40 Years of Electron Cooling at CERN

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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
Why electron cooling at CERN?

• Improve the quality of low energy ion beams
  • Many experiments on LEAR and AD were/are not possible without electron cooling
  • Used to cool (anti)protons, $H^-$, oxygen, argon, xenon and lead ions

• Increase the duty cycle of the machine
  • At low energies electron cooling is faster than stochastic cooling

• LHC and North Area request a variety of ions
  • Injection scheme requires fast cooling and stacking
The ICE (Initial Cooling Experiment) Age

- 74.38 m proton storage ring
- 2.1 to 0.3 GeV/c
- Experimental ring to test the principle of beam cooling: stochastic & electron
- Operation close to transition
  - Pole face windings to change the tune
- 2 x 10^8 protons per pulse from PS
- Average vacuum pressure 2 x 10^{-9} Torr
- 5 cm 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
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

Profile observed on the horizontal IPM

Schottky noise, taken at the beginning and end of the cooling process
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 $5 \times 10^{-5}$ to $6 \times 10^{-3}$ were created. The proton acceleration was observed as a change of revolution frequency, with the longitudinal pickup...
King LEAR (Low Energy Antiproton Ring)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (energy) range</td>
<td>0.1 - 2 GeV/c (5.3 MeV – 1.3 GeV)</td>
</tr>
<tr>
<td>Circumference</td>
<td>78.54 m</td>
</tr>
<tr>
<td>Focussing structure</td>
<td>4 superperiods, separated function BoDFOFDoB</td>
</tr>
<tr>
<td>Betatron wave numbers</td>
<td>$Q_h = 2.3$, $Q_v = 2.7$</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$\gamma^{-2} = -0.048$</td>
</tr>
<tr>
<td>Maximum acceptances</td>
<td>$\epsilon_h = 240 , \pi , \text{mm mrad}$, $\epsilon_v = 48 , \pi , \text{mm mrad}$</td>
</tr>
<tr>
<td>RF system frequency range</td>
<td>0.4 – 3.5 MHz</td>
</tr>
<tr>
<td>Design pressure</td>
<td>$10^{-11} – 10^{-12}$ Torr</td>
</tr>
</tbody>
</table>
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 $10^{-10}$ 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
• Extensive studies with anti(protons), H⁺, oxygen and lead ions
  • First cooling/stacking of ions
  • Instabilities – development of a damper
  • Influence of lattice parameters on beam cooling
  • Electron beam neutralisation
  • Recombination of ions

• New electron collector for reliable operation with full perveance gun
• New electron gun allowing the online control of the electron beam intensity
• Electron beam energy feedback system

Adiabatic optics
Fixed magnetic field of 600 G (easier for operation)
5 cm Cathode
«steering» electrode to give the desired current
Anode (drift) at ground potential
Oxygen ion cooling and accumulation in LEAR

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

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

Using the circulating ion beam as a probe it was possible to measure the radial distribution of the electron beam potential. 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.
<table>
<thead>
<tr>
<th>Twiss parameters at injection septum</th>
<th>Machines used up to 1996 (Machine no.)</th>
<th>Machines used in 1997 (Machine no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>$\beta_H$ [m]</td>
<td>1.9</td>
<td>9.5</td>
</tr>
<tr>
<td>$\beta_V$ [m]</td>
<td>6.4</td>
<td>10.5</td>
</tr>
<tr>
<td>D [m]</td>
<td>3.6</td>
<td>0</td>
</tr>
<tr>
<td>Twiss parameters at electron cooler</td>
<td>$\beta_H$ [m]</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>$\beta_V$ [m]</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>D [m]</td>
<td>3.6</td>
</tr>
<tr>
<td>Twiss parameters maximal values</td>
<td>$\beta_H$ [m]</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>$\beta_V$ [m]</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>D [m]</td>
<td>3.6</td>
</tr>
<tr>
<td>Working point</td>
<td>$Q_H$</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>$Q_V$</td>
<td>2.62</td>
</tr>
<tr>
<td>Transition</td>
<td>$\gamma^2_{ir}$</td>
<td>-39</td>
</tr>
</tbody>
</table>
Cooling down time for Pb$^{54+}$ ions at 4.2 MeV/nucleon. The electron current was 350 mA and the cooling length 1.5 m.

Cooling down time for protons at 50 MeV. The electron current was 1.2A and the cooling length 1.5 m. The measured time is the time needed to cool about $2 \times 10^9$ from a horizontal emittance of $40\pi$ mm mrad down to $4\pi$ mm mrad.

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.
Low Energy Ion Ring

100 to 200 μA Pb^{7+}

ECR

4.2 MeV/u, β = 0.094 rep. rate up to 5 Hz

RFQ

LINAC3

Stripper Pb^{7+} to Pb^{54+}

592 bunches and ~10 min filling time per ring.
PS batch pattern = 3*(13, 13, 12)+1*(13, 13, 8)
7.10^7 b, 2.76 TeV/u, L = 1.10^7 cm^2 s^-1
3h Luminosity life, 2exp

~13 PS inj./SPS cycle
1 ej./1 mm at 177 GeV/u
4 pairs of bunchlets recombined to 4b.(100ns)

Stacking of 0.9 10^9 ions at 4.2 MeV/u, accel. to 72 MeV/u
2 bunches of 4.5 10^8 ions each every 3.6 s.

accel. to 5.9 GeV/u
Two bunch splitting
4 pairs of bunchlets / 3.6 s.

Stripper in TT2 Pb^{54+} to Pb^{52+}

LHC

SPS

PS

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

$E_e$ up to 6.5 keV
$I_e = 600 \ mA$
$k = 3, \ r = 14 \ to \ 25\ mm$
$B$ (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)
Grid voltage (controls the electron current)

Main magnetic field

N_{\text{charges from beam current transformer}}

Cooling

Start acceleration

1st injection

2nd injection

1.0 s

578.36 mV

EIX.AMC - TS

EX. INJ - TRAIN | EX. RF - TRAIN
0 | 0
400.0 ms/div | -1.004 s
600.0 mV | + slope L

ER.MTR12 - 2E10 - AS
200.0 mV/div | -771.93 mV

ER.GSECVGRID - AS
500.0 mV/div | -87.719 mV

ER.GSEH - AS
500.0 mV/div | -1.645 V

FREE

volt/div | offset

Beam profile evolution during a complete LINAC cycle measured on the injection profile monitor. Two LINAC pulses are accelerated to 4.1 MV in 80 ns, then the beam is braked and accelerated to 71 MeV for transfer to the next machine in the chain, the PSI. The measured emittance at extraction is typically 8.4 μm.

Longitudinal intensity spectrum evolution on the LINAC injection plate. The injected pulses are dragged and cooled at the stack momentum. The lower than the nominal momentum. After the second pulse, the electron beam is dragged and cooled to the required momentum before bunching and acceleration.
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
### Antiproton Decelerator

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>182 m</td>
</tr>
<tr>
<td>Production beam</td>
<td>$1.5 \times 10^{13}$ Pbars/cycle</td>
</tr>
<tr>
<td>Injected beam</td>
<td>$4 \times 10^7$ Protons/cycle</td>
</tr>
<tr>
<td>Beam momenta max-min</td>
<td>3.57-0.1 GeV/c</td>
</tr>
<tr>
<td>Momenta for beam cooling</td>
<td></td>
</tr>
<tr>
<td>- Stochastic</td>
<td>3.57 and 2.0 GeV/c</td>
</tr>
<tr>
<td>- Electron</td>
<td>0.3 and 0.1 GeV/c</td>
</tr>
<tr>
<td>Transverse emittances h/v</td>
<td>200 – 1 $\pi$<em>mm</em>mrad</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>$6 \times 10^{-2} – 1 \times 10^{-4}$ dp/p</td>
</tr>
<tr>
<td>Vacuum pressure, average</td>
<td>$4 \times 10^{-10}$ Torr</td>
</tr>
<tr>
<td>Cycle length</td>
<td>&lt;100 seconds</td>
</tr>
<tr>
<td>Deceleration efficiency</td>
<td>85 %</td>
</tr>
</tbody>
</table>
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 $1\sigma$~1mm
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (MeV/c)</td>
<td>35</td>
<td>13.7</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.037</td>
<td>0.015</td>
</tr>
<tr>
<td>Electron beam energy (eV)</td>
<td>355</td>
<td>55</td>
</tr>
<tr>
<td>Electron current (mA)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>$B_{\text{gun}}$ (G)</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>$B_{\text{drift}}$ (G)</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Expansion factor</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Cathode radius (mm)</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Electron beam radius (mm)</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Flange-to-flange length (mm)</td>
<td></td>
<td>2330</td>
</tr>
<tr>
<td>Drift solenoid length (mm)</td>
<td></td>
<td>1000</td>
</tr>
</tbody>
</table>

![Diagram](image_url)
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 reincarnations 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.