Low-Energy RHIC electron Cooling (LEReC): Specifications and Parameters

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Low-energy RHIC operation

Electron cooling (a well known method of increasing phase-space density of hadron beams):

- "cold" electron beam is merged with ion beam which is cooled through Coulomb interactions
- electron beam is renewed and velocity spread of ion beam is reduced in all three planes

requires co-propagating electron beam with the same average velocity as velocity of hadron beam.

At low energies in RHIC luminosity has a very fast drop with energy (from γ^3 to γ^6). As a result, achievable luminosity becomes extremely low for lowest energy points of interest.

However, significant luminosity improvement can be provided with electron cooling applied directly in RHIC at low energies.

Energy scan of interest:

$\sqrt{s_{NN}}$ = 5, 6.3, 7.6, 8.6, 12, 16, 20 GeV

Electron accelerator:

$E_{e,kinetic}$=0.86-4.9 MeV

Low-Energy RHIC electron Cooler (LEReC)

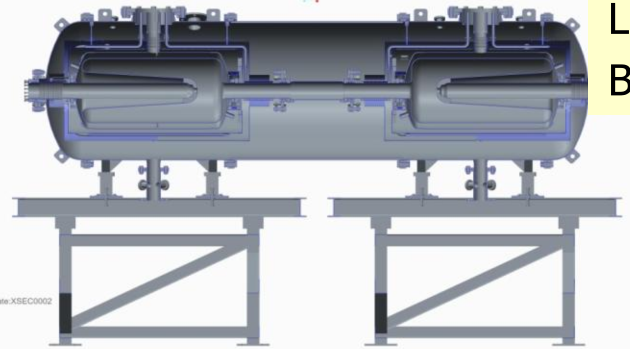
Different approaches are possible:

BNL C-AD Tech Note C-A/AP/307 (April 2008)

1. DC accelerator (Pelletron from FNAL) →
   suitable for cooling: < $\sqrt{s_{NN}}$ =20 GeV
   was baseline approach until September 2012

2. RF-gun bunched beam electron cooler -
   (100 MHz SRF gun and booster cavity) →
   designed to reach $\sqrt{s_{NN}}$ =20 GeV
   present baseline approach since September 2012

compact approach (5 MeV):

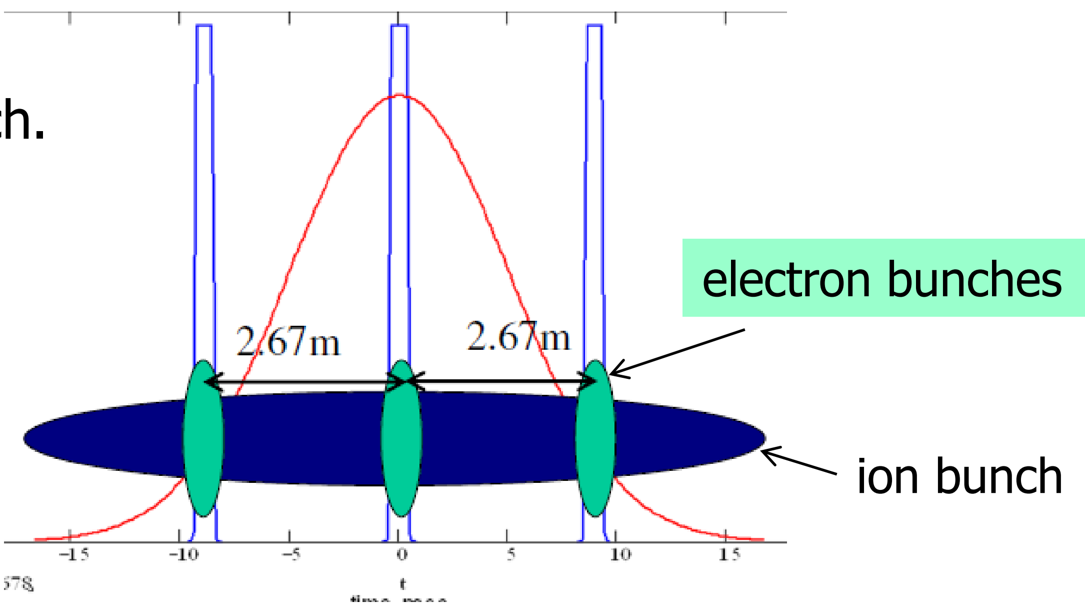


Layout by B. Martin

Bunched beam electron cooling

- **First bunched beam electron cooling.**
- **First electron cooling in a collider.**
- **Opens roadmap for electron cooling at higher energies.**

1) Putting a "train" of electron bunches on a single ion bunch.
2) Can use "painting".



We use analytic formalism and numerical models developed for RHIC-II bunched beam cooling.

RHIC Electron Cooler approach

"Non-magnetized cooling" – means no strong magnetic field in the cooling section is used and thus transverse angular spread of electron beam is not removed from cooling dynamics, and keeping it within the specs becomes important.

Two possibilities:

1) FNAL's choice:

small magnetic field on the cathode (100G) and in cooling section (100G).

2) Zero magnetic field on the cathode and zero magnetic field in cooling section - short solenoids to counteract space-charge defocusing every 2 meter (+undulators).

- **FNAL considered both possibilities 1) and 2) and concluded that choice #1 is required for their parameters.**
- **For LEReC based on DC beam, choice #1) was also required.**
- **For LEReC based on RF electron beam continuous magnetic field (in cooling section) is not required. This will be the first cooling without any magnetization.**

Problem of over focusing from ion beam for LEReC

1. For approach based on DC e-beam:

Peak current of ions: 0.2-1A (depending on which RF is used)

Electron DC current: about 0.05A

So, instead of defocusing in the cooling section due electron beam space charge we have focusing of electron beam by ion beam.

Such focusing is weak. But for cooling, resulting angles exceed requirement:

solution: continuous weak magnetic field in cooling section as @FNAL

2. For approach based on RF e-beam:

As long as peak electron current (about 1A) > Ion peak current: no significant problem from over focusing. We then have only defocusing due to direct electron beam space-charge, which is corrected by short solenoids every few meters.

Putting several electron bunches on a single ion bunch leads to a "mismatch"/over focusing for some of them (some loss from optimum cooling).

see presentation by D. Kayran

Friction force on the ion (without magnetic field)

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{\vec{V} - \vec{v}_e}{\left|\vec{V} - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

$$\rho_{\min} = \frac{Ze^2}{m} \frac{1}{\left|\vec{V} - \vec{v}_e\right|^2}$$

$$f(v_e) = \left(\frac{1}{2\pi}\right)^{3/2} \frac{1}{\Delta_\perp^2 \Delta_\parallel} \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)$$

$$F_\parallel = -\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 n_e}{m \Delta_\perp^2 \Delta_\parallel} \int_0^\infty \int_{-\infty}^\infty \int_0^{2\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_\parallel - v_\parallel) \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)}{\left((V_\parallel - v_\parallel)^2 + (V_\perp - v_\perp \cos\varphi)^2 + v_\perp^2 \sin^2\varphi\right)^{3/2}} v_\perp d\varphi dv_\parallel dv_\perp$$

$$F_\perp = -\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 n_e}{m \Delta_\perp^2 \Delta_\parallel} \int_0^\infty \int_{-\infty}^\infty \int_0^{2\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_\perp - v_\perp \cos\varphi) \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)}{\left((V_\parallel - v_\parallel)^2 + (V_\perp - v_\perp \cos\varphi)^2 + v_\perp^2 \sin^2\varphi\right)^{3/2}} v_\perp d\varphi dv_\parallel dv_\perp$$

"3-D"
in BETACOOL

Asymptotic expressions for anisotropic ("flattened") electron distribution

$$\Delta_{\parallel} << \Delta_{\perp}$$

$v_i >> \Delta_{\perp}$

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \cdot \frac{\vec{v}_i}{v^3}$$

$\Delta_{||} << v_i << \Delta_{\perp}$

$$\vec{F}_{\perp} = -\frac{4\pi Z^2 e^4 n_e L}{m} \cdot \frac{v_{i,\perp}}{\Delta_{\perp}^3} \qquad F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{v_{\parallel}}{|v_{\parallel}|\Delta_{\perp}^2}$$

$v_i << \Delta_{||}$.

$$F_{\parallel} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{v_{\parallel}}{\Delta_{\parallel}\Delta_{\perp}^2}$$

We have distribution close to isotropic.

asymptotic for $v_{ion} < \Delta_e$:

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m}\frac{\vec{v}_i}{\Delta^3}$$

$$\Delta = \sqrt{\Delta_\perp^2 + \Delta_\parallel^2}$$

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m}\frac{\vec{v}_i}{\beta^3 c^3((\gamma\vartheta)^2 + \sigma_p^2)^{3/2}}$$

In simulations, we use full numerical evaluation for anisotropic distribution.

Requirement on electron angles:

γ=4.1: σ_p=5e-4; θ<1.5e-4 ($\gamma\theta$=5.8e-4, sufficient)

γ=10.7: σ_p=5e-4; θ<0.9e-4 ($\gamma\theta$=8.6e-4, already far from optimum)

Effects on electron angles

- **Many effects which can contribute to angular spread of electron beam were evaluated.**
- **On the next few slides we summarize contributions from some beam dynamics effects which were expected to be significant.**
- **Contributions resulting from beam transport and technical components will be covered in talks by:**

D. Kayran and I. Pinaev:

- Electron beam emittance; energy spread

-Power supplies ripple and drifts

-Accuracy of mechanical alignment of solenoids

-Vibrations and drifts of solenoids

-BPM noise (for BBA and orbit feedback)

Effect of images currents on beam pipe

- If the beam is offset from the center of vacuum chamber, one gets coherent force from image charges, which can result in exponential growth of beam offset.
- For bunched beam, the force has both AC and DC components. While AC component is reduced by an additional factor 1/gamma^2 (cancelation of electric and magnet field), the DC component does not have such cancelation.

$$F_x^{ac} = \frac{2e^2 N_e x}{\gamma^2 b^2 l_b} \qquad F_x^{dc} = \frac{2e^2 N_e \eta x}{b^2 l_b}$$

For FNAL with design DC current >1A the growth length was very short.

For LEReC: average beam current is very small (about 20 mA @γ=4.1):

$\lambda_{.ac} = 55.614\,\mathrm{m}$ $\mathrm{theta}_{.ac} = 3.233 \times 10^{-6}$ $\lambda_{.dc} = 42.787\,\mathrm{m}$ $\mathrm{theta}_{.dc} = 5.462 \times 10^{-6}$

Requirement: keep total rms angular spread $< 150\times10^{-6}$.

Control of electron angles is essential

for γ=4.1

Example 1:

2.0 μm mittance: 129 μrad spread (with beta function 30m)

2.0 μm mittance: 100 μrad spread (with beta function 50m)

space-charge: – 100 μrad ; other contributions - 40 μrad

Resulting rms angular spread: 147 μrad - OK

Example 2:

emittance - 100 μrad

remaining space-charge – 150 μrad

other contributions – 50, 50, 50 μrad

Resulting rms angular spread: 200 μrad -> factor of 2 reduction from optimum cooling with 150 μrad spread.

- **Try to keep contributions, other than emittance and space charge, to a small level < 50 μrad.**

Contributions to angles of electron beam in cooling section @ γ=4.1

Effects	Contribution [μ rad]	Measures/tasks	Remaining contribution [μ rad]
Emittance (thermal contribution)	129 (for 2.0 μm, β=30m) 100 (for 2.0 μm, β=50m)		100-130
Space-charge	140 (after L=2m, Q=0.5nC)	Compensating solenoids (200G, every 2m). Develop approach to minimize non-linear contribution	100 (on average)
Effect of wall images		Requirement on beam centroid 1 mm offset from beam pipe center	<6
Residual magnetic field	70 (for 2.5mGauss after L=2m)	Shielding (and possibly correctors)	<35
e-cloud (1nC/m)	430	NEG coating – reduction by about factor of 10.	<40 (not expected)
Aberrations/non-linearities			See beam dynamics simulation
Envelope mismatch		Requires very good matching	See beam dynamics simulations
e/ion defocusing (for electron bunches sliding through ion bunch)		Different effect for different location within ion bunch.	may result in reduction from optimum cooling

Ion beam parameters	γ=4.1 (4.5 MHz RF)	γ=10.7 (4.7 MHz RF)
Number of particles per bunch, $\times 10^9$	0.75	3.0
Space-charge tune shift (initial)	0.019	0.015
Rms bunch length, m	5.8	4.2
S_95%, eV-s	0.5	1.2
A_s (80 kV, 4.55MHz RF)	1.3	6.0
Peak current, A	0.2	1
Emittance_n95%, mm mrad	15	15
Rms size in cooling sec, mm	4.3	2.7
Angular spread, mrad (for β function=30 m)	0.14	0.09
Transverse and longitudinal IBS rates for emittances (initial), 1/sec	x=2e-4, z=3e-3	x=6e-5, z=2.7e-3
Electron beam parameters		
Total charge Q, nC	4 (spread over 9 bunches)	7 (spread over 5 bunches)
dp/p, rms	< 5e-4	< 4e-4
Angular spread, mrad (contribution from all sources)	< 0.15	< 0.09
Rms emittance_norm. , μm	< 2.5	< 2.0
Rms size, mm	4.3	2.7
Cooling length, m	12	12

Cooling section

- **The cooling section is the region where the electron beam overlaps and co-propagates with the ion beam to produce cooling. The electron beam first cools ions in Blue RHIC ring then it is turned around (U-turn) and cools ions in Yellow RHIC ring and then goes to the dump. The electron beam must maintain its good quality all the way through the second cooling section in Yellow ring.**
- **The Blue and Yellow ring cooling sections are about 12 meters each (exact length to be fixed). No recombination suppression is planned. Some space is taken up by correction solenoids, steering dipoles and beam position monitors used to keep the electron beam and ion beam in close relative alignment.**
- **Short (10cm) correction solenoids will be place every 2 m of the cooling section.**
- **Distance covered by magnetic field from solenoids (100-200 G) will be lost from cooling. Expect about 20-25 cm to be lost from cooling from each solenoid, every 2m of cooling section (design by W. Meng).**

Requirement of magnetic field suppression in cooling section:

γ=4.1: B_residual=2.5mG ->angles: 70 μrad after L=2m.

Requirement on total rms angular spread : < 150 μrad (γ=4.1)

Passive (mu-metal shielding) or active (Helmoltz coils) should guarantee that B_residual is below required level in free space between compensating solenoids.

Emittance of 2 μm gives 130 μrad for 30m β-function.

Present approach: shielding <0.2mG (angles <35 μrad after 12 m).

transverse momentum imparted to the electron beam by these magnetic fields is acceptably low if the fields can be limited to approximately 2 mGauss.

In order to accomplish this, the Electron Cooling section will be shielded by three concentric cylindrical layers of high initial permeability alloy. A geometry that achieves this goal and that fits within the radial limitations imposed by the solenoid design is parameterized in Table 2.

Table 2: Magnetic Shielding Parameters

FNAL

Mu (initial)	11000
Layer thickness	1 mm
Inside radius of layer 1	109.5 mm
Inside radius of layer 2	120.6 mm
Inside radius of layer 3	133.3 mm
Total magnetic attenuation for DC fields	3000

Using an 80% Nickel-Iron-Molybdenum alloy satisfies

Continuous weak focusing?

Using single long solenoid 10-20G:

For beam without magnetization, B_z=10G results in rotational angles of 750 μrad (at γ=4).

To avoid such angles it would require magnetization on the cathode.

For our present approach with magnetization on the cathode, we thus selected lumped focusing with short solenoids and require B_z to be < 1 G for cooling (75 μrad).

Residual magnetic field from solenoids in cooling region

W. Meng

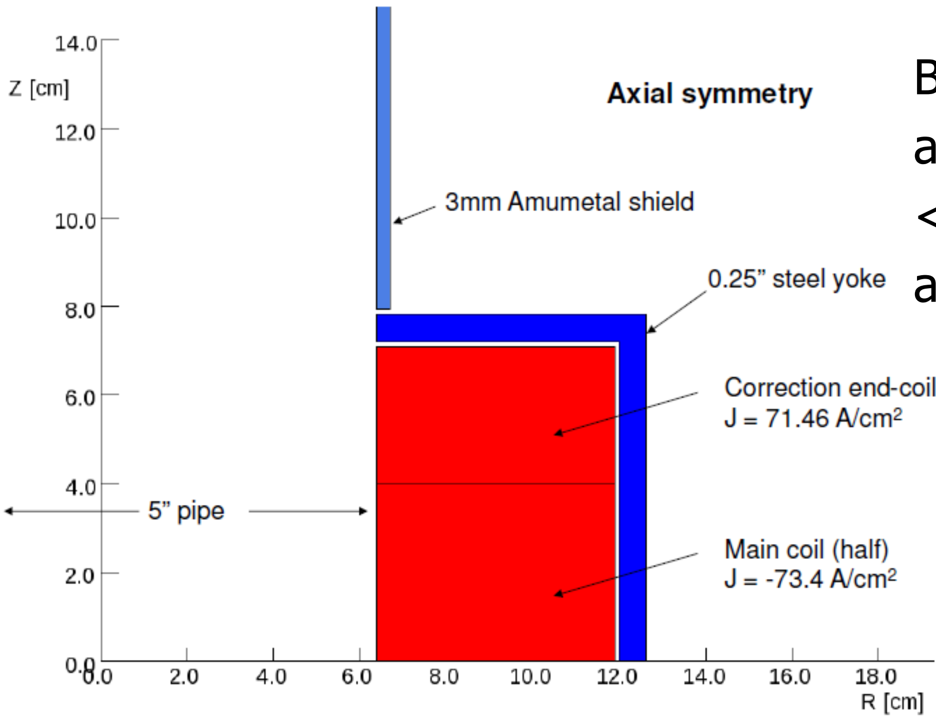
$$B_z < 1G$$

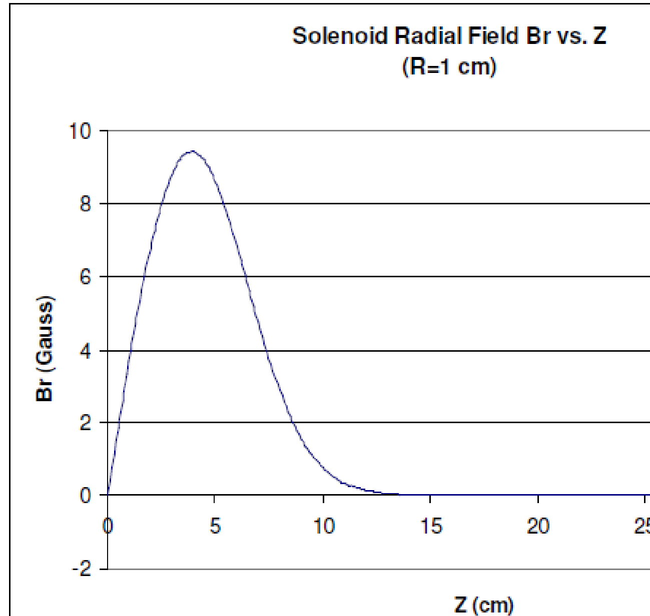
$$\int B_r dz < 0.5G \cdot cm$$

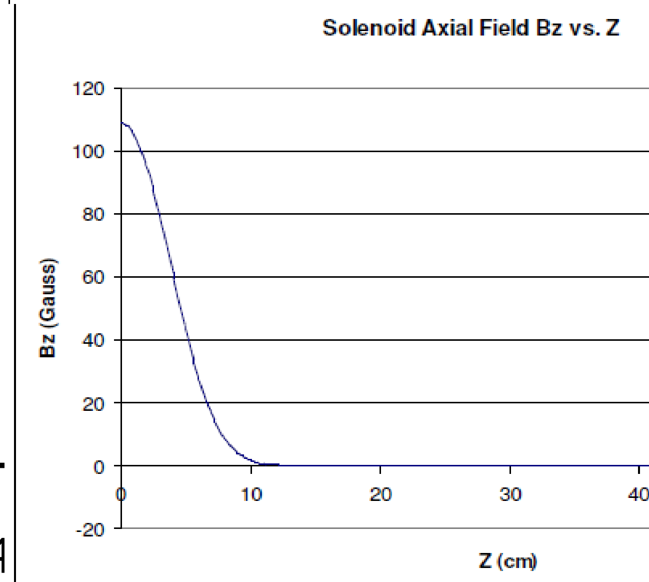
at z=10.7 cm

B_z=0.5 G at z=11.3cm

<0.01 G at Z=13cm







Effects on hadron beams

- Consideration of effects of electron bunches on ion beam dynamics led to requirement to lock electron beam on fixed location within ion bunch to avoid "random noise effect".

- Resulting requirements are:

Jitter on electron bunch timing: < 120ps

Bunch current jitter: < 7%

details will be presented
by G. Wang

Scope of LEReC project

1. 100 MHz SRF gun with maximum energy of 2.5 MV.
2. 2.5 MV booster 100 MHz SRF cavity in the same cryostat with the gun.
3. Solenoid inside the cryostat between the gun and cavity.
4. 500 MHz energy correction warm cavity (5^{th} harmonic).
5. Electron beam transport from IR2 section to the cooling section in Warm Sector 2.
6. Cooling section in Blue RHIC ring – 14 m long. Short (10cm) correction solenoids (200G) located every 2m. Free space between the solenoids is covered by mu metal to shield magnetic field to a required level.
7. U-turn between cooling section in Blue and Yellow Rings.
8. Cooling section in Yellow Ring.
9. Dump for the electron beam (250 kW).
10. Beam transport magnets and diagnostics.

Summary:

Electron beam parameters should be kept within the specs for the entire beam transport line.