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ON THE USE OF THE ICE GUN FOR ELECTRON COOLING IN LEAR

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1. INTRODUCTION

The application of electron cooling to beams stored in LEAR [1] is of importance for various reasons. The cooling results in an increase of beam lifetime, essential for a long spill; in a reduction of beam emittances, allowing for loss-free deceleration; and for reaching very low extraction energies. The use of electron cooling is indispensable for the operation of an internal jet target over a wide energy range to prevent the beam from blowing-up (beam loss) and thus allows reasonable target thicknesses. During this operation it is of particular importance that the energy can be altered easily by changing the high voltage and magnetic fields correspondingly. From the electron gun high voltage the stored beam momentum can be determined with a high relative accuracy without knowing the machine parameters. Circulating $\bar{p}$ and H^- ions can be cooled simultaneously.

From what has been said above it can be concluded that an electron gun reaching the highest possible voltages and currents would be desirable. A new system would have to be built to reach energies close to $\bar{p}$ transfer energy from the PS to LEAR. In the following, however, we study the possibility to use the present ICE electron cooling system with small modifications, in LEAR and discuss the improvements achievable with this system on the LEAR beams.

We first give a short description of the ICE gun and resume the results from the cooling experiments in ICE. From these measurements we scale the cooling performance to other energies, discuss the deceleration procedures and the jet target operation. We then describe the existing equipment, the required modifications, diagnostics, controls and operation and give cost and manpower estimates as well as a tentative time schedule.

2. SUMMARY OF THE ELECTRON COOLING EXPERIMENTS IN ICE

2.1 The ICE electron gun

A description of the electron gun is given in Ref.2) and the set-up is shown in Figs. 1-3. The cooling system consists of three parts , the electron gun, the drift section and the collector, all immersed in the field of three solenoïds. The gun and collector are joined to the drift tube at an angle of 36 degrees by two toroids. The Pierce type flat cathode is in the magnetic field of the gun solenoid. The gun is operated in space charge limited flow, hence voltage and current are related through Child's law :

$$I = P\ V^{3/2}$$

where the perveance P is set by the voltage applied to the anodes.

Through resonant focusing the electrons emerge with small transverse velocities from the gun. Perpendicular to the beam axis they have, however, an energy distribution originating from the space charge depression across the electron beam. In the collector the electrons are decelerated to about 1.5 keV in a tapered magnetic field before they are collected. The collector consists of a repeller to shape the field at the entrance, the spike to deflect the axial electrons to the collector walls, the mesh to repell low energy secondaries and the collector itself (Fig. 3).

The electron cooling system was designed for 60 kV. The cooling experiments in ICE were performed around 26 kV. The maximum high voltage reached so far that could be held continously was 33 kV (3.1 Amp). In Table 1 a summary of the design characteristics are given.

TABLE 1 - DESIGN CHARACTERISTICS OF THE ICE ELECTRON COOLER

Cathode diameter (cm)	5
Cathode type	flat dispenser
Cathode temperature for space charge limited operation (°K)	1350
Cathode heating power (W)	100
Maximum perveance P ($A \cdot V^{-3/2}$)	$6 \cdot 10^{-7}$
Number of anodes	5

Bore of anodes (cm)	6
Gun focusing	resonant
Basic length of gun section (cm)	130
Length of cooling section (cm)	300
Basic length of collector section (cm)	109
Length between vacuum valves (cm)	660
Toroid angle (degrees)	36
Diameter of gun, drift and collector tubes (cm)	20
Collector deceleration	non resonant
Collector magnetic field	tapered
Collector diameter/beam diameter	5
Collector voltage/full voltage (%)	95
Maximum high voltage (kV)	60
Maximum beam current (A)	8
High voltage stability	$8 \cdot 10^{-5}$
Maximum solenoid field (kG)	3
Magnetic field stability	$5 \cdot 10^{-5}$
Magnetic field rms angle	$5 \cdot 10^{-4}$
Number of correction coils	20

2.2 Cooling results

Electron cooling experiments have been performed in ICE [3)-5)] on coasting proton beams with an intensity of 10^8 at an energy of 46 MeV. Protons have also been stacked and accumulated to 2.10^9 particles and the cooling performance under these conditions and density dependent effects have been investigated. Moreover, the cooling of bunched beams has been studied. Measurements have been performed above and below the transition energy of ICE. In Table 2 the initial proton beam properties and the ICE characteristics are listed.

TABLE 2 - CHARACTERISTICS OF THE ICE MACHINE AND THE PROTON BEAM (below transition)

ICE Circumference (m)	74.38
Proton energy (MeV)	46
Proton momentum (MeV/c)	300
Horizontal acceptance (mm mrad)	80 π
Vertical acceptance (mm mrad)	40 π
Momentum acceptance	$\pm 3\cdot 10^{-3}$
Horizontal Q value	1.71
Vertical Q value	1.17
γ transition	1.3
Horizontal beta in cooling section (m)	3.
Vertical beta in cooling section (m)	12
Momentum compaction in cooling section (m) αp	5
Horizontal beam width in cooling section (mm)	$\pm$ 20
Vertical beam width in cooling section (mm)	$\pm$ 20
Horizontal beam divergence in cooling sect. (mrad)	$\pm$ 4
Vertical beam divergence in cooling sect. (mrad)	$\pm$ 1.6
Average number of protons per single injection	2.10^{8}
Average pressure (Torr) gauge reading	10^{-9}
Beam life-time (without cooling) (sec)	180
Maximal stacked intensity	2.10^{9}
Bunching factor for bunched beam	0.33

Cooling experiments were performed with currents of 2.3, 1.2 and 0.6A in space charge limited operation and also with a temperature limited current at 0.6A. The longitudinal frictional force was measured over a wide range of velocity differences by imposing a voltage step, ramp or sine wave on the gun high voltage and observing the rate of change of the proton beam momentum. The transverse cooling times were investigated through the damping of horizontal betatron oscillations excited by a kicker.

Momentum, and momentum spread, of the coasting beam were deduced from the Fourier spectrum of the Schottky noise induced in a pick-up. The horizontal and vertical beam distributions were measured with a beam profile monitor installed in the straight section opposite to the cooling region. This device was also used to monitor the intensity and to determine the beam lifetime. Neutral hydrogen atoms formed in the cooling process and leaving tangentially the cooling region were detected with a MWPC and a scintillation counter at the end of a 10m long prolongation of the straight section. The neutral beam was used to analyse the proton beam distribution and its divergence in the cooling region. From the formation rate of neutral hydrogen atoms the transverse electron temperature was determined. Some of the experimental results are summarized in Table 3 [3)-5)].

TABLE 3 - TYPICAL COOLING RESULTS AT 46 MeV PROTON ENERGY AND 10^8 STORED PROTONS FOR OPERATION BELOW TRANSITION

Electron gun high voltage (kV)	25.9
Electron beam current (A)	1.25
Electron beam current density (A/m^2)	640
Solenoid magnetic field (G)	500
Space charge depression within the electron beam (V)	120
$\frac{1}{e}$ momentum cooling time $\tau_{\parallel}$ (sec) *)	0.5
$\frac{1}{e}$ betatron cooling time $\tau_{\perp}$ (sec)	2.5
Equilibrium momentum spread $\Delta p/p$ (FWHM)	$1.4 \cdot 10^{-4}$
Equilibrium horizontal emittance ε_H (mm mrad)	π
Equilibrium vertical emittance ε_V (mm mrad)	4π
Equilibrium horizontal beam FWHM (mm)	±1
Equilibrium vertical beam FWHM (mm)	±3.5
Equilibrium horizontal divergence (mrad)	±0.3
Equilibrium vertical divergence (mrad)	±0.3
Neutral hydrogen rate (sec^{-1})	400
$\frac{1}{e}$ lifetime of cooled beam (sec)	> 2000
Average gun vacuum (Torr) (gauge reading)	$2 \cdot 10^{-10}$
Collector gun voltage (kV)	1.2
Collector efficiency (%)	98
Transverse electron temperature (eV)	0.2
Longitudinal electron temperature (eV)	< 0.01

*) These values correspond to the reduction of the initial momentum spread.

3. ELECTRON COOLING IN LEAR WITH THE ICE EQUIPMENT

3.1 Accessible momentum range

The cooling experiments in ICE had been performed with electron gun high voltage at 26 kV. This voltage could be kept for days without problems and the operation of the gun was stable and reliable. Initial difficulties with the high voltage was cured at a later stage of the experiments. The highest voltage reached was 35 kV (corresponding to 337 MeV/c). Limitations arose from the continuously deteriorating vacuum caused by unsatisfactory electron collection. Electron beams were produced frequently at lower voltage levels. These conditions are much less stringent and running the electron gun is less problematic. In the following we estimate the cooling time for 26 kV (corresponding to 300 MeV/c) and 2.8 kV (100 MeV/c) where reliable operation of the gun can be guaranteed and a good electron beam can be expected. In addition it should be noted that in Novosibirsk, experiments had been performed at .8 kV (53 MeV/c) and all the features of electron cooling had been observed at this low energy.

3.2 LEAR parameters relevant for electron cooling

In the following sections we shall estimate the cooling performance of the ICE gun on stored beams in LEAR. The machine and beam parameters used in the calculations are listed in Table 4 [1].

3.3 Operation at 300 MeV/c for the stretcher mode

From comparison of Table 2 with Table 4 it is obvious that the initial emittances of a precooled beam at a momentum of 300 MeV/c are smaller than those in ICE and further that the lattice functions in the cooler are similar. Hence, we are confident that the cooling times obtained in ICE (Table 3) easily can be reproduced.

The emittances of a beam decelerated without precooling to 300 MeV/c would be roughly equal to those in ICE and only the momentum spread would be a factor 2 higher. The increase in longitudinal cooling time as compared with Table 3 would, however, be less than a factor of 3. Without precooling, precautions should be taken to prevent coupling of horizontal and vertical emittances, which could be caused amongst other things by the solenoidal field of the cooler. Such a coupling would lead to intensity losses, because the vertical acceptance in LEAR is smaller than the horizontal.

TABLE 4

Transfer line		
Transverse acceptance E_H (mm mrad)	$40\ \pi$	
E_V (mm mrad)	$20\ \pi$	
Momentum acceptance $\Delta p/p$	$\pm 5\cdot 10^{-3}$	
Bunch area A (mrad)	15 mrad	
LEAR		
Transverse acceptance E_H (mm mrad)	$240\ \pi$	
E_V (mm mrad)	$48\ \pi$	
Momentum acceptance $\Delta p/p$	$\pm 1.1\ 10^{-2}$	
Bunching factor	0.8	
Average pressure (Torr N_2-equivalent)	10^{-10} (10^{-11})	
LEAR circumference (m)	78.54 m	
Q_H	2.33	
Q_V	2.75	
Transition energy γ_t^2	$-(14.5)^2$	
Lattice functions in cooling section		
β_H (m)	3.4	
β_V (m)	4.9	
α_p (m)	3.9	
	Without	after 1min.
Injected beam (600 MeV/c)	stochasting cooling at 600 MeV/c	
Assumed geometrical emittance ε_H (mm mrad)	$30\ \pi$	$10\ \pi$
ε_V (mm mrad)	$15\ \pi$	$7\ \pi$
Momentum spread $\Delta p/p$	$\pm\ 3.10^{-3}$	$\pm 6.3\cdot 10^{-4}$
Beam decelerated to 300 MeV/c		
(adiabatic blow-up only) ε_H (mm mrad)	$60\ \pi$	$20\ \pi$
ε_V (mm mrad)	$30\ \pi$	$14\ \pi$
$\Delta p/p$	$\pm\ 6.10^{-3}$	$\pm 1.3\cdot 10^{-3}$
Total beam cross-sections and divergency in straight section at 300 MeV/c		
a_H (mm)	± 28	± 9.7
a_V (mm)	± 12	± 8.3
Θ_H (mrad)	± 4.2	± 2.4
Θ_V (mrad)	± 2.5	± 1.7
Transverse proton temperature $T_\perp$ (eV)	2300	830
Longitudinal proton temperature $T_\parallel$ (eV)	3100	220

In equilibrium the transverse angular divergences of the stored beam, was, in the ICE experiment, limited by multiple scattering diffusion on residual gas molecules. Since the design pressure in LEAR is more than one order of magnitude lower, better equilibrium values than those in Table 3 are expected.

The achievable equilibrium values are, however, by far better than what is required for the slow extraction and are only relevant for further deceleration and extraction at very low energies.

Operation below 300 MeV/c

As an example for extraction momentum, we consider the case of 100 MeV/c.

After deceleration of the $\bar{p}$ beam previously cooled at 300 MeV/c, to an extraction energy of 100 MeV/c, the geometrical 90% emittances and momentum spread are typically

$E_H = 3\ \pi$ mm mrad $\qquad E_V = 12\ \pi$ mm mrad $\qquad \Delta p = \pm 4\times10^{-4}$

where we have taken into account the adiabatic blow up of emittances in Table 3.

The corresponding beam sizes and angular divergences in the cooler are hence

$\Theta_H = \pm\ 9\times10^{-4} \qquad \Theta_V = \pm 1.5\times10^{-3} \qquad a_H = \pm\ 4$ mm $\qquad a_V = \pm\ 8.0$ mm

If we scale according to the equation in Appendix I, we arrive at a cooling time of 25 sec at 100 MeV/c. This is, however, an extremely conservative scaling. Firstly, the transverse temperature of the electron beam here is lower than at 300 MeV/c ; secondly, for such small angular divergence of the stored beam, magnetization effects in betatron cooling, as observed at Novosibirsk and in ICE, are of extreme importance. A cooling time below 500 msec is found from a detailed calculation.

The equilibrium angular divergence of the stored beam can be found by balancing the betatron cooling rate with the relevant heating term, which here is multiple scattering diffusion on residual gas molecules. Scaling of values in Table 3 according to equations in Appendix I, for an average pressure in LEAR of 10^{-11} Torr, gives a rather conservative value of $\Theta_p = \pm 4\times10^{-4}$.

The equilibrium momentum spread is, as observed in ICE, limited by intrabeam scattering. Since, however, the cooling is always faster in longitudinal direction than in transverse, we can at the very most obtain a momentum spread corresponding to an isotropic velocity distribution of the stored beam, i.e., $\Delta p/p \lesssim \gamma\Theta p$. It should be noted that with these equilibrium values further loss free deceleration to even lower energies is possible.

The ultra slow extraction process requires a high momentum spread (typically 10^{-3})[6], whereas the equilibrium momentum spread with electron cooling is by far lower than that. However, intermediate cooling in addition to stochastic precooling would allow loss free deceleration. Prior to extraction small emittances could be achieved even at lowest energies by further cooling at the extraction momentum. However, we are also investigating the possibility of having transverse cooling operating during the extraction.

One possible operational procedure for the slow extraction mode could then be the following :

i) Antiprotons are injected at 600 MeV/c and the electron gun is set to the high voltage corresponding to 300 MeV/c. After deceleration of the beam (eventually precooled at 600 MeV/c), to 300 MeV/c the electron cooling will, within a total time of 10 sec, reduce the emittances and momentum spread to values better than stated in Table 3.

ii) The electron gun is then set to the voltage corresponding to the extraction energy and the $\bar{p}$ beam is decelerated to that value. The cooling automatically sets in then. When the adiabatic blown up emittances are cooled back to equilibrium values, after a few second, cooling would be removed during extraction.

The final version of the operation procedure depends however on the actual machine cycle and the controls of the system as well as on the stochastic precooling.

3.4 Operation with internal jet target

For the operation of internal jet-target, the electron cooling is of extreme importance for increasing the beam lifetime through compensation of the multiple scattering blow-up occurring mainly in the target. A low beta-value at the target results in a considerable lifetime gain when the cooling is applied. This is due to the fact that the single scattering lifetime is determined by local pressure, whereas the multiple scattering lifetime concerns mainly average pressures, since the time-scale for growth of betatron amplitudes are large compared with the revolution frequency.

The optimum jet target thickness has to be found by equalizing the loss rate due to single scattering and the average anti-proton accumulation rate i.e., 10^6/sec. This criteria fixes only the product of target thickness and stored beam intensity, and in principle, the equilibrium beam quality may be improved by reducing the jet thickness and consequently increase the stored beam intensity. In the following we estimate the maximum acceptable jet target thickness and the equilibrium properties of the antiproton beam in the presence of cooling. For the angular acceptances of the storage ring and at the jet target position we assume $\Theta^{max} = \pm 3\times10^{-3}$ and $\Theta^{max}_{H_2} = \pm 6\times10^{-3}$, respectively. We work out the values at the two momenta 300 MeV/c and 100 MeV/c.

The maximum target thickness is determined by $\tau^{m.s.}_{H_2}(\Theta^{max}) > \tau_{\perp}$ the transverse cooling time has to be shorter than the blow-up time constant due to multiple scattering in the jet. For this maximum thickness the single scattering lifetime $\tau^{ss}_{H_2}(\Theta^{max}_{H_2})$ is calculated, which gives a considerable gain in lifetime ($\sim$50 at 300 MeV/c and $\sim$26 at 100 MeV).

Table 5 lists the expected equilibrium values of the stored beam for jet target thicknesses giving $\tau^{ss} = 2\times10^3$ sec. The equilibrium angular divergences are calculated by balancing the multiple scattering diffusion due to interaction with jet target atoms with the correction due to transverse cooling. The equilibrium momentum spread is similarly obtained by balancing the momentum cooling with heating due to intrabeam scattering and energy straggling in the jet target.

In conclusion we note that with the use of the ICE-gun, equilibrium angular divergences and momentum spreads around or better than $\pm 4\times10^{-4}$ may be obtained for reasonable target thicknesses in the momentum range of the stored beam of 300 MeV/c to 100 MeV/c.

TABLE 5 - INTERNAL H_2 JET TARGET OPERATION
AT STORED BEAM INTENSITY OF $2x10^9\bar{p}$

Energy	46.8 MeV	5.3 MeV
Momentum	300 MeV/c	100 MeV/c
Max H_2 jet density for $\tau_{H_2}^{m.s.}=e\tau$	$2x10^{-9}g/cm^2$	$6x10^{-11}g/cm^2$
Max H_2 jet density for $\tau_{H_2}^{ss}=2x10^3sec$	$4x10^{-10}g/cm^2$	$1.6x10^{-11}g/cm^2$
Lifetime gain "L_Z" = $\tau^{ss}/\tau^{m.s.}$	50	26
Equilibrium parameters		
Angular divergence Θ_p	$\pm 4x10^{-4}$	$\pm 3x10^{-4}$
Momentum spread $\Delta p/p$	$\pm 8x10^{-5}$	$\pm 4x10^{-4}$

A possible cooling procedure for internal target operation could be the following :

i) as before (point i) for slow extraction

ii) the electron gun is set to the voltage corresponding to the working momentum (between 300 MeV/c and 100 MeV/c) and the $\bar{p}$ beam is decelerated to this value. After a few seconds of cooling to compensate the adiabatic blow up, the internal target is activated and cooling continues.

3.5 Cooling of H^- beams at 300 MeV/c

H^--ions produced in the old Linac can be injected into LEAR at 300 MeV/c and need no deceleration to be within the accessible range of the ICE electron cooler. Provided the vacuum in the ring is good enough to prevent the H^- -ions being rapidly stripped by the rest gas, this particle beam can be cooled under conditions which are worked out in Chapter 6.1

4. EXISTING HARDWARE

4.1 High voltage system

HT supply

This consists of essentially two parts. One part ("Seifert", 120 kV, .5A) supplies most of the required voltage and consists at present of a polyphase transformer rectifier set paralleled with a 180 nF capacitor. A thyristor primary regulator has been abandoned due to stability problems. The other part, connected between the positive terminal of the Seifert and ground, is a low voltage power supply ($\leq$ 1 kV). The function of this supply is to stabilize the total output voltage to the required value. Its disadvantage is its high fault rate, presumably because it has to carry the total fault current in case of breakdown inside the gun.

The gun cathode is connected directly to the HT supply. The anode voltages are taken from a 1 MΩ resistive divider between cathode and ground.

Collector supply

A 185 kVA transformer supplies a rectifier-capacitor bank. This assembly is used to bias the collector positive with respect to the cathode and supplies the total gun current. The power needed is below 10 kW. With this arrangement the HT supply is not required to supply the full beam current.

There are three smaller supplies for biasing auxiliary electrodes inside the collector.

Faraday cage

Most of the electrical equipment is housed inside a Faraday cage connected to ground potential. The cathode supply connects to a second insulated cage inside the first one. This houses the collector supplies, cooling systems and other equipment at or near cathode potential. Power is supplied to this potential level by means of an isolation transformer rated 100 kV and 40 kVA.

4.2 Magnet system

The longitudinal magnetic field for restricting the transverse motion of the electron beam is produced by three solenoids, which are connected through two toroids (see Fig. 1). The length of the gun and collector is 1.3, and .7m, respectively ; whereas in the interaction length of 3m the field is produced by two solenoids of 1.5m each. The toroid major radius is 1.05m and the angle 36^{o}.

The coils of the solenoids are wound in two layers of opposite twist whereas in the toroids there are three layers to allow for optimization of fields.

All magnets are connected in series, with the third layer of the toroids shunted. The maximum field strength which may be produced is 3 kG. At the normal working point of 500G the power consumption is around 13 kW.

A high field homogeneity is required to prevent heating of the electron beam. The rms homogeneity in the cooling region is measured to be around 5×10^{-4}, sufficient not to excite the electron or the circulating beam. To steer the electron beam each section of the magnet system contains two sets of correction elements (in total 20) for producing transverse fields. Each of these elements are powered separately.

4.3 Vacuum system

A ultra high vacuum is required to prevent high voltage breakdowns and reduce the ionization of residual gas molecules through electron impact. The latter may cause accumulation of ions, which lead to instability and changed optics of the electron beam. Further a too high pressure may result in sputtering of the cathode and collector surface.

The materials for the vacuum system of the ICE gun have hence been carefully selected and cleaned, and the assembly baked out for 100 hours at 200^{o}C.

In the drift region the vacuum chambers are stainless steel tubes with diameter Ø=20cm in each solenoid separated by manifold vacuum vessels in the toroids. These manifolds, through which the proton beam enters, contains several feedthroughs and saphire windows (Fig. 6).

The system is equipped with three 220 l/s sputter ion pumps (Fig. 1) and two Ti-ball sublimation pumps situated in the toroid manifolds. On ultimate pressure of $7x10^{-11}$ Torr, gauge reading, virtually all due to hydrogen was reached in the cooler when it was disconnected from the ICE vacuum system. This corresponds to a real pressure of about 1.4×10^{-10} Torr (H_2) which is compatible with the required LEAR vacuum down to 100 MeV/c [7]. The pressure increased to around 1×10^{-10} Torr when heating the cathode to working temperature. During cooling experiments, when the cooler was connected to the ICE-vacuum system,the pressure in the cooler was essentially determined by the vacuum of ICE ($\sim 2 \cdot 10^{-9}$)*. The pressure reading in the cooler was then $3 \cdot 10^{-10}$ Torr. It should be noted that because of the poor vacuum in ICE no effort was put into a further improvement of the cooler vacuum.

The ICE gun vacuum system is further equipped with two fast valves, through which the gun may be isolated from the storage ring.

4.4 Collector

The main difficulty in such a high power electron beam device is the recuperation of electron beam power through deceleration. This efficiency may be expressed by the power and current efficiencies η_p and η_i :

$$\eta_p = 1 - \frac{\Delta W}{W} \qquad \eta_i = 1 - \frac{\Delta I}{I}$$

The power loss ΔW consists mainly of two terms $V_o \Delta I$ and $V_{cc} I$, where the first is supplied by the stabilized high voltage supply and the second by the collector power-supply operating at potential V_{cc} with respect to the cathode. The power loss is in general dissipated as heat on the vacuum chambers ($V_{cc} I$ in the collector), where it causes degassing and desorption of residual gas molecules. It is hence preferred to collect the current at as low a collector potential as possible.

There are several contributions to the loss current ΔI :

i) imperfections in guiding field (beam optics) ;

ii) recuperation of rotational energy in the cyclotron motion ;

iii) secondary electrons emitted from the collector surface escaping from the collector.

For the ICE collector in particular i) and ii) limit the efficiency, whereas secondary electrons to a large extent are suppressed by the retarding field created by the electrostatic mesh. The optimum collection efficiency, which has been obtained at 10 keV is $\Delta I/I \simeq 8x10^{-4}$. However, as the electron gun high voltage, and hence the magnetic field, is increased, the efficiency becomes progressively worse and for 26 keV $\Delta I/I \simeq 6x10^{-3}$.

* gauge reading

A power efficiency of η_p = .96 is here obtained.

The main difficulty is the decceleration of the electron beam in the tapered magnetic field and the matching of magnetic potentials for recuperation of rotational energy in the cyclotron motion. Experiments have shown that the effective collector aperture is somewhat too small as the coherent ripples of the electron beam intersects the aperture. At present experiments are continuing with a simple set-up of the gun for the purpose of changing the beam optics at the collector entrance.

However, even if these tests are not successfull the existant collection efficiency is sufficient to assure safe operation (low pressure) in the energy range up to 32 kV.

4.5 Correction elements

The transverse component of the magnetic field in the toroids causes a radial shift of the proton beam in the cooling region, which at 26 keV amounts to 5mm. To prevent a closed orbit distortion two dipoles positioned at the ends of the interaction region are used with a bending power equal to the toroidal field. We note that since the horizontal machine aperture is by far the largest it is preferred to have this local distortion in the horizontal plane, which dictates that the electron gun symmetry plane is vertical.

These dipoles are also used for horizontal angular alignment of the proton beam to the electron beam. Their specifications are given in Appendix II. Their bending power is high enough to be usefull for closed orbit corrections in LEAR [8).

In addition the electron beam may be deflected and parallel shifted in both planes for adjusting cooling efficiency , with the aid of the small correction elements already mentioned. The angular alignment should be within 5×10^{-4} radians.

5. MODIFICATIONS NEEDED FOR INSTALLATION INTO LEAR

5.1 High voltage supply

A priori there are several possible solutions

i) One unique supply capable of supplying up to 100 kV with a stability in the order of 3.10^{-5}.

ii) One unique power pack to provide up to 40 kV with a stability better than 10^{-4} and using the existing divider to connect the anodes.

iii) Four different supplies, one to supply the cathode with similar specification as i) but with lower current capability and three supplies stable to 10^{-3} with low current ratings to supply the anodes.

iv) Use the existing ICE equipment. Two modifications would then be needed. One would be to have fast control on the Seifert, i.e., introducing thyristor regulation on the primary side. The other concerns the transistor regulation which would need a practically complete rebuilt in order to achieve the necessary reliability.

Solution i) is preferred for reasons of a later upgrading of the system to higher voltages and of economy in manpower and equipment.

Solution ii) would be preferred if cooling higher energies would not be envisaged or costs have to be reduced.

For extremely low voltages, where possibly the stability of the HT supply could not be guaranteed, switching over to a smaller one may be envisaged.

5.2 Vacuum system

Some modifications apart from a general overhaul are needed [9]. The present correction windings have to be replaced to allow a bakeout at 300°C. The toroid vessels have to be cleaned and vacuum tested. The Ti pumps might have to be changed. An ion pump at the collector end should be added.

At present the vacuum system is dismantled and will be cleaned. Test measurements will be made to determine the final modifications. There seem to be no principal limitations to achieve the required vacuum.

The integration of vertical dipoles into the electron cooling system would require some modification of the pumping port at the entrance and the exit of the $\bar{p}$ beam.

The vacuum chamber in the interaction region has a circular diameter of 200 mm. The chamber at the entrance and exit of the antiproton beam has approximately a rectangular shape with a horizontal width of 152mm and a vertical width of 60 mm (Fig. 6). Hence it presents no aperture limit for LEAR beams [8].

5.3 Magnets

In principle no changes in the components of the magnet system apart from the correction windings are required, if the total length of the system could be kept. However, it turns out that the length has to be reduced for an installation in LEAR. This is possible if one of the central solenoid halves is taken out. It entails some modification of the solenoid flange, the vacuum tube and the support structure. The use of the correction dipoles for closed orbit corrections in LEAR requires power supplies adapted to the LEAR control system.

5.4 Collector

The present collection efficiency is sufficient to assure reliable operation in the discussed energy range, although it would be of advantage to do some measurements on a test bench in conjunction with computer calculations. This would in particular facilitate the goal of further increasing the high voltage.

5.5 Support

Some changes in the support structure are needed to account for the beam height of LEAR and to have the system length reduced.

5.6 Upgrading to 100 kV

As written before the system is designed for 60 kV. The magnetic field would be sufficient for operation at 100 kV. The present high voltage capability could be improved by modifying the limiting components. In order to reach 100 kV the electron gun and the collector have to be replaced.

These two elements could be mounted together with a drift region in between them. The relevant electron beam properties and vacuum conditions could then be measured on a test bench. At a later stage the new components could be exchanged with the present elements possibly without a removal of the entire cooling system.

6. DIAGNOSTICS AND CONTROLS

6.1 Diagnostics

In order to optimize the electron beam properties and to achieve satisfactory cooling performance it is essential to have adequate diagnostics.

Prior to its operation in LEAR the ICE electron cooler has to be optimized in the entire energy range of the later application and the proper settings have to be found. This can be achieved if the electron beam diagnostics presently available for the ICE system are improved and supplemented. These systems can be upgraded without requiring many modifications in the actual hardware.

A crude but effective method to pre-adjust the electron beam was through the observation of the loss current. Crossed tungsten wires in the electron beam gave a possibility of measuring the position and size of the beam at low beam power. They have to be re-installed for the study of the low energy beam properties. Furthermore, we have considered the possibility of measuring the electron density with a miniature Faraday cup. The detection of the microwave radiation emitted by the electrons spiralling in the solenoidal field was very useful for the minimization of the transverse electron temperature. The electronics for this detection system might be improved.

A sensitive, and also non-destructive, method to determine the electron density and the longitudinal electron temperature is provided by observation of the backscattered laser light sent head on to the electron beam. This requires a powerful far-red or infra-red laser and a simple optical spectrum analysing system. The photon count rates are at the level of 1 Hz [10]. The background is suppressed due to the Doppler shift of the backscattered light and can be further reduced by pulsing the laser. This system can operate over a wide range of electron energies and may also be used for a new electron cooling system at a later stage. These methods are the essential diagnostics to deduce the relevant electron beam properties.

Once installed in LEAR the cooling performance of the electron cooler can be studied with diagnostics for the circulating beam. The matching of the velocities is achieved by the analysis of the frequency spectrum of the Schottky noise induced in pick-up electrodes by the circulating beam. This method will also be used to investigate the momentum cooling of coasting beams. Emittance cooling will be studied by measuring the transverse distributions of the circulating beam with a beam profile monitor.

Cooling performance should initially be studied with circulating protons (requires reversed LEAR polarities) because the formation of neutral hydrogen atoms provides a very powerful diagnostic. The neutral beam comes out along the straight section and the neutral beam distribution will be measured with multiwire proportional chambers (MWPC) and the formation rate with a scintillator. This system provides a possibility of measuring the beam emittances and facilitates the alignement of the beams. From the neutral rate the effective transverse electron temperature can be determined.

When cooling antiprotons no neutral atoms are formed and this important diagnostics is lost. However, information about the cooling performance from a neutral beam may be obtained for the same LEAR settings, if the ring is filled with H^- instead of $\bar{p}$ [10)*)]. Loss free cooling of H^- is possible, if the energy difference between the H^- ions and the electrons is below the neutralisation threshold which is 0.75 eV. Hence, the initially hotest part of the H^- beam will be stripped and neutral hydrogen atoms emerge from the straight section until this condition is reached. Since the transverse and longitudinal (including space charge) temperatures of the electrons are well below the H^- binding energy, neutralisation is essentially due to the transverse and longitudinal velocity spread of the H^- beam and the velocity matching. Using the above given lattice functions we reckon that the neutralisation threshold will not be exceeded for H^- beam emittances below 20π mm mrad and a momentum spread below $\pm 3.10^{-3}$ for an operation at 300 MeV/c. In addition to the stripping by the electron beam, intra-beam scattering may lead to a rapid neutralisation of the hot part of the H^- beam. Once the temperatures are below the binding energy the beam lifetime will increase and the neutral atom rate will drop. The properties of such a cold beam, however, can be investigated by inducing neutralisation through a rapid step in the electron gun high voltage. A step of 1 KV within a few milliseconds would be sufficient.

*) This would only be possible if the final design vacuum of LEAR is reached.

In addition to the results listed in Table 3 we show in Fig. 4 the cooling of horizontal betatron oscillations for coasting and bunched beams. The equilibrium momentum spread as a function of stored proton beam intensity is shown in Fig. 5 and compared with the intra beam scattering limit [4].

We want to emphasize that the above given cooling times and equilibrium beam properties are typical and much better values had been obtained under optimised conditions [3]. More detailed measurements had been performed for different gun configurations. Details and a summary of all results can be found in Ref. 4).

6.2 Controls

As for all other components of LEAR complete computer control for the electron cooling system is desirable. Most of the parameters like correction coil currents, cathode current, etc., can be treated as ordinary parameters. There is, however, a certain problem with the acquisition and command of the HT of the gun. The necessary precision requires a 15 bit converter. After deceleration the same precision is needed. Allowing for the necessary dynamic range, this requires then an 18 bit converter. This seems to be on the limit of what is technologically feasible [11]. Perhaps a solution like the switching off the HT power supply to cope with the full range (as proposed above) might be envisaged.

Apart from the action that needs to be taken for deceleration, all parameters are varying slowly and normally no fast computer action is needed. For the case of conditioning, however, fast response is needed. It is hoped that the computer can take over the main workload during this process. Experience gained on the new Linac with the automatic formation of the preinjector column [12] should be helpful.

7. INSTALLATION IN LEAR

The ICE cooling system could be installed in the long straight sec. 3 or 4 of LEAR. The overall length (between valves) of the present system is 6.6m. As mentioned above the total length has to be reduced because space requirements in the straight section. This can be achieved by removing one part of the central solenoid. The total length is then 5.1 m (Fig. 7) which would be acceptable [8]. This takes into account collector and gun which bend away from the drift tube at an angle of 36^{o} and leads to a vertical extension of the system (without support) of ± 1.5m. On both sides 50cm are needed for various installations. The entire system could be mounted on rails in order to easily move the system.

It is desirable that the system is installed in the center of the straight section. An extension of the straight section vacuum tube is required for the observation of the neutral beam (few meters). From the end of the chamber in addition a length of about 0.50m is needed for the H^{o} detector.

If the existing Faraday cages are used, they should be installed close to the straight section. The size of the inner cage is 4.2 x 2.2 m^2. It is located inside an outer cage with an area of 5.5 x 5.4 (3.2)m^2 and a height of 3.8 m.

However, if the high voltage system and the Faraday cages are rebuilt, the space requirements can be reduced considerably.

It should be noted that the reduction of the cooling section by a factor 2 leads to a corresponding increase in cooling time. It can be compensated at least at lower voltage by working with full perveance and having hence doubled the electron current. This assumes that end effects in the cooling region can be neglected.

8. OPERATION

The basic cooling system should be fairly reliable within the limits of equipment using oxide cathodes. The operational reliability will rather depend on the external components, e.g., power supplies.

Concerning the availability, however, it must be pointed out that letting the cooling region up to air or changing the cathode required in ICE four months of reconditioning. It is hoped that more computer control would help this aspect and a two-month delay might be achieved. The main reason for this rather long delay is that the presence of the electron beam provokes quite a high degassing and for the operation of the cathode a vacuum of better than 10^{-6} mbar is required to avoid poisoning.

9. BUDGETING AND MANPOWER

The following table is a breakdown of cost and effort for installing the 5.1m cooling system in LEAR.

	Cost (KF)	Manpower (contract labour)
40 kV, HT supply	65	
Transformers (isolation and collector)	10	
HT instrumentation	20	
Vacuum system (gauges, adaptors, seals, vacuum pumps, auxiliary equipment)	30	
Magnets (bisection, correction coils)	10	
Collector (improvements)	10	
Gun (improvements, spare parts, running in)	10	
Supports	15	
Controls	80	
Diagnostics	20	
Dismantling, reassembly and installation of cooling equipment	10	
Power supply for solenoids and toroids	25	
Power supply for correction elements	8	
Power supply for correction dipoles	40	
Power and controls cabling	5	
Total	358	2 man years

These figures are based on the assumption of satisfactory equipment condition and include only the installation and outlined modifications. Proper allowance must be made for tests and running-in (including beam time).

The cost and manpower will be shared approximately equally by CERN and KfK.

It is also assumed that standard equipment like beam current monitors, profile monitors *), pick-up electrodes, spectrum analyzer **), etc., are available.

*) desirable : resolution better than 1 mm and scan period down to 100 ms

**) sweep times of 10 ms should be possible provided the pick-up signals are high enough.

10. TIME SCHEDULE

A precise time schedule depends on the availability of man-power and workshop time as well as on the time schedule of LEAR itself. It also depends on the location where the system could be assembled and the electron beam measurements could be performed. It would be desirable to do these measurements close to the final position in LEAR. For the modifications and test measurements which can be done outside of LEAR we give the following tentative time schedule.

Remaining 80	:	definition of modifications for the support structure ; vacuum tests and gun-collector tests
1981-1982	:	design, modifications and tests in parallel ; installation and electron beam measurements.

The objective is to have the system well tested and available without interference with the construction and running-in time of LEAR. If satisfactory vacuum conditions and electron beam properties are achieved in the cooler it will be installed at the earliest possible opportunity in LEAR which could be between mid 1982 to mid 1983.

This time schedule assumes no major additional workload for α's, new linac improvements or major failures, etc., and satisfactory state of the equipment recuperated from ICE. It might be subject to changes if the time schedule or the operation program for LEAR is altered. In addition it is assumed that the time required for the HT conditioning and degassing can be reduced.

ACKNOWLEDGEMENTS

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A P P E N D I X I

SCALING OF LIFE TIMES AND COOLING TIMES

Multiple scattering life time

$$\tau_{ms} \propto \frac{\beta^3\gamma^2}{P}$$

β, γ : relativistic factors of the circulating beam

P : average pressure in the storage ring

Single scattering life times

$$\tau_{ss} \propto \frac{\beta^3\gamma^2}{P}$$

τ_{ss}/τ_{ms} = constant ≃ 7 for pencil beams

≃ 40 for large emittance beams and jet target operation

Electron current density

$$j_e \simeq \frac{\beta^3\gamma^3}{(\gamma+1)^{3/2}}$$

for constant perveance

Proton beam divergence

$$\Theta_p^2 = \theta_\perp^2 + \theta_\parallel^2$$

ε_H, ε_V geometric emittance

$$\Theta_\perp^2 = \Theta_V^2 + \Theta_H^2 = \frac{\varepsilon_V}{\pi\beta_V} + \frac{\varepsilon_H}{\pi\beta_H}$$

$\beta_{V,H}$ beta function of the lattice

$$\Theta_\parallel = \frac{1}{\gamma}\frac{\Delta p}{p}$$

$\frac{\Delta p}{p}$ beam momentum spread

Electron beam divergence

$$\Theta_e = \frac{v_{e\perp}}{\beta\gamma c}$$

Temperature

$$T = \beta^2\gamma^2\, mc^2\, \Theta^2$$

m : mass of considered particle

Transverse cooling time

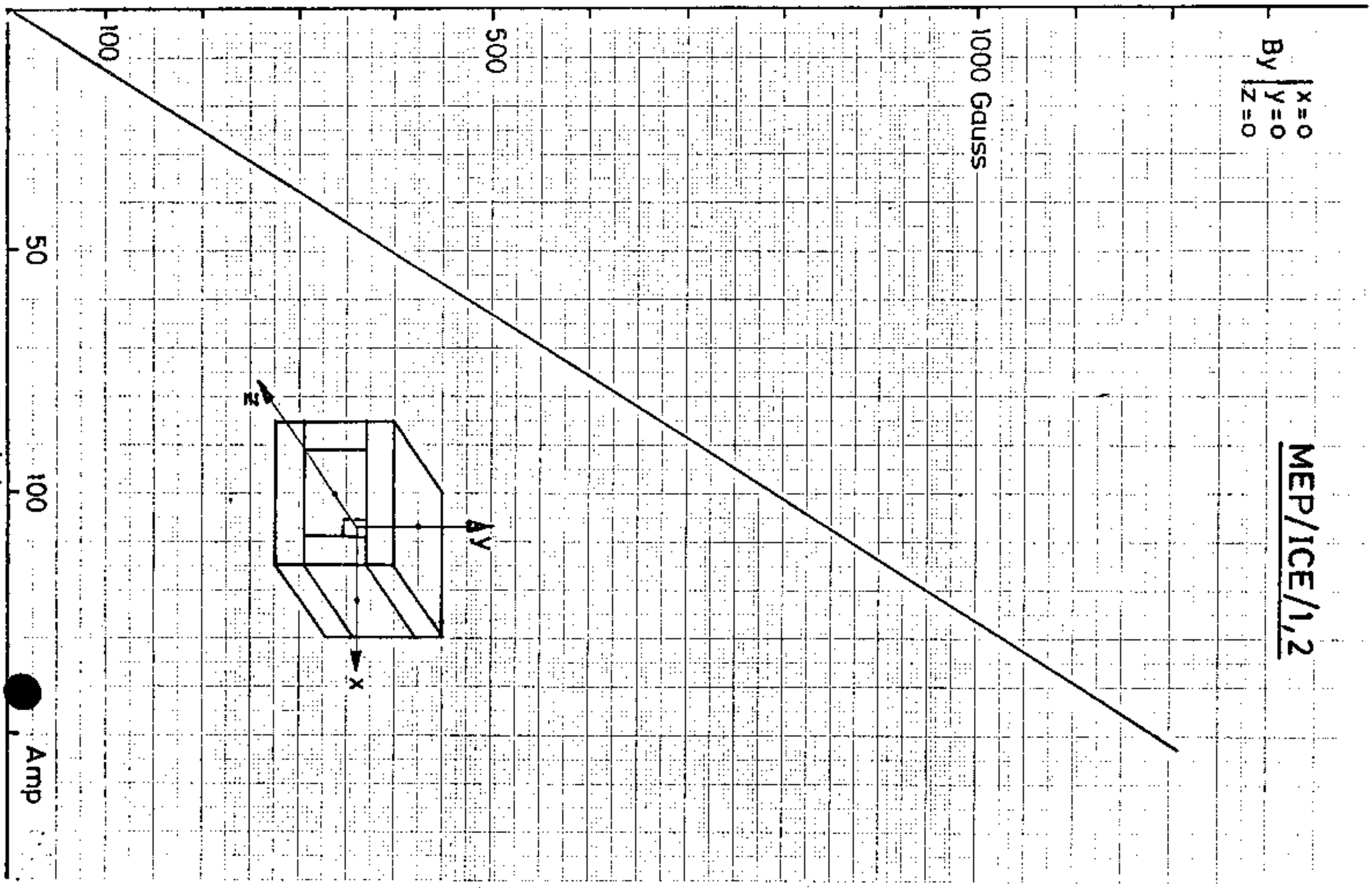
$$\tau \sim \frac{\beta\gamma^2}{j_e}\left[\frac{T_\perp}{mc^2}\right]^{3/2}$$

$$\sim (\gamma+1)^{3/2}\, \beta\gamma^2\Theta_e^3$$

(for $v_p < v_e$)

A P P E N D I X   II

Name or function	-	Steering manget for ICE electron gun	
Serial number	-		MEP/ICE/1 and 2
Main sizes	-	over-all length	260 mm
		over-all width	360 mm
		over-hall height	200 mm
		gap	92 mm
		useful aperture	92 x 200 mm^2
		conductor cross-section	(5 x 5 ∅ 3.0) mm
		iron weight	54 Kg
		Cu weight	18.5 Kg
Electrical data	-	power consumption	∿ 2 kW
		max. exc. current	150 Amp
		ohmic resistance at 20°C	0.125 Ω at 40°C
		number of turns	192 total (2 x 64 + 2 x 32)
		insulation to earth	>10 MΩ
Magnetic data	-	equivalent length before yoke saturation	0.261 m
	-	field or gradient at max. ex. current	1180 Gauss
	-	bending power or max. lens strength at max. exc. current	307 Gauss x m
Cooling	-	by	demineralized water
		pressure drop	18 bars
		water temperature increase at max.power	30° C
		water flow	∿ 1 l/min
Manufactured	-	yoke	MSC/EP workshop
		coils	
		support	
Reference drawings	-	assembly	TA 7985 - 1
		winding	
		yoke	
		support	
Fuses and safety devices	-	Thermoswitches set at 60°C	


MEP/ICE/1,2
By |x=o y=o z=o
1000 Gauss
500
100
50
100
Amp
x
y
z

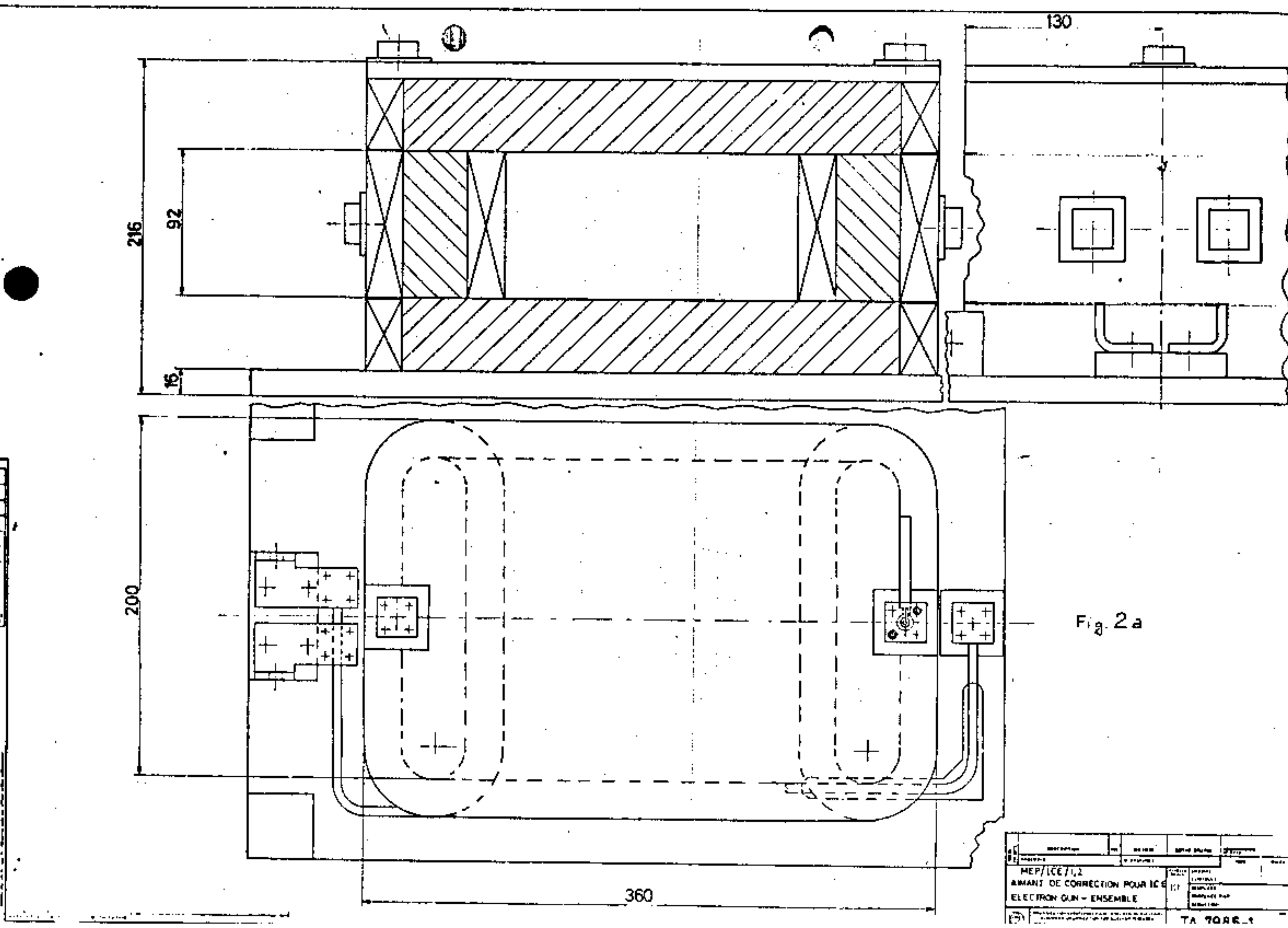

130
216
92
16
200
360
MEP/ICE/1,2
AIMANT DE CORRECTION POUR ICE
ELECTRON GUN - ENSEMBLE

Fig. 2 a

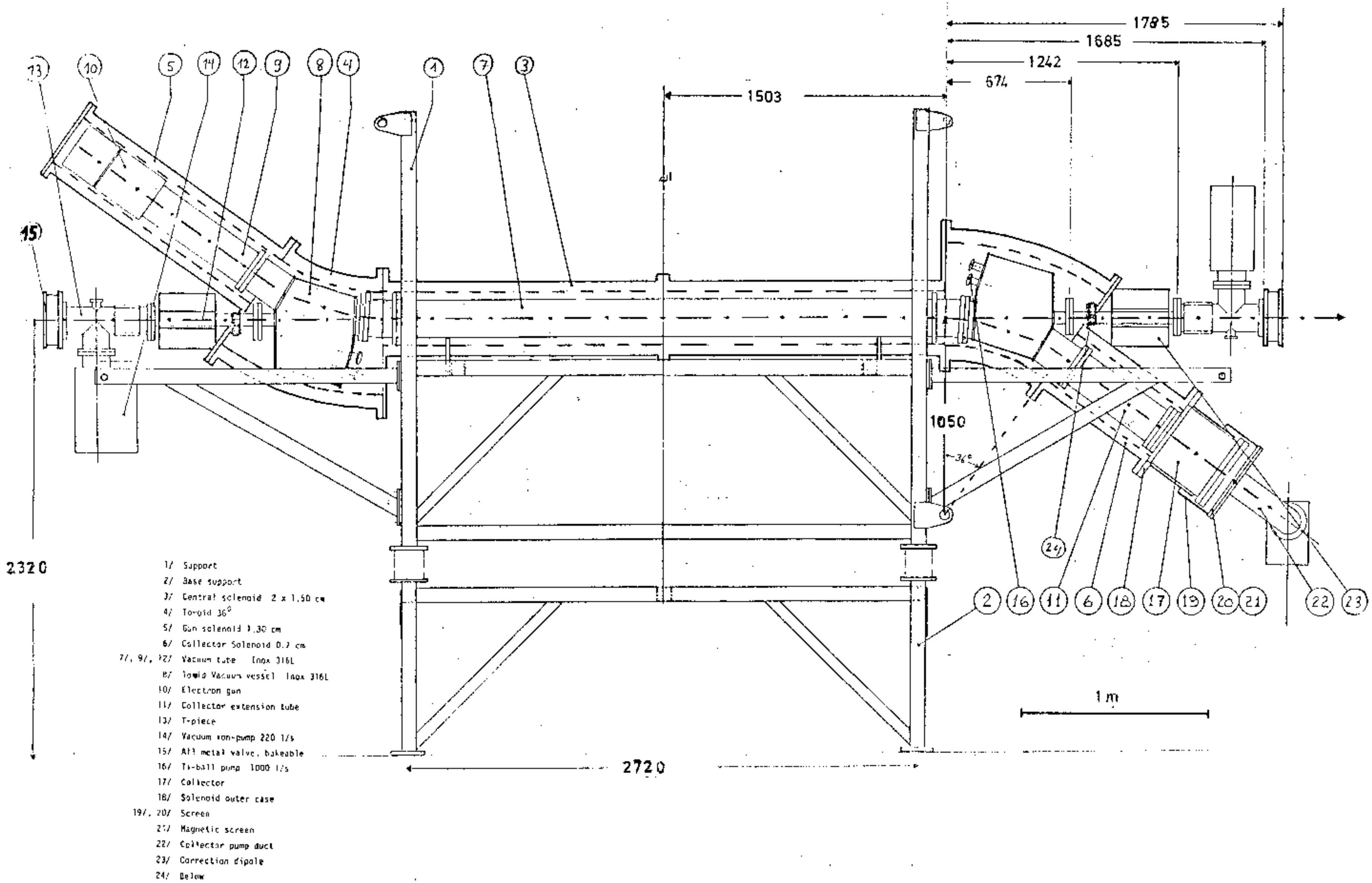
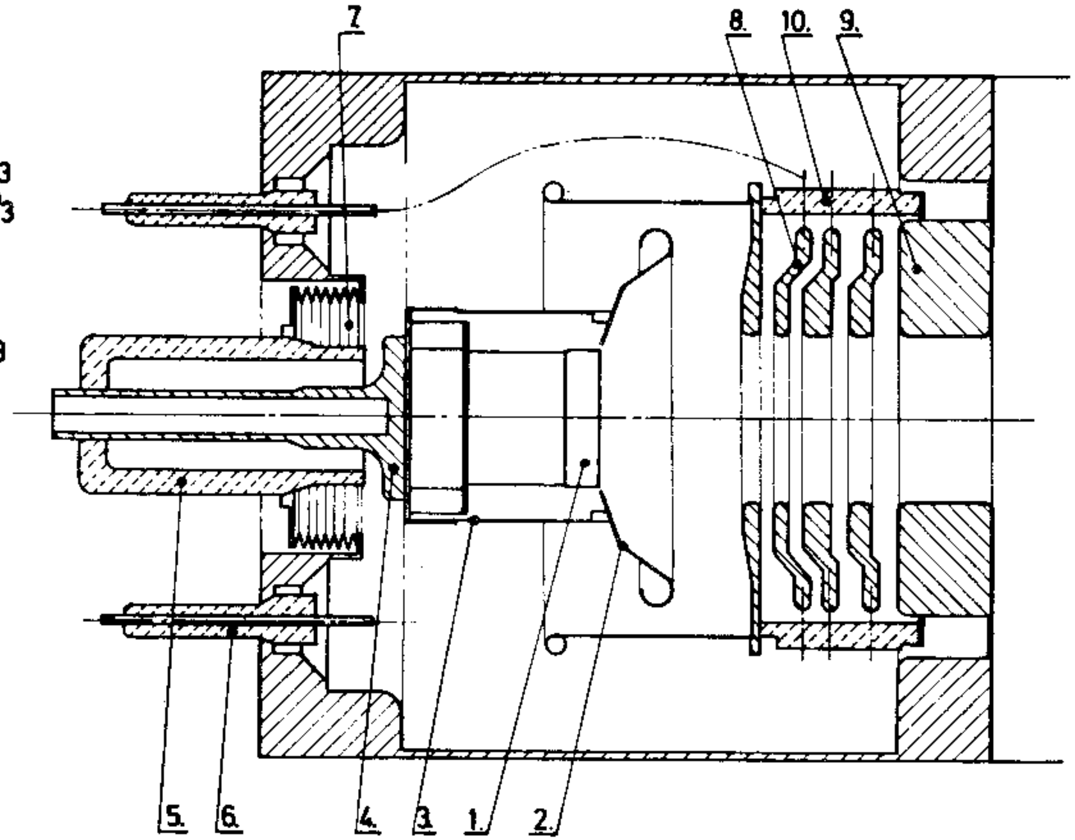


Fig.1 ICE electron cooler



1.	Cathode	W
2.	Pierce shield	Ta
3.	Heat sink	Mo
4.	Gas cooled base	Cu
5.	Cathode feedthrough	Al_2O_3
6.	Anode feedthrough	Al_2O_3
7.	Bellows	s.s.
8.	Anodes	Ti
9.	Anode	Cu
10.	Anode support	Al_2O_3

Fig. 2 Gun

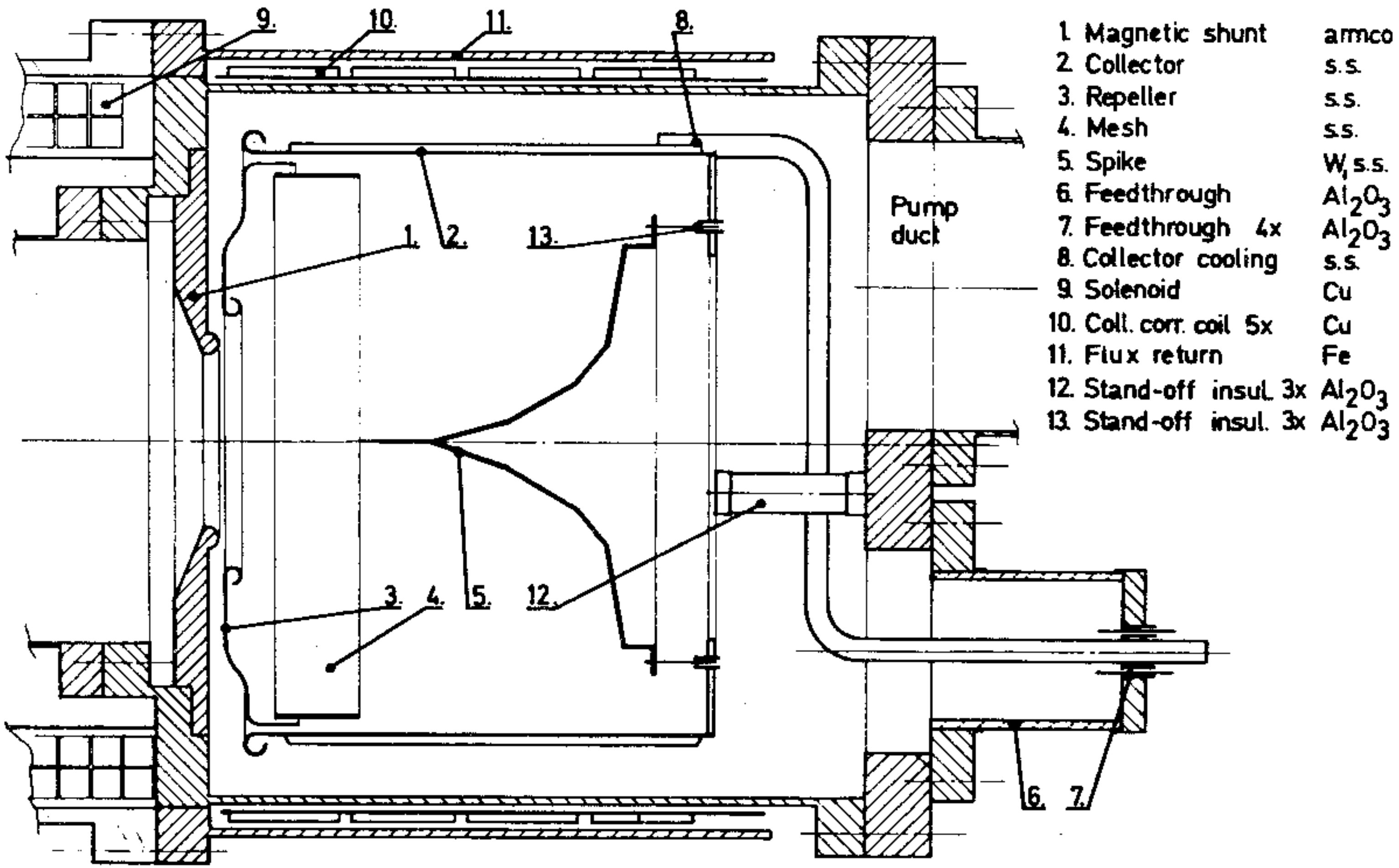
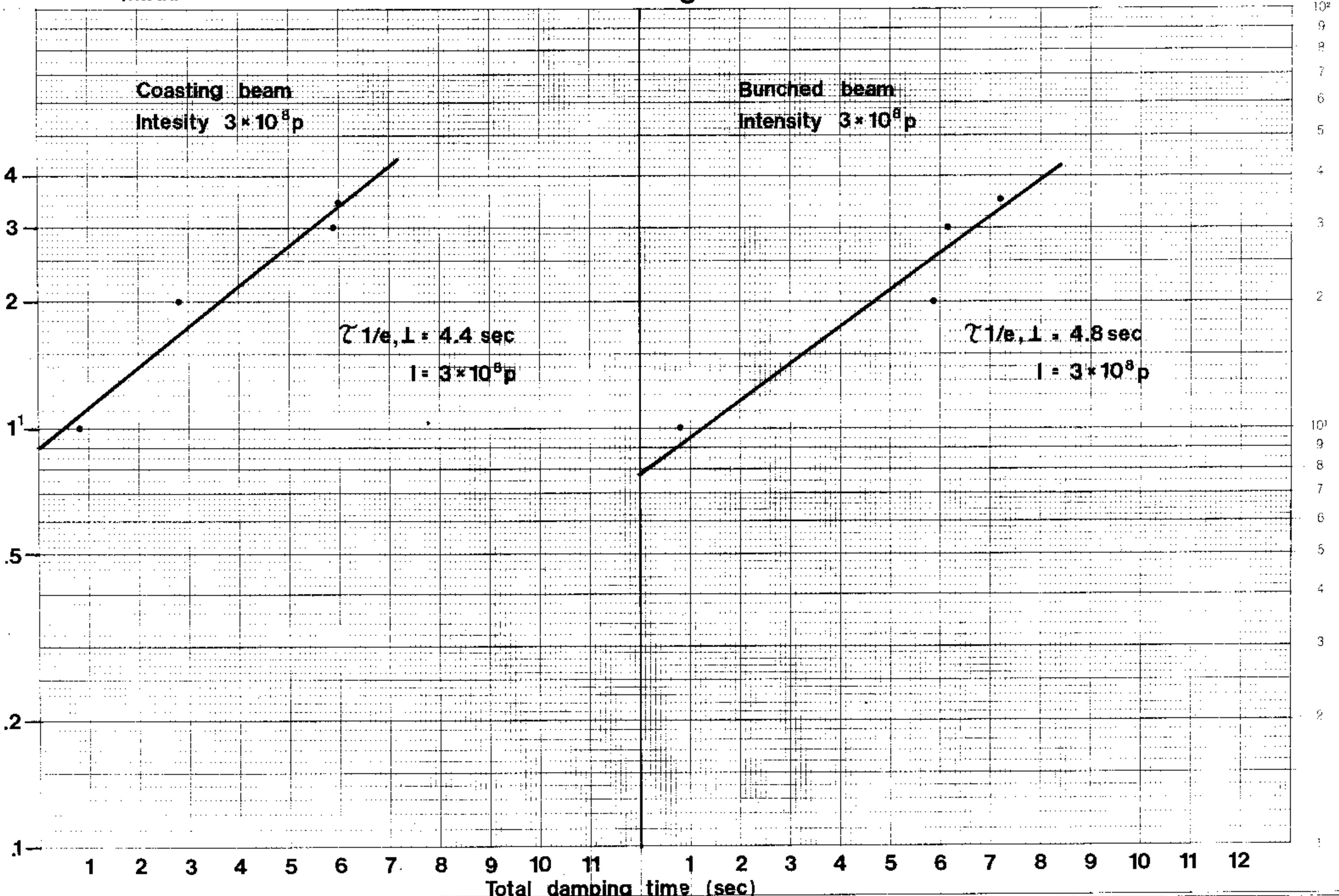


Fig. 3 Collector

FIG. 4: Transverse cooling times



Logar. Teilung 1-100 Einheit 83.33 mm

Nr. 527

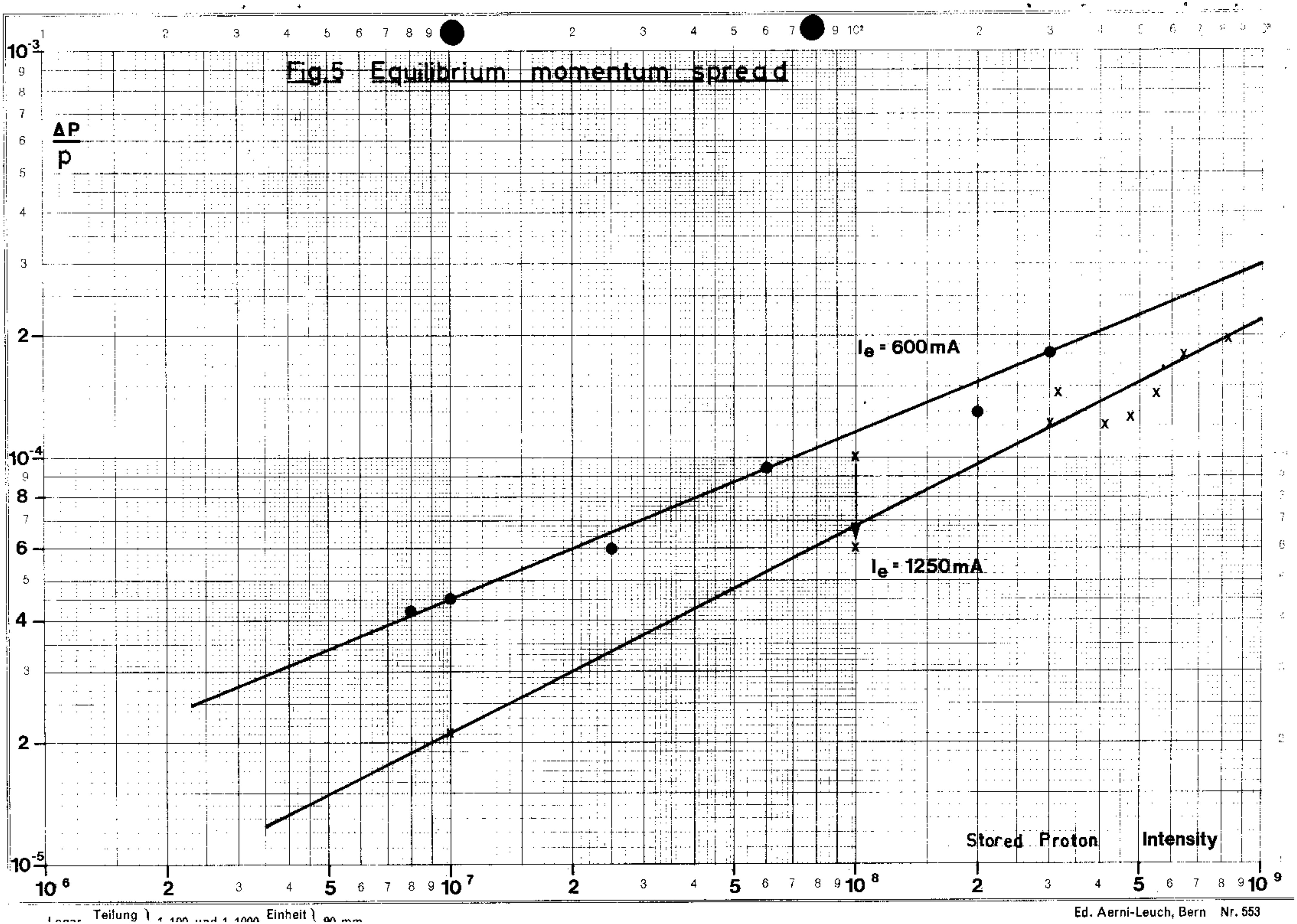


Fig.5 Equilibrium momentum spread
ΔP / p
I_e = 600mA
I_e = 1250mA
Stored Proton Intensity
10^{-3}
10^{-4}
10^{-5}
10^{6}
10^{7}
10^{8}
10^{9}
Teilung
Einheit
Ed. Aerni-Leuch, Bern Nr. 553

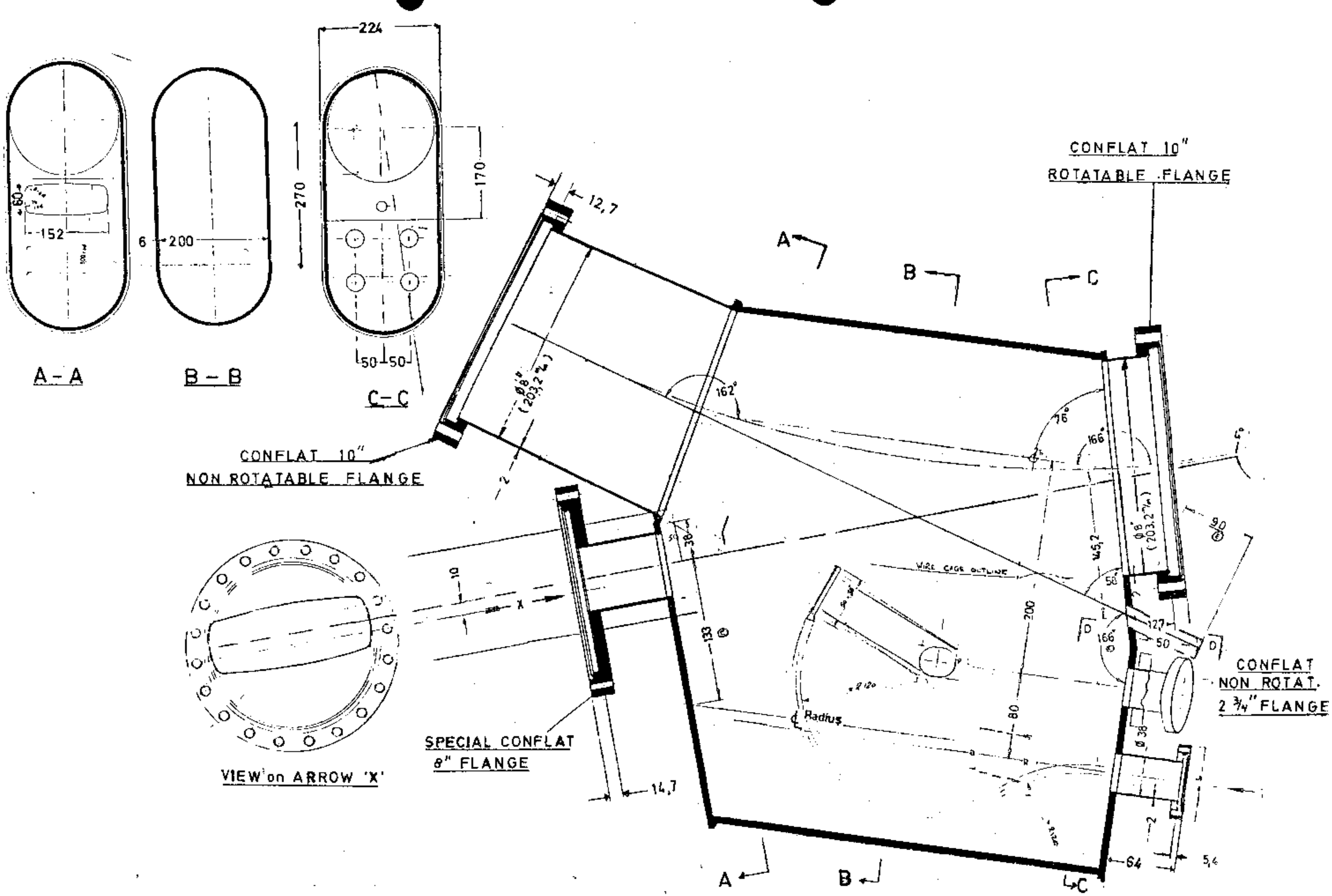


Fig. 6 Toroid vacuum vessel

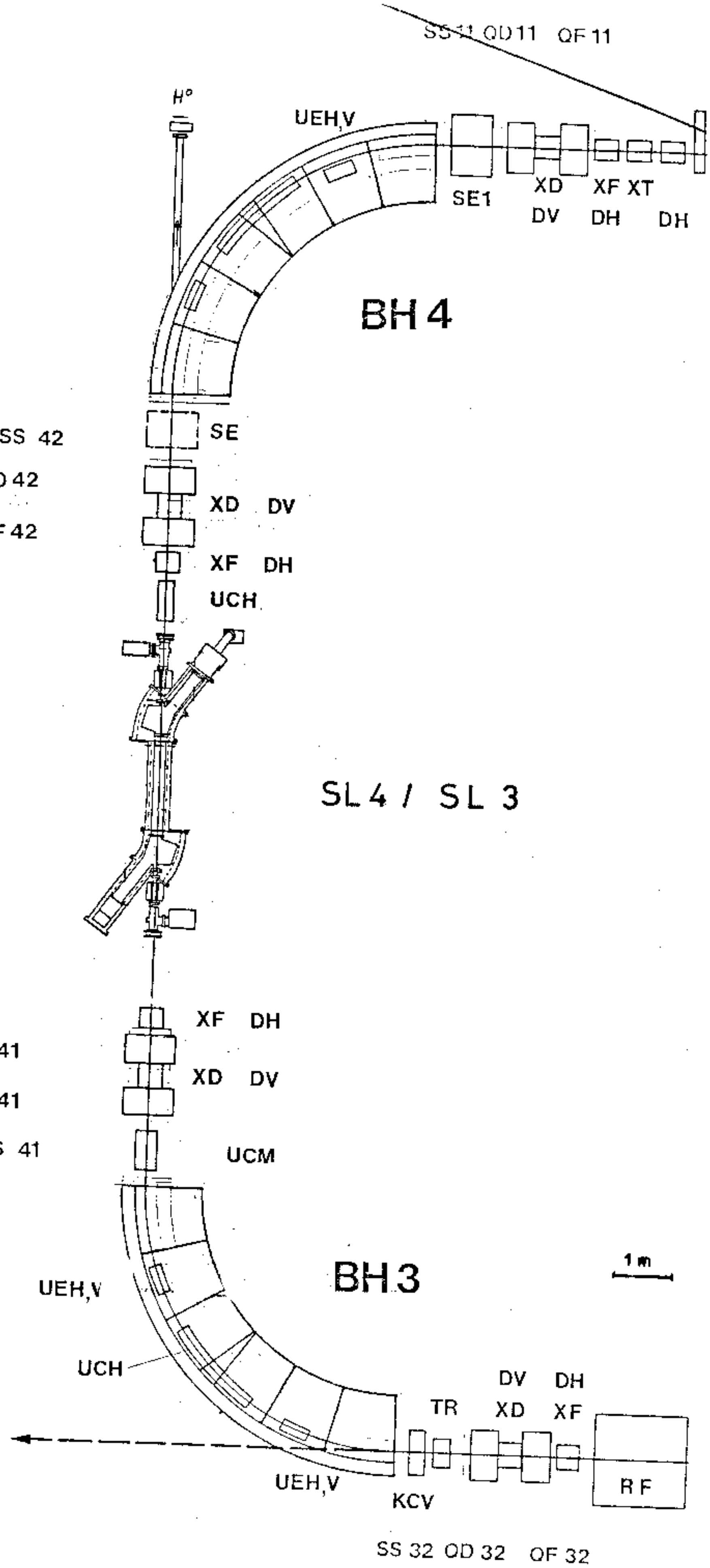


Fig. 7 Installation in LEAR