Development and Commissioning of 2 MeV DC Cooler

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Abstract
The 2 MeV electron cooling system for COSY-Julich started operation in 2013 years. The cooling process was observed in the wide range energy of the electron beam from 100 keV to 908 keV. Vertical, horizontal and longitudinal cooling was tested at bunched and continuous beams. The cooler was operated with electron current up to 0.9 A.
COSY Accelerator Facility

- 4 internal and 3 external experimental areas
- electron cooling at low momenta
- electron cooling at high momenta
- stochastic cooling at high momenta

P=183.6 m, E=2880 MeV
3D design of high energy COSY cooler

Electrostatic Accelerator

gun

collector

Cooling section

Transport channel

electron beam

proton beam
Each section contains:
- high-voltage power supply +/- 30 kV;
- power supply of the coils of the magnetic field (2.5 A, 500 G);
- section of the cascade transformer for powering of all electronic components;
- control electronics;
- 33 high-voltage section
2MeV electron cooler – integration into COSY
Start of the assembling

Commissioning in COSY
Cooling section is transported to the permanent residence

Commissioning in COSY
Commissioning in COSY

Transportation channel is close to finish state
Start assembling of the accelerator
Accelerator column is finished

Commissioning in COSY
Now in operation in COSY FZJ

\[ \text{Np} = 1.5 \cdot 10^8, \text{Ee} = 909.5 - 910 - 909.5 \text{ kV}, \]
\[ \text{Je} = 400 \text{ mA} \]
\[ \lambda = \frac{\delta p}{\delta t} = 3 - 7 \cdot 10^{-6} \text{ s}^{-1} \]

Collector current is up to 900 mA at voltage 0.900 MeV and leakage current less 1 mkA

Now using 0.9 A e-current is positive for cooling process
Main feature of cooler COSY

1. Classical design with longitudinal magnetic field;
   - very wide range of the operation, the preferable smallest energy is 25 keV, it is injection energy;

2. Section-module principle of the design of the electrostatic accelerator;
   - each section contains the high-voltage module and coils of the magnetic field;

3. Possibility for on-line control of the quality of the magnetic field
   - in order to have high cooling rate;

4. Cascade transformer for power supply of the magnetic coils;
   - smooth longitudinal magnetic field along accelerated tube demands power to many coils;

5. Electron Collector
   - with Wien Filter
   - in order to have small leakage current from the collector

6. “Magnetized” electron motion

7. “4-sectors” electron gun for diagnostics of the electron beam motion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2 MeV Electron Cooler</th>
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</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.025 ... 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>
First cooling experiment - cooling at 109 kV

Longitudinal cooling

Transverse cooling

Before cooling

Cooling
\[ \frac{\Delta p}{p} = 5.5 \times 10^{-3} \]

Cooling process is fast enough. The initial proton momentum spread was widened using white noise beam excitation to \( \frac{\Delta p}{p} = \pm 2 \times 10^{-3} \), and it was cooled down during 100 s.

**Example of the longitudinal cooling**

\[ N_p = 7 \times 10^8, \quad J_e = 400 \text{ mA}, \quad \eta = -0.066, \quad E_e = 909 \text{ kV}, \quad \gamma = 2.77, \quad \gamma_{tr} = 2.25, \quad \gamma > \gamma_{tr} \]

Np=7\cdot10^8, Je=400 mA, \( \eta=-0.066 \), \( E_e=909 \text{ kV} \), \( \gamma=2.77 \), \( \gamma_{tr}=2.25 \), \( \gamma>\gamma_{tr} \)

**Example of the transverse cooling**

\[ N_p = 3 \times 10^8, \quad J_e = 800 \text{ mA}, \]

Np=3\cdot10^8, Je=800 mA,
Transverse e-cooling

3.6 \times 10^8 \text{ protons}
1.66 \text{ GeV}

I_e = 0.8 \text{ A}
1.3 \text{ kG}

1. Noise + EC
2. Noise only
3. Reference
4. EC

\varepsilon_x = 1.1 \rightarrow 0.1
\varepsilon_y = 1.3 \rightarrow 0.2
\text{mm} \cdot \text{mrad},
\text{normalized beam core within 200s}

IPM screenshot
Electron Cooling of a proton beam and turning off EC

Longitudinal electron cooling process. e-beam turned off leading to fast $\Delta p/p$ growth. $5 \cdot 10^8$ protons, 1.66 GeV, electron current 0.8 A
e-cool can well operate with barrier bucket RF

$N_p = 3 \times 10^8$, $J_e = 550\ mA$, $\gamma > \gamma_{tr}$ $\eta = -0.066$

longitudinal cooling at barrier bucket RF voltage

$f_{BB} = 1.523918\ MHz$, $U_{RF} = 240\ V$

Barrier bucket signal and Phase probe signal of $p$-beam
RF of 1\textsuperscript{st} harmonic and Phase probe signal of p-beam

One can see that the combine action of the RF and e-cool produces very short beam with high quality. The off-duty factor of the proton beam is 650 ns/30 ns=20. So, the bunched e-cool of the bunched ion may have the gain of the electron current 20 without increasing average current.

The use of bunched e-beam may be some reserve for improvement of DC e-cool. The use of the e-bunch at the same time proton bunch with larger current can increase cooling rate in 20 times! Certainly the special pulse e-gun and the collector for higher current should be constructed.

RF on, e-cooling with 550 mA, final $\Delta p/p = 10^{-4}$
Stochastic cooling + ecool

COSY, $E_e = 908$ kV, $J_e = 400$ mA, $N_p = 7 \cdot 10^8$

Linear scale

\[ \gamma > \gamma_{tr} \eta = -0.066 \]

Stochastic cooling only
Combine action of stochastic and electron cooling

**Only stochastic**

- Electron energy: 908 keV
- Proton energy: 1.66 Gev
- Stochastic cooling: vertical and horizontal
- E-cool time: 120 s
- Stochastic cooling time: 400 s
- Beta function x/y: 4m/3m

**Stochastic+e-cooling**

initial no longitudinal cool, after e-cooling
Summary

- The key problems of the electron cooler 2 MeV (modular approach of the accelerator column, the cascade transformer, the compass base probe located in the vacuum chamber, the design of the electron gun with 4-sectors control electrode) are experimentally verified during commissioning in Novosibirsk and COSY.
- The fine tune of the electron beam with diagnostics and correction schemes allowed for faster cooling $\Delta p/p = 10^{-5}$ in less than 100 s
  $\varepsilon_x = 1.1 \rightarrow 0.1$, $\varepsilon_y = 1.3 \rightarrow 0.2$ mm·mrad, within 200s (beam core)
- Electron cooling may work well together with stochastic cooling, RF and barrier bucket RF.
- It is desirable more experimental time in COSY hardware for expand our understanding of cooling processes and receiving highest possible parameters of e-cool.