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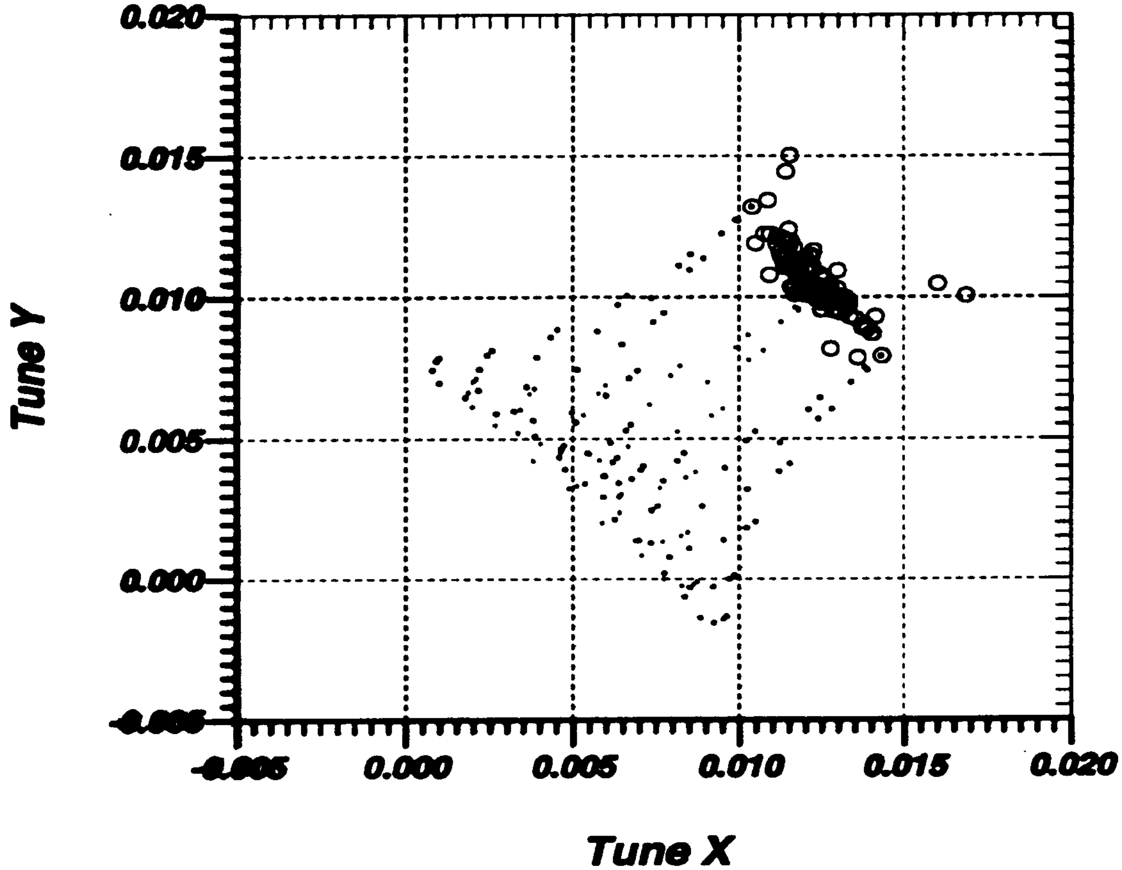
Compensation of Beam-Beam Effects in Tevatron with Electron Beams: R&D Status and Plans

1. Introduction: overview of beam-beam compensation with electron beams

2. Electron lens experiment:
   a) goals
   b) schedule
   c) design parameters

3. Electron beam studies in the Linac lab:
   a) prototype set-up
   b) magnetic field
   c) electron beam

Tune spread in the $\bar{p}$ beam for TEV33



Tune spread in the $\bar{p}$ beam for the TEV33 Tevatron upgrade [P.Badley, *et. al*, 1996]. Large circles are for tunes of core particles in 121 antiproton bunches. Small circles are tunes of non-zero betatron amplitude particles in some bunches.

$\Delta\nu_{\bar{p}} \approx 0.02$ is about the maximum experimentally achieved value for hadron colliders

$\longrightarrow$ enhanced diffusion due to high order resonances, increased background, limit on the beam lifetime and luminosity.

Can these beam-beam effects be corrected?

Goal #1: Compensation of bunch-to-bunch tune spread with time variable "electron lens"

Goal #2: Compensation of nonlinear beam-beam effects with "electron compressor"

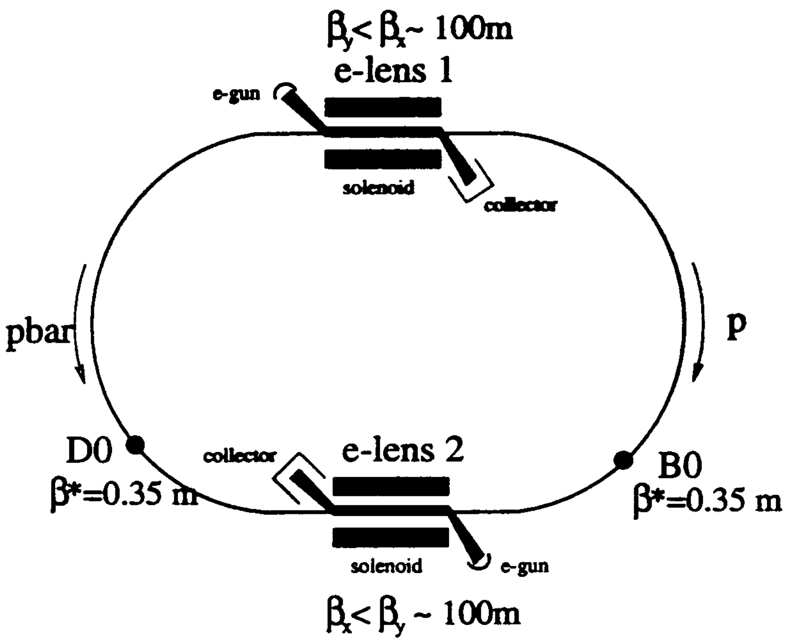
Goal #3: Beam dynamics studies, TMCI in the Tevatron, TEL as a diagnostics tool, etc.

Linear Electron Lens

The linear electron beam lens can compensate the bunch-to-bunch tune spread in the $\bar{p}$ beam by the electron current variation in time. For a round, constant density electron beam with total current J, radius a, and interacting with antiprotons over length L the tune shifts are

$$\xi_z^e = -\frac{\beta_z}{2}\frac{(1+\beta_e)n_e L r_{\bar{p}}}{\gamma_{\bar{p}}} = -\frac{\beta_z}{2\pi}\frac{(1+\beta_e)JLr_{\bar{p}}}{e\beta_e c a^2 \gamma_{\bar{p}}}$$

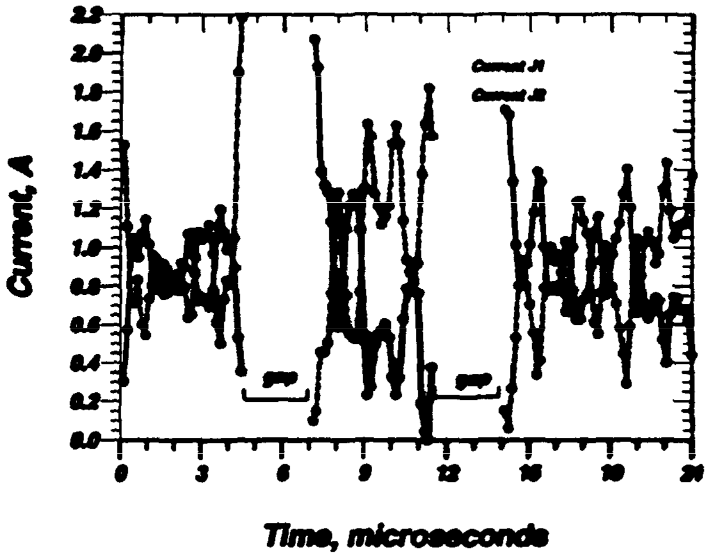
For example the beam with $J \approx 3.7$ A, $L = 2$ m, $a = 1.5$ mm, 10 kV ($\beta_e = 0.2$) gives $\xi^e \approx -0.01$ in the Tevatron $\gamma_p \approx 1066$, β_z=100m.



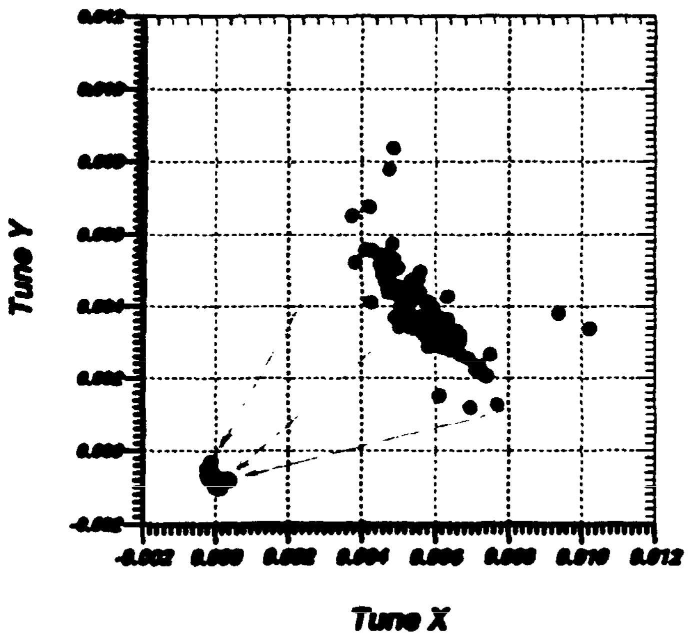
Tevatron layout with two electron lenses. Two electron lenses installed in locations with different β_x/β_y allows to compensate both x and y bunch-to-bunch tune spread.

The electron lens should be installed so that a) e-beam does not interact with proton beam; b) beta-functions are high enough so the electron current density is reasonable; c) dispersion function is small enough.

Linear compensation of the bunch to bunch tune spread

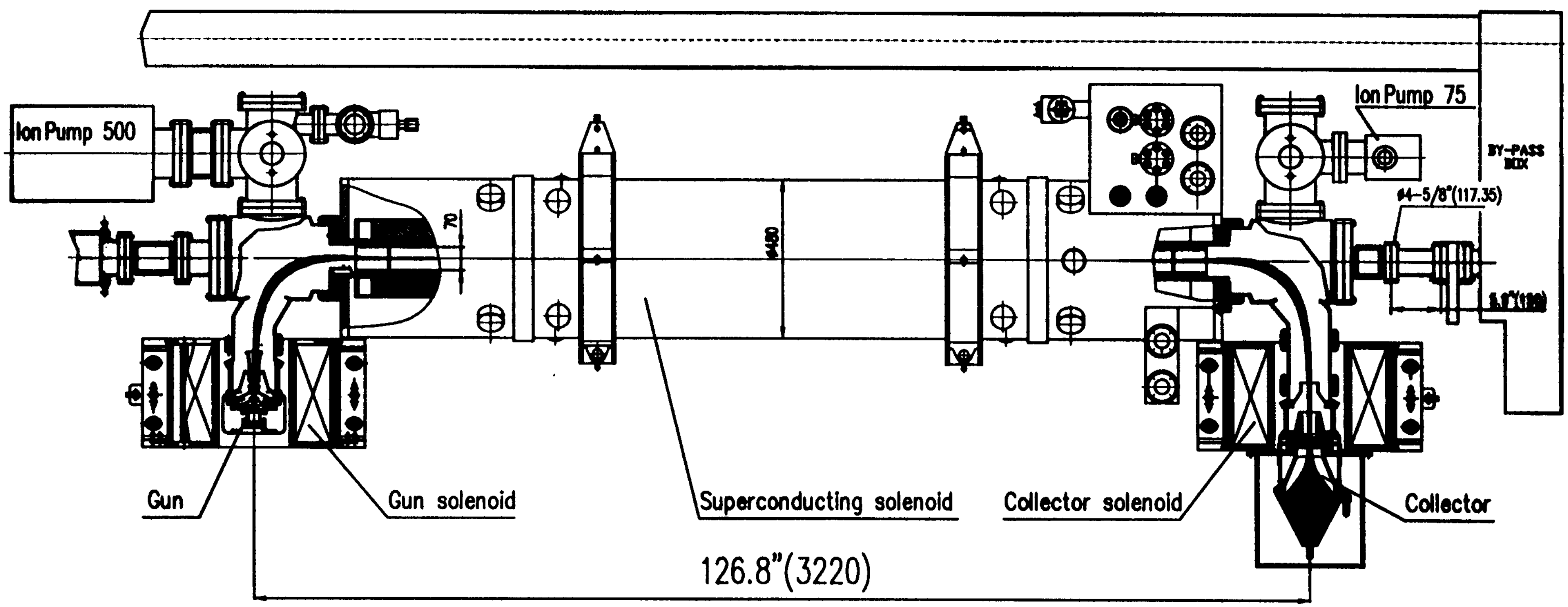


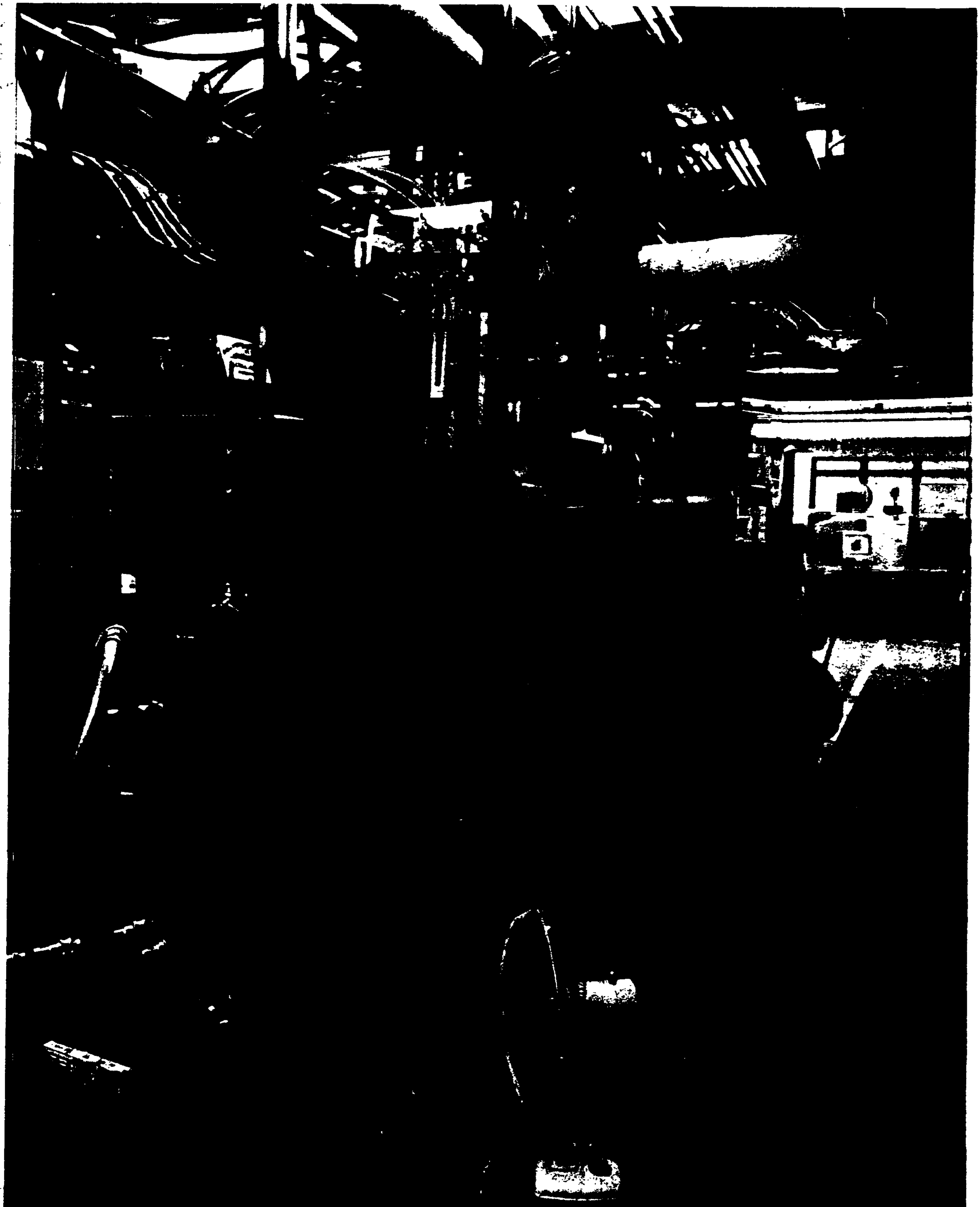
Currents in the two electron lenses to compensate the bunch-to-bunch tune spread in the 140×121 bunches scenario.



The initial 121 $\bar{p}$ bunch tunes (core particles only) and the resulting bunch tunes assuming a 10% compensation error.

Tevatron Electron Lens





99-2766

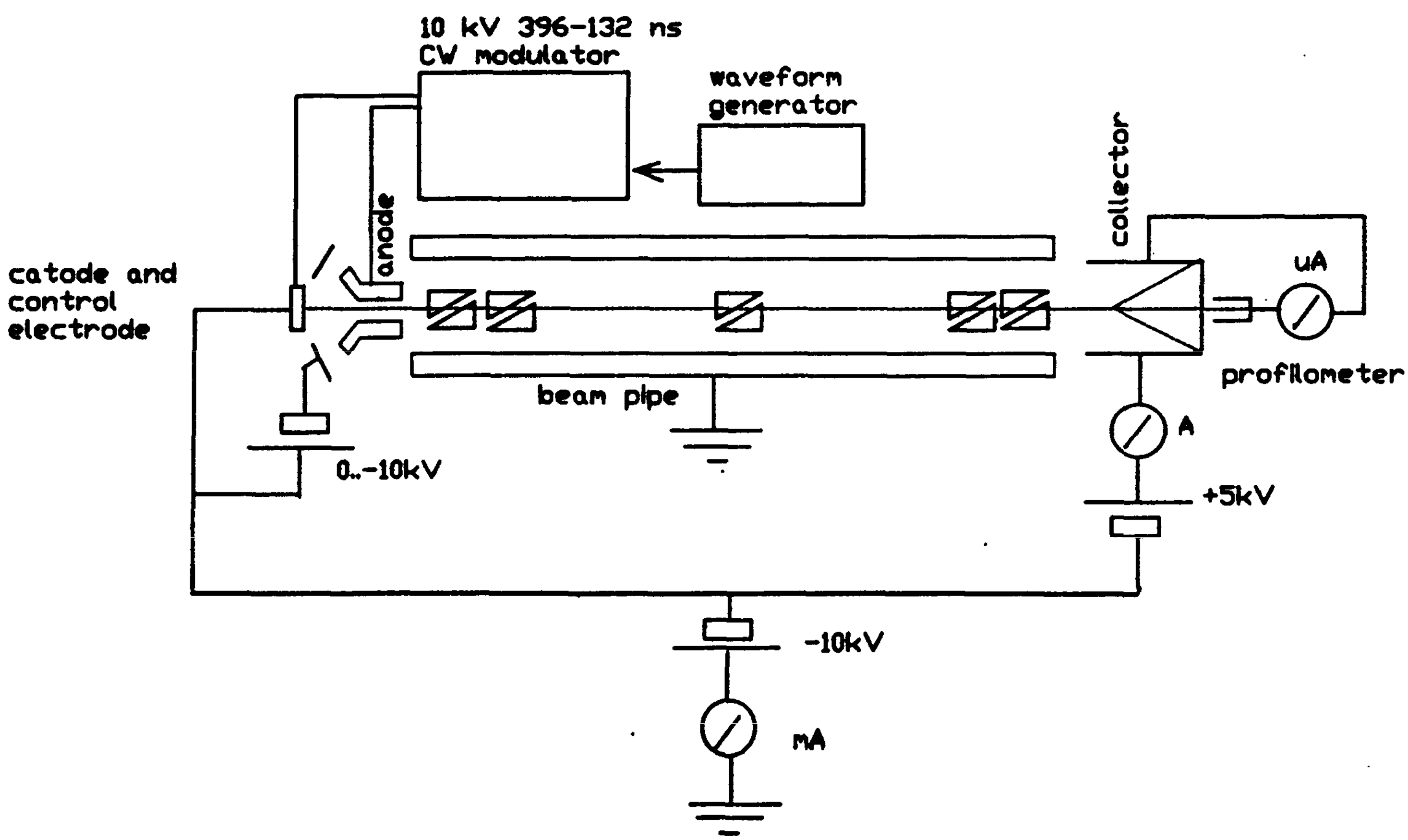
Electron lens

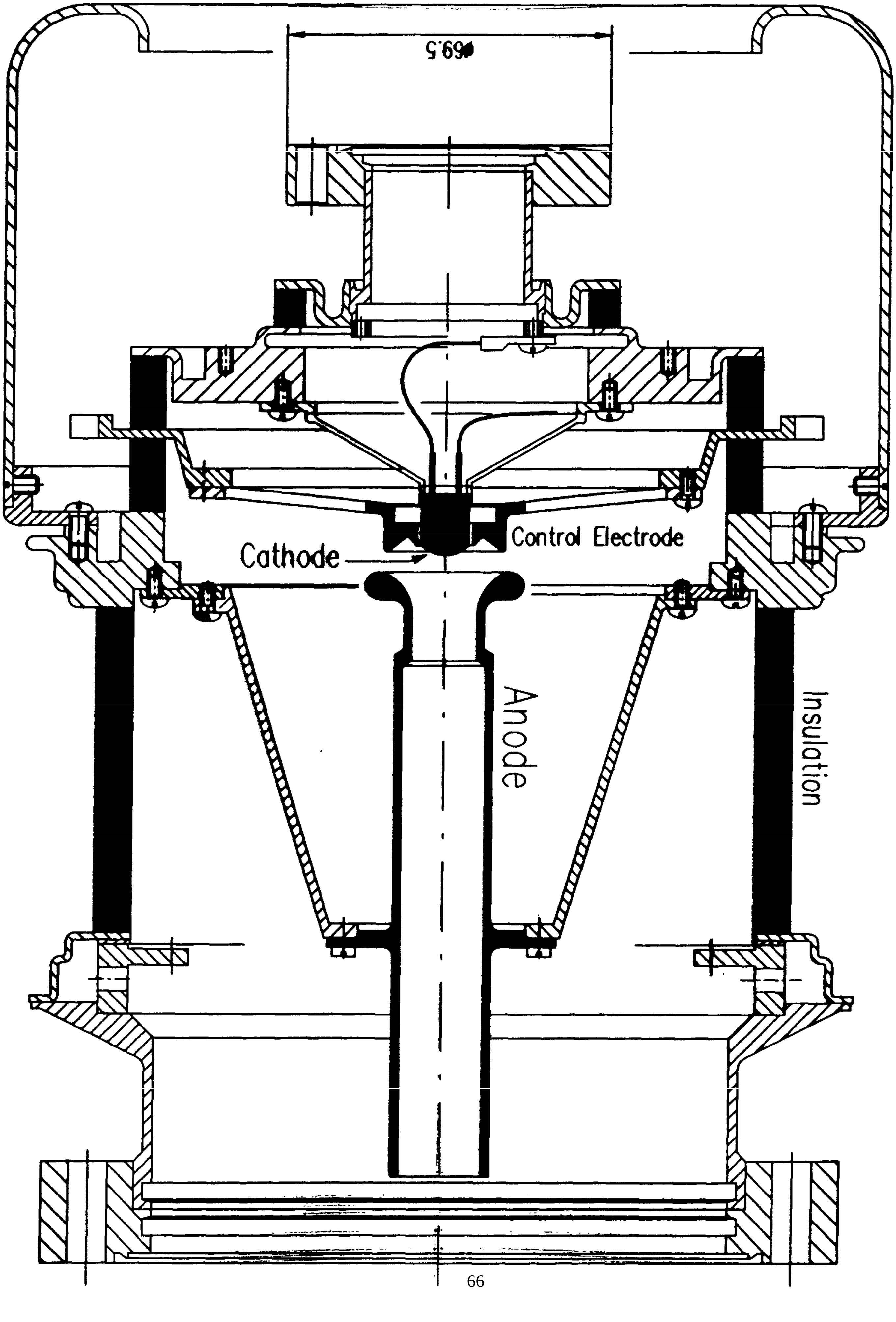
	Linac Lab prototype	Tevatron 1st e-lens
main solenoid length	1.96 m	2.50 m
total length	3.26m	3.67 m (v-v)
configuration	straight	2 bends
e-energy	7-20 kV	10-15 kV
max e-current	3A (DC), 12A(pulsed)	2-8 A
current stability	<0.1%	<0.1%
current modulation	160 ns	396 (132) ns
cathode radius	5 mm	5 mm
e-beam radius	2.5-5 mm	1-2 mm
area compression	upto 4	10-25
B field solenoid/gun	4/1 kG	50/2 kG
B straightness, rms *	0.05 mm**	0.05 mm
beam shape control	yes	yes
vacuum	$<10^{-7}$ Torr	$<10^{-9}$ Torr

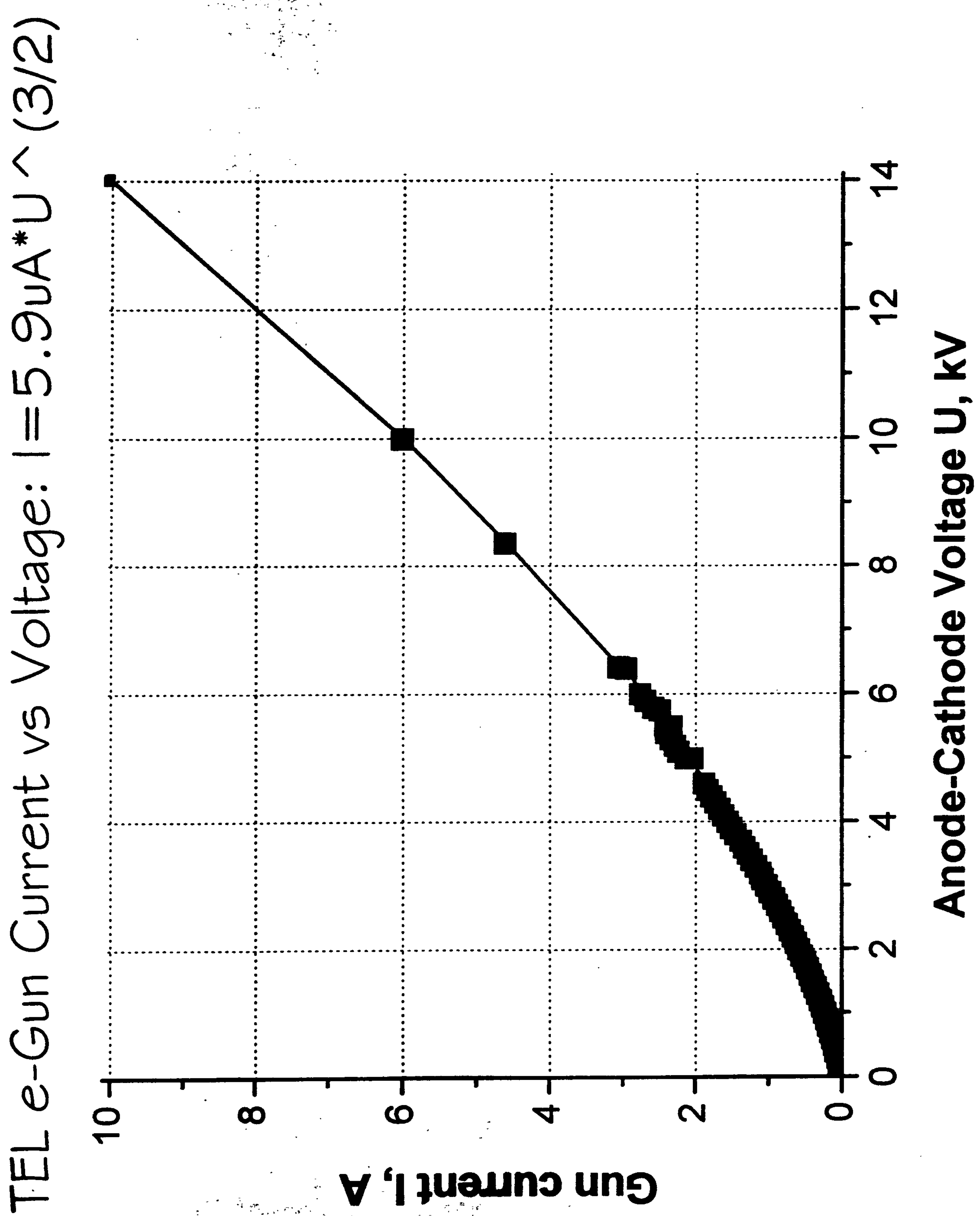
* over 80 % of length

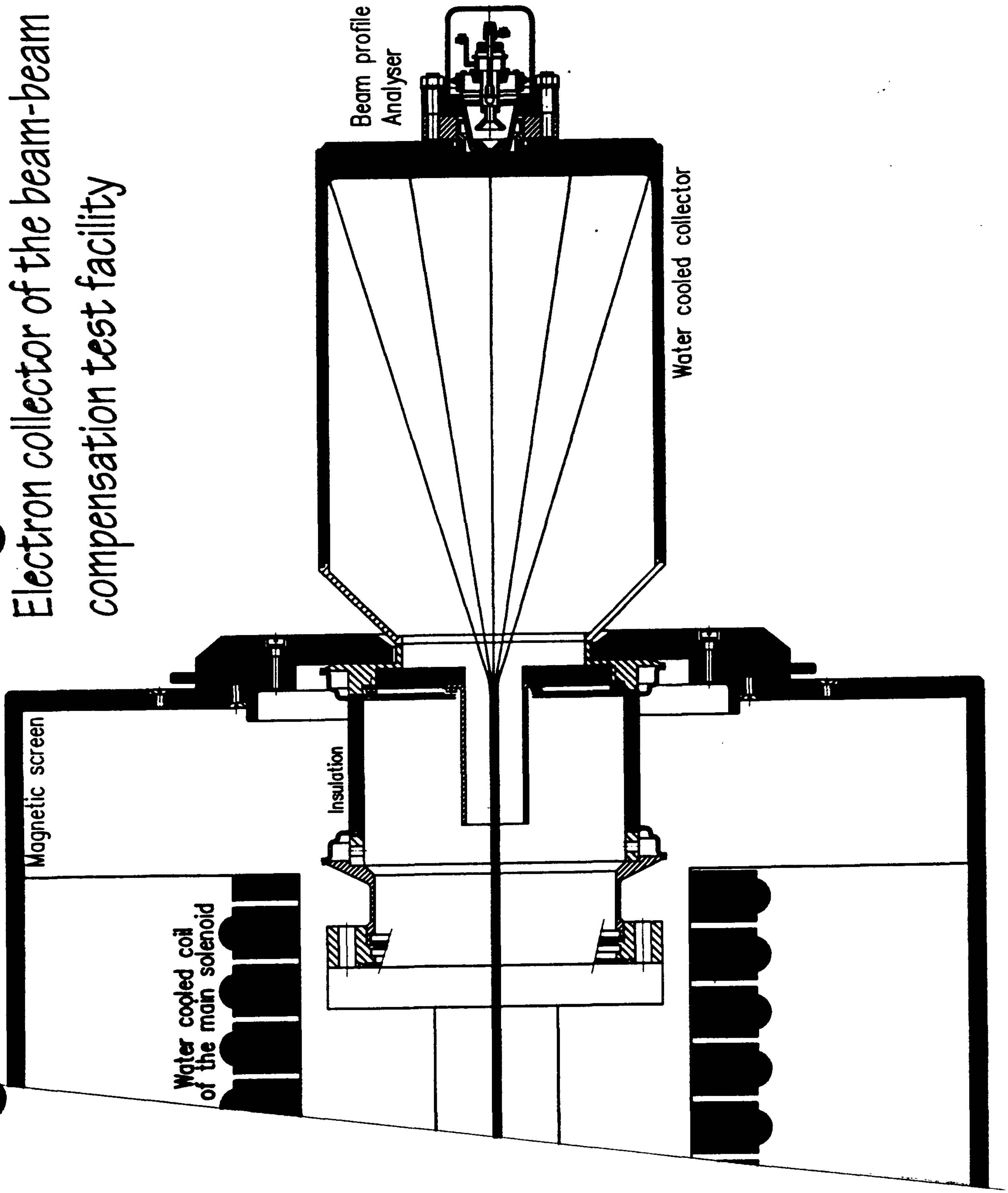
** 0.005 mm with use of corrector coils

TEL Electric Circuit

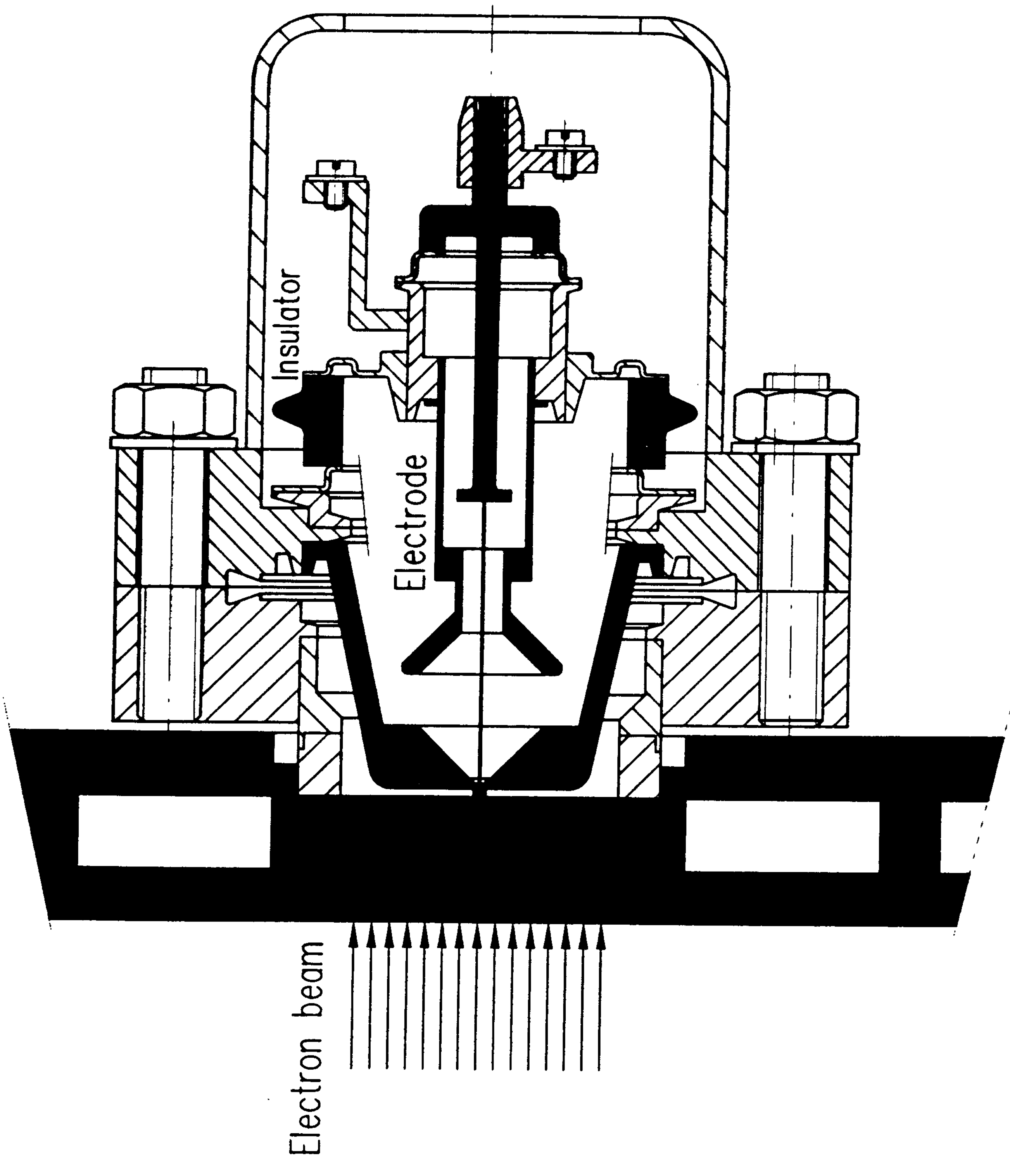


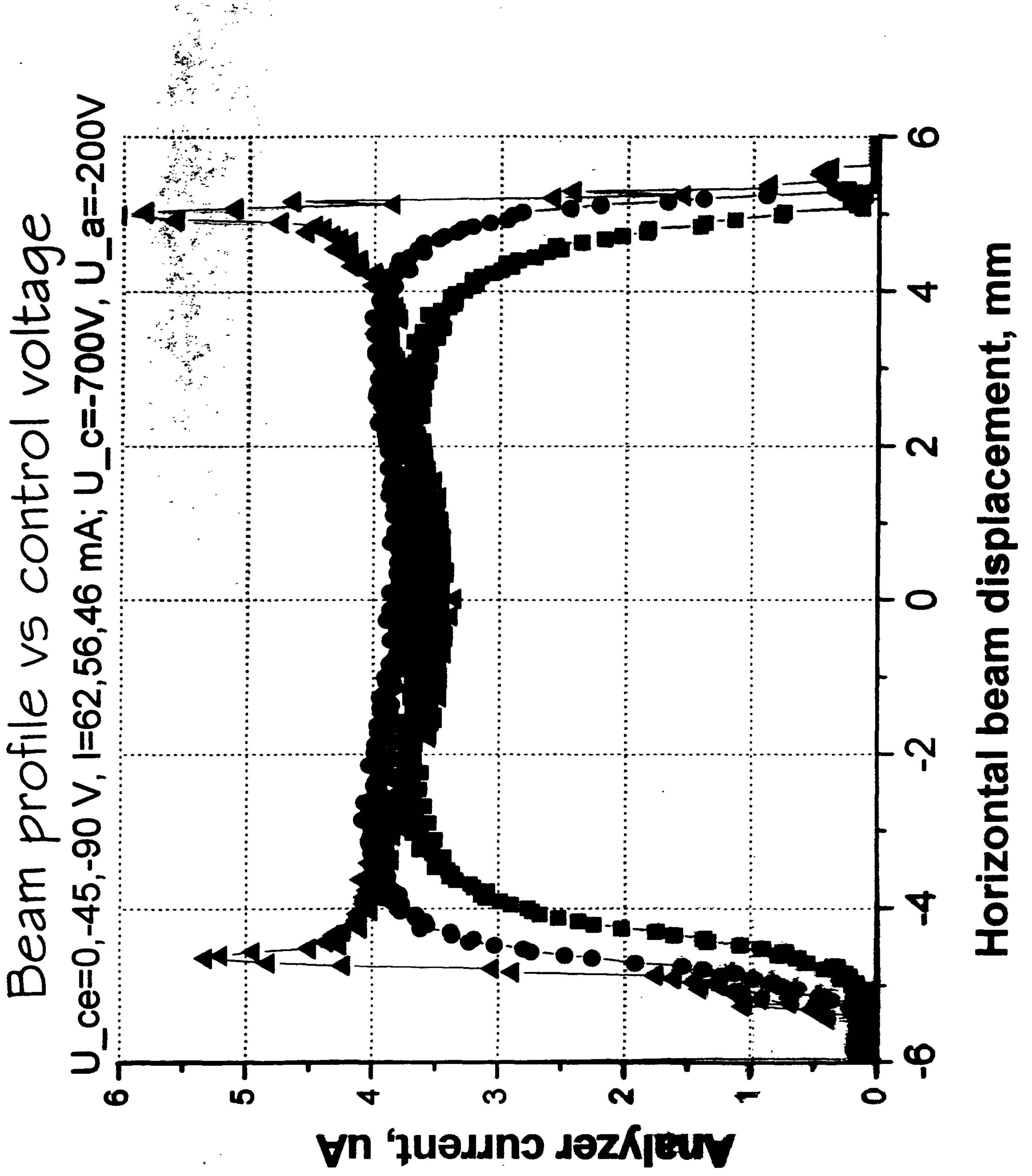

Control Electrode
Cathode
Anode
Insulation

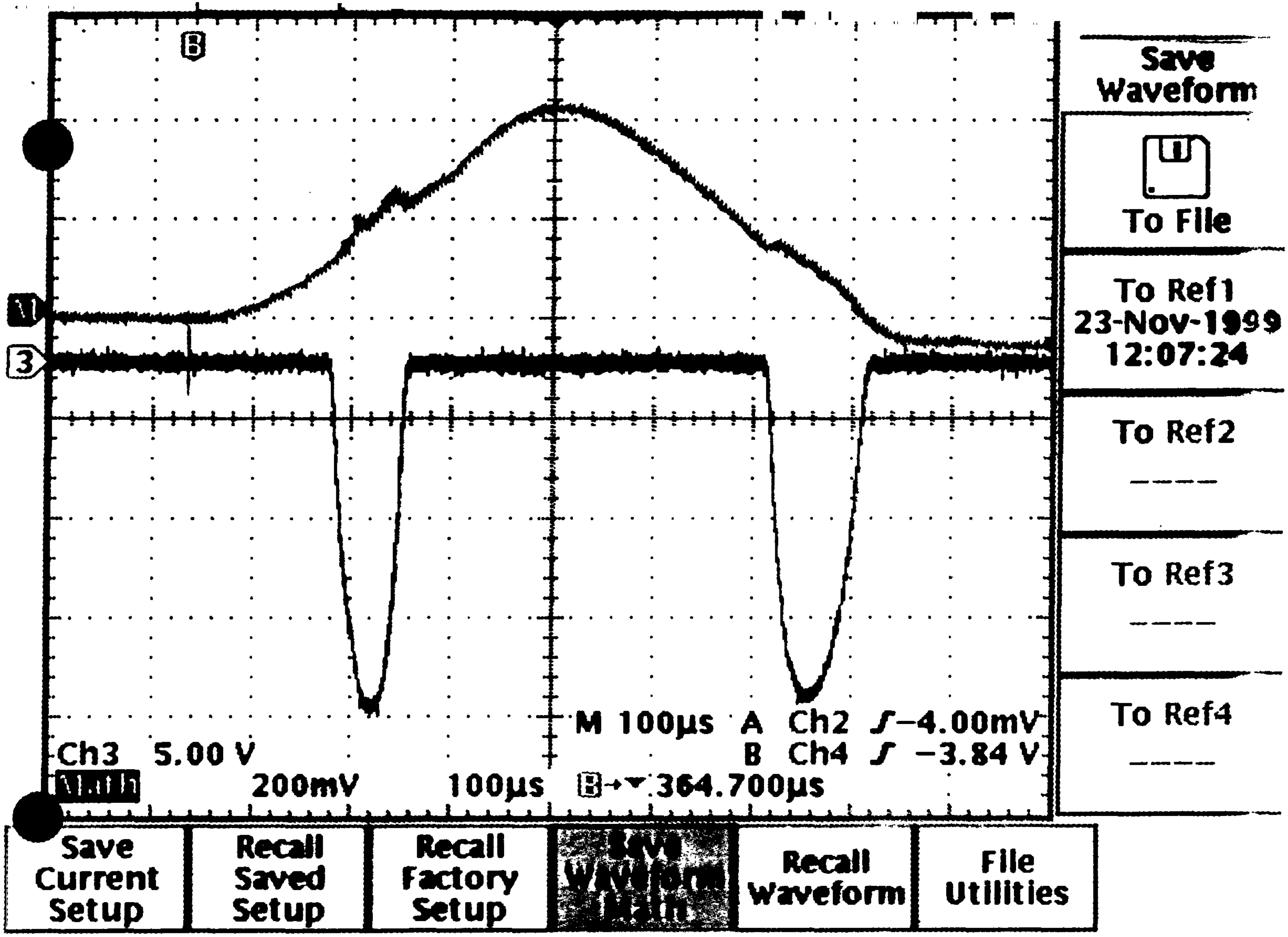

TEL e-Gun Current vs Voltage: I=5.9uA*U^(3/2)
Gun current I, A
Anode-Cathode Voltage U, kV
0
2
4
6
8
10
12
14

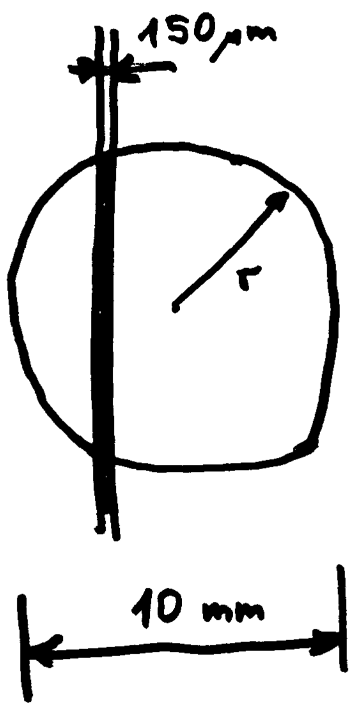

Electron collector of the beam-beam
compensation test facility
Beam profile
Analyser
Water cooled collector
Insulation
Magnetic screen
Water cooled coil
of the main solenoid

Beam temperature and profile analyser




Beam profile vs control voltage
U_ce=0,-45,-90 V, I=62,56,46 mA; U_c=-700V, U_a=-200V
Analyzer current, uA
0
1
2
3
4
5
6
Horizontal beam displacement, mm
-6
-4
-2
0
2
4
6



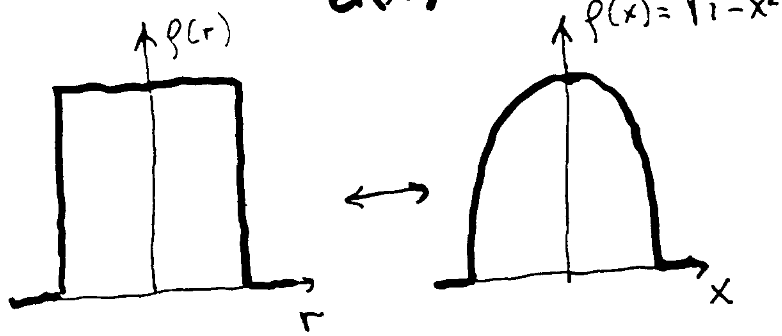


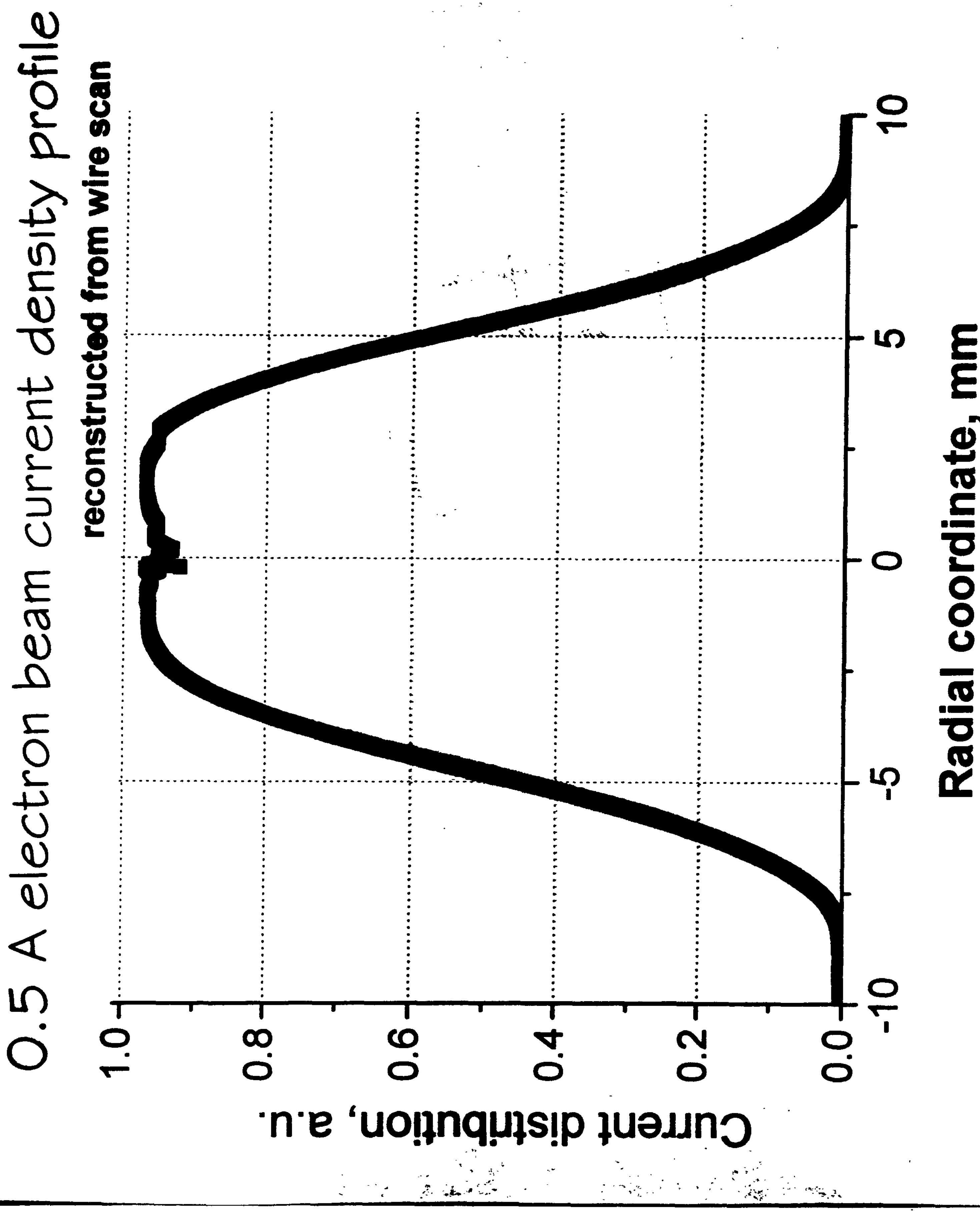
we measure $\rho(x)$

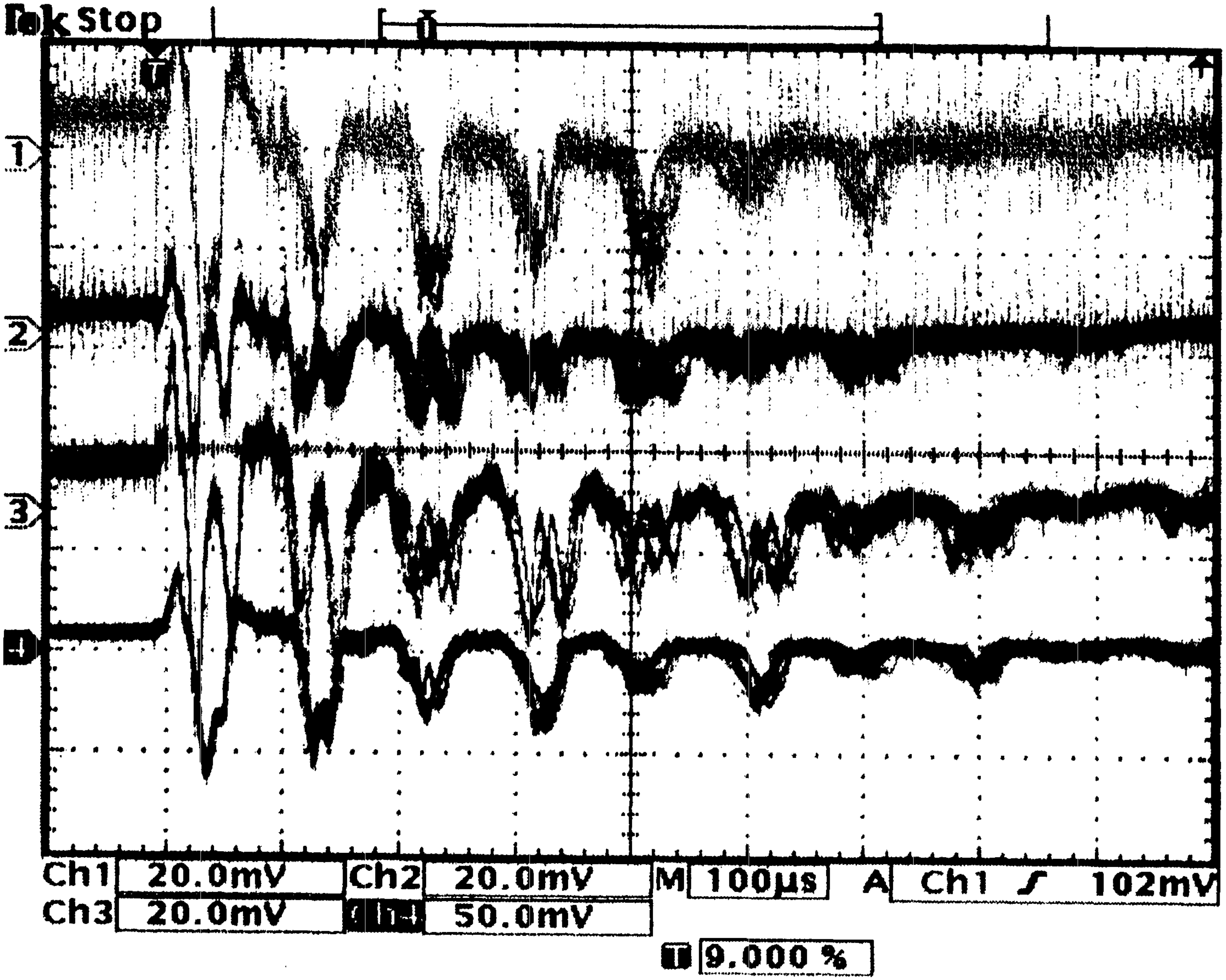
if $\rho(x,y) = \rho(r)$, $r = \sqrt{x^2+y^2}$

$$\rho(r) = -\frac{d\left(\rho^2(x)\right)}{d(x^2)}$$

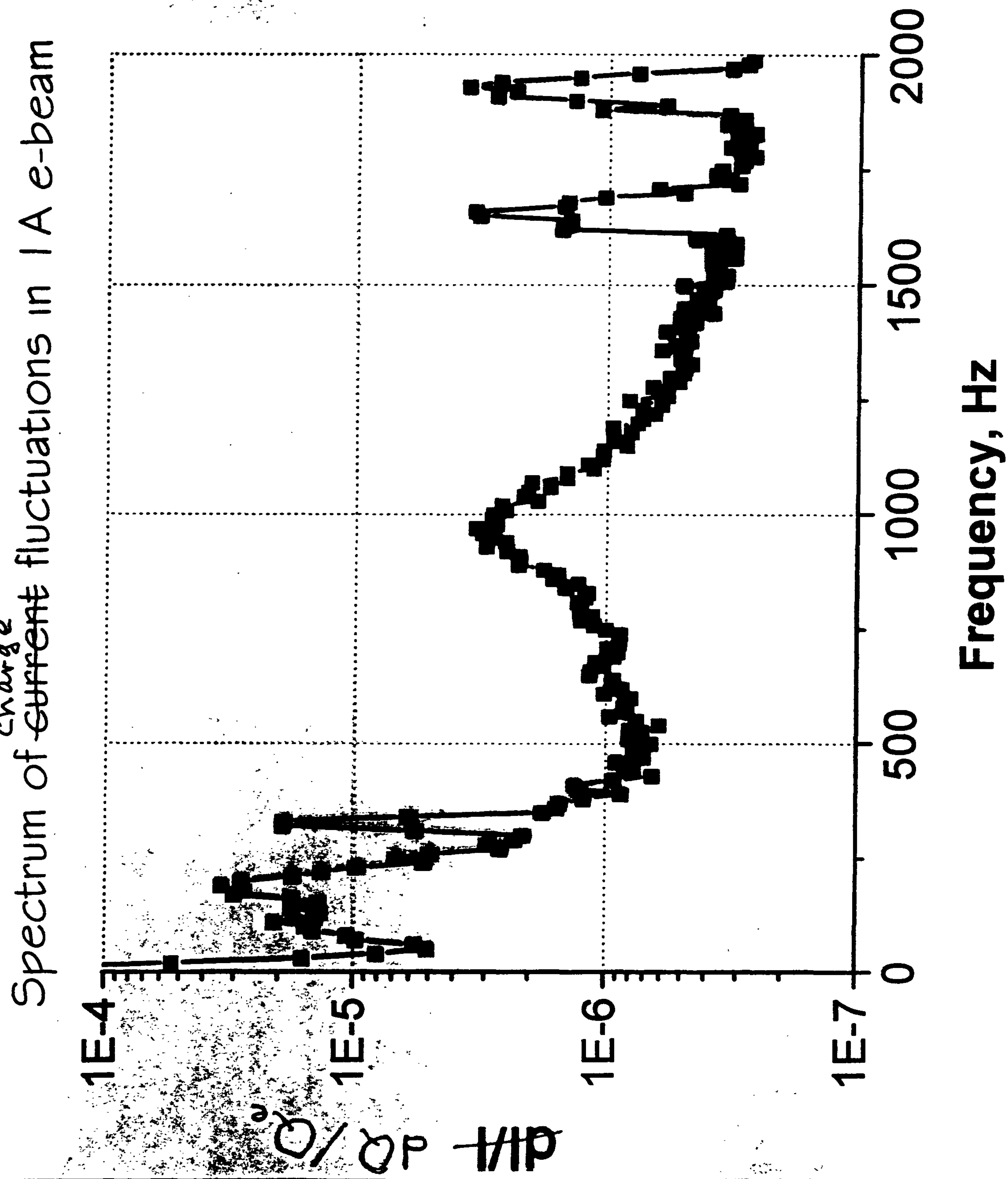
, e.g.

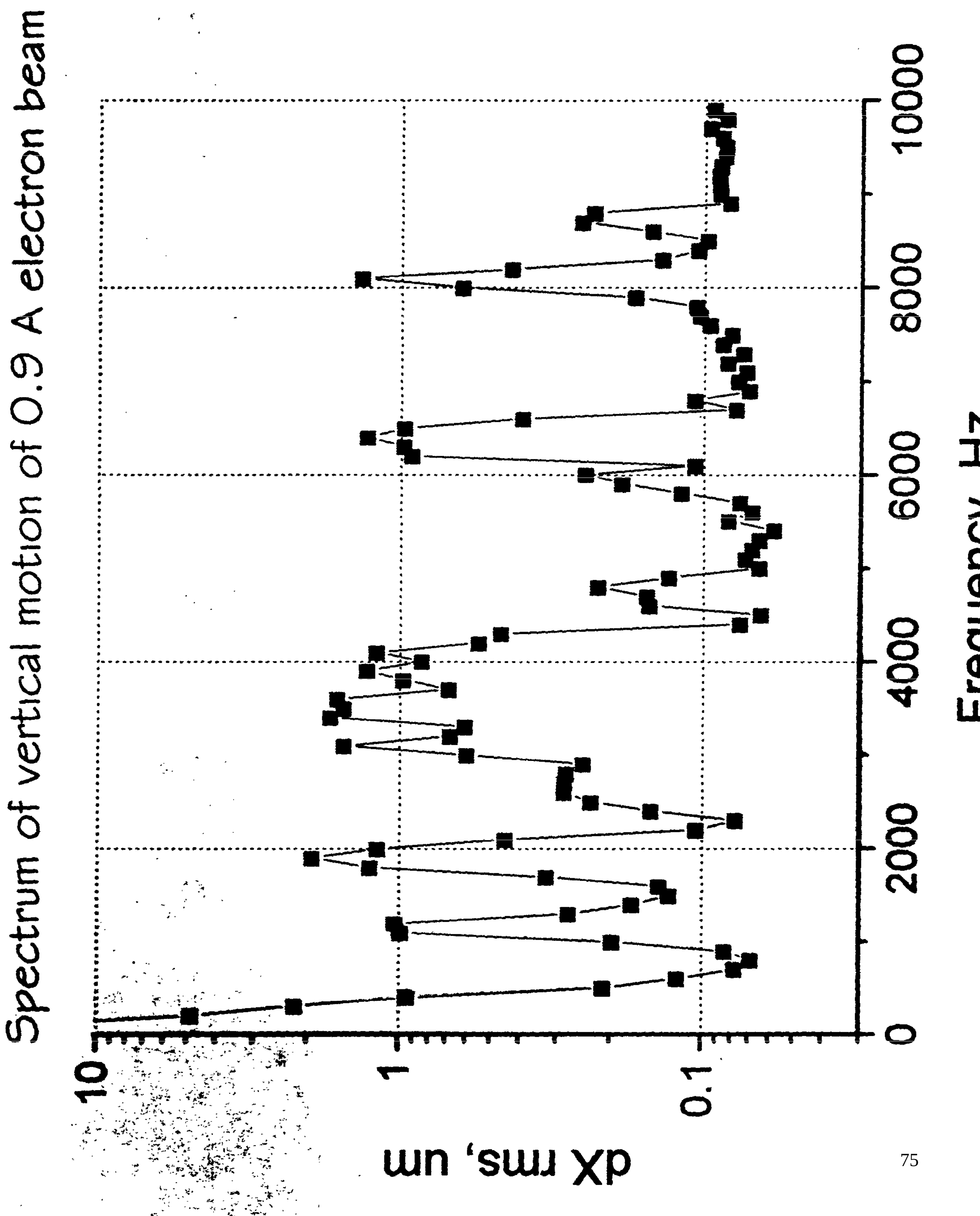



0.5 A electron beam current density profile
reconstructed from wire scan
1.0
0.8
0.6
0.4
0.2
0.0
Current distribution, a.u.
-10
-5
0
5
10
Radial coordinate, mm



Large amplitude waves in ion column around 0.1A electron beam: 1,2,3,4 – "sum" pick-up electrode signals along 2 m long system, $u=\omega_p a(\ln(b/a)/2)^{1/2} \approx 4$ cm/µs → $1.4 \cdot 10^{10}$ ions/m → 17% Q-compensation

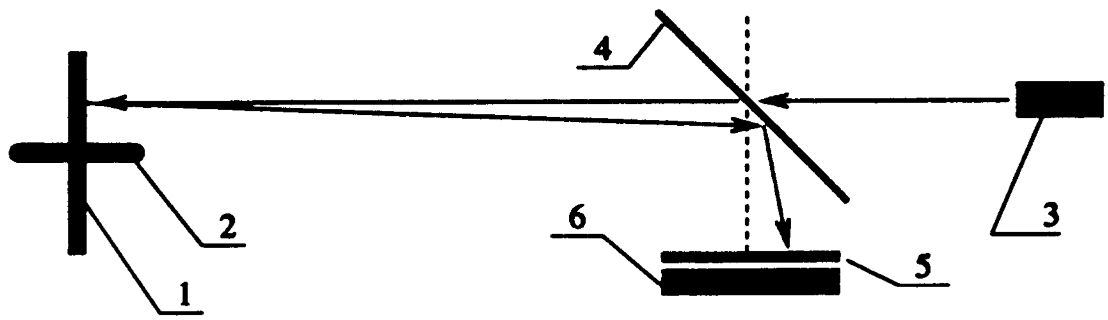

Spectrum of charge current fluctuations in 1 A e-beam
dI/I dQ/Q
Frequency, Hz
1E-4
1E-5
1E-6
1E-7
0
500
1000
1500
2000



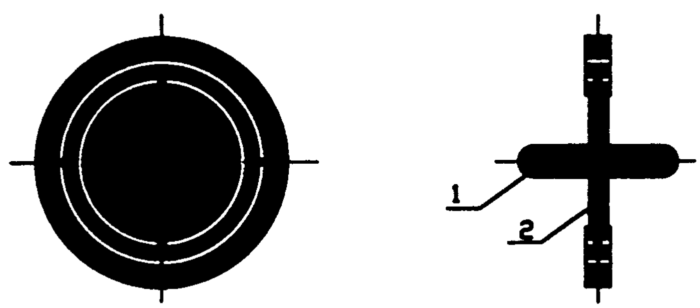
Spectrum of vertical motion of 0.9 A electron beam
dX rms, um
10
1
0.1
0
2000
4000
6000
8000
10000
Frequency, Hz

Magnetic field straightness in the e-lens

Magnetic field in the e-lens should be straight with accuracy $\sim 1 - 2 \cdot 10^{-4}$ rad.



Scheme of magnetic field straightness measurements. 1 and 2 – mirror with magnetic arrow, 3– diode laser, 4– beam splitter, 5– optical filter, 6– Position Sensitive Device.

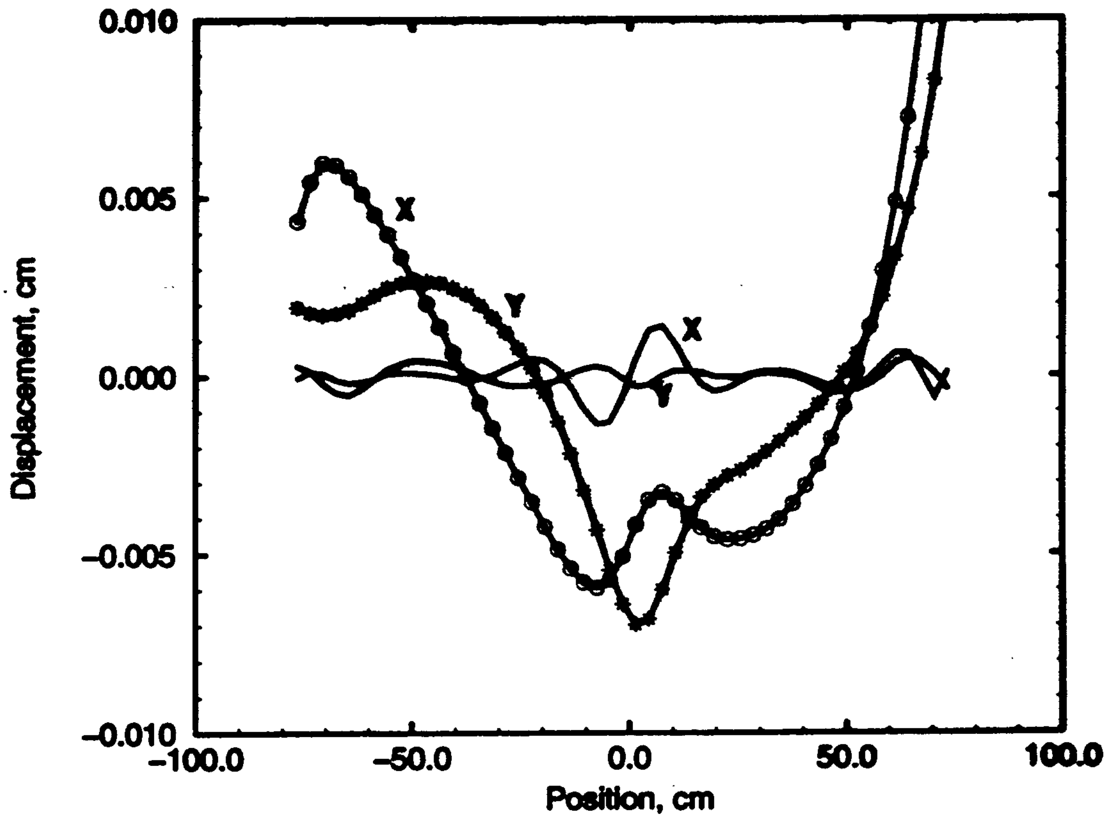


The probe allowed to measure the direction of magnetic field is a flat mirror with an attached magnetic arrow wich has 2 degrees of freedom. Here 1– arrow, 2– reflective surface.

The precision of the method is $\alpha_{\mathrm{rms}} \approx 1.5 \times 10^{-4}\,(1\mathrm{kG}/B)^2$ in low fields with saturation of the arrow at $B \sim 1.5$ kG. The precision in a higer field of about 4 kG is ~10–20 μrad.

Magnetic field alignment

Deviation of the electron trajectory (i.e. of the magnetic field line) from the straight line in the "electron lens" should be $\Delta x_e \lesssim 0.1a$ that is about 0.01 cm.



Deviation of the magnetic field line in the main solenoid of the electron lens prototype without (stars and circles) and with (lines) simulated correction by dipole coils.

The field deviation was measured optically, using a magnetic arrow attached to the mirror which has two rotational degrees of freedom.

Beam-Beam Compensation Project

Summary of accomplishments to date:

1. LINAC LAB:

a) Electron lens prototype in the Linac lab provided some 1000 Ampere-hours of operational experience.

b) We achieved e-beam currents of 3A DC, 5A in pulsed regime 50 kHz rep rate, and 12 A maxumum in pulsed regime. That exceeds BBCompensation requirements.

c) Experimentally demonstrated that multi-Ampere electron beams can very stable. High-frequency fluctuations of the electron current can be less than 0.01%. Beam transverse position jitter is some microns. That's better than B.B.Compensation criteria.

d) We have designed, fabricated and tested a number of electron beam diagnostic tools, including ion/electron clearing electrodes, BPMs and low-noise electronics, "staying wire" beam profile monitor.

2. TEVATRON ELECTRON LENS:

a) we have designed TEL magnetic system in collaboration with IHEP, Protvino and assured it fits Tevatron infrastructure and safety requirements Fabrication of the magnetic system is underway in IHEP, Protvino and to be finished in June 2000.

b) 50 kW collector and 8 A electron gun designs are finished. Fabrication started.

c) preparations of the E4R building for the TEL test experiments has been started.

Near future plans:

a) finish design and fabrication of the TEL vacuum chamber, beam diagnostics.
b) finish fabrication of the full scale HV modulator (400 ns, 10 kV CW).
c) after getting SC solenoid magnet – perform full scale test in E4R building (June-Dec 00)
d) install the 1st TEL at F48

e) Tevatron beam studies:

Plan PB: TEL with I=0A does not make any harm (vacuum, orbit, QPS)

Plan A: single bunch operation, demonstration of dQ=-0.01

Plan AA: 36 bunch operation @Run II dt<400ns, dQ=-0.01

after that decision about the 2nd TEL will be made