Highlights of the COOL05 Conference

K.Beard, TJNAF

with support from

Muons, Inc.
some distance west of FNAL
at a big golf course resort, 9/18-23/2005

http://conferences.fnal.gov/cool05/Presentations/
Topics

• overview
• stochastic cooling
• muon cooling
• electrostatic rings
• low energy electron cooling
• high energy electron cooling
• laser cooling
Overviews
M01 general introduction
It's tough to make predictions, especially about the future. - Yogi Berra

P. Oddone, FNAL
Neutrino Program (delayed ILC)

Strategic context: U.S. contribution

Domestic accelerator program with new and redirected investment

- = leading
X  = secondary

Neutrino Frontier | Flavor frontier | Energy Frontier

2015

X

2010

X X

2005

X X

P. Oddone, FNAL cont.
M02 Einstein

A. Sessler, LBNL

“The state has become a modern idol whose suggestive power few men are able to escape.”

“If we knew what we were doing it would not be called research, would it?”
M03 Why cool?

W.Oelert, FZI
antihydrogen

W. Oelert, FZI, cont.

Status of CPT invariance in leptonic and hadronic systems

\[
\frac{R_e[\ell]}{R_e[H]} = \frac{m[e^+]}{m[e^-]} \left(\frac{q[p]}{q[p]}\right)^2 \left(\frac{q[p]}{q[p]}\right)^2 \left(1 + \frac{m[e^+]}{M[p]}\right) \\
\]

Standard model of physics

G – fairly well understood

G – experimentally not known, not studied

earth

anti-earth

earth

apple

anti-apple

anti-apple
Overview of recent trends in beam cooling methods and technology

Igor Meshkov and Dieter Möhl
(JINR, Dubna) (CERN, Geneva)

Menu
1. Introduction: What's new since COOL'03?
2. Cooling by electrons
3. Stochastic cooling
4. Stability of electron cooled beams
5. Theory and numerical simulations
6. Muon cooling
7. Beam Ordering
Conclusion

1. Introduction: What's new since COOL'03?

Demonstration of the first electron cooling at intermediate energy:
8 GeV antiprotons in the FERMILAB recycler! CONGRATULATIONS!

Commissioning of three state-of-the-art low energy electron coolers
(LANZHOU & LEIR) built in Budker INP.

Commissioning of LEPTA at JINR (Dubna) ⇒ under way to e-cooling
of positrons and e-cooling with circulating electron beam.

Construction of a special “dispersionless” ring for laser cooling/beam
ordering started (Kyoto University).

International effort and great progress in the conception.

Approval of Muon Ionisation Cooling Experiment (MICE) at Rutherford
Appleton Lab.

Start of elaboration of International FAIR project at GSI, where
cooling methods will play a key role.

New proposals for compact machines for medical applications (MRI).

The hot news in brief

Bad news: Shutdowns of CELSIUS and CRYRING.

Good news: CRYRING will be used as a cooler storage ring in FLAIR - subproject of FAIR.
F06 RFQ cooler/buncher for TRImP   L. Willmann KVI
# M05 Future Directions
## D. Sutter, DOE (retired)

### Where Next? – What are the Real Physics Needs?

<table>
<thead>
<tr>
<th>Facility</th>
<th>Status</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC @ 0.5 to 1 TeV</td>
<td>R&amp;D – GDE In place.</td>
<td>Location! Politics!</td>
</tr>
<tr>
<td>Super B-Beams @ Fermi</td>
<td>R&amp;D – Hope!</td>
<td>Funding, Timing &amp; the ILC</td>
</tr>
<tr>
<td>CLIC @ 2 to 4 TeV HEP</td>
<td>R&amp;D – A Prayer</td>
<td>The ILC, Energy needs a</td>
</tr>
<tr>
<td>Japanese Super B-Beams</td>
<td>Unclear</td>
<td>H.C in Japan?</td>
</tr>
</tbody>
</table>

**Proposed but Not Approved**

### Facilities Available for HEP Research

- **Fermilab Tevatron**
  - Shut down in 2008 – 2010?

- **Fermilab Neutrino Beam**
  - Upgrades? In - - - ?

- **SLAC B-factory**
  - Shut down in 2008

- **SLAC 50 GeV linac**
  - Off in 2006. LCLS { 10 GeV }, SABER @ 30 GeV > 2008?

- **KEK B-factory**
  - Upgrade to Super B?

- **RHIC**
  - Shut down or continue? { NSAC Study! }

- **LHC**
  - First operation in 2007 – 2008

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**Thomas Jefferson National Accelerator Facility**

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Advanced R&D – To give Access to New Research Ability

The Principal Thrusts:

- Plasma Accelerators – Particle and laser driven
- Very high gradient structures – for warm and cold radio frequency systems
- Beam Cooling – beyond stochastic and radiation means
- Space charge dominated Beams – There is life after $\mathcal{L}$
- Super conducting Magnets – The future is Al5 & other compounds [Nb$_3$Sn, MgB$_2$]
- Accelerator Theory – Advanced simulation & the merging of particle & plasma physics

The above areas of R&D are by no means the only ones supported by the DOE and NSF. They are the principal ones addressing new approaches to facilities.
muon cooling
Review of Muon Cooling R. Palmer BNL

Why a Muon Collider

- Muons are point-like, similar to electrons
- Can probe the same physics, and some more
- But have 40,000 less radiation
- So Muon Colliders can be much smaller than Linear Colliders
Ionization Cooling

- Absorbers: \( \frac{dE}{dx} \) for \( E \) and \( \frac{dE}{dx} \) for \( \frac{dE}{dx} \).
- RF cavities between absorbers replace \( E \).
- Net effect: reduction in \( p_y \), i.e., transverse cooling.

Note: The physics is not in doubt, but in principle, ionization cooling has to work! ... but in practice, it is subtle and complicated.

Avatars of MICE

- Measurement precision relies crucially on precise calibration & thorough study of systematics:
  
  **STEP I: 2007**
  - Characterize beam

  **STEP II**
  - Calibrate Spect. 1

  **STEP III**
  - Intercalibrate Spect. 2 w.r.t. Spect. 1; demonstrate 0.1% emittance measurement

  **STEP IV: 2008?**
  - Study 1st abs./focus-cell pair, check \( dE/dx \) and scattering

  **STEP V**
  - Cooling study w/1/2 lattice cell

  **STEP VI:** Cooling study w/full lattice cell & 2009? realistic field flip
Mucool Hydrogen Absorber R&D, M.Cummings NIU

Mucool Test Area

- The MTA is becoming our focus of Mucool activity
  - LH$_2$ Absorber tests
  - RF testing (805 and 201 MHz)
  - Finish cryo infrastructure
  - High pressure H$_2$ gas absorbers
  - High intensity beam design

MuCool: cooling channel R & D

- MuCool: MC subset based at FNAL and charged with the development of muon ionization cooling channels
  - Goal: Cooling cell test in high-powered beam (MTA)
- SFOFO Cooling Lattice – transverse cooling for ν factories

MTA High Intensity Beam

Beamline designed and costed by C. Johnstone for the MTA.
Part of the Linac Instrumentation Test Program

MTA new magnets F. Mills

stable beam

BEAM IN 2006

Linac beam

M. A. C. Cummings, Cool 05
September 20, 2005

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Application 3: Forced-flow LH₂ absorber Process and Instrumentation Proposal

Total heat load estimation

<table>
<thead>
<tr>
<th>Heat load (W)</th>
<th>80 K</th>
<th>17 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Supports</td>
<td>87</td>
<td>6</td>
</tr>
<tr>
<td>Superinsulation</td>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Cryostat windows</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>LH₂ pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>66.5</td>
<td>73.2</td>
</tr>
</tbody>
</table>

vs. 500 W for total refrigeration system

Safety issue:
25 liters of LH₂ released into the air and ignited with only a 10% yield; the energy equivalent to 4 kg of TNT.
T10. 6D cooling of a circulating muon beam
A. Garren UCLA

1.8T Dipoles and 200 MHz Closed Orbits for 4 Cell Demonstration Ring

Fix the closed orbits for a 1.8T dipole ring such that the total path length is a harmonic of 200 MHz.

Then:
- Harmonic 2
  - Circumference = 1.76 m
  - $P_0 = 77$ MeV/c
- Harmonic 3
  - Circumference = 3.76 m
  - $P_0 = 165$ MeV/c
- Harmonic 4
  - Circumference = 5.45 m
  - $P_0 = 240$ MeV/c

4 Sector Ring, 1.8 T Dipoles

- Harmonic 3
- 40 Atmosphere H₂
- Total Merit without decay is 20

UCLA
Al. Garren
inverse cyclotron - Y. Yorin ITT

**Single Turn Energy Loss Injection**

- Four Magnet (1.8T) Sector Cyclotron.
  Soft edged fields, ICOOL simulation.
  Multiple scattering and straggling on.
  Radial LiH wedges surrounded by hydrogen.
  Matter decreases adiabatically with radius.
  3 identical 172 MeV/c muons are injected.

- ±5 cm vertical motion along the 70 m spiral

- Injection scaling relation: \( \Delta p = 0.3 B \Delta r \).

**Emittance Reduction Goals**

- A muon collider needs \( 10^6 \) cooling.

- \( \varepsilon = (\Delta p_x \Delta x)(\Delta p_y \Delta y)(\Delta p_z \Delta z) \)

- \( \Delta p_x: 30 \text{ MeV/c} \rightarrow 0.3 \text{ MeV/c} \)

- \( \Delta p_y: 30 \text{ MeV/c} \rightarrow 0.3 \text{ MeV/c} \)

- \( \Delta p_z: 30 \text{ MeV/c} \rightarrow 0.3 \text{ MeV/c} \)

- \( \Delta x: 70 \text{ mm} \rightarrow 50 \text{ mm} \)

- \( \Delta y: 70 \text{ mm} \rightarrow 50 \text{ mm} \)

- \( \Delta z: 10000 \text{ mm} \rightarrow 50 \text{ mm} \)

- In: \( 10 \times \) transverse cooler, physics/0411123.

- Out: “Frictional \( \mu \) cooling,”
T09 Innovations in Muon Beam Cooling
R.Johnson, Muons Inc.

Muon Colliders: Back to the Livingston Plot

Eight New Ideas for Bright Beams for High Luminosity Muon Colliders supported by SBIR/STTR grants
- H$_2$-Pressurized RF Cavities
- Continuous Absorber for Emittance Exchange
- Helical Cooling Channel
- Z-dependent HCC
- MANX 6d Cooling Demo
- Parametric-resonance Ionization Cooling
- Reverse Emittance Exchange
- RF capture, phase rotation, cooling in HP RF Cavities

Neutrinos from an 8 GeV SC Linac
Muon cooling to reduce costs of a neutrino factory based on a storage ring
Cooling must be 60 to fit in 1.3 GHz SC RF, where the lost 6.8 GeV of 8 GeV are \( \sim 1 \). New concept: Run Linac CW, increase rep rate from 10 to 100 or more, for more 3.
Muon Trajectories in 3-m MANX

The design of the coils and crystals are the next steps for MANX, as seen in the next slides on the technology of the HCC.

Idea #2: Continuous Energy Absorber for Emittance Exchange and 6d Cooling

Idea #8: Simultaneous RF Capture, Bunch Rotation and Cooling in HP RF Cavities

- Proton bunches have $\sigma = 1$ns such that produced pion bunches do too.
- Placing RF cavities close to the production target allows 1/4 synchrotron period rotation to get longer pion bunches with smaller momentum spread.
- Subject of new STTR grant to use HP RF (see Dave Neuffer & Kevin Paul)

Yuriy Derbenev et al., Ionization Cooling Using a Parametric Resonance, PAC06
Kevin Beard et al., Simulations of Parametric-resonance IC..., PAC06

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T14: Muon Cooling R&D  Y.Torun, IIT

- Precursor to breakdown
- Electrons tunnel through work function of metal
- Current rises very steeply with field (hard to make measurements)

\[ j_{\text{FN}}(E) = \frac{A}{\phi} \left( \frac{\beta E}{3} \right)^{2/3} \exp \left( \frac{-B \phi^{1/3}}{\beta E} \right) \]

\[ n = \frac{E}{j} \frac{dE}{j} \propto 2 + \frac{0.74 \text{G} \text{V/m}}{\beta E} \]
Simulations of A Helical Muon Beam Cooling Channel
Katsuna Yonehara, Dan Kaplan (Illinois Institute of Technology, Chicago, Illinois, USA), Kevin B. Beard, S. Alex Bogacz, Yaroslav Derbenev (Jefferson Lab, Newport News, Virginia, USA), Roland F. Johnson, Kevin Paul, Thomas J. Roberts (Muons, Inc, Batavia, Illinois, USA)

Abstract
A helical tunneling channel (HTC) has been proposed for a muon treatment channel. The cross-sections of the HTC are shown in Figure 1. The HTC is designed to be the second helical tunneling channel in the Muon Cooling Experiment (MCE). The HTC has a duality with the MCE, in that it contains a large number of turns, similar to the MCE. The HTC has two main components: the helical tunneling channel and the helical magnet. The helical tunneling channel is designed to provide a negative beam momentum at the desired momentum. The helical magnet is designed to provide a negative beam momentum at the desired momentum. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 1: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 2: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 3: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 4: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

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Figure 6: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 7: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 8: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 9: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 10: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

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Figure 14: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 15: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

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Figure 18: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 19: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 20: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 21: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 22: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.

Figure 23: Schematic of the HTC, beam injection at the left and beam extraction at the right. The HTC is designed to be the second helical tunneling channel in the MCE.
T11: Parametric Resonance Ionization Cooling and Reverse Emittance exchange, Ya.Derbenev, TJNAF

Basic principles of PIC
- Assume initially the tune spread for a beam in a focusing channel to be smaller than the cooling decrement
- Weak lenses installed every half oscillation period drive a half-integer parametric resonance that creates a hyperbolic beam evolution at the absorber plates:

\[
\begin{pmatrix}
  x \\
  x'
\end{pmatrix}_{n+1} = \begin{pmatrix}
  k^{-1} & 0 \\
  k & k x'
\end{pmatrix} \begin{pmatrix}
  x \\
  x'
\end{pmatrix}_n ; \quad k = \exp(\Lambda_x \lambda / 2) \\
0 < \Lambda_x \lambda << 1
\]

Achromatic channel for PIC
- Compensation for chromaticity requires relatively large orbit dispersion – which is a constraint to PIC because of increase of energy straggling impact on transverse emittance
- A resolution of this constraint is: design a dispersion function that follows the beam envelope at PR

Scheme: Achromatic wiggler

- Field index \( n = 1/2 \) (symmetric focusing, \( f \equiv (\lambda / 2\pi) R \sqrt{2} \))
- Betatron phase advance \( \pi / 2 \) per bend segment (bend angle \( \pi / \sqrt{2} \))
- Dispersion then oscillates with period equal to half of the betatron oscillation period
- Sextupole alternates in tact with the beam bend
- Orbit plane interchanges

However, compensation for chromaticity leads to a revival of the angle aberration. This seems possible to compensate by superimposing octupole field in combination with solenoid one (both relatively week) /under study/

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**P24: G4Beamline simulations of Parametric Resonance Ionization Cooling  K. Beard, TJNAF**

**Abstract**

The technique of using a parametric resonance to allow better ionization cooling is being developed to enable small emittance beams so that high collider luminosity can be achieved with smaller machines. While parametric resonance ionization (PRI) cooling of muons has been shown to work in matrix-based simulations when the system is properly tuned, doing the same using an amorphous more detailed GEANT-based pbeamline simulation has been more difficult. The starting point for this work is a non-linear channel, a half integer resonance is induced such that the normal elliptical motion of particles in $x'$-$x''$ phase space becomes hyperbolic, with particles moving to smaller $x'$ and larger $x''$ as they pass down the channel. The absorbers placed at the focal points of the channel form the angular divergence of the beam by the usual ionization cooling mechanism where each absorber is followed by RF cavities to replenish the energy. Thus the phase space of the beam is compressed in transverse position by the dynamics of the resonance and its angular divergence is compressed by the ionization cooling mechanism.

The pbeamline and OptiM simulations show the importance of synchrotron motions as an averaging mechanism for chromatic damping. Multiple scattering and energy straggling play a significant role that must be addressed via further optimizations and additional compensation solutions.

**Typical values:**

- KE: 200 MeV
- $\beta_0 = 0.8 \text{ mm}\cdot\text{mrad}$
- $\gamma = 0.8 \text{ mm}$
- $L_{\text{abs}} = 7.2 \text{ m}$
- Absorber: 32.8 mm Be
- $95\%$ off axis (Voigt) RF: 13.98 MHz/m
- $90\%$ on axis RF (Voigt): 57.26 MV/m
- $100\%$ transmission w/o stochastic processes
- $10\%$ transmission w/ stochastic processes

**PIC beam line with 8 cells**

- **$p_x$**
- **$p_y$**
- **$r_x$**
- **$r_y$**

- **Particle making by g4beamline, color by retrace**
- **When multiple scattering, energy straggling, and other processes are enabled the emittance increases somewhat as shown in the figure to the left.**
- **The attempt has been made yet to optimize the parameters in the presence of these stochastic processes.**
- **The final bunch with stochastic processes enabled is shown in red, the final bunch without stochastic processes is shown in green.**

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stochastic cooling
T01 Stochastic Cooling at GSI, F. Nolden GSI

Stochastic Cooling Slip Factor

\[ \eta_{\phi} = \frac{1}{\gamma^2} - \alpha_p = \frac{1}{\gamma^2} - \frac{1}{\gamma_p} \]

\[ \alpha_p = \frac{1}{s - s_p} \int_{s_p}^{s} \rho(s) \, ds \]

Stochastic Cooling Electrode Development

3D field calculations: L. Thorndahl (CERN)

Prototype design: C. Peschke (GSI)

See his poster on Wednesday!

Overview of the FAIR Complex

Front side (towards beam)

Rear side

The Small Storage Rings

Collecting Ring
bunch rotation
adiabatic deceleration
fast stochastic cooling
isochronous mode

from Super-FRS/pbar-Separator
to atomic physics cage, HITRAP, FLAIR

CR/RESR

SIS100/300

HESR

NESR
Investigations on Pick-Up and Kicker Electrodes for Stochastic Cooling

Claudius Peschke, Fritz Nolden (GSI, Darmstadt); Lars Thorndahl (CERN, Geneva)
T03 bunched beam stochastic cooling at RHIC
M. Brennan - BNL

Coherent Lines

- This has been Nemesis of bunched-beam cooling.
- Not as severe for ions as for protons.
- Nevertheless, can cause saturation and disable the electronics. The problem is high peak voltages in the time domain.

Origin of the Coherent Lines

- M. Blaskiewicz has a talk at this conference on our studies of the coherent lines.
- We believe the origin is different for ions and protons in RHIC.
  - The key difference is that ions are stored in completely filled buckets (large synchrotron frequency spread) and protons are short bunches in long buckets (28 MHz, if small).
  - For protons, the coherent signals come from the motion of the bunch.
  - For ions, they come from the shape of the bunch.
- The ion bunches have very high frequency structure because of the satellite bunches
  - The Fourier transform of the bunch shape is not negligible at 8 GHz.
  - All bunches have the same shape so they contribute coherently to the spectrum.
  - The low frequency spectrum envelope reflects the bunch fill pattern.
  - As does the high frequency spectrum.

PickUp to Kicker Delay

- Fiber optic link runs via the tunnel against the beam.
- $V_{light} = c/1.47 \cdot 1550 \text{nm}$
- Effectively 2/3 turn delay.
- Mixing factor is about 4 turns.
- Simulations (J. Wei) indicate that >90% beam is still bunched after 10 hours.

Beam Transfer Function

- The BTF measures the entire loop.
  - Calibrates kickers (corrected for duty factor).
  - Obtains beam response.
  - Determines loop phase (stability).
  - Reveals filter response.
- The filter flips the sign of the real part at each freq.
- The phase is stable on the 10-minute time scale.
- Run-time BTFs will be used to correct drifts.

Magnitude: red is no filter, yellow is with 2-turn filter

Real (yellow) and Imaginary parts. Real part changes sign at freq.
Coherence in Heavy Ion Beams

Two distinct types:
2) Strong revolution lines
3) Strong signals associated with synchrotron motion
We see the first type with heavy ions and both with protons.
Heavy ions are “rebucketed”
to shorten the bunch and combat IBS.

Coherence in Proton Beams
Wide band (top) observed with
28 bunches in 30 bunch fill pattern.
b=360. Similar to what would be expected due to band edge bunch.
Zoom of the strong right peak (bottom).
99% of the power in dipole lines (40 Hz)
100% in rev and +/- 120 Hz.
<1% Schottky.
T07: Schottky Spectroscopy, F. Nolden GSI

207Tl$^{81+}$ Decay Spectra with Isomer

Decay of one Ion out of Two
electron cooling
M12 Optics of Electron Beam in Recycler: A. Burov, FNAL

Current density distribution on TRA07 for $U_{\text{pulse}} = 4.5$ kV ($I_{\text{beam}} = 0.56$ A)

- Measurements for $I_{\text{peak}} = 6$ A
- BEAM calculations for $I_{\text{peak}} = 6$ A
- Measurements for $I_{\text{peak}} = 11$ A
- BEAM calculations for $I_{\text{peak}} = 11$ A
- Measurements for $I_{\text{peak}} = 22$ A
- BEAM calculations for $I_{\text{peak}} = 22$ A

Electron cooling beam line:
- Acceleration section
- Supply line
- Cooling section
- Return line
- Transfer line
- Deceleration section

Total length: 100 m
Cooler length: 20 m
Kinetic energy: 4.35 MeV
Phase advance: ~30 rad

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Office of Science
U.S. Department of Energy

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
high-quality electron beam @ FNAL's 4.3MV cooler
A.Shemyakin FNAL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value (for cooling)</th>
<th>Value (maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>MeV</td>
<td>4.338</td>
<td>5</td>
</tr>
<tr>
<td>Beam current used for cooling</td>
<td>A</td>
<td>0.05 - 0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Magnetic field in the cooling section</td>
<td>G</td>
<td>105</td>
<td>190</td>
</tr>
<tr>
<td>Beam radius in the cooling section</td>
<td>mm</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>nTorr</td>
<td>0.2 - 1</td>
<td></td>
</tr>
<tr>
<td>Total length of the beam line</td>
<td>m</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>

Figure of merit: magnetic flux inside the beam in the cooling section = effective emittance outside the longitudinal magnetic field.

A 3D beam line has to provide an axially symmetrical beam transformation.
**Recycler Electron Cooling**

- The maximum antiproton stack size in the Recycler is limited by:
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling:
  - Electron beam: 4.34 MeV - 0.5 Amps DC - 200 μrad angular spread

**Recycler-Only Operations**

- Recycler has been participating in Collider Operations in the Combined Shot mode because the Recycler Stack size has been limited to ~120x10^10 pbars.
  - Longitudinal Cooling
  - Transverse Stability
- With Electron Cooling operational and the transverse dampers commissioned, the Recycler stack size can now be increased to over 200x10^10 pbars.
  - The Collider complex is now transitioning from Combined Shot mode to Recycler-Only mode.
  - Faster average stacking.
  - Smaller pbars emittances in the TEV.

**Electron beam parameters**

- Electron kinetic energy: 4.34 MeV
- Uncertainty in electron beam energy: 0.3%
- Energy ripple: ≤ 10^{-4}
- Beam current (max): 0.5 A DC
- Duty factor (averaged over 8 h): 95%
- Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms: ≤ 0.2 mrad
T02 antiproton rate increase D. McGinnis - FNAL

Recycler Electron Cooling

- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV - 0.5 Am; DC - 200 μrad beam spread - 99% recirculation efficiency

Antiprotons and Luminosity

- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Antiproton Production - Slip Stacking

- Slip Stacking is the process of combining two Booster batches at injection into in the Main Injector to effectively double the amount of protons on the antiproton production target
Recuperation of electron beam in coolers with electrostatic bending  
V. Parkhomchuk  
BINP
F05 electron cooling of highly charged ions in traps
G.Zwicknagel, Erlangen U.
W06: Studies of electron cooling frictional force
A. Fedotov BNL

Friction force for ion velocity along magnetic field line
$V_\perp = 0$

- Au ions: $Z = 79$
- Electron distribution: $n_e = 2 \times 10^{15}$ m$^{-3}$ (PRF)
- $\Delta_{||} = 1.0 \times 10^5$ m/s
- $\Delta_{\perp} = 1 \times 10^7$ m/s
- $B = 5$ T

COOL05, September 19-23, 2005
R05: benchmarking magnetized friction force  A.Fedotov BNL

March 2 data: B=0.1T, electron current Ie=250 (pink color), 100 (red), 50 (blue) mA

Green curves – calculated using VP formula (no averaging) with the same numeric coefficient for Ie= 250, 100, 50 mA

COOL05, September 19-23, 2005

BROOKHAVEN NATIONAL LABORATORY

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
R10: COSY 2-MeV cooling system proposal J.Dietrich FZ/IKP
R11: Budker INP proposals for HESR and COSY electron cooling systems  V.Reva BINP
T05: Moving Barrier Bucket, T. Katayama GSI

Operational Scheme of Moving Barrier Bucket System

Variation of emittance during 1000 times injection

400 times denser phase space density
5. Coherent instability

5.4. IBS (?) and longitudinal modulation

Influence of transverse heating: $Atn = \text{attenuation}$

$(V_{\text{noise}})_{\text{rms}} = 6 \text{ V/}Atn$, $\Delta f = 0.1 - 2 \text{ MHz}$, $I_e = 250 \text{ mA}$

Schottky noise: 18th harmonics, $f = 5.8 \text{ MHz}$

$N_p = 1 \times 10^7$, No heating

$N_p = 1 \times 10^8$, Heating, $Atn = 35 \text{ dB}$

---

5. Coherent instability (single injection)

Coherent instability development in COSY

Beam Position Monitor analog signals clearly demonstrating the collective oscillations of the p-beam: the signals from differential horizontal (H) and vertical (V) PU’s and sum (S) PU.

Note: longitudinal oscillations (sum signal) appear together with horizontal one and present later on.
R09: HESR electron cooling proposal D.Reistad TSL
P18: cooling of ions & antiprotons with magnetized electrons  G.Zwicknagel – Erlangen U.
W07: Simulations of dynamical friction, D. Bruhwiler, Tech-X

“cld” parameters – $\Lambda_{\text{ms,||}} = 3000$ (no field errors)

Unmagnetized simulations for “wiggler” param.’s
R01: Coolers with Hollow e beam & electrostatic cooling
V. Parkhomchuk BINP

Wave at electron beam by moving Bi ion

How to proceed for cooling high ion beam current?

→ Hollow electron beam!

\[ \lambda = \lambda_0 \left(1 - \omega_i^2 \omega_e^2 \tau^4 \ast k\right) \]

- Decreasing electron beam density results in
- Increasing threshold ion beam density

Electric field around moving ion Bi at plane (color map) and along axis (down figure)

Red boat (as Bi ion) exit visual wave

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Fermi National Accelerator Laboratory

OTR MEASUREMENTS AND MODELING OF THE ELECTRON BEAM PARAMETERS AT THE E-COOLING FACILITY

A. Warner1, A. Burov1, K. Carlson1, G. Karatkevich1, S. Nagaitssev1, L. Prost1, M. Sutherland1, and M. Timonov2
1FNAL, Batavia IL, USA, 2BINP, 030090 Novosibirsk, Russia

INTRODUCTION

The electron beam diagnostics at the E-Cooling Facility have been improved for the purpose of studying the beam dynamics and understanding of the impact of the E-cooling system on the beam quality. The diagnostics include measurements of beam parameters such as beam current, beam emittance, and beam quality. The measurements are performed using a combination of optical and electrical diagnostics, which provide information on the beam properties and allow for the optimization of the E-cooling system. The data is used to validate the theoretical models and simulations, which are used to predict the beam behavior in the E-cooling system.

DATA ACQUISITION

The data acquisition system includes a combination of optical and electrical diagnostics, which provide information on the beam properties and allow for the optimization of the E-cooling system. The data is used to validate the theoretical models and simulations, which are used to predict the beam behavior in the E-cooling system.

MEASUREMENTS

The measurements include the following:

- Beam current
- Beam emittance
- Beam quality
- Beam position
- Beam energy spread
- Beam phase

The data is acquired using a combination of optical and electrical diagnostics, which provide information on the beam properties and allow for the optimization of the E-cooling system.

SUMMARY

OTR monitoring and data acquisition systems have been developed for the analysis of beam behavior in the E-Cooling Facility. The observations are compared to the predictions of the models and simulations, which are used to optimize the E-cooling system. The data is collected and analyzed to validate the theoretical models and simulations, which are used to predict the beam behavior in the E-cooling system.

BIBLIOGRAPHY


electrostatic rings
M12 Dispersion Control: M. Tanabe - Kyoto

**Issue in storing ordered beam**

- Shearing force want to be canceled
- Less time
- More time

**How to overcome ‘Shearing force’**

- Decelerated
- Lines of electric force
- Potentials are adjusted
- Accelerated

Ordering particles at a bending section
W01: LN2-cooled electrostatic ring T. Azuma TMU

Monitor for Beam Diagnosis

Pickup Detector x 4

Neutral Detector x 1

Storage Time of Rare Gas Ions

~5.0 x 10^{-9} Pa, observation of storage = ~ a few min.

<table>
<thead>
<tr>
<th>Rare Gas</th>
<th>Electron Capture Rate</th>
<th>Ionization Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>He^+</td>
<td>2.5 x 10^{-4}</td>
<td>4s</td>
</tr>
<tr>
<td>Ne^+</td>
<td>6.0 x 10^{-7}</td>
<td>12s</td>
</tr>
<tr>
<td>Ar^+</td>
<td>8.0 x 10^{-8}</td>
<td>7.5s</td>
</tr>
</tbody>
</table>

20 keV
5 x 10^{-8} Pa
### Why Electrostatic Rings?

Electrostatic rings are used to contain the charged particles in a ring, allowing the particles to be accelerated and deflected. They are used in accelerators to manage the energy levels of the particles. The diagram below illustrates the layout of a typical ring and some of its components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1 / Ring 2</td>
<td>2 / 2</td>
</tr>
<tr>
<td>160° cylindrical bend</td>
<td>2</td>
</tr>
<tr>
<td>Quadrupole doublets</td>
<td>4 / 4</td>
</tr>
<tr>
<td>10° deflections</td>
<td>4 / 2</td>
</tr>
<tr>
<td>Variable deflections</td>
<td>6</td>
</tr>
<tr>
<td>Symmetries</td>
<td>2 / 1</td>
</tr>
</tbody>
</table>

Platform voltage: $\leq 25/100$ kV
Electrode voltage: $\leq 16$ kV
Beam energy: $5$–$100$ g kV
Ion mass ratio: $1$–$20$ ($q = \pm 1$)

### Low Temperatures

The rings will be cooled with cryogenators to 5–10 K.

This will allow internal degrees of freedom of (infrared-active) molecular ions to cool radiatively, and ions produced in a cold ion source will stay cold. Also, the vapor pressure of all gases except $\text{H}_2$ and $\text{He}$ is below $1 \times 10^{-13}$ mbar at $T < 18$ K.

Development in atomic and molecular physics since 1990: Cooled ions -> cold electrons ($\rightarrow 20$ K) -> low quantum states. Figure shows rate for $\text{H}_2^++e^- \rightarrow \text{H}_2+\text{H}$ with ions from hot plasma source/cold expansion source.

DESIREE will allow measurements as a function of temperature by controlling the cryostat temperature from room temperature and down.

![Graph showing energy distribution](image)
W04: Ultra-cold electron target D. Orlov, MPI-K

Electron beam formation

Acceleration

\[ kT_\parallel \text{ reduction: } kT_\parallel = \frac{kT_0}{2eU'} + \frac{C'}{4\pi n_0} \]

Magnetic adiabatic expansion

adiabatic invariant: \( E_0 / \beta = \text{const} \)

\[ \alpha = \frac{B_0}{B_{\text{drive}}} \]

\[ kT_\perp - \frac{kT_\perp}{\alpha} \]

Phase-space conservation

\( C = 1.9 \) - fast acceleration
\( C < 1.9 \) - slow (adiabatic) acceleration

\( kT_\parallel = 0.1 \text{ meV} \)

\( kT_\perp \ll kT \)

\( kT_C = 110-120 \text{ meV} \)

\( kT_\perp = 5-6 \text{ meV} \) (CR)

\( kT_\perp = 2 \text{ meV} \) (CR)

Photocathode

\( kT_C = 10 \text{ meV} \)

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laser cooling
F04: cooling techniques for trapped particles  Y.Yamazaki RIKEN

Why? CPT: $\mu^-$ vs $\mu^+$  H vs. H

Plank mass $M_{pl} = \sqrt{\frac{hc}{G}} = 10^{19}$GeV/c$^2$

$(m_p/M_{pl}) m_p \sim$ vibrational level 10 Khz traps
F01: Laser cooling for 3D crystalline state at S-LSR
A. Noda, Kyoto ICR
ion–ion cooling and stopping
the idea

precision Penning-trap mass measurements of short-lived nuclei require high charge states \(\rightarrow\) charge breeding and cold ions \(\rightarrow\) fast cooling without charge exchange

\(\rightarrow\) fast cooling of \(\sim 1\text{eV}\) HCIs in a continuously laser-cooled Mg-ion cloud or crystal

hot HCIs from EBIT \(\Rightarrow\)

ramping the main trap while ions are oscillating

\(\Rightarrow\) fast extraction

energy deposition can be compensated by continuous laser cooling

green dots mark Mg-ions above 0.1 meV

\(\Rightarrow\) kicked out of the lattice

\(\Rightarrow\) stopping of the HCI in \(\sim 10\mu s\)
F02: Laser cooling of relativistic heavy ion beams
U. Schramm LMU

Laser cooling of relativistic heavy ion beams

Why laser experiments under such 'extreme' conditions?

→ huge Doppler shift and pulse shortening

→ laser spectroscopy of heavy few-electron systems

→ short pulse (high intensity) interaction studies

Laser cooling of bunched C$^{3+}$ beams

( rf – tuned )

b) small detuning:
- lowest energy spread
- space charge dominated

Schottky–frequency
time [10s steps]

Laser heating
ion deceleration out of the bucket

Laser cooling of bunched C$^{3+}$ beams
laser vs ecool – momentum spread

ecool ref. data
- N$^{1/6}$ (IBS regime)

- N$^{-1/3}$ (constant detuning)

Laser cooling of bunched C$^{3+}$ beams
laser vs ecool – transverse profiles

ecool ref. data
- N$^{1/6}$ (IBS regime)

- (Schottky)
- (Fluorescence)

Laser cooling of bunched C$^{3+}$ beams
laser vs ecool – bunch length

ecool ref. data
- N$^{1/6}$ (IBS regime)

- (Schottky)

Laser cooling of bunched C$^{3+}$ beams
laser vs ecool – transverse profiles

→ about one order of magnitude lower momentum spread than for electron cooled bunch (below 10 µA)

→ with little ecool (1mA) and even without (few ion current) beams are cold in 3D!
phase space manipulations
**Motivation**

- IBS growth rate measurements usually done by observing the free expansion of bunches
  - Must be on time scale of interest [15 min at injection, hrs at store]
  - Need precise emittance measurement [not easy transversely]

- Echo measurements are
  - Much faster (~1000 turns), allow parameter scans
  - Potentially very sensitive
  - Do not rely on precise emittance measurement

**Transverse echoes – dipole moment simulation**

![Diagram of transverse echoes with and without quadrupole kick]

Figure 3: Left: The dipole moment of the distribution versus time after a dipole kick. Right: The same signal with an additional quadrupole kick at 500 turns after the dipole kick.


**Summary – Transverse Echoes in RHIC**

- Transverse echoes observed in RHIC with Au^{+}, Cu^{+}, p^{+}
  - Dipole kick with injection under angle
  - Air core quadrupole provides 1-turn kick
- Diffusion with p^{+} stronger than with heavier ions (unexpected)
- Observed intensity dependent echoes with Au^{+}, Cu^{+}, → were fitted to simulation results to extract diffusion rates

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M15 Simulation of Beam Dynamics in Cooler Rings, A. Smirnov - JINR

Analytical and MD simulation of IBS for ESR

Ordered state of ion beam

Equilibrium between ECOOL and IBS

Ordered beam simulation for COSY

Np=1e6

IBS growth rates
(Martini model)

MD simulation

transverse

longitudinal
M10 Phase Space Manipulations, K.-J.Kim, ANL

Schematics of Flat Beam Experiment at FNPL

Minimum Achievable Pulse Length

For 6 MV, 2800MHz (h=8) deflecting system, get ~0.4 ps!

Normal APS bunch is 40 ps rms
7. Conclusions

for Transverse-Longitudinal Correlations: FEL Performance and Emittance Exchange

- If conditioning can be achieved it would have a very large impact on FEL performance. (Li-Hua Yu, Whittum).
- Conditioning without growth of effective emittance is possible in a symplectic system (Vinokorov, Wolski).
- It appears to be difficult (but maybe not impossible) to achieve the amount of conditioning likely to be required by real FELs (Kim, Emma, Wolski et al).
- Non-conventional (laser/wiggler (Zholents), laser backscattering (Schroeder), and laser-plasma (Wurtele and Penn) conditioning holds promise.

- Emittance transfer would benefit x-ray FELs (Kim)
- Emittance transfer from a large emittance to a small emittance is possible (Wei and Okamoto)
- Practical emittance transfer schemes have yet to be developed (but no one has even tried yet).

Laser-Wiggler Conditioner

Proposed by Sasha Zholents
Use a laser/wiggler rather than an rf cavity

Plasma Channel Conditioner

Work by Jonathan Wurtele, Gregg Penn, and myself.
Send a laser through a gas in a tube. Blow out all the electrons and make an ion channel. Send the high energy beam just behind the laser before the slow electrons return.

In the plasma channel $\beta = (2\gamma)^{1/2} c/\omega_p$
where $\omega_p = 6 \times 10^{12} (n \text{ cm}^{-3})^{1/2} / 10^{16} \text{ GeV}^{1/2}$ and $\lambda_p = 2\pi c/\omega_p$

For example at $n = 10^{17} \text{ cm}^{-3}$ and 1 GeV, $\omega_p = 2 \times 10^{13} \text{ s}^{-1}$,
$1/\omega_p = 50 \text{ fs}$, $\lambda_p = 100 \mu\text{m}$, and $\beta = 0.1 \text{ cm}$

Simulations, to follow, by Gregg Penn. Two cases (similar to Zholents and Emma and Stupakov [a FOFO channel at 100 MeV])
Clearly at 100 MeV only condition a small time slice.
P20: Hamiltonian analysis in Longitudinal Magnetic Field
V.Reva BINP

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rings
P09: electron cooling for cold beam synchrotron for cancer therapy  V.Vostrikov BINP
F03: status of LEPTA  I. Seleznev JINR

Design of the LEPTA

Helical quadrupole

“stellarator windings”

Quadrupole Length \( L = 160 \text{ cm} \)

Helix step \( h = 80 \text{ cm} \)

\[
G = \frac{2\pi NI}{c \cdot d^2}
\]

Cross section of the quadrupole is similar to Panofsky lens

Experimental results and theoretical fitting

Lifetime vs Energy

\[ \Delta B/B \sim 20\% \]

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R04 Longitudinal cooling force measurements B. Galander TSL

The CELSIUS Ring

- Last CELSIUS run in June 2005
  Now dismantled
- WASA to COSY, Jülich

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>81.8 m</td>
</tr>
<tr>
<td>Length of cooling and injection</td>
<td>9.6 m</td>
</tr>
<tr>
<td>Length of target straight sections</td>
<td>9.3 m</td>
</tr>
<tr>
<td>Bending radius</td>
<td>7.0 m</td>
</tr>
<tr>
<td>Maximum rigidity</td>
<td>7.0 Tm</td>
</tr>
<tr>
<td>Maximum kinetic energy (protons)</td>
<td>1.38 GeV</td>
</tr>
<tr>
<td>Maximum kinetic energy per nucleon</td>
<td>470 MeV</td>
</tr>
<tr>
<td>for ions with Q/A = 1/2</td>
<td></td>
</tr>
</tbody>
</table>

Transient cooling measurements

Transverse Mg-Jet profiles

Cooling of core vs. tails
Electron current 10 mA and proton current 0.3 mA, Np = 1.7 x 10^9.
Can be used in comparisons of calculations with IBS models.
M09 Cooling Experiments at COSY  D.Prasuhn, FZJ/IKP

The Accelerator Facility

- COSY accelerates (polarized) protons and deuterons between 300 and 3700 MeV/c
- 4 internal and 3 external experimental areas
- Electron cooling at low energy
- Stochastic cooling at high energies

Observation of initial losses

Initial losses disappear at smaller injected proton beam emittance

Protons outside the electron beam see a non-linear focusing by the electron beam
M08 Antiproton Decelerator
P. Belochitskii, CERN

Schematic view of ELENA cycle

- No electron cooling is performed at injection energy; beam is cooled already in AD. After injection beam is decelerated immediately.
- One intermediate cooling (at 40 MeV/c probably) is needed to avoid beam losses.

Requirements to ELENA:

- Compact machine located inside of AD Hall with minimum of reshuffle.
- Energy range from 5.3 MeV (AD extraction energy) down to 100 keV.
- Equipped with electron cooler to make beam phase space smaller in about two orders of magnitude with respect what we have today.
- Machine assembling and commissioning has to be done without disturbing current AD operation.
M06 FAIR project
M. Steck, GSI

The New FAIR Accelerators

Goals:
- High beam intensity
- High beam energy
- High beam quality

- Synchrotrons
  - SIS100
  - SIS300
- HESR
- SuperFRS
- Separators
- pbar separator
- CR-complex (CR, RESR)
- Storage Rings
- NESR
Stored antiproton beams at keV energies

GSI Darmstadt
FAIR project

Antiproton collector ring

Low energy antiproton facility
FLAIR

Existing GSI machines
New machines

30 MeV ... 300 keV: LSR (magnetic)
300 keV ... 20 keV: USR (electrostatic)

> 2010

Antihydrogen collision experiment

\[
\text{H} + \bar{\text{H}} \rightarrow e^+ + e^- + p + \bar{p} \\
\rightarrow \text{Ps} + p + \bar{p}
\]

\[
\text{E}_e \leq 13.6 \text{ eV} \\
\text{positron ring}
\]

\[
\text{Elab} \leq 25 \text{ keV}
\]

\[
\text{USR}
\]

\[
\text{E}_e \leq 13.6 \text{ eV}
\]

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Jefferson Lab

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Office of Science

U.S. Department of Energy
P10: antiproton-ion collider for FAIR  V.Vostrikov - BINP

Antiproton - Ion Collider for FAIR Project

P. Beller¹, B. Franzke¹, P. Kienzle²,², R. Kruelken³, I. Koop³, V. Parkhomenko³, Y. Shatunov³, A. Skrinsky³, V. Vostrikov³, E. Widmann⁴

¹ GSI, Darmstadt, Germany; ² TUM, Munich, Germany; ³ BINP, Novosibirsk, Russia; ⁴ SMI, Vienna, Austria.

An antiproton-ion collider (AIC) is proposed to independently determine rms radii for protons and neutrons in stable and short lived nuclei by means of antiproton absorption at medium energies. The experiment makes use of the electron ion collider complex with appropriate modifications of the electron ring to store, cool and collide antiprotons of 30 MeV energy with 740 A MeV ions in the NESR. Antiprotons are collected, cooled and slowed to 30 MeV. Hereafter the antiprotons are transferred to the electron storage ring using a new transfer line. Radioactive nuclei are produced by projectile fragmentation and projectile fission of 1.5 A GeV primary beams and separated in the Super FES. The separated beams are transferred to the collector ring (CR) and cooled at 740 A MeV and transported via the RESR to NESR, in which especially short lived nuclei are accumulated continuously to increase the luminosity.

Main parameters of EC for AIC

- Maximum electron energy: 70 Kev
- Maximum electron current: 2 A
- Electron beam diameter: 5 - 20 mm
- Magnet field in cooling section: 0.2 T
- Length of cooling section: 3.5 m

Design Luminosity $L = 10^{23}$ s cm$^{-2}$

Sn$^{132}$ ion beam cooling in NESR, $N = 10^7, 10^6, 10^5$

Energy is 740 MeV/u

Pbar cooling in AIC, $N = 10^9, 10^8$

from top to bottom, $E = 30$ MeV
USR - Main Goals

- Variable down to very low energies
  - 300 keV ~ 20 keV
- High luminosity for in-ring experiments
- Well defined extracted beams:
  - small emittance
  - small momentum spread
- Multi-User operation:
  - 2 straight lines for in-ring experiments
  - 1 extraction port
  - additional beam lines possible
- Central requirements
  - $\Delta t \sim 500$ nsec for injection into trap
  - $\Delta t \sim 2$ nsec / $10^4$ ions for collision experiments

Carsten P. Welsch

Coo05, Galena, IL, USA

$T_{\text{Rev}}(\text{pbar}; 20\text{keV}) = 15\ \mu\text{sec}$

Circ. = 30 m

4 mm
T04 Cooling at HESR, H.Stockhorst - FZJ/IKP

Cooling Scenario for the HESR

- HESR Layout
- Electron Cooling at Momenta $p = 4.9 \text{ GeV/c}$ for the High Resolution Mode
- Small Angle and Energy Scattering
- Stochastic Cooling with Internal Target for $p = 3.9 \text{ GeV/c}$ in the High Luminosity Mode

Longitudinal Stochastic Cooling Performance for Different Momenta in the HL mode

Transverse and Longitudinal Cooling
Including IBS + Target

$p = 3.9 \text{ GeV/c}$

$L = 2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$

$N = 10^{11}$

$N_t = 4 \times 10^{19} \text{ atoms/cm}^2$

Electron Cooling at 8 GeV

HESR Layout

- Basic Parameters:
  - Circumference: 574 m
  - Arc Length: 155 m
  - Straight Section: 132 m

- Ions:
  - anti-protons
  - protons

- Momentum Range:
  - 1.5 GeV/c – 15 GeV/c

- Anti-proton injection at 3 GeV beam from BESR

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M07 antiproton cooling at FNAL
S. Nagaitsev, FNAL

- $1 \times 10^8$ 8-GeV PbPars are collected every 2-4 seconds by striking $7 \times 10^{12}$ 120-GeV protons on a Nickel target
- 8 GeV PbPars are focused with a lithium lens operating at a gradient of 760 Teslas/meter
- 30,000 pulses of 8 GeV PbPars are collected, stored, and cooled in the DeBuncher, Accumulator and Recycler Rings
  - The stochastic stacking and cooling increases the 6-D phase space density by a factor of $600 \times 10^9$
- 8 GeV PbPars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON
R03 HIRFL-CSR  X.Yang IMP

HIRFL-CSR Layout

Cooling time as a function of transverse energy of electron

- $E_x = 219.44 \text{ keV}$
- $I = 3 \text{ A}$
- $R = 0.0225 \text{ M}$
- $\Delta EB = 1.0 \times 10^4$
- $\beta = 7.5 \text{ M}$
- $L_e = 4 \text{ M}$

Cooling time $\tau / \sec$

Transverse energy of electron $E_x / \text{ eV}$
The Ions for LHC project

- LHC needs $L = 10^{27}$ cm$^{-2}$s$^{-1}$ at 2.7 TeV/n
- 592 bunches, $7.10^7$ ions/bunch, $\epsilon=1.5$ $\mu$m, $\beta^*=0.5$m
- Implies $9 \times 10^8$ ions with $\epsilon=0.7$ $\mu$m every 3.6s in LEIR

- First run, early scheme, $L=5 \times 10^{25}$ cm$^{-2}$s$^{-1}$ (60 bunches, $7 \times 10^7$ ions/bunch, $\beta^*=1$) $\Rightarrow 2.25 \times 10^8$ ions in LEIR.
R07: high-current ERL-based electron cooling for RHIC  Ben-Zvi  BNL

Lattice for magnetized beam

The use of a helical undulator
- Large coherent velocity can be achieved to reduce recombination.
- Small circle radius can be made with low field.
- Undulator provides focusing of the electron beam.

Non-magnetized beam
- The combined use of ellipsoid bunch, high electric field and no magnetization results a good emittance.

\[ B_0 \sigma_z^2 = 500G \times (10 mm)^2 \]
\[ \mathcal{M} \sim 380 \text{mm}\text{m} \]

\[ \theta = \frac{K}{\gamma} = \frac{93AB\lambda}{\gamma} \]
\[ r_0 = \frac{\theta \lambda}{2\pi} \]
\[ L = \ln \frac{2\pi}{r_0} \]

Take \( \lambda = 5 \text{cm}, B = 20 \text{Gauss}, R = 5 \text{cm}, l = 72 \text{Amp} \)
Then \( r_0 = 0.7 \text{ mm}, \beta_0 = 180 \text{ m} \)

25 hours recombination
Lifetime:
More than enough
http://conferences.fnal.gov/cool05/Presentations/