Electron Cooling at CERN
Past, present and future

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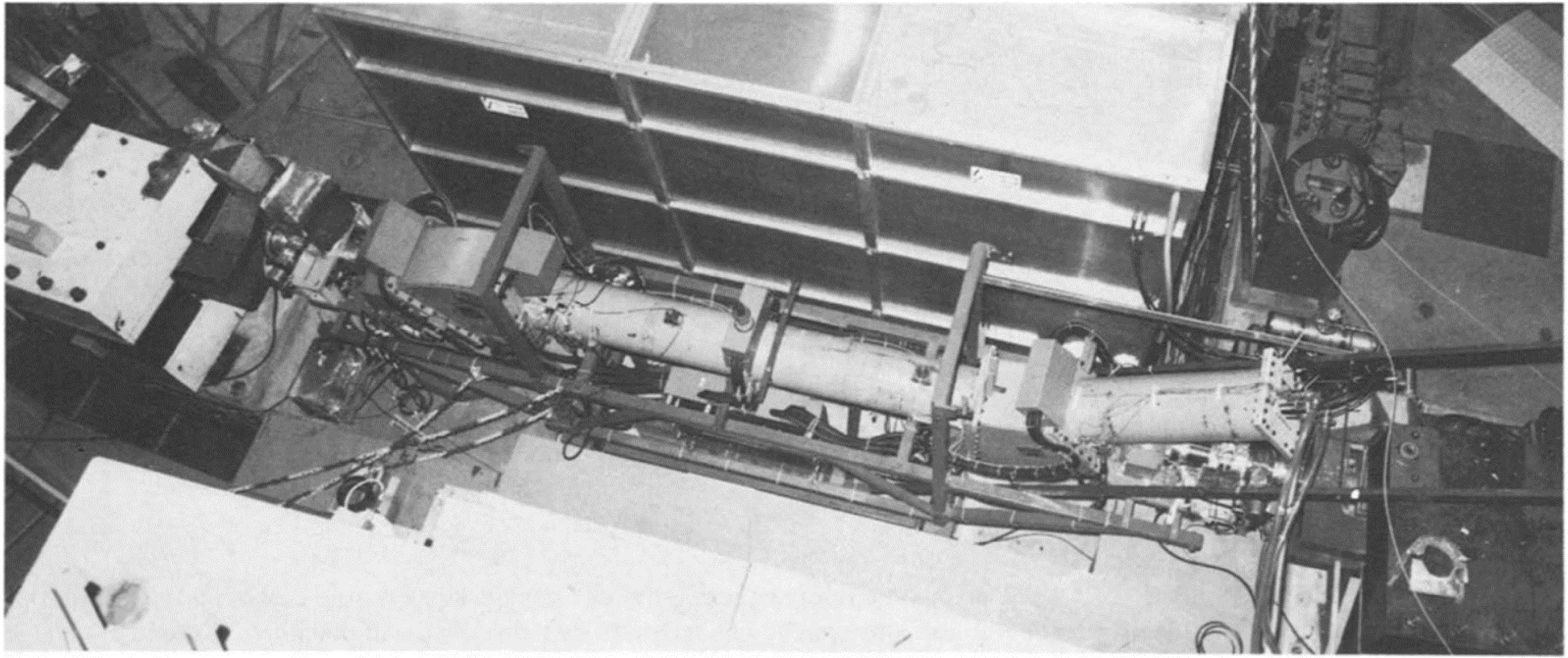
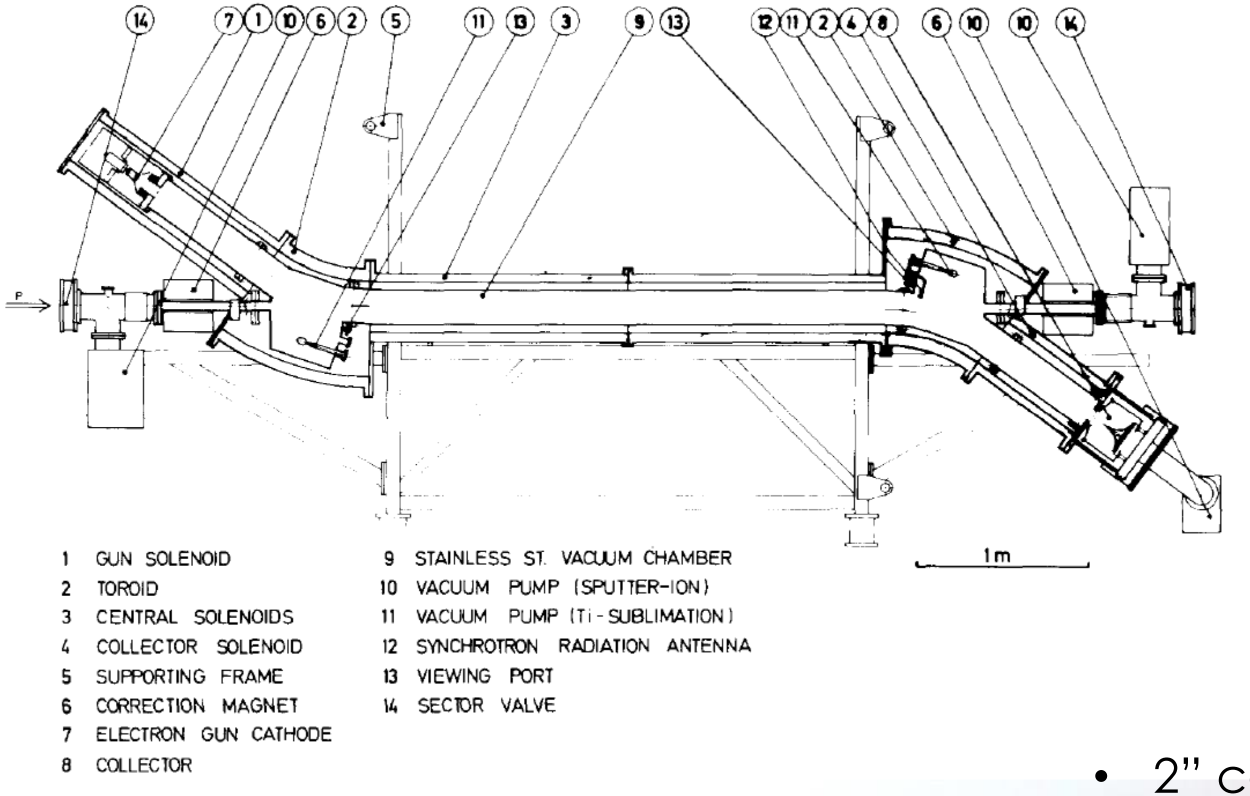
OUTLINE

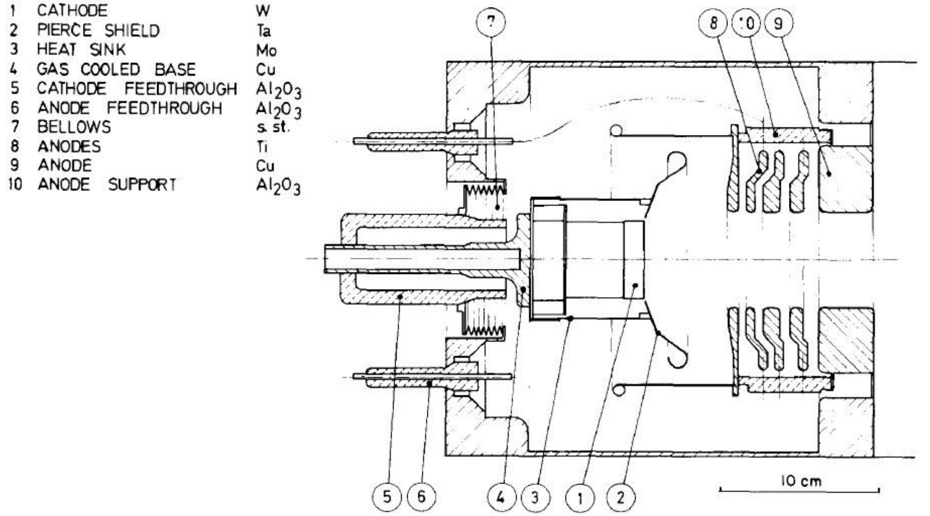
- The ICE age - the birth of electron cooling at CERN
- LEAR – electron cooling in operation
- From LEAR to LEIR
- AD – cooling for antimatter
- ELENA and the future

ICE (Initial Cooling Experiment)

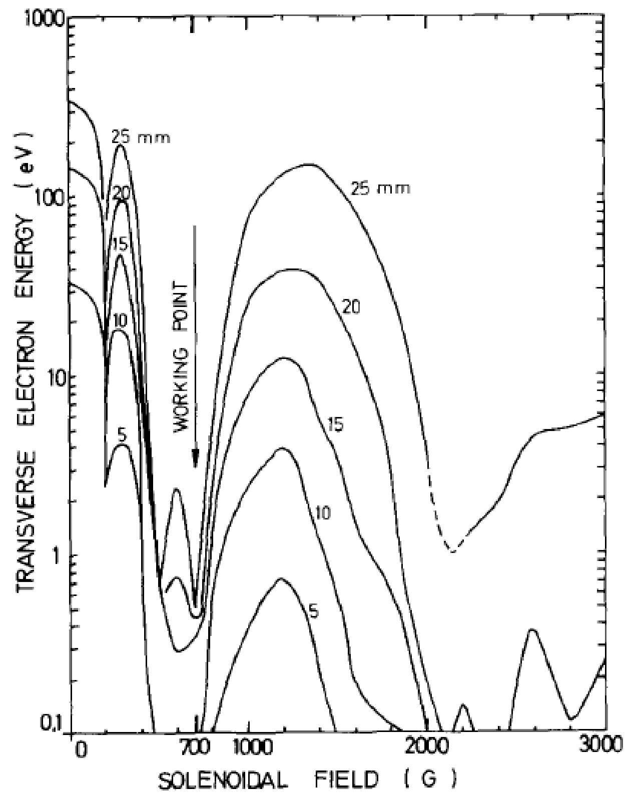


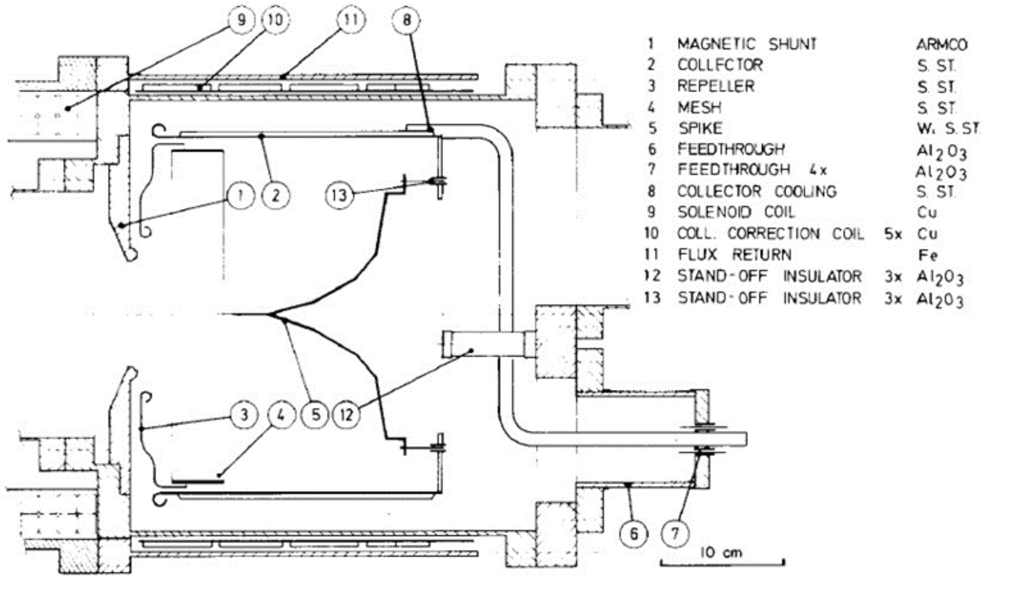


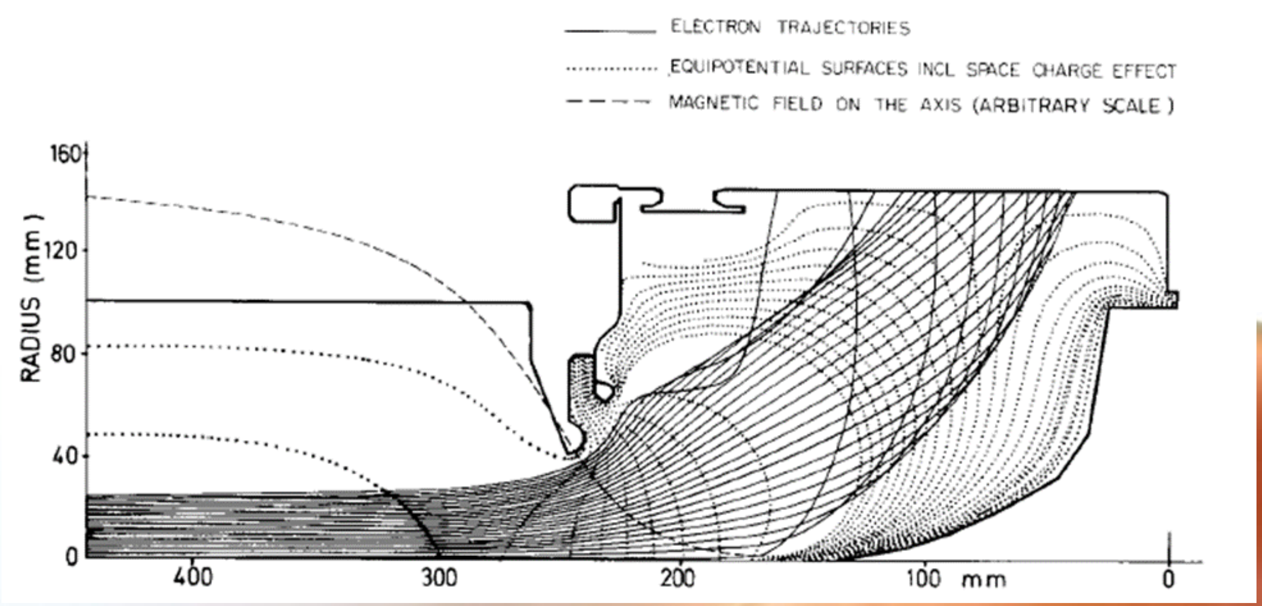
	Design	Operational
Cathode voltage	-60 kV	-26 kV
Cathode diameter	5.08 cm	
Electron current	8.3 A	1.3 A
Cooling length	3 m	
Magnetic field	700 G	500 G



- 2" cathode surrounded by a Pierce shield
- Five iris shaped electrodes set on increasing potentials
- Four operational modes :
  - full perveance
  - half perveance
  - quarter perveance
  - temperature limited
- Resonant optics





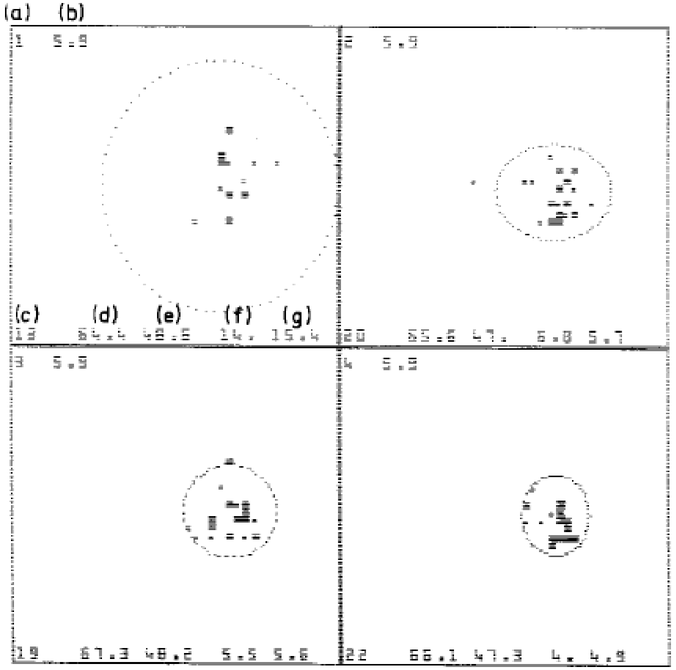


- Cylindrical water-cooled anode for absorbing the electrons
- Iris shaped shunt at entrance to reduce the magnetic field
- Repeller electrode to decelerate the electrons (set a few kV above Vcath)
- The spike refelects electrons towards the collector
- Mesh electrode repels the low energy secondaries

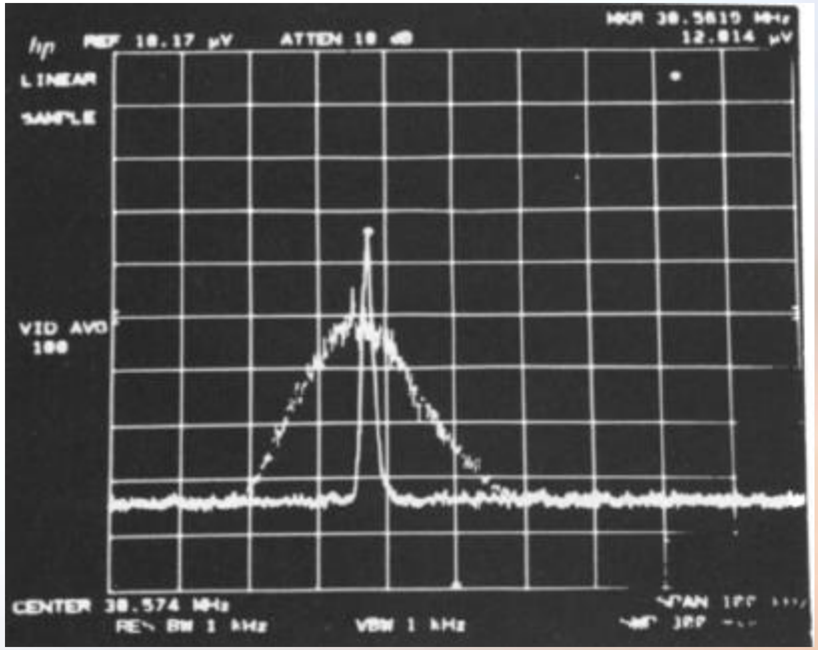
Cooling experiments

- Transverse cooling
- Longitudinal frictional force
- Equilibrium momentum spread

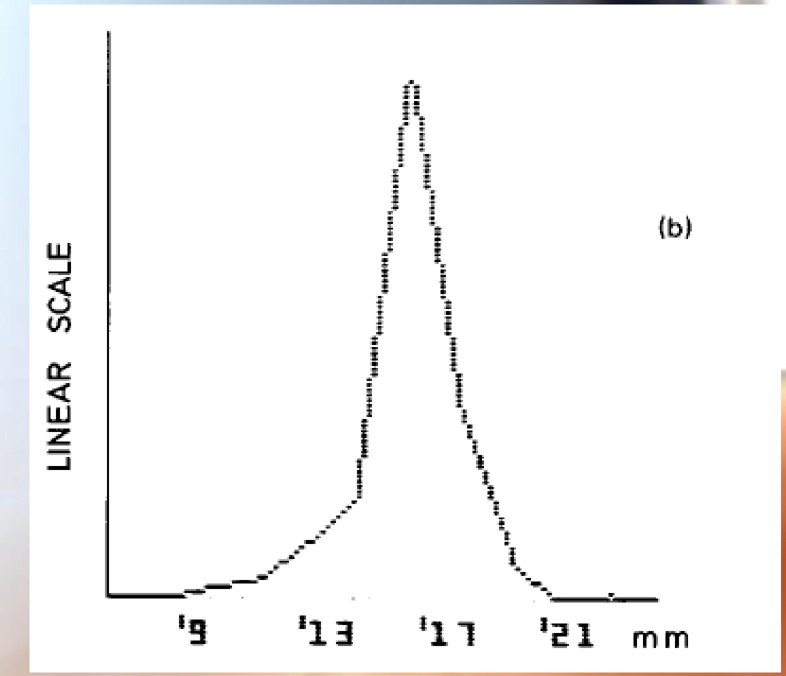
- To measure the cooled beam diameters or angular divergences, three methods were used:
  - neutral beam profile
  - beam scraper
  - horizontal ionisation beam profile monitor
- Schottky signal used for the longitudinal measurements



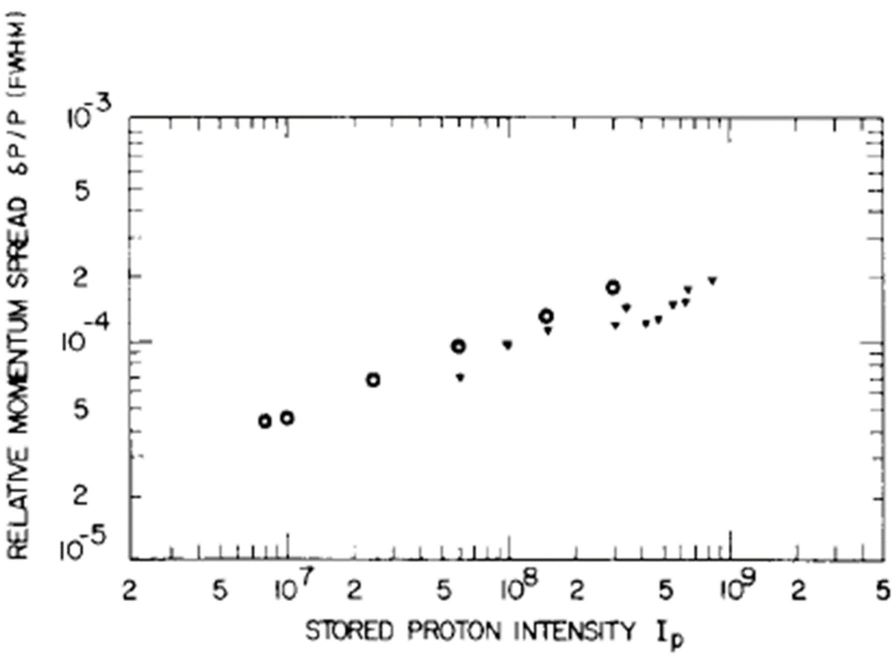
Cross-sections of neutral atom beam as seen by the two-dimensional MWPC



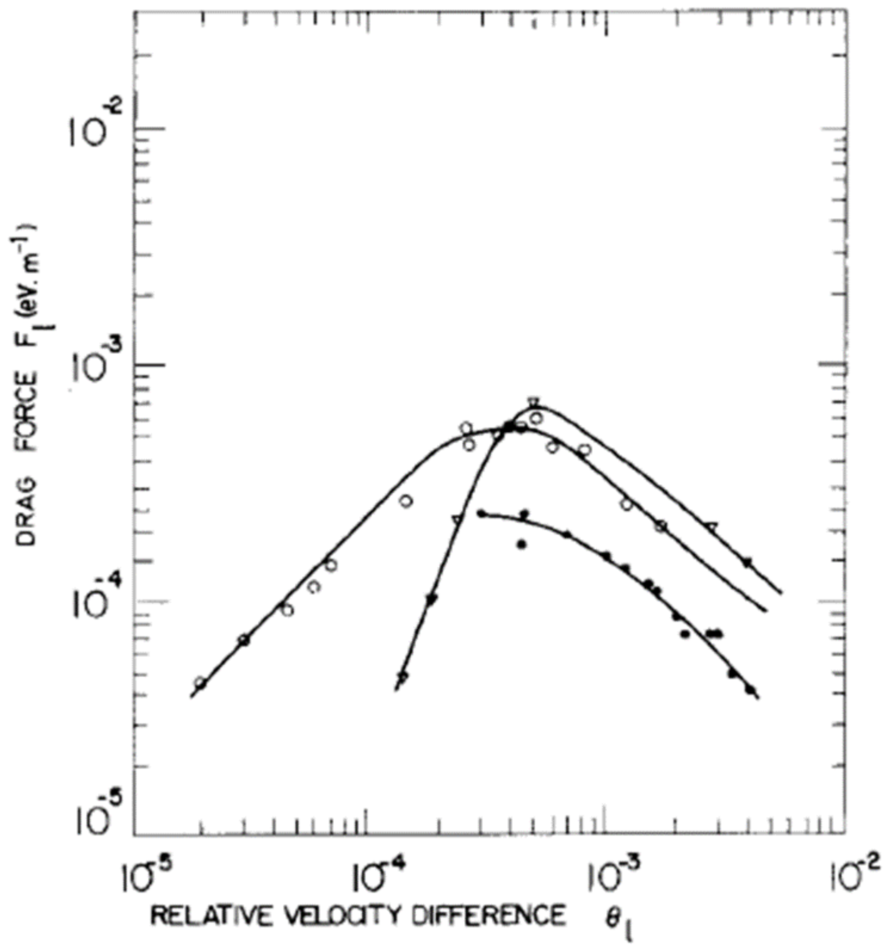
Schottky noise, taken at the beginning and end of the cooling process



Profile observed on the horizontal IPM



Equilibrium momentum spread of 45 MeV protons versus intensity. (o) temperature limited T/2 electron beam (590 mA). (∇) space charge limited P/2 electron beam (1250 mA).



The momentum cooling force, for small betatron amplitudes, was measured separately by first cooling the beam and then suddenly increasing the gun voltage and observing the subsequent acceleration of protons.

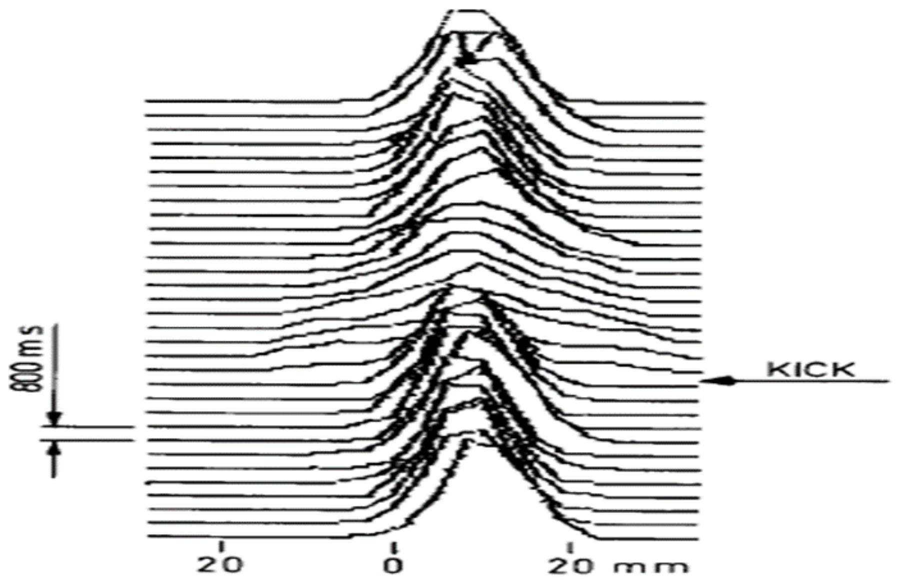
By voltage increases in the range 2-300 V fractional relative velocities in the range $5x10^{-5}$ to $6x10^{-3}$ were created. The proton acceleration was observed as a change of revolution frequency, with the longitudinal pickup

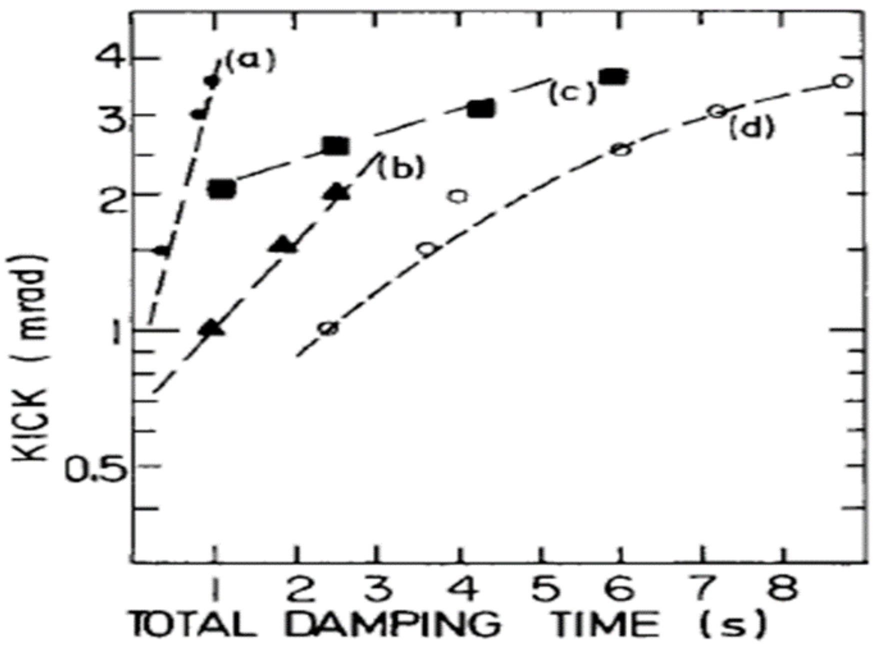
Horizontal betatron oscillations were excited artificially on the cooled beam by a short (700 ns) coherent pulse from the Full Aperture Kicker. Damping was then followed on the horizontal beam profile monitor. Repeated excitation to various amplitudes were made and the total damping time measured as a function of excitation amplitude.

The figure on the top right shows an example of such observations. The time between frames is 800 ms. The total damping time, down to the resolution of the monitor, is here about 7 s.

The damping could also be observed with the neutral atom profile.

The horizontal acceptance of the storage ring, taking into account closed orbit distortion, limited the excitation amplitude to about 3.8 mrad. The minimum observable amplitude was determined by the resolution of the horizontal beam profile monitor.

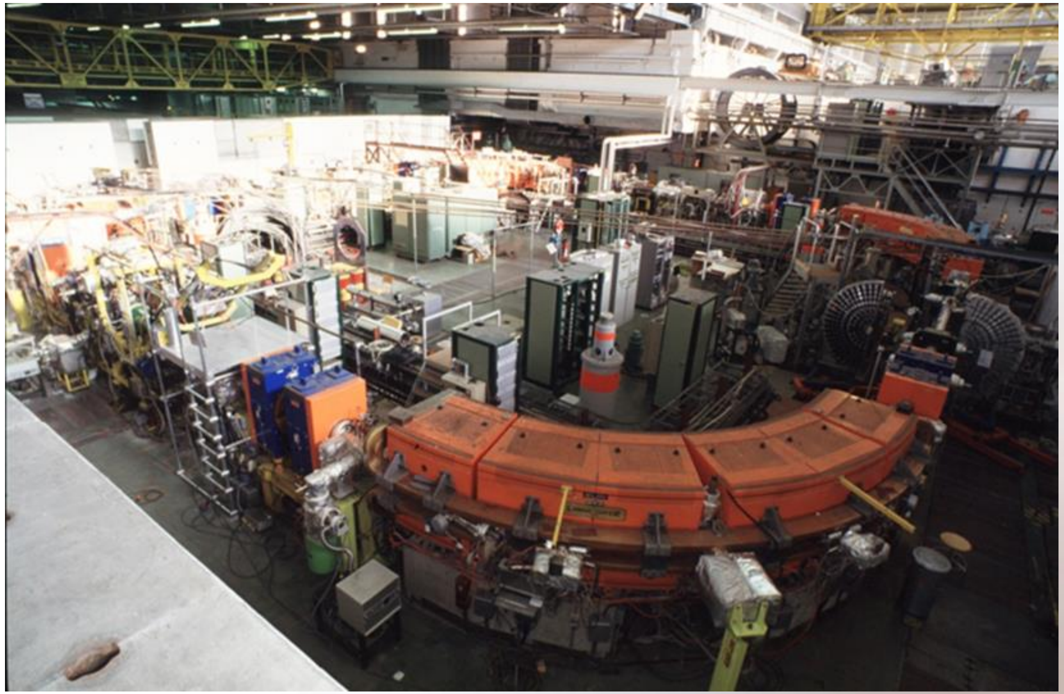


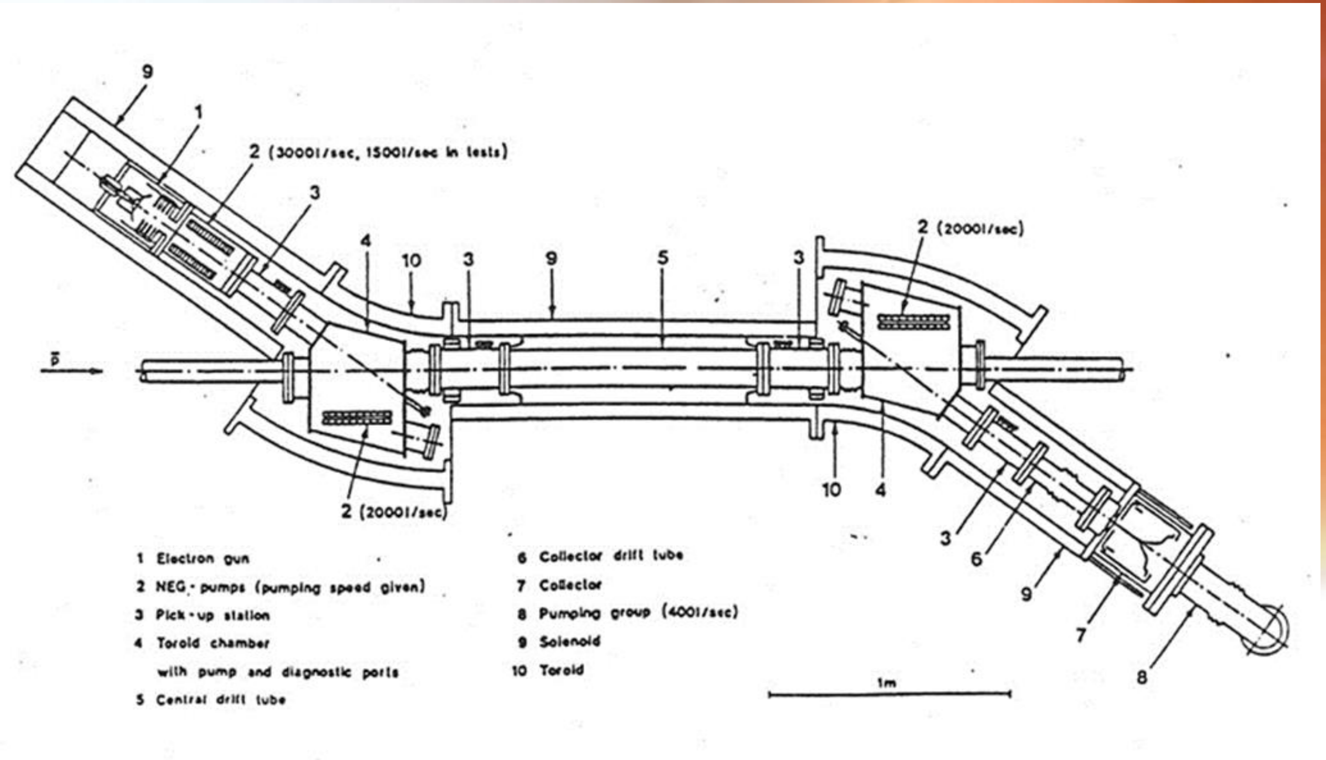


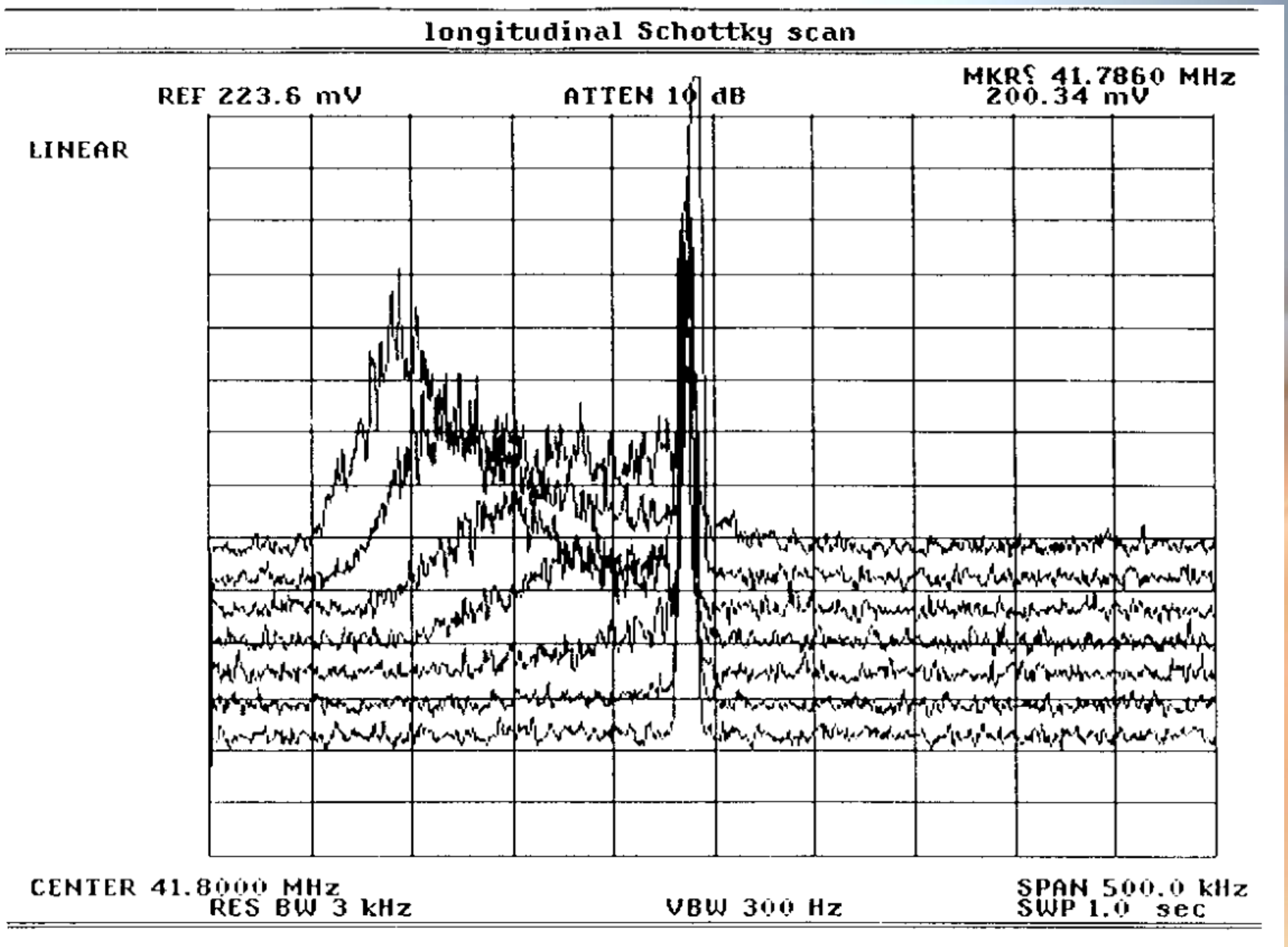
LEAR (Low Energy Antiproton Ring)

The required static vacuum level of less than 10^{-11} torr meant that the cooler needed a major upgrade of its vacuum system.

- best obtainable vacuum was in the order of 10^{-9} torr on ICE
- the complete vacuum envelope was re-designed and built using high quality AISI 316LN stainless steel
- designed to be bakeable at 300˚C in situ (permanently installed jackets)
- use of NEG (non evaporable getter) strips

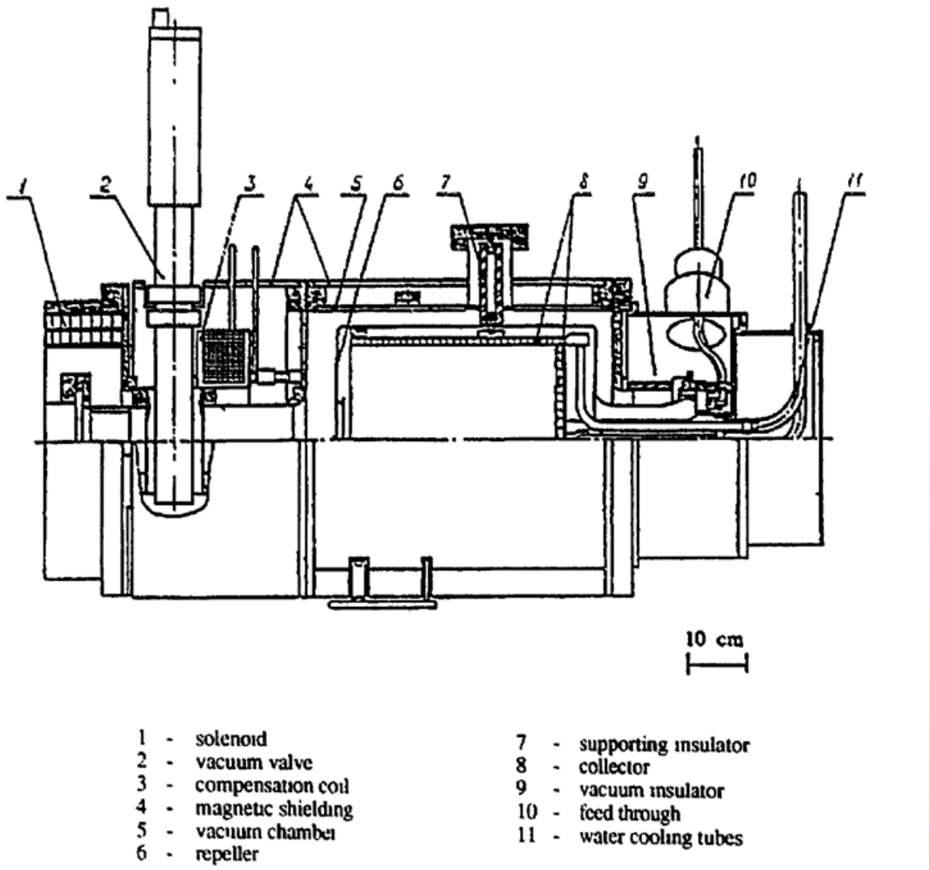




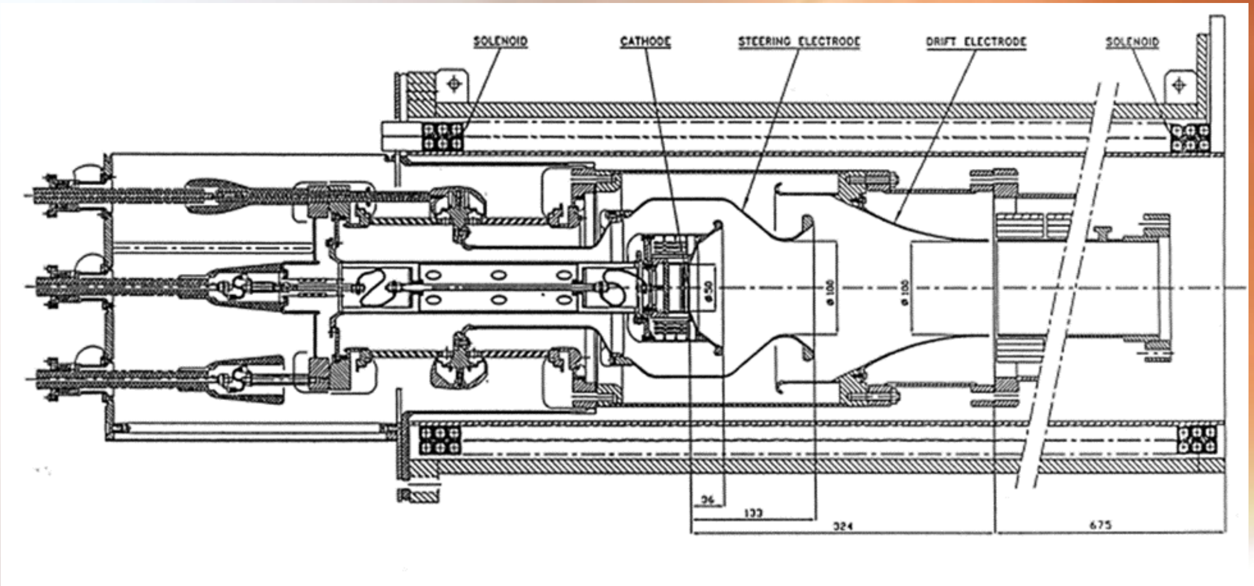


1st cooling of 50 MeV proton from Linac 1 (October 1987)

- New electron collector for reliable operation with full perveance gun (1991)
- New electron gun allowing the online control of the electron beam intensity (1992)
- Electron beam energy feedback system

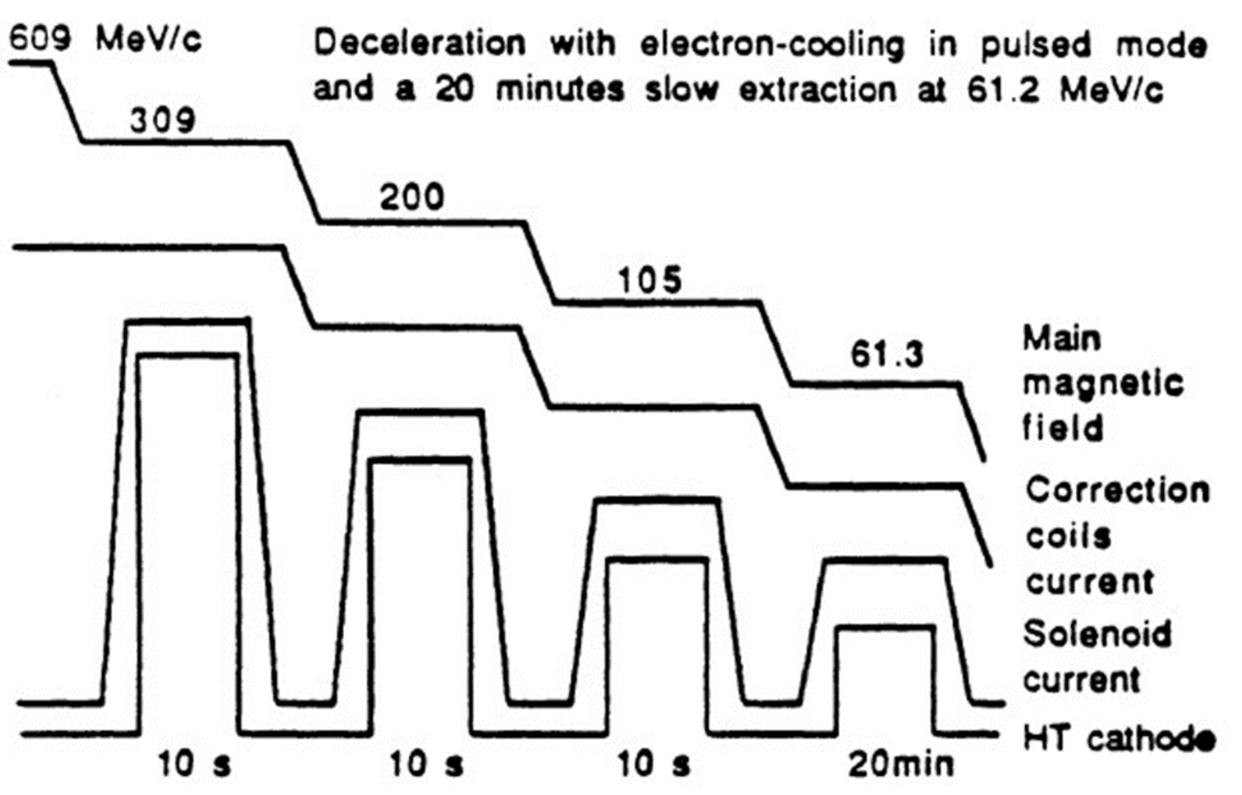


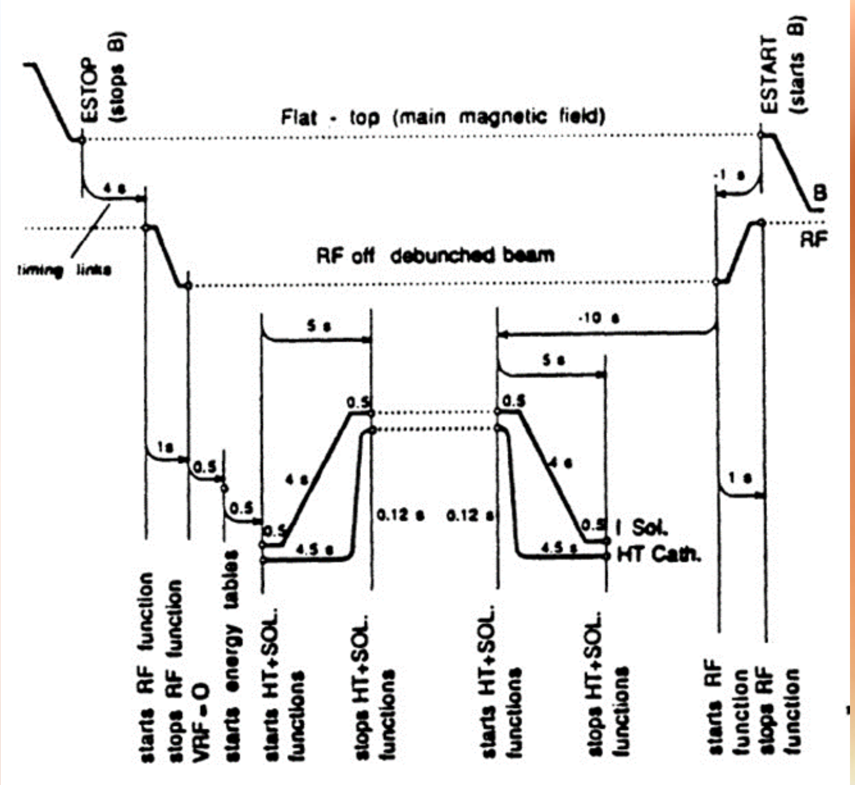
Adiabatic optics
Fixed magnetic field of 600 G (easier for operation)
5 cm Cathode
«grid» electrode to give the desired current
Anode (drift) at ground potential



Operation (with antiprotons) of cooler was made in the “pulsed” mode

Electron cooling was applied at fixed flattops (plateaus) during deceleration
Required careful programming and synchronisation of the function generators

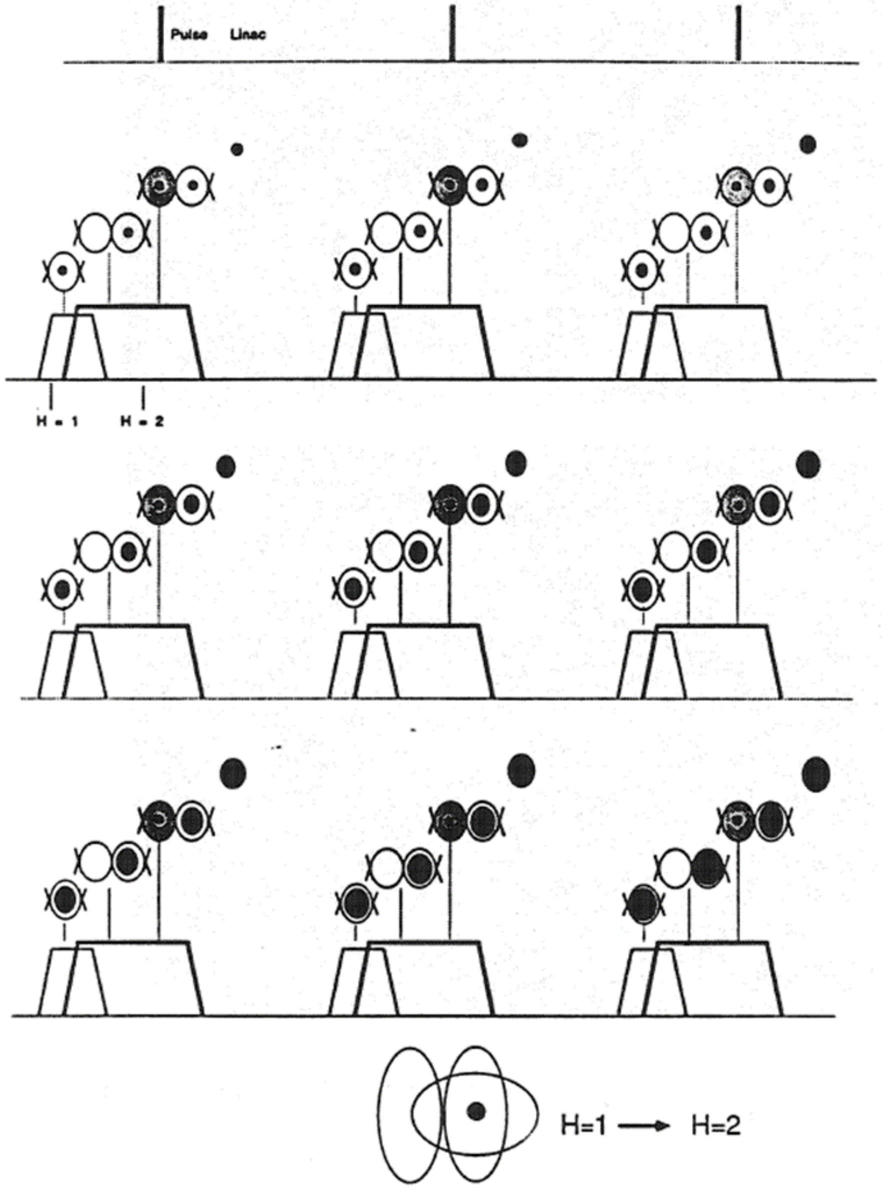




Oxygen ion cooling and accumulation in LEAR

11.4 MeV/nucleon
4×10^8 charges per Linac pulse
On average 8×10^9 charges accumulated (max 13×10^9)
Damper needed to fight instabilities

Accumulation scheme based on H1-H2 bunching with electron cooling and injection into empty bucket



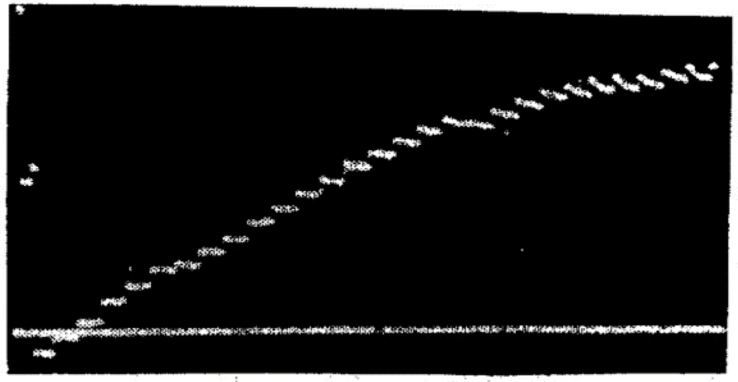
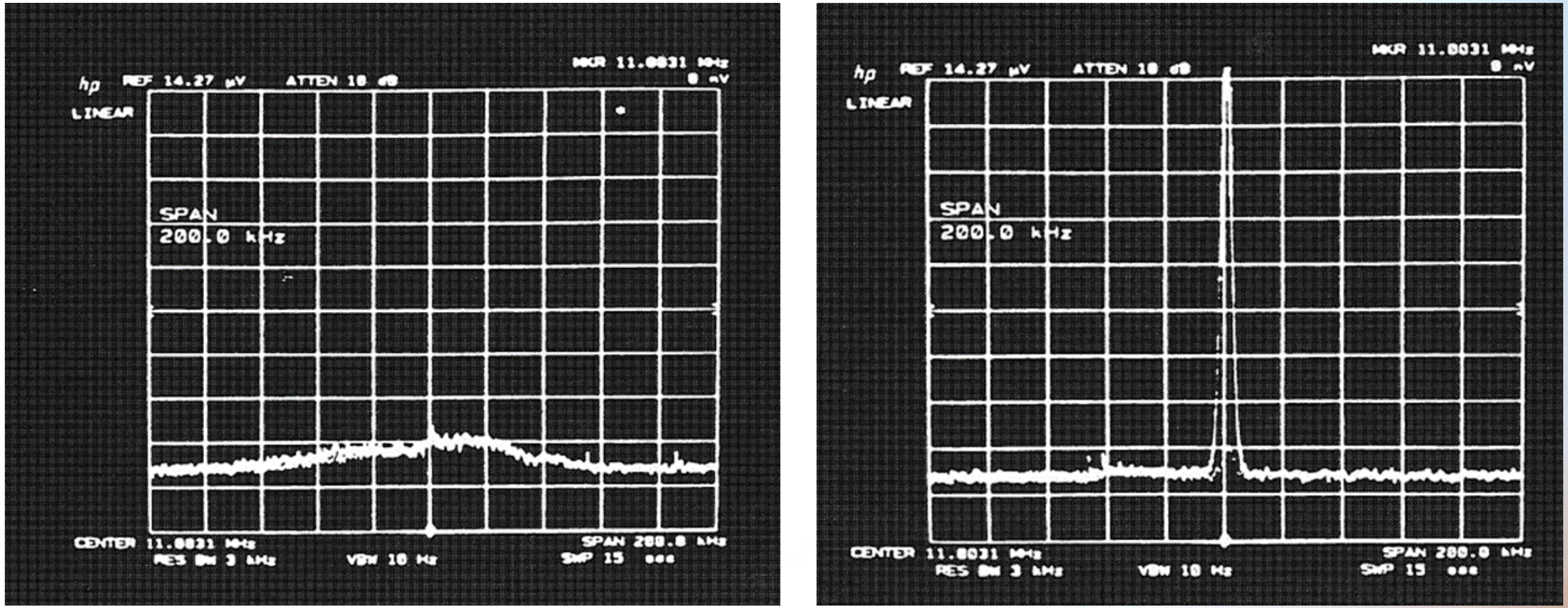
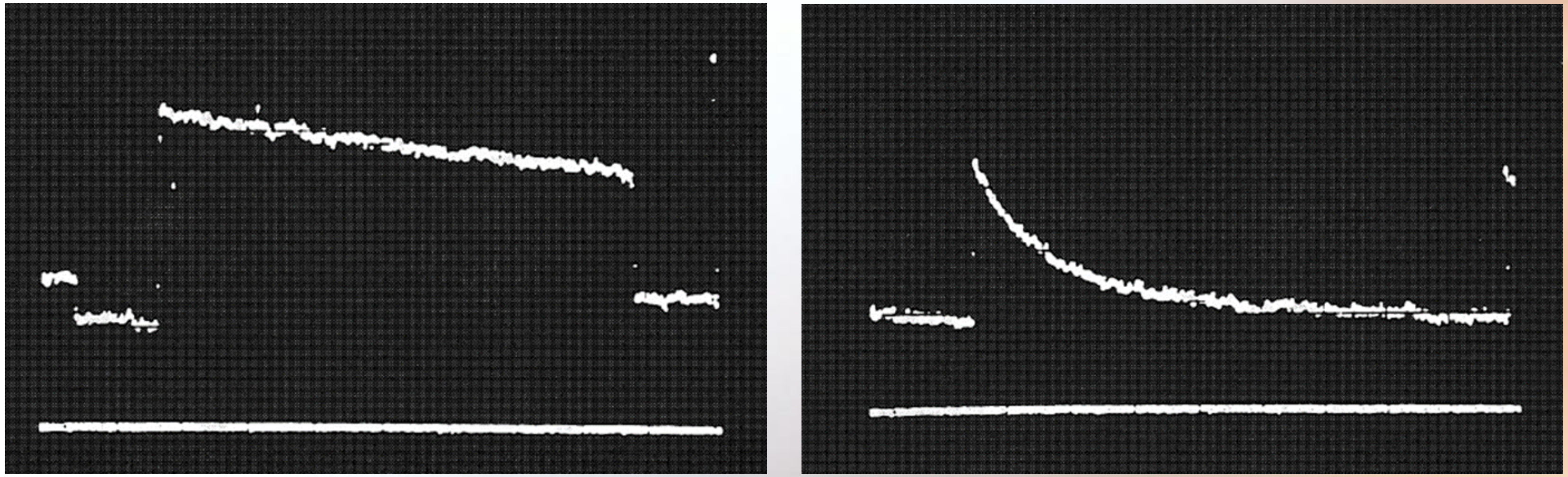


Figure 1: Current transformer reading during injection sequence. The repetition rate has been set to 7.2 seconds. Saturation occurs when the losses are of the same magnitude as the injected batch.

Cooling of H^- ions



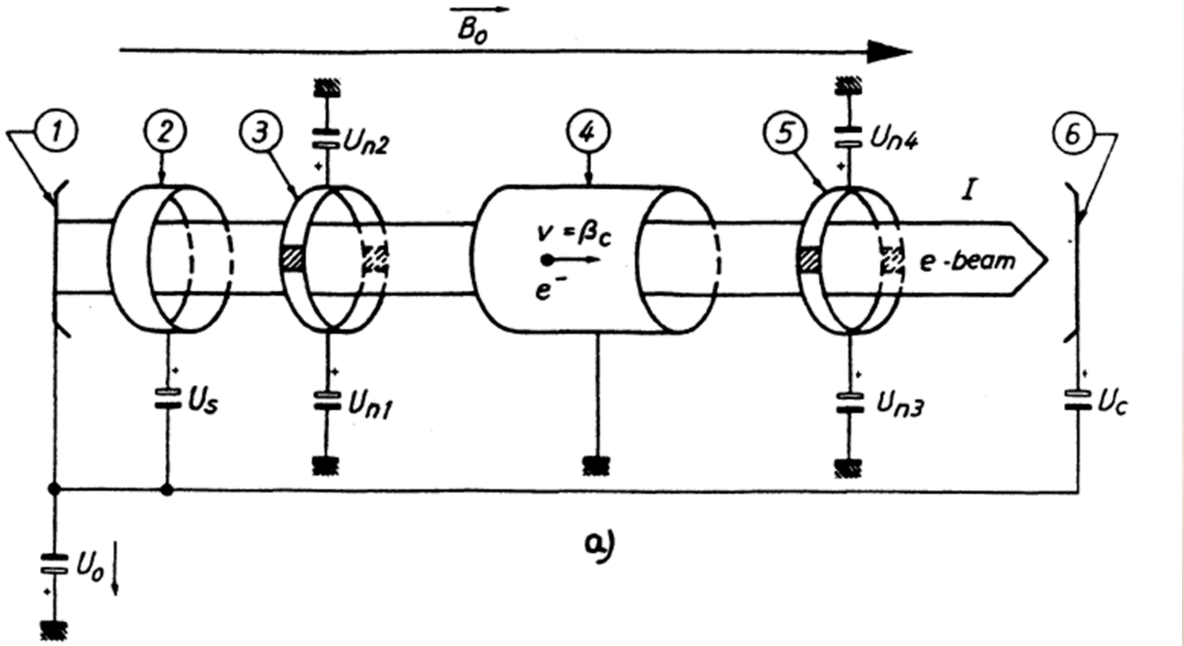
Longitundial beam distribution before (left) and after (right) electron cooling



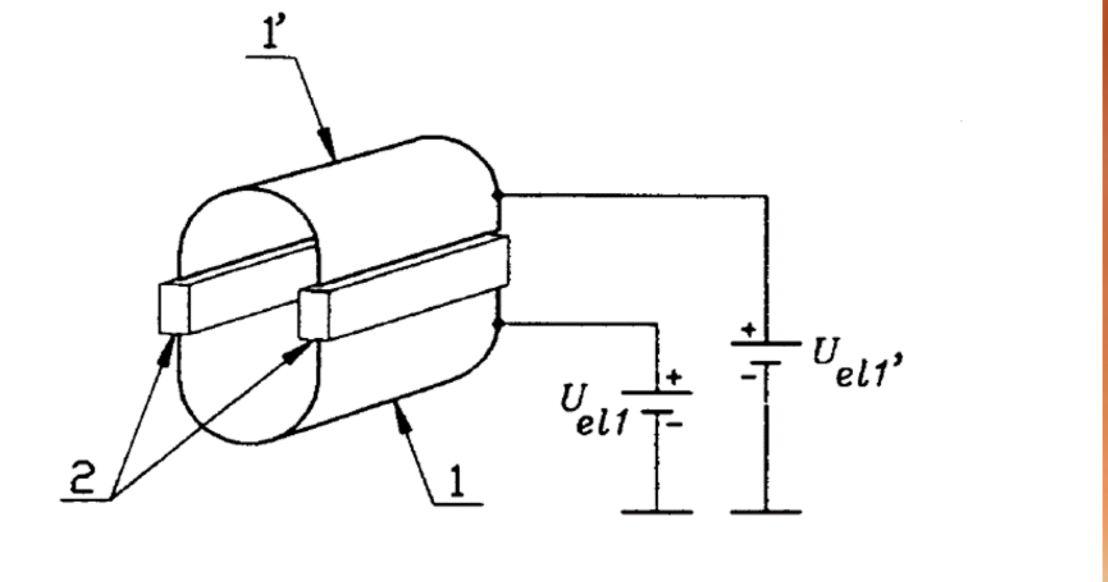
Beam intensity evolution without (left) and wit (right) electron cooling

Electron beam space-charge induces an azimuthal drift velocity which is detrimental to the cooling process.
This effect can be reduced by neutralising the electron beam.

Electron beam neutralisation is obtained by trapping ions from the residual gas in a volume between two trap electrodes. These electrodes create a transverse electric field which causes the ions to be reflected at the level of the traps. The ions oscillate and accumulate between the trap electrodes while low energy secondary electrons created through ionization escape due to the crossed electric and magnetic fields.

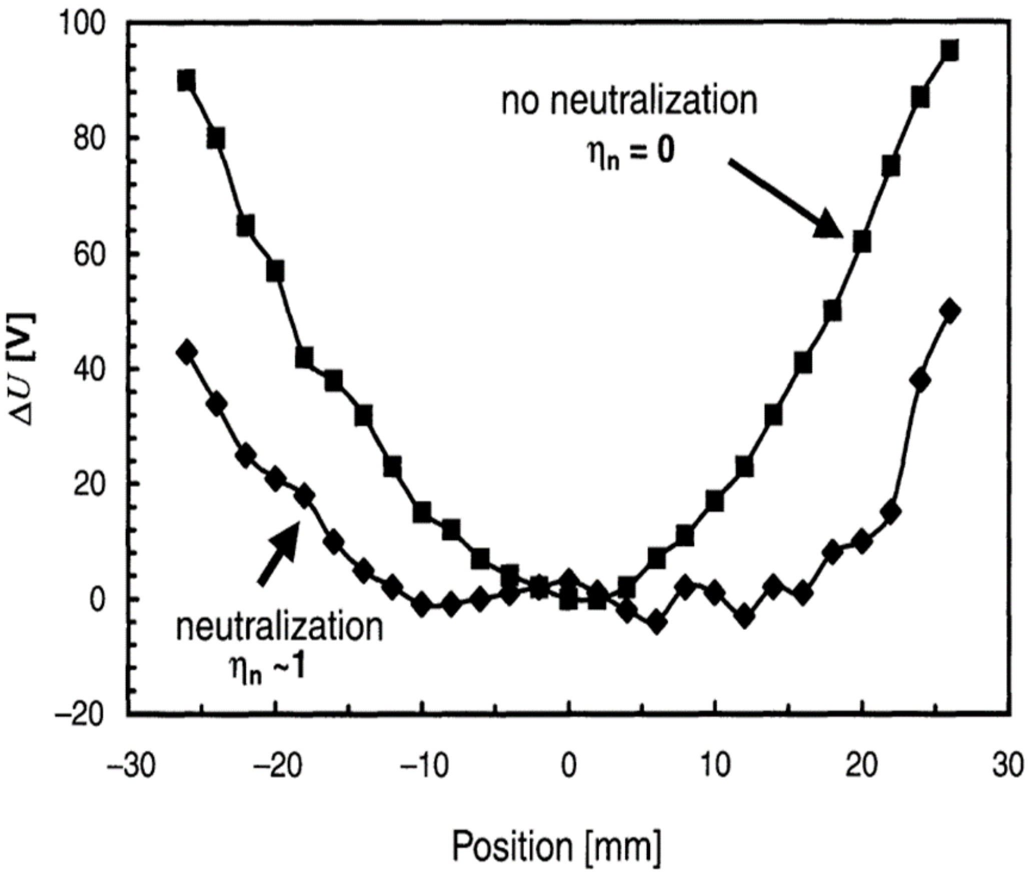


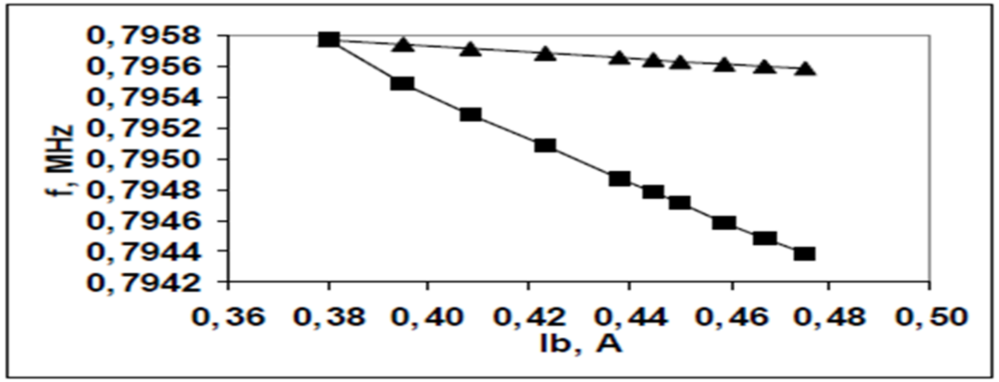
Principle of the electron-cooler set-up. 1: Cathode, 2: Steering electrode, 3: Cathode neutralisation electrode Elg, 4: Drift tube or drift space at ground potential, 5: Collector neutralisation electrode Elc, 6: Collector.



The electrostatic trap. 1,1') metallic electrode, 2) glass insulators.

Using the circulating ion beam as a probe it was possible to measure the radial distribution of the electron beam potential. By displacing the ion beam horizontally in the cooling section, the change in electron energy needed in order to bring the circulating beam back to its original momentum was recorded. In this manner we were able to reconstruct the potential distribution within the electron beam. The left figure shows a classical parabolic distribution which is measured when the electron beam is not neutralised. On the right, one sees that when neutralisation is switched on, the potential is constant in the central part of the beam and increases abruptly on the edges. The radius over which the potential is constant depends on the degree of neutralisation. Therefore the flatter the distribution, the greater the neutralisation coefficient.

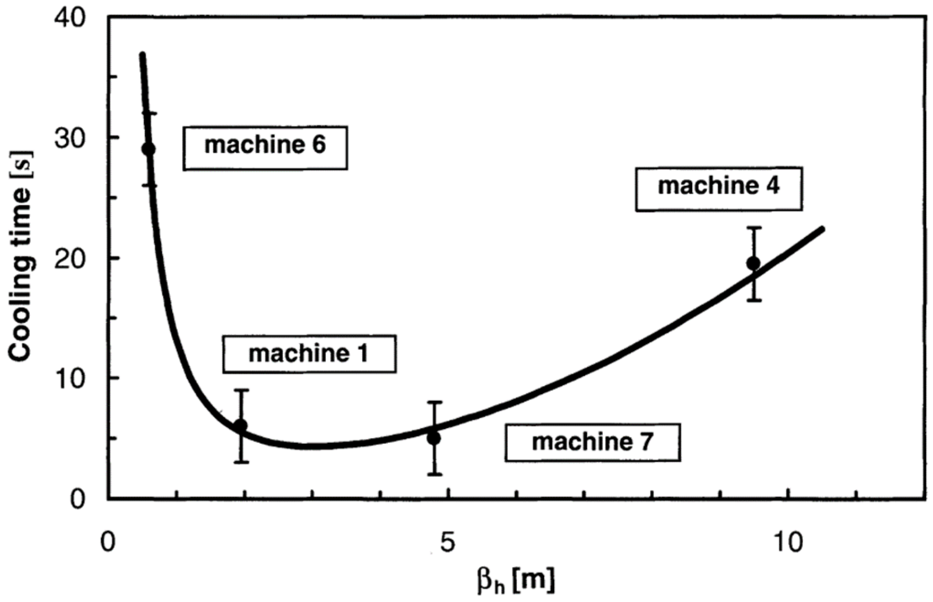




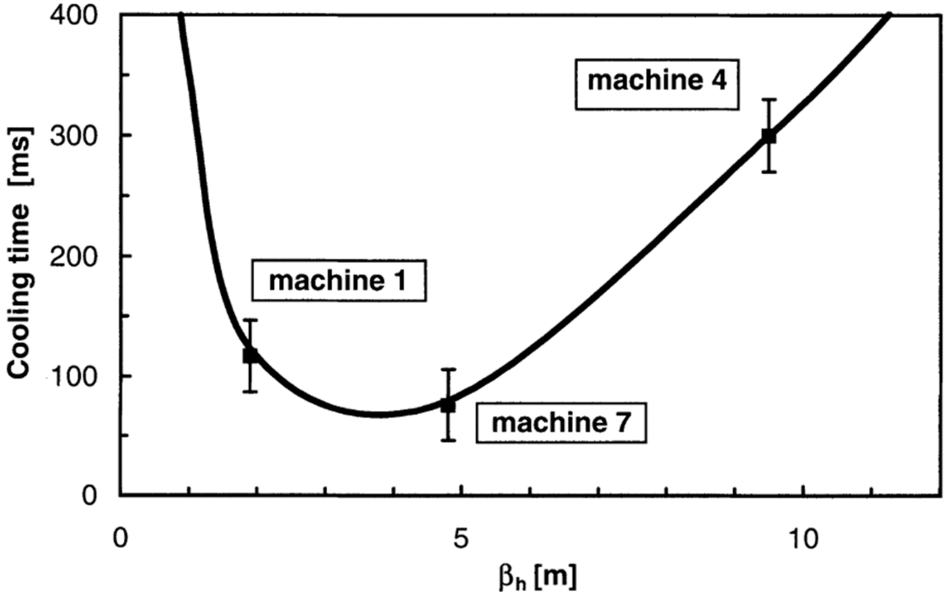
Influence of Lattice Functions

TABLE II Lattice functions for the optical settings of LEAR used in the experiments

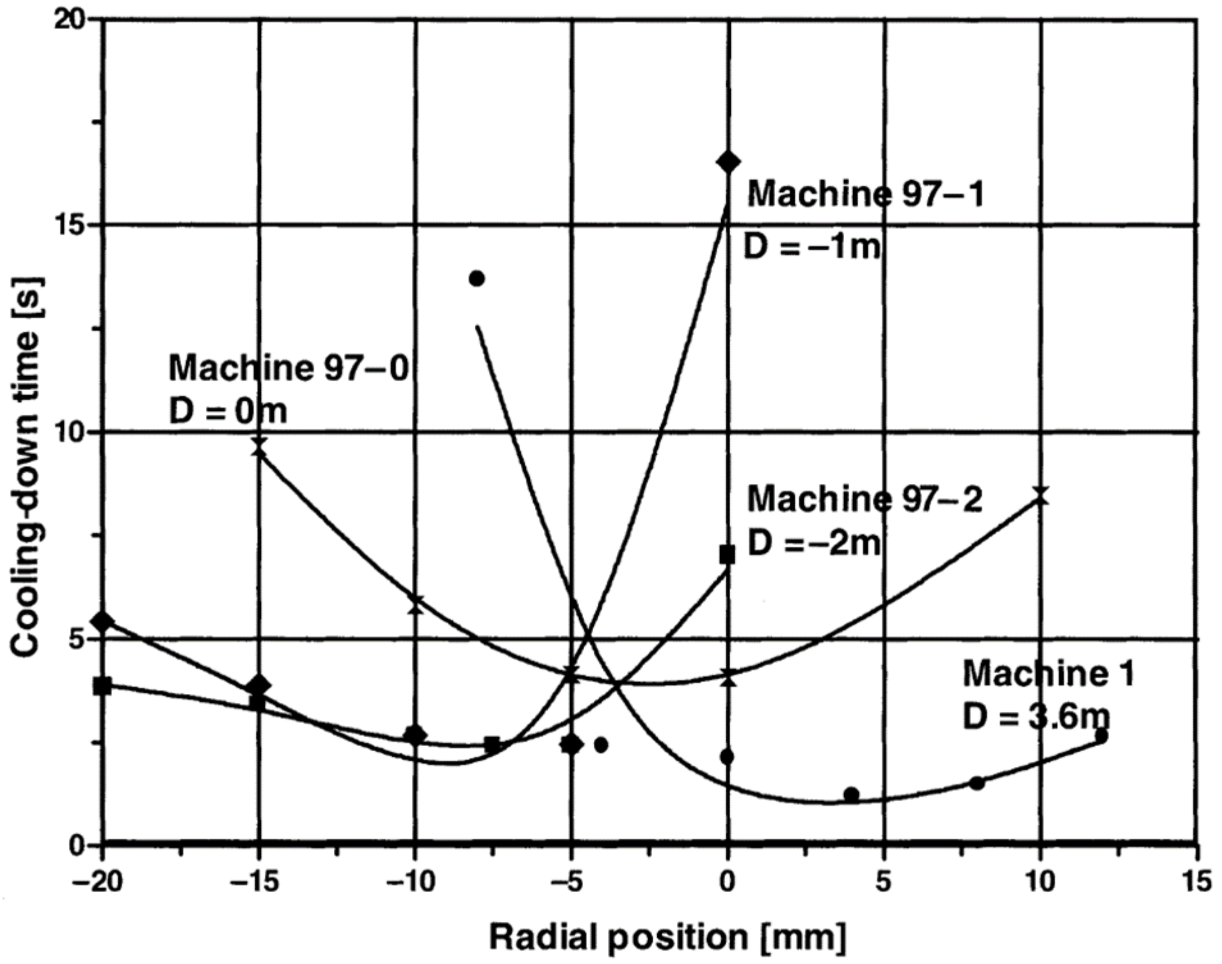
		Machines used up to 1996 (Machine no.)				*Machines used in 1997 (Machine no.)*		
		1	4	6	7	97-0	97-1	97-2
Twiss parameters at injection septum	β_H [m]	1.9	9.5	0.65	4.8	3.7	3.0	2.2
	β_V [m]	6.4	10.5	5.5	5.0	6.5	6.6	6.3
	D [m]	3.6	0	0	5.0	10	9.9	9.5
Twiss parameters at electron cooler	β_H [m]	1.9	9.5	0.65	4.8	5.0	5.0	5.0
	β_V [m]	6.4	10.5	5.5	5.0	5.0	5.0	5.0
	D [m]	3.6	0	0	5.0	0	−1.0	−2.0
Twiss parameters maximal values	β_H [m]	11.2	13.6	28.7	16.0	20.5	21.6	25
	β_V [m]	22.7	21.8	26.9	25.2	20.2	20.9	21.5
	D [m]	3.6	9.9	10.2	5.1	10	10.1	10
Working point	Q_H	2.31	1.62	2.76	2.55	1.59	1.59	1.59
	Q_V	2.62	2.42	2.72	2.70	2.57	2.57	2.57
Transition	γ_{tr}^2	−39	8.1	8.1	−28	8.1	18	−33



Plot of the proton-beam cooling time vs. horizontal beta function at the cooler. The electron current was 1.2A and the cooling length 1.5 m. The measured time is the time needed to cool about 2 x 10^9 protons at 50 MeV from a horizontal emittance of 40π mm mrad down to 4π mm mrad. The initial vertical emittance and momentum spread were about 10π mm mrad and 2 x 10^{-3} respectively. The curve corresponds to a fit $\tau \approx 0.2\beta_h + 13/\beta_h^{3/2}$

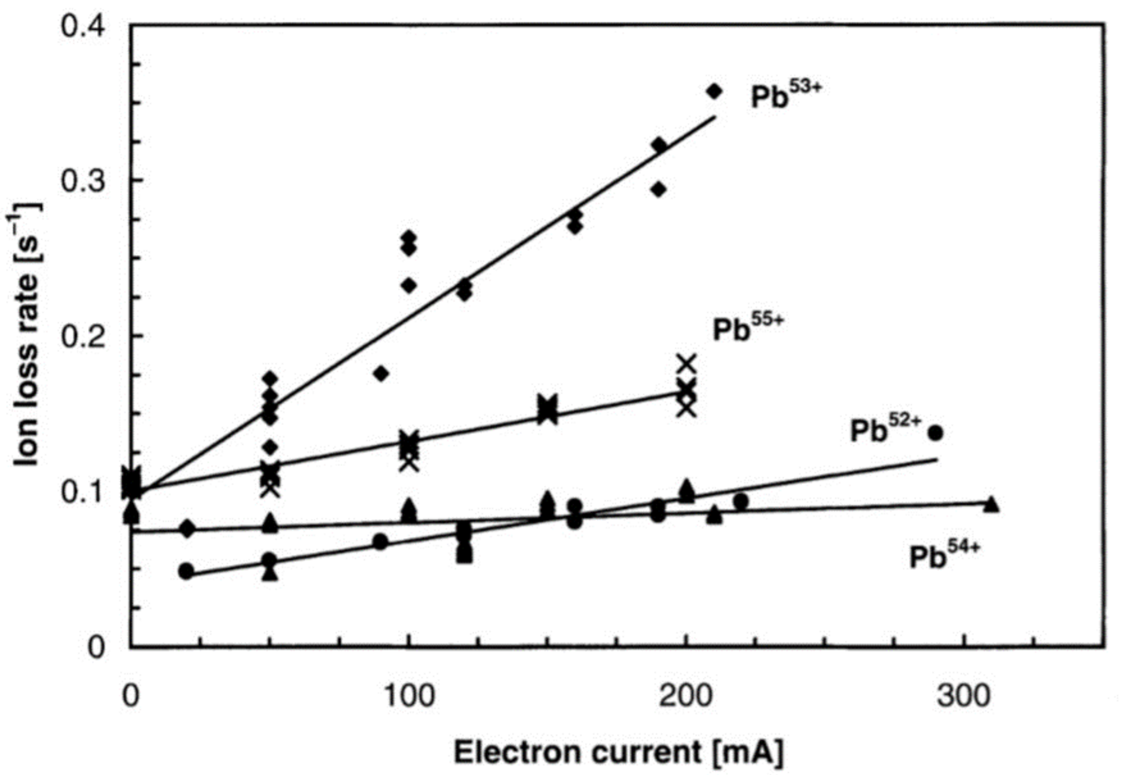


Cooling-down time for Pb^{54+} ions at 4.2 MeV/nucleon vs. horizontal beta function. The electron current was 350 mA and the cooling length 1.5 m. The curve corresponds to a fit $\tau \approx 3.2\beta_h + 230/\beta_h^{3/2}$



Cooling-down time for 50 MeV protons as a function of the horizontal offset between proton and electron beam for machine 1 and machines 97-0, 97-1 and 97-2. The electron current in this measurement series was 1.1 A and the cooling length was 3 m.

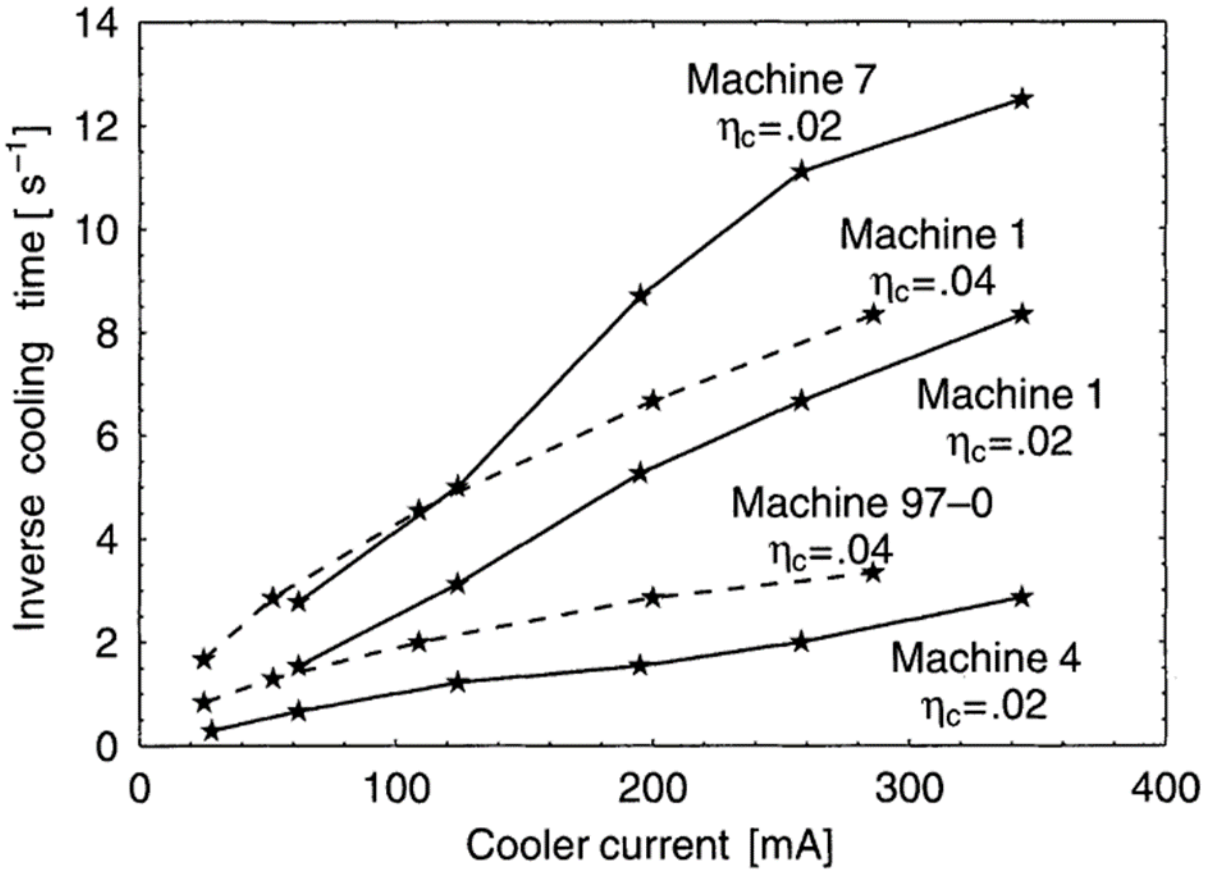
LEAR to LEIR



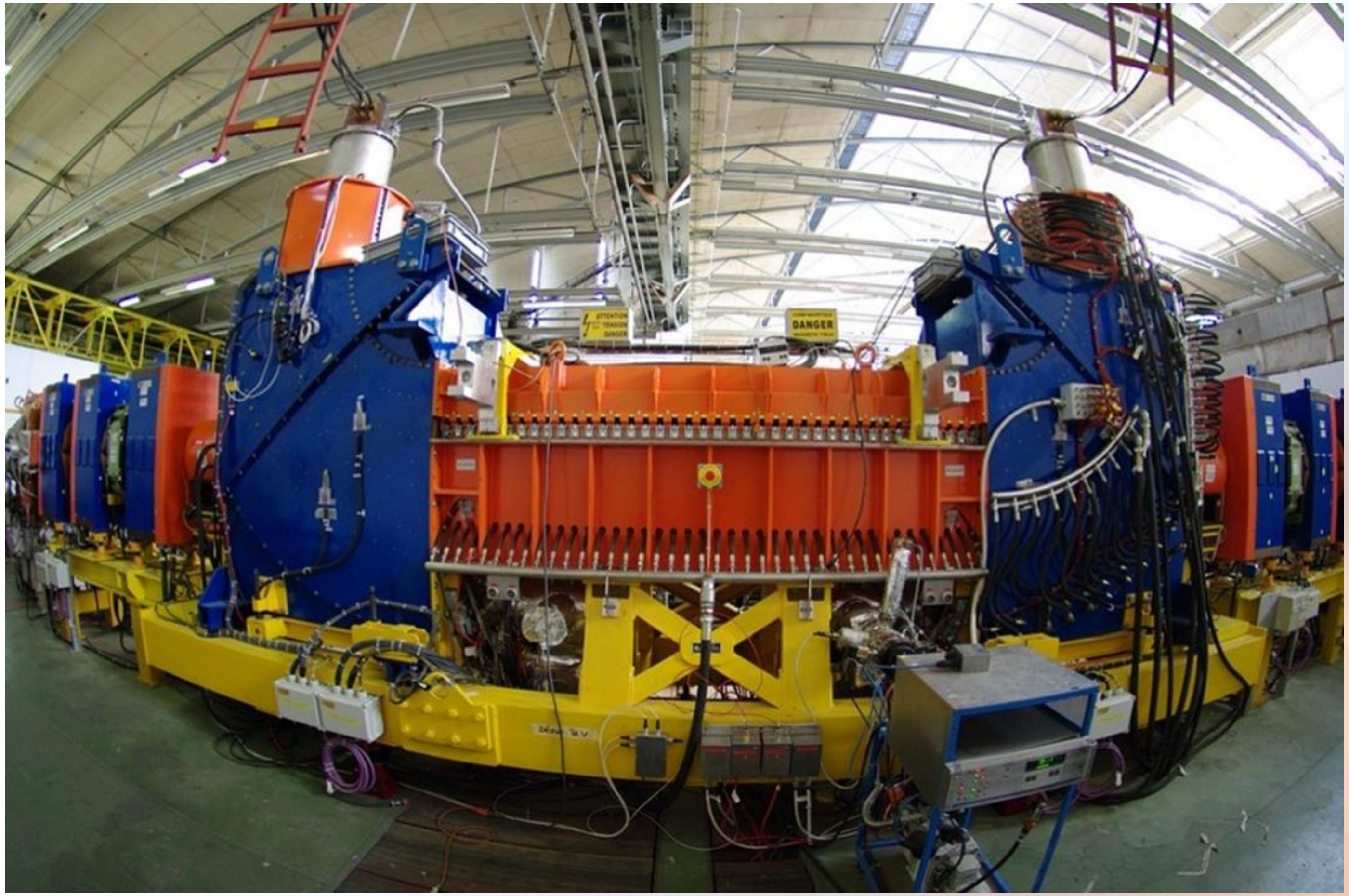
Pb^{53+} originally planned for accumulation
However the short beam lifetime lead us to investigate the possibility of using another more stable charge state.

Pb^{52+} to Pb^{54+} lifetimes were measured.
Vacuum lifetime in good agreement with semi-empirical formula of Franzke for a gas composition: 82% H_2 and 18% heavier molecules (CO, N_2).

From the slope one can estimate the recombination rate coefficient.
Measured rates higher than what one would expect for radiative recombination.
For Pb^{53+} the rate is even higher.

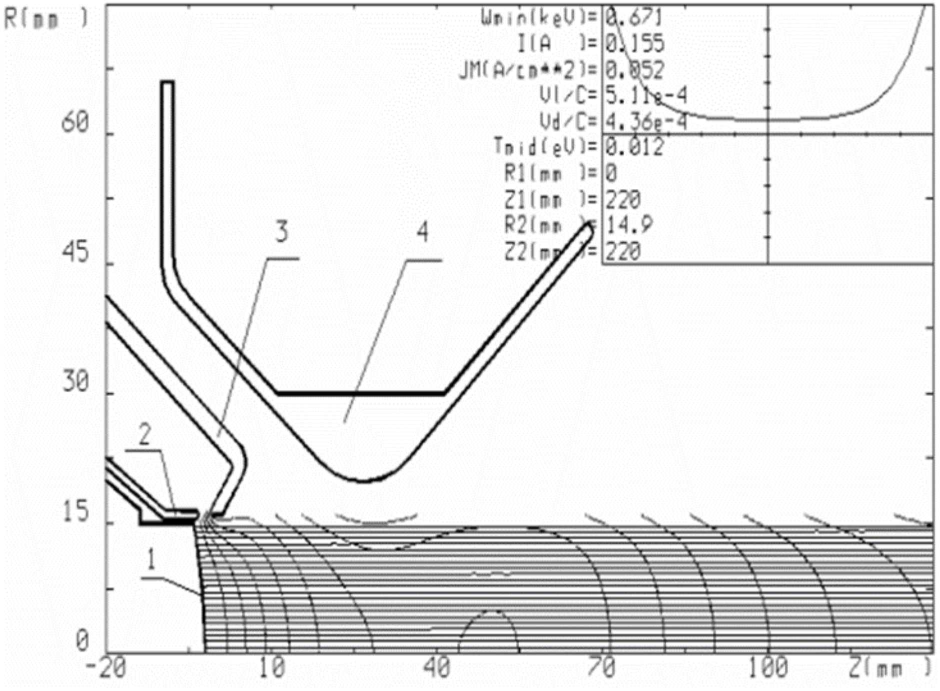


Cooling rate of Pb^{54+} ions as a function of the electron-beam current for different lattice parameters and different lengths η = 0.02, i.e. l_e = 1.5m and η = 0.04, i.e. l_e = 3m]. The cooling rate is defined as the inverse of time needed to cool from a horizontal emittance 40π mm mrad down to 4π mm mrad. The initial vertical emittance and momentum spread were about 7π mm mrad and 0.5 x 10^{-3} respectively.

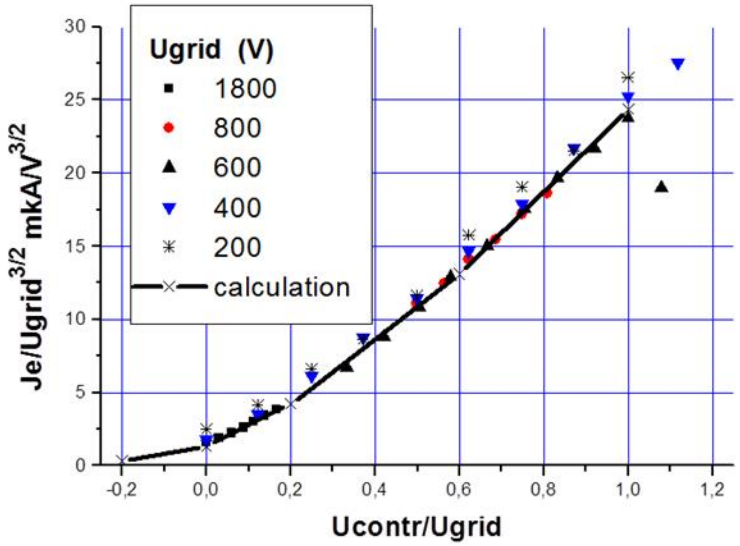


High perverance gun
Beam expansion
Electrostatic bend
Pancake structure of magnets
NEG coated vacuum chambers
NEG strips in gun/collector regions
Static vacuum pressure 4 x 10^{-12} Torr

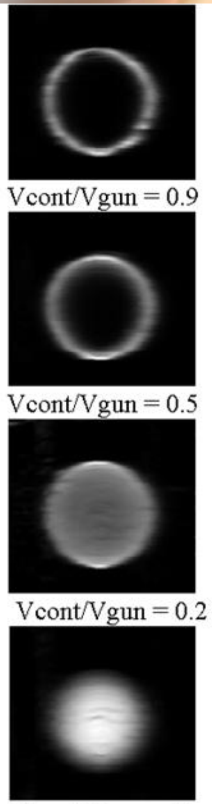
E_e up to 6.5 keV
Ie = 600 mA
k = 3, r = 14 to 25mm
B (in cooling section) = 750 G



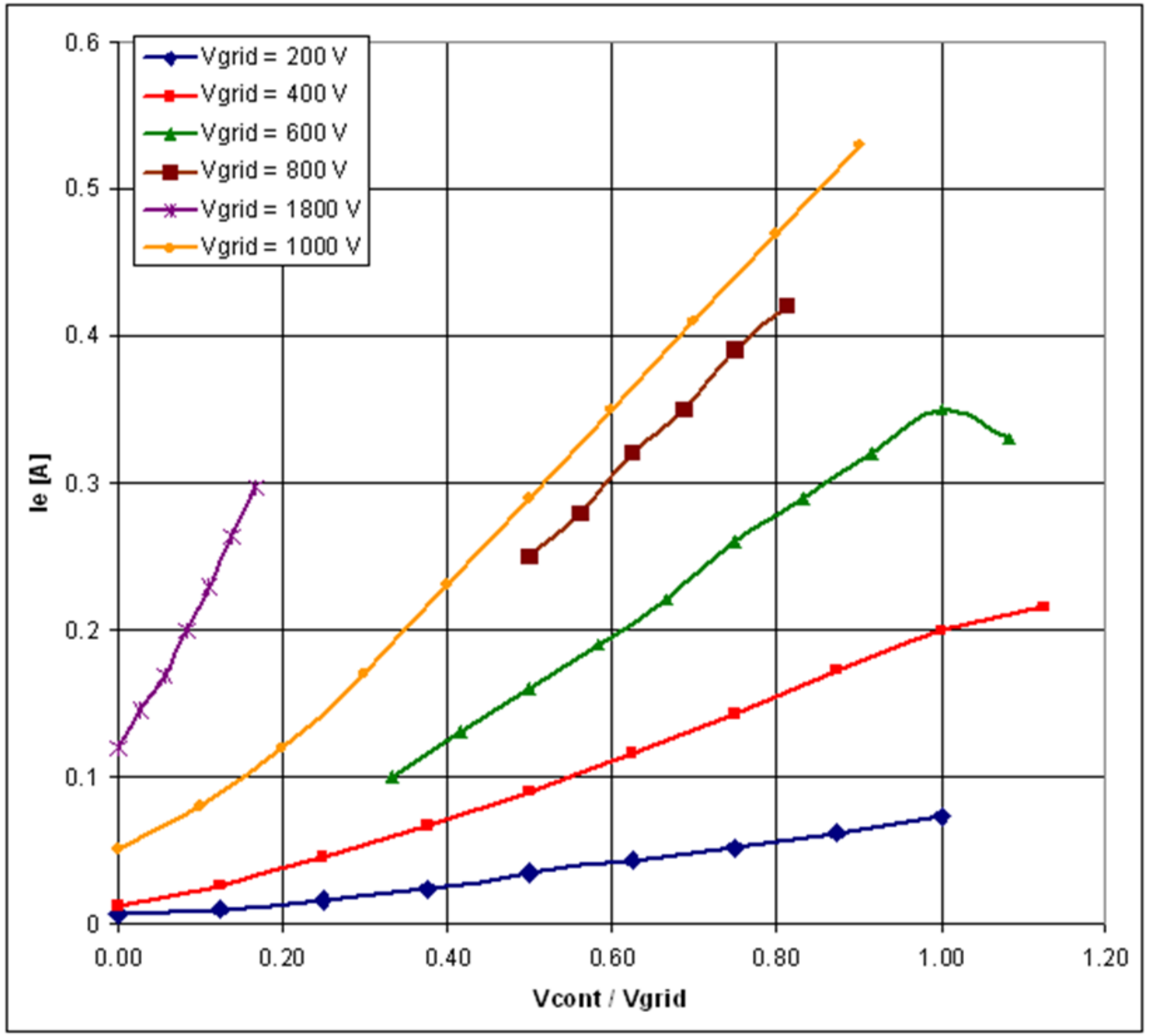
1. 14mm convex cathode
2. Control electrode (modifies density distribution and intensity)
3. Pierce electrode
4. Grid electrode (fixes the intensity)



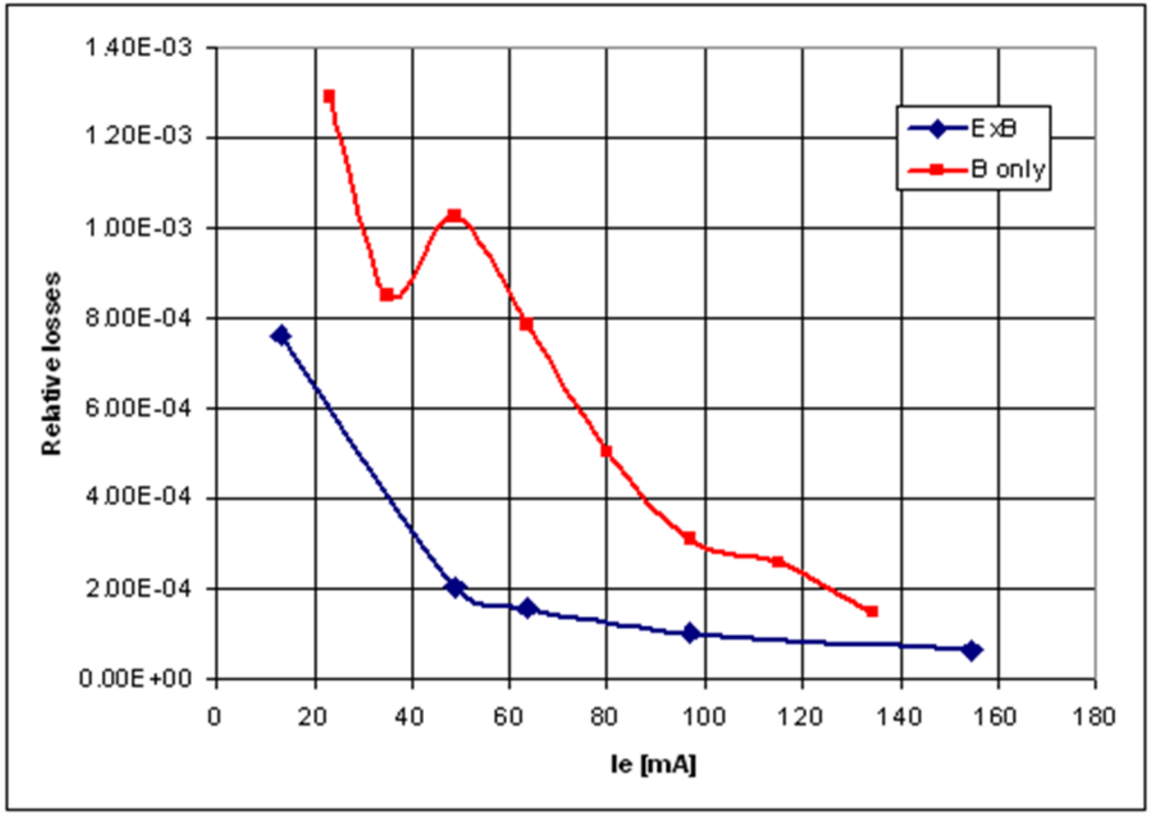
Electron beam current normalized on the grid voltage as a function of V_{cont}/V_{grid} for E_e = 2.5 keV The solid line is calculation of electron gun SuperSam code after fitting the position of the gun electrodes.



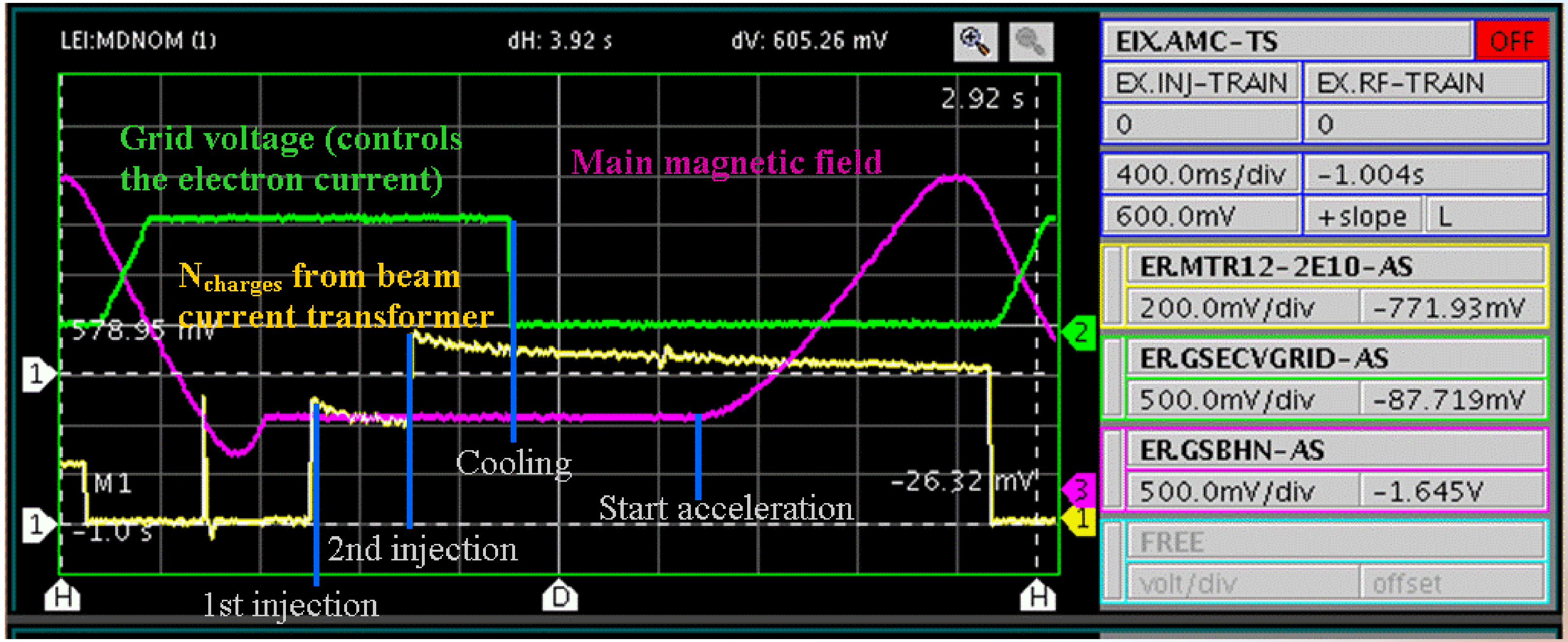
Vcont/Vgun = 0.9
Vcont/Vgun = 0.5
Vcont/Vgun = 0.2
Vcont/Vgun = 0

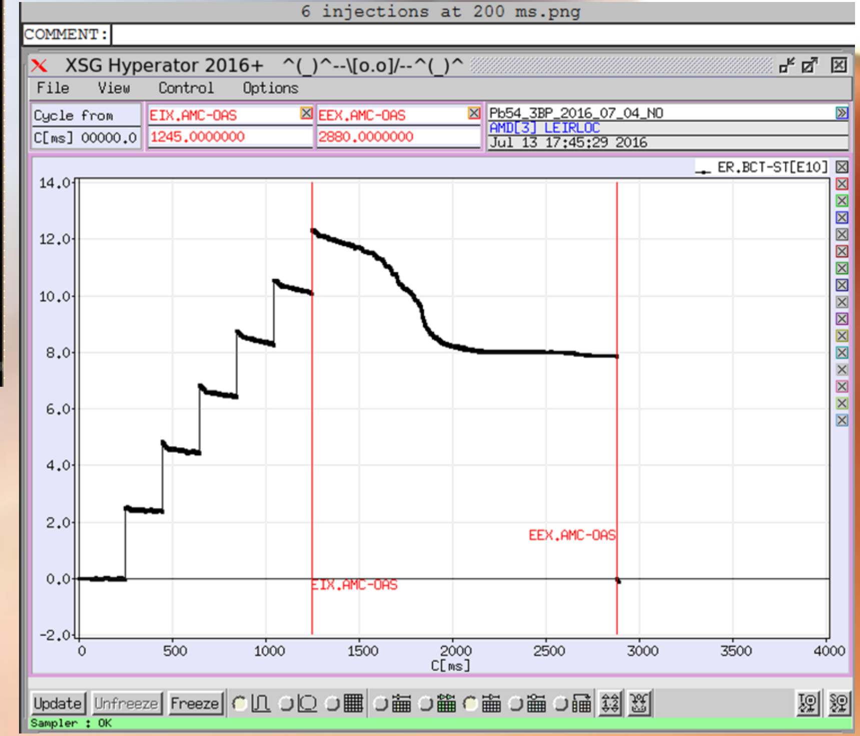


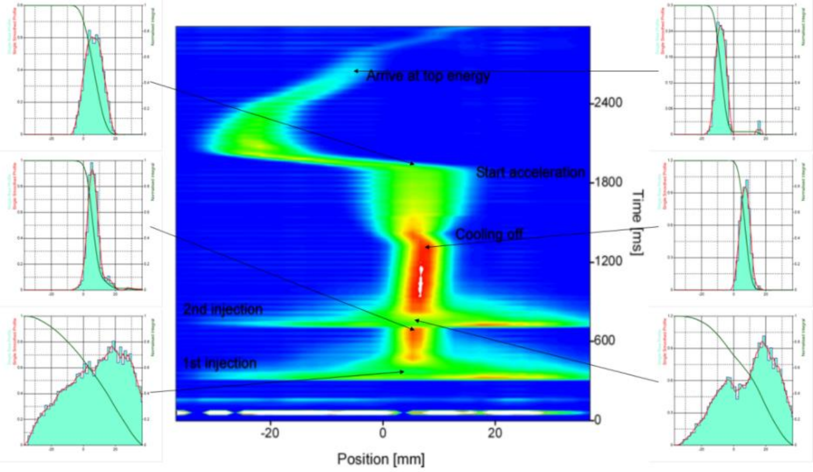
Vgrid = 200 V
Vgrid = 400 V
Vgrid = 600 V
Vgrid = 800 V
Vgrid = 1800 V
Vgrid = 1000 V
Ie [A]
Vcont / Vgrid
0
0.1
0.2
0.3
0.4
0.5
0.6
0.00
0.20
0.40
0.60
0.80
1.00
1.20



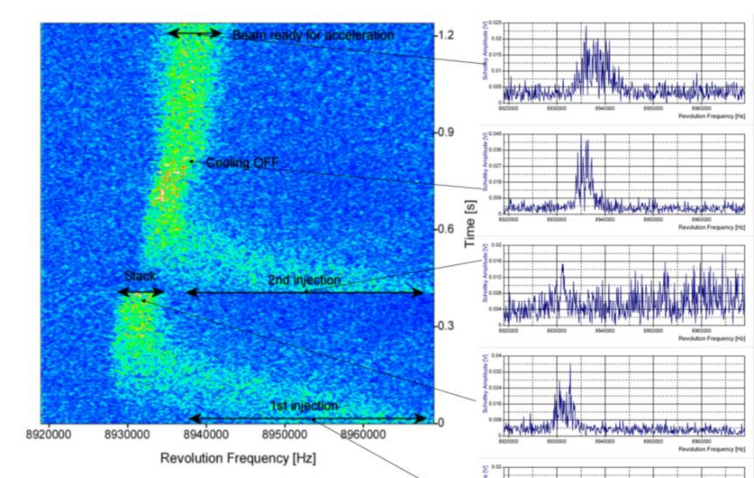
ExB
B only
Relative losses
Ie [mA]
0.00E+00
2.00E-04
4.00E-04
6.00E-04
8.00E-04
1.00E-03
1.20E-03
1.40E-03
0
20
40
60
80
100
120
140
160
180



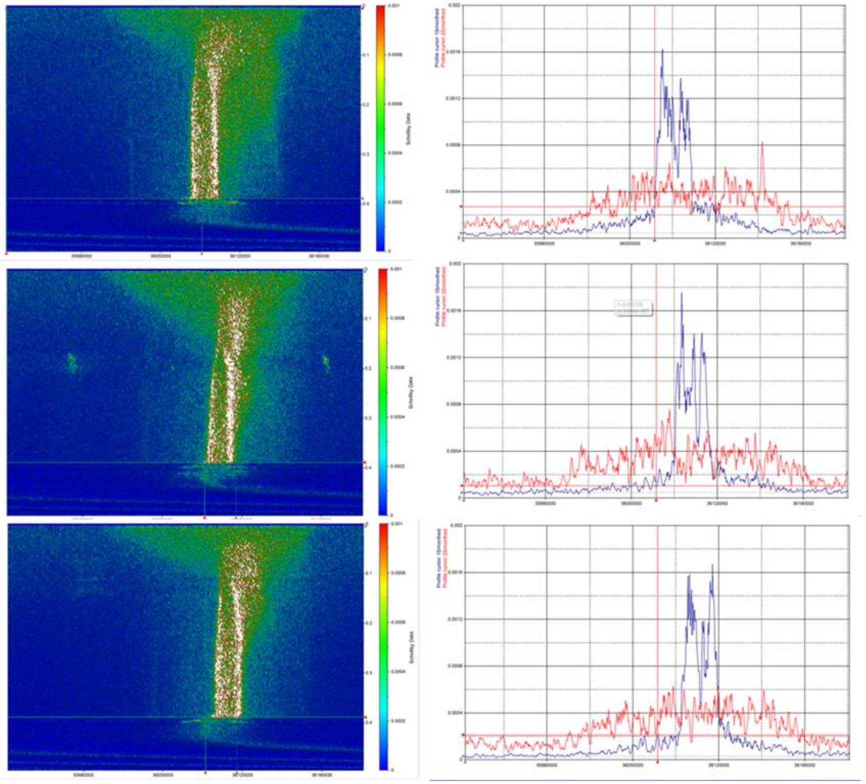




Horizontal beam profile evolution during a complete LEIR cycle measured on the ionisation profile monitor. Two LINAC pulses are cooled-stacked at 4.2 MeV/n in 800 ms, then the beam is bunched and accelerated to 72 MeV/n for transfer to the next machine in the chain, the PS. The measured emittance at extraction is typically 0.4 µm.



Longitudinal Schottky spectrum evolution on the LEIR injection plateau. The injected pulses are dragged and cooled at the stack momentum, 2‰ lower than the nominal momentum. After the second pulse, the electron beam energy is stepped up to bring the cold stack to the nominal momentum before bunching and acceleration.



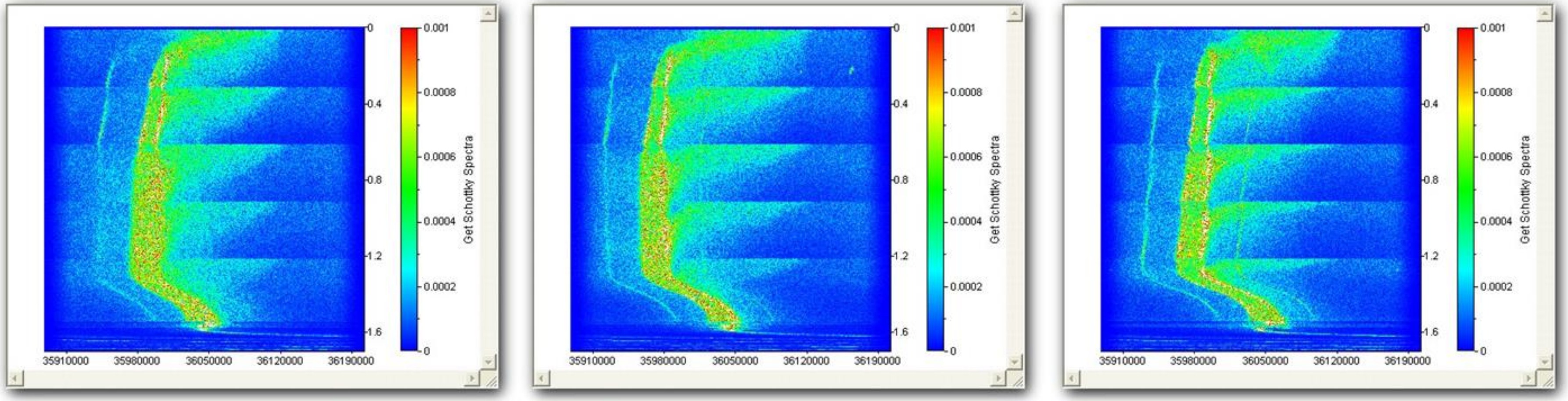
Ie = 210 mA
Vc = 290 V
Vg = 1450 V
Vc/Vg = 0.2

Ie = 210 mA
Vc = 440 V
Vg = 600 V
Vc/Vg = 0.733

Ie = 210 mA
Vc = 455 V
Vg = 455 V
Vc/Vg = 1.0

Hollow electron beam gives best results when cooling at fixed energy (i.e. one injection)

For stacking, a flat electron beam distribution gives the fastest cooling rates



Ie = 291 mA, Vc/Vg = 0.94

Ie = 297 mA, Vc/Vg = 0.5

Ie = 294 mA, Vc/Vg = 0.197

Influence of adiabatic expansion

- Needed for:
  - Adapting the electron beam size to the injected beam size for optimum cooling.

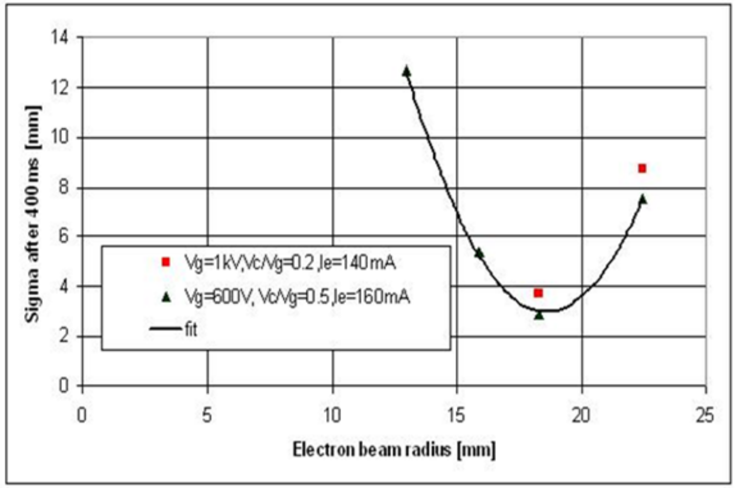
$$B_{//} r^2 = const \Rightarrow r = r_o \sqrt{\frac{B_o}{B}}$$

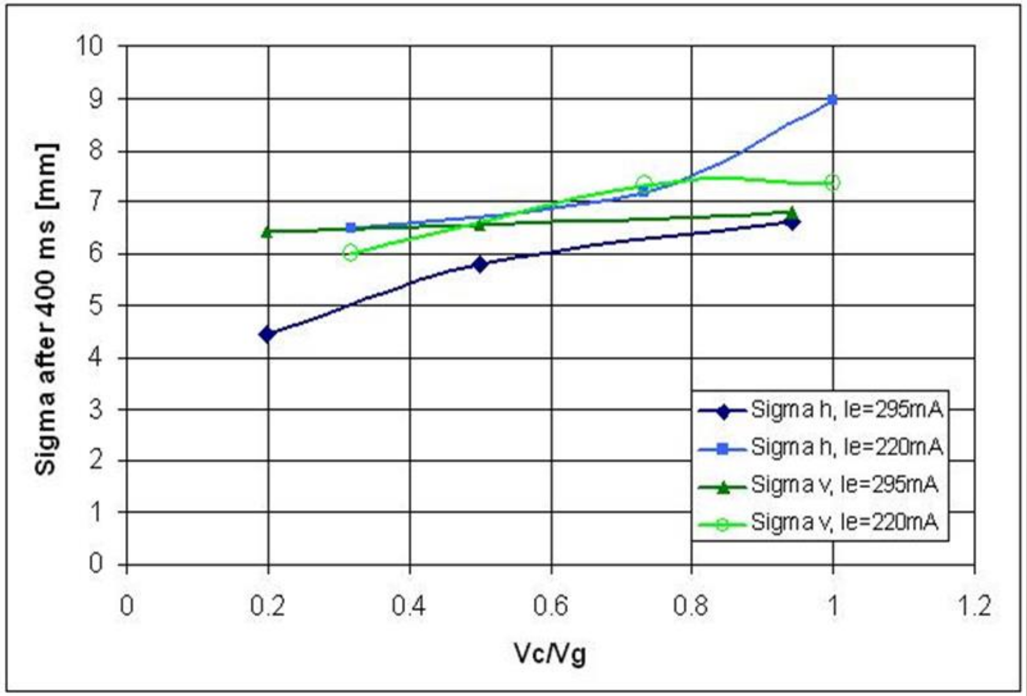
B_o=0.235T, B=0.075T, r_o=14mm => r=24.8mm

  - Reducing the magnetic field in the toroids, thus reducing the closed orbit distortion.
  - Reducing the transverse thermal temperature of the electron beam.

$$\frac{E_t}{B_{//}} = const \Rightarrow E = E_o \frac{B}{B_o}$$

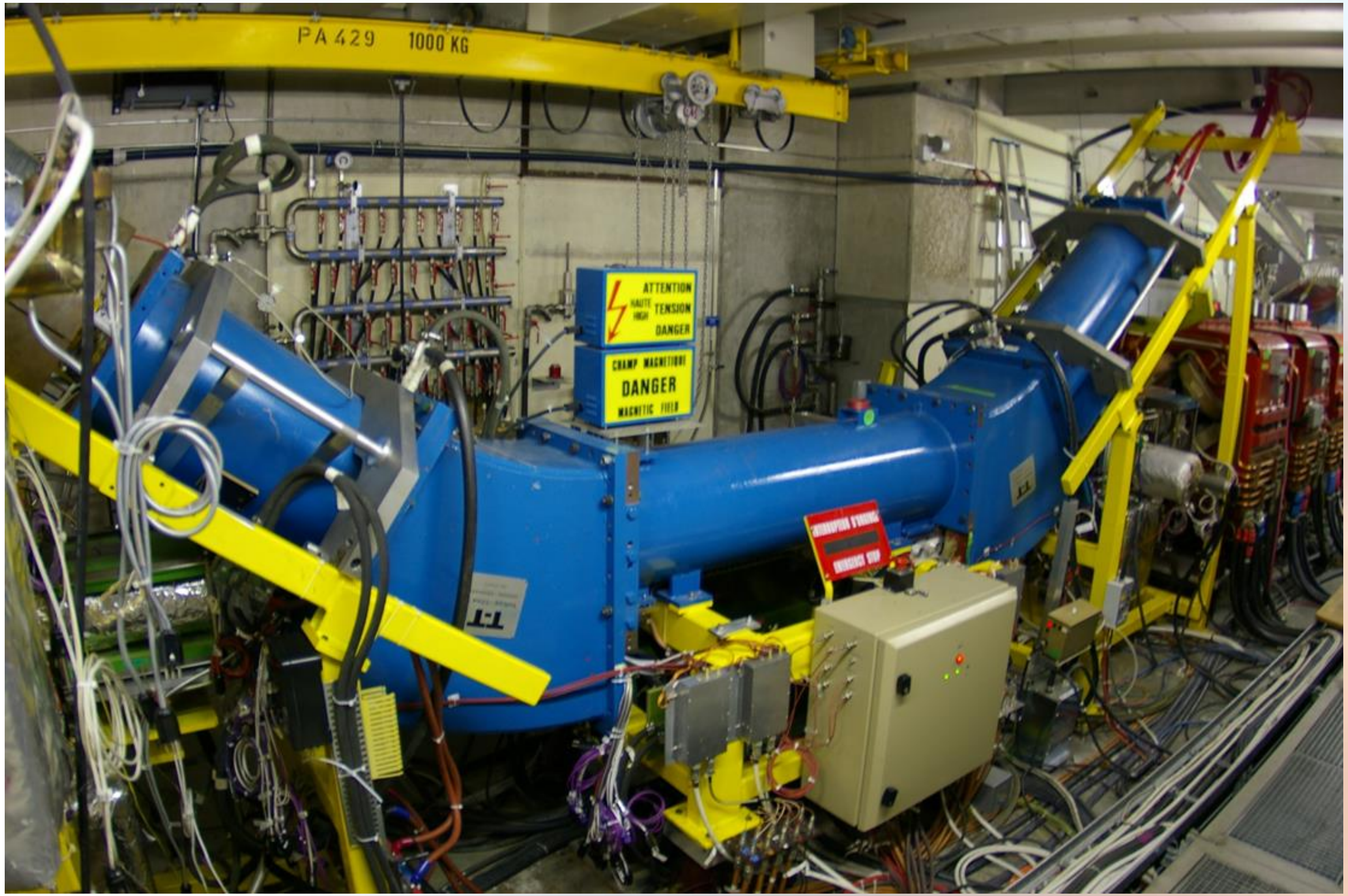
B_o=0.235T, B=0.075T, E_o=100meV => E=32meV





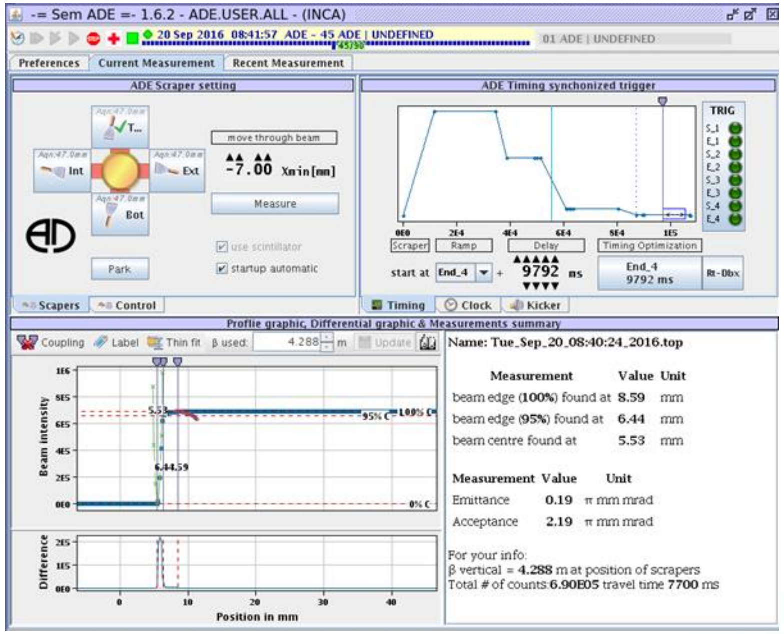
Beam size as a function of electron beam density distribution for constant current

The Antiproton Decelerator



After the dedicated Pb ion run on LEAR in 1997 the electron cooler was moved to the AD

- S to U configuration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01 ADE | UNDEFINED
Preferences
Current Measurement
Recent Measurement
ADE Scraper setting
ADE Timing synchronized trigger
move through beam
-7.00 Xmin[mm]
Measure
use scintillator
startup automatic
Park
Int
Ext
Bot
TRIG
Scraper
Ramp
Delay
Timing Optimization
start at End_4
9792 ms
End_4
9792 ms
Scapers
Control
Timing
Clock
Kicker
Profile graphic, Differential graphic & Measurements summary
Coupling
Label
Thin fit
β used: 4.288 m
Update
Beam intensity
Difference
Position in mm
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Measurement Value Unit
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beam edge (95%) found at 6.44 mm
beam centre found at 5.53 mm
Measurement Value Unit
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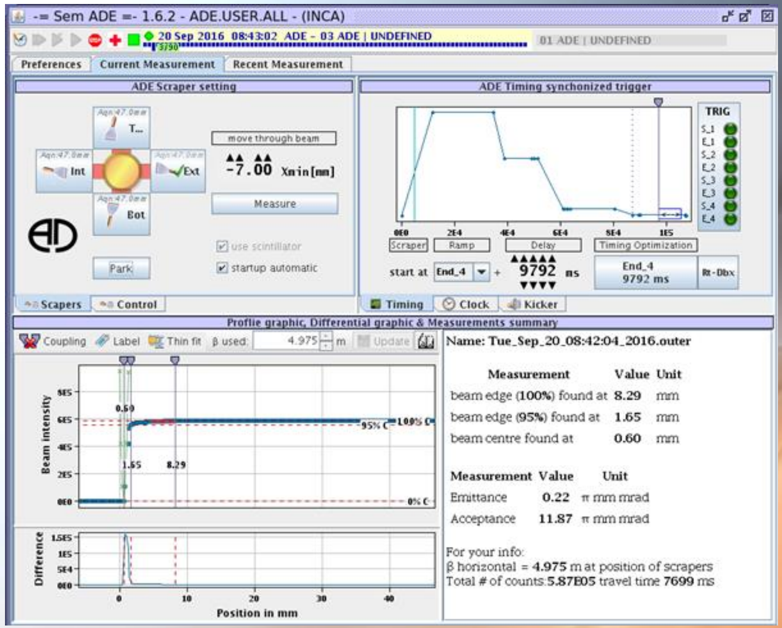
Acceptance 2.19 π mm mrad
For your info:
β vertical = 4.288 m at position of scrapers
Total # of counts:6.90E05 travel time 7700 ms

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ADE Timing synchronized trigger
move through beam
-7.00 Xmin[mm]
Measure
use scintillator
startup automatic
Park
Int
Ext
Bot
TRIG
Scraper
Ramp
Delay
Timing Optimization
start at End_4
9792 ms
End_4
9792 ms
Scapers
Control
Timing
Clock
Kicker
Profile graphic, Differential graphic & Measurements summary
Coupling
Label
Thin fit
β used: 4.975 m
Update
Beam intensity
Difference
Position in mm
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Measurement Value Unit
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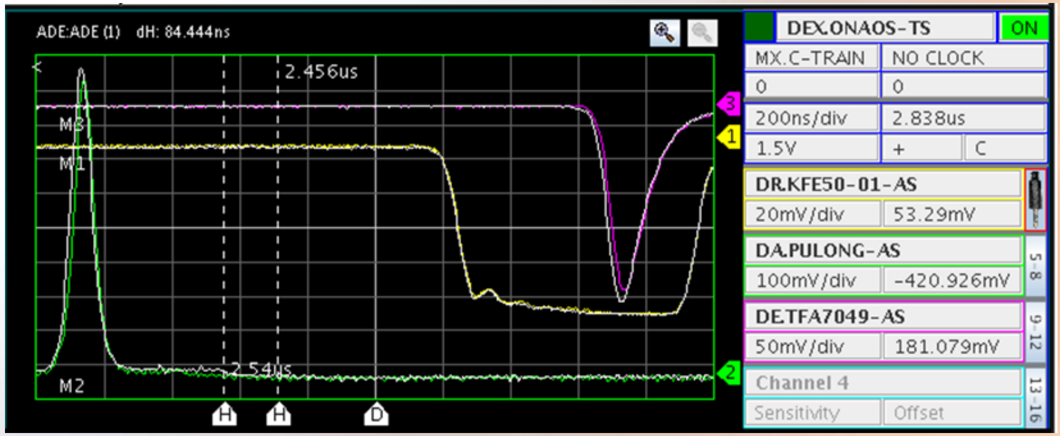
beam edge (95%) found at 1.65 mm
beam centre found at 0.60 mm
Measurement Value Unit
Emittance 0.22 π mm mrad
Acceptance 11.87 π mm mrad
For your info:
β horizontal = 4.975 m at position of scrapers
Total # of counts:5.87E05 travel time 7699 ms

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2.54us
M3
M1
M2
DEX.ONAOS-TS
ON
MX.C-TRAIN
NO CLOCK
0
0
200ns/div
2.838us
1.5V
+
C
DR.KFE50-01-AS
20mV/div
53.29mV
DA.PULONG-AS
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DE.TFA7049-AS
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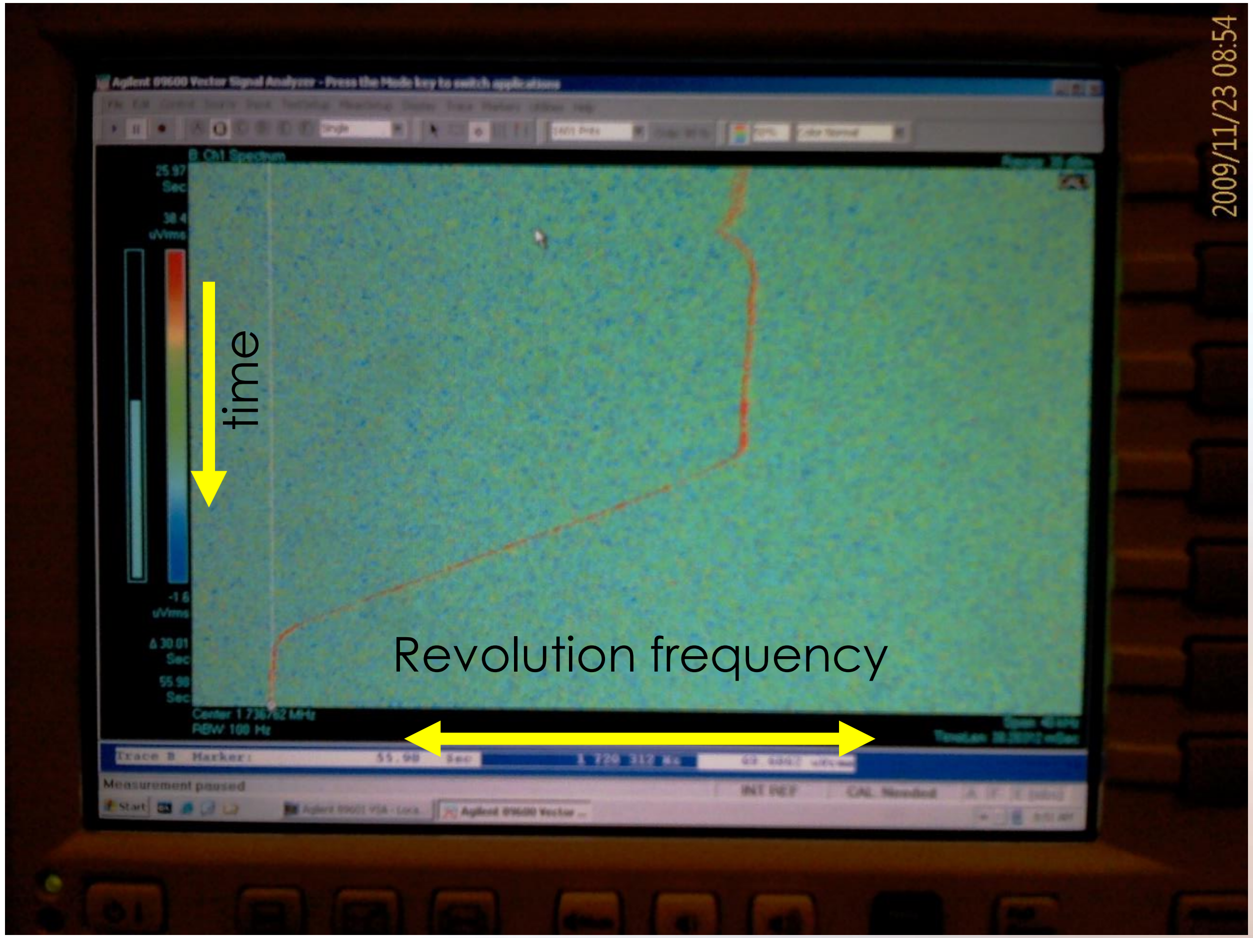
Channel 4
Sensitivity
Offset

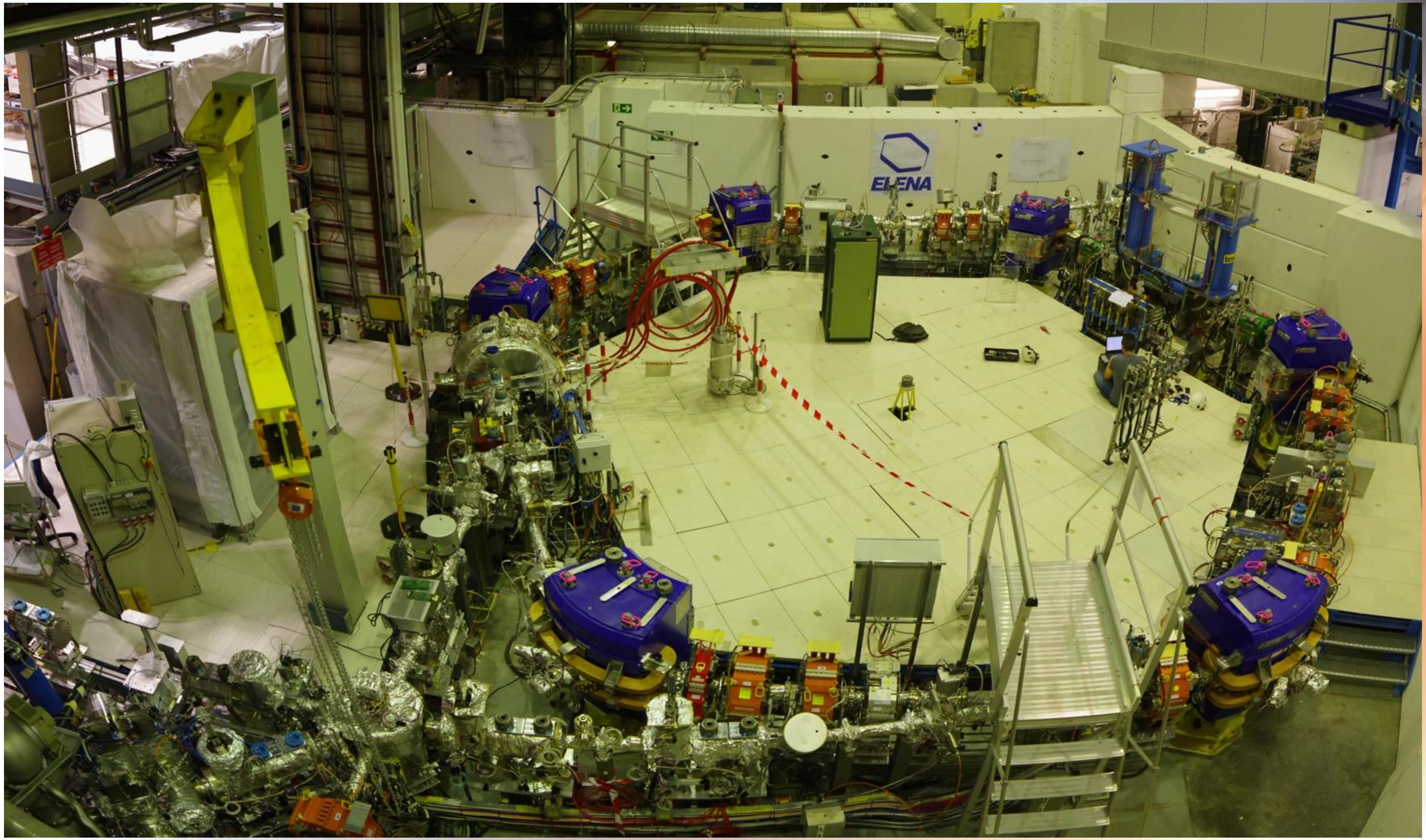
ECOOL deceleration

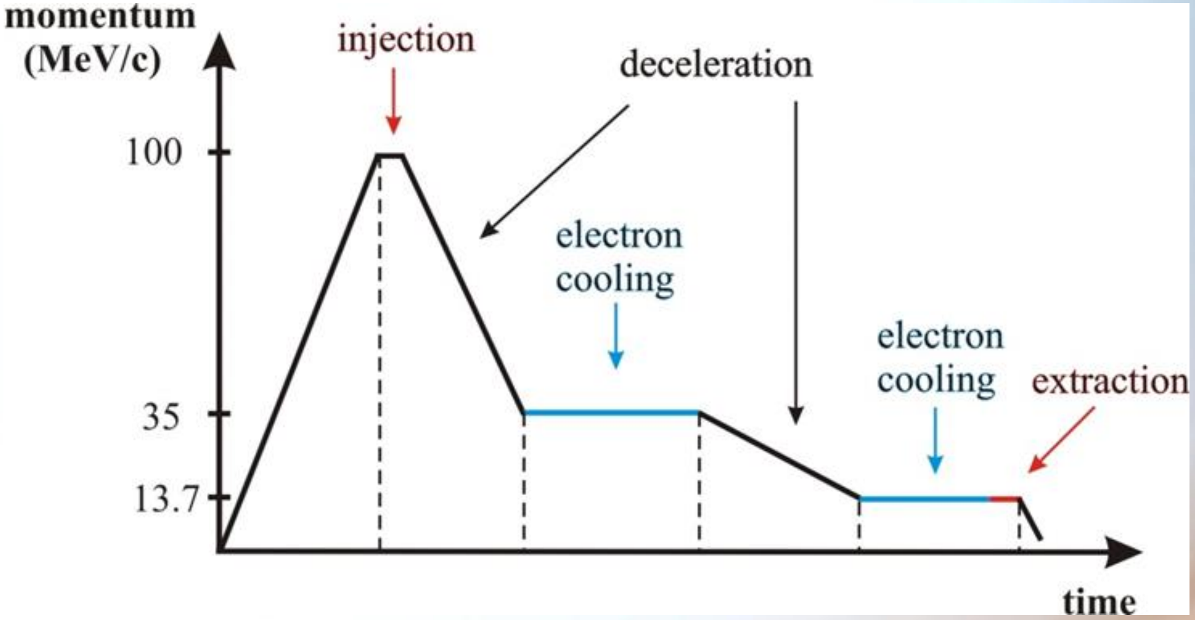


Beam successfully decelerated from 100 MeV/c (5.3 MeV) to 95.3 MeV/c (4.8 MeV).

-Electron cooler used to "drag " the antiproton beam to a lower energy.
- AD magnets ramped synchronously with electron beam energy.
- Small emittances and momentum spread are preserved during the deceleration .
- No need for an RF cavity.

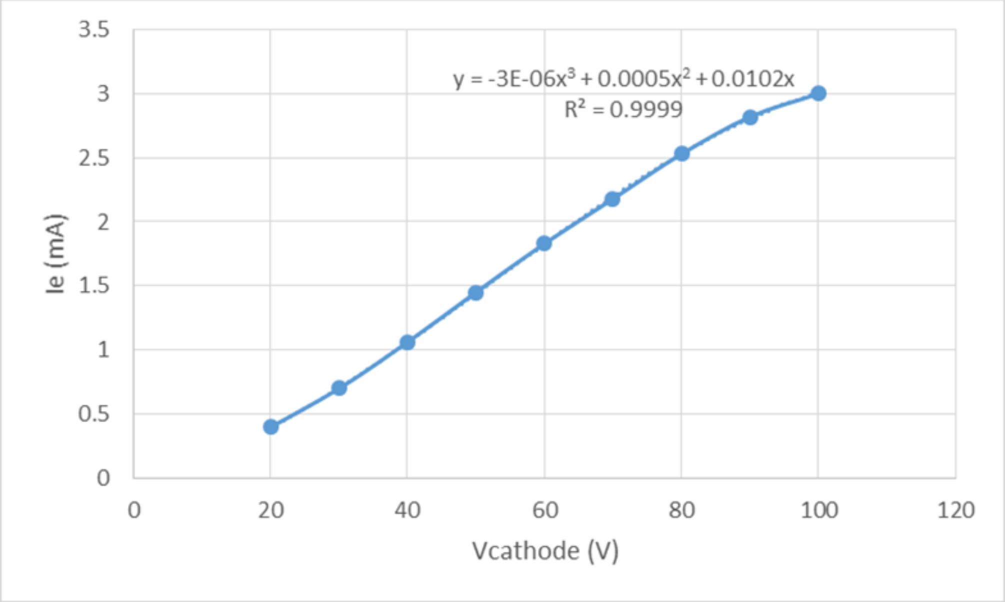
ELENA

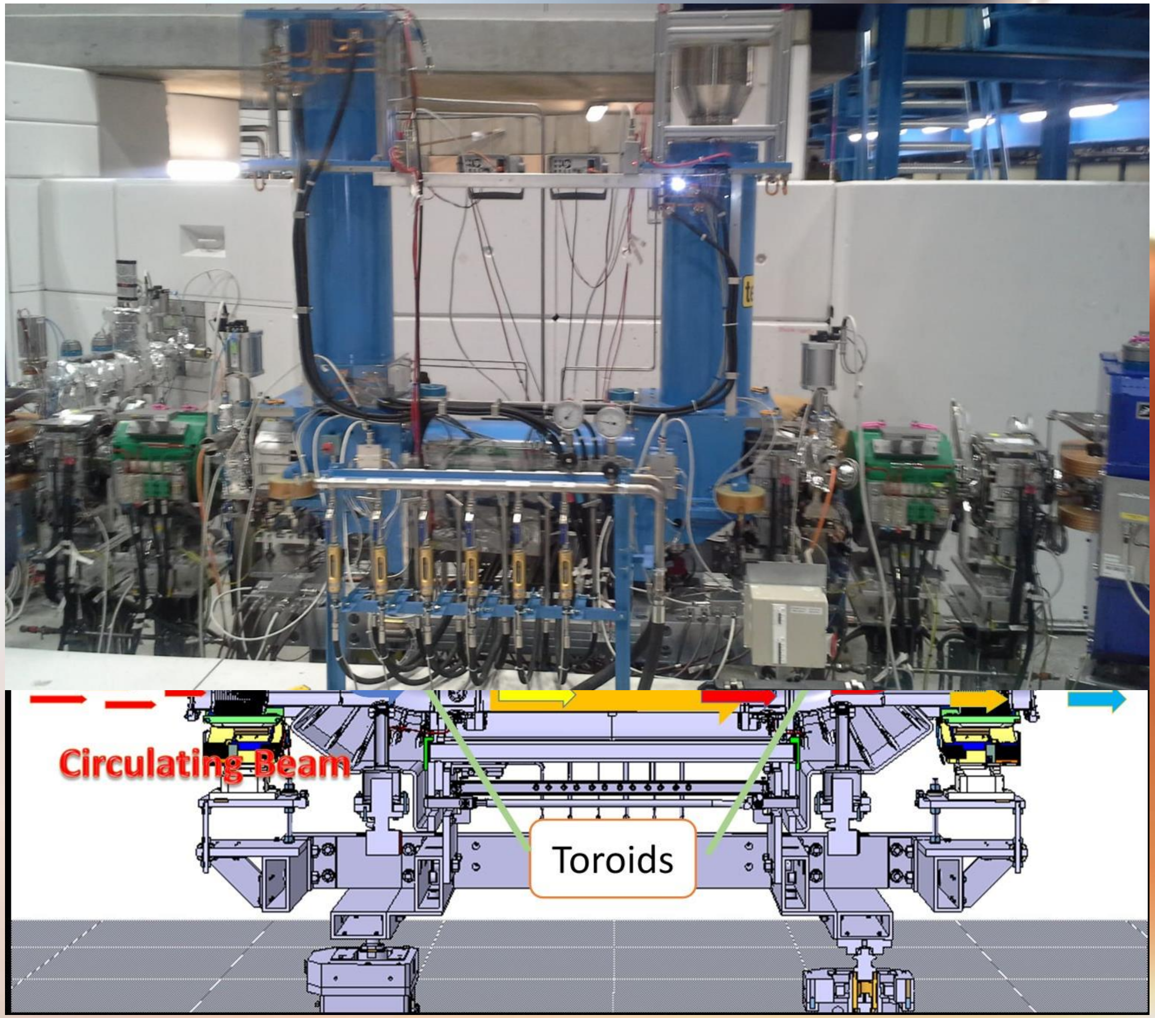




- Small post-decelerator employing electron cooling for efficient deceleration down to 100keV kinetic energy.
  - Injection of a bunched beam followed by deceleration
  - Beam cooling at intermediate momentum to counteract beam emittances and momentum spread blow up
  - Deceleration down to extraction energy, beam cooling, bunching at harmonic *h*=4, then compression to provide required bunch length and fast extraction
  - The final goal is delivering to experiments beam 1.3m long with 1σ~1mm

Momentum (MeV/c)	35	13.7
β	0.037	0.015
Electron beam energy (eV)	355	55
Electron current (mA)	5	1
B_{gun} (G)	1000	
B_{drift} (G)	100	
Expansion factor	10	
Cathode radius (mm)	8	
Electron beam radius (mm)	25	
Flange-to-flange length (mm)	2330	
Drift solenoid length (mm)	1000	

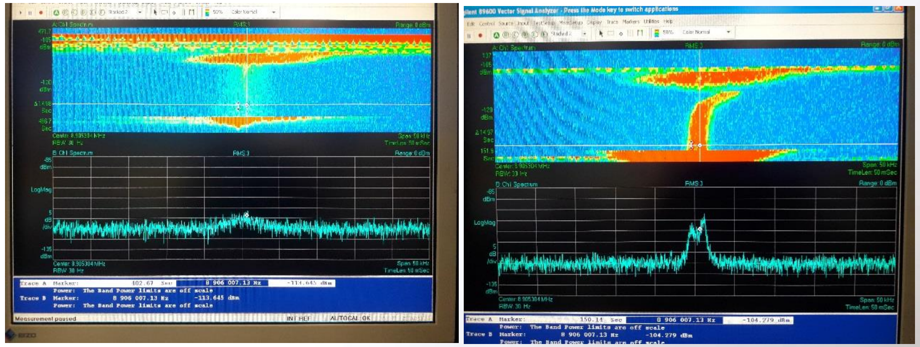




Cooling of antiprotons at 648 keV (35 MeV/c). Electron beam energy: 355 eV.

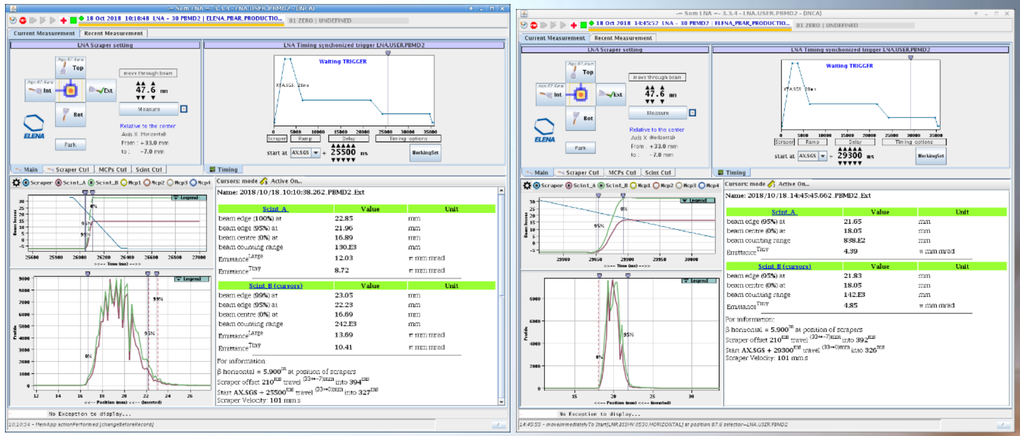
Horizontal emittance before (left) and after 4 seconds of electron cooling (right).

Vertical emittance before (left) and after 4 seconds of electron cooling (right).

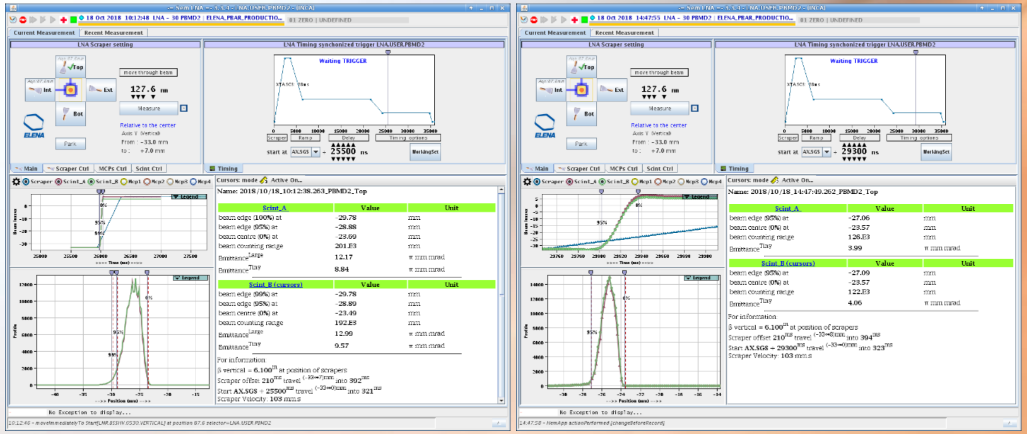


Longitudinal Schottky signal of uncooled (left) and cooled (right) beam.

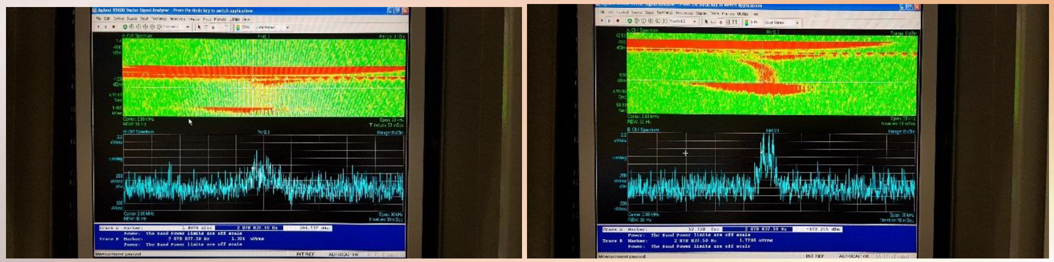
Cooling of antiprotons at 100 keV (13.75 MeV/c). Electron beam energy: 55 eV.



Horizontal emittance before (left) and after 2 seconds of electron cooling (right).



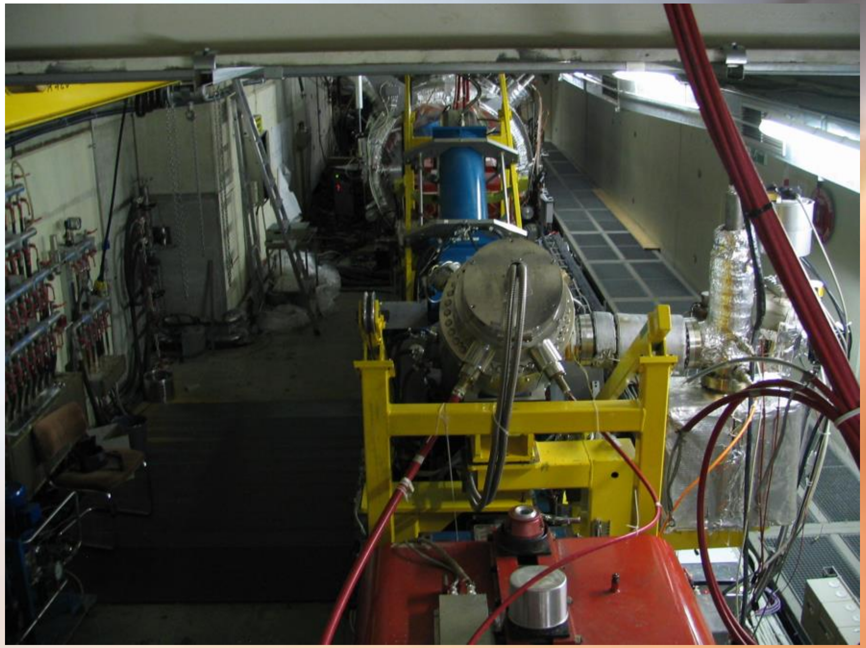
Vertical emittance before (left) and after 2 seconds of electron cooling (right).



Longitudinal Schottky signal of uncooled (left) and cooled (right) beam.

The Future? A new cooler for AD

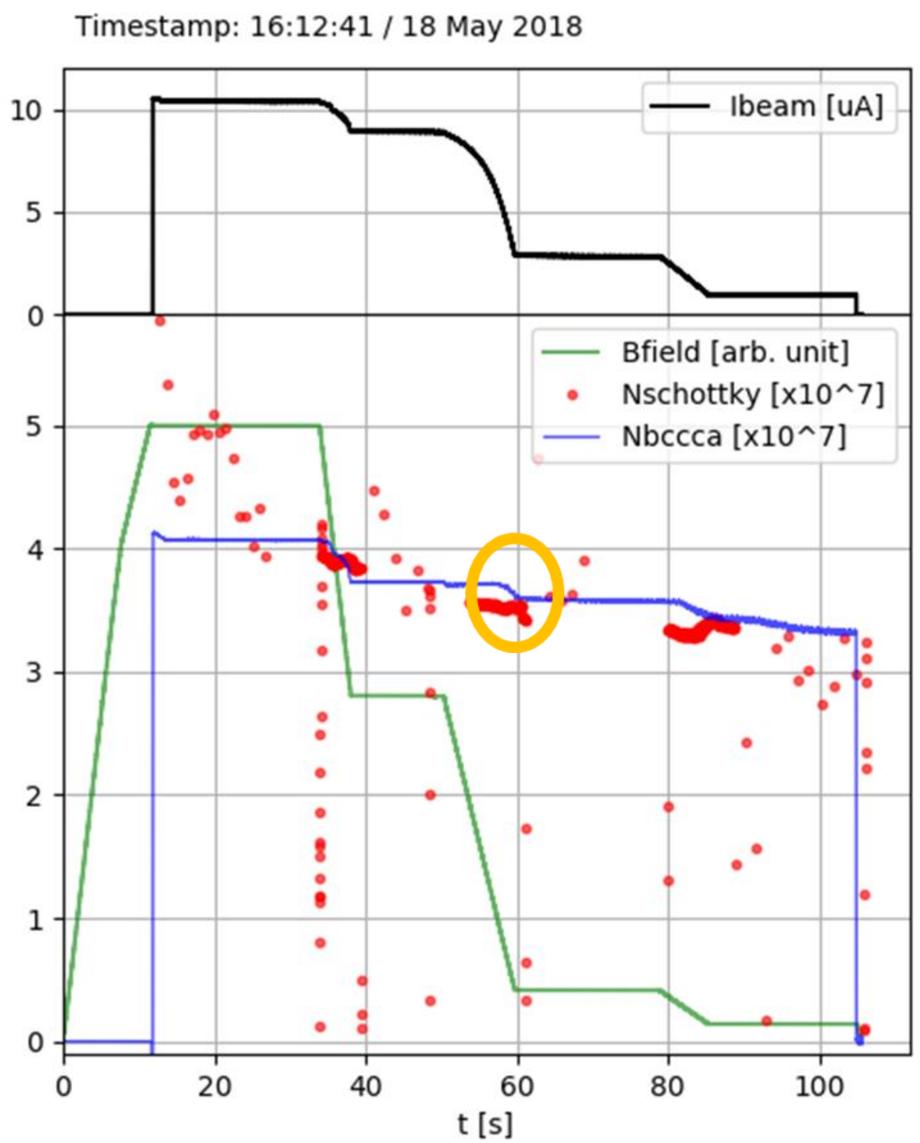
- Maximum energy: 80 keV
- Electron beam energy: 68.125 keV
- Antiproton beam momentum: 500 MeV/c
- Accelerating voltage: 68.808 kV
- Relativistic beta: 0.471
- Maximum electron current: 3.5 A
- Cathode radius: 1.25 cm
- Magnetic field in gun: 2400 G
- Magnetic field in drift: 600 G
- Expansion factor: 2
- Beam radius in drift: 2.5 cm
- N_e $7.9 \times 10^{13}\ m^{-3}$



Toroid bending angle:	90° (2 X 45°)
Toroid bending radius:	1 m
Drift solenoid length:	1.5 m
Transition solenoid length:	0.5 m (X4)
Cooler orientation:	horizontal (?)
Vacuum chamber diameter:	140 mm

What’s different?

- Cooling at a higher antiproton momentum (500 MeV/c)
- Horizontal orientation
- Electrostatic plates in each toroid.
- NEG coated vacuum chambers.
- Fast ramping of the expansion solenoid to adapt the electron beam size during cooling.
- New solenoid design using pancakes and iron bars for the return-flux.
- Compact orbit correctors (as used on ELENA).



x6.6 adiabatic blow-up between 2 GeV/c and 300 MeV/c

x3 blow-up between 300 MeV/c and 100 MeV/c

Most of the losses occur at arrival on the 300 MeV/c plateau

Less blow-up by cooling at a higher momentum and more efficient cooling without tails

Summary

Electron cooling has played a pivotal role in the success of the low energy physics program at CERN for nearly 40 years. The first electron cooler has seen two re-incarnations and is still used today to provide cold antiproton beams to the AD experiments. The heavy ion program for the LHC and the fixed target experiments would not be possible without the LEIR electron cooler which accumulates and cools a variety of ions and is central in the whole injection chain. The future looks bright for electron cooling at CERN with a new low energy cooler being commissioned on ELENA and a new cooler foreseen for the AD such that the original ICE cooler can finally retire after so many years of excellent performance