Bunched Beam Cooling Experiment

Yuhong Zhang and Haipeng Wang

Jefferson Lab

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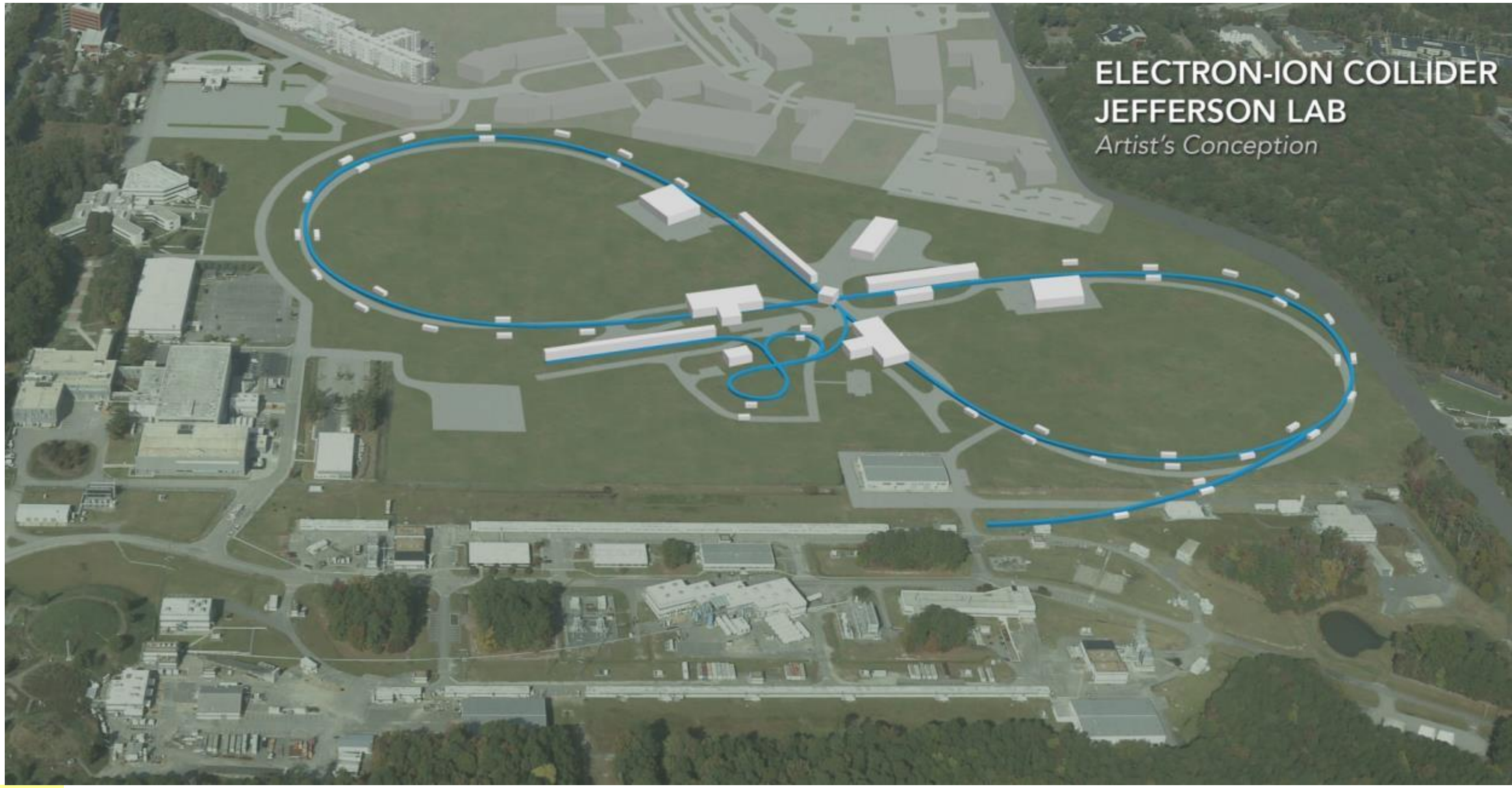

Jlab-IMP Cooling Collaboration

Y. Zhang (PI), A. Hutton, K. Jordan, T. Powers, R. Rimmer, M. Spata, **H. Wang**, S. Wang, H. Zhang, JLab and L. Mao (PI), J. Li, X. Ma, R. Mao, M. Tang, J. Yang, X. Yang, Y. Yuan, H. Zhao, H.W. Zhao, T. Zhao, IMP, China

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Introduction

- Strong cooling of ion beams is essential for EIC to achieve high luminosity above > $10^{34}/cm^2/s$
- JLEIC baseline has adopted a multi-phased cooling scheme, which includes cooling during collision to suppress IBS induced emittance growth
- The cooling electron beam with energy up to 55 MeV is provided by an ERL cooler, and is highly bunched
- All electron cooling to this day were performed using a DC electron beam. The technology is mature
- Bunched electron cooling has never been demonstrated experimentally before, nor systematically studied
- We carried out an experimental study utilizing a DC cooler at Institute of Modern Physics (IMP) of China

Multi-Phased Cooling Scheme

Ring	Functions	Kinetic energy (GeV / MeV)			Cooler type
		Proton	Lead ion	Electron	
booster ring	Accumulation of positive ions		0.1 (injection)	0.054	DC
collider ring	Maintain emitt. during stacking	7.9 (injection)	2 (injection)	4.3 (proton) 1.1 (lead)	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	DC
	Maintain emitt. during collision	Up to 100	Up to 40	Up to 54.5	BB ERL

- Demonstration of cooling by a bunched electron beam ➔ retiring a critical risk of the JLEIC design
- A systematic/ parametric study of bunched beam electron cooling ➔ providing guidance of choice of JLEIC bunched beam cooling design parameters
- Benchmarking simulation codes against bunched beam cooling experimental data ➔ providing accurate estimation of the JLEIC performance

Bunched Beam Cooling Experiment (JLab FY17 Base Fund)

- **Description**
  - This project aims to demonstrate experimentally cooling of ions by a bunched electron beam utilizing a DC cooler at IMP
  - The voltage of the thermionic gun is modulated with a RF pulse generator provided by JLab to produce a pulsed e-beam.
  - It is critically important to JLEIC as its cooling concept is evolved toward a parameter regime that the cooling electron bunch may be significantly shorter than ion bunches, as the technical design of the high energy cooler is underway.
  - Such a cooling scheme can be directly validated in the planned experiment.
- **Goals**
  - To perform follow-on measurements with better electron and ion beam diagnostics installed. Measurements with more control over the electron phase space distribution, and with better diagnostics for the cooled ion beam are expected.
- **Deliverables**
  - The experimental data will be analyzed for extracting key cooling information & for examining parameter dependences.
  - The experimental results will be used to benchmark cooling codes (and submitted for publishing toward the end of 2017)
- **Status**
  - Completed.
  - The study will be continued by support of a FY18 FOA fund

Electron Cooler Design Project Budget

- Budget

	FY'17	Totals
a) Funds allocated	$108,000	$108,000
b) Actual costs to date	$108,000	$108,000

Highlights on the Recent Progress

1st experiment (April, 2016)

- Performed analyses of the data collected from the 1st experiment, preliminarily demonstrated cooling of a coasting and bunched ion beam by a bunched electron beam
- Developed a 1D model for qualitatively explaining cooling of an ion beam by a bunched electron beam

2nd experiment (April, 2017)

- Developed a test plan and successfully executed the experiment
- Confirm the bunched beam cooling qualitatively by time domain (strong BPM) and frequency domain (schottky) signals, and compared with simulations based on a 3D pulsed cooling model and 1D pulse+RF models
- Identified deficiency of the IMP cooling operation and calibration of key equipment required to achieve quantitative benchmarking
- Developed an improvement plan for the IMP CSRm beam diagnostics, assisted the IMP team in designing a new BPM, and remotely participated & advised the IMP staffs in commissioning and calibration of the new hardware

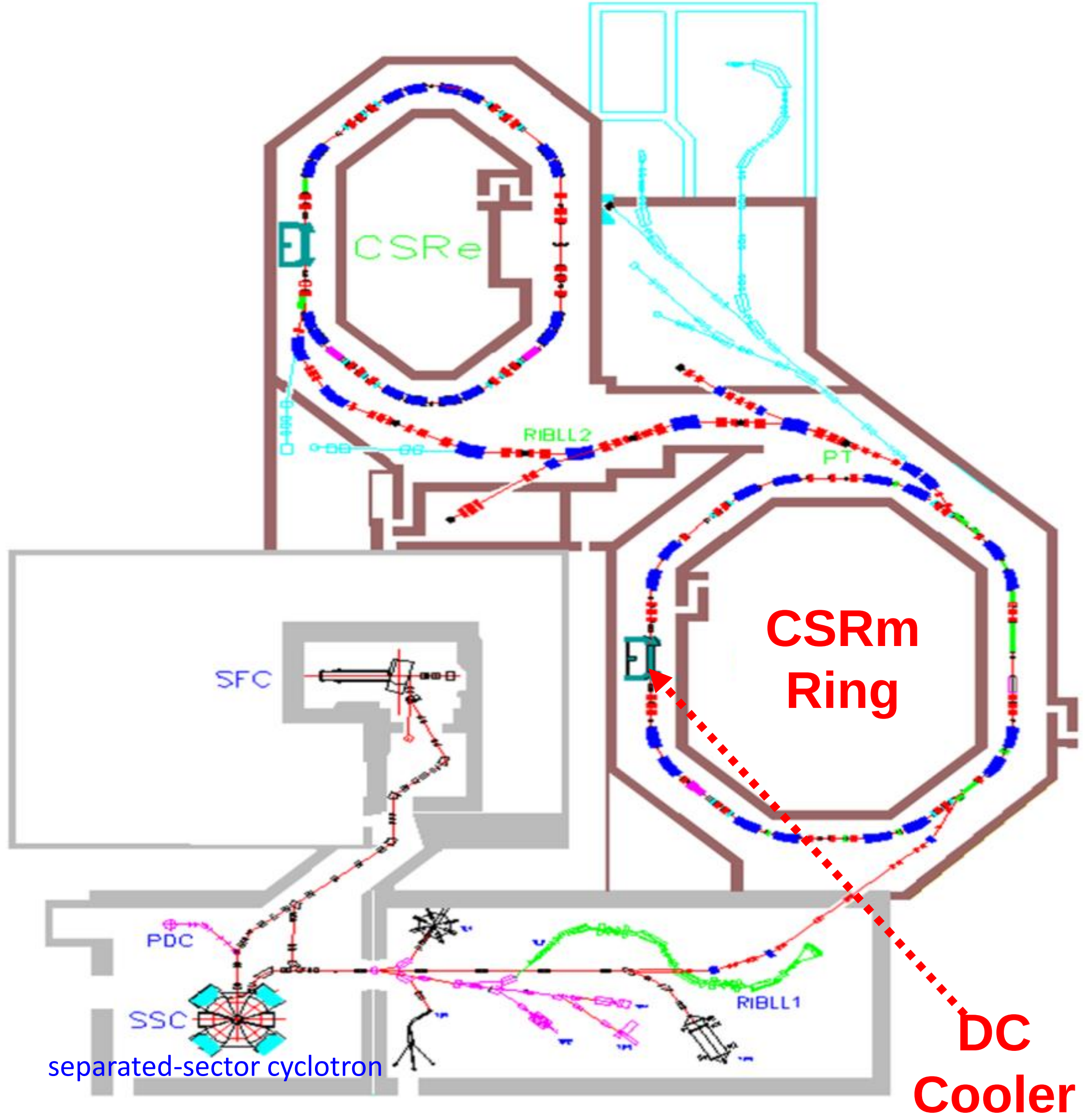
3rd and 4th experiment

- Planed the next experiment at IMP (tentatively scheduled on Dec. 6-13, 2018)
- Started planning/pre-study of the 4th experiment at the 2nd DC cooler in the CSRe ring at IMP (2019-2020)

Development of A Proof-of-Principle Test of Bunched Beam Cooling

- The idea of utilizing an existing DC cooler for a P-o-P experiment of bunched beam electron cooling was proposed four years ago by A. Hutton
- Initially, it suggested replacing a thermionic gun in the DC cooler by a photo-cathode gun for generating a bunched electron beam, and using the driven laser to control the bunch length and repetition frequency.
- A collaboration between JLab and IMP, China was initiated for this study. IMP has two DC coolers
- The idea had further evolved to utilizing a method of modulating the grid voltage of a thermionic gun to generate a pulsed beam with pulse length as short as ~100 ns.
- The advantages of the revised plan are least invasive to the IMP DC cooler and also requiring a minimum funding.
- We received a JLab LDRD grant (2015, Y. Zhang was the PI) to further develop the concept and design of the experiment.
- At the same time, IMP colleagues received a special grant from Chinese Academy of Sciences (CAS) for supporting international collaboration (L. Mao as the PI)

HIREL-CSR Layout and Machine Parameters



	CSRm		CSRe	
Circumference (m)	161.0014		128.8011	
Geometry	Race -track		Race -track	
Max. energy (MeV/u)	900 (C^{6+}) 400 (U^{72+})	1100 (C^{6+}) 2800 (p)	600(C^{6+}) 400(U^{90+})	700(C^{6+}) 450(U^{90+})
B ρ (Tm)	0.91/10.64	0.81/12.04	1.20/8.40	0.50/9.00
B(T)	0.12/1.40	0.10/1.59	0.20/1.40	0.08/1.50
Ramping rate (T/s)	0.05 ~ 0.4		0.1 ~ 0.2	
Repeating circle (s)	～ 17 (～ 10 s for Accumulation)			
Acceptance			Normal mode	
A_h (π mm -mrad)	200 (Δp/p = ±0.15 %)		**150** (Δp/p = ±0.5%)	
A_v (π mm -mrad)	30		**75**	
Δ p/p (%)	1.25 (ε_h= 50 π mm -mrad)		**2.6** (ε_h= 10 π mm -mrad)	
E -cooler				
Ion energy (MeV/u)	8 - - -50		25 --- 400	10 --- 450
length (m)	4.0		4.0	
RF system	Accel. Accum.		Capture	
Harmonic number	1 16 , 32,64		1	
f_{min} /f_{max} (MHz)	0.24 /1. 81 6.0 / 14.0		0.5 / 2.0	
Voltages (n ´ kV)	1 ´ 7.0 1 ´ 20.0		2 ´ 10.0	
Vacuum (mbar)	6.0 ´ 10^{-11}		(3.0 ´ 10^{-11})	

P-o-P Experiment Setup: Making a Pulsed Electron Beam

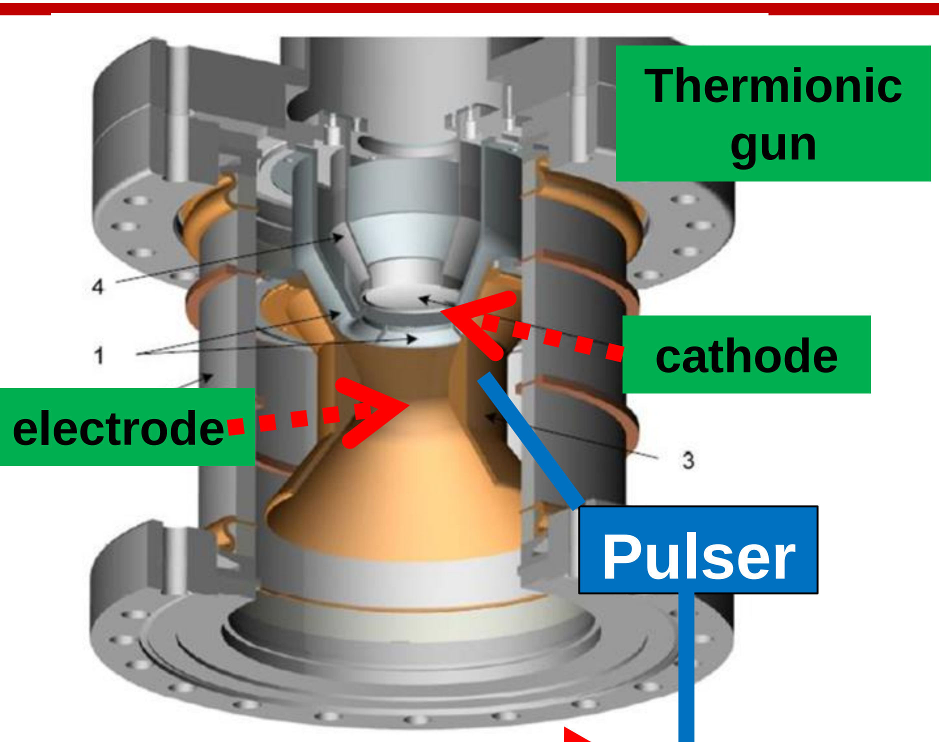
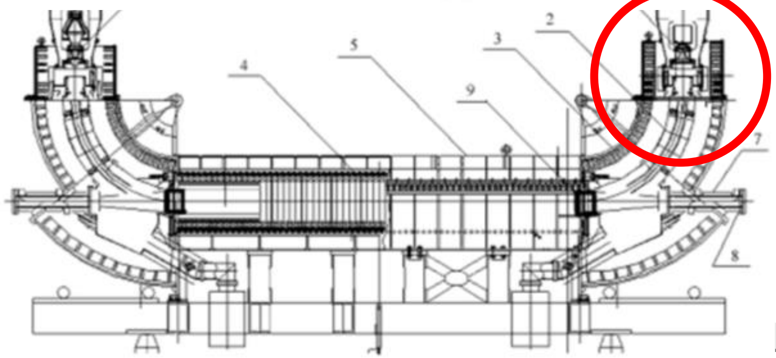
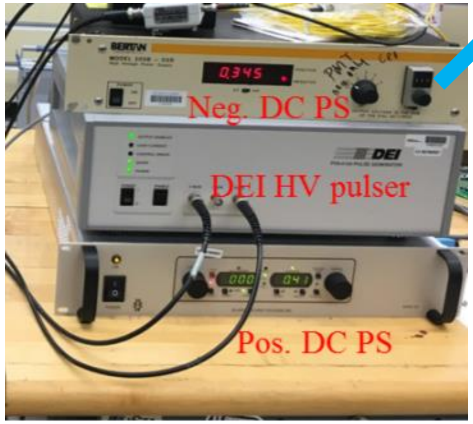
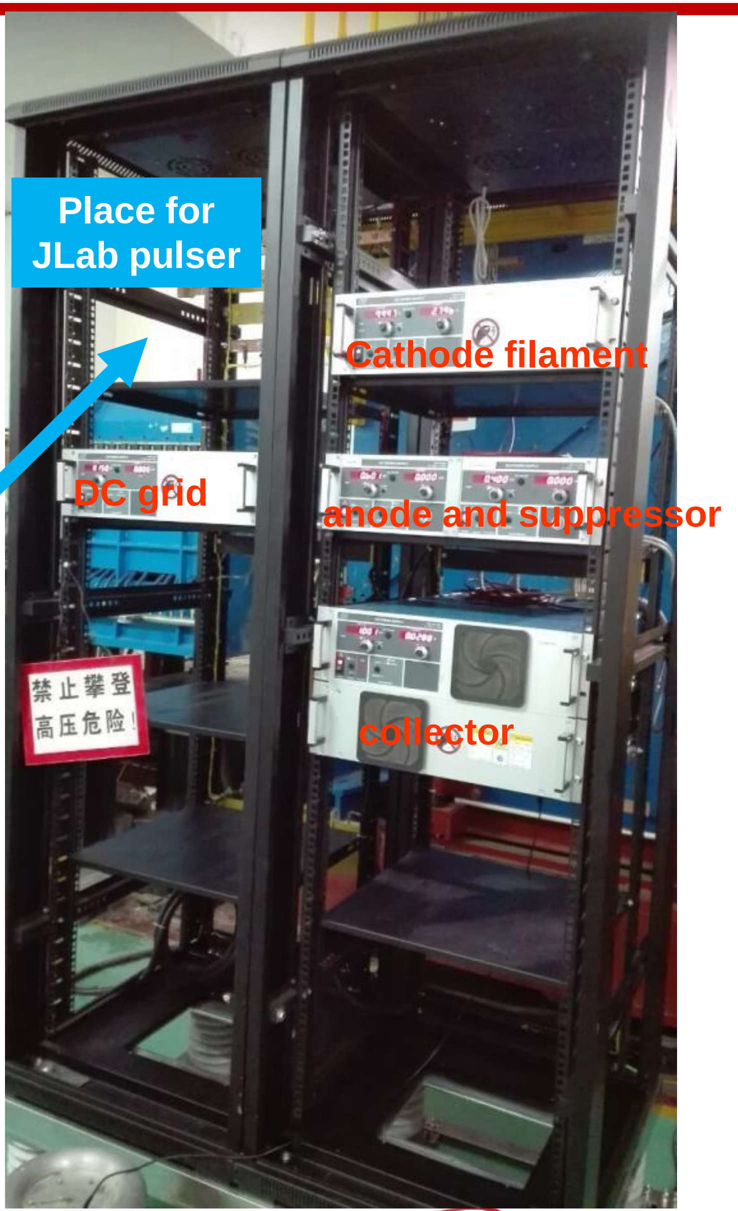


Fig.1 The sketch of the electron gun

1 – four-sector control electrode, 2 – oxide cathode, 3 – anode, 4 – cathode housing, 5 – ceramics.







Bunched Beam Cooling Experiment Parameters in 2016/2017

ION RING	IMP (CSRm ring)			
specieses	12C6+	12C6+	12C6+	
bunch charge				
charge per nucleon	0.5	0.5	0.5	
kinetic energy per nucleon	7.0	30.0	19.0	MeV
beta	0.121	0.247	0.198	
gamma	1.007	1.032	1.020	
revolution time	4.427	2.177	2.712	us
revolution frequency	225.907	459.342	368.687	kHz
Harmonic Number	2	1	2	
Vrf	1200	1200	1200	V
RF frequency	451.814	459.342	737.374	kHz
Electron Cooler	**IMP (CSRm cooler)**			
kinetic energy	3.81	16.34	10.35	keV
electron pulse edge width	25	25	25	ns
dI/dt	2.64	2.64	2.64	mA/ns
Cooling section length	3.4	3.4	3.4	m
Electron kick δE per turn	0.306	0.071	0.112	keV
E beam radius at cooler section	1.25-2.5	1.25-2.5	1.25-2.5	cm
High Voltage Pulser, DEI PVX-4150				
maximum average switching power	150	150	150	W
optimum anode voltage	1	1	1	kV
maximum Pulse Rep Rate at clamped grid voltage	571.2	571.2	571.2	kHz
maximum pulse grid voltage at revolution frequency	575.0	291.0	371.0	V
maximum pulsed peak current at revolution frequency	177.36	89.09	110.91	mA
maximum pulse grid voltage at bunch frequency	297.0	291.0	145.0	V
maximum pulsed peak current at bunch frequency	90.64	89.09	55.42	mA
minimum negative baise to supress the dark current	-400.00	-400.00	-400.00	V
grid voltage clamp for the 150W	220.000	220.000	220.000	V
maximum peak current at clamped voltage	71.719	71.719	71.719	mA

A lot of data taken at 7 MeV/u during the 2nd cooling experiment run (April 21-27, 2017)

JLab modified DC e-gun pulse generator's limitation

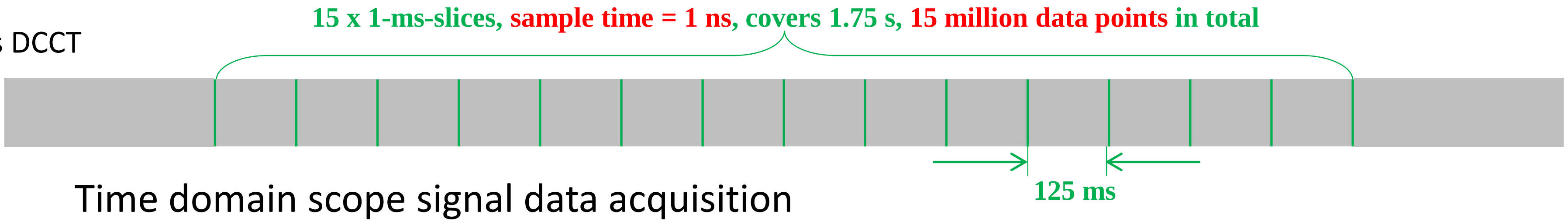
Beam Diagnostics at CSRm for Bunched Cooling Experiment

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

1.350 s After Application of Electron Pulses

Due to deficiency of low impedance pre-amplifier

Only trustable calibrated beam device is DCCT



Time domain scope signal data acquisition

1^{st} Bunched Beam Cooling Experiment (May 17-22, 2016)

- **Beam cycle**
  - Carbon ($^{12}C^{6+}$) ions were injected at 7 MeV/u from a cyclotron and stored in the CSRm ring
  - The ion beam was either coasting or captured into two long bunches (h=2 w/ 450 kHz);
  - The pulsed electron beam was turned on
  - Pulsed beam cooling proceeded very fast in time scale of 1 second
  - At 7 second, the stored beam was dumped, then restarted the cycle

- **Cooling electron beam**
  - Pulse length varies from 2.2 μs (half of the ring circumference) to 60 ns (limit of the pulser),
  - Corresponding to 79.2 m to 2.2 m FWHM pulse length (relativistic $\beta = 0.12$)
  - The pulse current was kept constant, thus the average current decreased with the pulse length

Enhancement in the Beam cycle in the 2^{nd} experiment

- The cooler was turned on in DC mode to assist ion accumulations for achieving higher current
- After accumulation, the DC cooling is turned off, let beam reheat by IBS
- Start the process same as the 1^{st} experiment

Test and Observations in 1st Experiment (May 17-22, 2016)

Test 1: Long pulsed (~5 μs) electron beam cools a coasting ion beam, two beams were not synchronized

- We observed a ***rapid ion loss*** at beginning of cooling; too fast such that cooling effect could not be observed
- Exact mechanism of the ion loss is still unknown, but it is suspected raise/fall of the electron pulse might act as a large transverse kicker which knocks ions out piece-by-piece
- It is also suspected the electron beam and ion beam were not perfectly aligned

Test 2: Long pulsed electron beam cools a coasting ion beam, two beams were synchronized

- We observed a modest to small ion loss
- We observed a rapid cooling effect (longitudinal cooling)

Test 3: Pulsed (~2 μs) electron beam cools a bunched ion beam, two beams were synchronized

- Only one of two ion bunches were cooled; electron bunches are longer than the ion bunches;
- Very small ion loss; we postulate the raise/fall of pulsed electron beam did not see ions so no ion was kicked out
- We observed cooling effect (longitudinal cooling)

Test 4: Pushing short pulse length of electron beam, two beams were synchronized

- The electron (FWHM) pulse length was pushed as short as 100 ns (~3.6m)
- No cooling were observed with electron pulse length short than 150 ns (~5.4 m); Longitudinal diffusion is too slow to spread cooling along the coasting beam
- With a little longer electron pulse length, we observed cooling effect.
- At 400 ns pulse length, ions were lost rapidly, suspected the ion beam had hit some instability

2nd Bunched Beam Cooling Experiment (April 17-28, 2017)

Test 1: Cooling of coasting ion beam by a pulsed e-beam (After beam synchron. & energy fine tuning)

- A "grouping" effect of ions was observed when electron pulse width is from 0.5 to 5 μs
- At electron pulse width < 0.25 μs, observed pulse edge kicking effect to the ion beam without a "grouping" effect.

Test 2: Pulsed e-cooling with RF voltage enhances the cooling rate and further reduces the pulse length

- Scanning through the e-pulse width and peak current, different cooling rates of ion bunch have been observed
- E-pulse shorter than initial ion bunch like 0.5us-2us has demonstrated cooling effect , the ion charge density increase within the cooling time, final cooled bunch length is less than the e-pulse width
- RF voltage plays a critical role in this process
- Observed ion pulse dip on the pulse-off period and pulse tilt during the pulse-on period from the ion BPM signals

Test 3: Fast cooling recorded by ion BPM scope (time domain) and Schottcky signals (frequency domain)

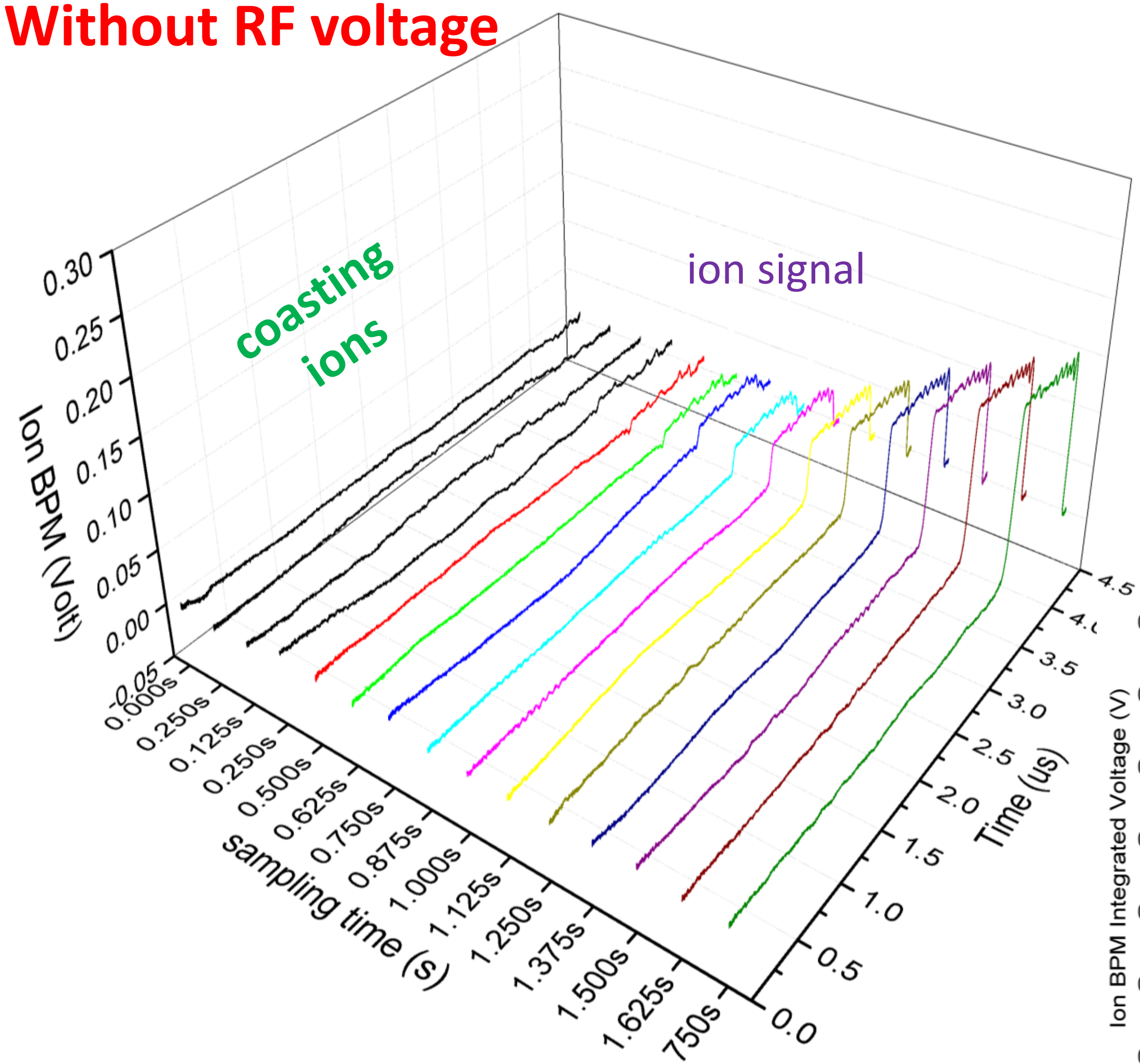
- Only one of two ion bunches were cooled, electron bunches are longer than the cooled ion bunches
- Unclear ion loss mechanism due to the RF focusing
- Understood the Schottcky synchrotron side band and energy spread shrinking signals after the experiment

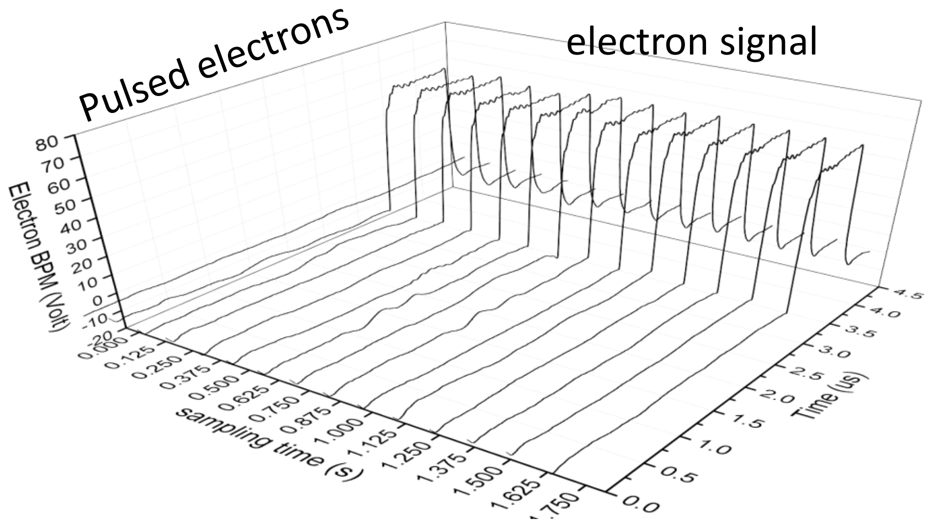
Test 4: Bunched beam cooling of 30 MeV/u $^{12}C^{+6}$ beam (not success)

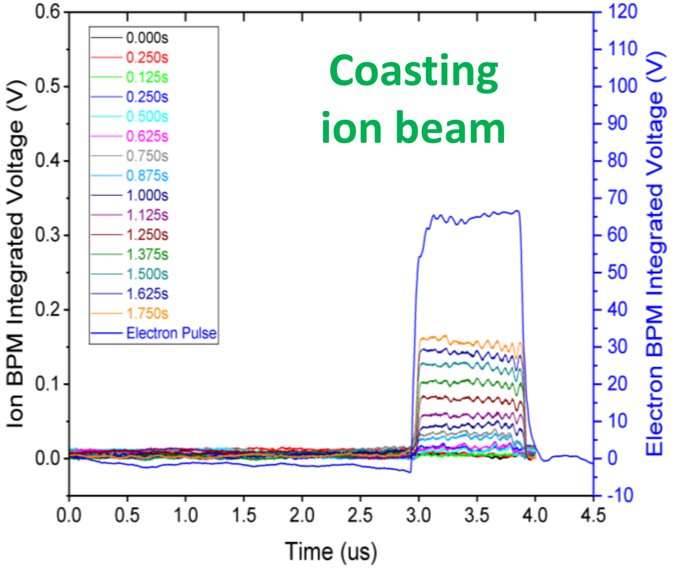
- There is no enough accumulation beam intensity at injection energy of 7 MeV/u for coasting beam.
- Captured the ion beam current was not high enough to demonstrated pulsed e-cooling.

BPM Data Demonstrated Bunched Beam Cooling

Without RF voltage







DCCT ion current = 99.4 uA
electron 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 us
e-pulse frequency = 222.97kHz
RF Voltage=off

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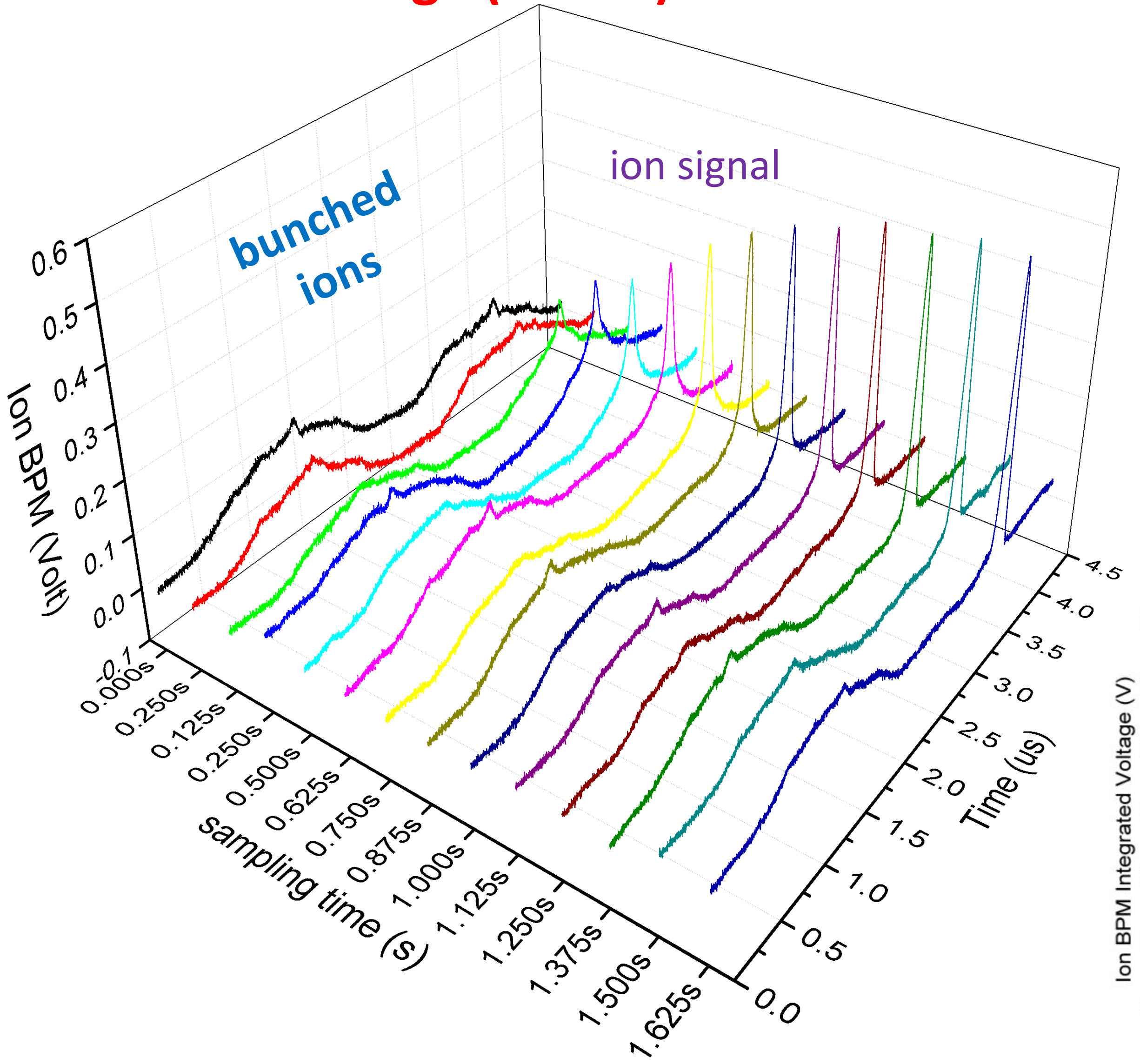
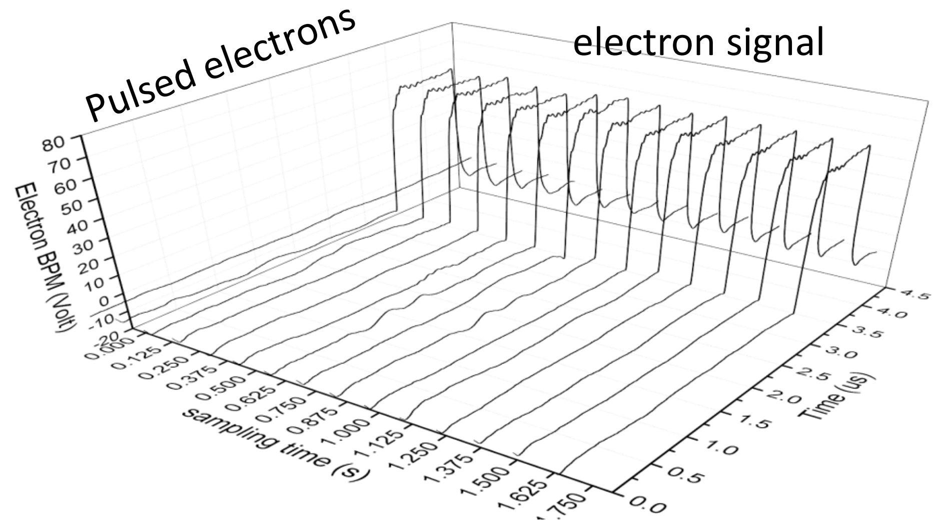
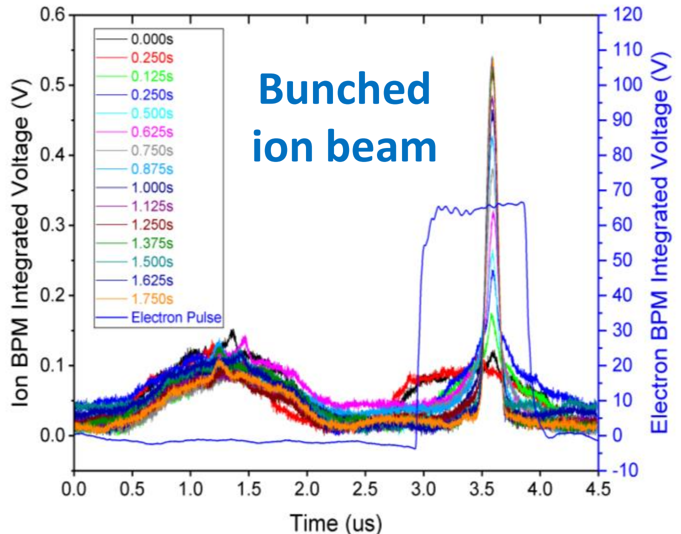
BPM Data Demonstrated Bunched Beam Cooling

With RF voltage (1.2 kV)







DCCT ion current=43.78uA
e energy=3.74keV
e DC collector current=67.2mA
e average pulsed current=9.5mA
RF Frequency=445.6577kHz
e-pulse width=1.0us
e-pulse frequency=222.8288kHz
RF Voltage=1.49/1.2kV (W/R)

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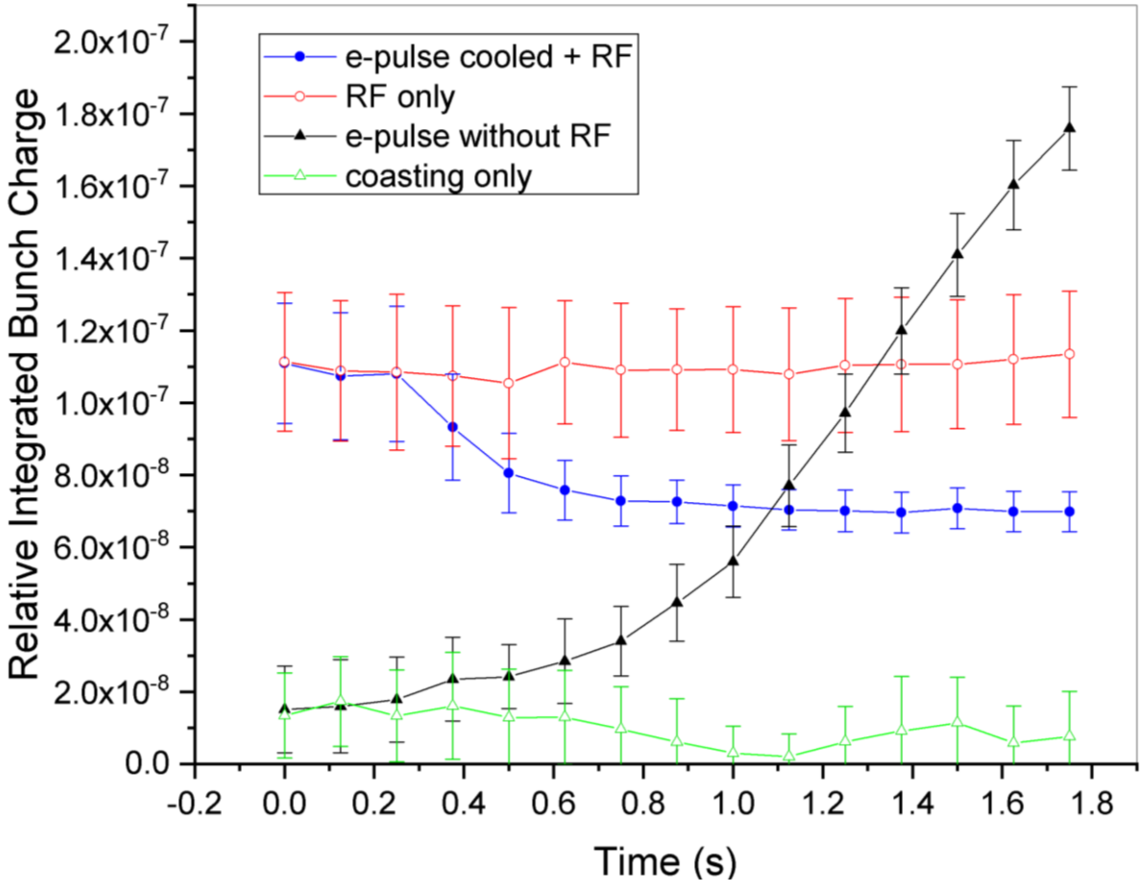
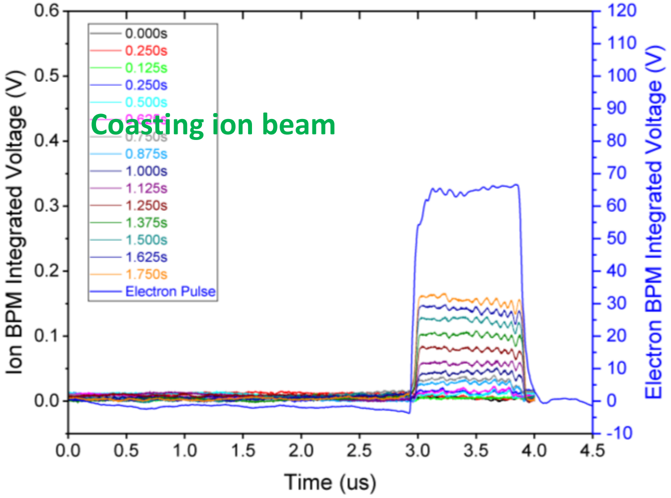
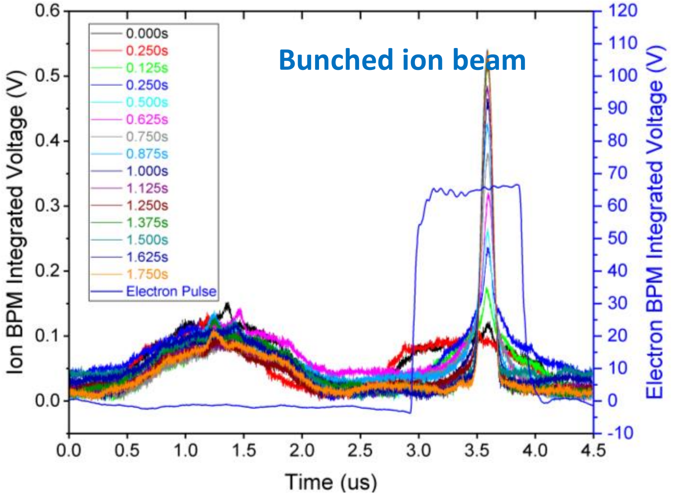
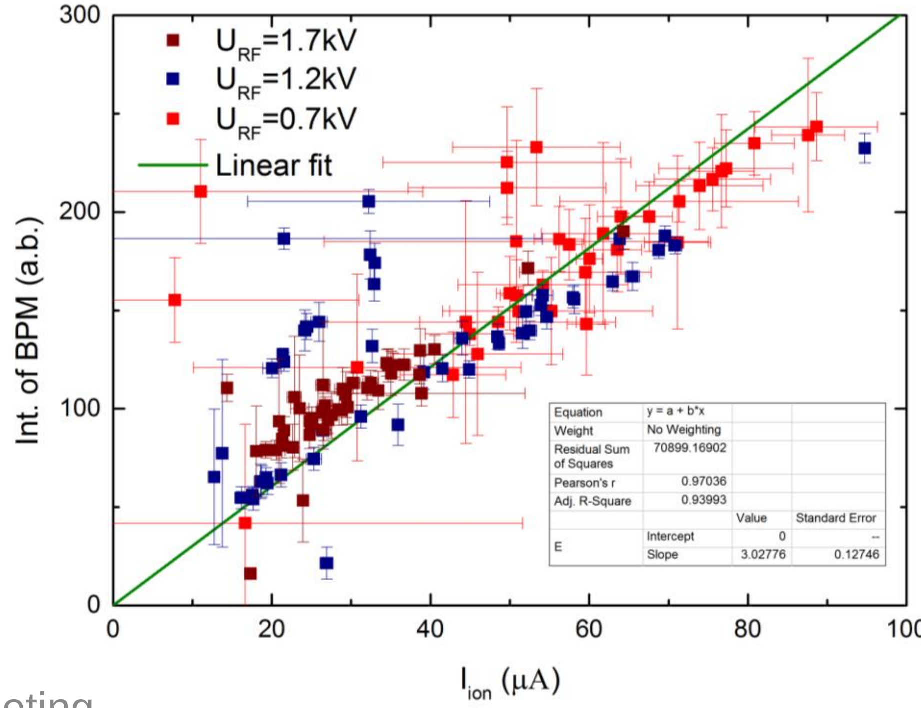
Integrated Charge of Cooled and Uncooled Ion Bunches



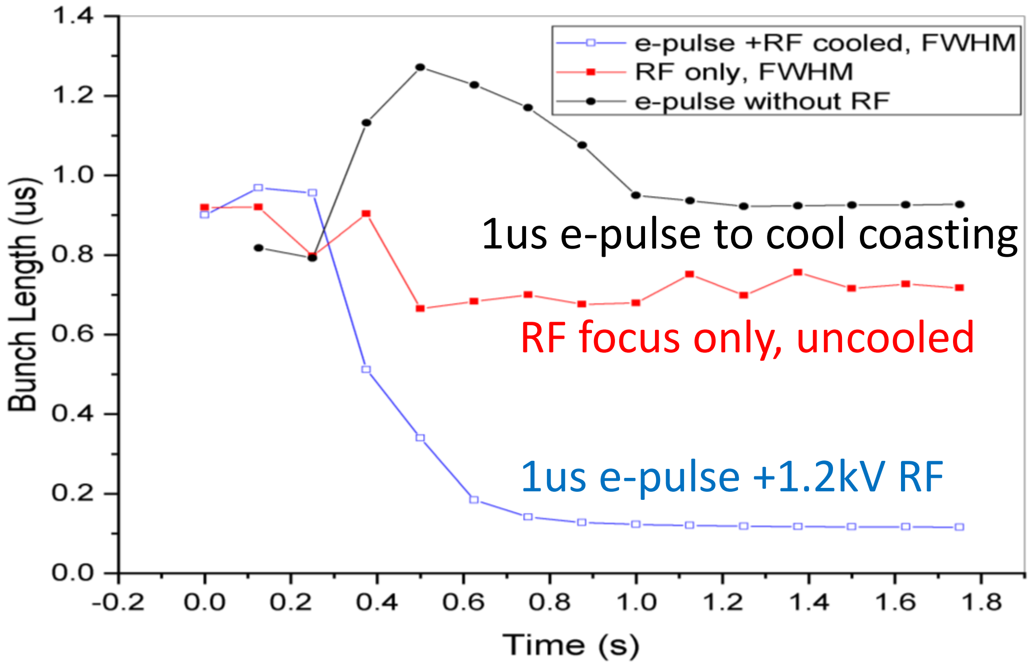






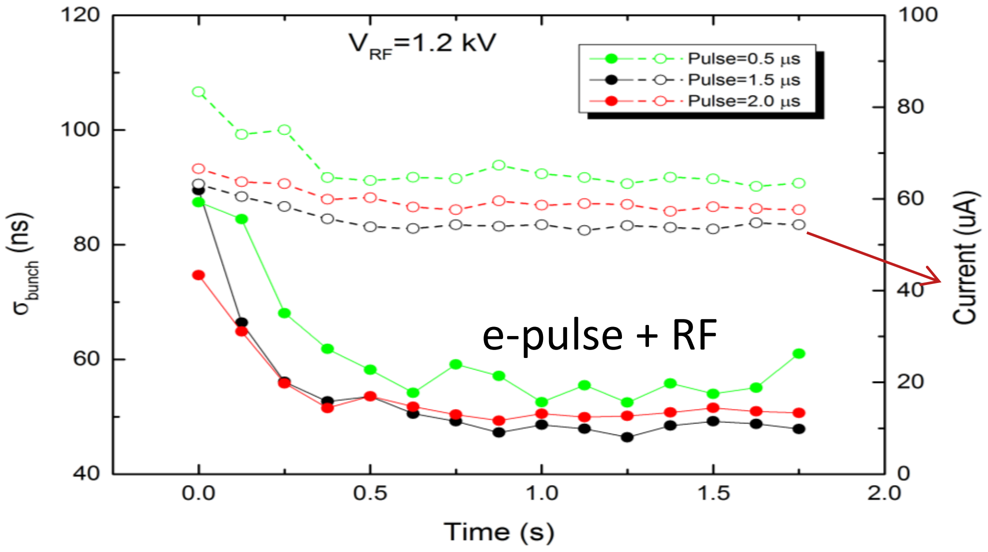
- Ion pulse shape distortion correction by FFT/IFFT data process
- Integrated charge at a given period can be better calculated
- Bunch length can be also better measured

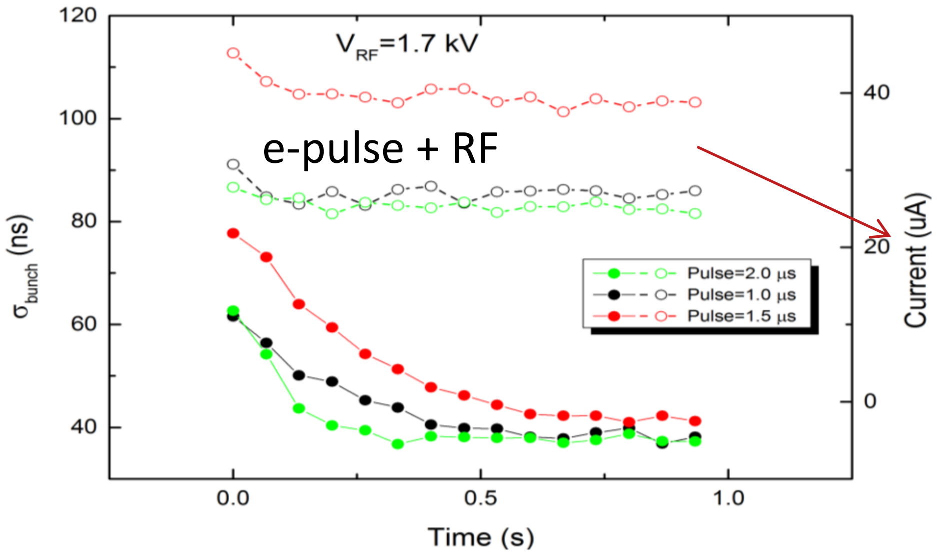
RMS Length of Cooled and Uncooled Ion Bunches



$$\delta = \sqrt{\frac{eV}{2\pi\beta^2 Eh|\eta|}}\Delta\varphi$$

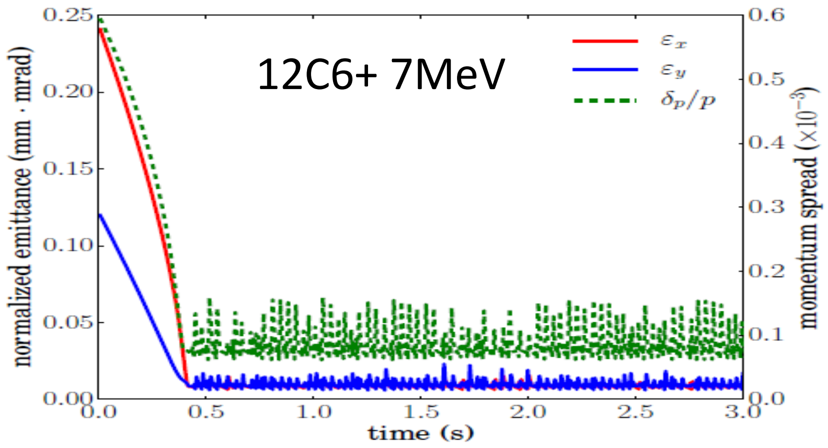
$$\varepsilon = \pi\sqrt{\frac{eV}{2\pi\beta^2 Eh|\eta|}}\Delta\varphi^2$$

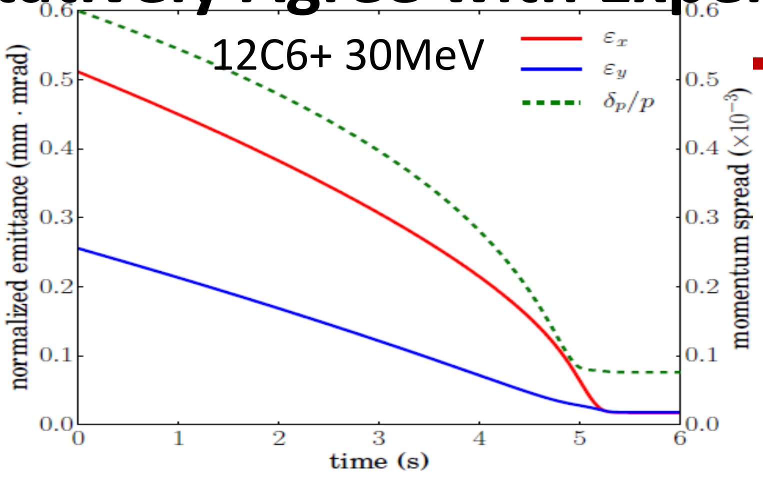


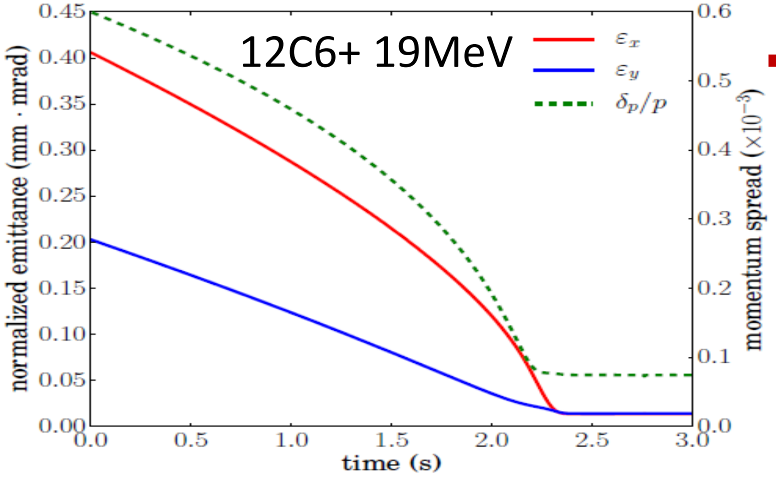


- In 2017 run, accumulation of ions was assisted by a DC cooling
- A factor of 5 decreasing in bunch length ➔ a factor of 5 decreasing in momentum spread ➔ a factor of 25 decreasing in longitudinal emittance
- Good quality of bunch-beam cooling data sets are limited due to lack of measurement of ion 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:

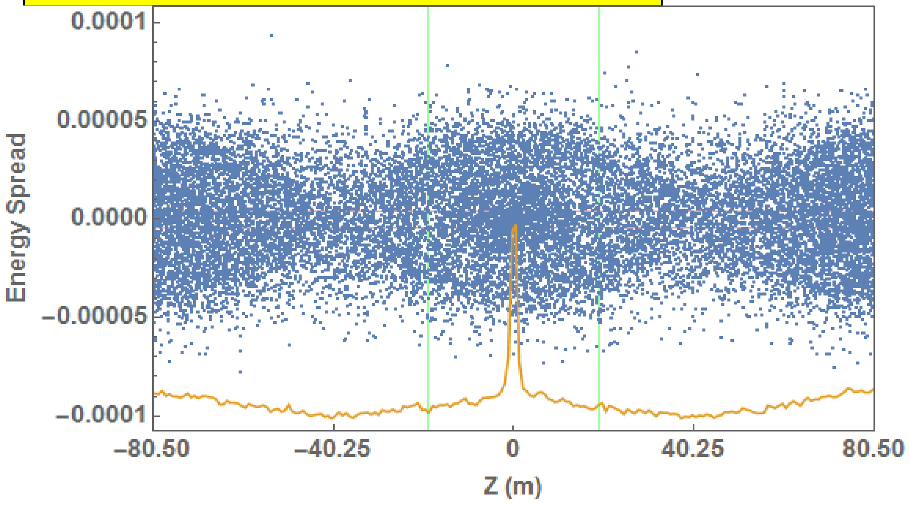
Modeling/Simulations Qualitatively Agree with Experimental Data





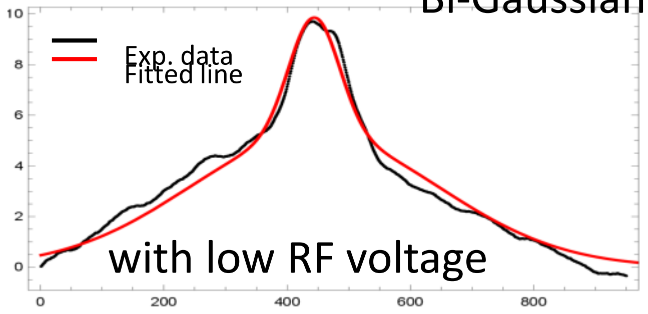


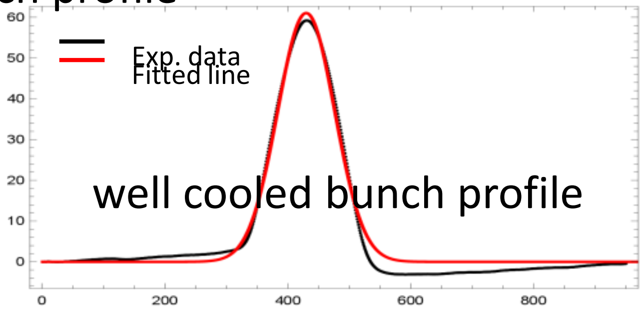
1D beam dynamic modeling

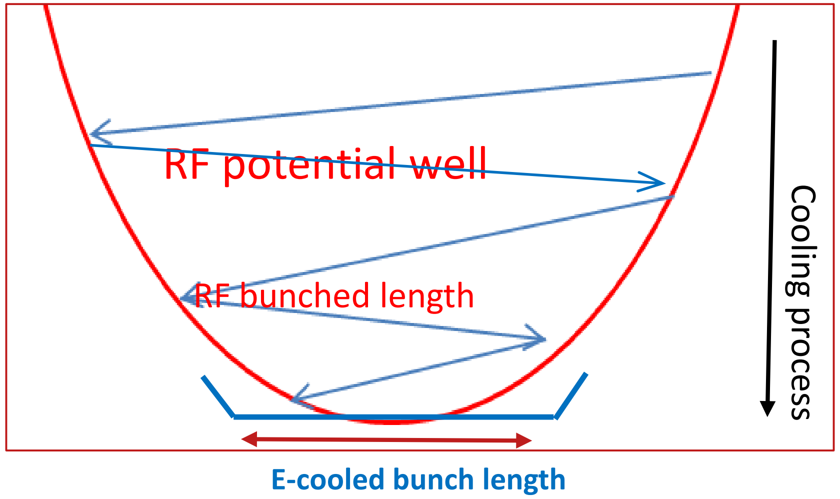


The cooled ions are trapped at the RF potential well bottom, forms the spike core. In this simulation, RF voltage is on with electron bunch cooling.

Bi-Gaussian bunch profile





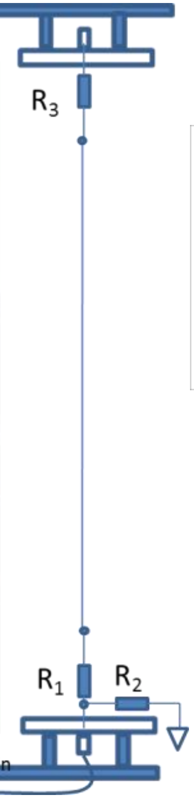


- Electron potential well is much shallow compare to RF potential well
- 1D modeling with RF + e-potential has demonstrated bunched e-cooling process.
- 3D simulation tool is under the development

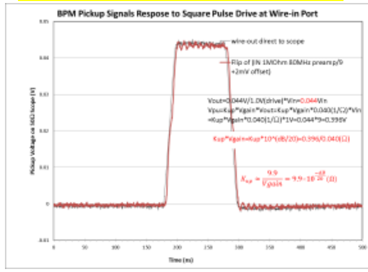
Experimental Data Quality Improvement Plan

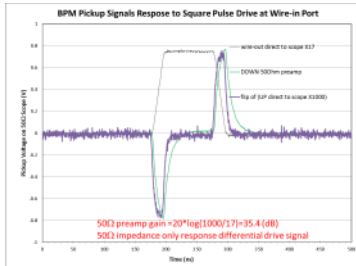
New ion BPM at CSRm, Installed 09/26/2018

- Build a new show-box BPM. Use 1 MW, 80 MHz BW preamp, so cutoff frequency drops to ~386 Hz, no FFT/IFFT correction in data post processing ***Completed!*** (Sept. 2018)
- 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 ***Completed!*** (Sep. 2018)
- Do the bench calibration by the wire-stretching technique ***Completed!*** (Sep. 2018)
- Bench calibrate old ion BPM, so all 2017 experimental data can be reevaluated
- Take measurement of transverse Schottky side band signals for transverse betatron oscillation damping (feasibility under study)



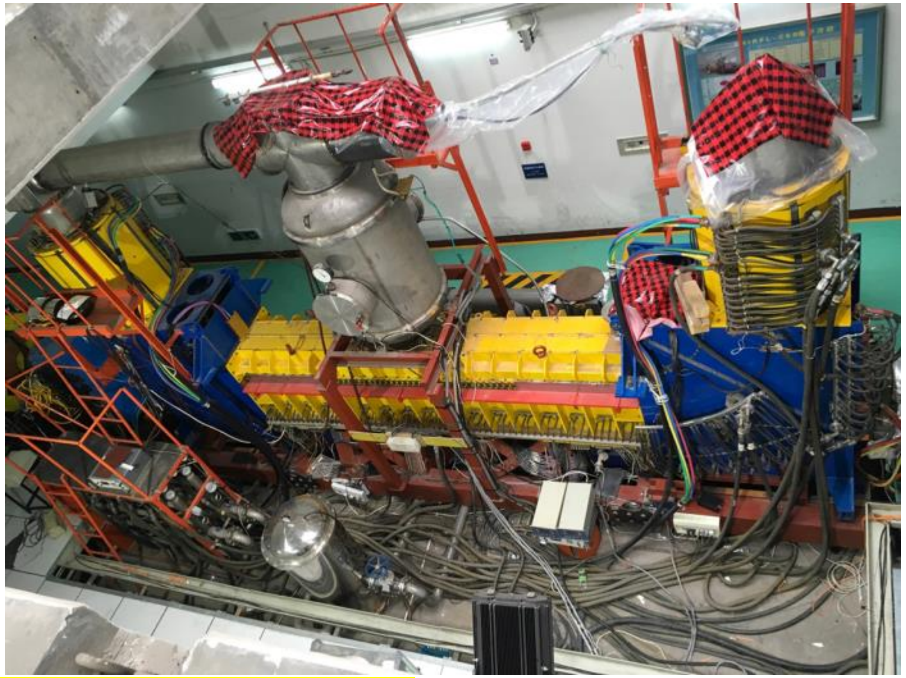
Time domain calibration result



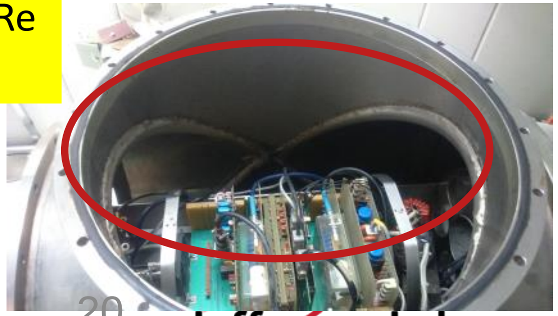


Plan for Future Experiment in the CSRe Ring (2019-2020)

- Move experiment from CSRm to CSRe ring.
- SC300 cooler in the CSRe ring will extend the ion energy from 30 MeV/u up to 400 MeV/u
- Will generate a similar electron pulse structure by a new pulser technology
- The electron pulse length can be decreased from present ~20 m down to ~2 m, comparable to the shorter ion bunch length
- JLab is responsible to design and build the HV pulse inside of SF6 tank (a new postdoc position is created for electronic work)
- 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



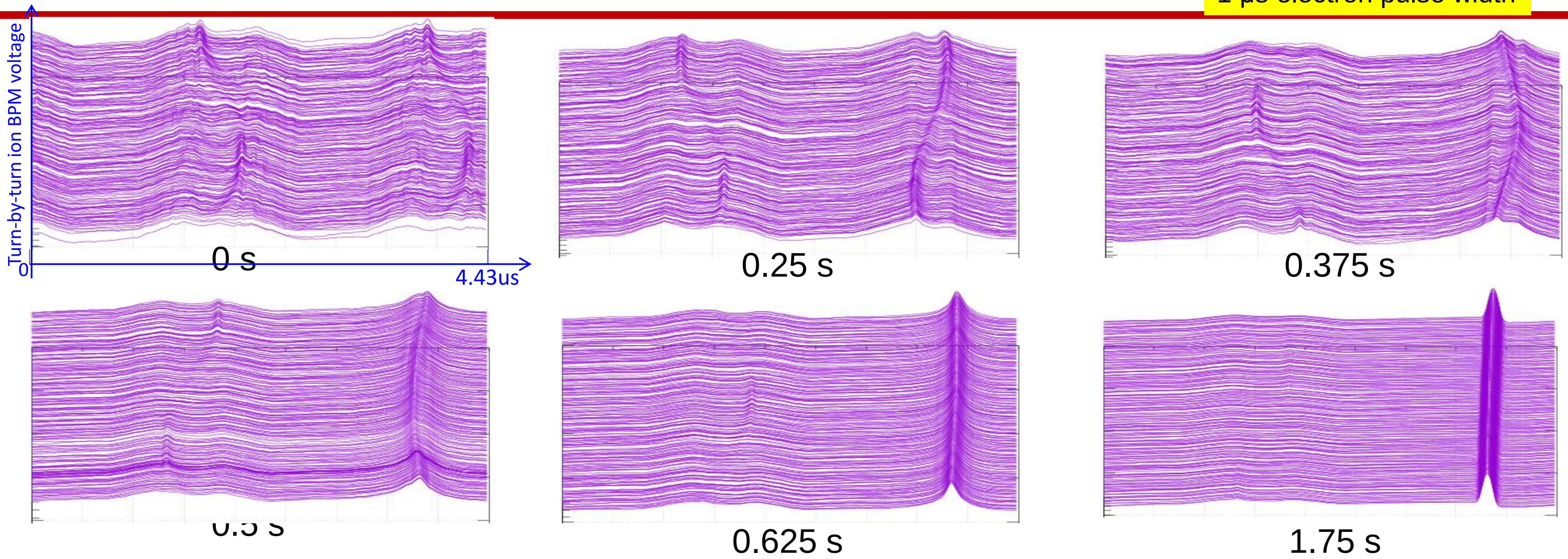
Jefferson Lab

Summary

- Cooling of a $^{12}C^{+6}$ ion beam at 7 MeV/u by a bunched electron beam was demonstrated at the CSRm ring by the Jlab/IMP collaboration team
- The Ion bunch length is reduced from coasting to ~3 m within about 0.5 second. The momentum spread is reduced from ~2e-3 to ~6e-4 with a similar cooling rate
- The simulation models developed so far agree with the measurements qualitatively. More progresses will be made in this area
- Beam diagnostics (ion BPM and Schottky signals) support these evidences however obtained data so far lacks of calibrations and measurement accuracies for a further quantitative analyses.
- Improvement of beam instrumentation (both hardware and software) has been planed and prepared for the 3rd experiment (scheduled on Dec. 6-12, 2018)
- The next phase of bunched beam cooling experiment is planed utilizing a higher voltage DC cooler at IMP CSRe ring with parameters more closed to the JLEIC parameter regime
- IMP is still the good place to demonstrate the strong bunched beam cooling in order to benchmark cooling simulation tools for JLEIC CCR/ERL cooler design

Turn-by-turn ion BPM Signal From Fast Oscilloscope

1 μs electron 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.

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