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

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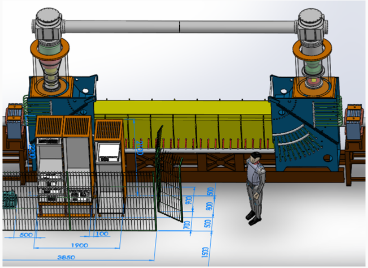
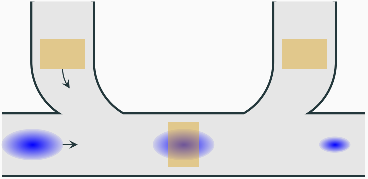
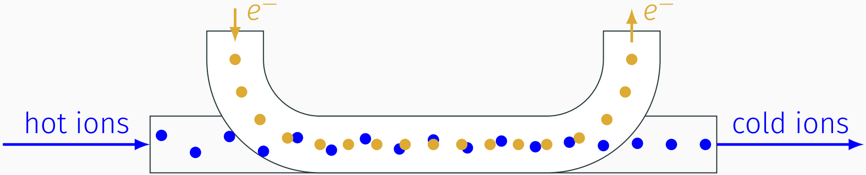


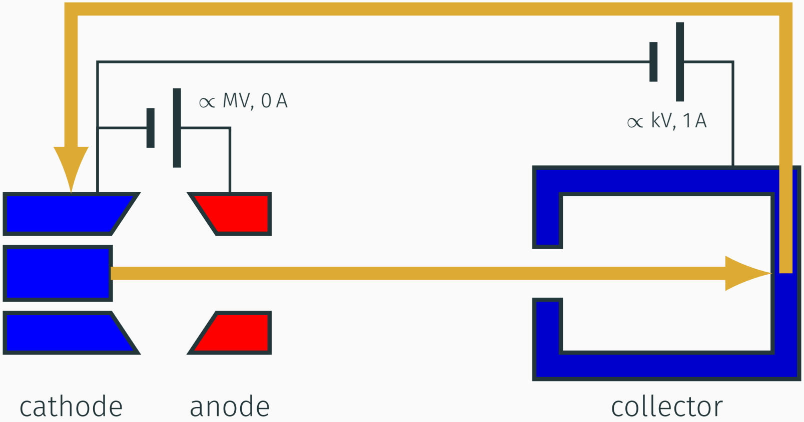


Principle of electron cooling

- reduce ion/proton beam emittance (“heat”) by mixing with cold medium
- $v_{\text{elec}} = \langle v_{\text{ion}} \rangle \quad \Rightarrow \quad E_{\text{kin,elec}} = \frac{m_{\text{elec}}}{m_{\text{ion}}} \langle E_{\text{kin,ion}} \rangle$
- 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



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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

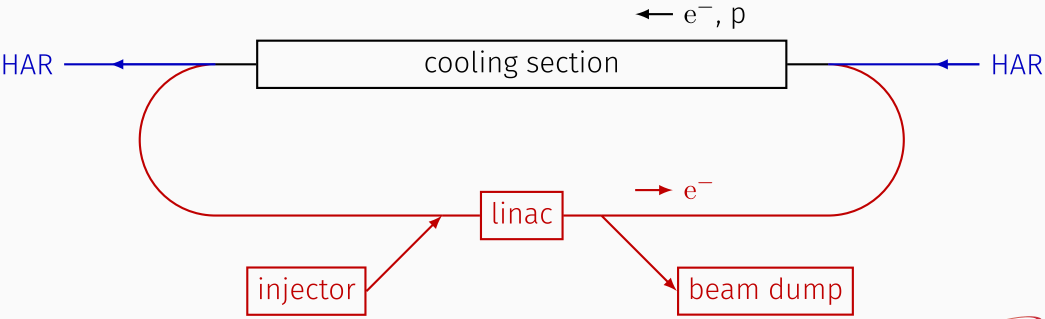
- If RF-based linac is used as electron cooler, electron beam has time structure
- How does this affect the cooling properties?
- Can we use it to our advantage to mitigate overcooling?

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

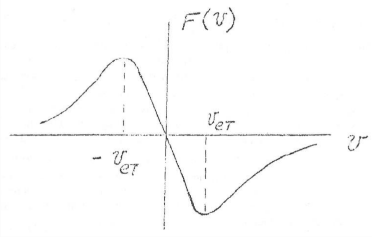
RF-based cooling considerations

- 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?

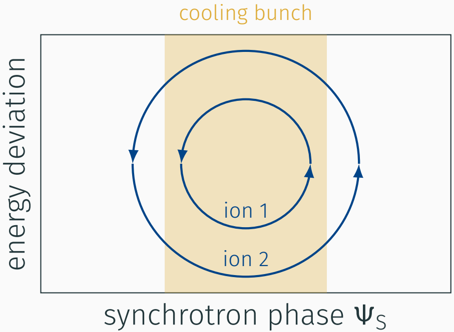


Bunched cooling with synchrotron dynamics

- 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)



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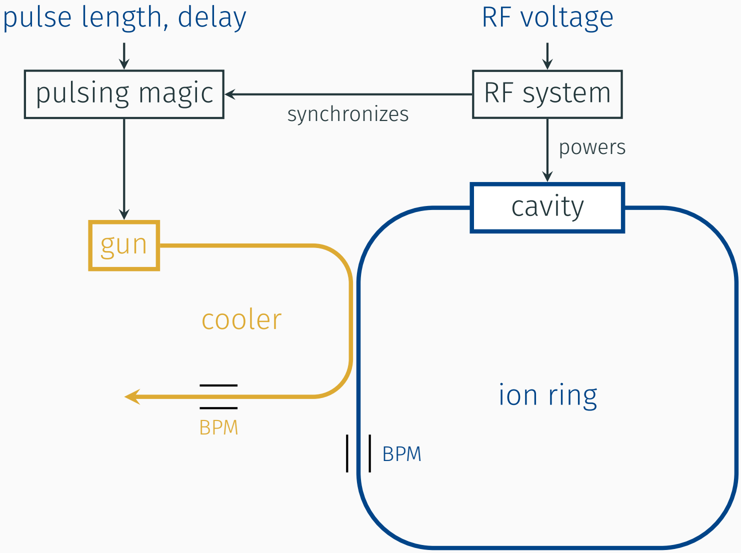
Principle of the bunched-beam cooling experiment



Beam parameters

Ion beam

Particle	$^{86}Kr^{25+}$
E_{kin}	5 MeV/nucleon
β	0.103
f_{rev}	191.5 kHz
h	2

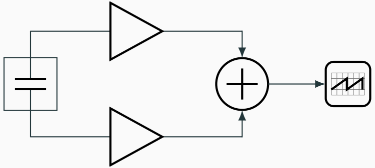
Electron beam

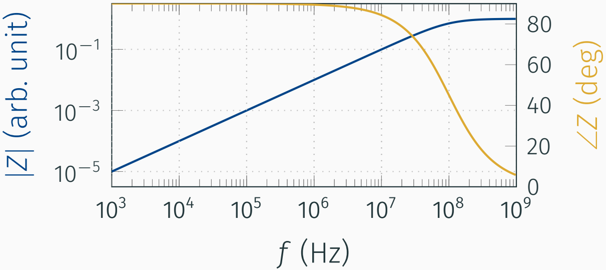
E_{kin}	2.7 keV
bunch rate	$hf_{rev} = 383$ kHz (phase adjustable)
bunch length	100–1000 ns, i.e. 3–30 m
bunch current	$\propto$ bunch length (uniform density, 30 mA)

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

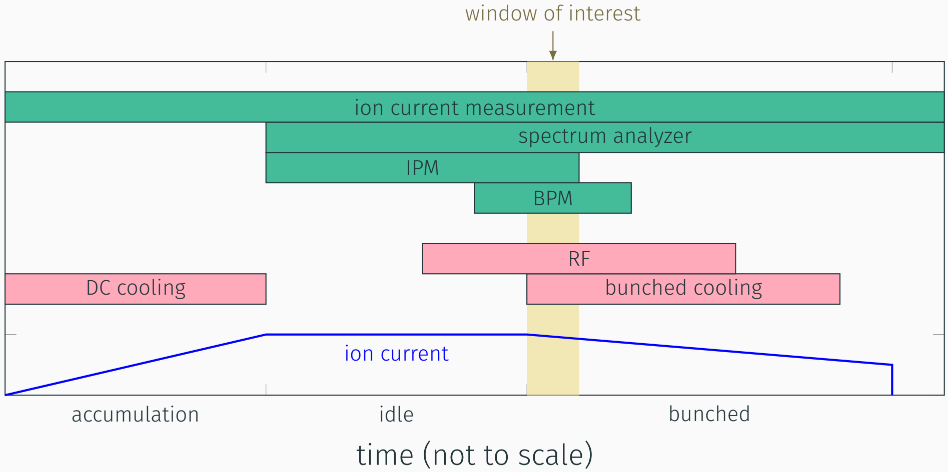
BPM setup and transfer impedance model





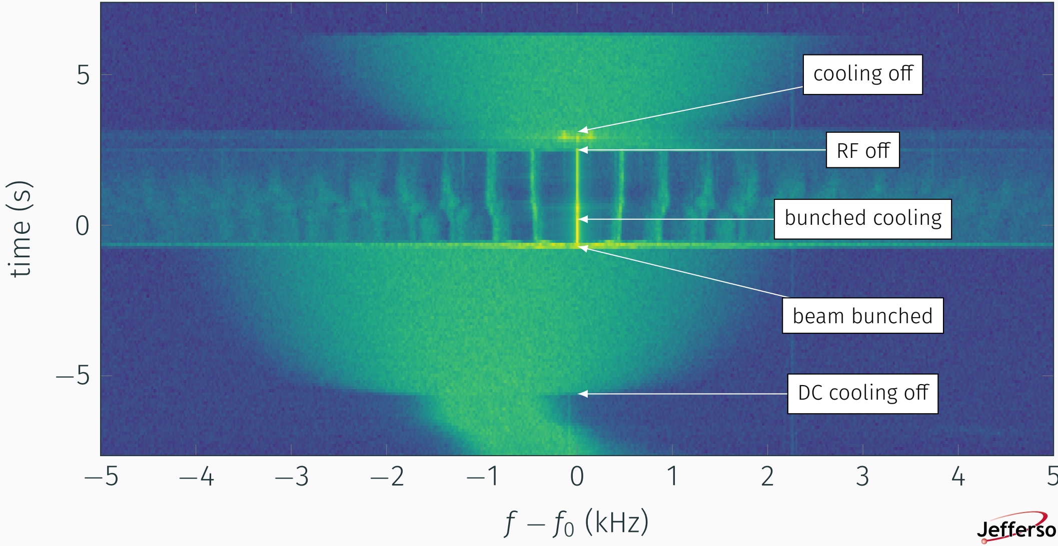
- sum signals of opposite plates to remove transverse information
- $U = ZI_{\text{beam}}$ with $Z(\omega) \propto \frac{i\omega RC}{(1+i\omega RC)}$
- record $U(t)$ with DSO
- $\mathcal{F}$ + Ohm's law + $\mathcal{F}^{-1}$ gives $I(t)$

Experimental procedure

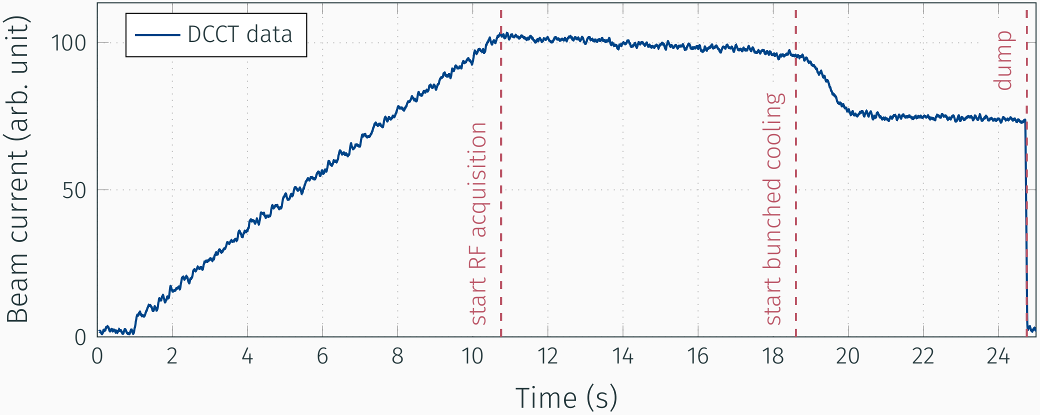


Experimental results: constant bunch phase

Synchronization of DAQ devices: spectrogram

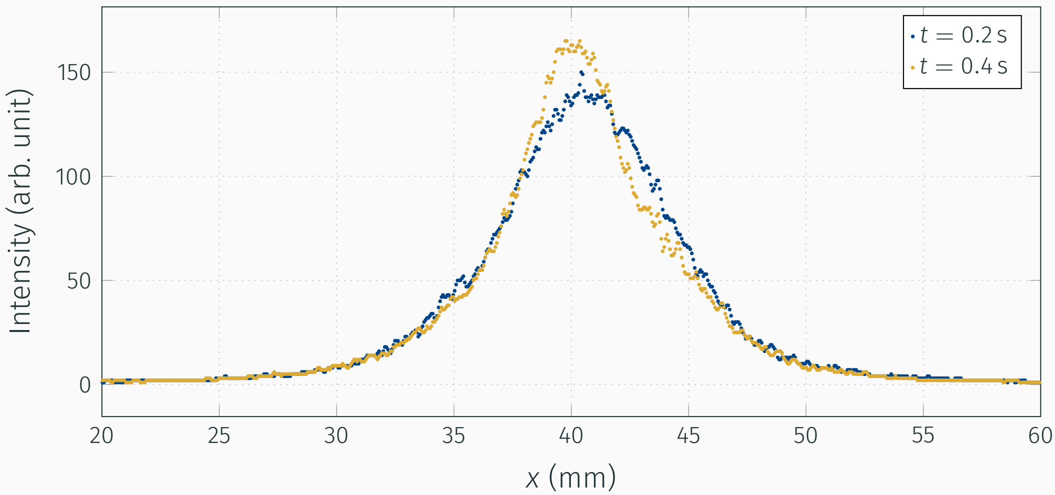


Synchronization: beam current measurement

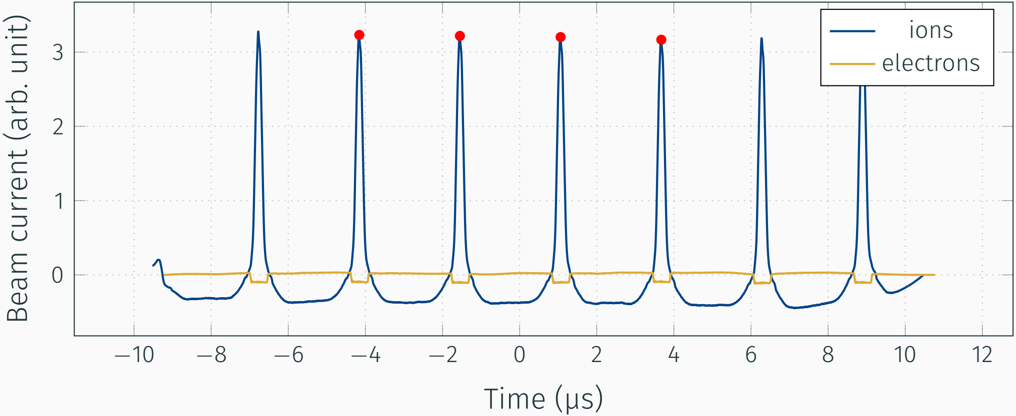


- consistency check with BPM intensity and global timing
- markers calculated from procedure; referenced to dump

Transverse profile example (500 ns, 1.0 kV)



Bunch delay measurement: whole frame (500 ns, 1 kV)

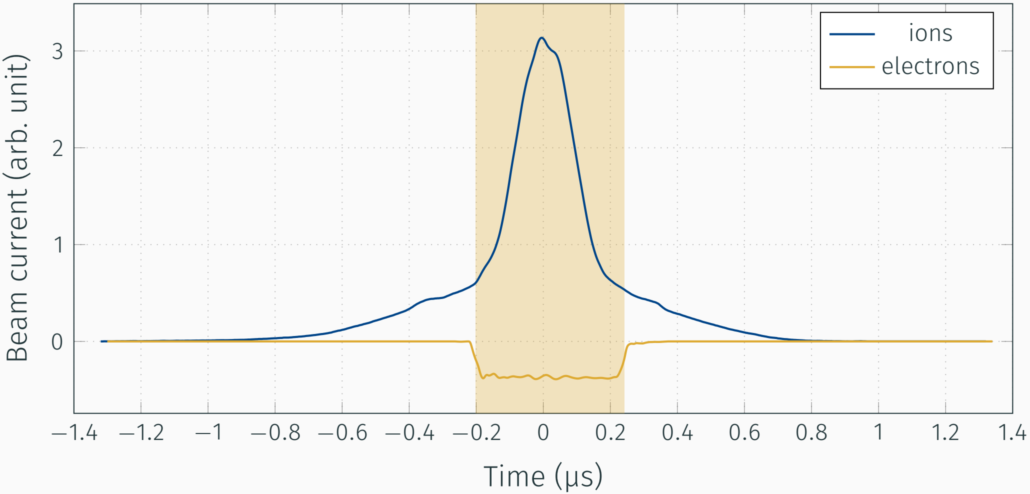


- electron time axis shifted by measured Δ in propagation delay: 286 ns

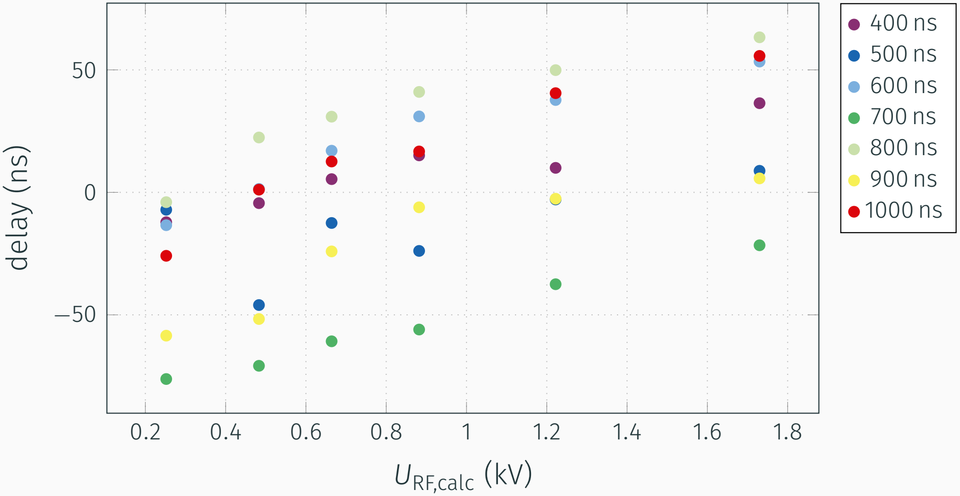
Method to determine $I_{\text{beam}}(t)$ bunch by bunch

- estimate location of ion peak maxima
- slice frame halfway between peaks; select 2nd–5th 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: $\sigma^2 = \frac{1}{n}\sum_i (x_i - \overline{x})^2$
  Excess kurtosis: $K - 3 = \frac{1}{\sigma^4}\frac{1}{n}\sum_i (x_i - \overline{x})^4 - 3$

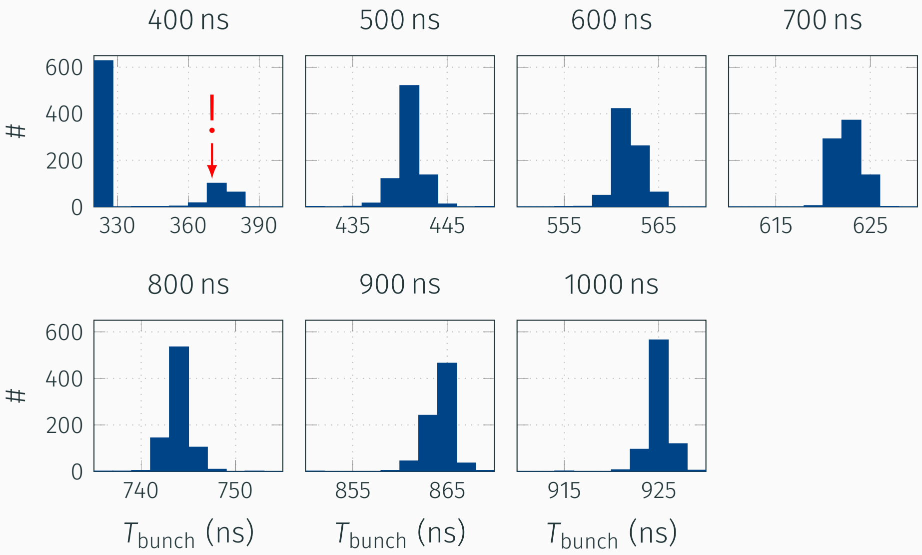
Example averaged bunch with corrections (500 ns, 1 kV)



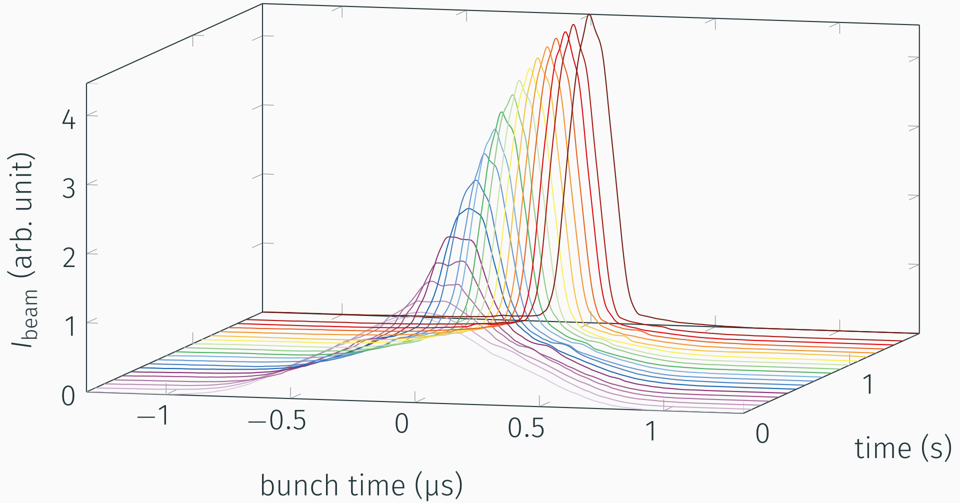
Bunch phase consistency between runs



Electron bunch length distribution



Evolution of longitudinal profile (example: 500 ns, 1.0 kV)



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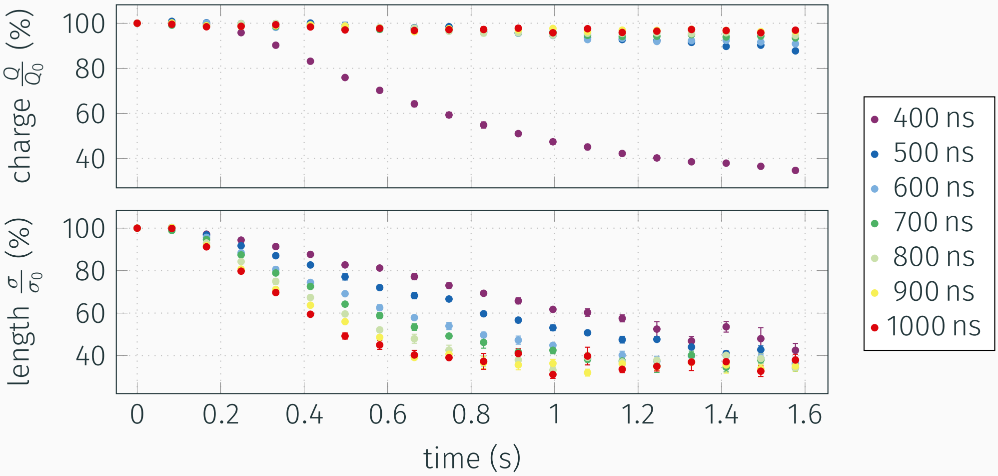
Evolution of statistical moments (example: 1.0 kV)



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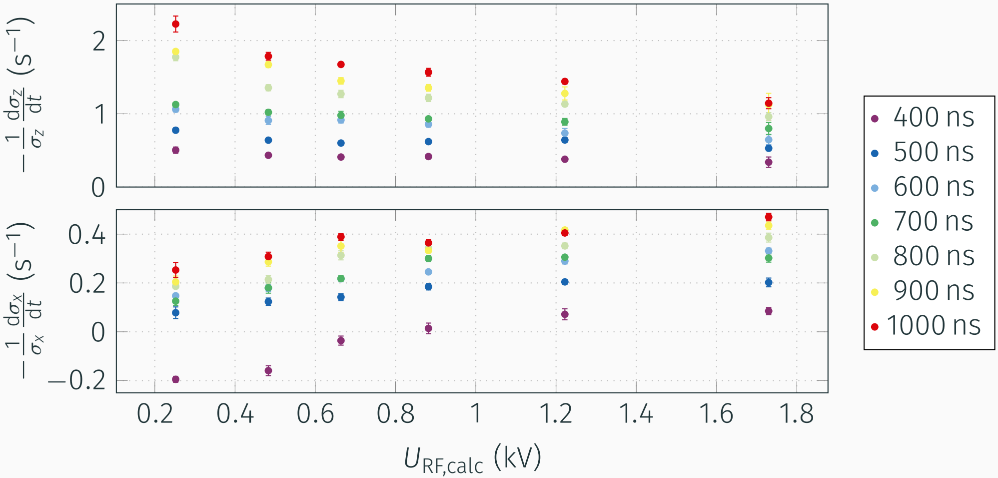
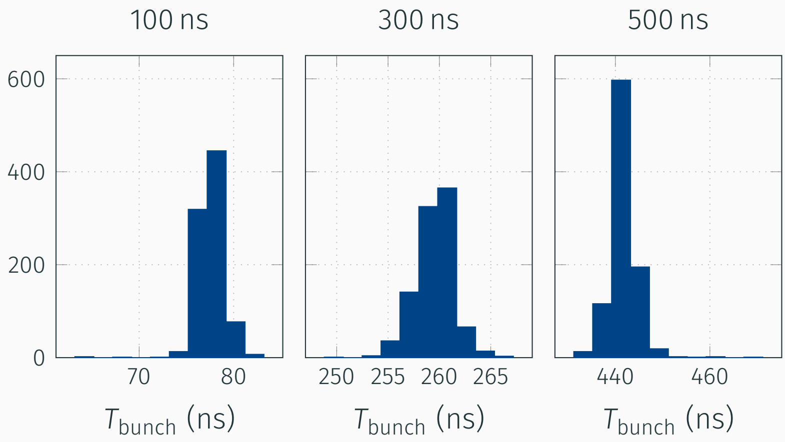
Cooling rates ($0.2\,\mathrm{s} < t < 0.4\,\mathrm{s}$)



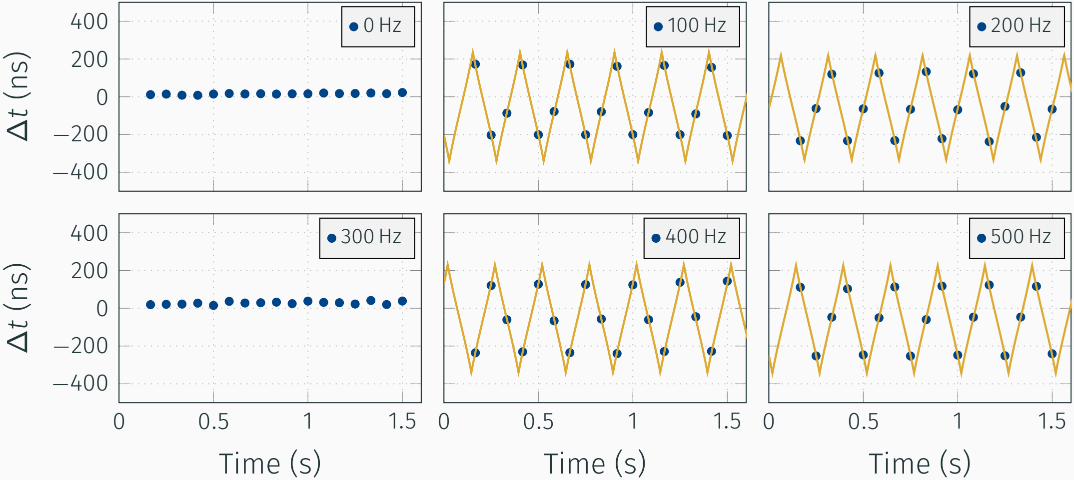
Experimental results:
Bunch phase modulation (“dithering”)
with triangle waveform

Electron bunch length distribution (with dithering)



- bunch length stable and without surprises
- also independent of delay

Aliasing image of modulation waveform (300 ns bunches)



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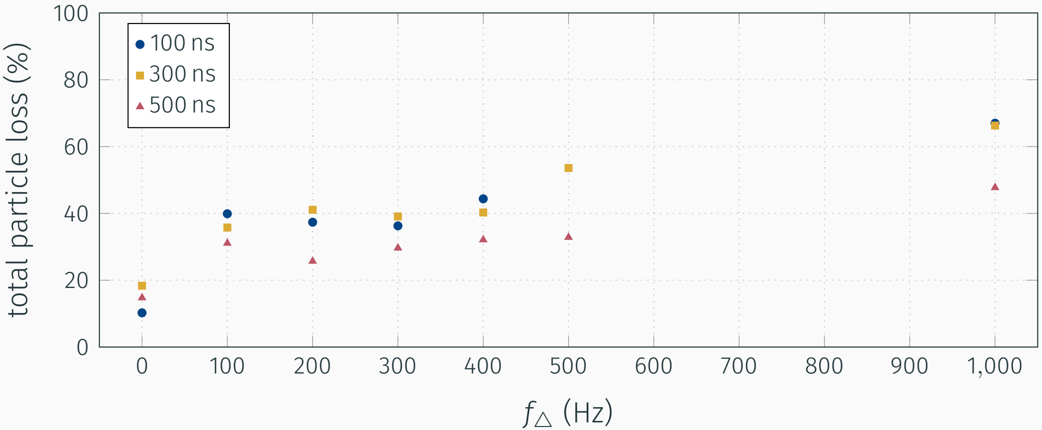
Particle loss with modulation



- Cooling investigation pointless. Find reason for loss first

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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)

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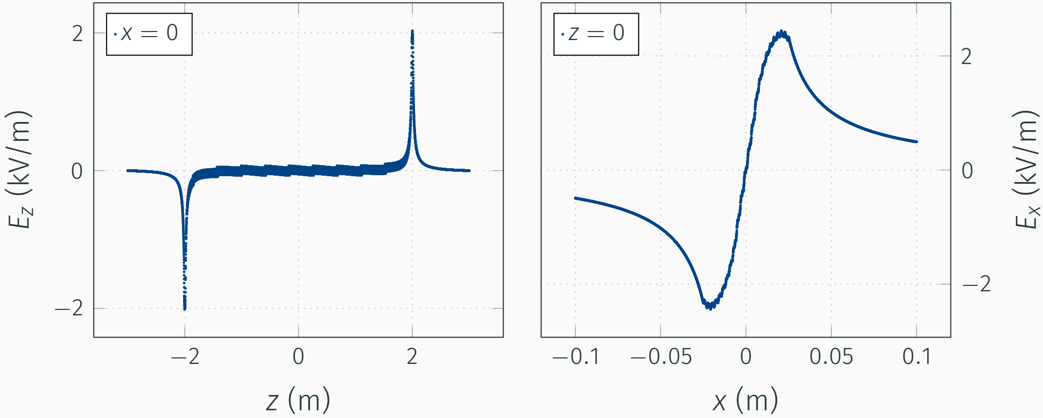
Simulation strategy

- In MAD-X: Divide the cooler into N drifts extending slightly beyond the actual edges
- Take transport matrices and track in 6-d phasespace
- 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)

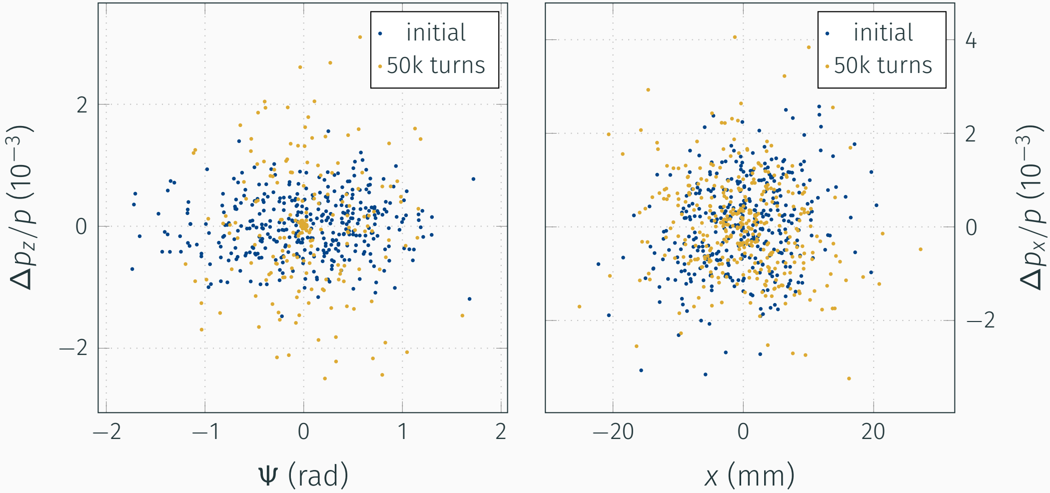


- Shape depends on longitudinal coordinate of ion. Shown for an ion located deep inside the electron bunch
- Beam pipe neglected; normally ought to be accounted for

Tracking simulation

- ion beam has no space charge $\Rightarrow$ 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



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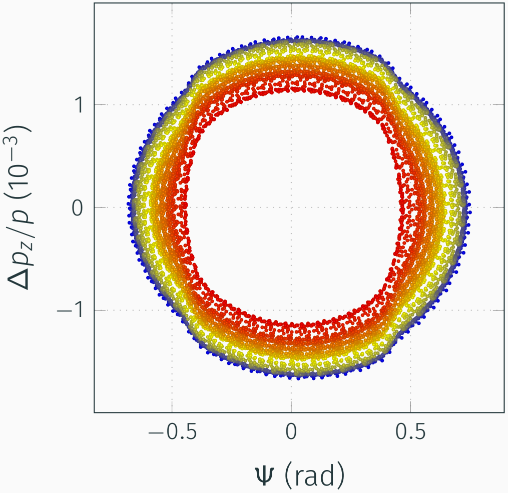
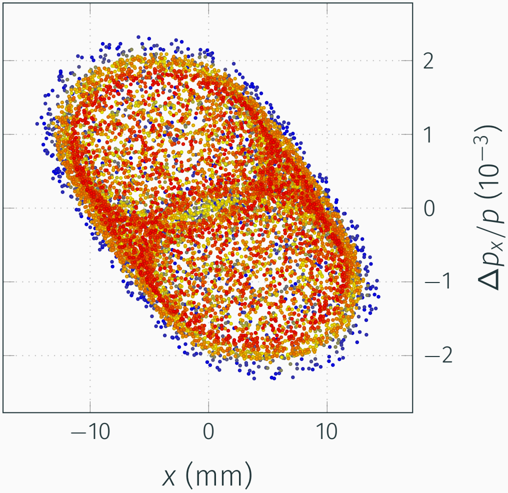
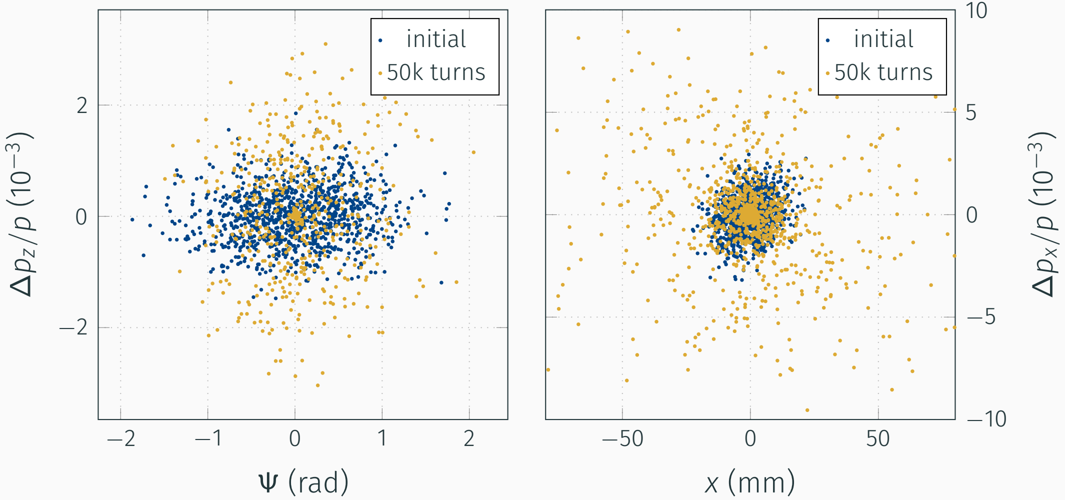
400 ns electron bunches, 30 ns rise/fall, central phase: Phase space trajectory of a single example ion





1/3 of bunches (random) with edge shift, $\Delta L = 50$ ns: Ensemble of 1000 ions according to initial emittance



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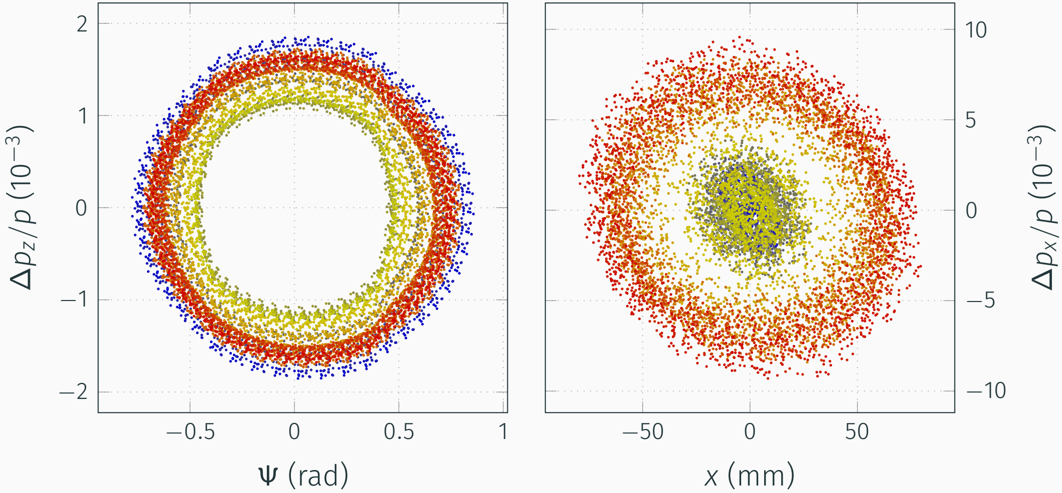
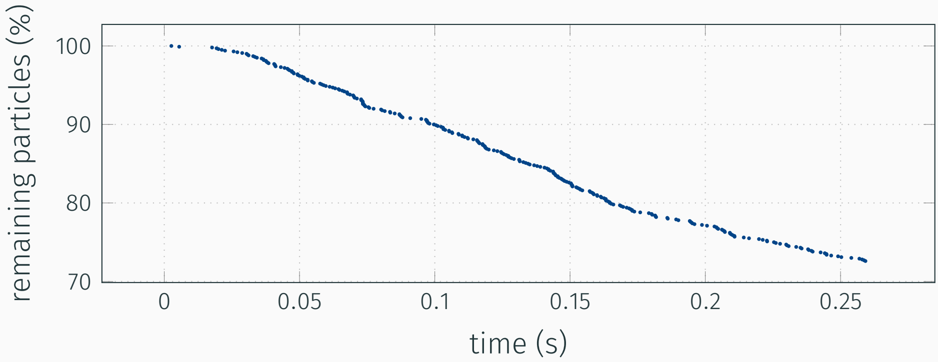


Particle loss rate (assuming transverse aperture ±50 mm)



- 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