Bunched Beam Cooling Experiment Report (and future plan)

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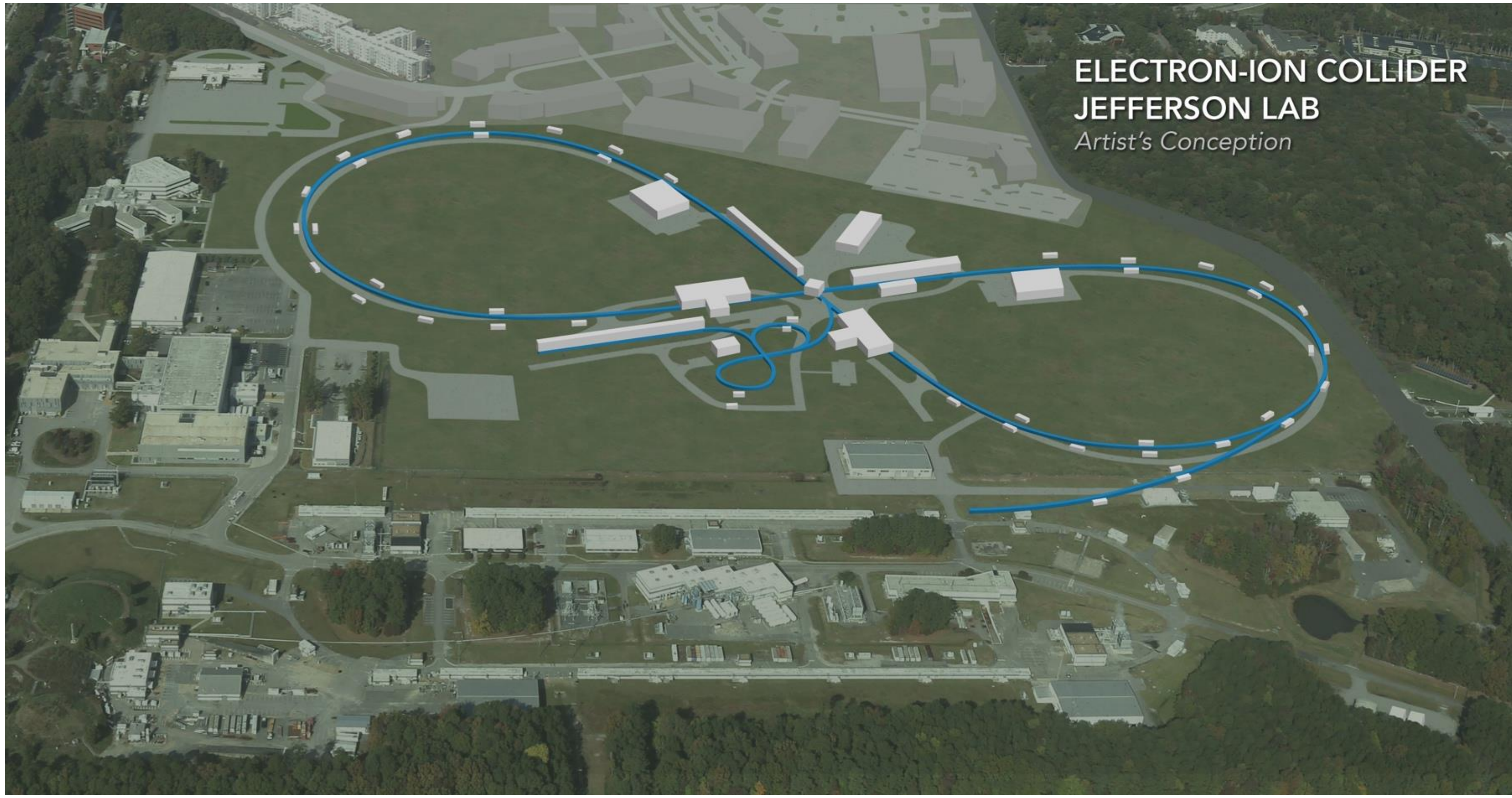


EIC Accelerator Collaboration Meeting

October 29 - November 1, 2018

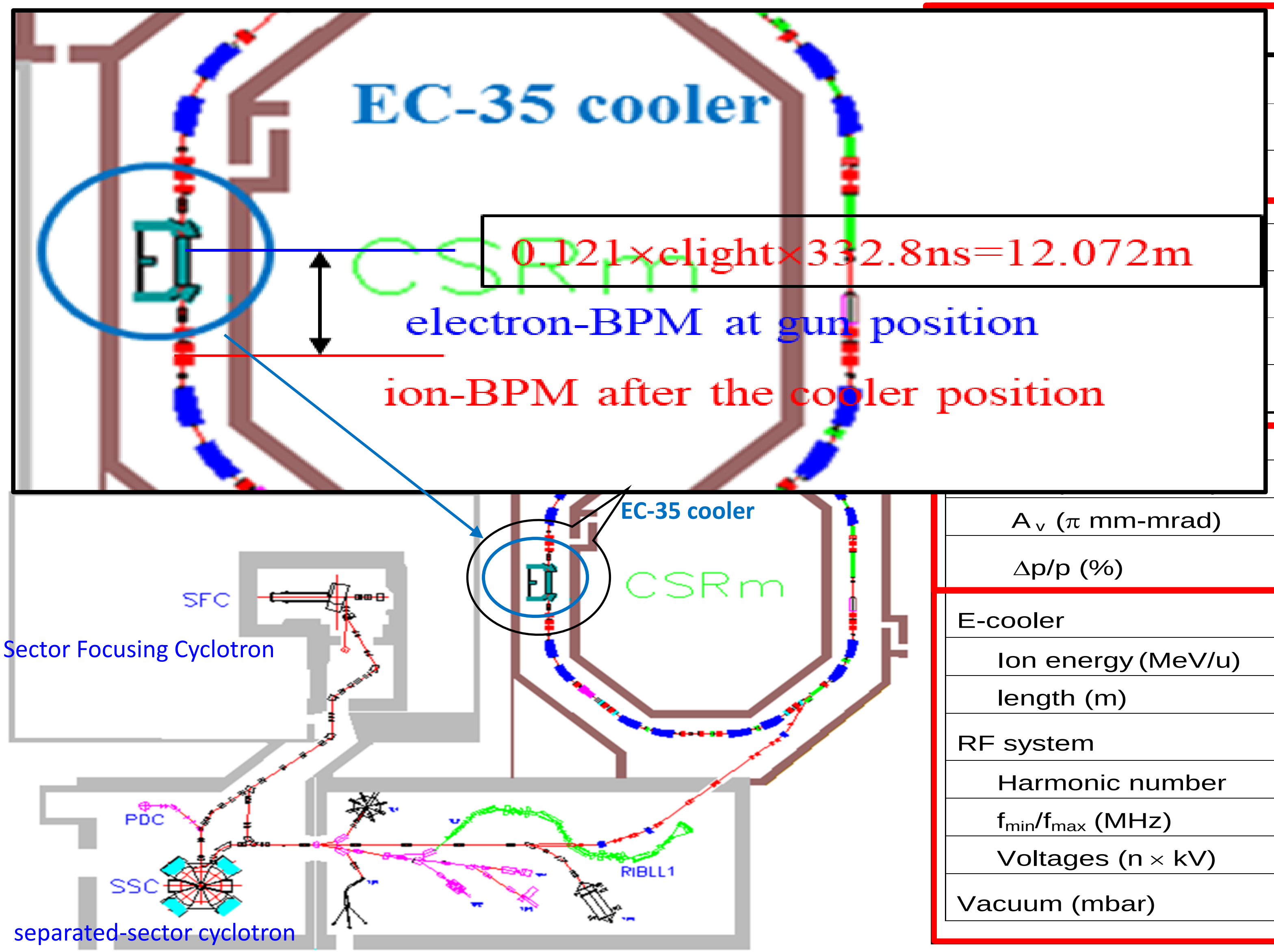
Motivation, Experiments and Data Analysis:

- 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, 2rd experiment: improved triggering control and beam instrumentation for taking data in the same injection fill so cooling process was more clearly observed

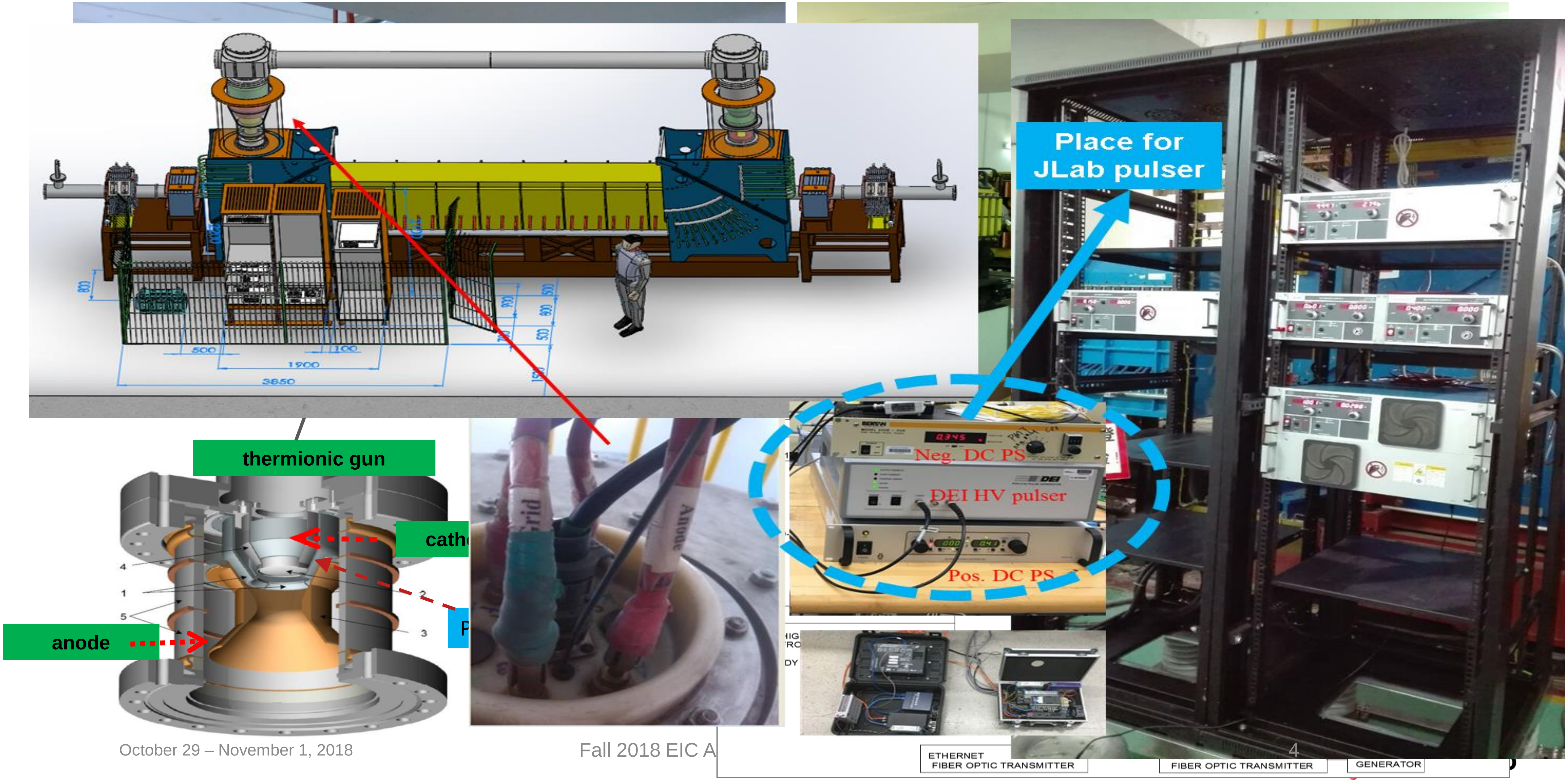
- Strong BPM (time domain) and Schottky (frequency domain) diagnostic signals confirmed the bunched beam cooling process qualitatively, implying a new physics process beyond the DC based strong cooling model
- Agree with 3D pulsed cooling model and 1D pulse + RF focusing models simulations but all of them are lack of quantitative benchmarks against to the experiemental 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

HIREL-CSR Layout at IMP and Machine Design Parameters



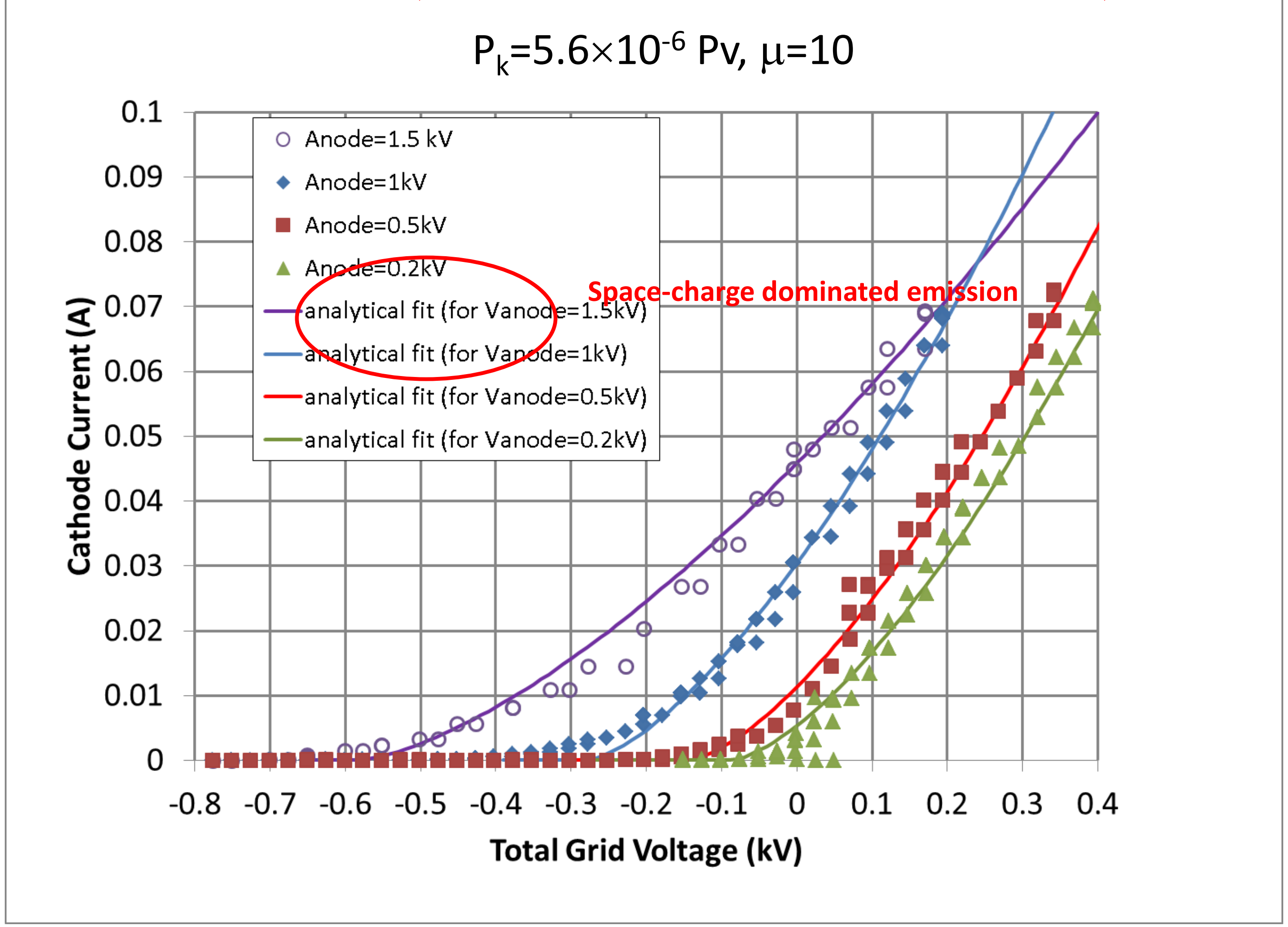
	CSRm		CSRe	
	161.0014		128.8011	
	Race-track		Race-track	
	900 (C^{6+}) 400 (U^{72+})	1100 (C^{6+}) 2800 (p)	600(C^{6+}) 400(U^{90+})	700(C^{6+}) 450(U^{90+})
	0.91/10.64	0.81/12.04	1.20/8.40	0.50/9.00
	0.12/1.40	0.10/1.59	0.20/1.40	0.08/1.50
	0.05 ~ 0.4		0.1 ~ 0.2	
	∼ 17 (∼10s for Accumulation)			
			Normal mode	
	200 ($\Delta p/p = \pm 0.15$ %)		**150** ($\Delta p/p = \pm 0.5$%)	
A_v (π mm-mrad)	30		**75**	
$\Delta p/p$ (%)	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})	

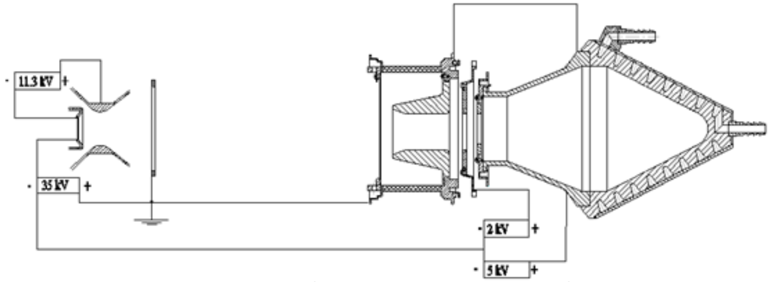
Modification of SC-35 Gun and New Switching Pulser and Fiber Optical Controller



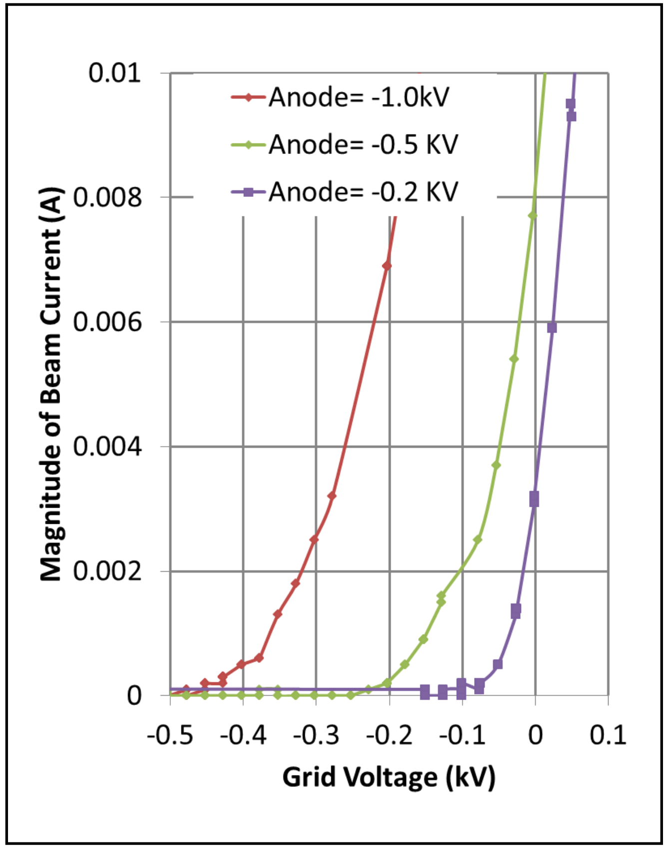
SC35 Cooler EX-35 E-Gun Measurement on Nov. 13, 2015

$$I_{cathode} = P_k \left(V_{grid} - V_{bias} + \frac{V_{anode} + V_{grid} - V_{bias}}{\mu}\right)^{1.5}$$





Electrical connection of the gun and collector for EX-35



Experiment Parameters and Data Taken 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**

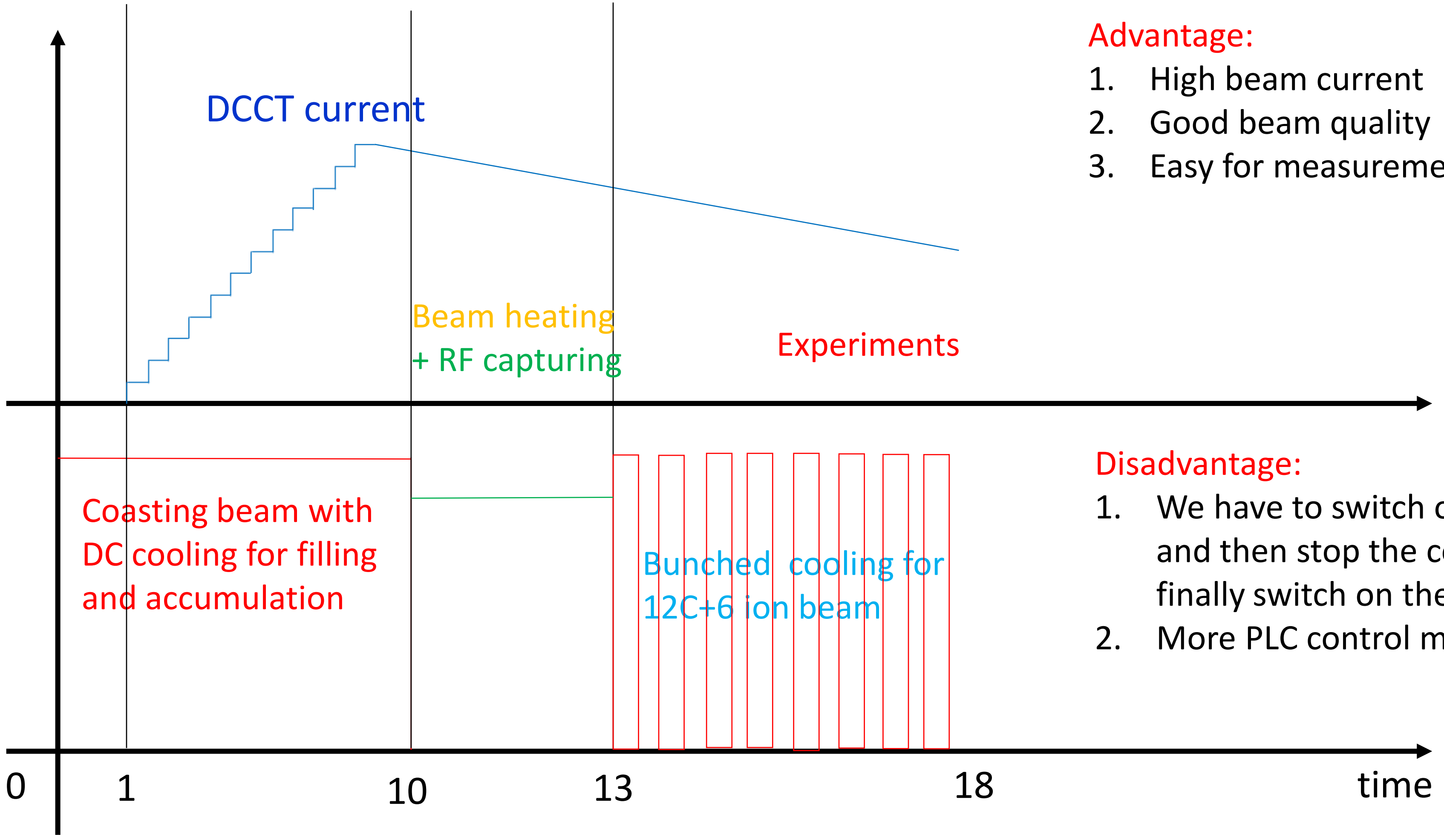
Experiment parameters

A lot of data taken at 7MeV/u from April 21-27, 2017.

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

JLab modified DC e-gun pulse generator's limitation

Cooling at injection energy at 7MeV/u [most experiment data taken at this energy]



Advantage:

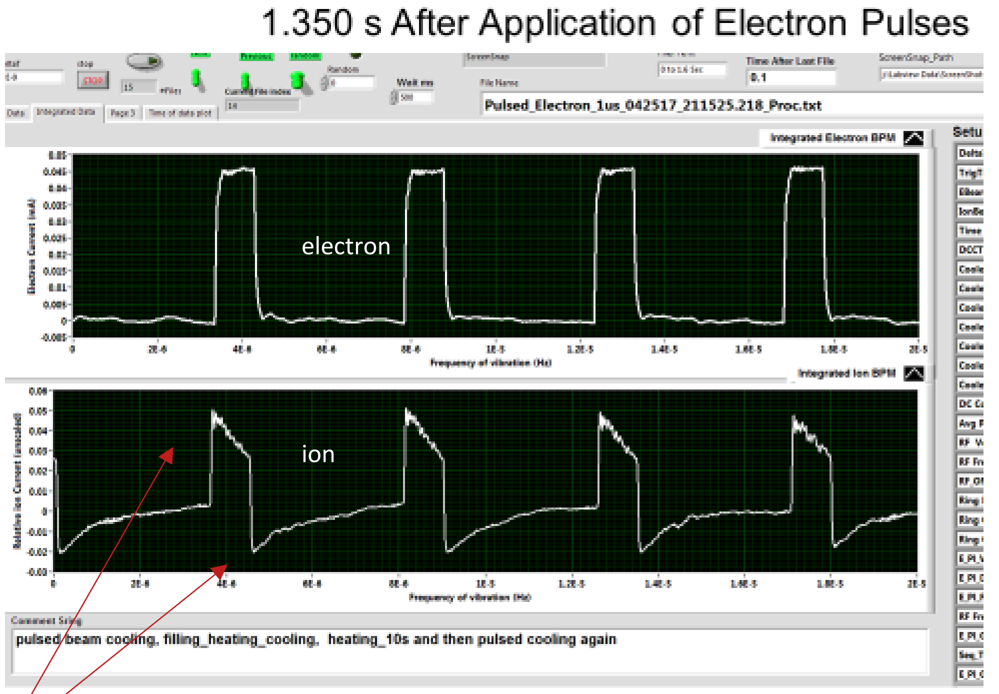
1. High beam current
2. Good beam quality
3. Easy for measurement

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

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)



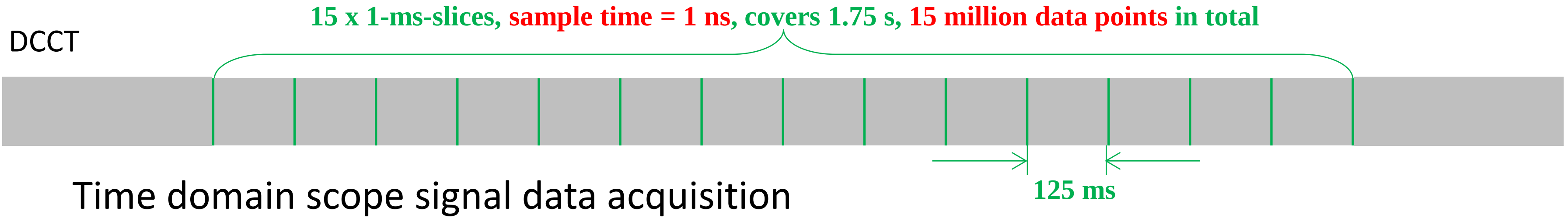
1.350 s After Application of Electron Pulses

Pulsed_Electron_1us_042517_211525.218_Proc.txt

pulsed beam cooling, filling_heating_cooling, heating_10s and then pulsed cooling again

Due to deficiency of low impedance pre-amplifier

Only trustable calibrated beam device is DCCT

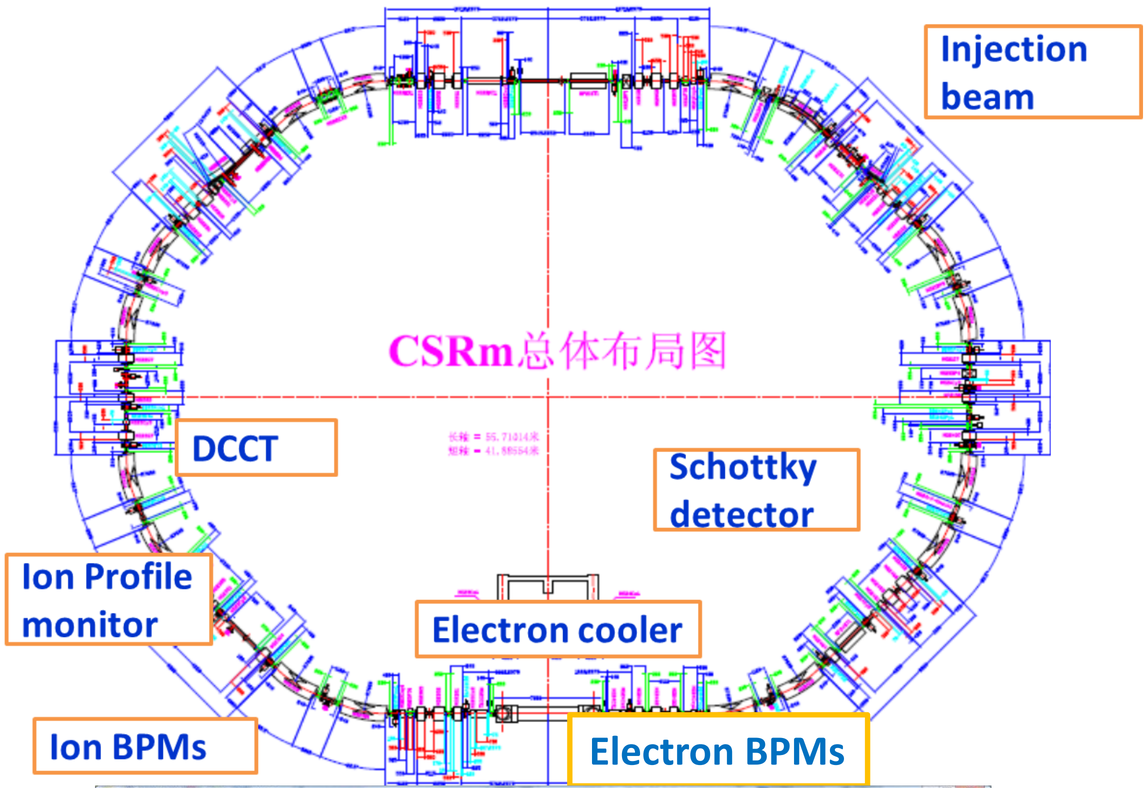


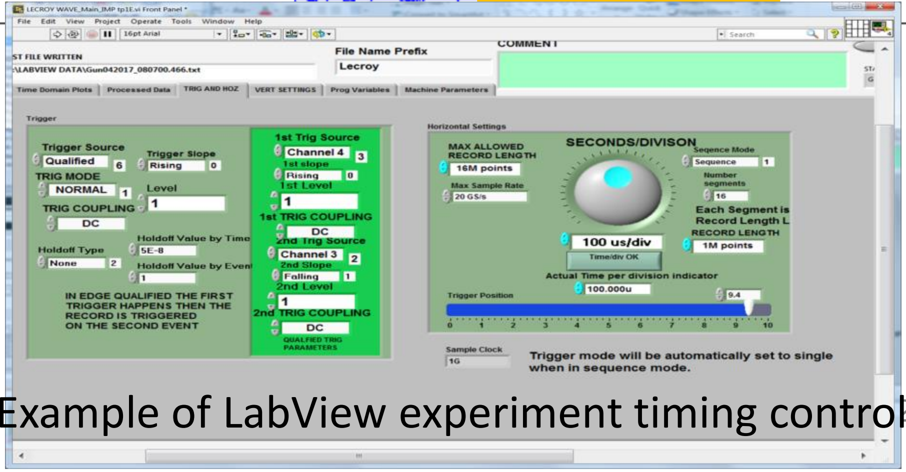
15 x 1-ms-slices, sample time = 1 ns, covers 1.75 s, 15 million data points in total

125 ms

Time domain scope signal data acquisition

Beam diagnostic system setup:





ST FILE WRITTEN: :\LABVIEW DATA\Gun042017_080700.466.txt

File Name Prefix: Lecroy

Trigger

Trigger Source: Qualified 6

Trigger Slope: Rising 0

TRIG MODE: NORMAL 1

Level: 1

TRIG COUPLING: DC

Holdoff Value by Time: 5E-8

Holdoff Type: None 2

Holdoff Value by Event: 1

IN EDGE QUALIFIED THE FIRST TRIGGER HAPPENS THEN THE RECORD IS TRIGGERED ON THE SECOND EVENT

1st Trig Source: Channel 4 3

1st slope: Rising 0

1st Level: 1

1st TRIG COUPLING: DC

2nd Trig Source: Channel 3 2

2nd Slope: Falling 1

2nd Level: 1

2nd TRIG COUPLING: DC

QUALFIED TRIG PARAMETERS

Horizontal Settings

MAX ALLOWED RECORD LENGTH: 16M points

Max Sample Rate: 20 GS/s

SECONDS/DIVISON: 100 us/div

Actual Time per division indicator: 100.000u

Seqence Mode: Sequence 1

Number segments: 16

Each Segment is Record Length L

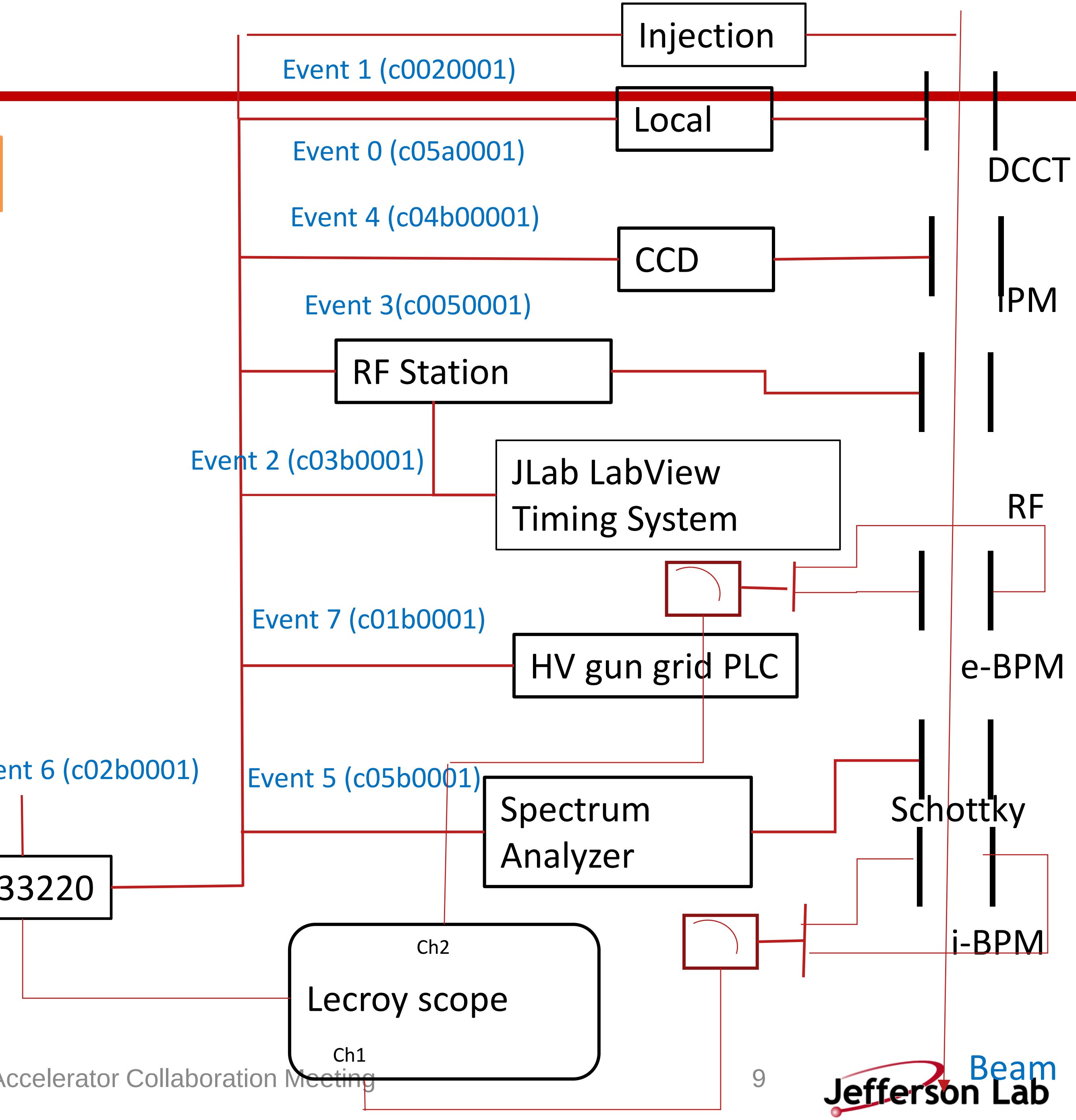
RECORD LENGTH: 1M points

Trigger Position: 9.4

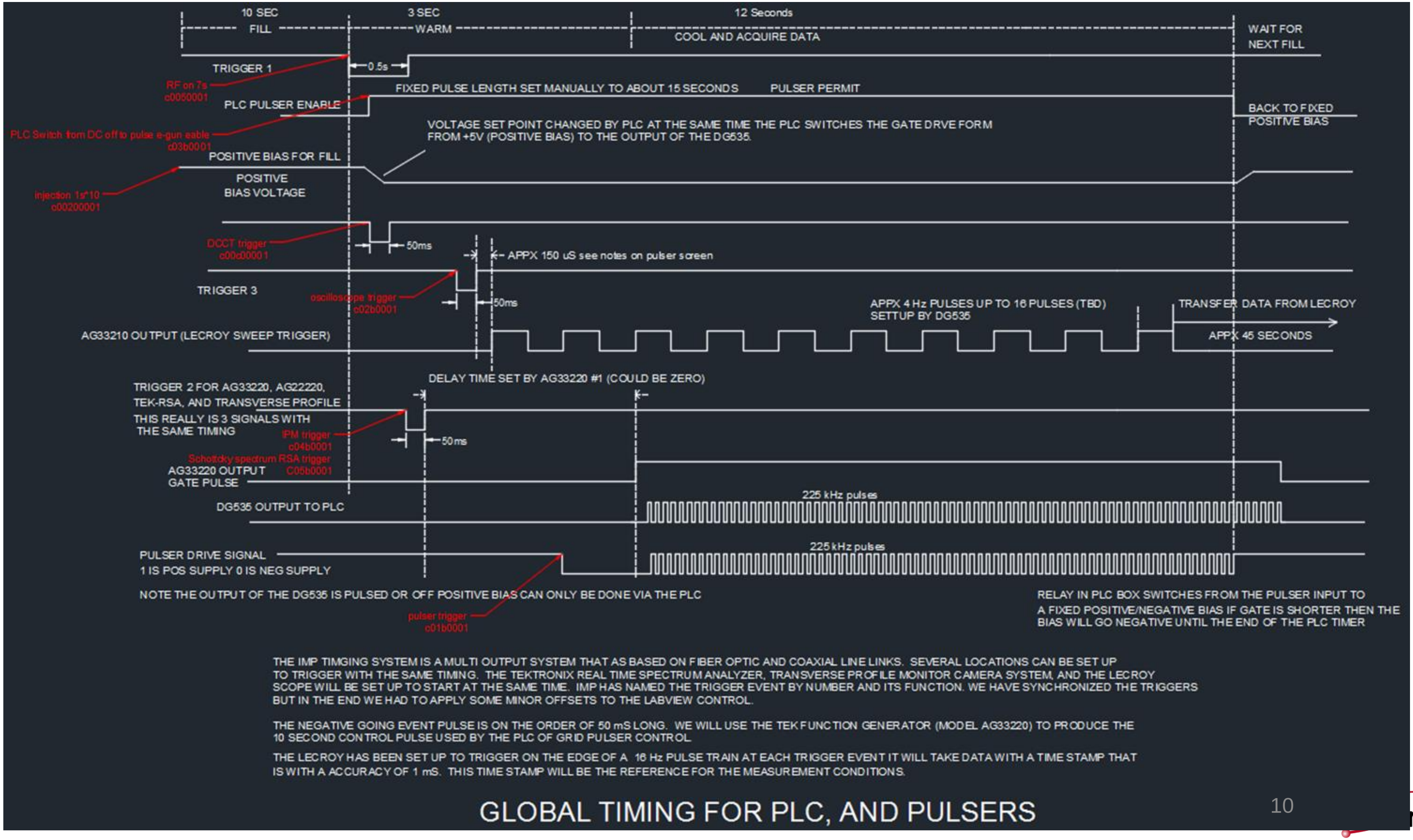
Sample Clock: 1G

Trigger mode will be automatically set to single when in sequence mode.

Example of LabView experiment timing control screen



Global timing and local triggering logics for the BPM data capturing within one filling Cycle



NOTE THE OUTPUT OF THE DG535 IS PULSED OR OFF POSITIVE BIAS CAN ONLY BE DONE VIA THE PLC

RELAY IN PLC BOX SWITCHES FROM THE PULSER INPUT TO
A FIXED POSITIVE/NEGATIVE BIAS IF GATE IS SHORTER THEN THE
BIAS WILL GO NEGATIVE UNTIL THE END OF THE PLC TIMER

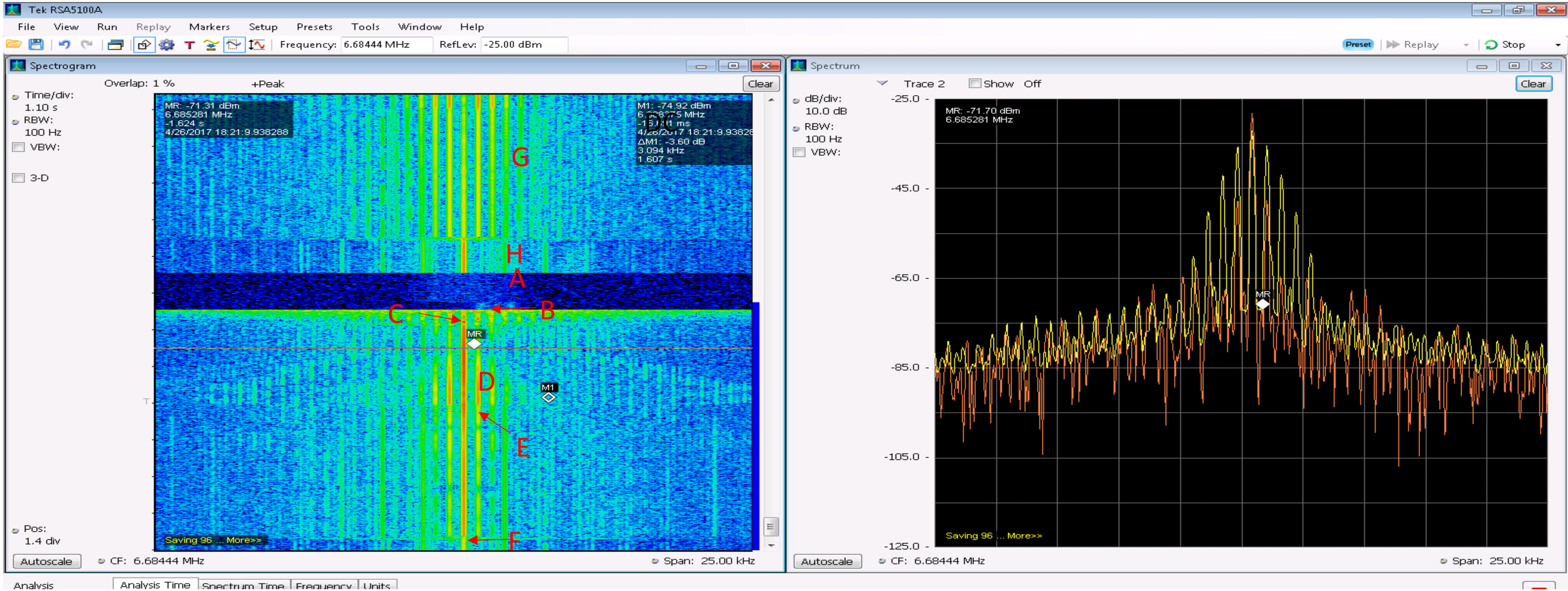
THE IMP TIMGING SYSTEM IS A MULTI OUTPUT SYSTEM THAT AS BASED ON FIBER OPTIC AND COAXIAL LINE LINKS. SEVERAL LOCATIONS CAN BE SET UP TO TRIGGER WITH THE SAME TIMING. THE TEKTRONIX REAL TIME SPECTRUM ANALYZER, TRANSVERSE PROFILE MONITOR CAMERA SYSTEM, AND THE LECROY SCOPE WILL BE SET UP TO START AT THE SAME TIME. IMP HAS NAMED THE TRIGGER EVENT BY NUMBER AND ITS FUNCTION. WE HAVE SYNCHRONIZED THE TRIGGERS BUT IN THE END WE HAD TO APPLY SOME MINOR OFFSETS TO THE LABVIEW CONTROL.

THE NEGATIVE GOING EVENT PULSE IS ON THE ORDER OF 50 mS LONG. WE WILL USE THE TEK FUNCTION GENERATOR (MODEL AG33220) TO PRODUCE THE 10 SECOND CONTROL PULSE USED BY THE PLC OF GRID PULSER CONTROL.

THE LECROY HAS BEEN SET UP TO TRIGGER ON THE EDGE OF A 16 Hz PULSE TRAIN AT EACH TRIGGER EVENT IT WILL TAKE DATA WITH A TIME STAMP THAT IS WITH A ACCURACY OF 1 mS. THIS TIME STAMP WILL BE THE REFERENCE FOR THE MEASUREMENT CONDITIONS.

GLOBAL TIMING FOR PLC, AND PULSERS

Typical cooling experiment cycle by injection filling, DC cooling on/off, RF on/off , e-pulse on/off conditions



Frequency: 6.68444 MHz
RefLev: -25.00 dBm

Spectrogram

Overlap: 1 %
+Peak

Time/div: 1.10 s
RBW: 100 Hz
☐ VBW:
☐ 3-D
Pos: 1.4 div
CF: 6.68444 MHz
Span: 25.00 kHz

MR: -71.31 dBm
6.685281 MHz
-1.624 s
4/26/2017 18:21:9.938288

M1: -74.92 dBm
6.[illegible]8275 MHz
-16.[illegible]1 ms
4/26/2017 18:21:9.93828
ΔM1: -3.60 dB
3.094 kHz
1.607 s

Spectrum

Trace 2
☐ Show Off

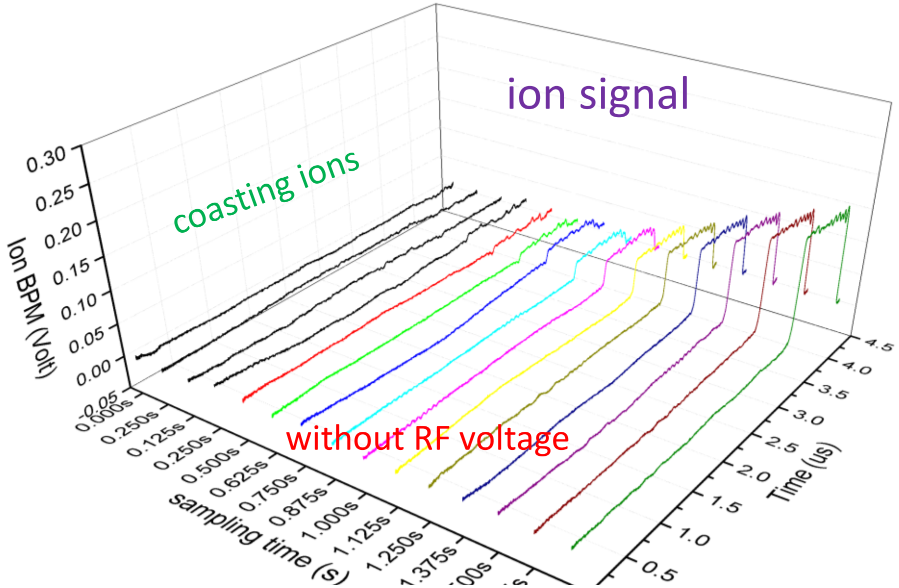
dB/div: 10.0 dB
RBW: 100 Hz
☐ VBW:
CF: 6.68444 MHz
Span: 25.00 kHz

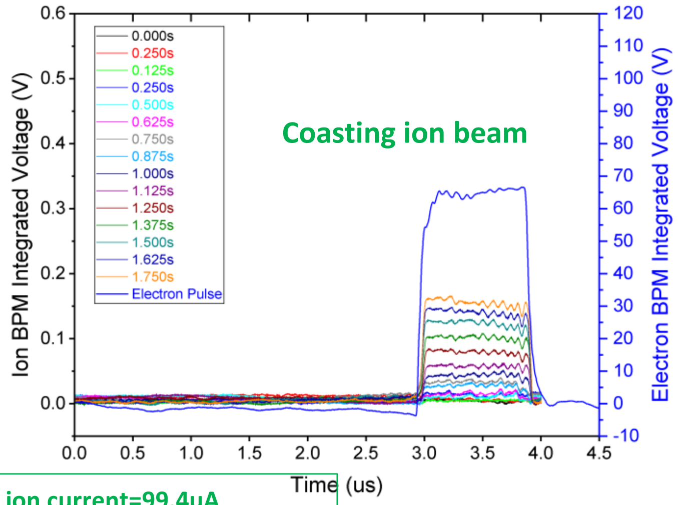
MR: -71.70 dBm
6.685281 MHz

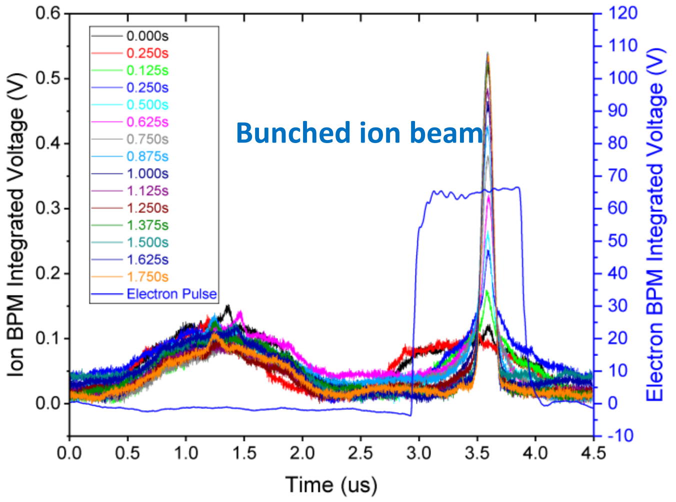
A. Start new cycle **B.** DC cooling on + filling **C.** +Vrf=400V **D.** DC cooling off for warmup but RF on

E. Pulsed mode cooling (2.5 us) on **F.** Pulsed cooling on but RF off **G.** Pulsed cooling +Vrf=400V **H.** Pulsed cooling off

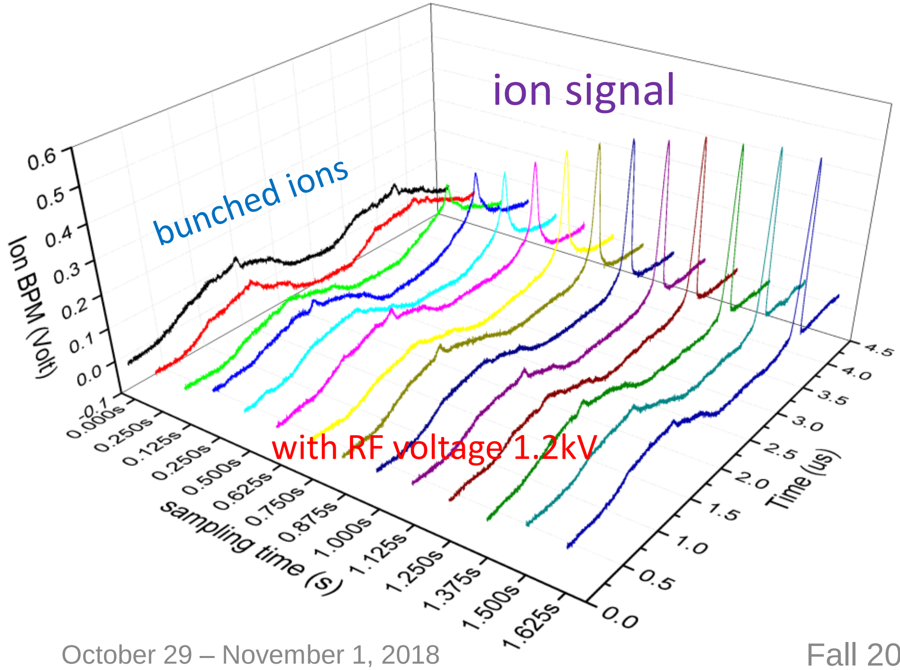
BPM data analysis demonstrated the bunched beam cooling feature



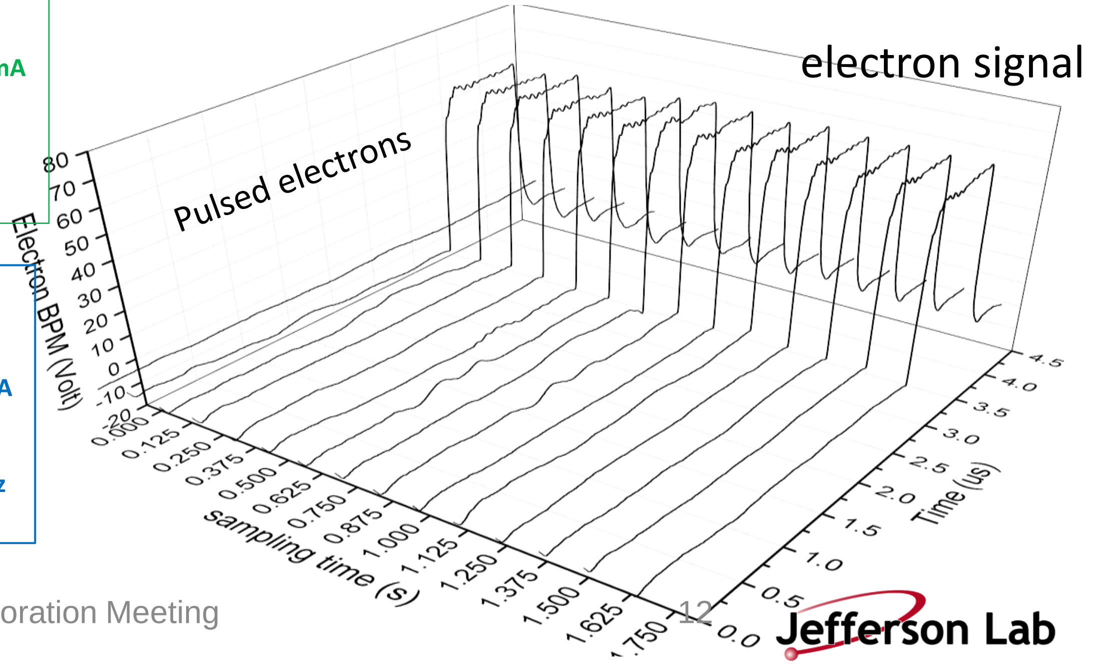




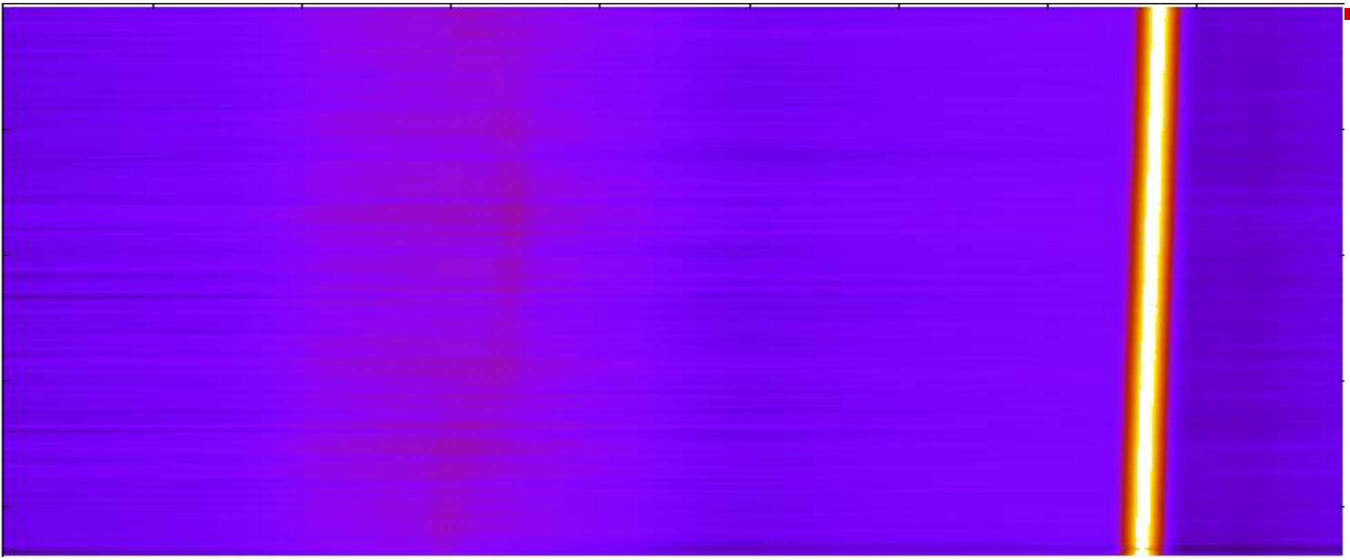
DCCT ion current=99.4uA
e energy=3.767keV
e DC collector current=67.0mA
e average pulsed current=13.8mA
RF Frequency=445.94kHz
e-pulse width=1.0us
e-pulse frequency=222.97kHz
RF Voltage=off

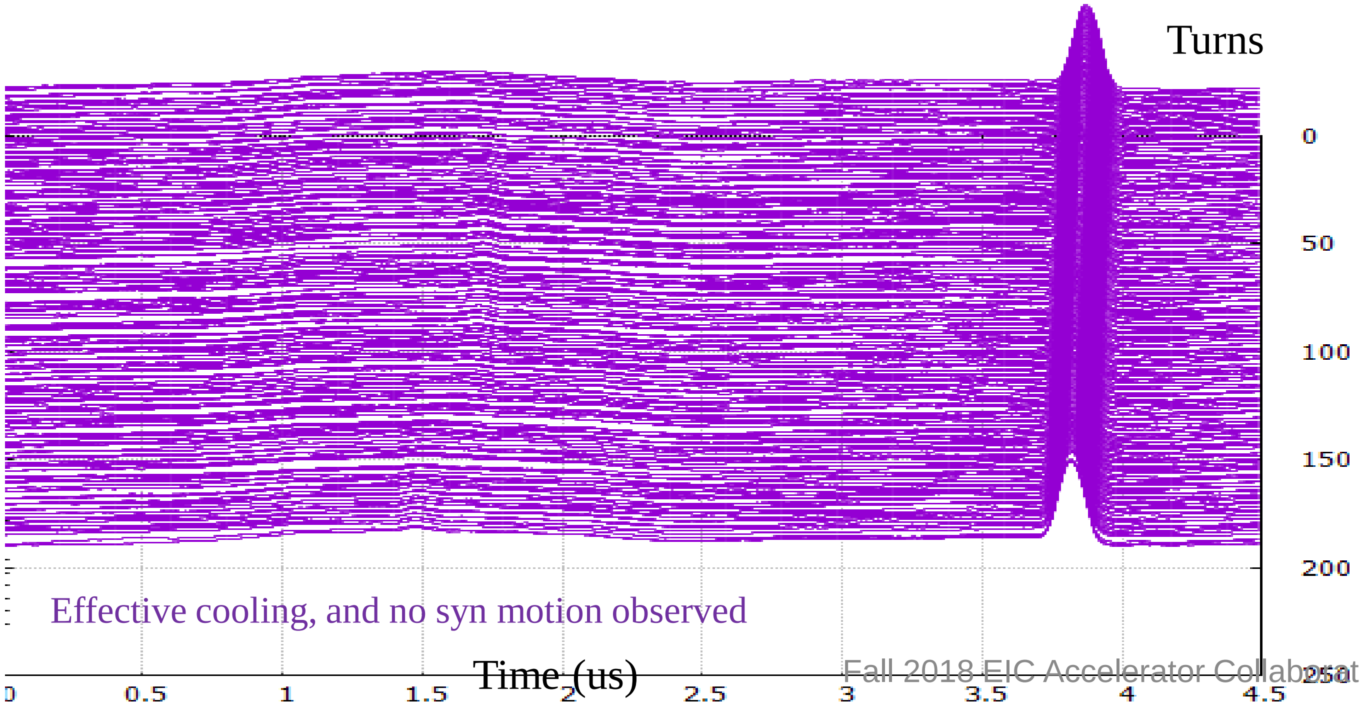


DCCT ion current=43.78uA
e energy=3.74keV
e DC collector current=67.2mA
e average pulsed current=9.5mA
RF Frequency=445.6577kHz
e-pulse width=1.0us
e-pulse frequency=222.8288kHz
RF Voltage=1.49/1.2kV (W/R)

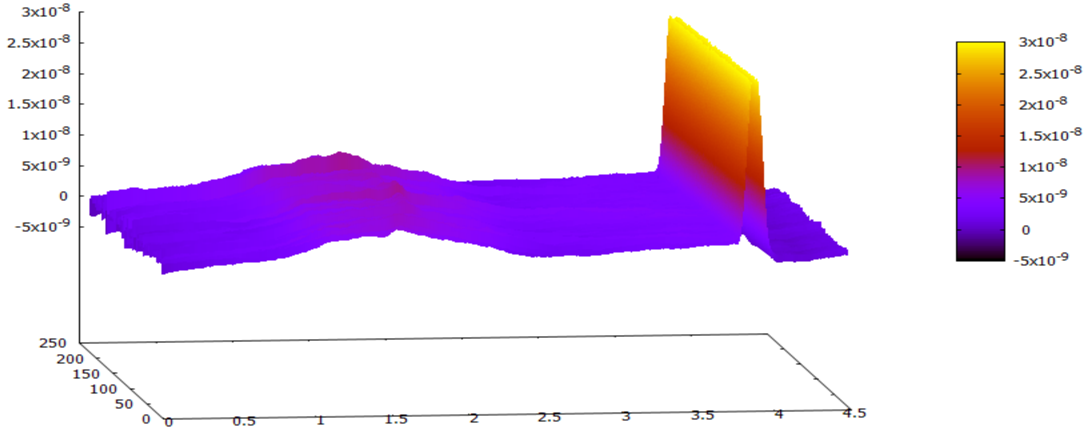


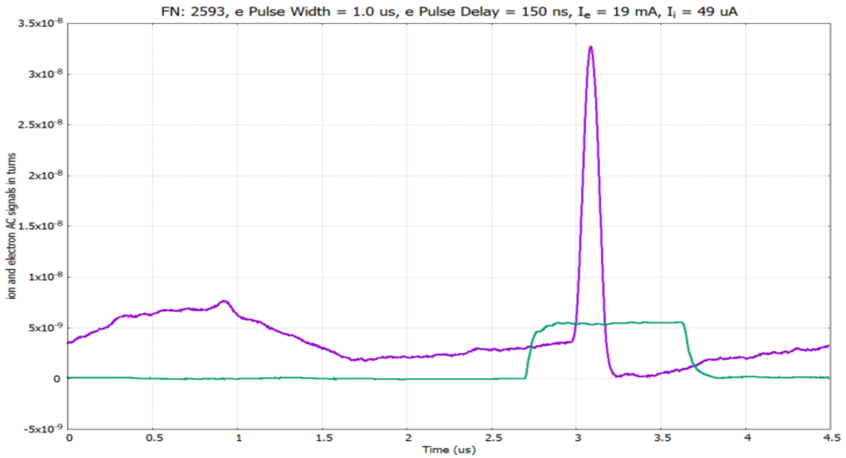
BPM data demonstrated the bunched beam cooling at equilibrium condition





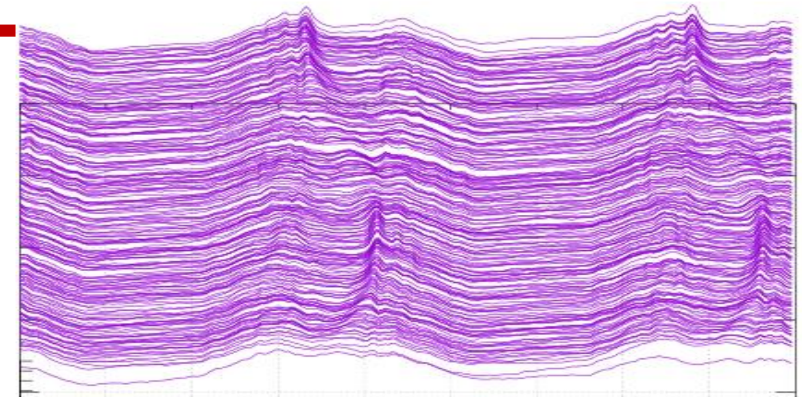
Effective cooling, and no syn motion observed



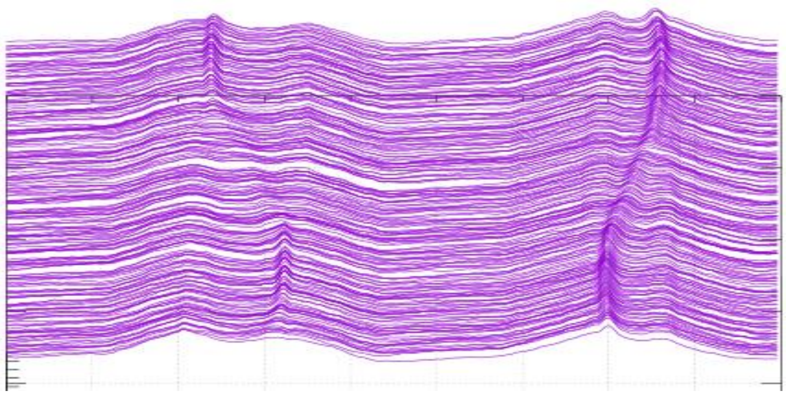


- At the end of the cooling process, single Gaussion distribution in cooled bunch is observed again, all available ions are cooled and attracted into the narrow spike.
- The right foot of the spike is obviously lower than the left one is due to the deficiency of pre-amp.

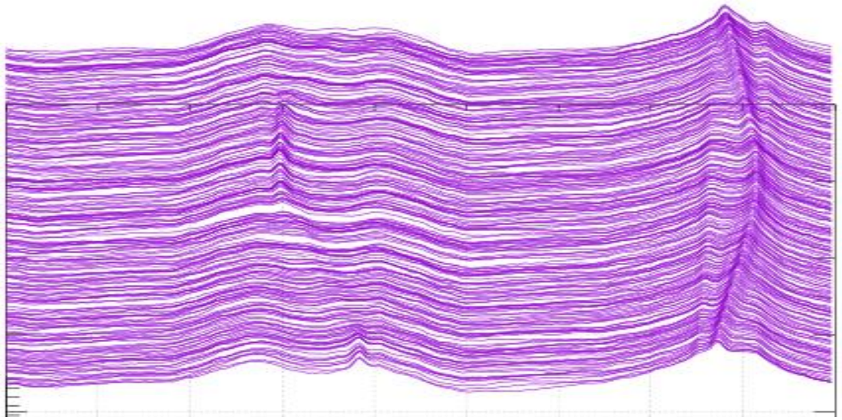
Turn-by-turn ion BPM signal from fast oscilloscope, 1us e-pulse width



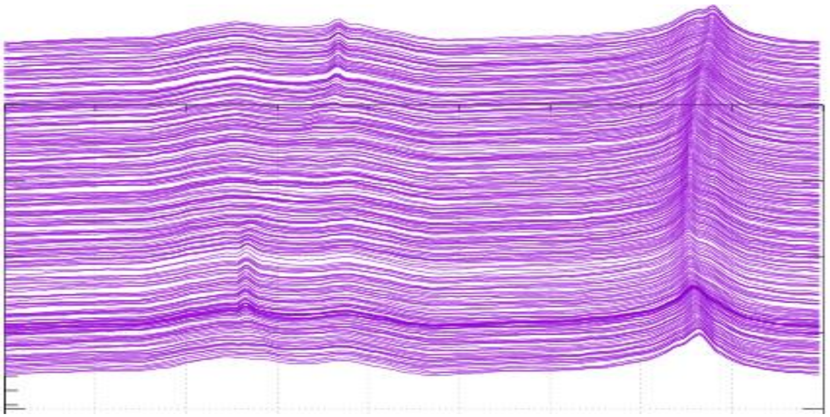
0 s



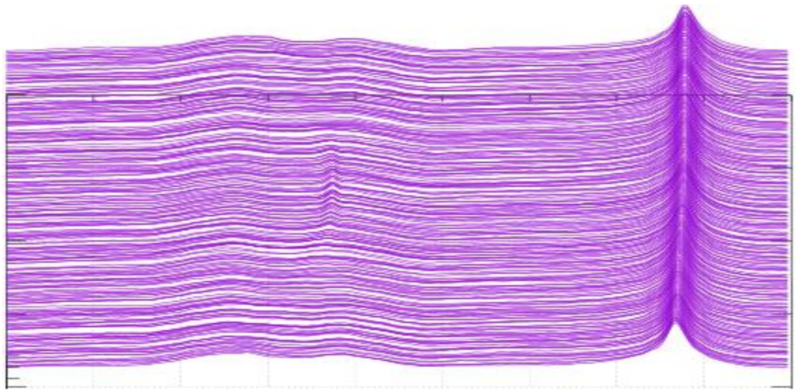
0.25 s



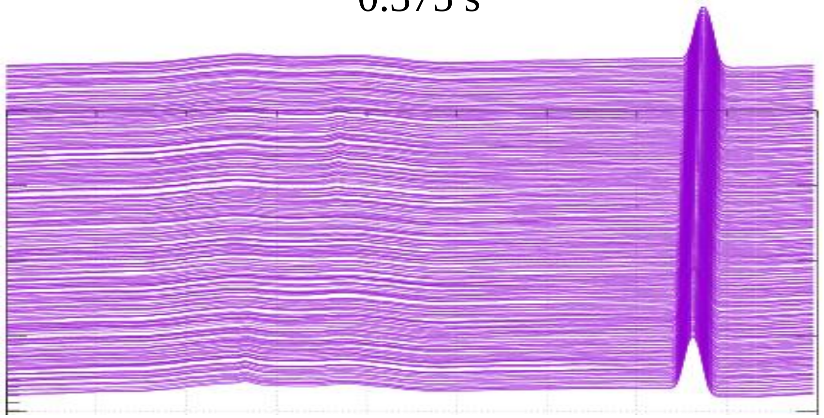
0.375 s



0.5 s



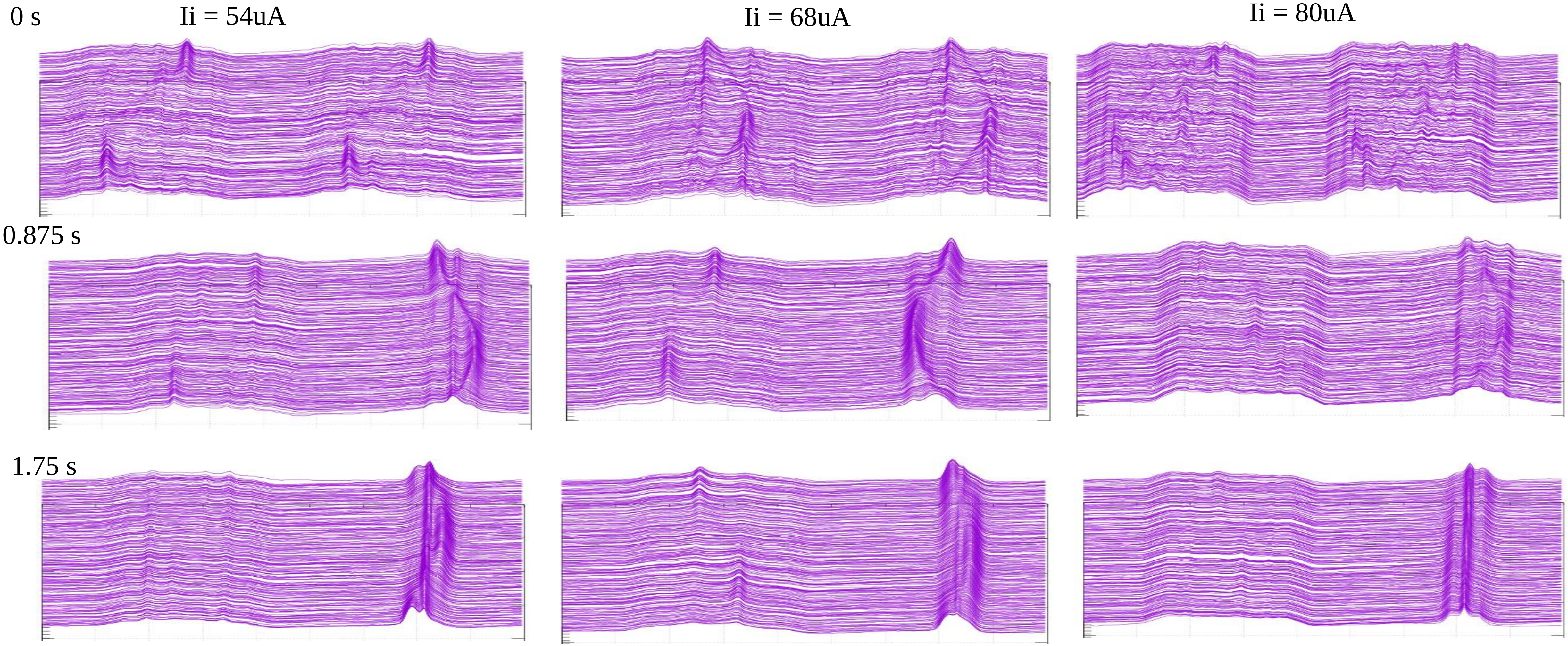
0.625 s



1.75 s

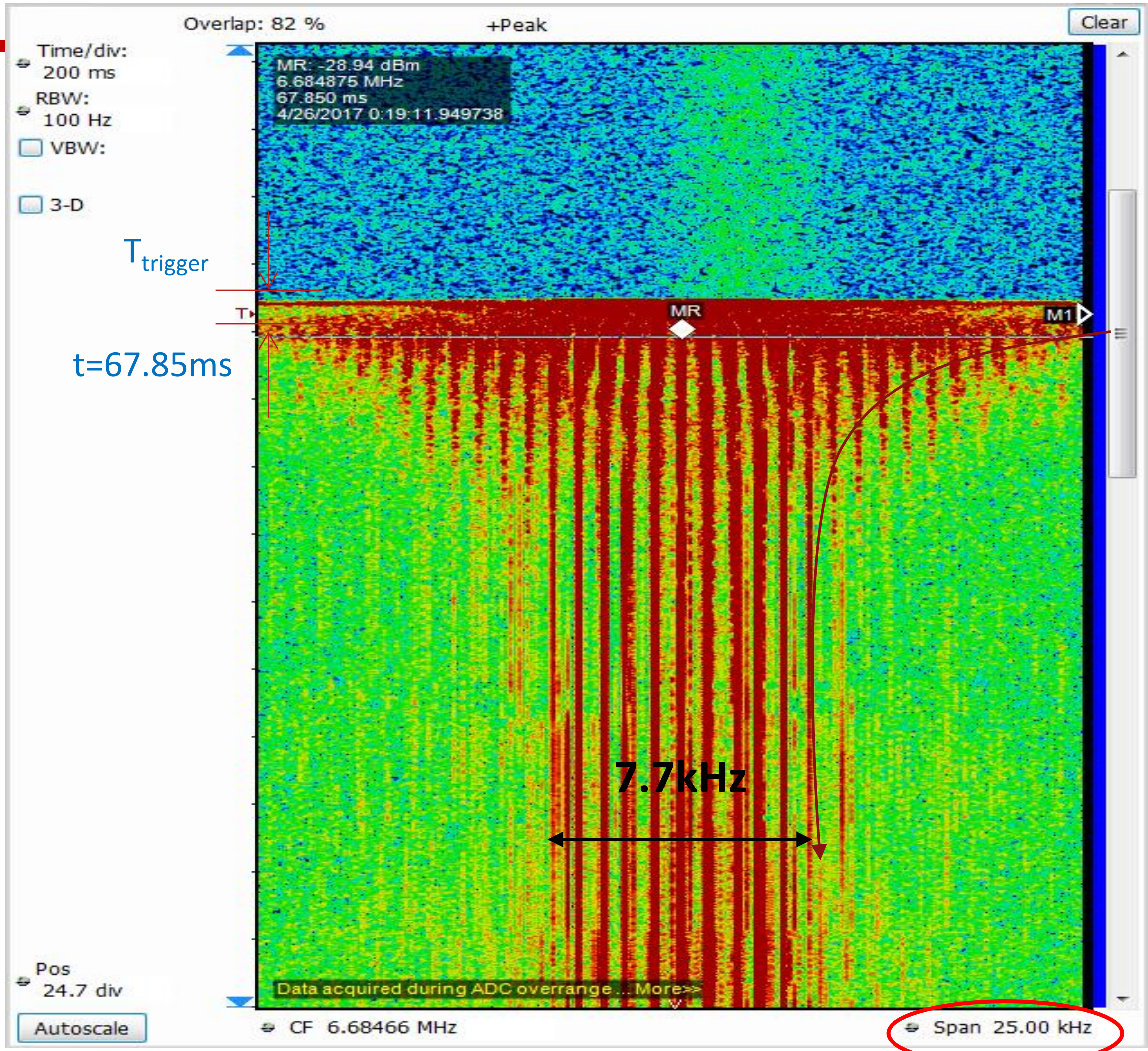
- Synchrotron motion in cooled bunch is observed to be limited to narrower and narrower region during the cooling process, eventually the synchrotron motion disappeared in the narrow spike of the cooled bunch.
- That is the double Gaussian and final single Gaussian distribution through the cooling process.
- The energy spread amplitude is lower and the phase space distribution becomes more uniform during the cooling process, instabilities disappeared.

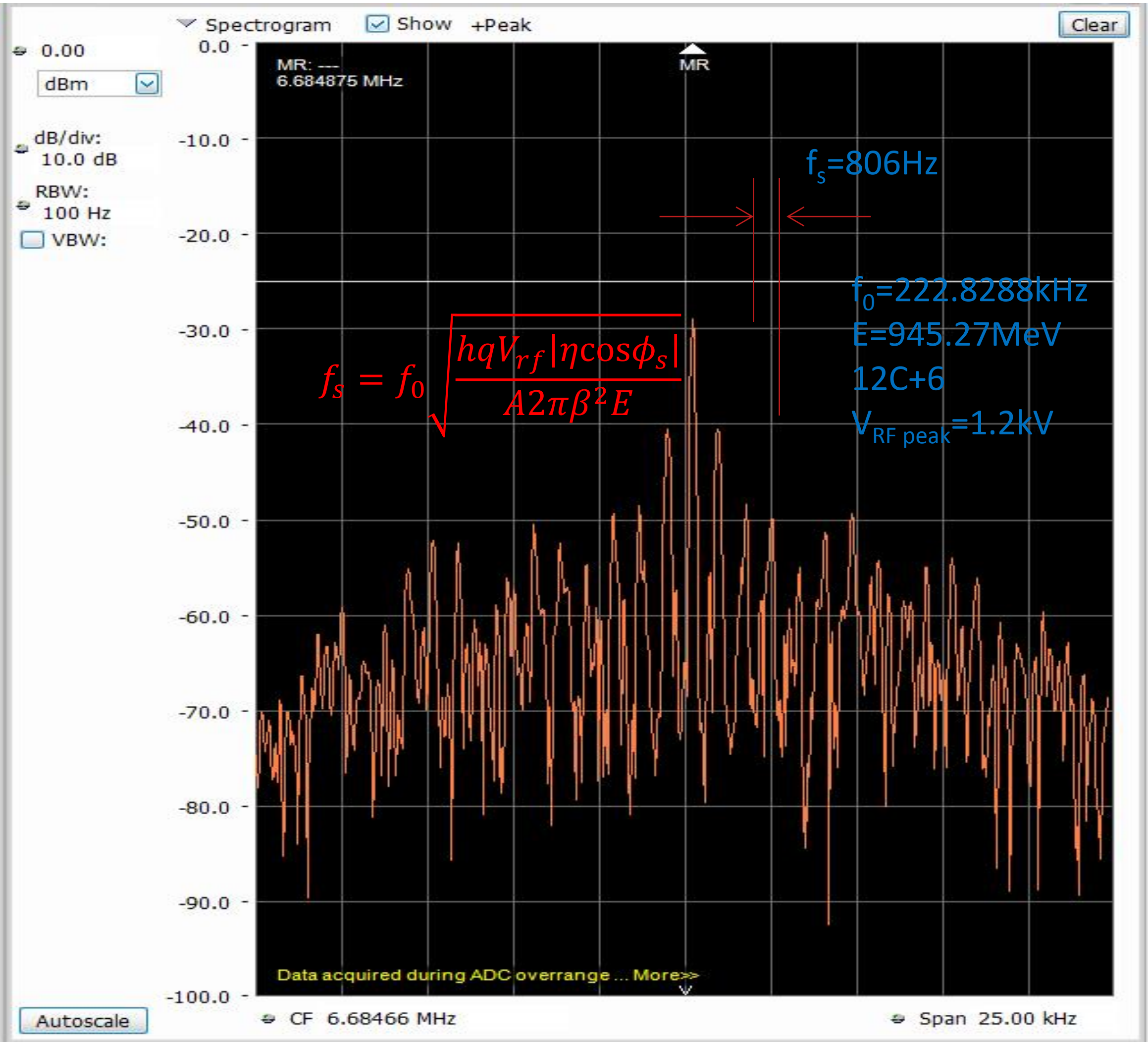
Turn-by-turn ion BPM signal from fast oscilloscope, 0.5us e-pulse width



- 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 τ_{cool} and dp/p estimation





$$f_s = f_0\sqrt{\frac{hqV_{rf}|\eta\cos\phi_s|}{A2\pi\beta^2E}}$$

Schottky movie to play

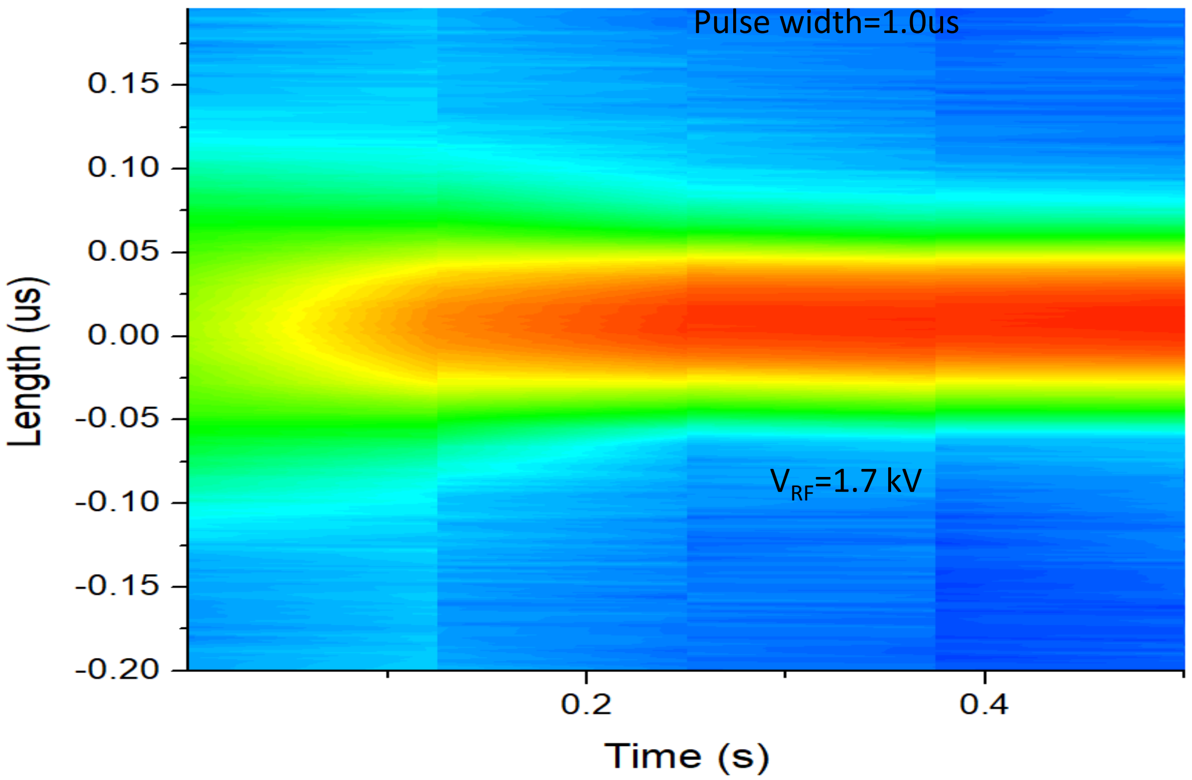
SchottkySignal_Large.mp4

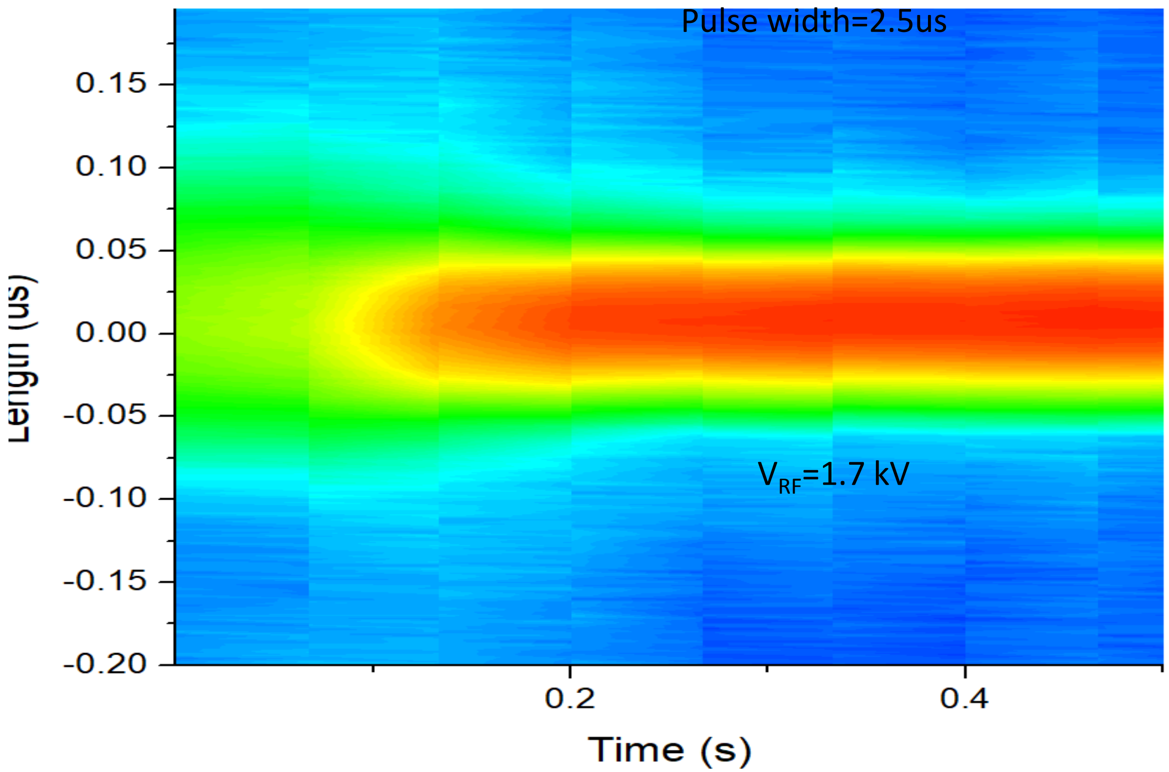
time

frequency

- 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

Ion BPM data by using calculated cutoff frequency for beam transfer function

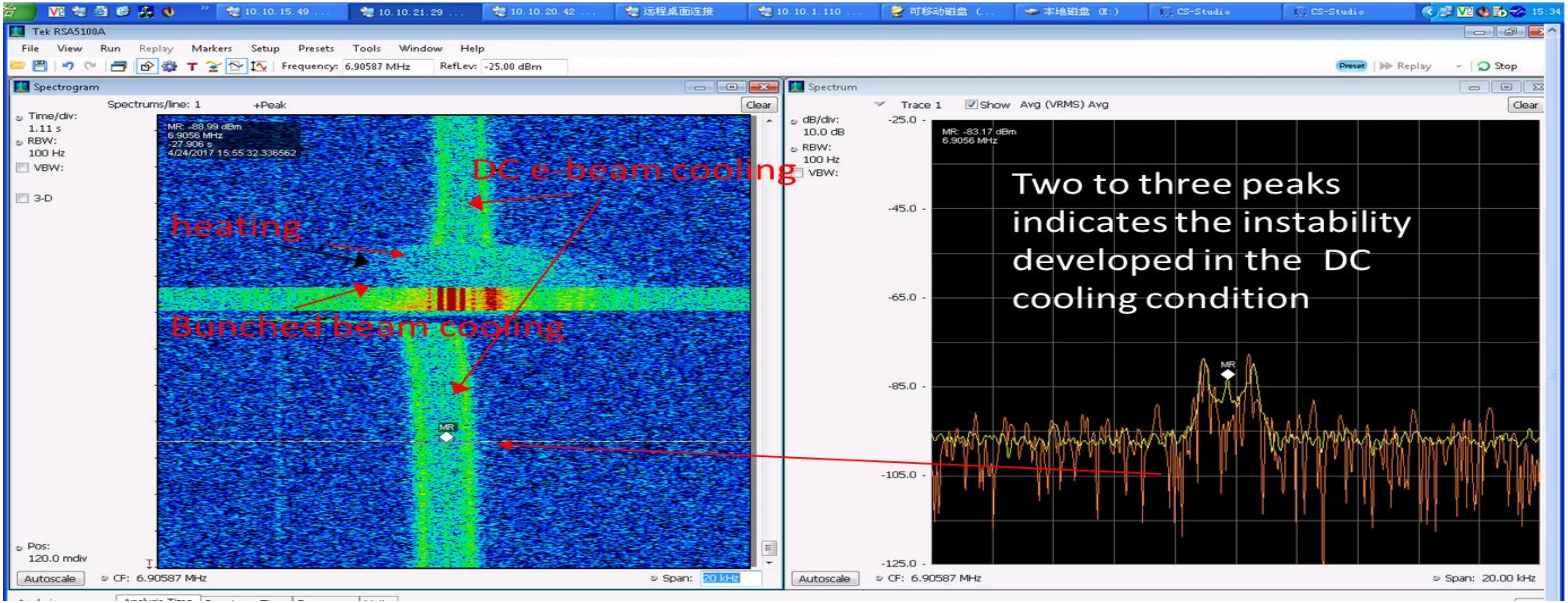




$$U_{im}(\omega)=Z_t(\omega)\cdot I_{beam}(\omega)$$

$$|Z_t|=\frac{A}{2\pi a}\cdot\frac{1}{\beta c}\cdot\frac{1}{C}\cdot\frac{\omega/\omega_{cut}}{\sqrt{1+\omega^2/\omega^2{}_{cut}}}$$

DC Cooling, heating and pulsed electron cooling processes



Tek RSA5100A

Frequency: 6.90587 MHz RefLev: -25.00 dBm

Spectrogram

Spectrums/line: 1 +Peak

Time/div: 1.11 s

RBW: 100 Hz

☐ VBW:

☐ 3-D

MR: -88.99 dBm
6.9056 MHz
-27.906 s
4/24/2017 15:55:32.336562

Pos: 120.0 mdiv

CF: 6.90587 MHz Span: 20 kHz

Spectrum

Trace 1 ☑ Show Avg (VRMS) Avg

dB/div: 10.0 dB

RBW: 100 Hz

VBW:

MR: -83.17 dBm
6.9056 MHz

CF: 6.90587 MHz Span: 20.00 kHz

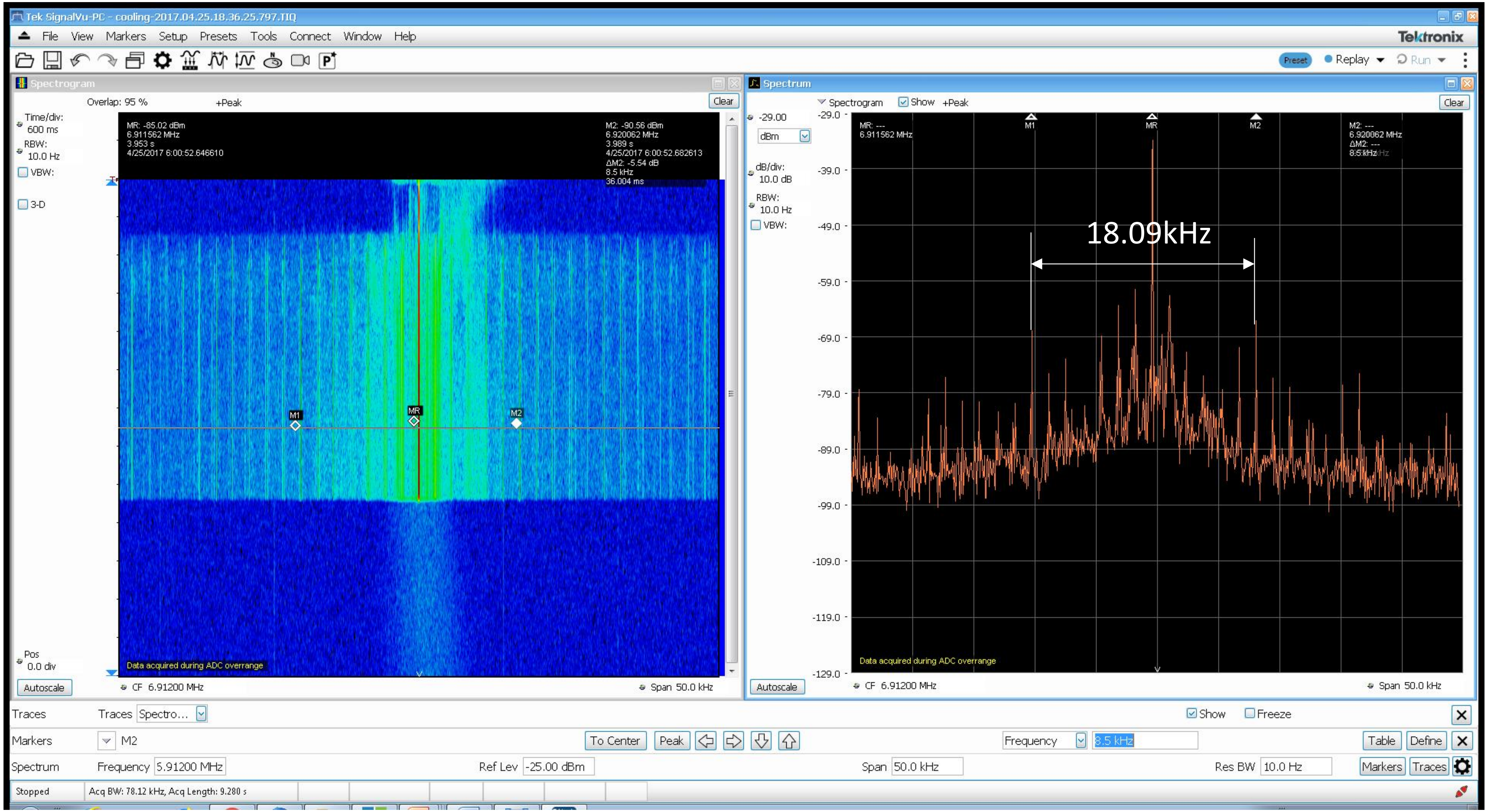
DC e-beam cooling

heating

Bunched beam cooling

Two to three peaks indicates the instability developed in the DC cooling condition

Pulsed electron cooling coasting beam without the help of RF focusing



Tek SignalVu-PC - cooling-2017.04.25.18.36.25.797.TIQ

Spectrogram

Overlap: 95 %

Time/div: 600 ms

RBW: 10.0 Hz

☐ VBW:

☐ 3-D

MR: -85.02 dBm
6.911562 MHz
3.953 s
4/25/2017 6:00:52.646610

M2: -90.56 dBm
6.920062 MHz
3.989 s
4/25/2017 6:00:52.682613
ΔM2: -5.54 dB
8.5 kHz
36.004 ms

Data acquired during ADC overrange

Pos 0.0 div

CF 6.91200 MHz

Span 50.0 kHz

Spectrum

▽ Spectrogram ☑ Show +Peak

-29.00 dBm

dB/div: 10.0 dB

RBW: 10.0 Hz

☐ VBW:

MR: ---
6.911562 MHz

M2: ---
6.920062 MHz
ΔM2: ---
8.5 kHz

Data acquired during ADC overrange

CF 6.91200 MHz

Span 50.0 kHz

Traces: Spectro…

☑ Show ☐ Freeze

Markers: M2

Frequency: 8.5 kHz

Spectrum Frequency: 5.91200 MHz

Ref Lev: -25.00 dBm

Span: 50.0 kHz

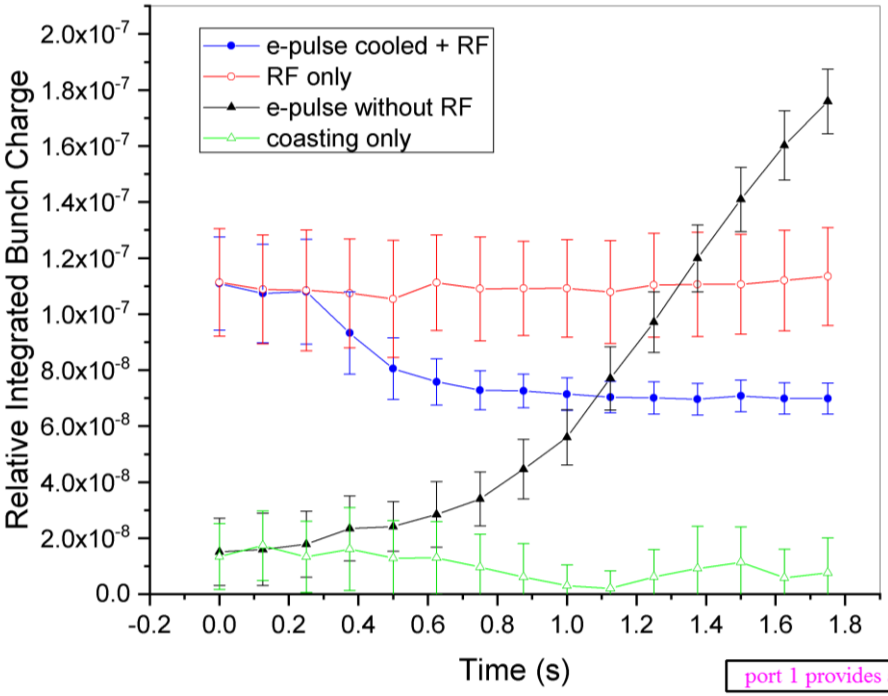
Res BW: 10.0 Hz

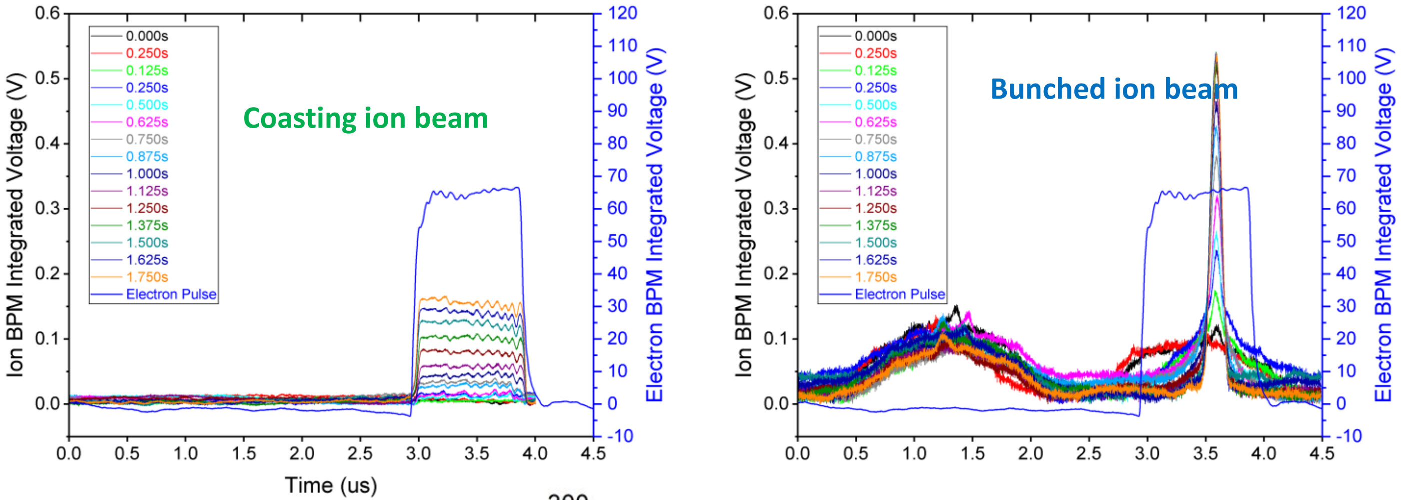
Stopped

Acq BW: 78.12 kHz, Acq Length: 9.280 s

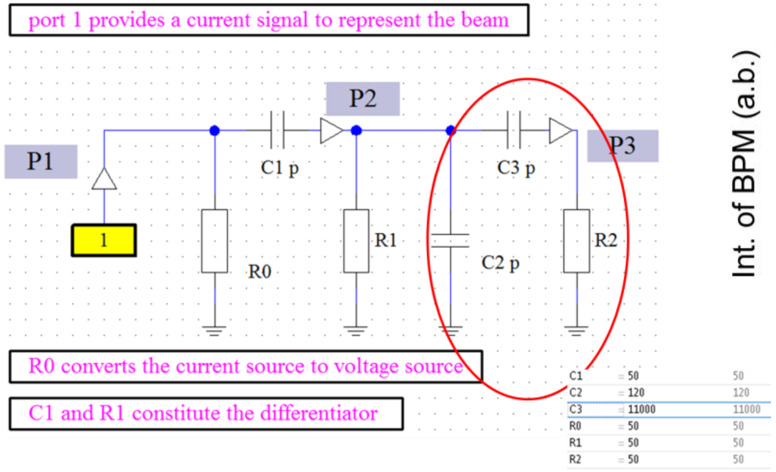
- At same e-pulse width 1us and ave. current of 9.6mA, without RF voltage on, the e-pulse barrier has a shallow potential well. The synchrotron oscillation motion is slower than with RF voltage, so cooled bunch would have a larger momentum spread than with additional RF 1.2kV focused cooled bunch
- 2.35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

Integrated charge comparison in cooled and uncooled ion beam





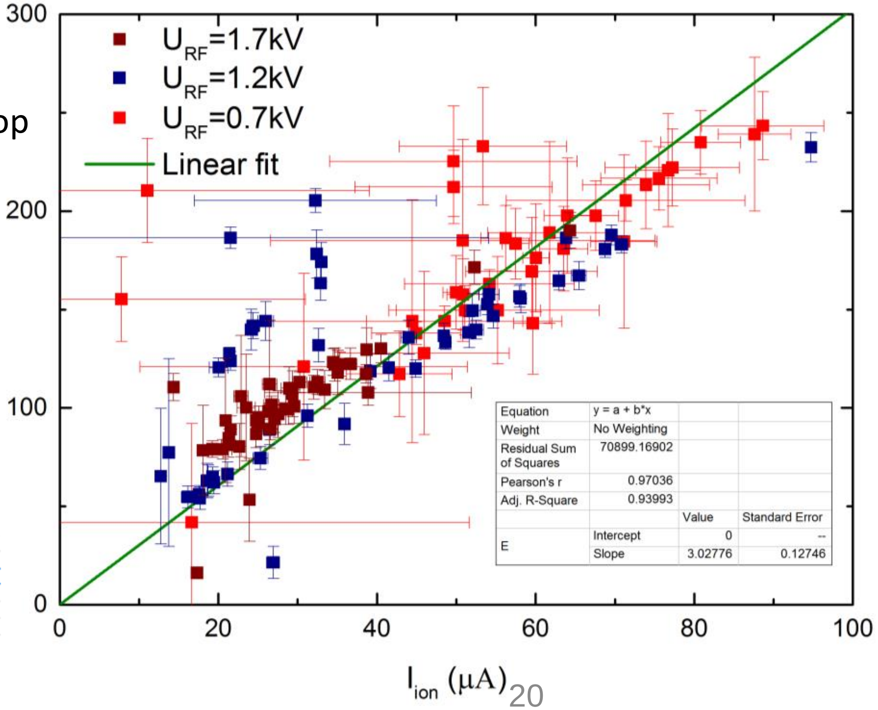
BPM signal FFT/IFFT process
To remove unphysical pulse dip/droop



port 1 provides a current signal to represent the beam

R0 converts the current source to voltage source

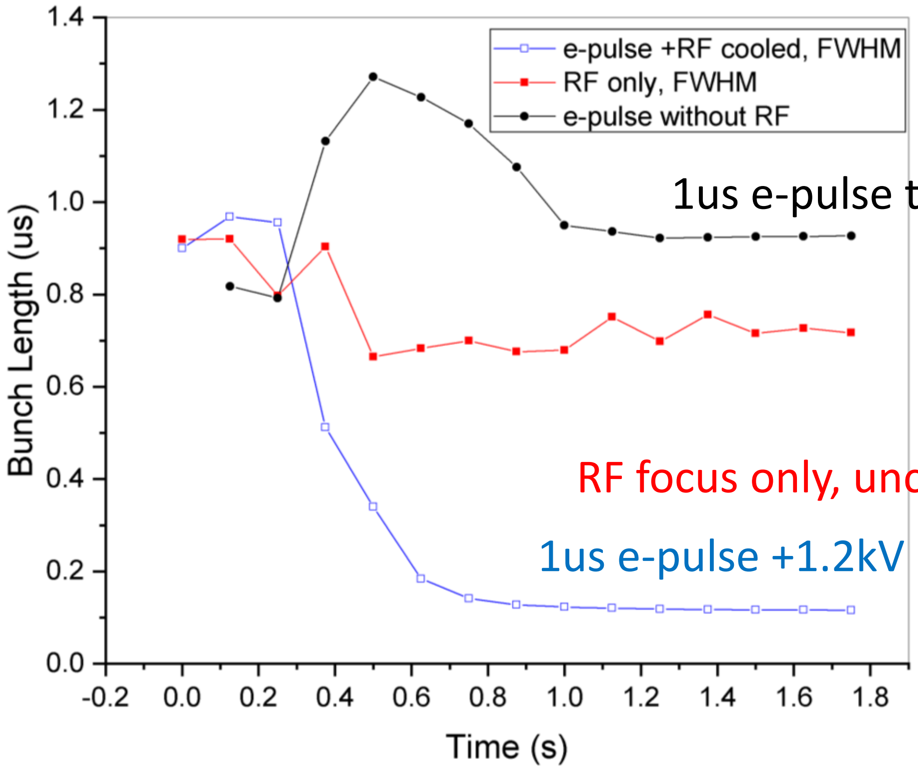
C1 and R1 constitute the differentiator



Equation	y = a + b*x	
Weight	No Weighting	
Residual Sum of Squares	70899.16902	
Pearson's r	0.97036	
Adj. R-Square	0.93993	
	Value	Standard Error
E Intercept	0	--
Slope	3.02776	0.12746

- 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

Bunch length comparison in cooled and uncooled ion beam



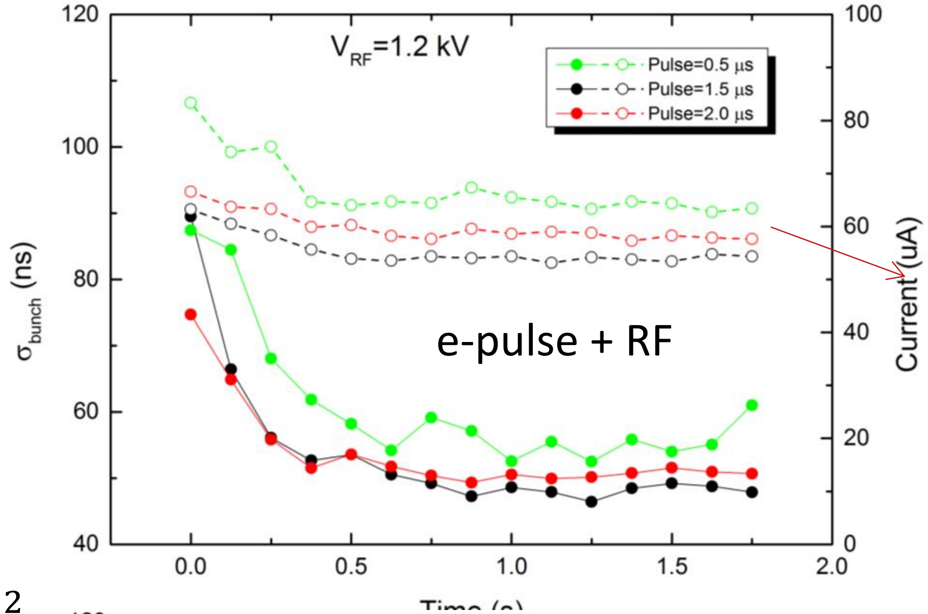
1us e-pulse to cool coasting

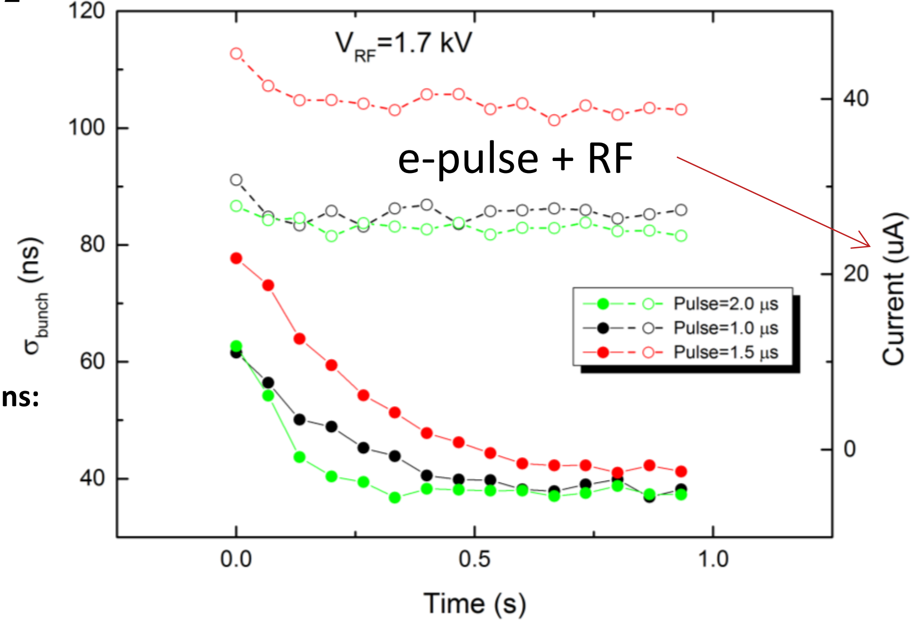
RF focus only, uncooled

1us e-pulse +1.2kV RF

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

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



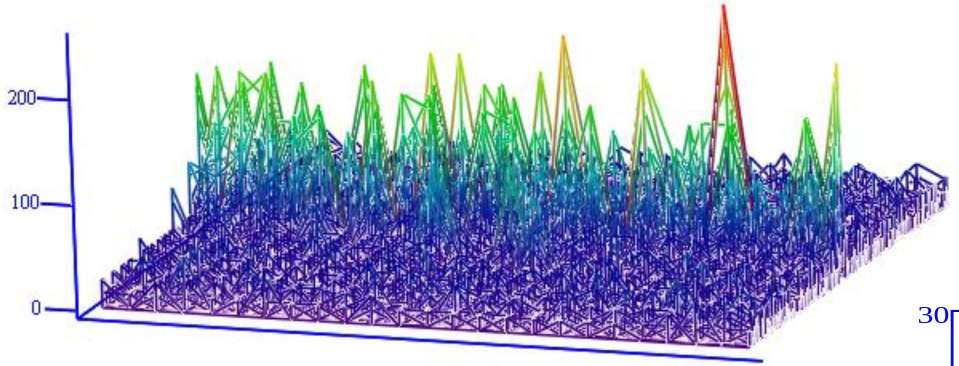


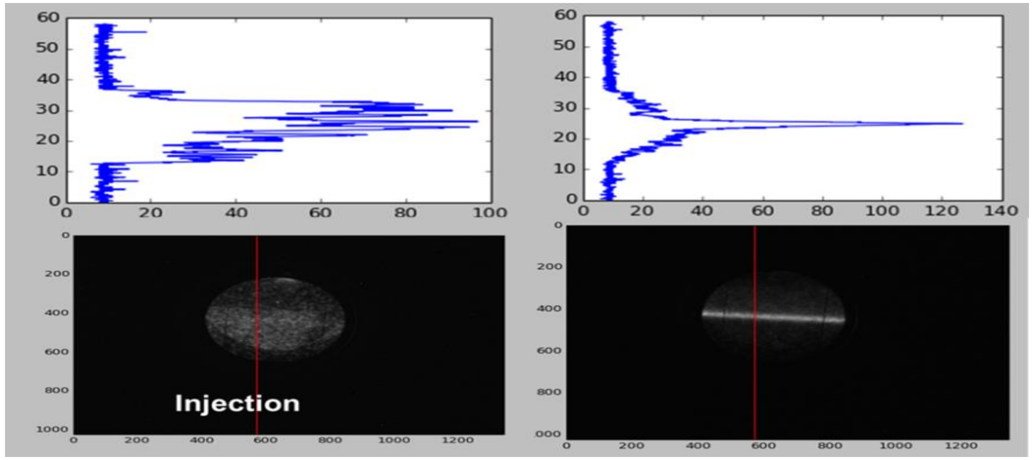
- A factor of 5 of decreasing in bunch length means a factor of 5 of decreasing in momentum spread, a factor of 25 of decreasing in longitudinal emittance.
- The most experiment data obtained in 2016/2017 are mostly for the DC assisted cooling
- Good quality of bunch-beam cooling data sets are limited 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?

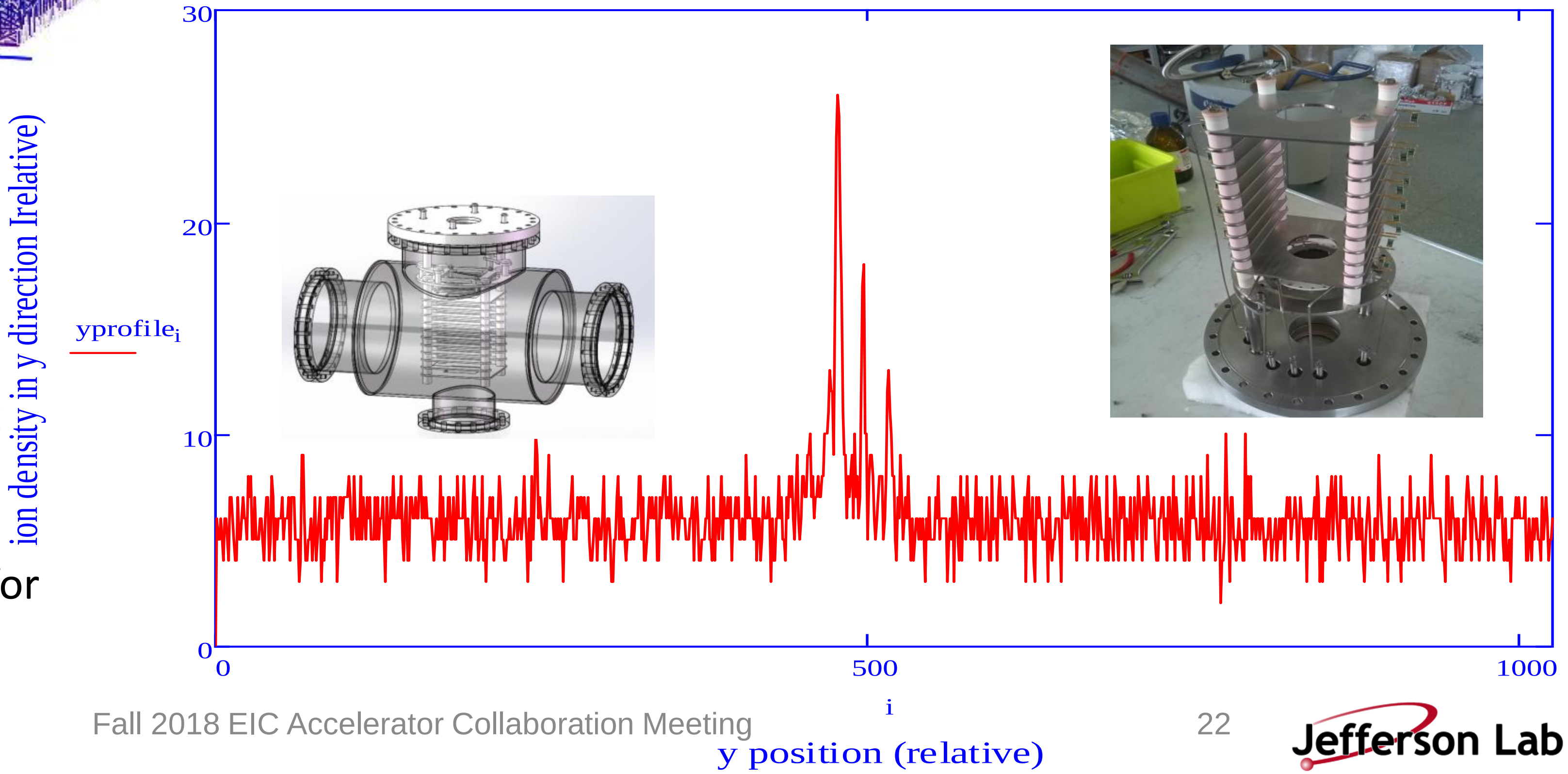
Ion Profile Monitor signal from the CCD Camera of the Ionization Chamber

Installed and commissioned in 2017 at CSRm

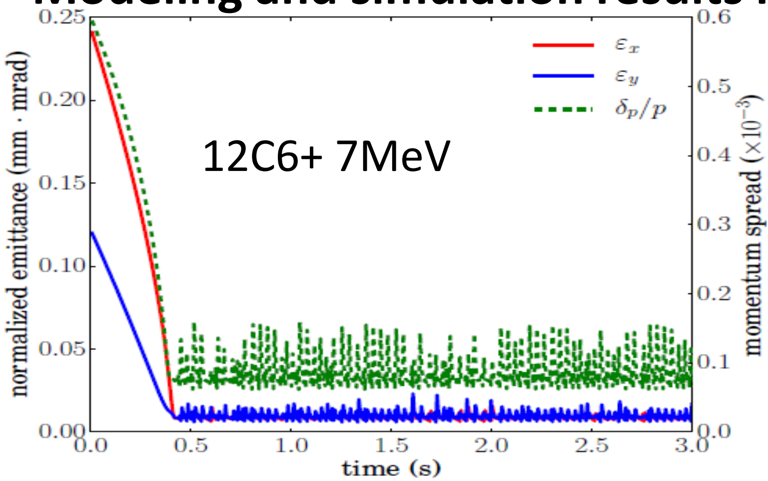


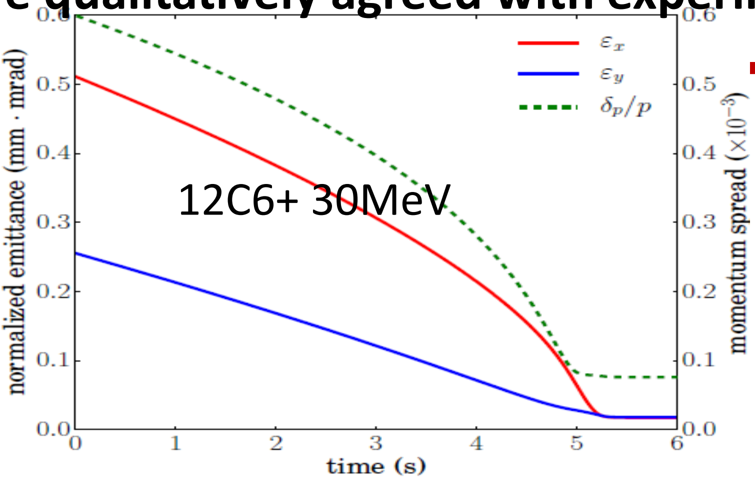


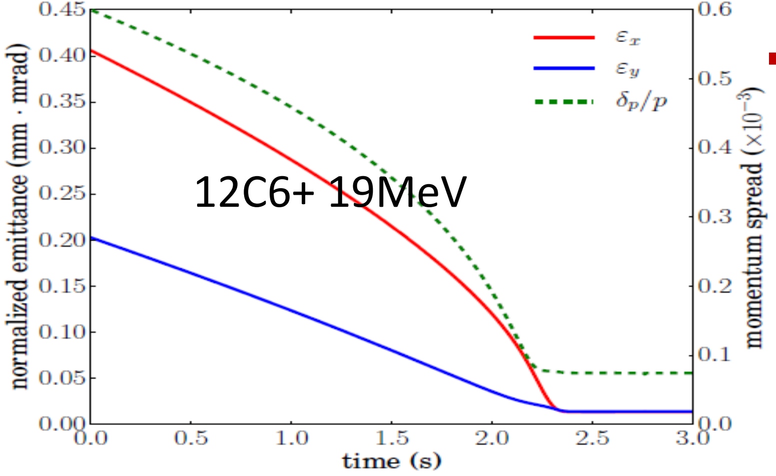
- Ion beam profile in Y direction only with 2D and 1D scans
- 4 frames per second has been obtained for slower cooling rate
- No data analysis for this data set yet
- Transverse (y) cooling rate is not known yet
- Slow scan rate and poor resolution for cooled beam profile



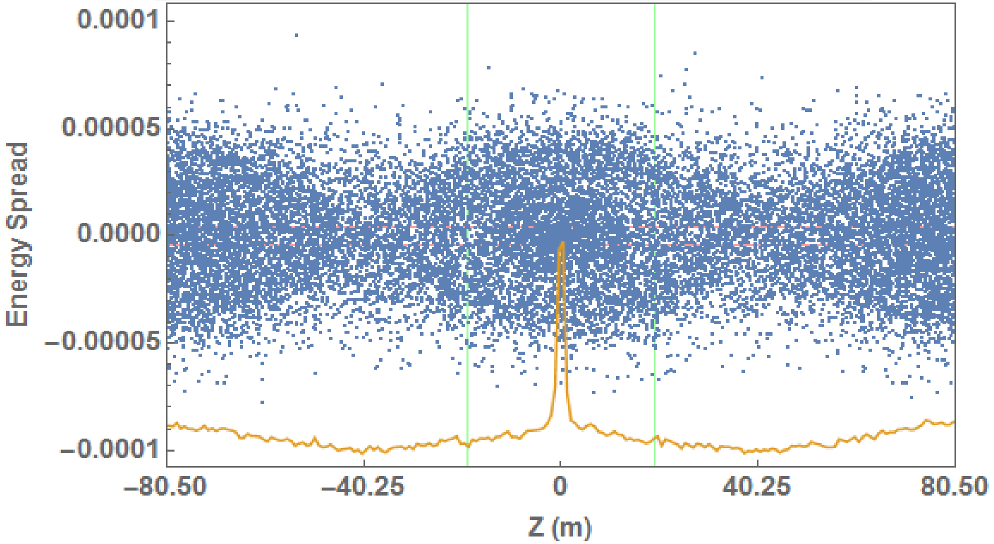
Modeling and simulation results have qualitatively agreed with experimental data





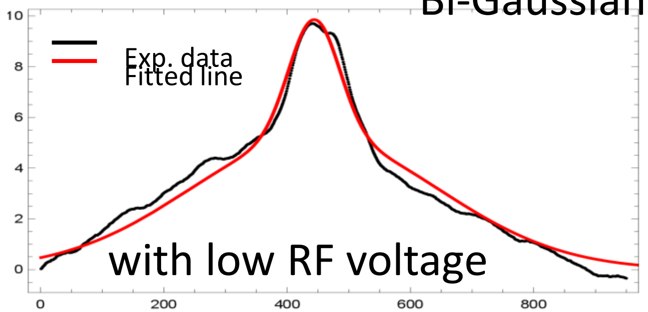


1D beam dynamic modeling

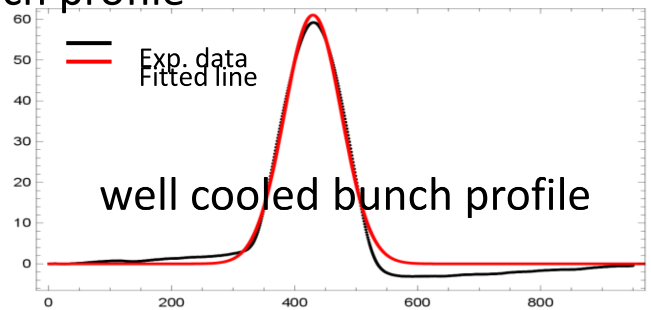


The cooled ions are trapped at the RF potential well bottom, forms the spike core. In this simulation, RF voltage is on with electron bunch cooling.

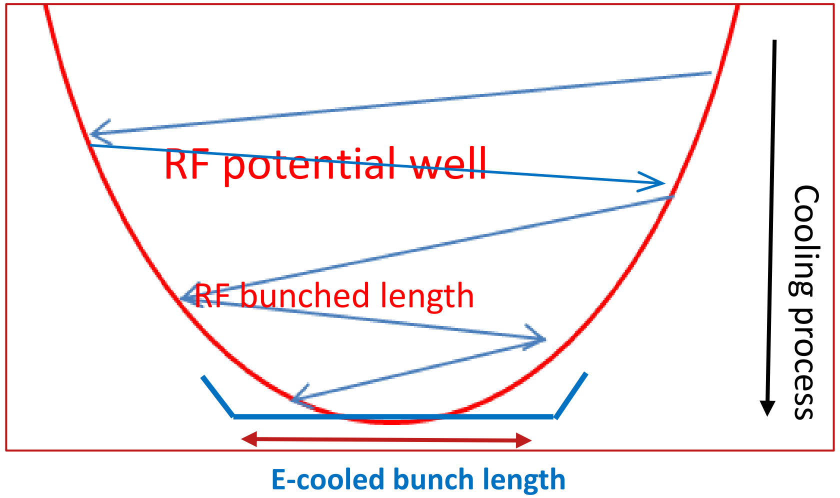
Bi-Gaussian bunch profile



with low RF voltage



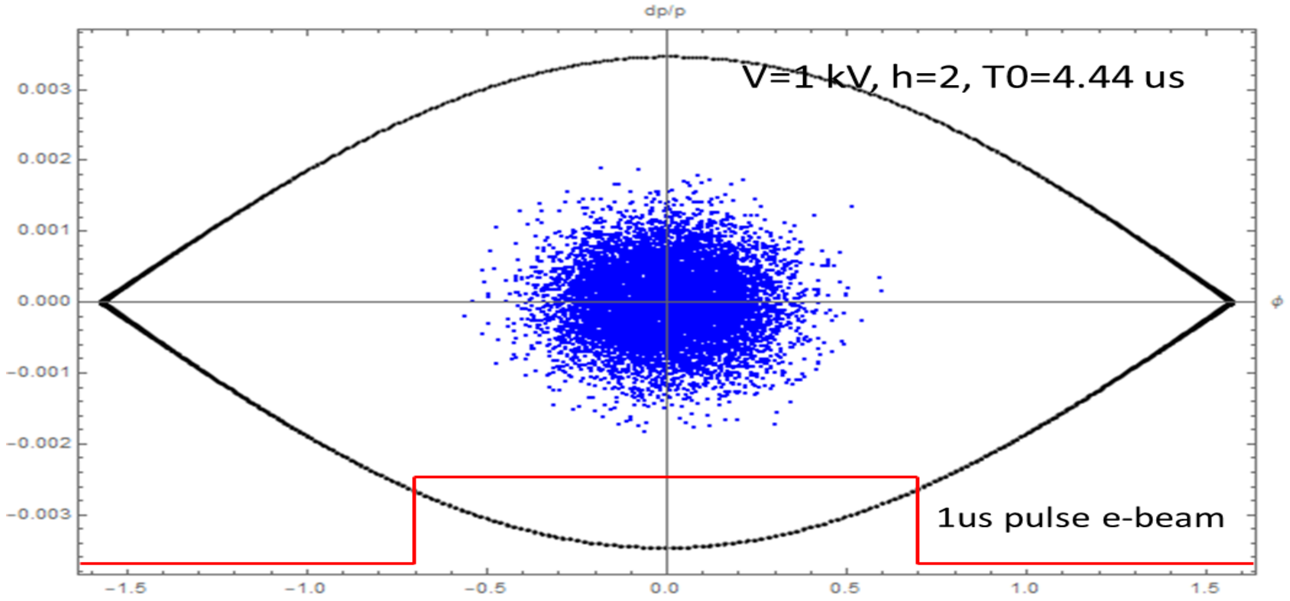
well cooled bunch profile



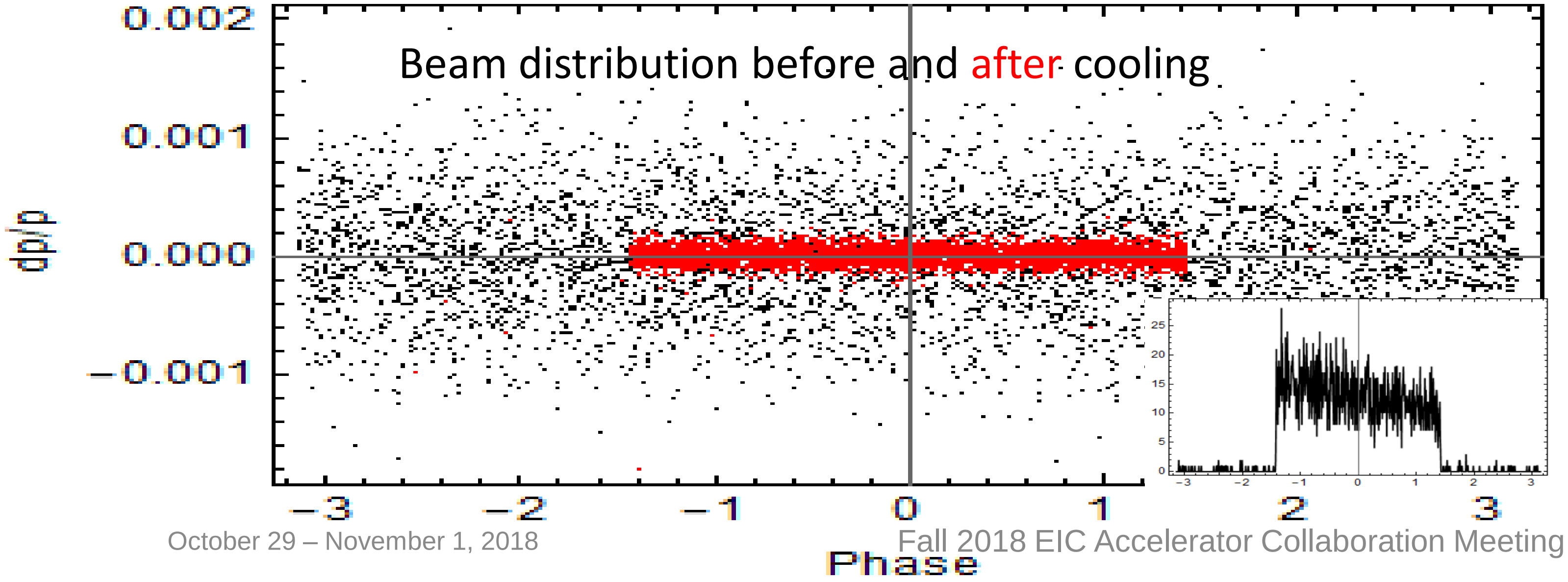
- Electron potential well is much shallow compare to RF potential well
- 1D modeling with RF + e-potential has demonstrated bunched e-cooling process.
- 3D simulation tool is under the development

Single-particle tracking simulation developed by IMP team

Similar with BETACOOL



- 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:

- dp/p reduction ~ from 3e-3 to 6e-4 with e-pulse + RF focus cooling
- dp/p reduction ~ from 3e-3 to 1e-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

Experimental data quality improvement plan (2017-2020):

Ion BPM signal data:

- From shoe-box type at CSRm with 50Ω input imp. preamp
- fcut~7.7MHz, 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:

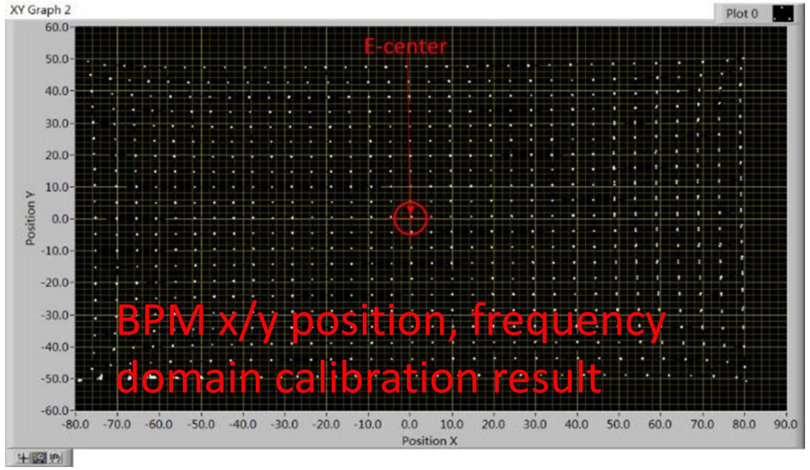
- Used same signal from ion BPM
- Poor S/N ratio in high freq. response for Schottky
- Used RSA5100A (RSA385A) spectrum analyzer. Saved slow IQ data.
- IQ data obtained has a low sampling rate 48.8kS/s
- RBW=100Hz, spectrum resolution is limited to ~32Hz only even with a CFFT/ICFFT HPF/LPF reprocessing
- 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 ~386Hz, 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)

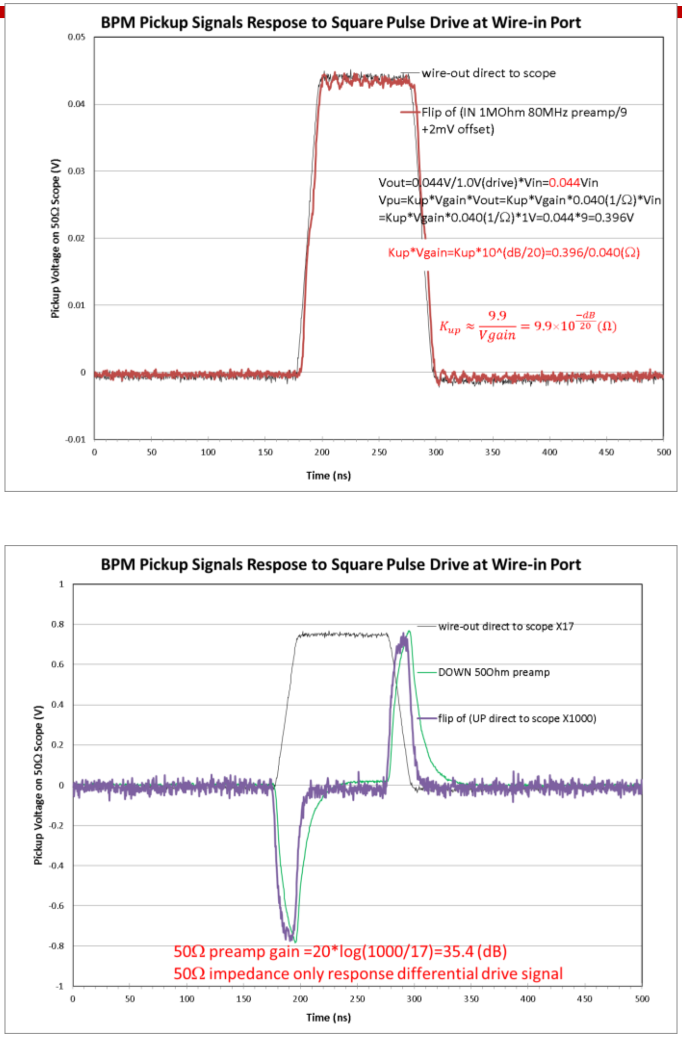
New ion BPM calibration results

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



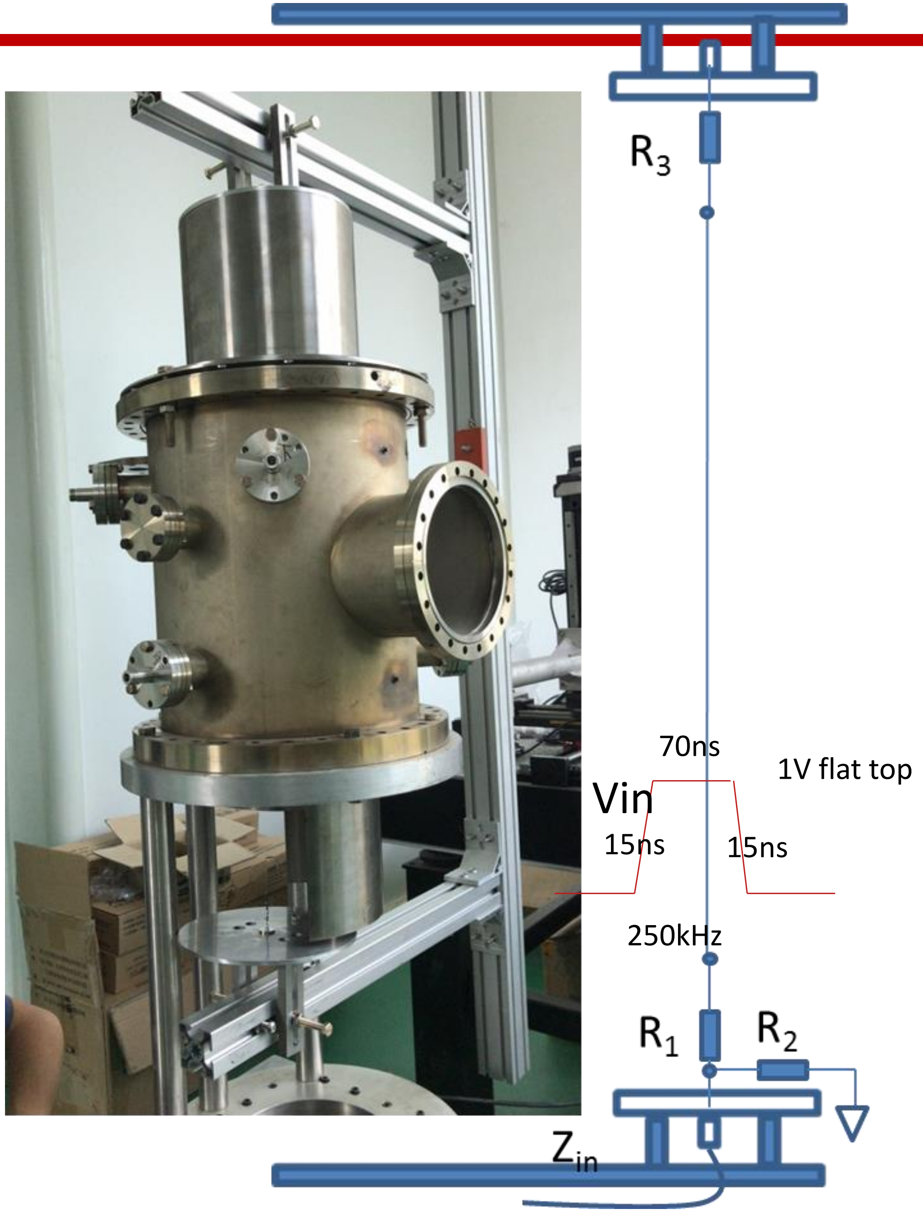
Vout=0.044V/1.0V(drive)*Vin=0.044Vin
Vpu=Kup*Vgain*Vout=Kup*Vgain*0.040(1/Ω)*Vin
=Kup*Vgain*0.040(1/Ω)*1V=0.044*9=0.396V

Kup*Vgain=Kup*10^(dB/20)=0.396/0.040(Ω)

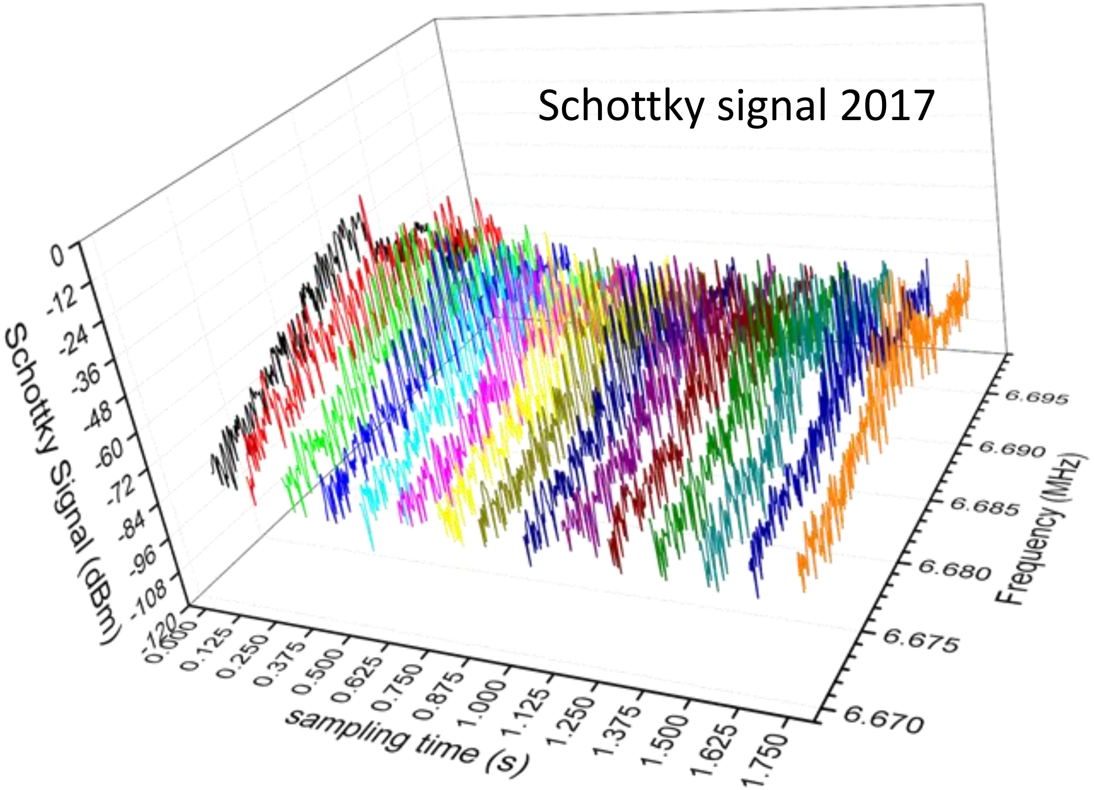
$$K_{up} \approx \frac{9.9}{Vgain} = 9.9\times10^{\frac{-dB}{20}}(\Omega)$$

50Ω preamp gain =20*log(1000/17)=35.4 (dB)
50Ω impedance only response differential drive signal

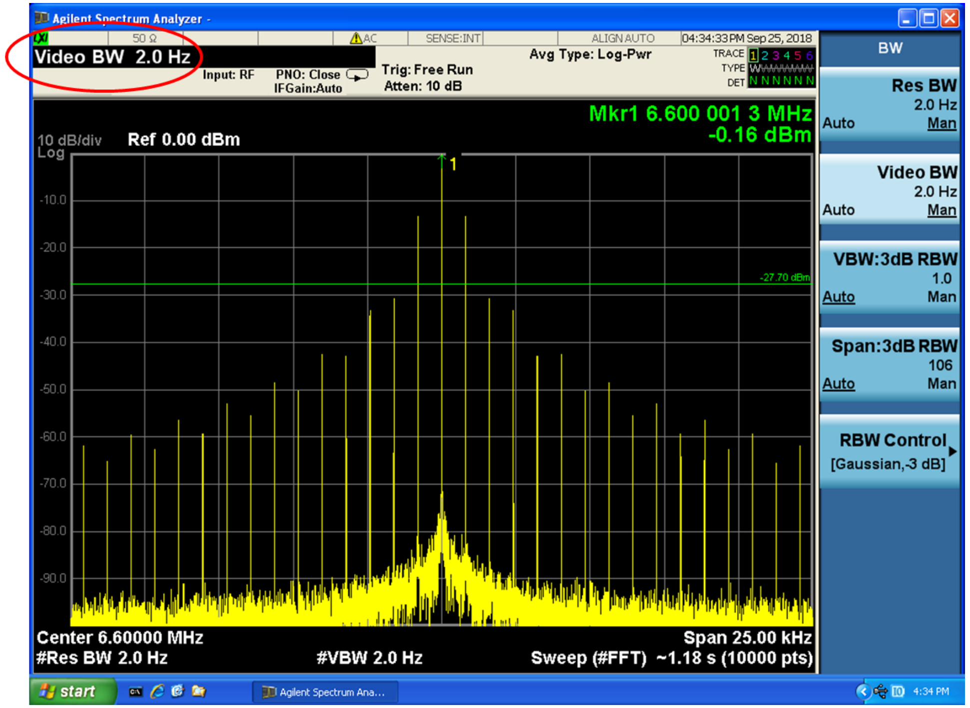
Time domain calibration result



Schottky signal improvement


Schottky signal 2017

Mock-up signal of Schottky by AFG with phase modulation on Agilent 9020a for experiment 2018


Video BW 2.0 Hz

Input: RF

PNO: Close

IFGain:Auto

Trig: Free Run

Atten: 10 dB

Avg Type: Log-Pwr

04:34:33 PM Sep 25, 2018

Mkr1 6.600 001 3 MHz

-0.16 dBm

10 dB/div Ref 0.00 dBm

Center 6.60000 MHz

Span 25.00 kHz

#Res BW 2.0 Hz

#VBW 2.0 Hz

Sweep (#FFT) ~1.18 s (10000 pts)

Res BW 2.0 Hz

Video BW 2.0 Hz

VBW:3dB RBW 1.0

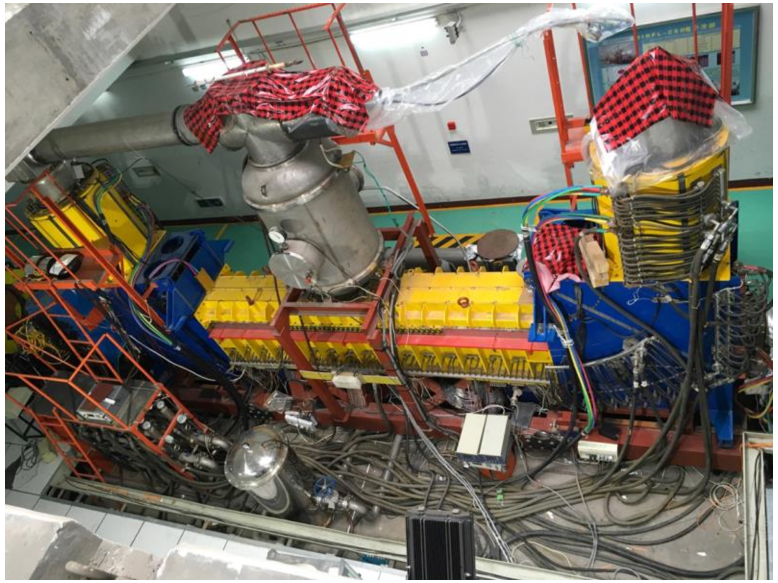
Span:3dB RBW 106

RBW Control [Gaussian,-3 dB]

- 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

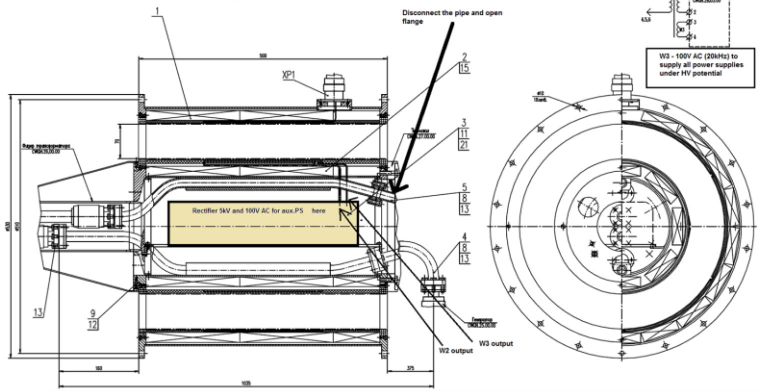
Future experiment plan on CSRe ring (2019-2020)

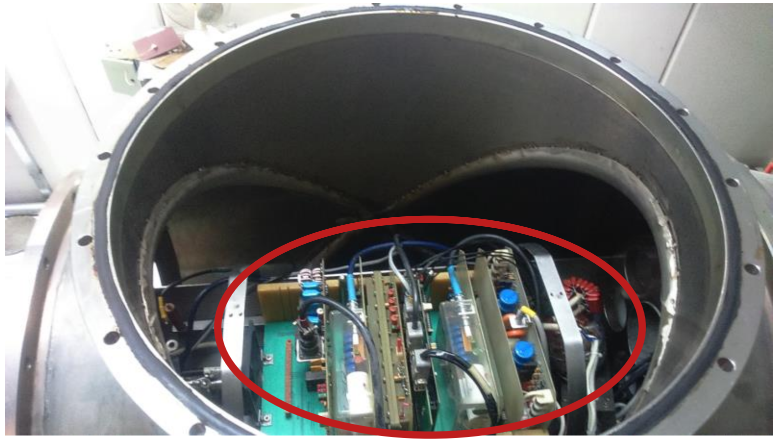
- Move experiment program from CSRm to CSRe ring. Modified SC300 Cooler with pulsing capability will extend the ion energy from current 30MeV/u up to 400MeV/u but similar e-pulse structure
- The electron pulse length from the current of 20m down to the pulse length comparable to the shorter ion bunch 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

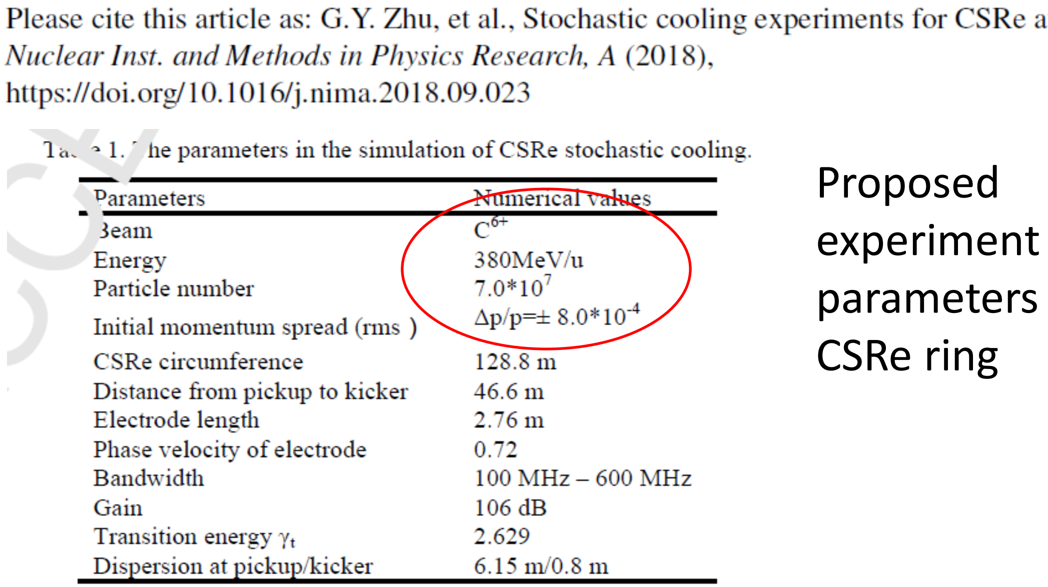
SC300 E-cooler at CSRe ring to be modified

47 cm ID; 7 cm gap; 33 cm inner electrode





Next Cooling Experiment in 2019 at CSRe with SC300 Cooler



Please cite this article as: G.Y. Zhu, et al., Stochastic cooling experiments for CSRe at IMP, *Nuclear Inst. and Methods in Physics Research, A* (2018), https://doi.org/10.1016/j.nima.2018.09.023

Table 1. The parameters in the simulation of CSRe stochastic cooling.

Parameters	Numerical values
Beam	C^{6+}
Energy	380MeV/u
Particle number	$7.0*10^7$
Initial momentum spread (rms)	$\Delta p/p=\pm 8.0*10^{-4}$
CSRe circumference	128.8 m
Distance from pickup to kicker	46.6 m
Electrode length	2.76 m
Phase velocity of electrode	0.72
Bandwidth	100 MHz – 600 MHz
Gain	106 dB
Transition energy γ_t	2.629
Dispersion at pickup/kicker	6.15 m/0.8 m

Proposed experiment parameters on CSRe ring

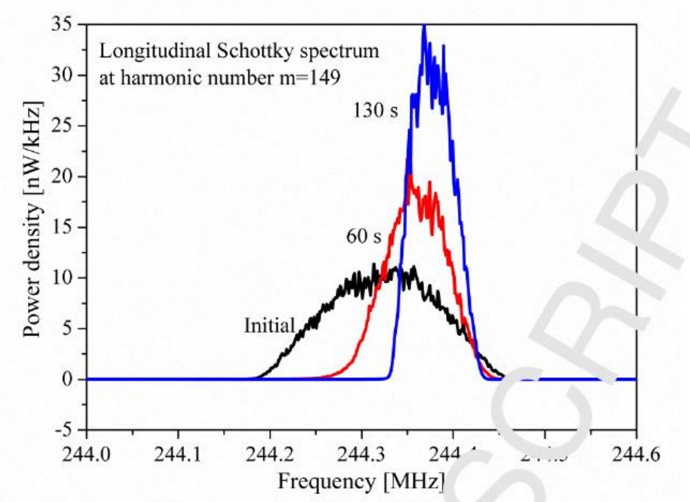
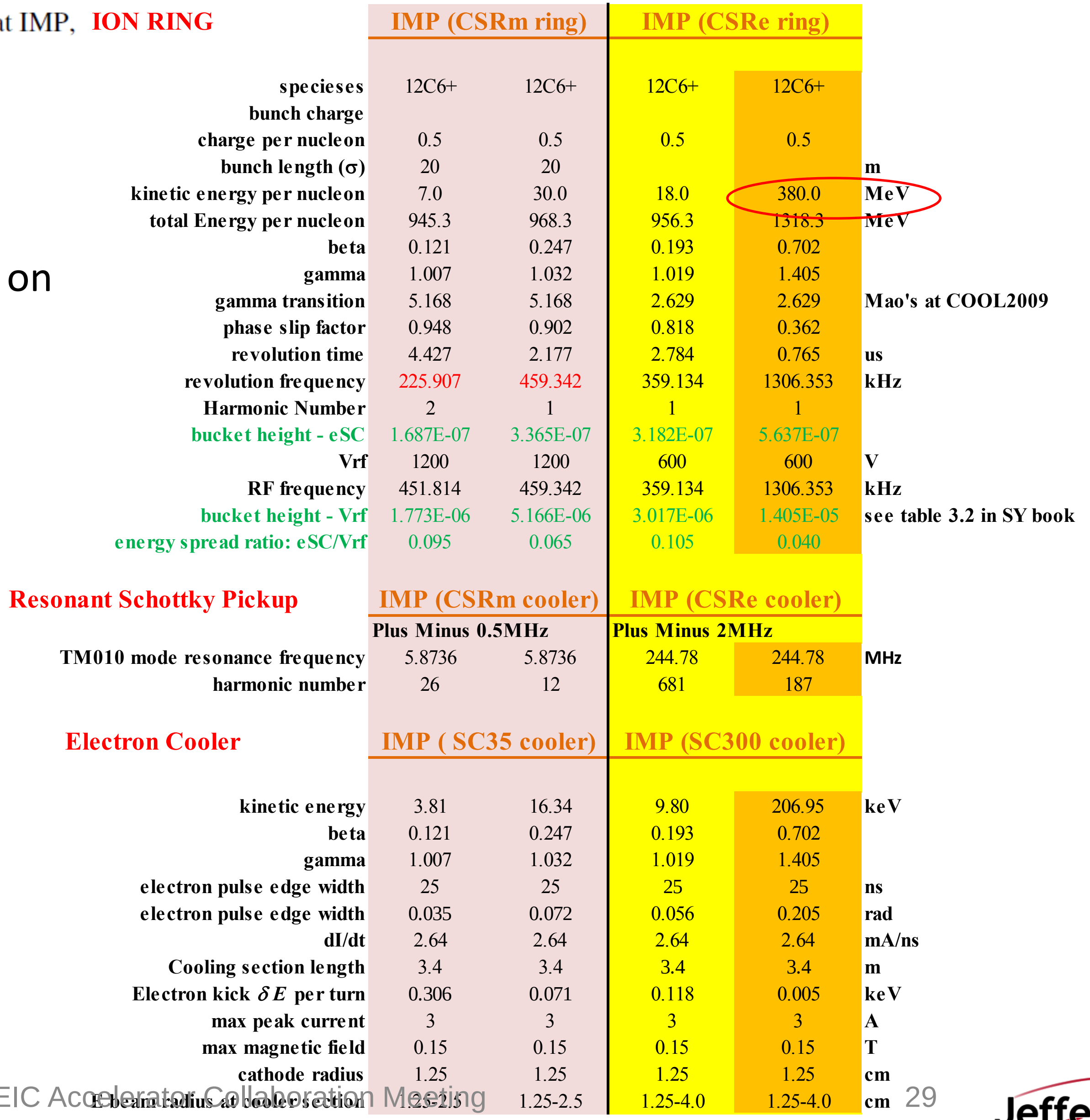


Fig. 17. Longitudinal stochastic cooling experiment with TOF method.



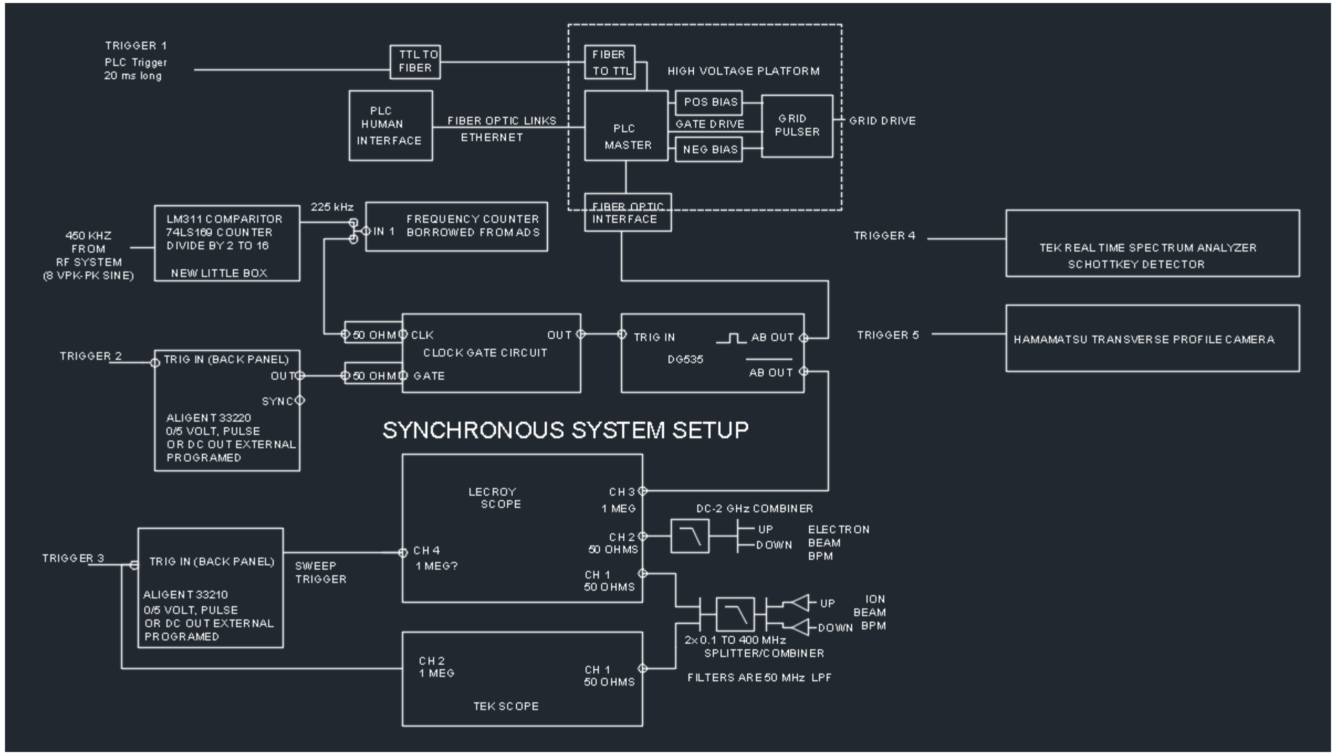
ION RING	IMP (CSRm ring)		IMP (CSRe ring)		
specieses	12C6+	12C6+	12C6+	12C6+	
bunch charge					
charge per nucleon	0.5	0.5	0.5	0.5	
bunch length (σ)	20	20			m
kinetic energy per nucleon	7.0	30.0	18.0	380.0	MeV
total Energy per nucleon	945.3	968.3	956.3	1318.3	MeV
beta	0.121	0.247	0.193	0.702	
gamma	1.007	1.032	1.019	1.405	
gamma transition	5.168	5.168	2.629	2.629	Mao's at COOL2009
phase slip factor	0.948	0.902	0.818	0.362	
revolution time	4.427	2.177	2.784	0.765	us
revolution frequency	225.907	459.342	359.134	1306.353	kHz
Harmonic Number	2	1	1	1	
bucket height - eSC	1.687E-07	3.365E-07	3.182E-07	5.637E-07	
Vrf	1200	1200	600	600	V
RF frequency	451.814	459.342	359.134	1306.353	kHz
bucket height - Vrf	1.773E-06	5.166E-06	3.017E-06	1.405E-05	see table 3.2 in SY book
energy spread ratio: eSC/Vrf	0.095	0.065	0.105	0.040	
Resonant Schottky Pickup	**IMP (CSRm cooler)**		**IMP (CSRe cooler)**		
	Plus Minus 0.5MHz		Plus Minus 2MHz		
TM010 mode resonance frequency	5.8736	5.8736	244.78	244.78	MHz
harmonic number	26	12	681	187	
Electron Cooler	**IMP (SC35 cooler)**		**IMP (SC300 cooler)**		
kinetic energy	3.81	16.34	9.80	206.95	keV
beta	0.121	0.247	0.193	0.702	
gamma	1.007	1.032	1.019	1.405	
electron pulse edge width	25	25	25	25	ns
electron pulse edge width	0.035	0.072	0.056	0.205	rad
dI/dt	2.64	2.64	2.64	2.64	mA/ns
Cooling section length	3.4	3.4	3.4	3.4	m
Electron kick δE per turn	0.306	0.071	0.118	0.005	keV
max peak current	3	3	3	3	A
max magnetic field	0.15	0.15	0.15	0.15	T
cathode radius	1.25	1.25	1.25	1.25	cm
E-beam radius at cooler section	1.25-2.5	1.25-2.5	1.25-4.0	1.25-4.0	cm

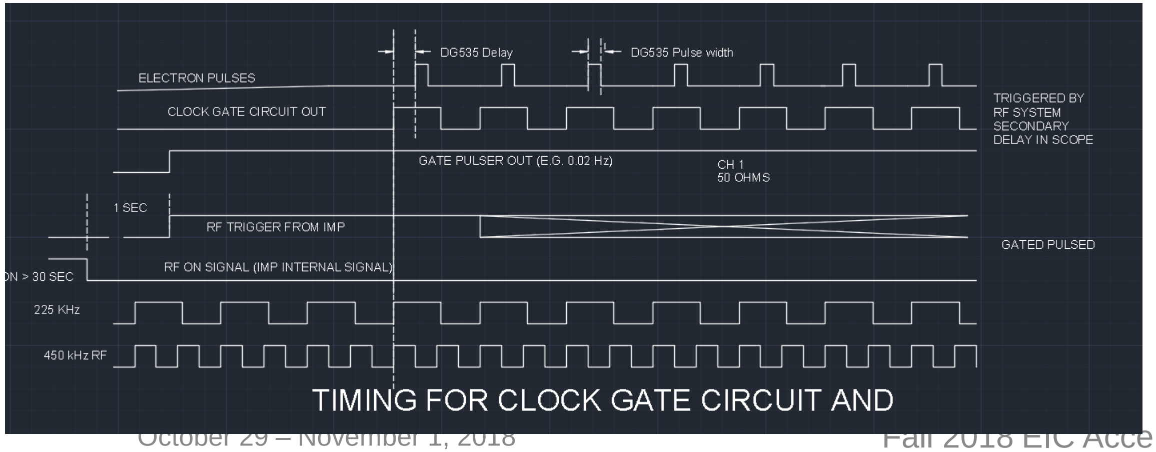
Summary

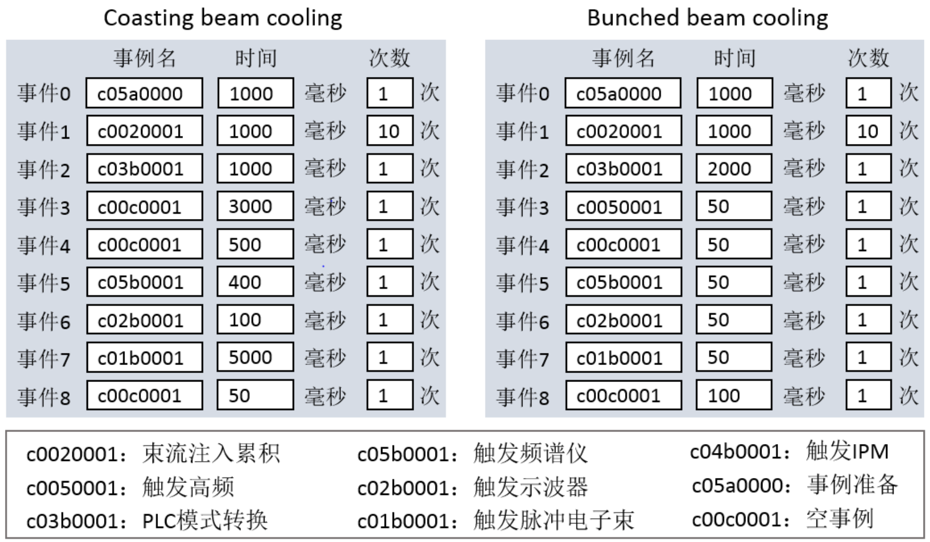
1. Bunched electron beam cooling 12C+6 ion beam at 7MeV/u has been demonstrated at CSRm ring at IMP, China by our IMP/JLab collaboration team
2. With the help of RF focusing, the Ion bunch length has been reduced from the coasting to ~3m long by a longer electron bunch but as short as 18m within about 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 sychronization







Coasting beam cooling

	事例名	时间		次数	
事件0	c05a0000	1000	毫秒	1	次
事件1	c0020001	1000	毫秒	10	次
事件2	c03b0001	1000	毫秒	1	次
事件3	c00c0001	3000	毫秒	1	次
事件4	c00c0001	500	毫秒	1	次
事件5	c05b0001	400	毫秒	1	次
事件6	c02b0001	100	毫秒	1	次
事件7	c01b0001	5000	毫秒	1	次
事件8	c00c0001	50	毫秒	1	次

Bunched beam cooling

	事例名	时间		次数	
事件0	c05a0000	1000	毫秒	1	次
事件1	c0020001	1000	毫秒	10	次
事件2	c03b0001	2000	毫秒	1	次
事件3	c0050001	50	毫秒	1	次
事件4	c00c0001	50	毫秒	1	次
事件5	c05b0001	50	毫秒	1	次
事件6	c02b0001	50	毫秒	1	次
事件7	c01b0001	50	毫秒	1	次
事件8	c00c0001	100	毫秒	1	次

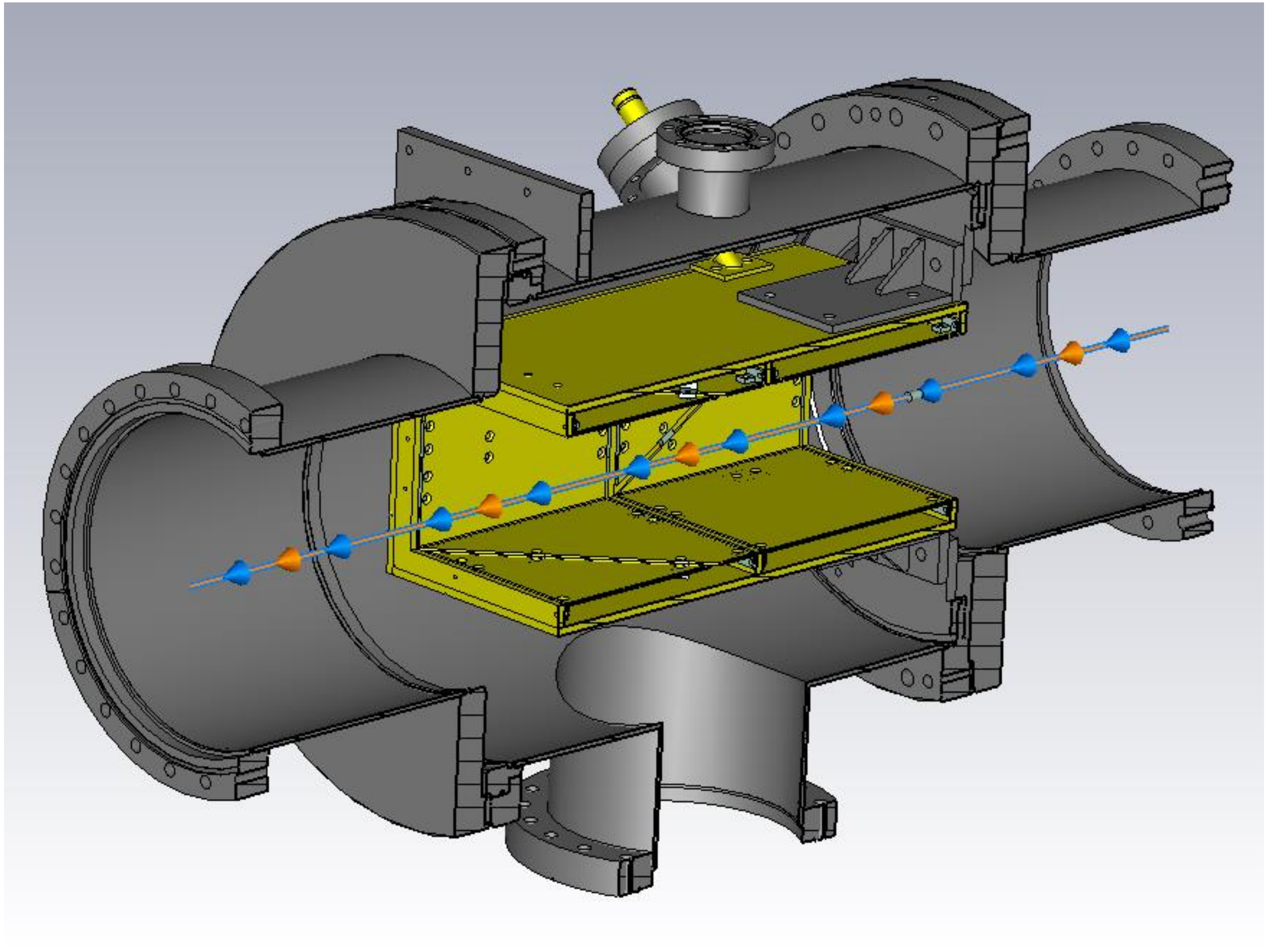
c0020001：束流注入累积
c0050001：触发高频
c03b0001：PLC模式转换
c05b0001：触发频谱仪
c02b0001：触发示波器
c01b0001：触发脉冲电子束
c04b0001：触发IPM
c05a0000：事例准备
c00c0001：空事例

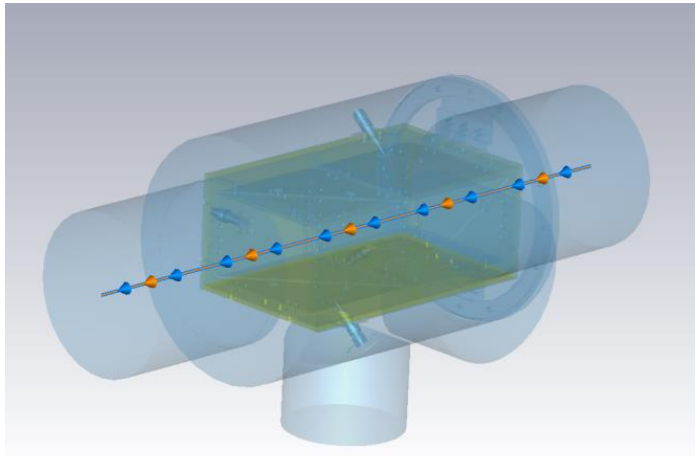
c0020001	1000×10 ms	10s注入，每次注入时间1s，注10次
c0050001	500×1	注入完成后直接开启高频，得到bunch 束团，500ms后关闭电子束，之前一直有dc电子束。（rf持续时间为7s，由rf文件独自设定）
c03b0001	2300×1	关闭电子束，plc转为脉冲模式，等待触发脉冲电子束
c00c0001	50×1	空事例
c04b0001	50×1	开启profile monitor
c05b0001	50×1	开启频谱仪
c02b0001	50×1	开启示波器
c01b0001	100×1.	开启脉冲电子束

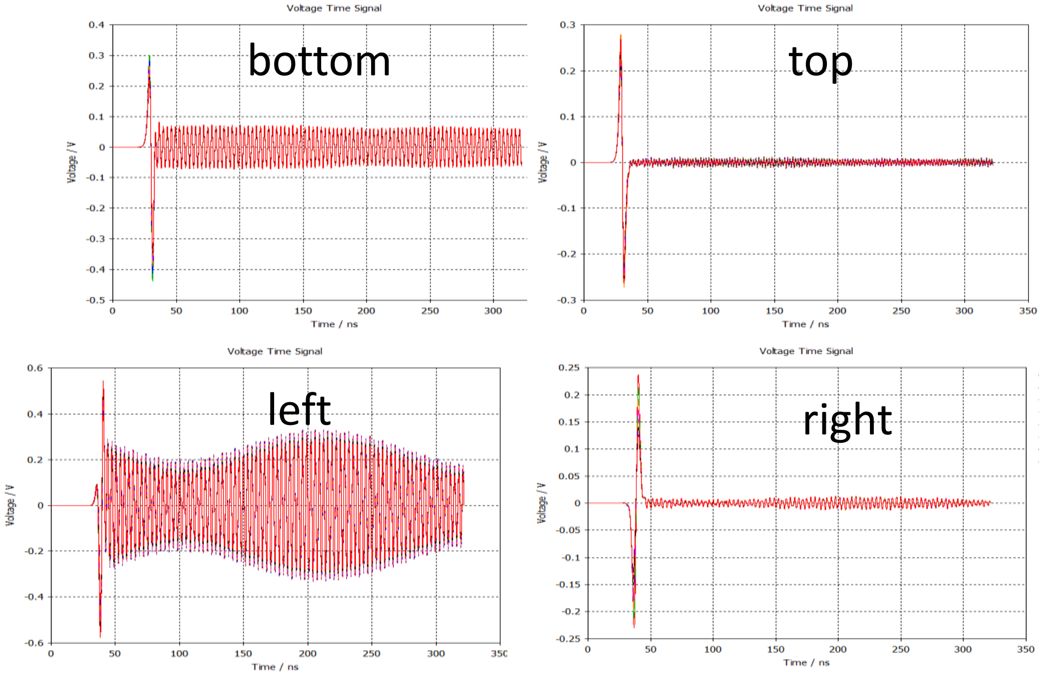
events

关闭dc电子到开启脉冲电子，bunch ion beam 有2.5s的heating

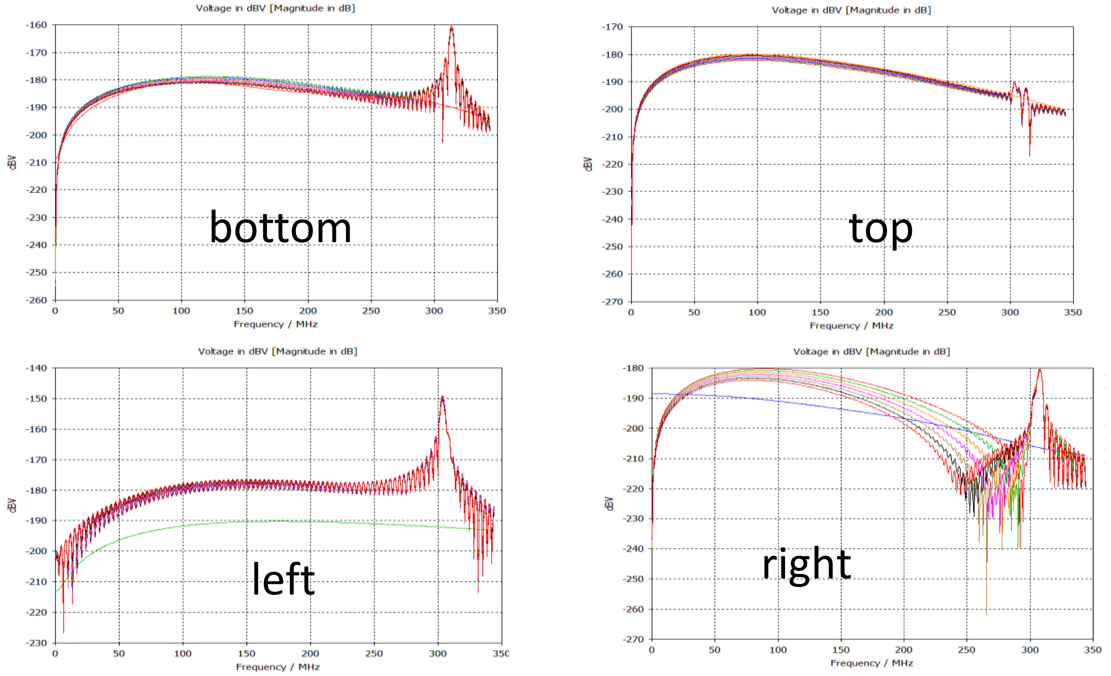
New Ion BPM Mechanical Assembly Model and CST Wakefield Simulation Setup



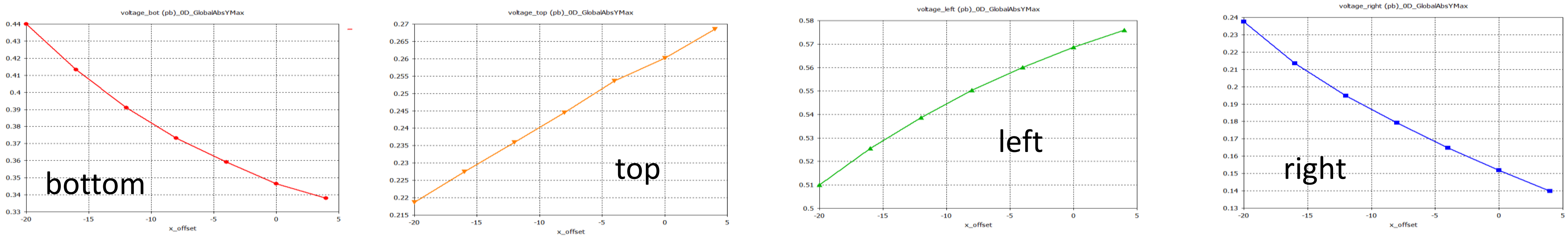




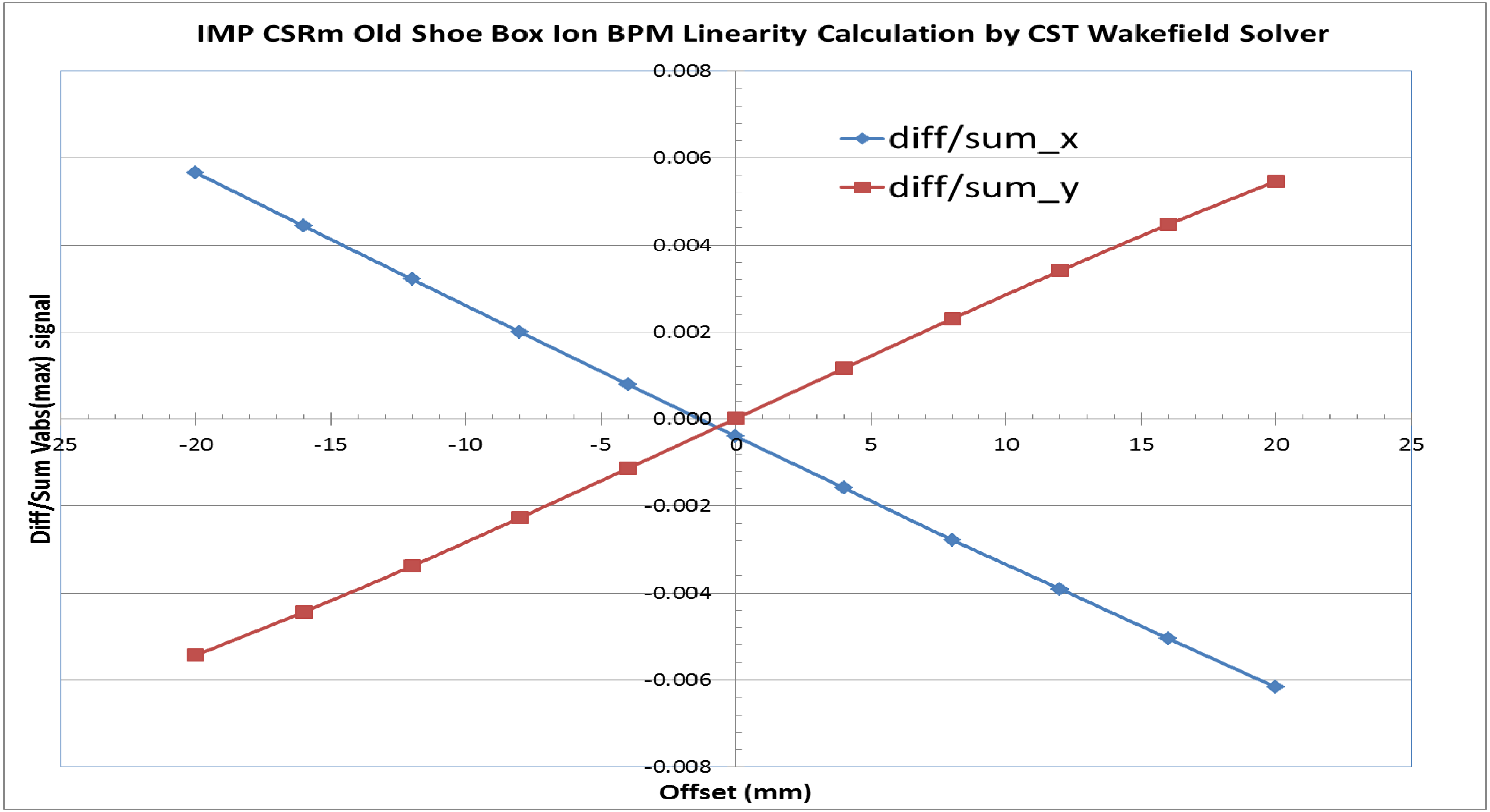
CST wakefield simulation on the pickup voltage signals



Frequency spectrums indicate a possible resonance structure ~310MHz



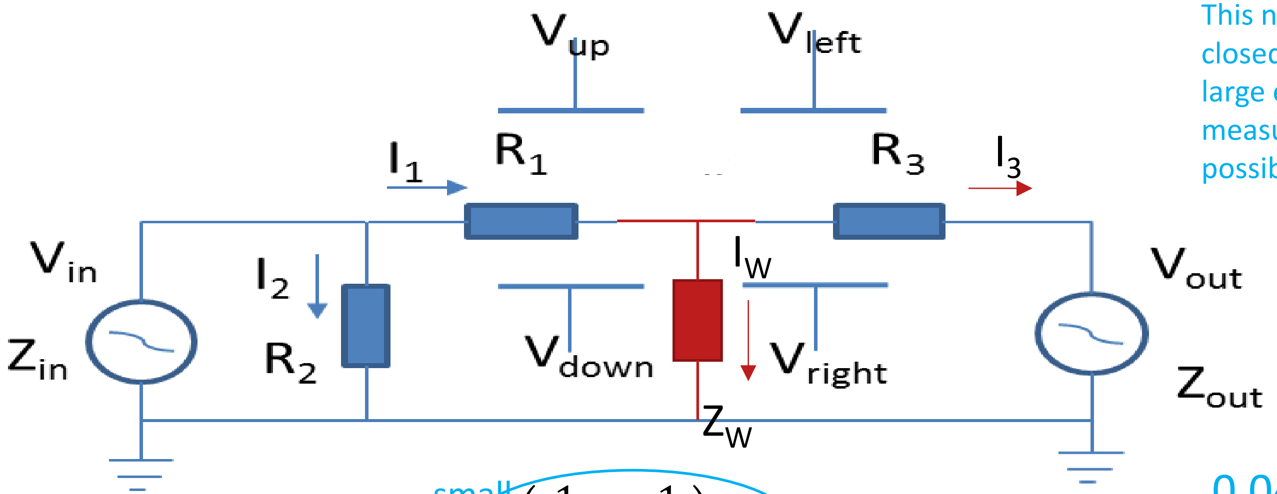
Non-linear responses of peak-to-peak voltage at pickups


IMP CSRm Old Shoe Box Ion BPM Linearity Calculation by CST Wakefield Solver
diff/sum_x
diff/sum_y
Diff/Sum Vabs(max) signal
Offset (mm)
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-25
-20
-15
-10
-5
0
5
10
15
20
25

Impedance matching and pulse current to pickup voltage transfer function calibration

Z_W=497.64 Ω, Z_{in}=Z_{out}=50 Ω, R_1= 471.98Ω, R_2= 52.72Ω, R_3= 447.64Ω

$V_{in} = I_2R_2$ $\quad$ $I_1 = I_3 + I_W$



This number is very closed to 50Ω, so a large error on measured Vout is possible

0.044

Check:

small

$$V_{out} = I_3Z_{out} = \frac{\left(\frac{1}{Z_{in}} - \frac{1}{R_2}\right)Z_{out}Z_W}{Z_W + R_3 + Z_{out}}V_{in} = \cancel{0.0258}V_{in}$$

Calibrate (using "up" as an example) K_{up}:

$$V_{up} = K_{up}I_1 = K_{up}\frac{Z_W+R_3+Z_{out}}{Z_WZ_{out}}V_{out}=K_{up}0.040V_{out}$$

Using high input impedance scope to measure V_{up}.

$$K_{up} = \frac{1}{25}\Omega\frac{V_{up}}{V_{out}}$$

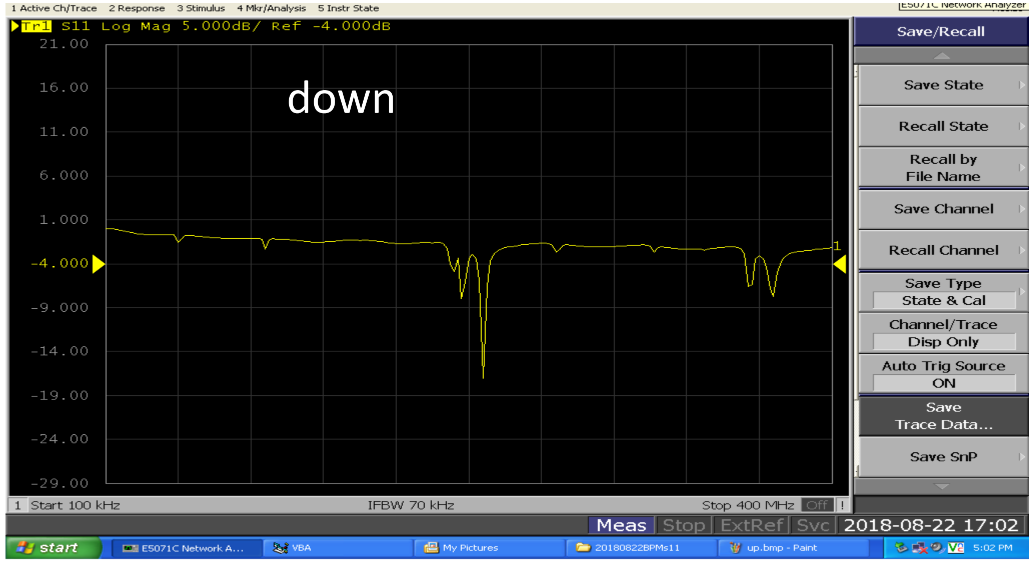
K_{xx} is calibration factor for future need

Confirm:

$$\boxed{q_1 = \int_0^T I_1dt = \int_0^T \frac{V_{up}}{K_{up}}dt = \int_0^T \frac{25V_{out}}{\Omega}dt}$$

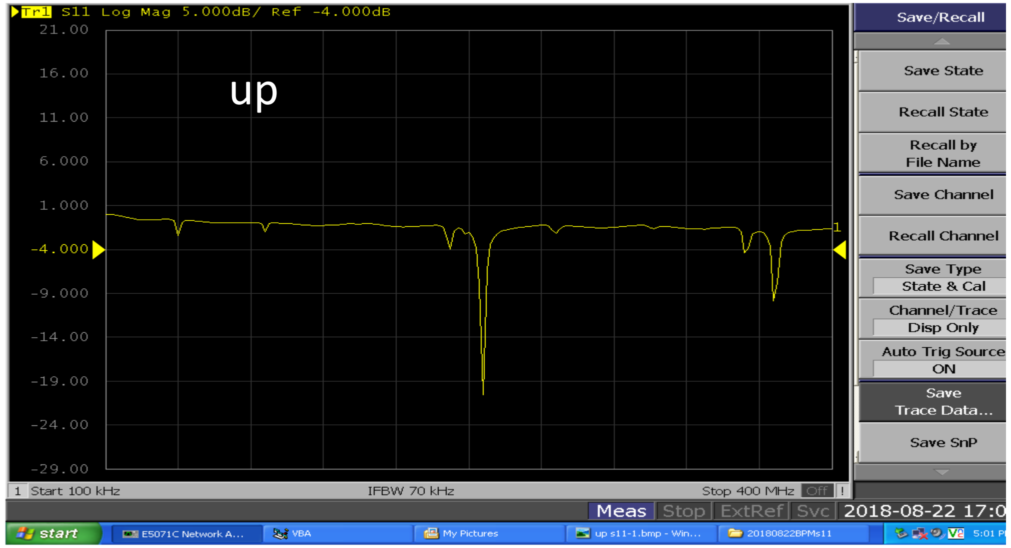
1. Using AFG in square pulse waveform in pulse width of ~100ns and frequency of 250kHz to simulate cooled ion bunch in the cooling experiment.
2. Exanimate the pickup signal (up/down, in/out) or their pair's sum signal for any distortion due to the circuit mismatch. A high input impedance scope connect 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 50Ω input impedance
4. Do the K factor calibration for all pickup ports. If Z_{out} is not connected to the scope, using a 50Ω 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 395MHz have been found. Their coupling to the pickups are strong β=0.5~1. Only "Out" plate's coupling is weaker. Their S11 measurement screen shots are shown as following
- S11 on the stretched wire also indicated strong coupling to these modes indication strong coupling to the beam and pickups


Tr1 S11 Log Mag 5.000dB/ Ref -4.000dB

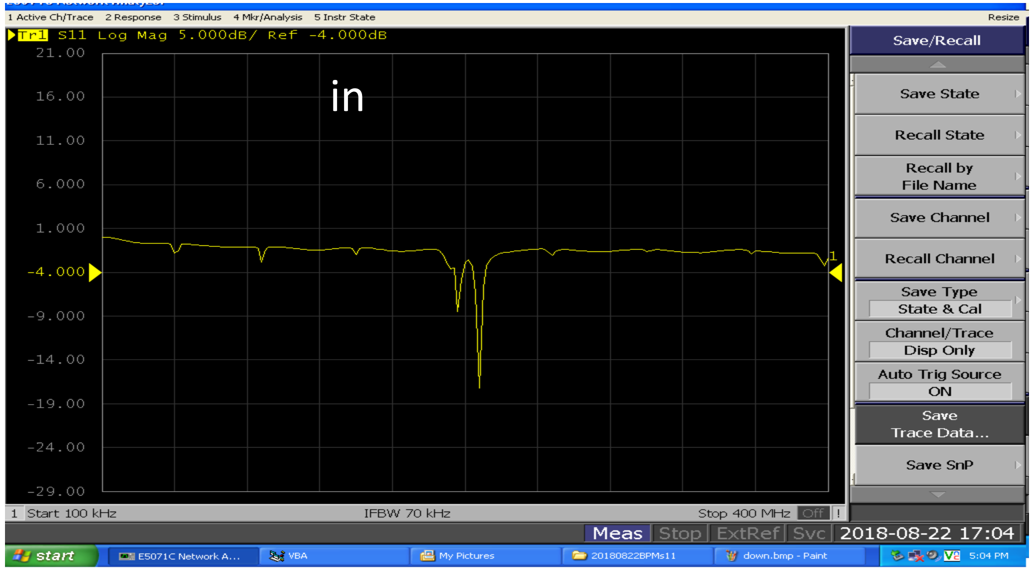
1 Start 100 kHz IFBW 70 kHz Stop 400 MHz

2018-08-22 17:02


Tr1 S11 Log Mag 5.000dB/ Ref -4.000dB

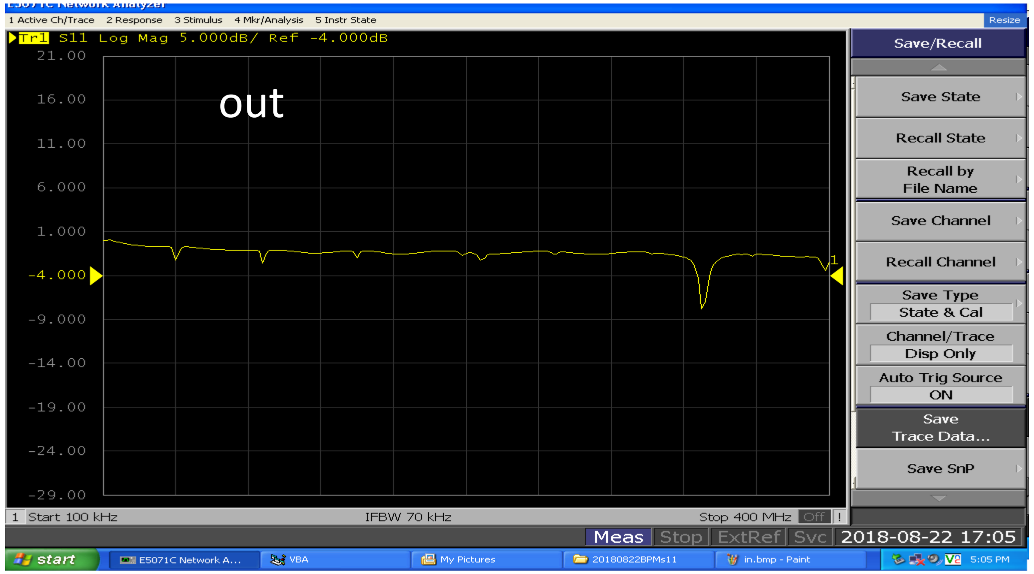
1 Start 100 kHz IFBW 70 kHz Stop 400 MHz

2018-08-22 17:0


Tr1 S11 Log Mag 5.000dB/ Ref -4.000dB

1 Start 100 kHz IFBW 70 kHz Stop 400 MHz

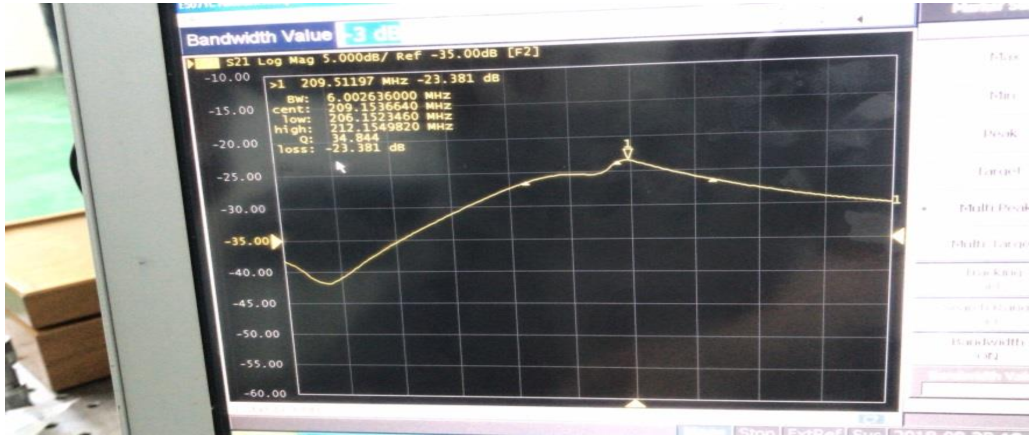
2018-08-22 17:04


Tr1 S11 Log Mag 5.000dB/ Ref -4.000dB

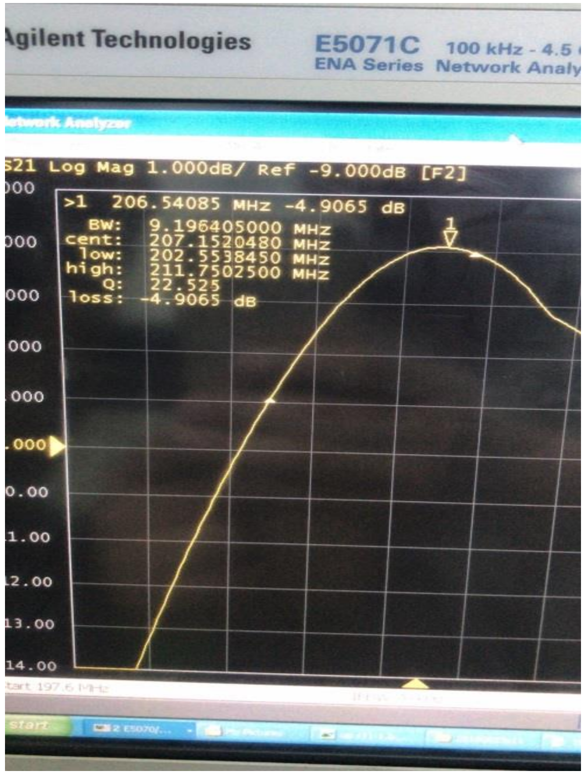
1 Start 100 kHz IFBW 70 kHz Stop 400 MHz

2018-08-22 17:05

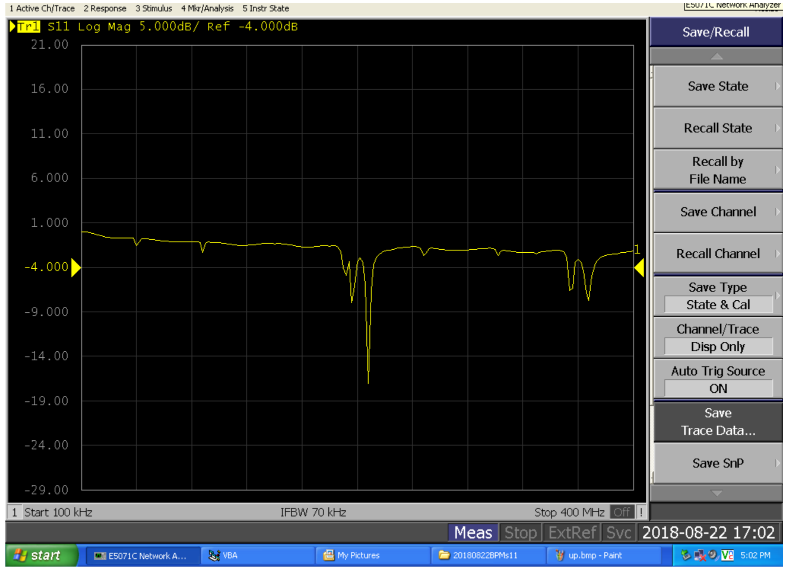
- In reality without a wire, the beam bunch could excite these two modes
- Further S21 measurements (from pickup to pickup or from pickup to the wire) indicated the loaded Q of the first mode is ~35. The second mode is ~65. Connect a 50ohm load on the third pickup ports lower the Q down to 20~25, confirmed 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

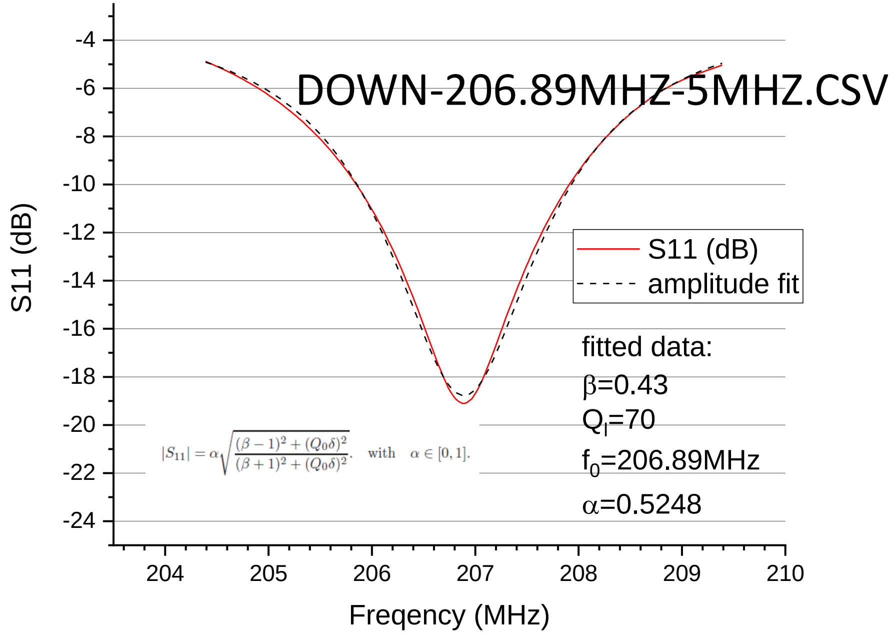


```
S21 Log Mag 5.000dB/ Ref -35.00dB [F2]
>1  209.51197 MHz -23.381 dB
  BW:   6.002636000 MHz
cent:   209.1536640 MHz
 low:   206.1523460 MHz
high:   212.1549820 MHz
   Q:   34.844
loss:   -23.381 dB
```



```
S21 Log Mag 1.000dB/ Ref -9.000dB [F2]
>1  206.54085 MHz -4.9065 dB
  BW:   9.196405000 MHz
cent:   207.1520480 MHz
 low:   202.5538450 MHz
high:   211.7502500 MHz
   Q:   22.525
loss:   -4.9065 dB
```





$$|S_{11}| = \alpha\sqrt{\frac{(\beta-1)^2+(Q_0\delta)^2}{(\beta+1)^2+(Q_0\delta)^2}}. \quad \text{with} \quad \alpha \in [0,1].$$

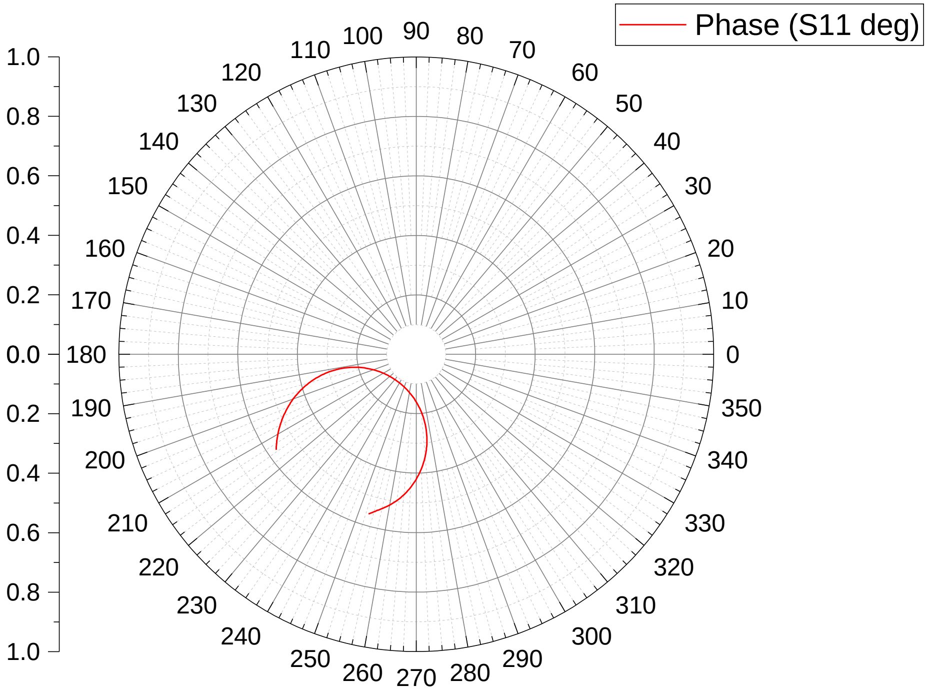
fitted data:

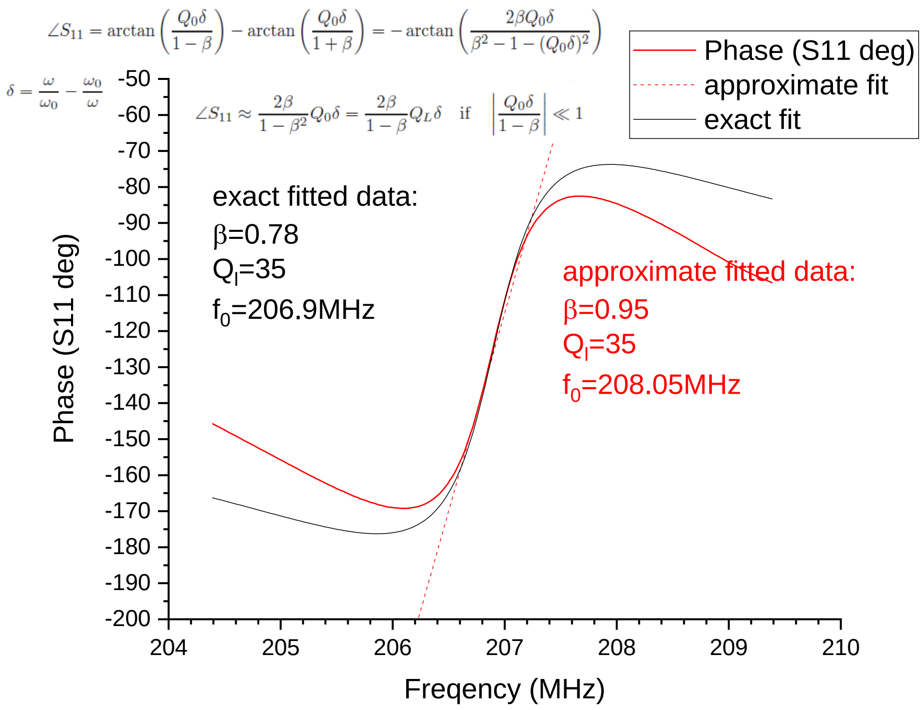
β=0.43

Q_l=70

f_0=206.89MHz

α=0.5248





$$\angle S_{11} = \arctan\left(\frac{Q_0\delta}{1-\beta}\right) - \arctan\left(\frac{Q_0\delta}{1+\beta}\right) = -\arctan\left(\frac{2\beta Q_0\delta}{\beta^2-1-(Q_0\delta)^2}\right)$$

$$\delta = \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}$$

$$\angle S_{11} \approx \frac{2\beta}{1-\beta^2}Q_0\delta = \frac{2\beta}{1-\beta}Q_L\delta \quad \text{if} \quad \left|\frac{Q_0\delta}{1-\beta}\right| \ll 1$$

exact fitted data:

β=0.78

Q_l=35

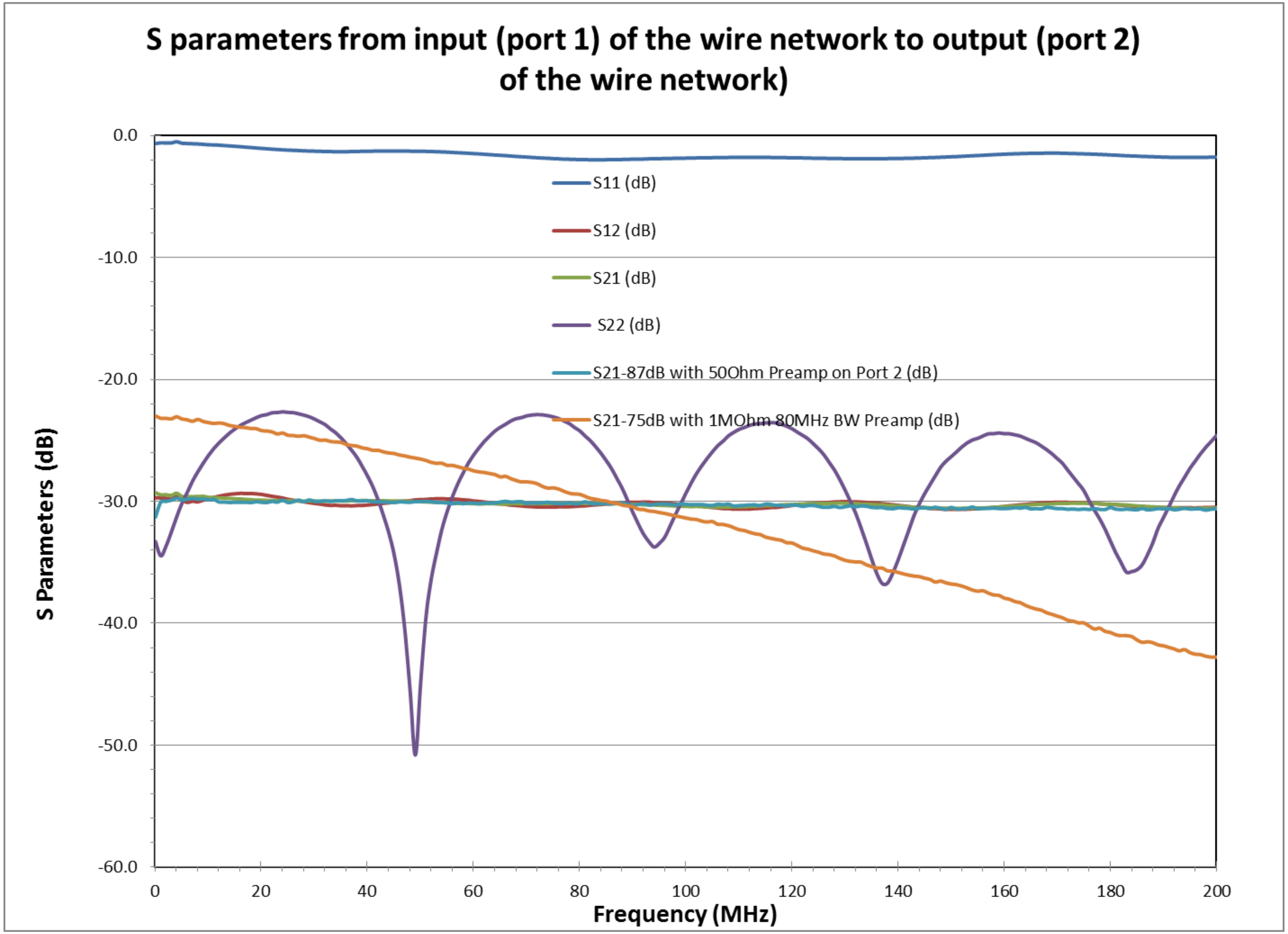
f_0=206.9MHz

approximate fitted data:

β=0.95

Q_l=35

f_0=208.05MHz



S parameters from input (port 1) of the wire network to output (port 2) of the wire network)