COSY experience of electron cooling

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Abstract
The 2 MeV electron cooling system for COSY-Julich has highest energy for the electron cooler with strong longitudinal magnetic field. During operation the cooling process was detailed investigated at different energies of electron beam. The proton beam was cooled at different regimes: RF, barrier bucket RF, cluster target and stochastic cooling. This report deals with the experience of electron cooling at high energy.
COSY Accelerator Facility

- 4 internal and 3 external experimental areas
- electron cooling at low momenta (LM)
- electron cooling at high momenta (HM)
- stochastic cooling at high momenta

**P** = 183.6 m, **E** = 2880 MeV

\[ \beta_x = 6.5 \text{ m}, \beta_y = 3.5 \text{ m} \] (High Voltage cooler)
3D design of high energy COSY cooler

Electrostatic Accelerator

Collector

Gun

electron beam

proton beam

Cooling section

Transport channel
## Design parameters of cooler COSY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>25 keV ... 2 MeV</td>
</tr>
<tr>
<td>Maximum Electron Current</td>
<td>1-3 A</td>
</tr>
<tr>
<td>Cathode Diameter</td>
<td>30 mm</td>
</tr>
<tr>
<td>Cooling section length</td>
<td>2.69 m</td>
</tr>
<tr>
<td>Toroid Radius</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Magnetic field in the cooling section</td>
<td>0.5 ... 2 kG</td>
</tr>
<tr>
<td>Vacuum at Cooler</td>
<td>$10^{-9} ... 10^{-10}$ mbar</td>
</tr>
<tr>
<td>Available Overall Length</td>
<td>6.39 m</td>
</tr>
</tbody>
</table>

## Electron cooling was investigated at following energies

<table>
<thead>
<tr>
<th>Proton energy, MeV</th>
<th>Electron energy, keV</th>
<th>Max. electron current, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>109</td>
<td>0.5</td>
</tr>
<tr>
<td>353</td>
<td>192</td>
<td>0.5</td>
</tr>
<tr>
<td>580</td>
<td>316</td>
<td>0.3</td>
</tr>
<tr>
<td>1670</td>
<td>908</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>2300</strong></td>
<td><strong>1250</strong></td>
<td><strong>0.5</strong></td>
</tr>
</tbody>
</table>
First cooling experiment - cooling at \( E_e = 109 \text{ keV} \)
Large intensity and low momentum spread may induce coherent instability

Increasing of proton intensity switch on the instability. It can be observed in the transverse plane and pickup spectrum both.

“First problem with coherent instability”
Next step - cooling at Ee=192 keV, electron current 300 mA

Transverse size versus time: 1 and 2 are horizontal and vertical width of proton beam, 3 is exponential estimation of cooling time, 4 is expansion of proton beam with diffusion coefficient $3 \cdot 10^{-2}$ mm$^2$/s.

Transverse cooling

Longitudinal momentum spread (r.m.s) versus time.

Longitudinal cooling

"First call" – transverse cooling may be worse than longitudinal one
Next step - cooling at 315.85 keV, electron current 300 mA

Spectrogram of the longitudinal distribution function versus time. Levels are intensity of Schottky signal

H/V, mm

hor, arb. unit

horizontal and vertical width versus time

horizontal profile before and after cooling
Larmour rotation can be essential for the cooling process

Jump of electron energy for estimation cooling rate

The electron energy is changed according schedule. 315.85 (0 s) → 316.15 (100 s) → 315.55 (300 s) → 315.85 (500 s).
The cycle duration is 600 sec.

\[ R_L = 0.2 \, \text{mm} \quad B_{cool} = 1275 \, \text{G} \quad E_e = 316 \, \text{keV} \quad \gamma = 1 + \frac{E_e}{mc^2} = 1.59 \]
\[ \rho = \frac{\gamma \beta m_e c^2}{e B_{cool}} = 1.7 \, \text{cm} \quad \rho_{\text{max}} = v_i \tau_{\text{flight}} = 0.7 - 2.7 \, \text{mm} \quad \frac{\delta p_{\perp}}{p_0} = \frac{R_L}{\rho} = 0.012 \]

Observation cyclotron rotation of the electron beam with BPM at changing of magnetic field (i.e phase shift of motion) in the cooling section.
Maximum experience - cooling at 909 keV, electron current up to 900 mA, many good experimental results was obtained

Fast longitudinal cooling

Longitudinal momentum spread (r.m.s) versus time

Exponential approximation

\[ \times 10^{-4} \sigma = \delta p_s / p \text{ (rms)} \]

\[ \tau_{cool} = 40 \text{ s} \]

Longitudinal distribution function for the different moments of cooling process

\[ \times 10^{-3} \sigma = \delta p_s / p \]

Base experiment parameters

\[ \text{Np} = 4 \times 10^8, \text{Ep} = 1.67 \text{ GeV}, \gamma_{tr} = 2.26 \]

\[ \text{Ee} = 909.05 \text{ keV}, \text{Je} = 520 \text{ mA}, \text{Uan} = 5.3 \text{ kV}, \text{Ugr} = 0.4 \text{ kV}, \text{Magnetic field in the cooling section} \ B_{cool} = 1380 \text{ G} \]
**Best transverse cooling at high energy**

- **H/V, mm**
  - τ = 100 s
  - hor
  - ver

- **Schottky signal from pick-up**
  - 100 kHz
  - $f_0 = 1.52$ GHz

- **Beam signal vs. time**
  - 3.6 $\times$ 10$^8$ protons, 1.66 GeV
  - $I_e = 0.8$ A
  - 1.3 kG
  - $E_e = 909$ keV

- **Traces**
  - 1. Noise + EC
  - 2. Noise only
  - 3. Reference
  - 4. EC
Electron cooling can well operate with usual RF
Cooling of bunched proton beam on COSY. Electron energy 908 keV. Electron current 0.5 A.

Measurements

Simulations with Parkhomchuk’s equation and space charge field

Cooling simulations for COSY
Fitting curves of the shape of the proton bunch for the start (left picture) and the end (right picture) of the cooling process.

RF on, e-cooling with 570 mA, \( N_p = 2 \cdot 10^9 \), \( E_e = 909 \) kV

\[
\sigma_s = 16 \text{ ns}
\]

1 is experimental profile, 2 is gauss shape, 3 is parabolic shape

The estimation of the length according equation gives the length 14 ns that is very close to the experimental data. So, the beam core attains equilibrium induced by the space charge force.

\[
\sigma_s^3 = \frac{eN_p \left( 2 \ln \left( \frac{b}{a} \right) + 1 \right)}{(2\pi)^{3/2} \gamma^2 U_{RF} \Pi^2}
\]

e-cool can help to obtain the space-charge limit
e-cool can well operate with usual RF and target

\[ E_e = 909 \text{ kV}, \quad N_p = 2 \cdot 10^9, \quad n_a = 2 \cdot 10^{14} \text{ cm}^{-2} \]
Next step - cooling at 1259 kV

Changing energy of electron beam to 100 V that corresponds to \( dp/p = 6 \cdot 10^{-5} \). The equilibrium momentum of proton beam is changed also that can be easily observed with Schottky spectrum analyzer.

Example of the longitudinal cooling at 1259 kV

\[
\times 10^{-4} \sigma = \delta p_s/p \text{ (rms)}
\]

\( \tau_{\text{cool}} \sim 90 \text{ s} \)

Evolution of the longitudinal distribution function during cooling process
e-cool can well operate with barrier bucket and target

Electron cooling with barrier bucket and target with density $E_e=1259.5$ kV, $n_a=2 \cdot 10^{14}$ cm$^{-2}$
Experiments with target without electron cooling

Target has a significant influence on the dynamic of the proton \( n_a = 2 \cdot 10^{14} \text{ cm}^{-2} \)

Spectrogram of Schottky noise at target action. The top picture shows ionization loss in cluster target corresponding to hydrogen density \( n_a = 2 \cdot 10^{14} \text{ cm}^{-2} \). The bottom picture shows the simultaneously action barrier bucket and target. All spectrum duration is about 550 s.
Electron energy 1259.65 kV, \( J_e = 500 \) mA

Experiments with e-target

Electron cooling suppressed the longitudinal action of the target with density \( n_a = 2 \cdot 10^{14} \text{ cm}^{-2} \) without help RF.

\[
\Delta \frac{p}{p} = 4.3 \cdot 10^{-4}
\]

Electron cooling practically suppressed longitudinal and transverse growth induced by target but the more precise tuning storage ring and e-cooler is necessary.
Next part of this report is more about puzzle and features that was observed during operation.

1. Dominance of the longitudinal friction force. The longitudinal cooling is more easy for realization
2. Essential influence of the Larmour oscillation of electron beam to transverse cooling rate at high energy but the longitudinal cooling rate was observed practically the same
3. Changing equilibrium momentum of proton beam at excitation of Larmour oscillation of electron beam
4. Influence of the angle between electron and proton beam on the transverse cooling rather than longitudinal cooling
5. Role of the collective phenomena at electron cooling of the proton beam to the small momentum spread of the proton beam
Milestones of the first cooling at new energy of the electron beam (1.25 MeV)

17:34

Weak shift to new energy $E_e = 1256$ keV

More strong shift to new energy $E_e = 1256.6$ keV

18:47

First cooling at new energy $E_e = 1259.5$ keV

19:07

Good cooling at new energy $E_e = 1259.55$ keV

After $\sim 1.5$ hours the longitudinal cooling process was obtained at new energy 1259.5 keV (after series experiments at 909 keV energy). The situation with transverse cooling isn’t such optimistic.
Transverse e-cooling at 1259 kV energy

The transverse cooling process was observed after spending much time and efforts.

Maximum attention was given to looking for a working point of storage ring where the electron cooling had maximum effectiveness.

Changing transverse size during cooling experiments. Curve 1 is reference cycle without cooling, curve 2 is cooling at energy 1259 kV, curve 3 is growth of the transverse size at changing working point despite of electron cooling action. Tune was shift at $\Delta Q_x/\Delta Q_y \approx 0.02/-0.01$ (estimation).
Essential influence of the Larmour oscillation to transverse cooling rate but the longitudinal cooling rate was observed the same momentum spread versus time

horizontal cooling decrement

\[ \times 10^{-4} \sigma_{\text{rms}} \]

\[ \times 10^{-3} \text{mm/s}, \delta_{\text{cool}} \]

Main parameters of experiment
Electron energy is \( E_e = 907.7 \text{ keV} \)
Proton energy is \( E_p = 1.67 \text{ GeV} \)
Anode and grid voltages are \( U_{\text{an}} = 3.27 \), \( U_{\text{gr}} = 0.83 \text{ kV} \), Electron current is \( J_e = 600 \text{ mA} \), Magnetic field in the electron gun is \( 230 \text{ G} \), acceleration column is \( 400 \text{ G} \), collector is \( 500 \text{ G} \). Longitudinal magnetic field in the cooling section is \( 1300 \text{ G} \), in the toroid section is \( 1200 \text{ G} \), bend magnet is \( 860 \text{ G} \). Slip-factor of the proton beam is \( \eta = -0.035 \).
The number of proton is \( N_p = 1.6 - 1.8 \times 10^9 \).

Amplitude of the Larmour oscillation was changed with help of corrector coils with short longitudinal length – \( \text{edipver} \_1 \).

1 A of corrector current may excite Larmour oscillation with radius 0.35 mm.
Another example of influence of Larmour oscillation to transverse cooling rate. It is possible to eliminate transverse cooling but the longitudinal decreases not so much.

\[ \delta_{\text{cool}} = \frac{1}{\tau_{\text{cool}}} \times 10^{-3} \text{ mm/s} \]

heating \[ \delta_{\text{cool}} > 0 \]

cooling \[ \delta_{\text{cool}} < 0 \]

If the Larmour rotation is strong enough it can kill the transverse cooling. The longitudinal cooling time is increased but it present.

Parameters of the experiments:
- \( E_e = 907.7 \text{ kV} \)
- \( J_e = 595 \text{ mA} \)
- \( U_{an} = 3.27 \)
- \( U_{gr} = 0.83 \text{ kV} \)

longitudinal momentum spread versus time for different value of current in electron dipole corrector ediphor1

- \( \sigma = \frac{\delta p}{p} \) (rms)
It is interesting that the correlation between changing of the dipole corrector and equilibrium momentum of the proton beam. Figure shows the distribution function of the protons in time 500 s for the different value of ediphor1 corrector.

Increase the transverse momentum (Larmour oscillation) leads to decrease the longitudinal momentum

$E_e = 909 \cdot 10^3 \text{ keV} \quad B_{\text{cool}} = 1380 \text{ G} \quad R_L = 0.35 \text{ mm}$

$\gamma = 1 + \frac{E_e}{mc^2} = 2.78 \quad \rho = \frac{\gamma \beta m_e c^2}{eB_{\text{cool}}} = 3.2 \text{ cm}$

$\delta \sigma = \frac{\delta p_{y}}{p_0} = \frac{1}{2} \left( \frac{R_L}{\rho} \right)^2 = 6 \cdot 10^{-5} \quad \frac{\delta p_{e_{\perp}}}{p_0} = \frac{R_L}{\rho} = 0.011$

The quality behavior is good. The quantitative difference can be explained that the transverse motion already has nonzero amplitude of Larmour oscillation.

Demonstration of excitation of Larmour oscillation of electron induced by edip corrector.
Essential influence of the incline of the magnetic force line to transverse cooling rate with compare to longitudinal rate

\[ \times 10^{-3} \text{ mm/s, } \delta_{\text{cool}} \text{ horizontal cooling decrement} \]

\[ \times 10^{-4} \sigma = \frac{\delta p_s}{p}, \text{ (rms)} \]

-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
0.1 0.2 0.3 0.4
0.1 0.2 0.3 0.4

horizontal cooling decrement

longitudinal momentum spread versus time

\[ \tau_{\text{cool}} \approx 60 \text{ s} \]

Changing angle between electron and proton beam with cooler corrector. This corrector induces the transverse magnetic field along whole cooling section. It leads to incline the magnetic force line and electron beam in the cooling section.

\[ J_{\text{cooler}} = 0.1 A \rightarrow \delta \theta \approx 4 \times 10^{-5} \]
\[ \delta \theta \cdot L_{\text{cool}} \approx 0.1 \text{ mm} \]
\[ L_{\text{cool}} = 2700 \text{ mm} \]
\[ B_{\text{cool}} = 1380 \text{ G} \]

Parameters of the experiments \( E_e = 907.7 \text{ kV, } J_e = 595 \text{ mA, } U_{an} = 3.27, U_{gr} = 0.83 \text{ kV} \)

So, fine tuning needs for transverse cooling but not for longitudinal cooling.
Role of the value of electron current

Longitudinal electron cooling. The electron current is changed at fixed ratio $U_{grid}/U_{an}$

$$N_p=4.7 \times 10^8, J_e=600 \text{ mA}, U_{gr}=0.83 \text{ kV},$$
$$U_{an}=3.27 \text{ kV}, E_e=907.9 \text{ kV}$$

The fixed ratio $U_{grid}/U_{an}$ allows to suppose that the regime of the electron gun isn’t changed.

Drift of equilibrium energy is induced by space charge of electron beam.

*The longitudinal cooling rate isn’t strongly depend from the electron current value.*

Example of the fitting of the core of the proton beam. The main part of particle has a small momentum spread.

RMS momentum spread versus time. The growth of the momentum spread is induced by the tail in the distribution function.

Experimental data, $t=960 \text{ s}, J_e=600 \text{ mA}$

Gauss fit $\sigma_{fit}=1.8 \times 10^{-5}$
Role of the value of electron current

Transverse electron cooling. The electron current is changed at fixed ratio $U_{\text{grid}}/U_{\text{anode}}$.

<table>
<thead>
<tr>
<th>Electron Current</th>
<th>$U_{\text{grid}}$ (kV)</th>
<th>$U_{\text{anode}}$ (kV)</th>
<th>$U_{\text{grid}}/U_{\text{anode}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>460 mA</td>
<td>0.7</td>
<td>2.72</td>
<td>0.257</td>
</tr>
<tr>
<td>600 mA</td>
<td>0.83</td>
<td>3.27</td>
<td>0.254</td>
</tr>
<tr>
<td>670 mA</td>
<td>0.9</td>
<td>3.54</td>
<td>0.254</td>
</tr>
<tr>
<td>759 mA</td>
<td>0.98</td>
<td>3.86</td>
<td>0.254</td>
</tr>
</tbody>
</table>

One can see that the transverse cooling suffers from electron current decreasing especially for $J_e=460$ mA.

The transverse cooling more depend from the electron current value.
Collective effects (fact or myth)?

The most experiments show long tails in the longitudinal distribution function. This tails slowly move during all time of experiment. What is the reason?

A possible criterion of collective effect is integral of Schottky signal along whole spectrum range. At presence of the collective effect this integral is larger in comparison with the situation when all particle is independent (no collective fluctuation) and the integral of power of Schottky signal is proportional to the particle number.

\[ \text{intJ} = \int J(f) df, \text{arb. units} \]

\[ N_p = 2.3 \times 10^9 \]

\[ N_p \approx 2.1 \times 10^9 \]

\[ N_p = 2.0 \times 10^9 \]

\[ N_p = 5 \times 10^8 \]

\[ J_e = 600 \text{ mA}, U_{gr} = 0.83 \text{ kV}, U_{an} = 3.27 \text{ kV}, E_e = 907.9 \text{ kV} \]
The changing of integral of Schottky signal at electron cooling is more clear at precooling with transverse stochastic cooling.

\[ \int J(f) df, \text{arb. unit} \]

\[ \times 10^{-4}, \sigma_{\text{rms}}, \quad \sigma = \frac{\delta p_s}{p} \]

Switch off stochastic cooling
Switch on electron cooling
Switch off stochastic cooling
Switch on electron cooling
Switch off stochastic cooling
Switch on electron cooling
Switch off stochastic cooling
Switch on electron cooling
Switch off stochastic cooling
Switch on electron cooling
Switch off stochastic cooling
Switch on electron cooling

\[ \int J(f) df – \text{integral of power of Schottky signal along whole frequency range. If the particle motion is independent the integral is constant. The collective mode of particle oscillation changes this result.} \]

\[ \sigma = \frac{\delta p_s}{p} \]

Preliminary stochastic cooling increase particle density so the collective effect may be more visualized.

We may observe the normal situation. Decreasing momentum spread leads to decreasing Landau damping. Let pay more attention to impedance problems.
Stochastic precooling strongly improve the ultimate parameters of proton beam

After stochastic precooling procedure the size of the proton beam may be cooled down to minimal value. Also the longitudinal momentum spread may be decreased to very low value. The electron cooling can be operated with transverse stochastic cooling together simultaneously.
Longitudinal stochastic and electron cooling

The joint action electron and longitudinal stochastic cooling doesn’t change the distribution function (180 and 300 s profiles). The r.m.s. spread after 550 s depends from tail and doesn’t show the cooling of bulk protons.

$H/V$ mm, $\sigma \times 10^{-4}$

$\sigma = \delta p_s / p$

$F(\sigma)$

$N_p = 3.3 \times 10^8$

$E_e = 907.9$ kV,

$J_e = 600$ mA

The electron cooling isn’t very effective in joint with longitudinal stochastic cooling. But the cooling power of electron cooling is strongly.

The main part of proton can be cooled to momentum spread $\sigma = 1.4 \times 10^{-5}$
Stochastic, electron cooling, barrier bucket RF and dense target

\[ N_p = 1 \cdot 10^9, \quad J_e = 600\, \text{mA}, \quad E_e = 908.085\, \text{kV}, \quad n_a = 2.0 \cdot 10^{15}\, \text{cm}^{-2} \]

Screenshot of oscilloscope. The barrier bucket RF signal is magenta, signal from Schottky pick (longitudinal beam shape) up is blue. The time after start of the experiment is about 420-450 s.

**So, the electron cooling helps to keep the longitudinal shape of the proton beam at action of dense target**
Unfortunately the single action of the electron cooling at high density target is not enough with point of view of transverse cooling.

One can see that the electron cooling isn’t enough for strong transverse cooling. It leads to decreasing of the longitudinal cooling rate. The start of growth of momentum spread is postponed to 100 s because the it need time for energy lost of particle in order to escape from RF well.

\[ \text{Horizontal, vertical sizes and momentum spread of the proton versus time} \]

\[ \text{Time schedule} \]
000 s – start of barrier bucket RF, p-p 1100 V
030 s – turn on electron cooling with current 600 mA,
100 s – turn on target

Np=1.7 \cdot 10^9, Je=600 mA, na=2.0 \cdot 10^{15} \text{ cm}^{-2}

\text{Only electron cooling}

\text{BUT the longitudinal cooling is strong despite of the growth of transverse size from 2.7/2.3 to 6.8/4 mm.}
Summary

1. COSY experience of use of electron cooling shows that it is enough powerful method in the different region energies
2. The electron cooling may work well together with, target, RF, barrier bucket RF and stochastic cooling
3. The physics of electron cooling may contain an open question and the puzzle with 50 years history may have unopened area.
4. Understanding of physics behavior of the transverse cooling may improve transverse electron cooling to compare today situation.
5. The simple optimization of transverse cooling optimization can be connected with increase of the beta function in the iteration point.