Demonstration of electron cooling using a pulsed beam from an electrostatic cooler


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August 6, 2020
Principle of electron cooling

- reduce ion/proton beam emittance ("heat") by mixing with cold medium
- \( v_{\text{elec}} = \langle v_{\text{ion}} \rangle \Rightarrow E_{\text{kin,elec}} = \frac{m_{\text{elec}}}{m_{\text{ion}}} \langle E_{\text{kin,ion}} \rangle \)
- e.g. protons @ EIC: \( E_{\text{kin,elec}} = 12.5 \text{ MeV} \) at \( E_{\text{kin,proton}} = 23.8 \text{ GeV} \)
- cooling depends on velocity deviation in rest frame
- takes high number of passes ⇒ limited to storage rings
Principle of energy recovery for DC beams

- Cathode
- Anode
- Collector

$\propto$ MV, 0 A

$\propto$ kV, 1 A
Some history

- First electron cooler: 1974, Novosibirsk (DC, 37 keV electrons)
- Highest energy: 2005–2011, Fermilab (DC, 4.3 MeV electrons)
- DC acceleration limited in energy; exact limit difficult to assess but likely too low for EIC
- 2012: JLab-IMP collaboration established to demonstrate cooling with electron bunches
- 2013: BNL proposes RF-based bunched-beam cooling facility LEReC at RHIC
- 2016–2019: bunched-beam cooling experiments at IMP
- Feb 2020: BNL publication on successful cooling at LEReC
- July 2020: JLab-IMP publication submitted for peer review
Purpose of the experiment

Open questions in electron cooling

• If RF-based linac is used as electron cooler, electron beam has time structure
• How does this affect the cooling properties?
• Can we use it to our advantage to mitigate overcooling?

Experimental approach

• Use available DC cooler at CSRm (IMP) and pulse the gun
• Synchronize electron pulses with ion ring RF
• But relative phase is adjustable and can be made time-dependent
RF-based cooling considerations

- cooling force scales unfavorably with energy ⇒ compensate with current
- option: use ERL to mitigate beam power issues (under consideration for EIC at low energy)
- move/“dither” bunches as a function of time to improve overlap pattern?

Diagram:

- HAR
- linac
- injector
- beam dump
- cooling section
- e^−, p
- HAR

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Bunched cooling with synchrotron dynamics

- Cooling force cares about velocity; bunch overlap is temporal/spatial
- High synchrotron amplitude results in...
  - Less time spent in region of overlap
  - High velocity deviation at $\Psi_S = 0$

(copied from Ya. Derbenev: Theory of electron cooling)
Principle of the bunched-beam cooling experiment

- Pulse length, delay
- Pulsing magic
- Gun
- Cooler
- BPM
- RF voltage
- RF system (synchronizes)
- Cavity (powers)
- Ion ring (BPM)
Beam parameters

**Ion beam**
- Particle: $^{86}\text{Kr}^{25+}$
- $E_{\text{kin}}$: 5 MeV/nucleon
- $\beta$: 0.103
- $f_{\text{rev}}$: 191.5 kHz
- $h$: 2

**Electron beam**
- $E_{\text{kin}}$: 2.7 keV
- bunch rate: $hf_{\text{rev}} = 383$ kHz (phase adjustable)
- bunch length: 100–1000 ns, i.e. 3–30 m
- bunch current: $\propto$ bunch length (uniform density, 30 mA)
Available instrumentation

- RF pickup for spectral analysis
  - gives the synchrotron frequency $\Rightarrow$ calibrate $U_{RF}$
  - may yield $\Delta p/p$ and tune spread
- individual BPMs for ions and electrons
  - measure relative longitudinal bunch position and overlap
  - also used as longitudinal profile monitor to observe cooling
- ionization profile monitor (IPM) for transverse profile measurement
- DCCT: ion current measurement
  - not strictly necessary but a nice consistency check
BPM setup and transfer impedance model

• sum signals of opposite plates to remove transverse information

• $U = Z I_{\text{beam}}$ with $Z(\omega) \propto \frac{i\omega RC}{(1+i\omega RC)}$

• record $U(t)$ with DSO

• $\mathcal{F} + \text{Ohm's law} + \mathcal{F}^{-1}$ gives $I(t)$
Experimental procedure

- ion current measurement
- spectrum analyzer
- IPM
- BPM
- DC cooling
- RF
- bunched cooling

Window of interest

Ion current

Time (not to scale)

Accumulation
Idle
Bunched
Experimental results:
constant bunch phase
Synchronization of DAQ devices: spectrogram

- DC cooling off
- beam bunched
- bunched cooling
- RF off
- cooling off

\[ f - f_0 \text{ (kHz)} \]

\[ \text{time (s)} \]
Synchronization: beam current measurement

- consistency check with BPM intensity and global timing
- markers calculated from procedure; referenced to dump
Transverse profile example (500 ns, 1.0 kV)

Intensity (arb. unit)

x (mm)

$t = 0.2 \, \text{s}$

$t = 0.4 \, \text{s}$
Bunch delay measurement: whole frame (500 ns, 1 kV)

- electron time axis shifted by measured $\Delta$ in propagation delay: 286 ns
Method to determine $I_{beam}(t)$ bunch by bunch

- estimate location of ion peak maxima
- slice frame halfway between peaks; select 2$^{\text{nd}}$–5$^{\text{th}}$ slices
- remove unphysical slope of background: fit line through left-sided and right-sided minimum and subtract it; set everything outside that region to zero
- “true” ion peak center determined by statistical mean
- average these four peaks, apply correction again
- from the resulting shape, compute central moments:
  Variance: $\sigma^2 = \frac{1}{n} \sum_i (x_i - \bar{x})^2$
  Excess kurtosis: $K - 3 = \frac{1}{\sigma^4} \frac{1}{n} \sum_i (x_i - \bar{x})^4 - 3$
Example averaged bunch with corrections (500 ns, 1 kV)
Bunch phase consistency between runs

![Graph showing bunch phase consistency between runs with different delays and RF voltages. The graph plots the delay (ns) against the calculated RF voltage ($U_{RF,calc}$) (kV). There are markers for different delay times (400 ns, 500 ns, 600 ns, 700 ns, 800 ns, 900 ns, 1000 ns) and RF voltages.](image)
Electron bunch length distribution

![Histograms of electron bunch length distribution at different times](image)

- **400 ns**
  - T\(_{\text{bunch}}\) (ns): 330, 360, 390
  - Count: 600

- **500 ns**
  - T\(_{\text{bunch}}\) (ns): 435, 445
  - Count: 400

- **600 ns**
  - T\(_{\text{bunch}}\) (ns): 555, 565
  - Count: 200

- **700 ns**
  - T\(_{\text{bunch}}\) (ns): 615, 625
  - Count: 0

- **800 ns**
  - T\(_{\text{bunch}}\) (ns): 740, 750
  - Count: 400

- **900 ns**
  - T\(_{\text{bunch}}\) (ns): 855, 865
  - Count: 200

- **1000 ns**
  - T\(_{\text{bunch}}\) (ns): 915, 925
  - Count: 0
Evolution of longitudinal profile (example: 500 ns, 1.0 kV)
Evolution of statistical moments (example: 1.0 kV)
Cooling rates \((0.2 \, \text{s} < t < 0.4 \, \text{s})\)

\[
-\frac{1}{\sigma_z} \frac{d \sigma_z}{dt} (\text{s}^{-1})
\]

\[
-\frac{1}{\sigma_x} \frac{d \sigma_x}{dx} (\text{s}^{-1})
\]

\[
U_{\text{RF,calc}} (\text{kV})
\]
Experimental results:
Bunch phase modulation ("dithering")
with triangle waveform
Electron bunch length distribution (with dithering)

- bunch length stable and without surprises
- also independent of delay
Aliasing image of modulation waveform (300 ns bunches)
Particle loss with modulation

- Cooling investigation pointless. Find reason for loss first
Understanding the particle loss issue: Tracking simulation
What are we dealing with here?

- Similar issue with bunch length jitter and phase modulation
- Assumption: unrelated to cooling, has to do with space charge
  - longitudinal: carrot force as function of synchrotron phase
  - transverse: lens that is turned on/off as function of synchrotron phase (synchro-betatron coupling)
Simulation strategy

- In MAD-X: Divide the cooler into $N$ drifts extending slightly beyond the actual edges.
- Take transport matrices and track in 6-d phase space.
- Use discrete 2-d or 3-d macrocharge distribution and calculate $\vec{E}(\vec{r})$ from first principles. Non-relativistic OK.
  - Caution: longitudinal coordinate in 6-d phase space is time with unit length.
  - *Position* of ion on $s$ axis is fixed by discretization of the drift.
  - Recalculate field distribution for every ion because it is a function of the arrival time.
Example field distribution (on-axis projection)

- Shape depends on longitudinal coordinate of ion. Shown for an ion located deep inside the electron bunch
- Beam pipe neglected; normally ought to be accounted for
Tracking simulation

- ion beam has no space charge ⇒ single-particle simulation
- synchrotron motion, per revolution:
  - $\Delta E_{\text{kin}} = Uq \sin \Psi$
- apply transport matrices one by one, check for transverse aperture
- for every transport matrix within the cooling drift:
  - compute electric field $\vec{E}$
  - $\vec{F} = \dot{\vec{p}} \Rightarrow \Delta \vec{p} = -\vec{E}q\frac{L_{\text{slice}}}{\beta_c}$
  - if coordinates are inside the cooling beam, apply friction force (wild guess just for fun, optional)
400 ns electron bunches, 30 ns rise/fall, central phase: Ensemble of 1000 ions according to initial emittance
400 ns electron bunches, 30 ns rise/fall, central phase: Phase space trajectory of a single example ion
1/3 of bunches (random) with edge shift, $\Delta L = 50$ ns:
Ensemble of 1000 ions according to initial emittance
1/3 of bunches (random) with edge shift, $\Delta L = 50$ ns:
Phase space trajectory of a single example ion
Particle loss rate (assuming transverse aperture ±50 mm)

- Considering the simplified assumptions, result not terrible
- Explains dithering issue as well (not shown here)
- Stable bunch length/phase more important than we thought
Conclusions

- Electron cooling with bunches works without major surprises
- Dithering does not! (not with high space-charge forces, anyway)
- Be careful to keep the bunch length and phase stable