Bunched Beam Cooling Experiment Report
(and future plan)

Haipeng Wang
Jefferson Lab

Funding Support by the EIC R&D FOA 2018-2019 award of US DOE under Contract No. DE-AC05-06OR23177 and by the NSF of China under Contract No. 11575264, No. 11375245, No. 11475235 and the Hundred Talents Project of the CAS.

Contributions:
L.J Mao (IMP PI), R. S. Mao, M.T. Tang, J. Li, X.M. Ma, J.C. Yang, X.D. Yang, Y.J. Yuan, H. Zhao, H.W. Zhao, T. C. Zhao Institute of Modern Physics, Lanzhou 730000, China

EIC Accelerator Collaboration Meeting
October 29 - November 1, 2018
Motivation, Experiments and Data Analysis:

- JLEIC design needs a bunched electron at 55-110MeV to cool ions to compensate the luminosity loss due to the IBS and counter balance the space charge effect on the beam emittance grow.
- Purpose of this experiment was using existing IMP’s SC 35 cooler at CSRm ring modified to make the pulsed electron beam to demonstrate the cooling of the ion beam from a coasting to an equivalent bunch length.
- Although the beam energy and bunch length is far from the JLEIC cooler design. Understanding the strong bunched beam cooling principle, benchmark simulation tools with right the physics model is the primary goal this experiment.

- May 2016, 1st experiment: bunched beam electron was formed by JLab’s HV pulser cooling was observed for the 1st time. Data was taken at different injection fills.
- April 2017, 2nd experiment: improved triggering control and beam instrumentation for taking data in the same injection fill so cooling process was more clearly observed.
- Strong BPM (time domain) and Schottky (frequency domain) diagnostic signals confirmed the bunched beam cooling process qualitatively, implying a new physics process beyond the DC based strong cooling model.
- Agree with 3D pulsed cooling model and 1D pulse + RF focusing models simulations but all of them are lack of quantitative benchmarks against to the experimental data.
- Design to improve the beam diagnostics both in hardware and software for next experiment Dec. 3-8, 2018.
- Plan to move next phase of experiment at CSRe ring in 2019-2020.
EC-35 cooler

electron-BPM at gun position

ion-BPM after the cooler position

0.121×c⊥×332.8ns=12.072m

<table>
<thead>
<tr>
<th></th>
<th>CSRm</th>
<th>CSRe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>161.0014</td>
<td>128.8011</td>
</tr>
<tr>
<td>Geometry</td>
<td>Race-track</td>
<td>Race-track</td>
</tr>
<tr>
<td>Max. energy</td>
<td>900 (C⁶⁺)</td>
<td>600 (C⁶⁺)</td>
</tr>
<tr>
<td></td>
<td>400 (U⁹⁰⁺)</td>
<td>400 (U⁹⁰⁺)</td>
</tr>
<tr>
<td></td>
<td>0.91/10.64</td>
<td>1.20/8.40</td>
</tr>
<tr>
<td></td>
<td>0.12/1.40</td>
<td>0.20/1.40</td>
</tr>
<tr>
<td>Ramping rate</td>
<td>0.05</td>
<td>0.1 ~ 0.2</td>
</tr>
<tr>
<td>Repeating circle</td>
<td>~ 17 (~ 10s for Accumulation)</td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>Normal mode</td>
<td>Normal mode</td>
</tr>
<tr>
<td>Aₜ (π mm-mrad)</td>
<td>200 (Δp/p = ±0.15 %)</td>
<td>150 (Δp/p =±0.5%)</td>
</tr>
<tr>
<td>Aₜ (π mm-mrad)</td>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td>Δp/p (%)</td>
<td>1.25</td>
<td>2.6</td>
</tr>
<tr>
<td>Δp/p (%)</td>
<td>(εₜ = 50 π mm-mrad)</td>
<td>(εₜ = 10 π mm-mrad)</td>
</tr>
<tr>
<td>Ion energy (MeV/u)</td>
<td>8---50</td>
<td>25---450</td>
</tr>
<tr>
<td>length (m)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>RF system</td>
<td>Accel.</td>
<td>Capture</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1 16, 32, 64</td>
<td>1</td>
</tr>
<tr>
<td>fₘᵢₙ/fₘₐₓ (MHz)</td>
<td>0.24/1.81</td>
<td>0.5 / 2.0</td>
</tr>
<tr>
<td>Voltages (n × kV)</td>
<td>1 × 7.0</td>
<td>2 × 10.0</td>
</tr>
<tr>
<td>Vacuum (mbar)</td>
<td>6.0 × 10⁻¹¹</td>
<td>(3.0 × 10⁻¹¹)</td>
</tr>
</tbody>
</table>
Modification of SC-35 Gun and New Switching Pulser and Fiber Optical Controller
$I_{\text{cathode}} = P_k \left( V_{\text{grid}} - V_{\text{bias}} + \frac{V_{\text{anode}} + V_{\text{grid}} - V_{\text{bias}}}{\mu} \right)^{1.5}$

$P_k = 5.6 \times 10^{-6} \text{ P}_v$, $\mu = 10$

Space-charge dominated emission

Electrical connection of the gun and collector for EX-35
### Experiment Parameters and Data Taken in 2016/2017

#### ION RING

<table>
<thead>
<tr>
<th>Specie</th>
<th>12C6+</th>
<th>12C6+</th>
<th>12C6+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Charge</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Charge per Nucleon</td>
<td>7.0</td>
<td>30.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Kinetic Energy per Nucleon</td>
<td>7.0</td>
<td>30.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Beta</td>
<td>0.121</td>
<td>0.247</td>
<td>0.198</td>
</tr>
<tr>
<td>Gamma</td>
<td>1.007</td>
<td>1.032</td>
<td>1.020</td>
</tr>
<tr>
<td>Revolution Time</td>
<td>4.427</td>
<td>2.177</td>
<td>2.712</td>
</tr>
<tr>
<td>Revolution Frequency</td>
<td>225.907</td>
<td>459.342</td>
<td>368.678</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Electron Cooler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>3.81</td>
<td>16.34</td>
<td>10.35</td>
</tr>
<tr>
<td>Electron Pulse Edge Width</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>dI/dt</td>
<td>2.64</td>
<td>2.64</td>
<td>2.64</td>
</tr>
<tr>
<td>Cooling Section Length</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Electron Kick dE per Turn</td>
<td>0.306</td>
<td>0.071</td>
<td>0.112</td>
</tr>
<tr>
<td>E Beam Radius at Cooler Section</td>
<td>1.25-2.5</td>
<td>1.25-2.5</td>
<td>1.25-2.5</td>
</tr>
</tbody>
</table>

#### IMP (CSRm ring)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>12C6+</td>
<td>12C6+</td>
<td>12C6+</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Charge per Nucleon</td>
<td>7.0</td>
<td>30.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Kinetic Energy per Nucleon</td>
<td>7.0</td>
<td>30.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Beta</td>
<td>0.121</td>
<td>0.247</td>
<td>0.198</td>
</tr>
<tr>
<td>Gamma</td>
<td>1.007</td>
<td>1.032</td>
<td>1.020</td>
</tr>
<tr>
<td>Revolution Time</td>
<td>4.427</td>
<td>2.177</td>
<td>2.712</td>
</tr>
<tr>
<td>Revolution Frequency</td>
<td>225.907</td>
<td>459.342</td>
<td>368.678</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Electron Cooler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>3.81</td>
<td>16.34</td>
<td>10.35</td>
</tr>
<tr>
<td>Electron Pulse Edge Width</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>dI/dt</td>
<td>2.64</td>
<td>2.64</td>
<td>2.64</td>
</tr>
<tr>
<td>Cooling Section Length</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Electron Kick dE per Turn</td>
<td>0.306</td>
<td>0.071</td>
<td>0.112</td>
</tr>
<tr>
<td>E Beam Radius at Cooler Section</td>
<td>1.25-2.5</td>
<td>1.25-2.5</td>
<td>1.25-2.5</td>
</tr>
</tbody>
</table>

#### IMP (CSRm cooler)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Pulse Edge Width</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>dI/dt</td>
<td>2.64</td>
<td>2.64</td>
<td>2.64</td>
</tr>
<tr>
<td>Cooling Section Length</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Electron Kick dE per Turn</td>
<td>0.306</td>
<td>0.071</td>
<td>0.112</td>
</tr>
<tr>
<td>E Beam Radius at Cooler Section</td>
<td>1.25-2.5</td>
<td>1.25-2.5</td>
<td>1.25-2.5</td>
</tr>
</tbody>
</table>

#### High Voltage Pulser, DEI PVX-4150

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Average Switching Power</td>
<td>571.2</td>
<td>571.2</td>
<td>571.2</td>
</tr>
<tr>
<td>Optimum Anode Voltage</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Maximum Pulse Rep Rate at Clamped Grid Voltage</td>
<td>575.0</td>
<td>291.0</td>
<td>371.0</td>
</tr>
<tr>
<td>Maximum Pulse Grid Voltage at Revolution Frequency</td>
<td>177.36</td>
<td>89.09</td>
<td>110.91</td>
</tr>
<tr>
<td>Maximum Pulsed Peak Current at Revolution Frequency</td>
<td>297.0</td>
<td>291.0</td>
<td>145.0</td>
</tr>
<tr>
<td>Maximum Pulsed Peak Current at Bunch Frequency</td>
<td>90.64</td>
<td>89.09</td>
<td>55.42</td>
</tr>
<tr>
<td>Maximum Pulsed Peak Current at Bunch Frequency</td>
<td>-400.00</td>
<td>-400.00</td>
<td>-400.00</td>
</tr>
<tr>
<td>Minimum Negative Base to Suppress the Dark Current</td>
<td>220.000</td>
<td>220.000</td>
<td>220.000</td>
</tr>
<tr>
<td>Grid Voltage Clamp for the 150W</td>
<td>71.719</td>
<td>71.719</td>
<td>71.719</td>
</tr>
<tr>
<td>Maximum Peak Current at Clamped Voltage</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### JLab modified DC e-gun pulse generator’s limitation

On April 27, 2017 trial to ramp higher ion energy, but failed to cool it due to lack of DC cooling at injection, so beam intensity was not high enough for the cooling demonstration.
Cooling at injection energy at 7MeV/u [most experiment data taken at this energy]

**Advantage:**
1. High beam current
2. Good beam quality
3. Easy for measurement

**Disadvantage:**
1. We have to switch on the DC cooling first, and then stop the cooling for few seconds, finally switch on the pulsed cooling
2. More PLC control modification on grid anode
## Beam diagnostics at CSRm for bunched cooling experiment

<table>
<thead>
<tr>
<th>Diagnostics</th>
<th>Function</th>
<th>Trigger</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion BPMs</td>
<td>Measure the ion bunch shape and current</td>
<td>Yes</td>
<td>Labview (JLab) with LeCroy Scope and E-gun PLC</td>
</tr>
<tr>
<td>Electron BPMs</td>
<td>Measure the electron pulse shape and current</td>
<td>Yes</td>
<td>Labview (JLab)</td>
</tr>
<tr>
<td>DCCT</td>
<td>Measure the ion beam (bunched/coasting) current</td>
<td>Yes</td>
<td>Labview (IMP)</td>
</tr>
<tr>
<td>Schottky</td>
<td>Measure the longitudinal cooling</td>
<td>Yes</td>
<td>Tektronics (IMP) Agilent (JLab)</td>
</tr>
<tr>
<td>IPM</td>
<td>Measure the transverse cooling</td>
<td>Yes</td>
<td>EPICS (IMP)</td>
</tr>
</tbody>
</table>

Only trustable calibrated beam device is DCCT

Due to deficiency of low impedance pre-amplifier

- 15 x 1-ms-slices, sample time = 1 ns, covers 1.75 s, 15 million data points in total
- Time domain scope signal data acquisition

1350 s After Application of Electron Pulses
Beam diagnostic system setup:

- **Injection beam**
- **DCCT**
- **IPM**
- **RF**
- **e-BPM**
- **i-BPM**
- **Event 0 (c05a0001)**
- **Event 1 (c0020001)**
- **Event 2 (c03b0001)**
- **Event 3 (c0050001)**
- **Event 4 (c04b00001)**
- **Event 5 (c05b0001)**
- **Event 6 (c02b0001)**
- **Event 7 (c01b0001)**

**Components:**
- **RF Station**
- **JLab LabView Timing System**
- **HV gun grid PLC**
- **Spectrum Analyzer**
- **Lecroy scope**
- **Local**

**Software and Tools:**
- **LabView**
- **Lecroy scope**
- **AG33220**

**Example of LabView experiment timing control screen**
Global timing and local triggering logics for the BPM data capturing within one filling cycle.

- **Global Timing for PLC and Pulsers**
- **October 29 – November 1, 2018**
- **Fall 2018 EIC Accelerator Collaboration Meeting**
Typical cooling experiment cycle by injection filling, DC cooling on/off, RF on/off, e-pulse on/off conditions

A. Start new cycle  
B. DC cooling on + filling  
C. $+V_{rf}=400V$  
D. DC cooling off for warmup but RF on  
E. Pulsed mode cooling (2.5 us) on  
F. Pulsed cooling on but RF off  
G. Pulsed cooling +$V_{rf}=400V$  
H. Pulsed cooling off
BPM data analysis demonstrated the bunched beam cooling feature.

Coasting ion beam:
- DCCT ion current: 99.4 uA
- e energy: 3.767 keV
- e DC collector current: 67.0 mA
- e average pulsed current: 13.8 mA
- RF Frequency: 445.94 kHz
- e-pulse width: 1.0 μs
- e-pulse frequency: 222.97 kHz
- RF Voltage: off

Bunched ion beam:
- DCCT ion current: 43.78 uA
- e energy: 3.74 keV
- e DC collector current: 67.2 mA
- e average pulsed current: 9.5 mA
- RF Frequency: 445.6577 kHz
- e-pulse width: 1.0 μs
- e-pulse frequency: 222.8288 kHz
- RF Voltage: 1.2 kV (W/R)
BPM data demonstrated the bunched beam cooling at equilibrium condition

Effective cooling, and no syn motion observed

- At the end of the cooling process, single Gaussian distribution in cooled bunch is observed again, all available ions are cooled and attracted into the narrow spike.
- The right foot of the spike is obviously lower than the left one is due to the deficiency of pre-amp.
Turn-by-turn ion BPM signal from fast oscilloscope, 1us e-pulse width

- Synchrotron motion in cooled bunch is observed to be limited to narrower and narrower region during the cooling process, eventually the synchrotron motion disappeared in the narrow spike of the cooled bunch.
- That is the double Gaussian and final single Gaussian distribution through the cooling process.
- The energy spread amplitude is lower and the phase space distribution becomes more uniform during the cooling process, instabilities disappeared.
Due to the shorter e pulse width, the ions are not sufficiently cooled within 1.75 seconds. The double Gaussian distribution and synchrotron motion can still be seen at 1.75 second, the end of measurement.

• Microbunching distribution is observed again.
Schottky signal analysis: cooling rate $\tau_{\text{cool}}$ and $dp/p$ estimation

- The profile of the Schottky band at $m*f_0$ (m=30) harmonic duplicates the longitudinal velocity distribution of the bunch.
- Width of each peak dominated by the signal RBW and coherence of the uncooled bunch in the same revolution.

$\nu s = \nu s_0$ \(\frac{\hbar V_{\text{rf}} \eta \cos \phi_s}{2 \pi \beta^2 E}\)

$V_{\text{RF peak}} = 1.2kV$

$E = 945.27 MeV$

$12C + 6$

$f_0 = 222.8288kHz$

$f_s = 806Hz$

October 29 – November 1, 2018

Fall 2018 EIC Accelerator Collaboration Meeting

16

Schottky movie to play
Ion BPM data by using calculated cutoff frequency for beam transfer function

\[ U_{\text{out}}(\omega) = Z_t(\omega) \cdot I_{\text{beam}}(\omega) \]

\[ |Z_t| = \frac{A}{2\pi \alpha} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{\omega / \omega_{\text{cut}}}{\sqrt{1 + \omega^2 / \omega_{\text{cut}}^2}} \]
DC Cooling, heating and pulsed electron cooling processes

Two to three peaks indicates the instability developed in the DC cooling condition.
Pulsed electron cooling coasting beam without the help of RF focusing

- At same e-pulse width 1µs and ave. current of 9.6mA, without RF voltage on, the e-pulse barrier has a shallow potential well. The synchrotron oscillation motion is slower than with RF voltage, so cooled bunch would have a larger momentum spread than with additional RF 1.2kV focused cooled bunch
- 2.35 times difference
- e-pulse has a typical ~1.3e-5 dp/p
Integrated charge comparison in cooled and uncooled ion beam

- Ion pulse shape distortion correction by FFT/IFFT data process
- Integrated charge at a given period can be better calculated
- Bunch length can be also better measured
A factor of 5 of decreasing in bunch length means a factor of 5 of decreasing in momentum spread, a factor of 25 of decreasing in longitudinal emittance.

The most experiment data obtained in 2016/2017 are mostly for the DC assisted cooling.

Good quality of bunch-beam cooling data sets are limited due to lack of measurement of ion bunch charge (current), shorter e-pulse widths and higher peak currents as well as poor BPM performance.

New ion BPM with calibration is necessary for a good quality of data to answer the following questions:

1. What is total charge of cooled bunch compare to uncooled bunch?
2. What is cooling quality and efficiency (charge density, bunch length and energy spread vs cooling time)?
3. Has any charge from outside cooled bunch been diffused into cooled bunch when the e-bunch is shorter than the ion bunch?
Two to three peaks indicates the best DC cooling condition.

Ion beam profile in Y direction only with 2D and 1D scans

4 frames per second has been obtained for slower cooling rate

No data analysis for this data set yet

Transverse (y) cooling rate is not known yet

Slow scan rate and poor resolution for cooled beam profile

Installed and commissioned in 2017 at CSRm
The cooled ions are trapped at the RF potential well bottom, forms the spike core. In this simulation, RF voltage is on with electron bunch cooling. The modeling and simulation results have qualitatively agreed with experimental data.

- Electron potential well is much shallower compared to RF potential well
- 1D modeling with RF + e-potential has demonstrated bunched e-cooling process.
- 3D simulation tool is under development.

1D beam dynamic modeling

12C^6+ 7MeV

12C^6+ 30MeV

12C^6+ 19MeV

Bi-Gaussian bunch profile

RF potential well

RF bunched length

E-cooled bunch length

Cooling process with low RF voltage

well cooled bunch profile
Beam distribution before and after cooling

V=1 kV, h=2, T0=4.44 us

1us pulse e-beam

• Multi particle Tracking
• Parkhomchuk Cooling Force
• Betatron + Synchrotron motion
• Martini IBS model (Ring Lattice)
• Space Charge Effect (longitudinal)

Simulation and Experimental Data Support following conclusions:
• $\frac{dp}{p}$ reduction ~ from $3\cdot10^{-3}$ to $6\cdot10^{-4}$ with e-pulse + RF focus cooling
• $\frac{dp}{p}$ reduction ~ from $3\cdot10^{-3}$ to $1\cdot10^{-3}$ with e-pulse cooling without RF focusing
• e-pulse has a grouping bucket effect of coasting beam, i.e. bunch length=e-pulse length
• Both cooling rate are ~ 0.5sec
Ion BPM signal data:
• From shoe-box type at CSRm with 50Ω input imp. preamp
• $f_{\text{cut}} \sim 7.7$ MHz, so the BPM signal is a differential signal of ion pulse shape
• Signal voltage integration includes noise buildup (with slope)
• After the slope correction, the signal at the pulse ends generated unphysical dips
• The pulse distortion has been ruled out due to the external circuit capacitance or amp/cable mismatch

Schottky signal data:
• Used same signal from ion BPM
• Poor S/N ratio in high freq. response for Schottky
• Used RSA5100A (RSA385A) spectrum analyzer. Saved slow IQ data.
• IQ data obtained has a low sampling rate 48.8kS/s
• RBW=100Hz, spectrum resolution is limited to $\sim 32$ Hz only even with a CFFT/ICFFT HPF/LPF reprocessing
• Data processing by further digital filtering out the high/low frequency coherence/incoherence noise is challenging

Improvement solution in next experiment (Dec. 3-8, 2018):
• Rebuild a new show-box BPM. Use 1MΩ, 80MHz BW preamp, so cutoff freq. drops to $\sim 386$ Hz, now push-pull effect, no FFT/IFFT correction in data post processing (Done now)
• Use a high sampling rate spectrum analyzer (Agilent N9020A) with a fast triggering with LeCroy scope (Waverunner 640 zi)
• Improve data triggering and sampling techniques on both instruments
• Do the bench RF measurement for the beam-to-signal transfer function (Done in Sep. 2018)
• Do the bench calibration by the wire-stretching technique (Done in Sep. 2018)
• Old ion BPM is going to be bench calibrated, so all old 2017 data can be reevaluated.
• Possible measurement of the transverse Schottky side band signals for transverse betatron oscillation damping (under study)
New ion BPM calibration results

Newly installed ion BPM at CSRm, IMP, Sep. 26, 2018

BPM x/y position, frequency domain calibration result

Grid: 5mm/grid; Scale: mm; Errors: up to +2mm in x direction; +2mm in +y direction

Time domain calibration result

Grid: 5mm/grid; Scale: mm; Errors: up to +2mm in x direction; +2mm in +y direction
• Better understanding to the Schottky signal harmonic sideband structure now
• Signal also indicates the dominated coherence response from other uncooled bunch
• Poor RBW (IF frequency) due to the slow requisition rate of IQ data
• Need to improve the triggering, avoid transverse resonance signal pickup, using LPF/HPF circuits
• Need to do a better instrument setup and signal processing to improve S/N ratio
Future experiment plan on CSRe ring (2019-2020)

- Move experiment program from CSRm to CSRe ring. Modified SC300 Cooler with pulsing capability will extend the ion energy from current 30MeV/u up to 400MeV/u but similar e-pulse structure.
- The electron pulse length from the current of 20m down to the pulse length comparable to the shorter ion bunch length at ~2m by a new pulser technology.
- JLab is responsible to design and build the HV pulse inside of SF6 tank.
- Better beam diagnostics with resonator Schottky and Stochastic cooling pickup/kicker pickups.
- Faster electronics, slower cooling rate at higher ion energy, better for the beam diagnostics.

SC300 E-cooler at CSRe ring to be modified.
Proposed experiment parameters on CSRe ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IMP (CSRm ring)</th>
<th>IMP (CSRe ring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specieses</td>
<td>12C6+</td>
<td>12C6+</td>
</tr>
<tr>
<td>Bunch charge per nucleon</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Bunch length (σ)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Kinetic energy per nucleon</td>
<td>7.0</td>
<td>380.0</td>
</tr>
<tr>
<td>Total Energy per nucleon</td>
<td>945.3</td>
<td>956.3</td>
</tr>
<tr>
<td>γ (beta)</td>
<td>0.121</td>
<td>0.193</td>
</tr>
<tr>
<td>γ (transitional energy)</td>
<td>1.007</td>
<td>1.019</td>
</tr>
<tr>
<td>Phase slip factor</td>
<td>0.948</td>
<td>0.818</td>
</tr>
<tr>
<td>Revolution time</td>
<td>5.168</td>
<td>2.629</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>225.907</td>
<td>359.134</td>
</tr>
<tr>
<td>1st harmonic number</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bucket height - eSC</td>
<td>1.687E-07</td>
<td>3.182E-07</td>
</tr>
<tr>
<td>Vrf frequency</td>
<td>1200</td>
<td>600</td>
</tr>
<tr>
<td>RF frequency</td>
<td>451.814</td>
<td>359.134</td>
</tr>
<tr>
<td>Energy spread ratio: eSC/Vrf</td>
<td>0.095</td>
<td>0.105</td>
</tr>
<tr>
<td>Resonant Schottky Pickup</td>
<td>IMP (CSRm cooler)</td>
<td>IMP (CSRe cooler)</td>
</tr>
<tr>
<td>TM010 mode resonance frequency</td>
<td>5.8736</td>
<td>244.78</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Electron Cooler</td>
<td>IMP (SC35 cooler)</td>
<td>IMP (SC300 cooler)</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>3.81</td>
<td>9.80</td>
</tr>
<tr>
<td>β (beta)</td>
<td>0.121</td>
<td>0.193</td>
</tr>
<tr>
<td>γ (gamma)</td>
<td>1.007</td>
<td>1.019</td>
</tr>
<tr>
<td>Cooling section length</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Electron kick dE per turn</td>
<td>0.306</td>
<td>0.118</td>
</tr>
<tr>
<td>Max peak current</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Max magnetic field</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Cathode radius</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Electron radius at cooler section</td>
<td>0.002</td>
<td>1.25-2.5</td>
</tr>
</tbody>
</table>

LONGITUDINAL SCHOTTKY SPECTRUM

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Power Density [eV/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>244.0</td>
<td>244.1</td>
</tr>
<tr>
<td>244.2</td>
<td>244.3</td>
</tr>
<tr>
<td>244.4</td>
<td>244.5</td>
</tr>
<tr>
<td>244.6</td>
<td>244.7</td>
</tr>
<tr>
<td>244.8</td>
<td>244.9</td>
</tr>
<tr>
<td>245.0</td>
<td>245.1</td>
</tr>
</tbody>
</table>

Resonant Schottky Pickup: IMP (CSRm cooler) vs. IMP (CSRe cooler)

- IMP (CSRm cooler): Plus Minus 0.5MHz, TM010 mode resonance frequency at 5.8736 MHz
- IMP (CSRe cooler): Plus Minus 2MHz, TM010 mode resonance frequency at 5.8736 MHz

Electron Cooler: IMP (SC35 cooler) vs. IMP (SC300 cooler)

- IMP (SC35 cooler): 3.81 keV
- IMP (SC300 cooler): 9.80 keV

Oct. 29 - Nov. 1, 2018

Fall 2018 EIC Accelerator Collaboration Meeting
1. Bunched electron beam cooling 12C+6 ion beam at 7MeV/u has been demonstrated at CSRm ring at IMP, China by our IMP/JLab collaboration team
2. With the help of RF focusing, the Ion bunch length has been reduced from the coasting to ~3m long by a longer electron bunch but as short as 18m within about 0.5 second cooling time
3. The longitudinal cooling of momentum spread has been reduced from ~2e-3 to ~6e-4 with a similar cooling rate
4. The simulation models developed so far agree with the measurement results qualitatively.
5. Beam diagnostics like ion BPM and Schottky signals strongly support these evidences but obtained data so far lacks of calibrations and measurement accuracies for a further quantitatively benchmark for the simulation codes.
6. Beam instrumentation improvement both in hardware and software has been designed, planned and prepared for the next experiment in Dec. 3-8, 2018
7. Pushing the next phase of experiment to be done in 2019-2020 at CSRe ring with a higher ion energy, modifying the SC-300 Cooler, and a better beam diagnostics are specified and under the upgrade
8. IMP in China is still the best place and the fastest way to demonstrate the strong bunched beam cooling in order to benchmark our cooling simulation tools for our CCR/ERL E-cooler design for JLEIC
Backup slides
Event triggers and timing logics for synchronization

<table>
<thead>
<tr>
<th>Coasting beam cooling</th>
<th>Bunched beam cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>事例名</td>
<td>时间</td>
</tr>
<tr>
<td>事件0</td>
<td>c05a0000</td>
</tr>
<tr>
<td>事件1</td>
<td>c02a0001</td>
</tr>
<tr>
<td>事件2</td>
<td>c03a0001</td>
</tr>
<tr>
<td>事件3</td>
<td>c00a0001</td>
</tr>
<tr>
<td>事件4</td>
<td>c00a0001</td>
</tr>
<tr>
<td>事件5</td>
<td>c05a0001</td>
</tr>
<tr>
<td>事件6</td>
<td>c02b0001</td>
</tr>
<tr>
<td>事件7</td>
<td>c01b0001</td>
</tr>
<tr>
<td>事件8</td>
<td>c00a0001</td>
</tr>
</tbody>
</table>

10s注人，每次注人时间1s，注10次

注人完成后直接开启高频。得到bunch束团，500ms后关闭电子束。之前一直有dc电子束。（由文件单独设定）

关闭电子束，p1c转为脉冲模式，等待触发脉冲电子束

空事例

开启profile monitor

开启脉冲谱仪

开启示波器

开启脉冲电子束

开启脉冲电子束

bunch ion beam 有2.5s的 heating
New Ion BPM Mechanical Assembly Model and CST Wakefield Simulation Setup
CST wakefield simulation on the pickup voltage signals

Frequency spectrums indicate a possible resonance structure ~310MHz

Non-linear responses of peak-to-peak voltage at pickups
Impedance matching and pulse current to pickup voltage transfer function calibration

\[ Z_w = 497.64 \, \Omega, \; Z_{in} = Z_{out} = 50 \, \Omega, \; R_1 = 471.98 \, \Omega, \; R_2 = 52.72 \, \Omega, \; R_3 = 447.64 \, \Omega \]

\[ V_{in} = I_2 R_2, \quad I_1 = I_3 + I_W \]

Check:

\[ V_{out} = I_3 Z_{out} = \left( \frac{1}{Z_{in}} - \frac{1}{R_2} \right) Z_{out} Z_w \]

\[ V_{in} = 0.0258 V_{in} \]

Calibrate (using “up” as an example) \( K_{up} \):

\[ V_{up} = K_{up} I_1 = K_{up} \frac{Z_w + R_3 + Z_{out}}{Z_w Z_{out}} V_{out} = K_{up} 0.040 V_{out} \]

Using high input impedance scope to measure \( V_{up} \):

\[ K_{up} = \frac{1}{25} \frac{V_{up}}{V_{out}} \]

\( K_{xx} \) is calibration factor for future need

Confirm:

\[ q_1 = \int_0^T I_1 \, dt = \int_0^T \frac{V_{up}}{K_{up}} \, dt = \int_0^T \frac{25}{\Omega} V_{out} \, dt \]

1. Using AFG in square pulse waveform in pulse width of \(~100\text{ns}\) and frequency of \(250\text{kHz}\) to simulate cooled ion bunch in the cooling experiment.

2. Examine the pickup signal (up/down, in/out) or their pair’s sum signal for any distortion due to the circuit mismatch. A high input impedance scope connect to these signals might be needed first in order to directly measure the pulse shape (or transfer function).

3. After the network impedance matching, do the \( V_{out}=0.0258V_{in} \) check, \( Z_{out} \) should use \( 50 \, \Omega \) input impedance.

4. Do the \( K \) factor calibration for all pickup ports. If \( Z_{out} \) is not connected to the scope, using a \( 50 \, \Omega \) load to terminate it.

5. Exercise the pulse pickup voltage integration over the pulse length \( T \). Last equation in calibration is critical for our bunch cooling experiment.
This resonance modes have been checked out yesterday by VNA Agilent 5701C (frequency). Two resonance frequencies at 207 MHz and 395 MHz have been found. Their coupling to the pickups are strong $\beta = 0.5 \sim 1$. Only “Out” plate’s coupling is weaker. Their $S_{11}$ measurement screen shots are shown as following

- $S_{11}$ on the stretched wire also indicated strong coupling to these modes indication strong coupling to the beam and pickups.
• In reality without a wire, the beam bunch could excite these two modes
• Further S21 measurements (from pickup to pickup or from pickup to the wire) indicated the loaded Q of the first mode is ~35. The second mode is ~65. Connect a 50ohm load on the third pickup ports lower the Q down to 20~25, confirmed the strong damping effect of this mode
• Using aluminum foils to cover the end flanges had nonsignificant effect to the resonance peaks, indicating that these modes are the resonance e-fields between the pickup plates. Then the S21 signal had a large change when using a screw drive to short corresponding plates, confirming this hypothesis.
• CST simulation in Eigen solver also indicated this at ~370MHz mode.
• The effectiveness of these mode depends on its loaded Q, it is stainless steel vacuum vessel, its Q if is less than 100, then it has a less effect to the beam bunch (length ~200ns) induced voltage signal, which is true from our bench measurement result
• Following slide shows the data fitting result on one of downloaded data from Agilent 5071C for “down” plate using the S11 signal only
S11 (dB) vs. Frequency (MHz)

- $\beta = 0.43$
- $Q_l = 70$
- $f_0 = 206.89\text{MHz}$
- $\alpha = 0.5248$

Phase (S11 deg) vs. Frequency (MHz)

- $\beta = 0.78$
- $Q_l = 35$
- $f_0 = 206.9\text{MHz}$

- $\beta = 0.95$
- $Q_l = 35$
- $f_0 = 208.05\text{MHz}$
S parameters from input (port 1) of the wire network to output (port 2) of the wire network.

- S11 (dB)
- S12 (dB)
- S21 (dB)
- S22 (dB)
- S21 - 87dB with 50Ohm Preamp on Port 2 (dB)
- S21 - 75dB with 1MOhm 20MHz BW Preamp (dB)

S Parameters (dB) vs. Frequency (MHz)