/sec) than the design one (33 mA/sec) and the usual 'slow' tuning is used. For the 2 lowest curves the instability limit is reached at $\phi_L \simeq 0°$, while for the 2 other curves the maximum beam current is obtained (saturation) without any beam loading instability. The same phenomenon is observed in fig. 10, where the lower curve (labelled 'slow tuning') encounters the instability as soon as the ϕ_L value is crossed, while the upper curve (labelled 'fast tuning') does not.*

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* *For this and the following figures the sign of ϕ_L has been reversed to make the measurements easier.*

This fact is compatible with theoretical predictions [4] for the limiting case of AVC + tuning loops; in our case the same is observed also with the AVC loop only, since the tuning loop is so slow that it cannot change the transfer function. The instability conditions depend on the AVC bandwidth, so that if this is reduced, we get stability even with $\phi_L < 0°$, as though the system were closer to the Robinson conditions. This has been verified recently in a run with positrons, where the $\phi_L = -10°$ value has been reached by a stable beam with an AVC bandwidth reduced by a factor 20 with respect to the other measurements (see fig. 11).

The improvement is not big anyway, and the maximum attainable current depends very much on the initial tuning. With $\phi^0_L = 46°$ and $V_C = 30$ kV a maximum of $4.9 \cdot 10^{11}$ electrons were stored in the ring in the normal operating conditions. With a 'fast' tuning system the improvement would be substantial, as shown in fig. 12. Unfortunately our tuners are conceived for compensation of slow thermal drifts and only exceptionally can be operated at higher sampling rates. If the cavity voltage is reduced to 10 kV, the need for a beam loading compensation system becomes absolute. As an example some measurements with $V_C = 10$ kV, $\phi^0_L = 34°$ are reported in Table I.

Table I

AVC	tuning	$I^{dc}_{B\,max}$ (mA)
on	off	36
on	slow	53
on	fast	155
off	off	58

The maximum attainable intensities are very low and the improvement produced by a fast tuning system is rather impressive. Unfortunately this is quite complicated and expensive to implement on our cavity while both a phase loop correcting AC-variations of the beam-cavity phase and a RF feedback around the power amplifier reducing the apparent shunt impedance seem more feasible and cheaper. The former was already existing in RF Electronics Laboratory of the PS Division, the latter has been built by A. Susini. With these 2 devices some improvements have been observed in EPA, but since the measurements are not yet complete I will not report on them here.

5. CONCLUSIONS

The beam cavity interaction was studied under various conditions. An analysis based on the standard, simple Robinson criterion is not sufficient to explain our data. In the case of no feedback loops. Perhaps a more sophisticated model could do it. The cavity shunt impedance at 19 MHz was measured and found in agreement with laboratory measurements. In the case of AVC and tuning loops, our data are consistent with theoretical analysis and display a strong dependence of the instability limits on the loading angle ϕ_L. These instabilities do not spoil the EPA nominal performances, but certainly constitute a troublesome limitation as soon as more intensity is required (e.g. for machine development studies). So it was decided to introduce 2 compensation schemes, the phase loop and the RF feeback loop. Their effects seem beneficial, though not yet completely understood.

ACKNOWLEDGEMENTS

I thank for interesting and useful discussions and help during data taking J.P. Delahaye, R. Garoby, K. Hübner and A. Susini. G. Molinari is thanked for providing me with the HP Chart Recorder.

REFERENCES

1 *M. Bell et al., PS/RF/Note 85-2 and K. Hübner, unpublished note of 4.2.1985.*

2 *LEP Design Report, Vol. I, CERN-LEP/TH/83-29*

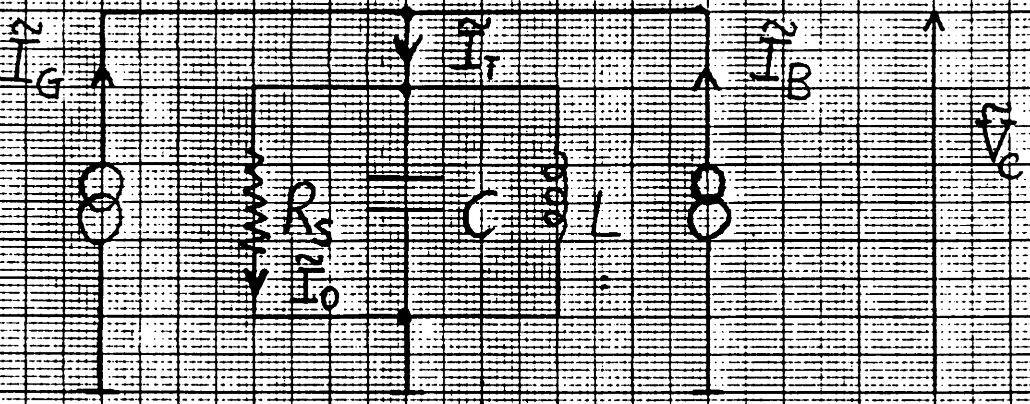
3 *S. Bartalucci et al., CERN PS/87-40 (LPI), submitted to the 1987 IEEE Particle Accelerator Conference*

4 *F. Pedersen, IEEE Trans. Nucl. Sci., NS-22 (1975), 1906.*

5 *K.W. Robinson, CEA Report No CEAL-1010 (1964)*

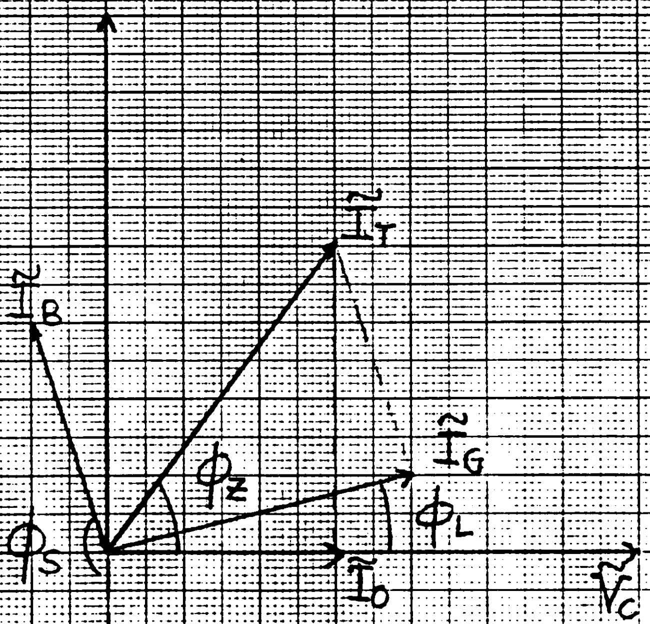
6 *A. Susini, unpublished note 29.02.1985*

7 *R. Garoby, private communication.*



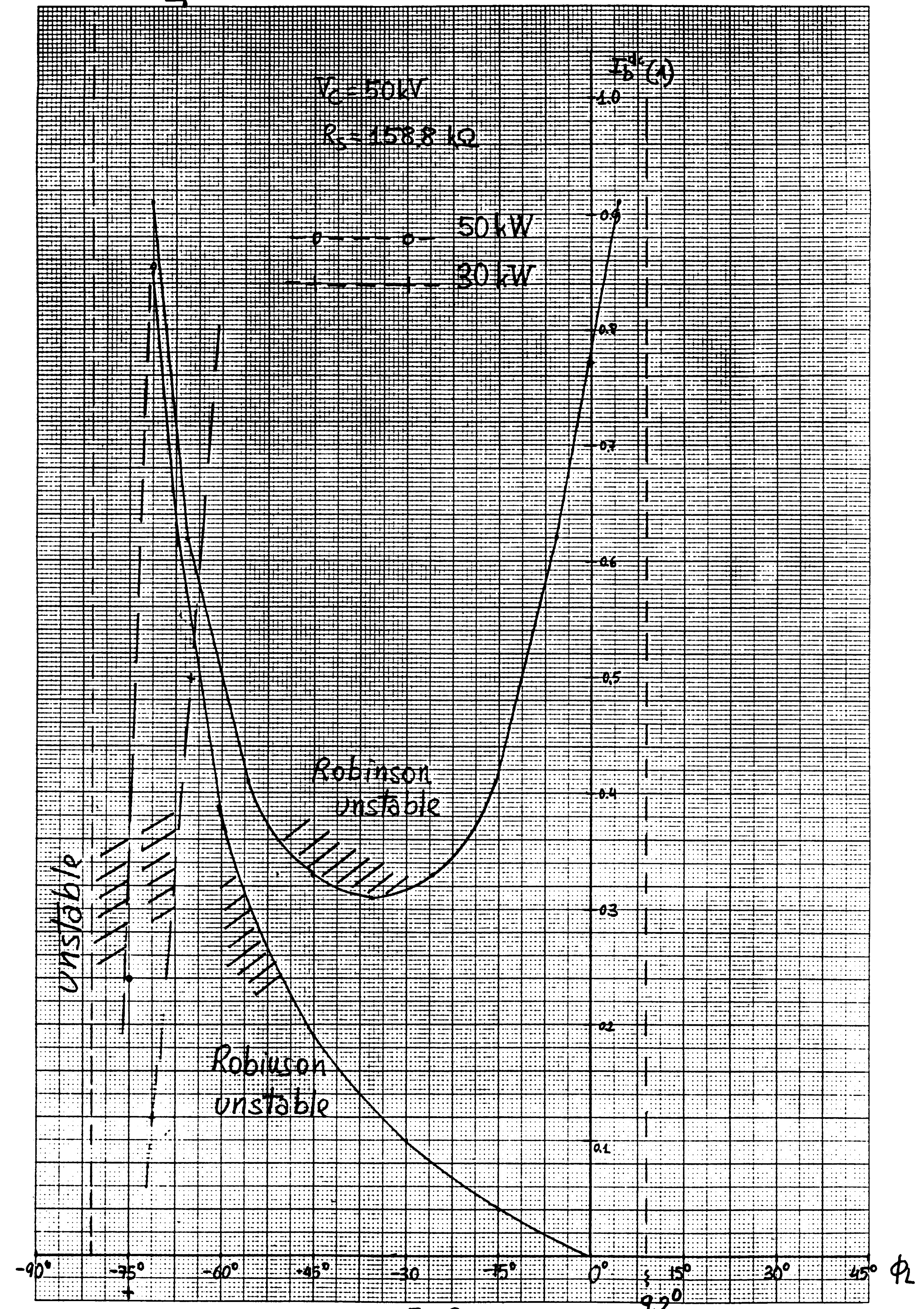
$\tilde{I}_G$
$\tilde{I}_T$
$\tilde{I}_B$
$\tilde{V}_C$
R_S
C
L
$\tilde{I}_0$

Fig. 1



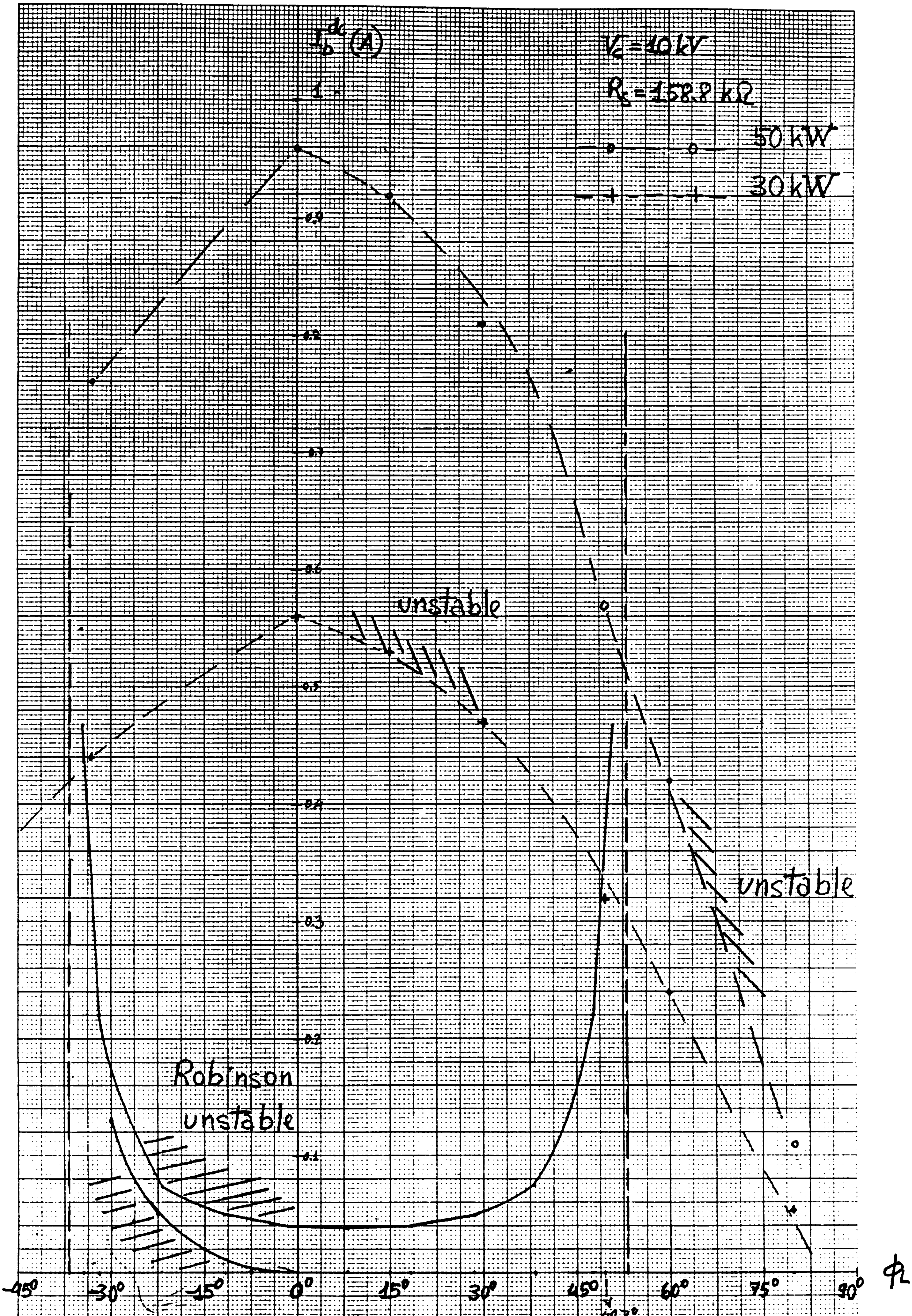
$\tilde{I}_T$
$\tilde{I}_B$
$\tilde{I}_G$
ϕ_Z
ϕ_L
ϕ_S
$\tilde{I}_0$
$\tilde{V}_C$

Fig. 2



I_b^{dk} (A)
$V_C = 50kV$
$R_S = 158.8\ k\Omega$
50 kW
30 kW
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Robinson unstable
Robinson unstable
unstable
-90°
-75°
-60°
-45°
-30
-15°
0°
15°
30°
45°
Φ_L
9.2°

Fig 3.



I_b^{dc} (A)
$V_c = 10\,kV$
$R_s = 158.8\,k\Omega$
50 kW
30 kW
unstable
unstable
Robinson
unstable
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-45°
-30°
-15°
0°
15°
30°
45°
49.7°
60°
75°
90°
Φ_L

Fig. 4

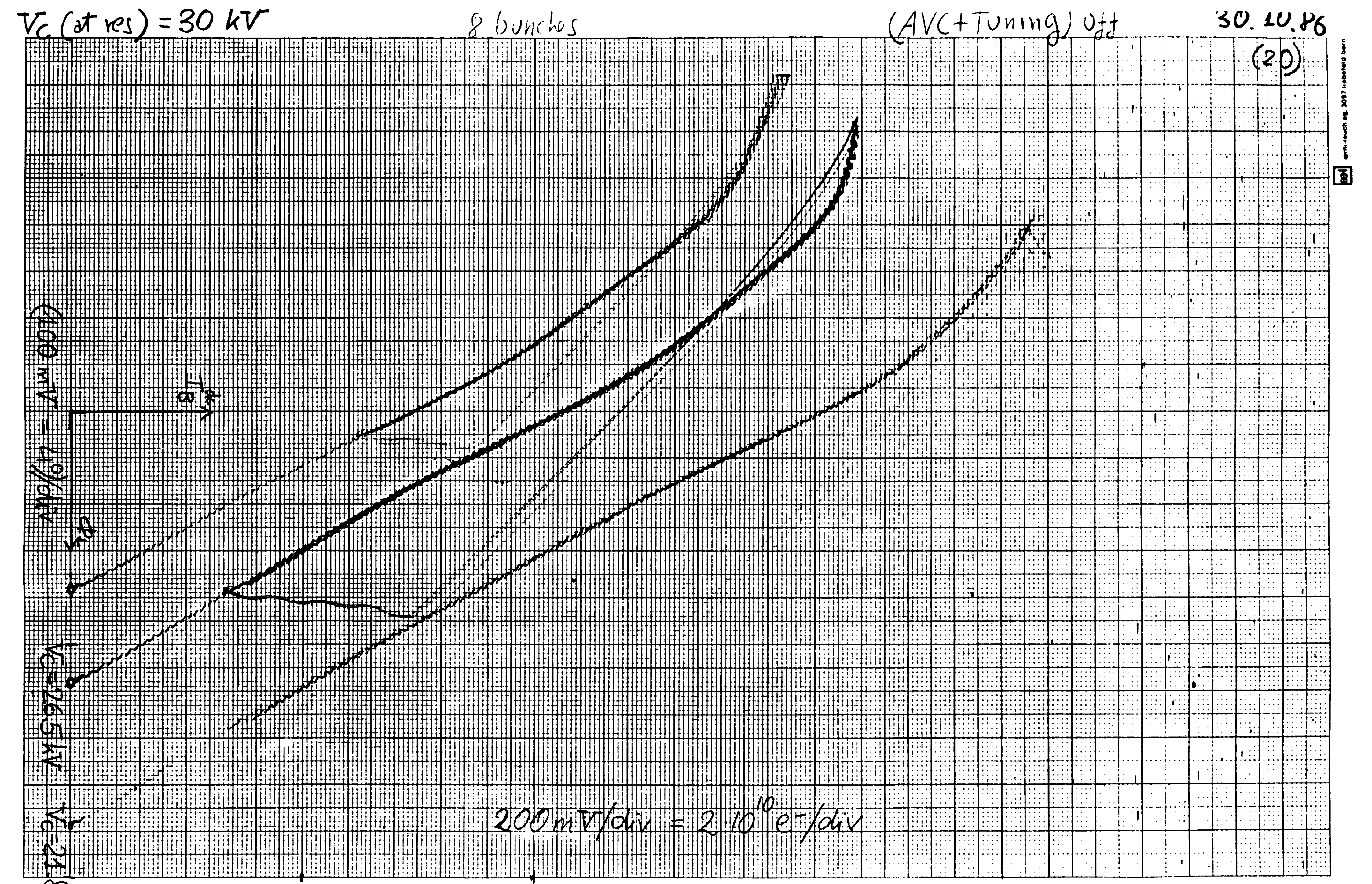

V_c (at res) = 30 kV
8 bunches
(AVC+Tuning) off
30.10.86
(20)
I_B^{dc}
Φ_c
(100 mV = 4°/div
V_c = 26.5 kV
V_c = 21.8 kV
200 mV/div = 2·10[10] e⁻/div

Fig.5

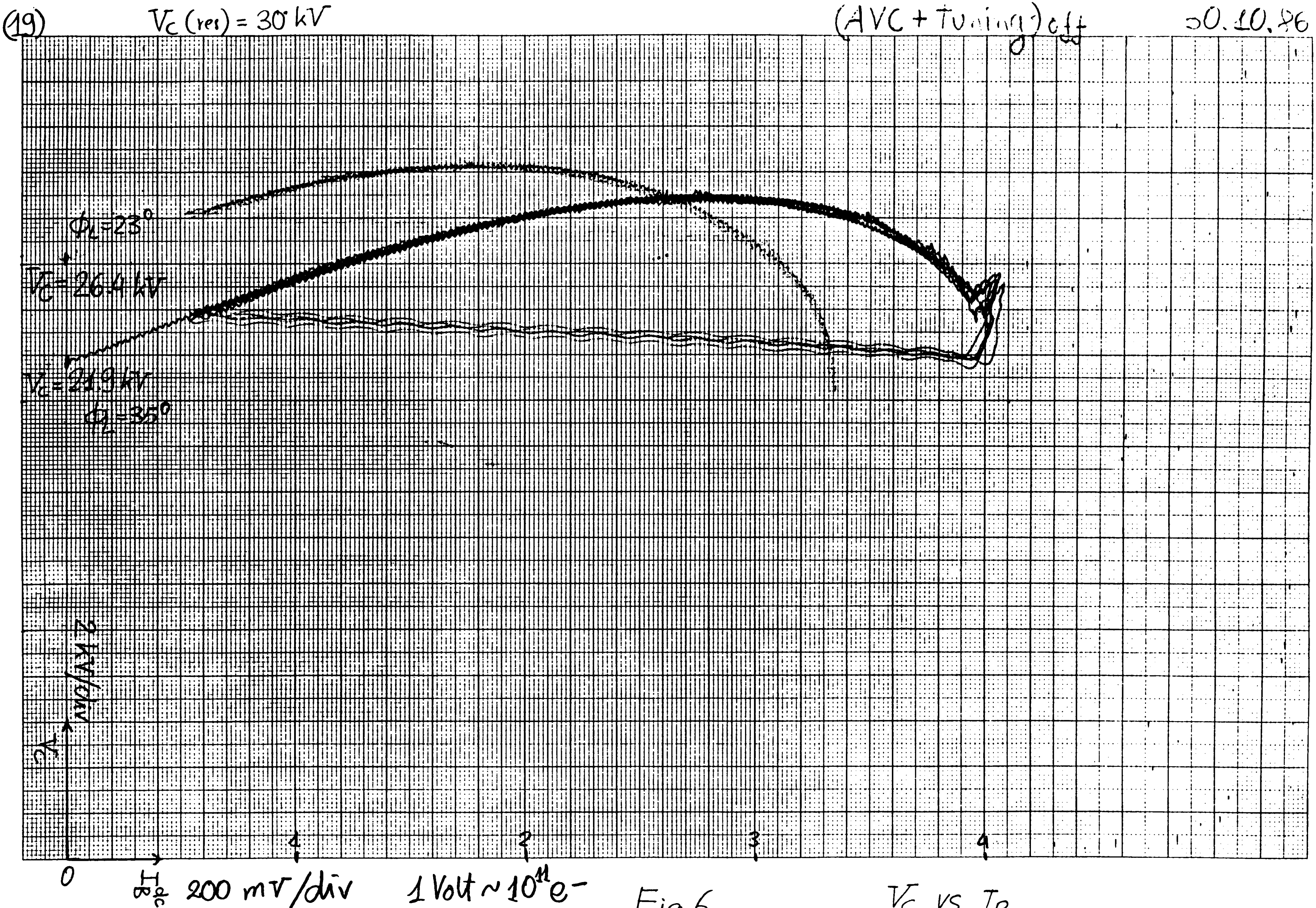
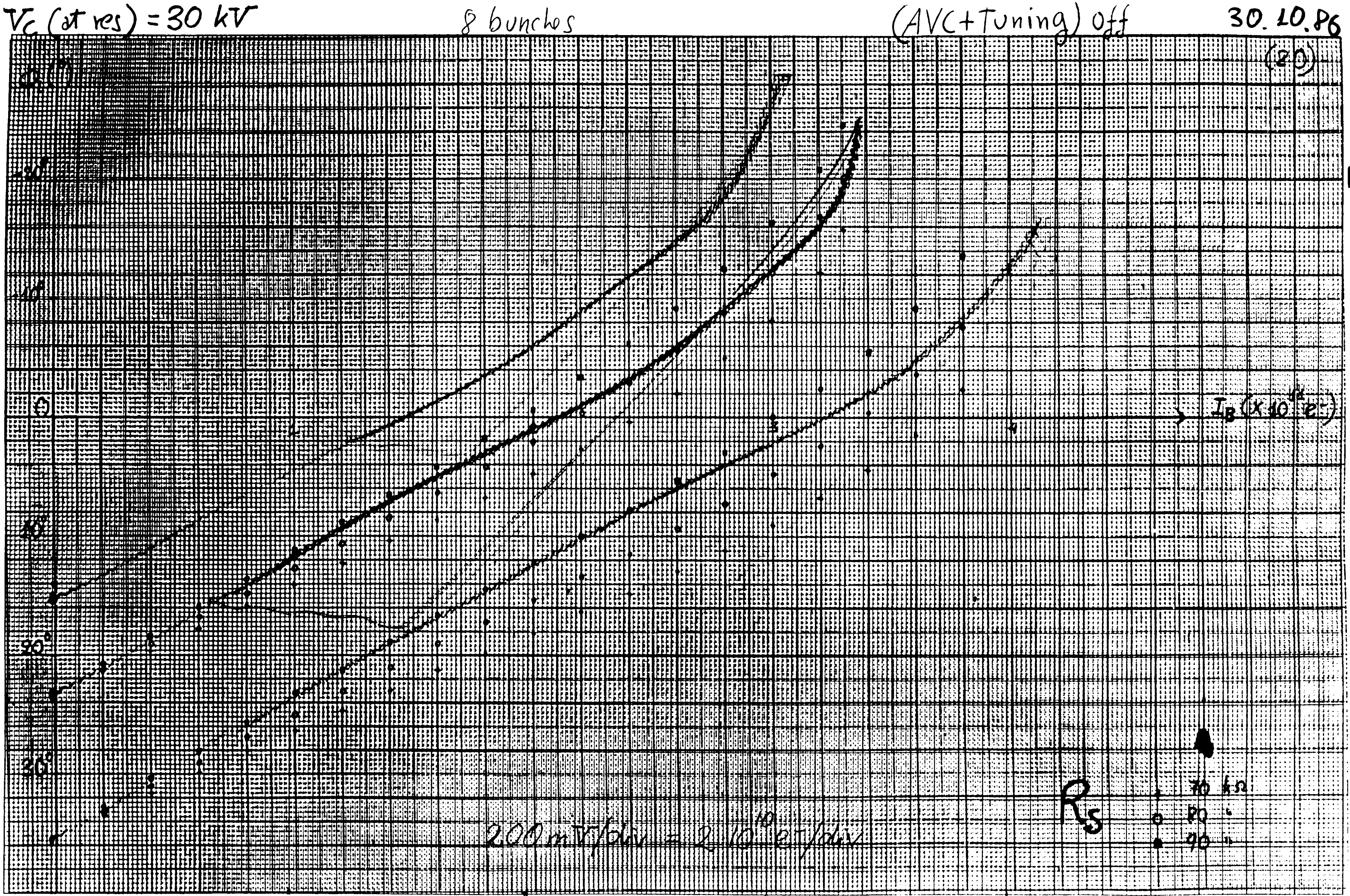

V_C (res) = 30 kV
(AVC + Tuning) off
30.10.86
Φ_L = 23°
V_C = 26.4 kV
V_C = 21.9 kV
Φ_L = 35°
2 kV/div
V_C
0
1
2
3
4
$\frac{I_B}{B_C}$ 200 mV/div
1 Volt ~ 10^{11} e-
V_C vs I_B

Fig 6



Φ_L vs. I_B (computed) Fig. 7

(34) 7.11.86

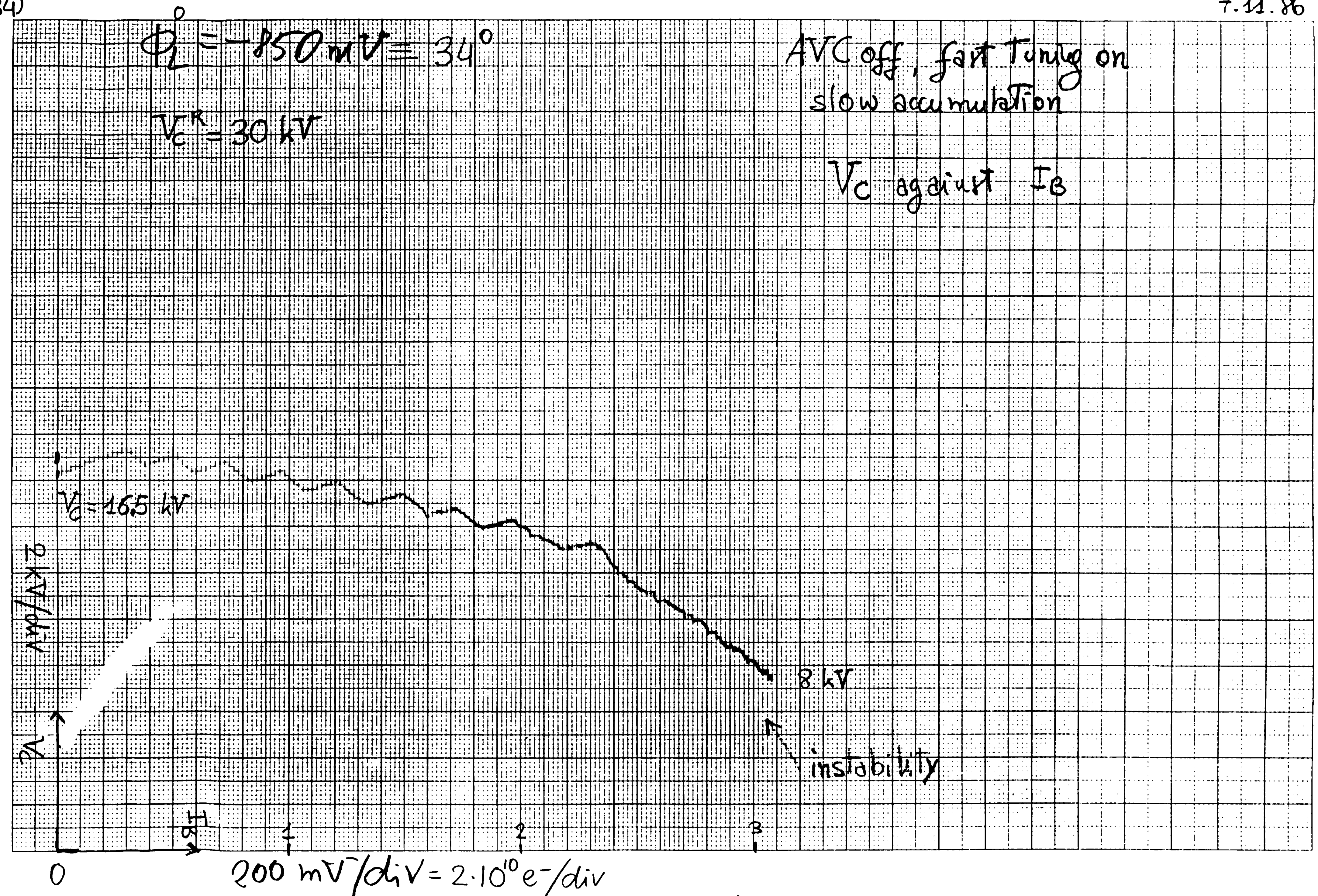


Fig. 8

(23)

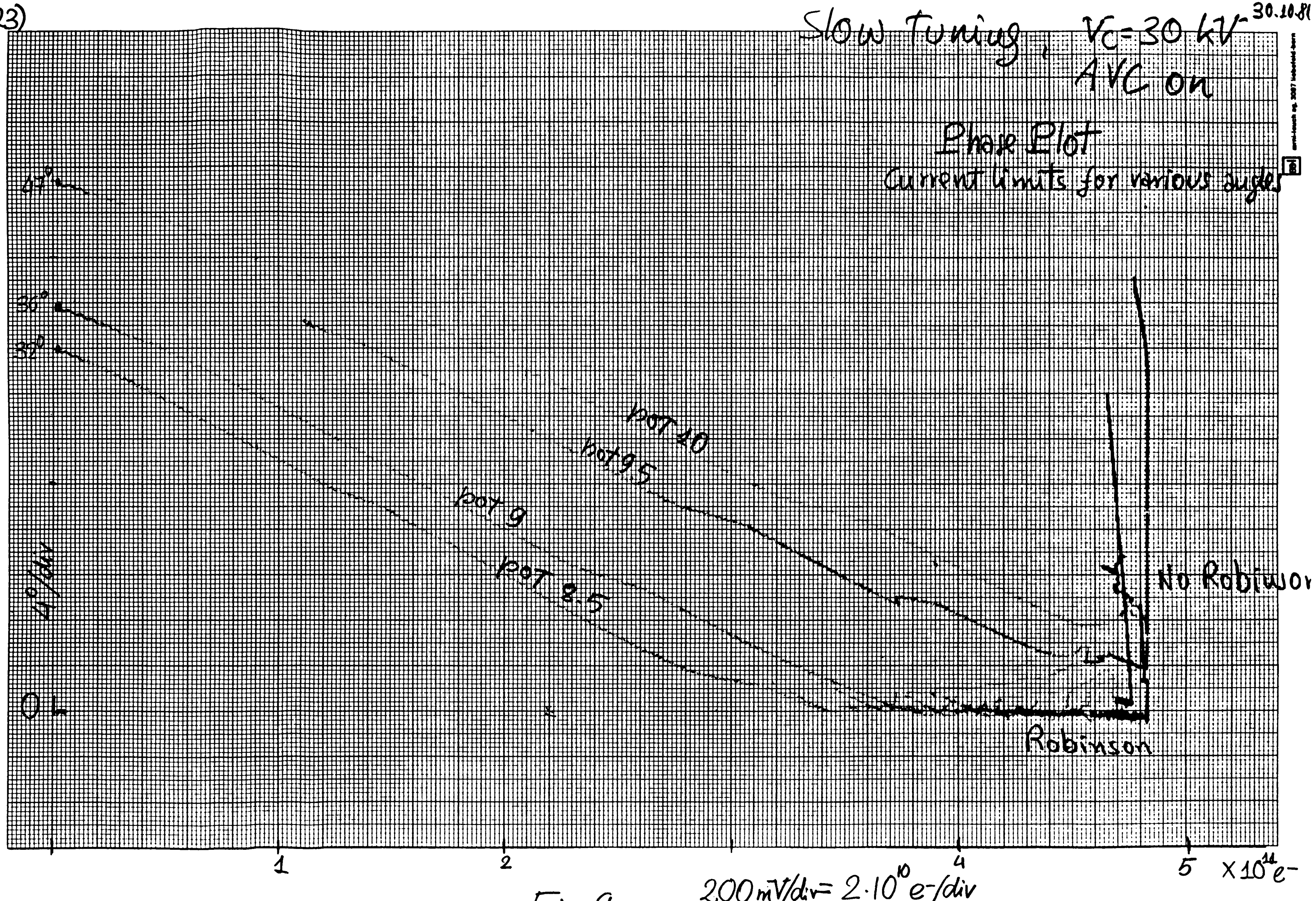

Slow Tuning, Vc=30 kV
30.10.81
AVC on
Phase Plot
Current limits for various angles
47°
36°
32°
4°/div
0
pot 10
pot 9.5
pot 9
pot 8.5
No Robinso
Robinson
1
2
4
5
x 10^11 e-
200 mV/div = 2·10^10 e-/div

Fig. 9

(24) V_C = 30 kV AVC on phase opposite sign 30.10.86

fast injection

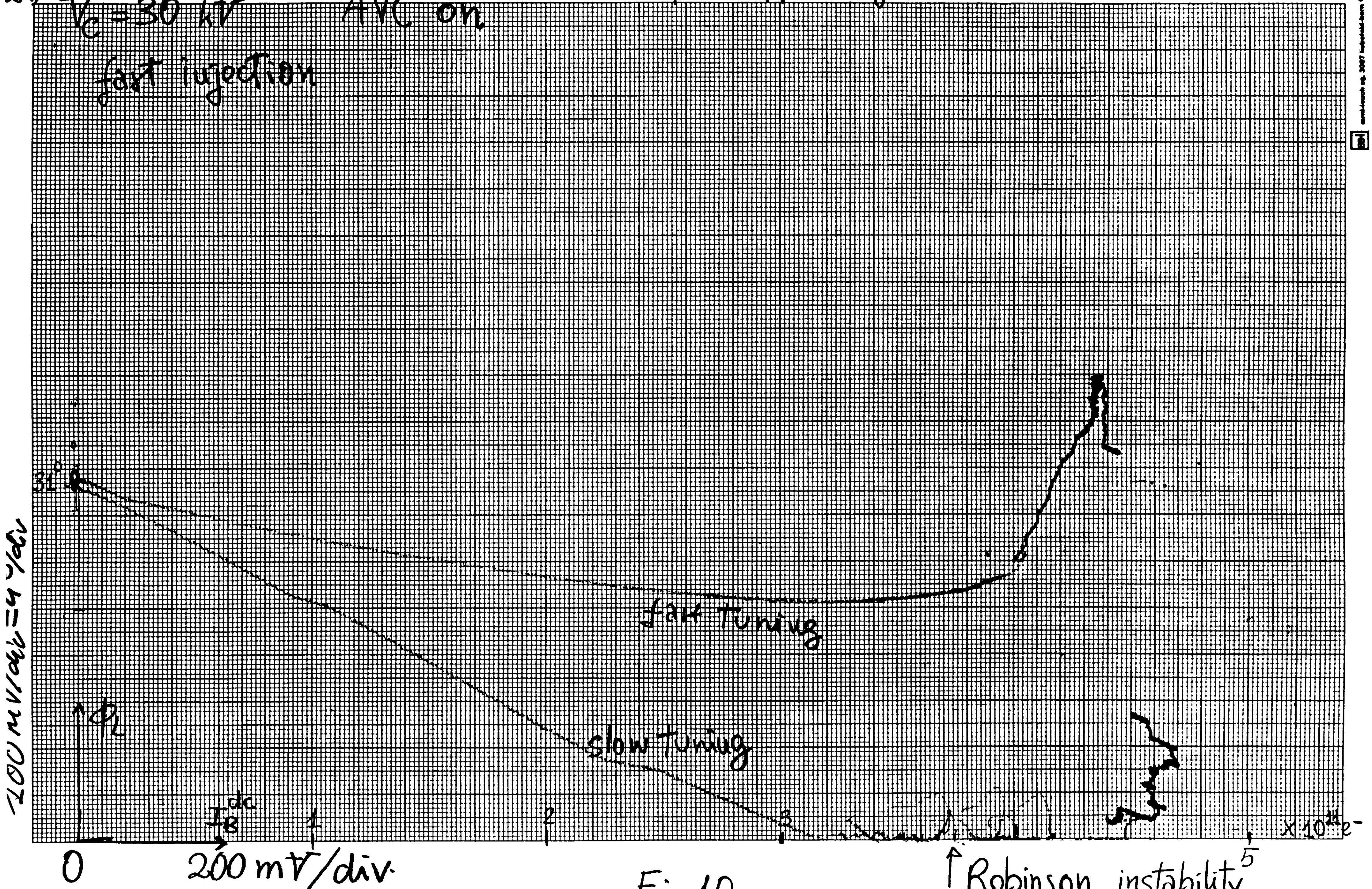
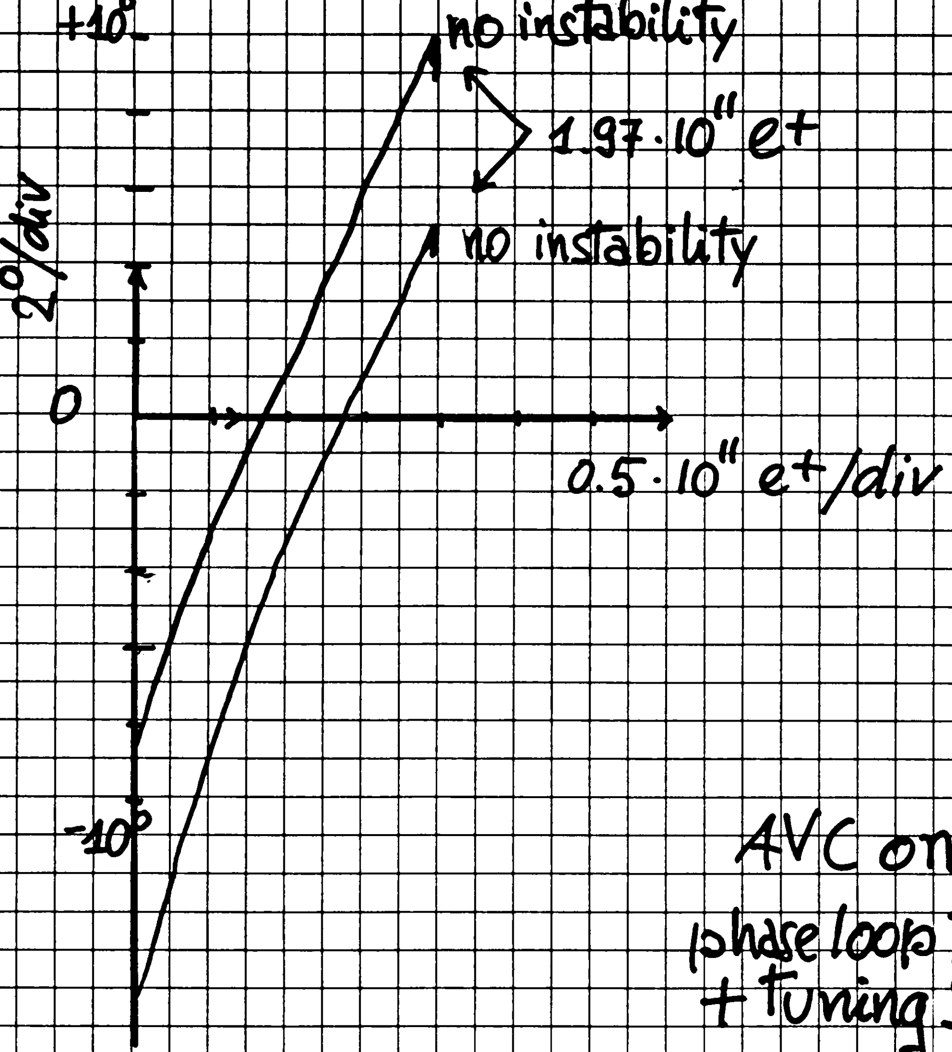


Fig. 10

$V_C = 30kV$



AVC on

phase loop + tuning } off

Fig. 11

(26)

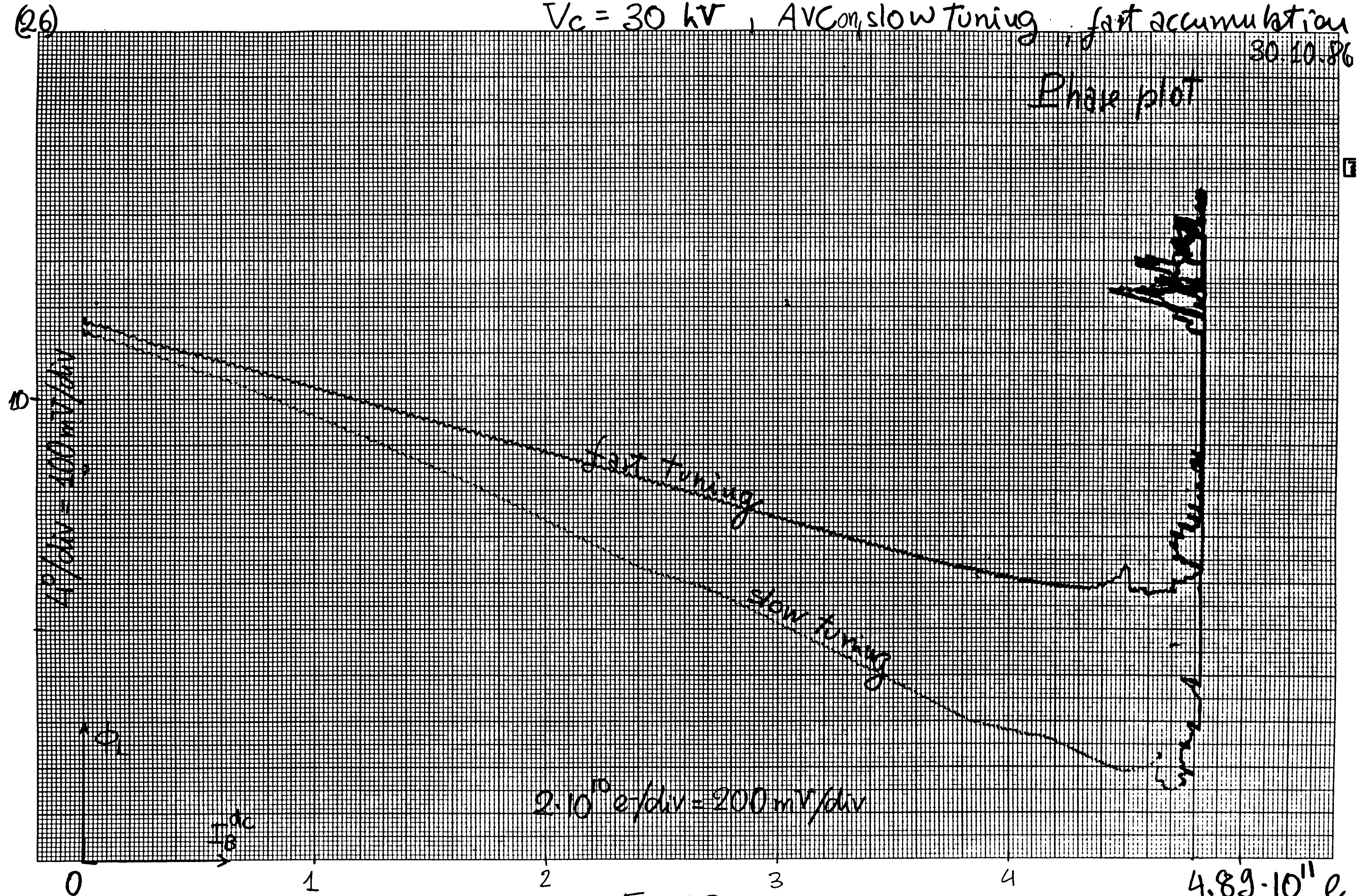

Vc = 30 kV , AVC on, slow tuning , fast accumulation
30.10.86
Phase plot
10
$\Delta\phi$/div = 100 mV/div
fast tuning
slow tuning
ϕ_L
I_B^{dc}
2·10¹⁰ e/div = 200 mV/div
0
1
2
3
4
4.89·10¹¹ e

Fig 12

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