New Developments in High Energy Electron Cooling

Jürgen Dietrich

TU Dortmund & HI Mainz
Outline

• Introduction

• Special Features of High Energy Electron Cooling

• Engineering Problems of High Energy Electron Coolers

• Electron Cooler - Status and Projects

• New Ideas and Further Developments- Turbines

• Beam Diagnostics

• Outlook

Jürgen Dietrich
RuPAC St.Petersburg
September 2012
Introduction

Benefits of Beam Cooling

**Improved beam quality**
- Precision experiments
- Luminosity increase

**Compensation of heating**
- Experiments with internal target
- Colliding beams

**Intensity increase by accumulation**
- Polarised beams
- Secondary beams (antiprotons, rare isotopes)
Principle: Immersing the ion beam in a very cold (in the moving frame $R_0$) electron beam over a given length.

If we suppose, at first, that the electron beam has no velocity and therefore no energy in $R_0$, due to Coulomb interaction the ions will undergo „collisions“ with electrons (binary collision model). As a result the ions will give up some of their energy to the electrons which will therefore be heated.

As a consequence the electrons must be renewed in order to obtain a very cold (in each plane) ion beam.

$$\langle P_i \rangle = \frac{\beta}{\beta_0} c = v_{0e}$$
High Energy Electron Cooling

Proton Energy Versus Electron Energy for Cooling $v_i = v_e$

$$\beta = \frac{v}{c} = \beta_e = \beta_i$$

$$\beta = \sqrt{1 - \left(1 + \frac{T_{kin}}{E_0}\right)^{-2}}$$

$$T_{kin} = \frac{E_{0i}}{E_{0e}} \cdot T_{kin_e}$$

State of the art
- COSY 180 MeV p
- 550 MeV p

Proton Energy [MeV]

100 keV e⁻ 300 keV e⁻

Electron Energy [MeV]

100 MeV e⁻ 300 MeV e⁻

High Energy Electron Cooling
- COSY (final energy 2.9 GeV)
  - 3.7 GeV p
  - 2.1 MeV e⁻
- FNAL 8 GeV p
  - 8 MeV e⁻ 4.3 MeV e⁻
- HESR 15 GeV p

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Technical Challenge:

**High Voltage** ($E_e > 0.5$ MeV, $I_e < 3$ A, confinement in a magnetic field)

**Magnetic field quality, straightness** in cooling section $< 10^{-5}$

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**Special Features of High Energy Electron Cooling**

Decreasing of “corrugation, waviness” of force line of the magnetic field is essential for obtaining maximum of friction force

$$\Delta \rho = \frac{\rho}{\tau} = -\frac{4e^4 n_e \nu}{m_e (\sqrt{V^2 + V_{\text{eff}}^2})^3} \ln \left(1 + \frac{\rho_{\text{max}}}{\rho_L + \rho_{\text{min}}} \right)$$

$$V_{\text{eff}}^2 = V_{\Delta \Theta}^2 + V_{E \times B}^2 + V_e^2$$

$$V_{\Delta \Theta} = \gamma \beta c \sqrt{\langle \Delta B^2 \rangle} \langle \Delta B^2 \rangle$$

“Waviness” of magnetic force line

Essential for experiment with internal target

<table>
<thead>
<tr>
<th>$E, \text{keV}$</th>
<th>$\gamma E \beta_E / \gamma_{30} \beta_{30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>100</td>
</tr>
<tr>
<td>8.0</td>
<td>1000</td>
</tr>
<tr>
<td>13.8</td>
<td>2000</td>
</tr>
</tbody>
</table>

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Cooling Time for Large Relative Velocities

\[ \tau_z \propto \frac{A}{Z^2 n_e \eta} \beta^3 \gamma^5 \Theta^3_z \]

\[ \Theta_{x,y} = \frac{v_{x,y}}{\gamma \beta c} \]

\[ \Theta_{||} = \frac{v_{||}}{\gamma \beta c} \]

- increases with energy \( \propto \gamma^2 \) (\( \beta \gamma \Theta \) is conserved)
- for hot beams \( \propto \Theta^3 \)
- linear dependence on electron beam intensity \( n_e \) and cooler length \( \eta = \frac{L_{ec}}{L_{ring}} \)
- short for highly charged ions \( A/Z^2 \)
- independent of hadron beam intensity
- independent of ion velocities and only dependent on electron temperature for cold beams

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The 4.3 MeV electron cooler at the RECYCLER ring (FNAL) achieves cooling time of about 1 h.

The new coolers for COSY and HESR should provide a few orders of magnitude more powerful longitudinal and transverse cooling that requires new technical solutions.

The basic idea of the new COSY cooler and for the future HESR cooler is to use high magnetic field along the orbit of the electron beam from the electron gun to the electron collector.
Engineering Problems of High Energy Electron Coolers

High voltage generators (> 0.5 MV)
High voltage performance
Limiting performance of accelerator tubes

Power transmission to accelerator “head”

Power transmission to magnetic coils (at accel/decel tubes)
Electron current and HV stability (1-3 A, 10^{-5})
Electron beam formation, transportation and recovering
Magnetic field measurement in the cooling section (straightness < 10^{-5})
Electron beam diagnostics
High Voltage Generators

Cockroft-Walton accelerator – up to 1 MV (practically)

“Electron- Beam Ventil” (ELV, BINP Novosibirsk) - a sophisticated version of insulating core transformer ≤ 2 MV (COSY 2MV)

Dynamitron ~ 4 MV max

Van de Graaff accelerators

Pelletron (Fermilab 4.3 MV )

“Record holder” of DC accelerators: Vivitron (Univ. Louis Pasteur, Strasbourg)

→ 35 MV project, 25 MV operation

N. Kuksanov
High Voltage ELV Accelerators for Industrial Application
This conference, FRXCH03
Power Transmission to Magnetic Coils (at accel/decel tubes)

Rotating shafts (Fermilab, Pelletron)

Cascade transformer (present solution 2 MeV COSY)

New: Gas turbine (idea of BINP)

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Electron Cooler - Status and Projects

- **In operation** state of the art
  
  25 - 350 kV at CERN, GSI, IMP Lanzhou, FZJ …

- **In operation** (September 2005 – September 2011)
  
  4.3 MV at FNAL (DC, non-magnetized)
  
  Longitudinal cooling time > 1h

- **In commissioning**
  
  2 MV for COSY (DC, magnetized)

- **Projects**
  
  2.5 MV for NICA collider (DC, magnetized)
  
  4-8 MV (?) for HESR, ENC (DC, magnetized)
4.3 MV at FNAL, Fermilab (non-magnetized, fixed energy)
2005-2011 in operation at TEVATRON

- Goal of cooling in the Recycler
  - Increase longitudinal (and transverse) phase space density of the antiproton beam in preparation for
    - Additional transfers from the Accumulator
    - Extraction to the Tevatron

- Main features
  - Electrostatic accelerator (Pelletron) working in the energy recovery mode
  - DC electron beam
  - Lumped focusing outside the cooling section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>MeV</td>
</tr>
<tr>
<td>Beam current used for cooling</td>
<td>A</td>
</tr>
<tr>
<td>Magnetic field in CS</td>
<td>G</td>
</tr>
<tr>
<td>Beam radius in the cooling section</td>
<td>mm</td>
</tr>
<tr>
<td>Pressure</td>
<td>nTorr</td>
</tr>
<tr>
<td>Length of the cooling section</td>
<td>m</td>
</tr>
</tbody>
</table>

COSY Juelich
2 MeV Electron Cooler COSY –Jülich in commissioning at BINP

Ions: (pol. & unpol.) p and d
Momentum: 300 to 3650 MeV/c for p
540 to 3650 MeV/c for d

Targets:
- Internal: solid, cluster, pellet, atomic beam
- External: solid, liquid

Beam cooling:
- Electron cooling at injection for
  beam accumulation
  high brilliance beams
- Stochastic cooling above 1.5 GeV/c for luminosity preservation

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2 MeV Electron Cooler COSY – Jülich
Technical Design – Layout BINP, Basic Parameters and Requirements

- Energy Range: 0.025 ... 2 MeV
- High Voltage Stability: < 10^-4
- Electron Current: 0.1 ... 3 A
- Electron Beam Diameter: 10 ... 30 mm
- Cooling section length: 2.694 m
- Toroid Radius: 1.00 m
- Variable magnetic field
- (cooling section solenoid): 0.5 ... 2 kG
- Vacuum at Cooler: 10^-9 ... 10^-10 mbar

- Available Overall Length: 6.390 m
- Maximum Height: 5.7 m
- COSY beam Axis above Ground: 1.8 m

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3D Design of the Accelerating Column

Modulare high voltage sections

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;

33 high-voltage section
High Frequency Cascaded Resonant Transformer

20 kHz, 40 kW, for individual power supplies of solenoid coils in the accel/ decel column and high voltage generation

High Voltage Section
amorphous ferrite foil core, cylinder filled with transformer oil for isolation, high voltage, input-output ceramic feedthrough for connection of HV sections

Transformer Column

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Cascade Generator Test Bench
Commissioning of the 2 MeV Electron Cooler at BINP, Novosibirsk.
COSY Cooler Location with Shielding Elements
**Results and Next Steps**

<table>
<thead>
<tr>
<th>Energy keV</th>
<th>Current A</th>
<th>Losses mA</th>
<th>Rad Sv/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.9</td>
<td>0.0015</td>
<td>0</td>
</tr>
<tr>
<td>150</td>
<td>0.6</td>
<td>0.0075</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>0.5</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>1250</td>
<td>0.35</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>1500</td>
<td>0.2</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

This conference:
HIGH VOLTAGE ELECTRON COOLER *
M. Bryzgunov, A. Bubley, A. Goncharov, V. Panasyuk, V. Parkhomchuk, V. Reva D. Skorobogatov (BINP SB RAS, Novosibirsk) Russia
J. Dietrich, V. Kamerdzhiev (FZJ, Jülich) Germany

Long time run at 1MV and 200 mA are demonstrated

The commissioning at BINP will be finished in autumn 2012

Shipping to Juelich in November 2012

Installing in COSY in January/ February 2013
High Energy Storage Ring HESR

- HESR
- Circumference 574 m
- Momentum (energy) range 1.5 to 15 GeV/c (0.8-14.1 GeV)
- Injection of (anti-) protons (from RESR) at 3.8 GeV/c
- Acceleration rate 0.1 (GeV/c)/s
- Electron cooling up to 8.9 GeV/c (4.5 MeV electron cooler)
- Stochastic cooling above 3.8 GeV/c

4 – 8 (?) MeV Electron Cooler for HESR, FAIR Darmstadt
Add e⁻-beam@HESR
3 GeV, 2A pol. Electron beam
15 GeV, 0.4 A pol. Proton beam
$s^{1/2}=14$ GeV (center of mass energy)

Ion ring and Detector funded and under construction within the FAIR complex:

Extensions & solutions needed:

Protons:
- Polarized proton source
- tune jump Quads in SIS18
- direct SIS-18/HESR beamline
- cooler solenoid+helical dipoles as SNAKE
- electron cooling at maximum energy

Electrons:
- polarized electron source
- full energy injector (synchrotron or pulsed linac)
- electron storage ring (in HESR tunnel?)
- spin lifetime under synchrotron radiation
- increased complexity: e+/e− beam dynamics together with spin stabilization.

Both:
IR + beam separation + polarization

Luminosity: $2-6 \cdot 10^{32}$ [cm$^2$ s$^{-1}$]
Parameters for the HESR cooler:

<table>
<thead>
<tr>
<th>e-beam parameters:</th>
<th>HESR</th>
<th>Fermilab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>0.45 - 4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Current (Amp)</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Solenoid field (T)</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Straightness (µrad rms)</td>
<td>10</td>
<td>200</td>
</tr>
</tbody>
</table>

The cooling force needs to be stronger than at Fermilab to counteract the internal target:

- **Higher magnetic field**
- **Better straightness**
A cyclotron for accelerating a beam of 1 mA H⁻ ions up to 8 MeV can be built from the commercial equipment purchased for the commercial cyclotrons.

Figure 1. High voltage cooler for HESR.  
1—transformation section; 2—electrostatic correctors, 3—energy analyzer of H⁻ beam for the precise voltage measurement, 4—point of convergence, 5—HESR triplets

V.V. Parkhomchuk et al., COOL’11, Alushta 2011

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September 2012
Electron cooling system at electron energy up to 2.5 MeV, one electron beam per each ring of the collider.
2.5 MV Electron cooler for NICA collider

Fig.1. General view of the electron cooler. 1, 3 – tanks with electron gun and acceleration tube and deceleration tube + collector for electron beam of opposite direction. 2 – tank with HV generator. 4 – beam transportation solenoids. 5 – electron cooling section.

<table>
<thead>
<tr>
<th>Table 1. Cooler parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy, MeV</td>
</tr>
<tr>
<td>Electron beam current, A</td>
</tr>
<tr>
<td>Beam diameter, cm</td>
</tr>
<tr>
<td>solenoid magnetic field, T</td>
</tr>
<tr>
<td>HV PS current, mA</td>
</tr>
<tr>
<td>Collector PS, kW</td>
</tr>
<tr>
<td>HV PS stability, ΔU/U</td>
</tr>
<tr>
<td>SF₆ gas pressure, at</td>
</tr>
</tbody>
</table>

Proceedings of COOL'11, Alushta, Ukraine

ELECTRON COOLER FOR NICA COLLIDER
At the working frequency of 20 kHz the total number of diodes (type 2Ц106Г by Russian standard) is equal to 2500, the total number of capacitors (type C2-29B-2 by Russian standard) is equal to 8316. The HV of $U = 2.0$ MV is controlled with three-phase autotransformer (AT) of the voltage of 380 V at 50 Hz.

High voltage (HV) generator is based on the principle of the **cascade scheme**. The chosen scheme has three diode columns and twelve multiplying levels.
New Ideas and Further Developments - Turbines

Gas Driven Turbine for individual power supplies of solenoid coils in the acceleration/ deceleration column and high voltage generation

Modular concept

High Voltage Section

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Gas Turbine and Generator Coils  Ø 300 mm, 600 W, 100 Hz

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Gas Driven Turbine
Layout of the Turbine Test Bench in BINP

Voltage between sections, SF₆ (1.6 atm), 60 kV

Relative stability of the high voltage
Hybrid System - Combination of Powerful Turbines (5 kW) and Cascade Transformers (Helmholtz Institut Mainz)

HESR ELECTRON COOLER
Design study
The Svedberg Laboratory
Uppsala University
Uppsala, 2009

Solenoids attached to the separations boxes (110 mm height)

Field free region (> 200 mm)

135 mm \( \Delta U = 750 \text{kV} \)

5 kW, DEPRAG, Amberg

Turbo Generator
Cascade Transformer Column
Separation Boxes
HV-Solenoid

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September 2012
Beam Diagnostics

Ionisation Profile Monitor IPM

C. Böhme, J. Dietrich, V. Kamerdzhiev, P. Forck, T. Giacomini, D. Liakin

Beam Test of the FAIR IPM Prototype in COSY
Scintillation Profile Monitor SPM

Light from the ion beam (1) is focused with a lens (2) on a multichannel PM (3).

Horizontal beam profile with $1.5 \times 10^{10}$ protons, 2.6 GeV/c. Temporary pressure bump at the SPM location amounted to $4 \times 10^{-8}$ mbar.
Scintillation Profile Monitor SPM

- $\varepsilon = 8 \, \mu\text{mrad}$
- $\varepsilon = 4 \, \mu\text{mrad}$
- beam current BCT
- N$_2$ pressure bump
- e-cooling
- $1\sigma$ beam width

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Proposed Electron Beam Profile Measurement in the Cooling Section with Thomson Scattering

T. Weilbach, HIM, Mainz

Schematic Measurement Setup

OPTICAL ELECTRON BEAM DIAGNOSTICS FOR RELATIVISTIC ELECTRON COOLING DEVICES
T. Weilbach, Helmholtz-Institut Mainz, Germany,
K. Aulenbacher, KPH Mainz, Germany
J. Dietrich, FZJ, Germany

Proceedings of COOL'11, Alushta, Ukraine
Diagnostics of the Electron Beam Shape, BINP Novosibirsk

Electron Gun

Profile of the electron beam at different voltages on the control electrode (calculated)

Profile of the electron beam at different voltages on the control electrode (calculated)

This conference:
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Gun control electrode is assembled of 4 separate sections. It allows measurements of the beam envelope along the transport section.
Outlook

• Installing the 2 MeV electron cooler in COSY next year- learning lessons …

• Further developments of powerful turbines- hybrid solutions for 4-8 MV electron coolers

• Improvements of beam diagnostics- alignment and overlap of electron and hadron beam in the cooling section

• Advance into higher energy range should be accomplished by development of novel ideas
O. Belikov,
Bypass Modules for Solenoid Shunting of 2 MeV Electron Cooler for COSY
WEPPC023

V. Chekavinskiy,
High Voltage Terminal in COSY Electron Cooler
WEPPC028

D. Skorobogatov
The Power Supply System for Accelerating Column of COSY 2 MeV Electron Cooler
WEPPC032

N. Alinovskiy
Oil Cooling System of the High Voltage Electron Cooler for COSY
WEPPC033

E. Bekhtenev
Beam Position Monitor System for 2 MeV Electron Cooler for COSY
WEPPD028
Thank you for your attention!

Thanks to my colleagues

V.V. Parkhomchuk, BINP Novosibirsk
I.N. Meshkov, JINR Dubna
S. Nagaitsev, Fermilab, Batavia
L. Conradie, iThemba LABS, Cape Town
K. Aulenbacher, Universität Mainz
V. Kamerdzhiiev, FZ Jülich