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

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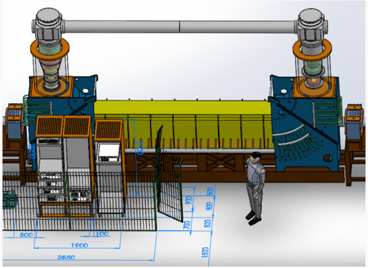

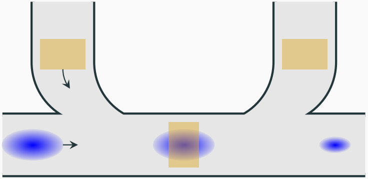

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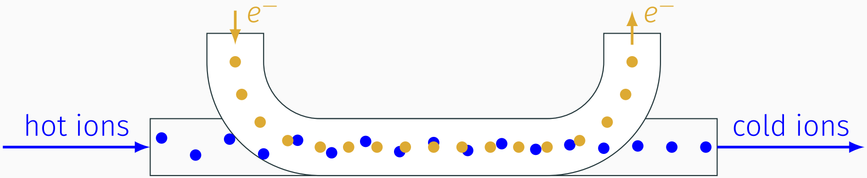
Principle of electron cooling

- reduce ion/proton beam emittance (“heat”) by mixing with cold medium
- $v_{\text{elec}} = \langle v_{\text{ion}} \rangle \quad \Rightarrow \quad E_{\text{kin,elec}} = \frac{m_{\text{elec}}}{m_{\text{ion}}} \left\langle E_{\text{kin,ion}} \right\rangle$
- e.g. protons: $\frac{E_{\text{kin,proton}}}{E_{\text{kin,elec}}} \approx 1836$
- cooling is a force that depends on the velocity deviation in the rest frame $\Rightarrow$ acts only on momentum components and relies on external focusing to affect the spatial bunch profile
- takes high number of passes $\Rightarrow$ limited to storage rings



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Purpose of the experiment

Open questions in electron cooling

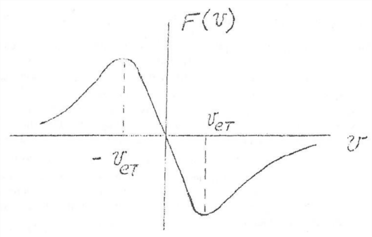
- If RF-based linac is used as electron cooler, electron beam has time structure
- How does this affect the cooling properties?
- Can we use it to our advantage to mitigate overcooling?

Experimental approach

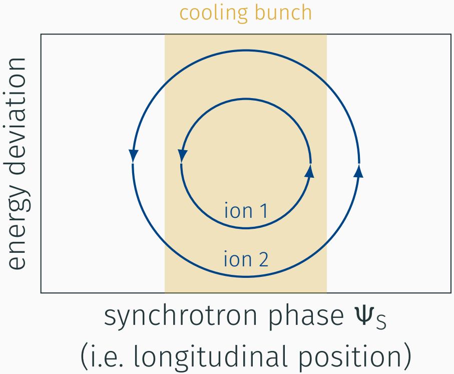
- Use available DC cooler at CSRm (IMP) and pulse the gun
- Synchronize electron pulses with ion ring RF
- But relative phase is adjustable and can be made time-dependent

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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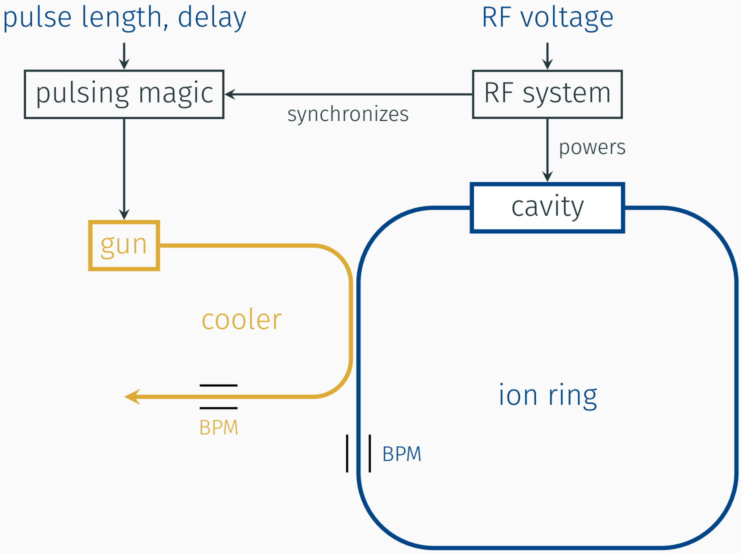
Experimental methods

Principle of the bunched-beam cooling experiment



Beam parameters

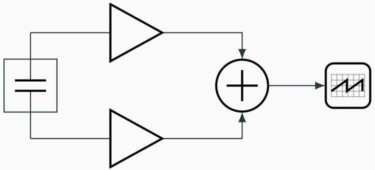
Ion beam

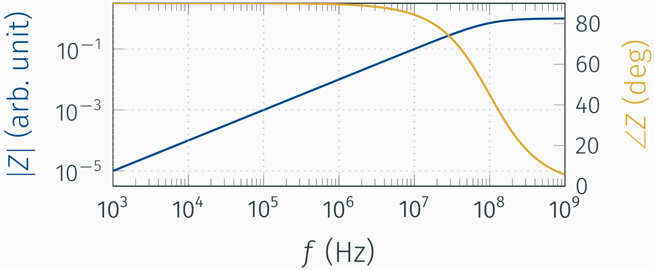
Particle	$^{86}\mathrm{Kr}^{25+}$
E_{kin}	5 MeV/nucleon
β	0.103
f_{rev}	191.5 kHz
h	2

Electron beam

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

BPM setup and transfer impedance model

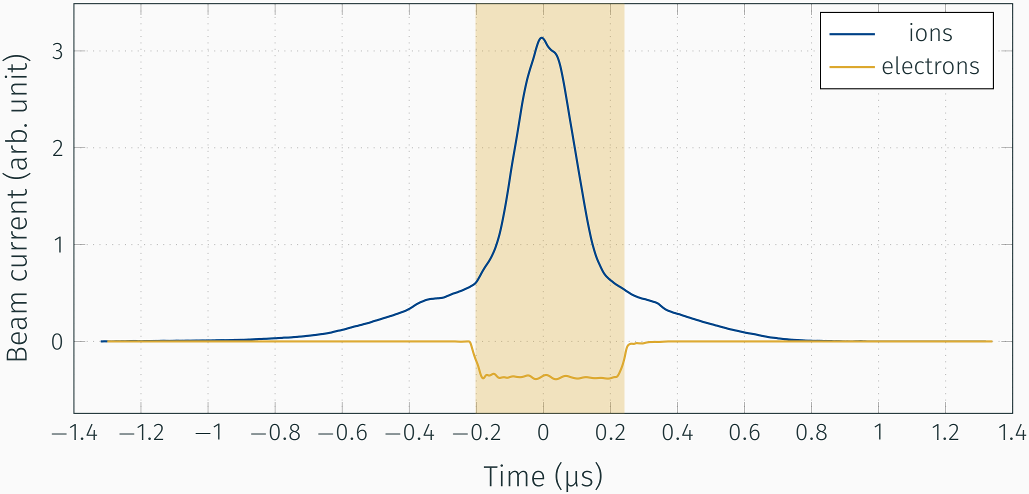




- By summing the signals of opposite BPM plates, we make the BPMs insensitive to the transverse beam position.
- The output signal is $U = ZI_{\text{beam}}$ with $Z(\omega) \propto \frac{i\omega RC}{(1+i\omega RC)}$.
- Digitize $U(t)$ and apply Ohm's law in the frequency domain to obtain $I_{\text{beam}}(t)$ ($\propto$ longitudinal bunch shape).

Experimental results: constant bunch phase

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



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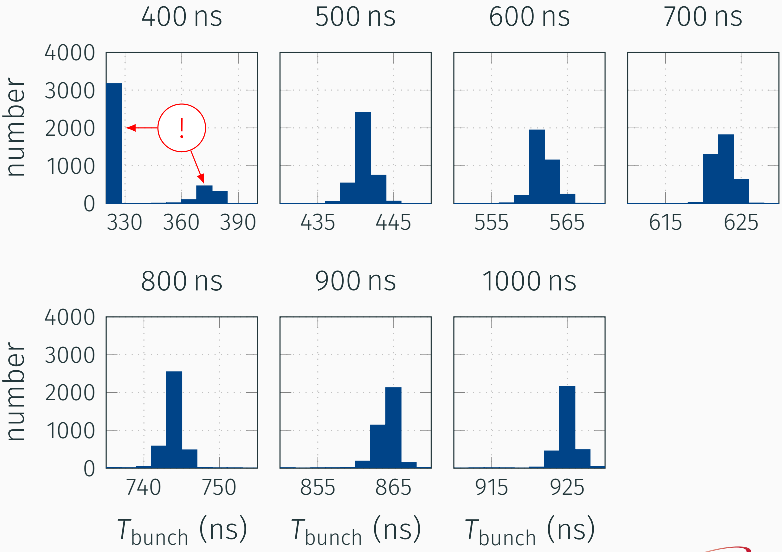
Electron bunch length distribution (accumulated from all runs)

- low RMS jitter $\propto 2$ ns
- but 400 ns bunches can have two lengths
- hardware bug



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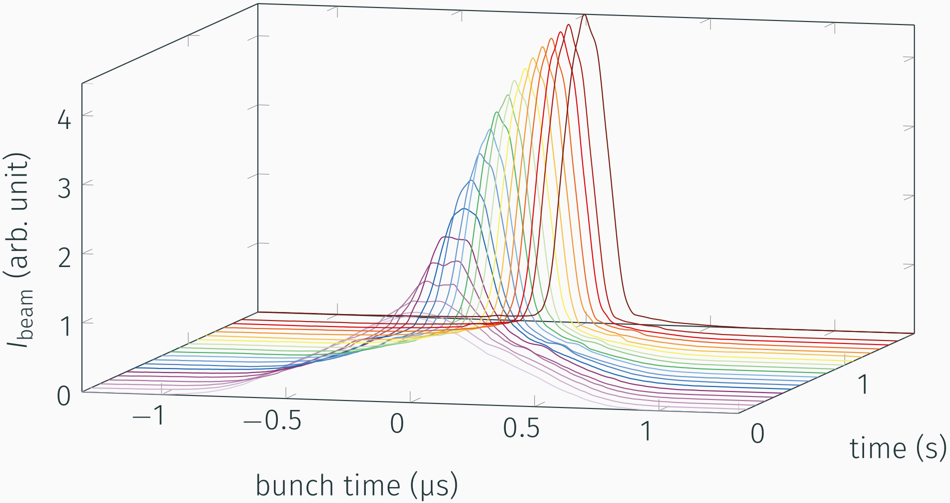
Evolution of longitudinal profile (example: 500 ns, 1.0 kV)



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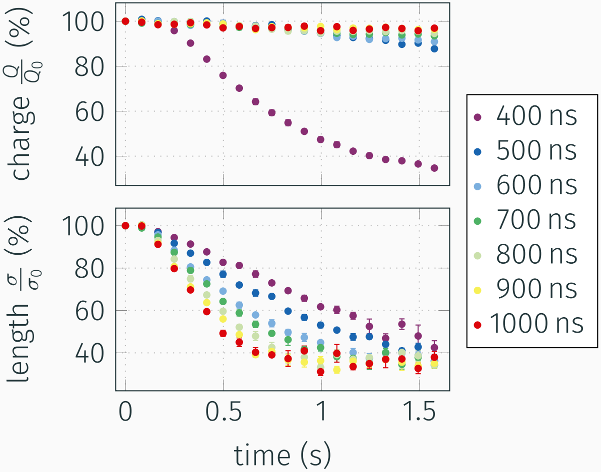
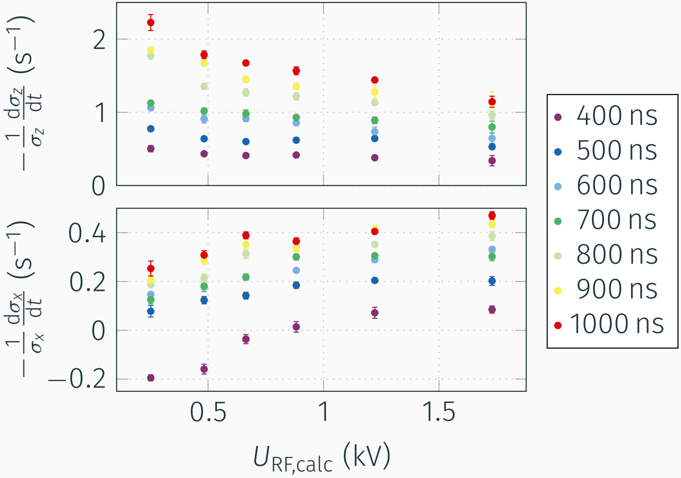
Evolution of statistical moments (example: 1.0 kV)

- Shorter bunches cool less quickly but also introduce less bunch shape distortion (not shown here).
- ∃ optimum depending on relative phase. Could not be measured due to lack of beam time.
- Note beam loss in jittering 400 ns case.



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

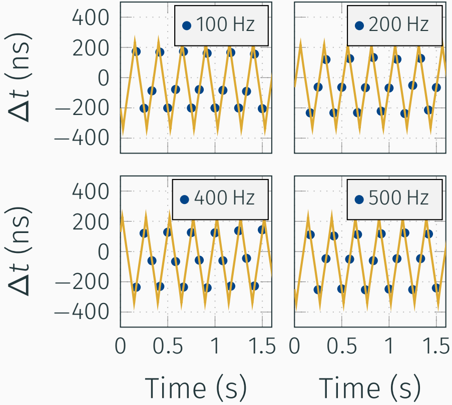
- Excessive RF focusing worsens the longitudinal cooling rate (higher velocity).
- But it increases the temporal overlap.
  $\Rightarrow$ compromise



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

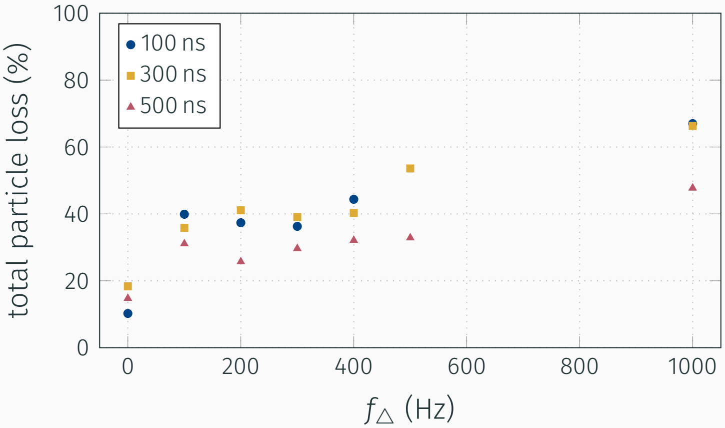
Phase dithering: Aliasing image of triangle waveform (300 ns bunches)

- Can short electron bunches be used more easily if they are intentionally moved around longitudinally at some low frequency?
- We imposed a triangle wave on the bunch phase to measure the cooling effect.
- Despite the low trigger rate (12 Hz), aliasing allows for a direct, beam-based measurement of the dithering function.



Particle loss with dithering

- Varying the phase causes particle loss.
- This method is not a good idea unless an extremely low frequency can be chosen.



Making sense of it all

Understanding the particle loss

Space charge problem

- Longitudinal: Electric force as function of synchrotron phase. Force can point in both directions.
- Transverse: Radial lens that is turned on/off as function of synchrotron phase (synchro-betatron coupling). Force always points inwards.

Tracking simulation

- ion beam has no space charge $\Rightarrow$ single-particle simulation
- apply synchrotron energy gain per revolution
- apply transport matrices one by one, check for transverse aperture
- slice cooler into drifts of length L_{slice}; for every element:
  - place macrocharges in cooler according to phase $\Rightarrow \vec{E}(\vec{r})$
  - $\vec{F} = \dot{\vec{p}} \Rightarrow \Delta\vec{p} = -\vec{E}q\frac{L_{\text{slice}}}{\beta c}$

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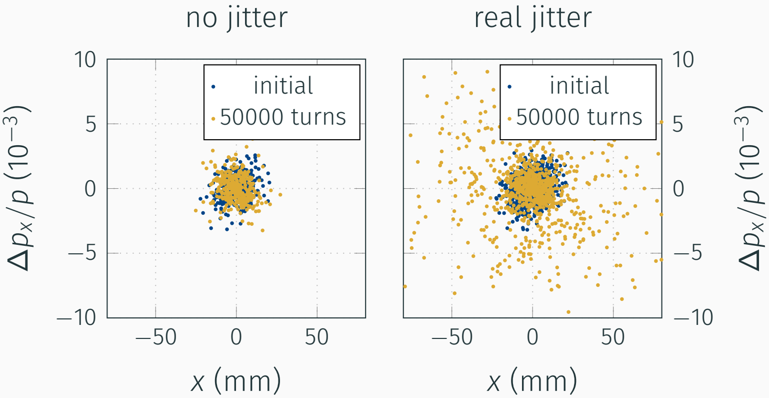
Tracking an ensemble of 1000 ions

- Varying bunch length blows up transverse phase space
- Same for phase dithering (not shown)



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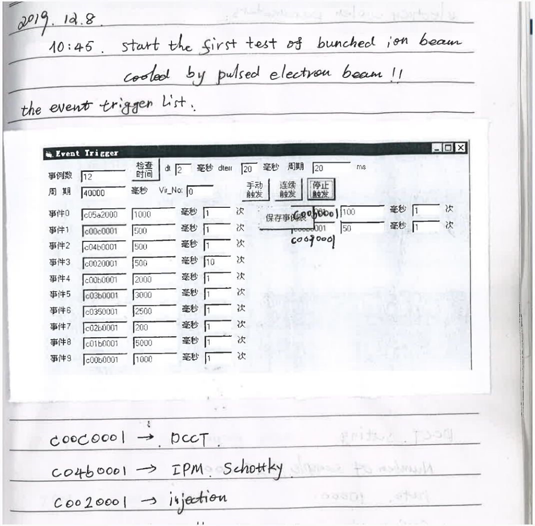
Conclusions

- Electron cooling with bunches works without major surprises.
- Dithering does not, and jitter needs to be avoided!
- This is an easy way to build a test setup that grants access to important aspects of cooling physics and corresponding beam-beam effects.



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Acknowledgments

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