Demonstration of Electron Cooling using a Pulsed Beam from an Electrostatic Electron Cooler--Dithering Cooling Result

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

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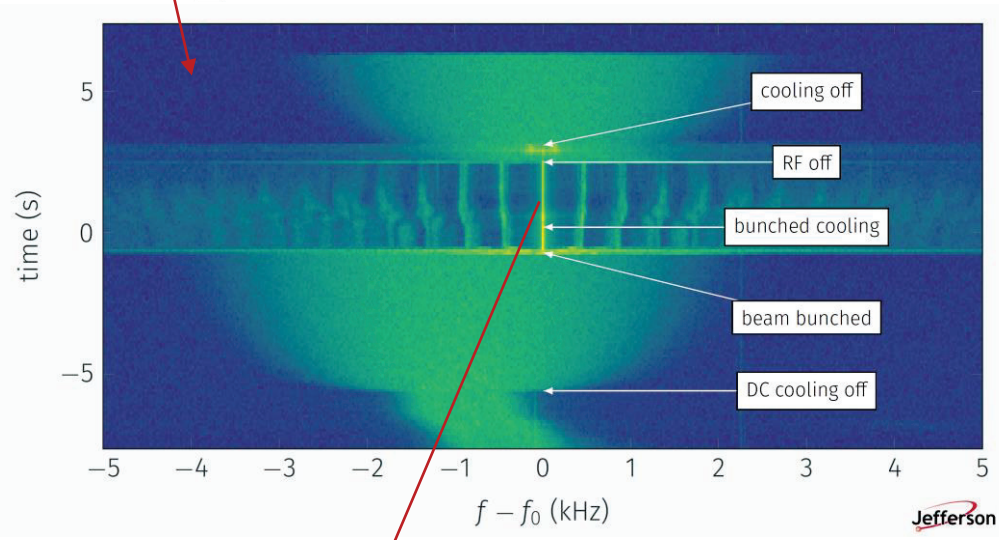
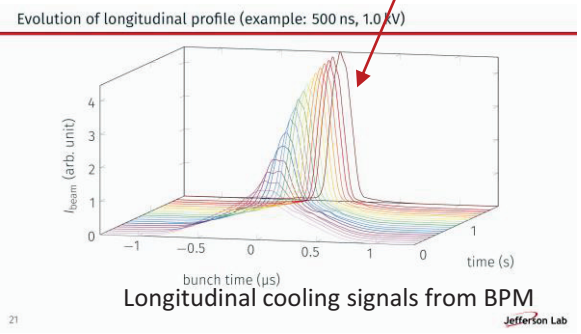
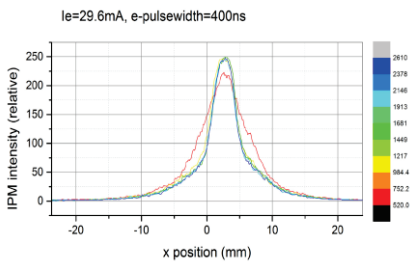




Longitudinal cooling signals from BPM



Transverse cooling signal from IPM

Haipeng Wang, Jefferson Lab, on behalf of JLab-IMP experiment team

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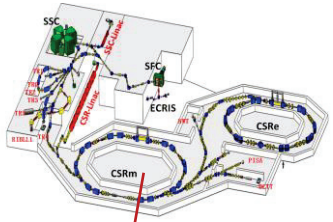
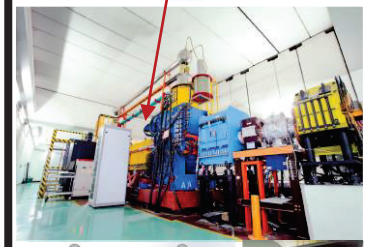
Jefferson Lab

- First demonstration of pulsed electron beam cooling to ions in 2016
- Data were mostly taken at IMP CSRm from /2016/2017/2019 in 3 runs
- Last experiment data was taken in Dec 2019 with JLab team in remote supports. The dithering data only took in last 6 hours
- "Dithering" technique is to modulate the electron pulse frequency relative the ion revolution frequency with a motivation to lower the cost of higher energy cooler (like ERL) by using a shorter bunch to cool a longer proton bunch (like for EIC) More precise terminology should be "longitudinal painting"
- Modulation frequencies from 100 to 1 kHz with triangle and square waveforms in arrival time Δt verses real time t
- After fixed frequency experiment at Δt=0, any higher frequency modulation showed a beam loss



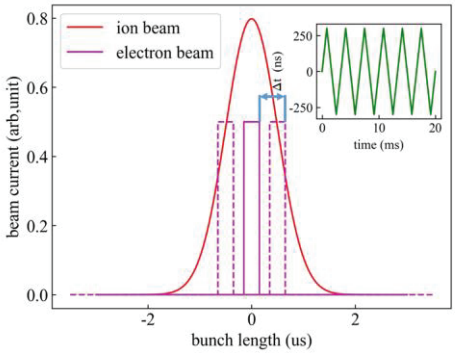


Experiment parameters for Dec. 2019 run

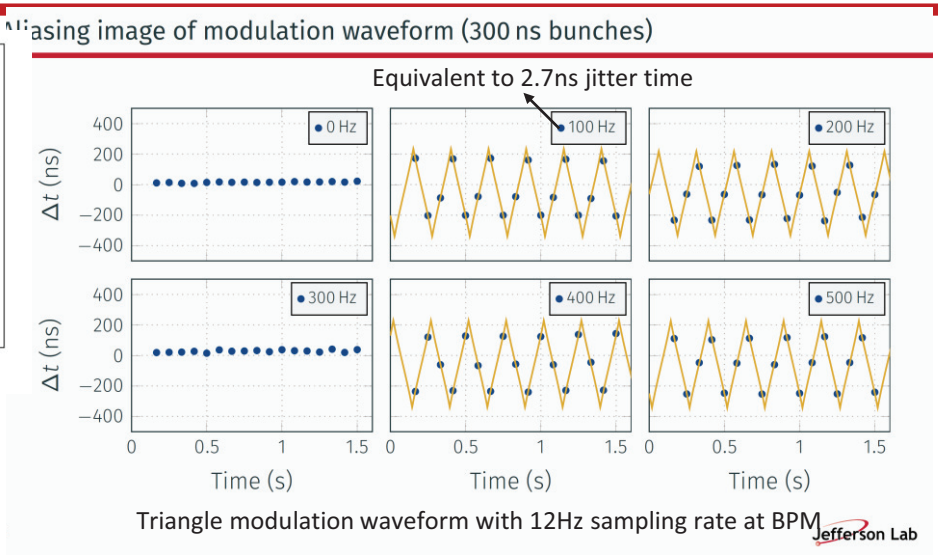
Table 1: Beam and Instrumentation Parameters

ion beam	
particle type	$^{86}Kr^{25+}$
beam current	< 100 μA
rest mass	930.5 MeV/nucleon
kinetic energy	5.0 MeV/nucleon
β	0.103
γ	1.005
revolution frequency f_{rev}	191.5 kHz
harmonic number h	2
RF voltage V_{RF}	0.6–2 kV
electron cooler	
acceleration voltage	2.7 kV
positive grid voltage	50 V
negative grid voltage	−551 V
peak current	30 mA
pulse length	> 100 ns

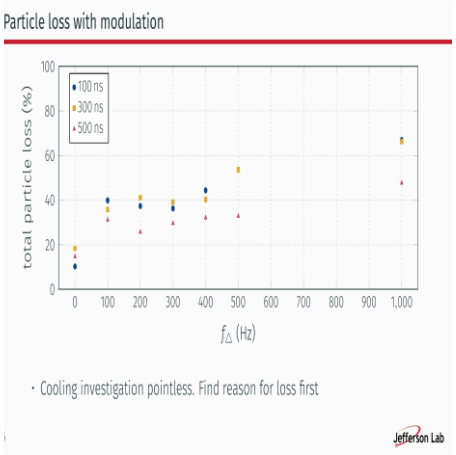
Dithering Experiment Result – More beam loss than fixed pulse frequency



Experiment setup for the longitudinal phase modulation



Triangle modulation waveform with 12Hz sampling rate at BPM



Experiment observation of beam loss from ion BPM signal

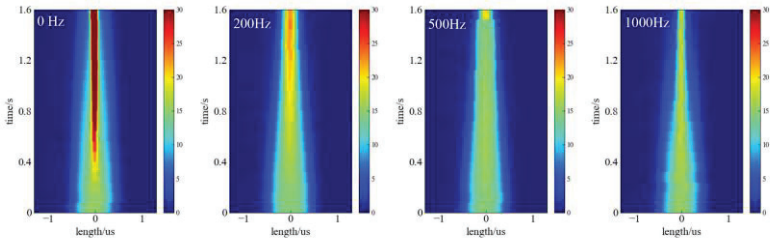


FIG. 4. Evolution of longitudinal beam profile of bunched ion beam during the cooling process with 300ns electron pulse length, and 300ns modulation amplitude

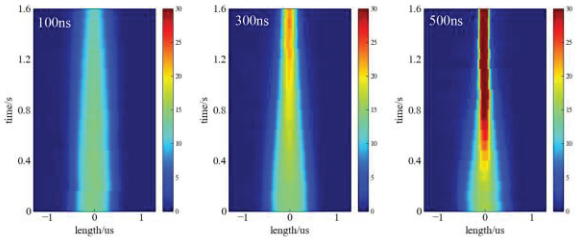


FIG. 5. Evolution of longitudinal beam profile of bunched ion beam during the cooling process measured at different electron beam bunch length for the 200Hz phase modulation frequency.

$^{86}Kr^{25+}$ emittance growth cooled by 400ns e-pulse length by tracking simulation

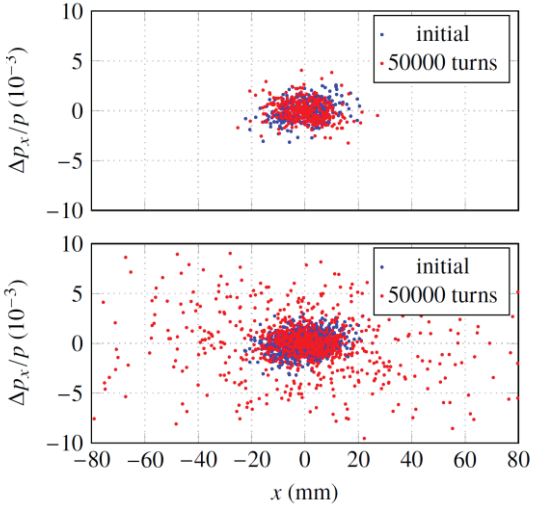
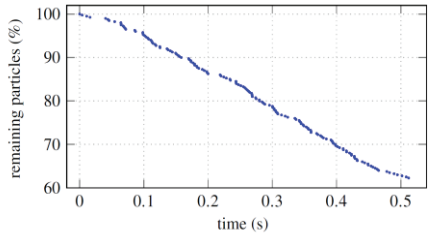
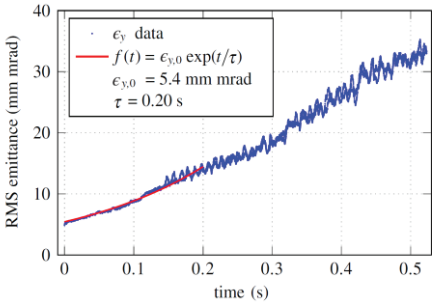


Figure 7: Comparison of the transverse phase space of the simulated ion ensemble after tracking with constant electron bunch parameters (top) and bunch length jitter as measured in the 400 ns experiment (bottom).

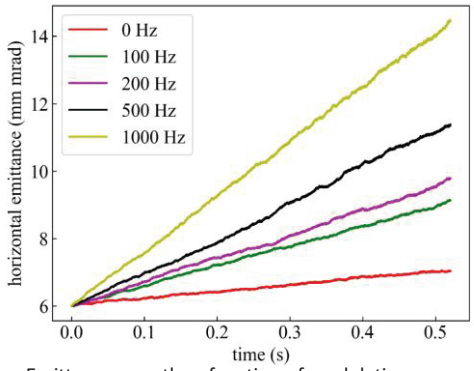
Particle loss due to beam aperture for 400ns case



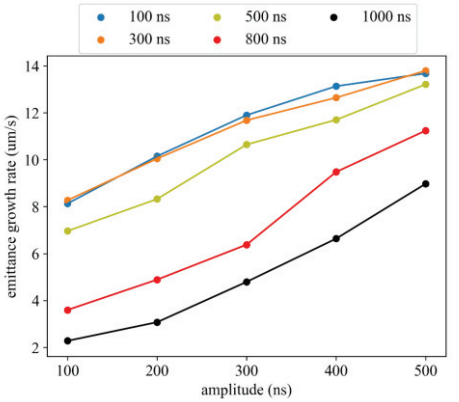
Ion emittance growth in y direction



Dithering Tracking Simulation Results [3-4] (Max Bruker and Fu Ma)– More beam loss

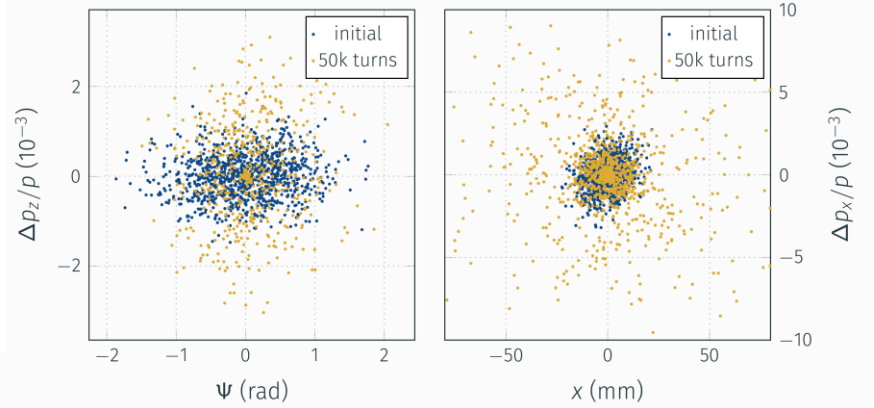


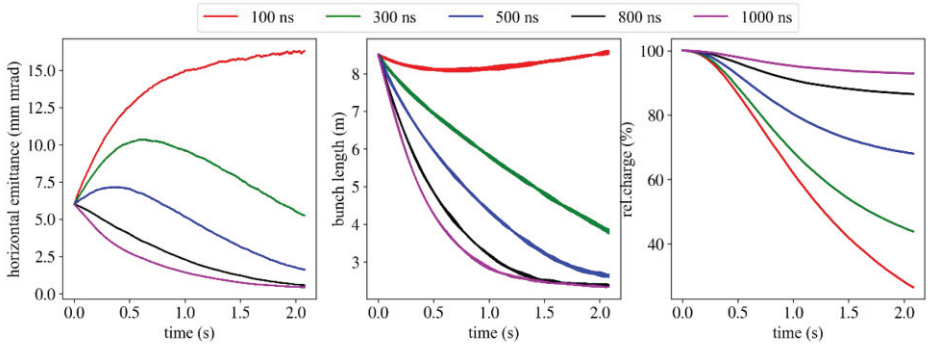
Emittance growth as function of modulation frequencies with modulation amplitude of 300ns



Emittance growth rate as function of modulation Amplitude and e-pulse lengths

ıering with 1/3 of bunches (random) with edge shift in 50 ns in 400ns pulse length





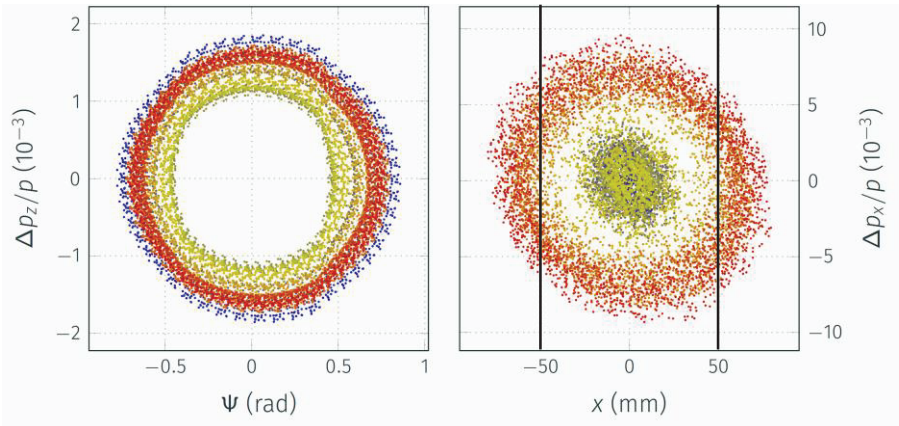


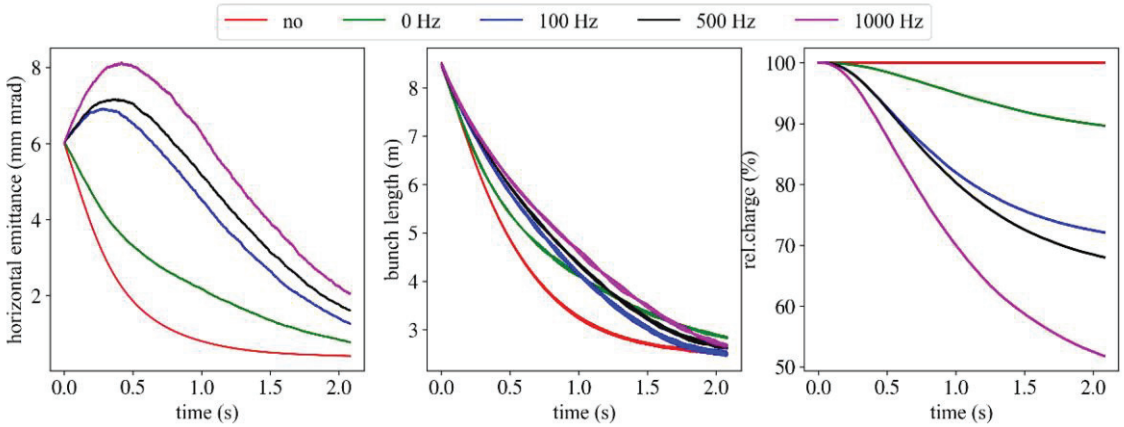
FIG. 10. The beam parameters revolution during the cooling process for different electron beam bunch lengths. The phase modulation frequency is 500 Hz and the modulation amplitude is 300 ns. From left to right are the changing process of emittance, beam length and beam loss.

Space-charge tune shift by e-bunch transiverse kicking

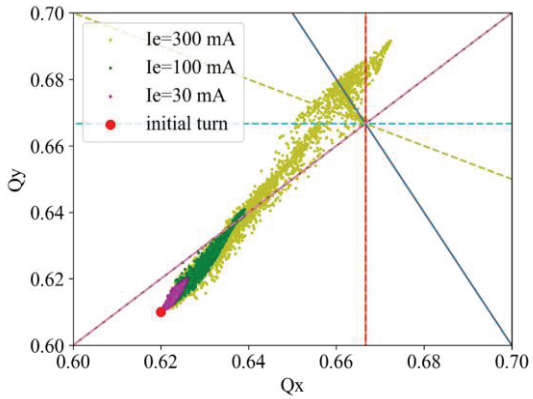
$$\Delta\nu_{\mathrm{peak},x/y} = \frac{N_e r_0 L_{\mathrm{cool}}}{(2\pi)^2 Q_{x/y} f_{\mathrm{rev}} \sqrt{2\pi}\sigma_e \gamma^3 \beta^2 a_e^2}$$

=4.1-5.6 x 10^{-3} at γ=1.005 low energy level, low $\gamma^3\beta^2$ causes high $\Delta\nu_{peak}$

Beam Loss Mechanisms [2] Summary [3,4] for Dithering Method



Different modulation frequencies with 300ns modulation amplitude and 500ns e-pulse length



Bunch current tune spread in transverse tunes map

- Large space charge tune at low energy can cause emittance growth (heating) and then further beam loss due to synchro-betatron coupling resonance.
- In our experiment, emittance growth time for ~20 ns arrival jitter is ~0.34-0.66 s, corresponding the space-charge tune shift and experimental data. 1 % of rms peak current fluctuation at 30 mA [2] can only tolerate the beam store time of 2.6s.
- Emittance growth can not easily avoid k=0, dc like, 30 mA synchro-betatron resonance with a large space charge kick (tune shift). More studies need to be done to explore the third Qz tune spread with RF focusing and e-pulse edge kicking and their coupling effect to the transverse emittance growth.
- However, for a higher energy cooler like LEReC, the space charge tune shift has been reduced by 10^4 times. The synchro-betatron coupling can tolerate up to k=4th order resonances.
- More precise triggering control of HV pulsing system and beam diagnostic systems need to be improved at CSR, IMP
- More meaningful experiment at higher energy like at the CSRe IMP is meaningful for the further scaling law study of future EIC SHC machine including the simulation supports to understand those data

[1] M. Bruker et al., "Demonstration of electron cooling using a pulsed beam from an electrostatic electron cooler," Phys. Rev. Accel. Beams, vol. **24**, 012 801(2021). doi: 10.1103/PhysRevAccelBeams.24.012801. https://link.aps.org/doi/10.1103/PhysRevAccelBeams.24.012801

[2] G.Wang, Ion Emittance Growth due to Focusing Modulation from Slipping Electron Bunch, BNL Tech Rep. No. C-A/AP/536, 2015

[3] M. Bruker, etc, Demonstration of electron cooling using pulsed beam from an electrostatic electron cooler, IPAC 2021, paper TUPAB181

[4] F. Ma, etc, Beam Cooling by a Bunched Electron Beam with Phase Modulation, unpublished manuscript, 2021.