Pulsed Beam Cooling Experiment Preparation for Dec. 2019 Last Experiment at IMP

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Motivation:

- Purpose of the last experiment is to improve and obtain the best bunched beam cooling experiment data with calibrated diagnostics avoiding saturation effects of RF amplifiers including all synchronized ion BPM, IPM, Schottky, DCCT signals. Demonstrate longitudinal (transverse ?) sweeping or dithering of the cooling electron bunch to improve the ion bunch distribution (avoid overcooling of the core or double Gaussian distribution)
- Demonstrate hollow beam cooling (stretch goal) to improve the transverse distribution (preferentially cool halo)
- All best data to calibrate JSPEC and allow us to complete a high quality of publications

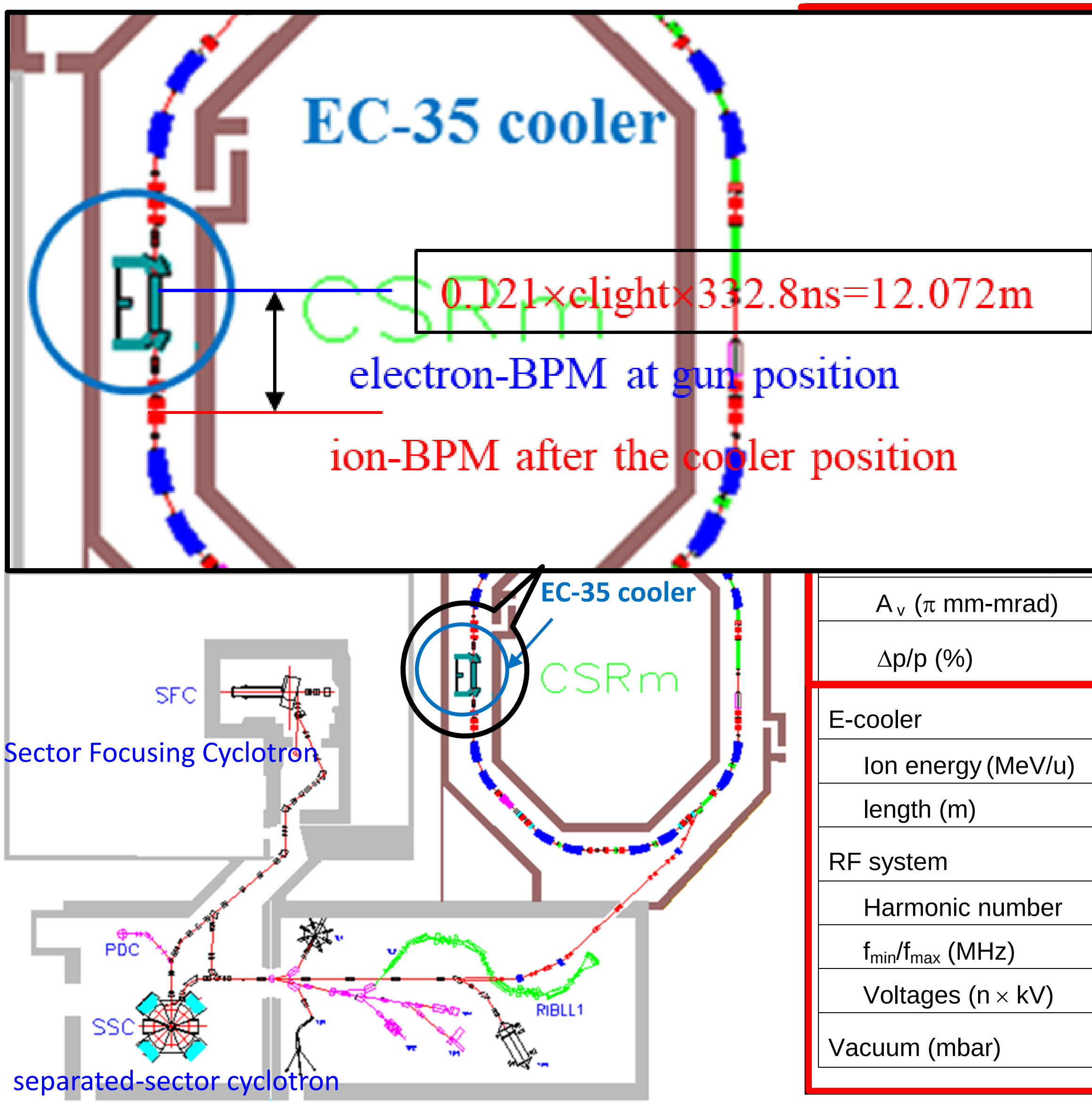
Experiments done so far:

- May 2016, 1st experiment: bunched beam electron was formed by JLab's HV pulser cooling $^{12}C^{6+}$ 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
- December 2018, 3rd experiment without JLab team due to the visa issue. The ion beam is $^{86}Kr^{25+}$. New BPM, IPM data obtained but missed calibration data. The Schottky signal missed resolution on sidebands

Publications so far:

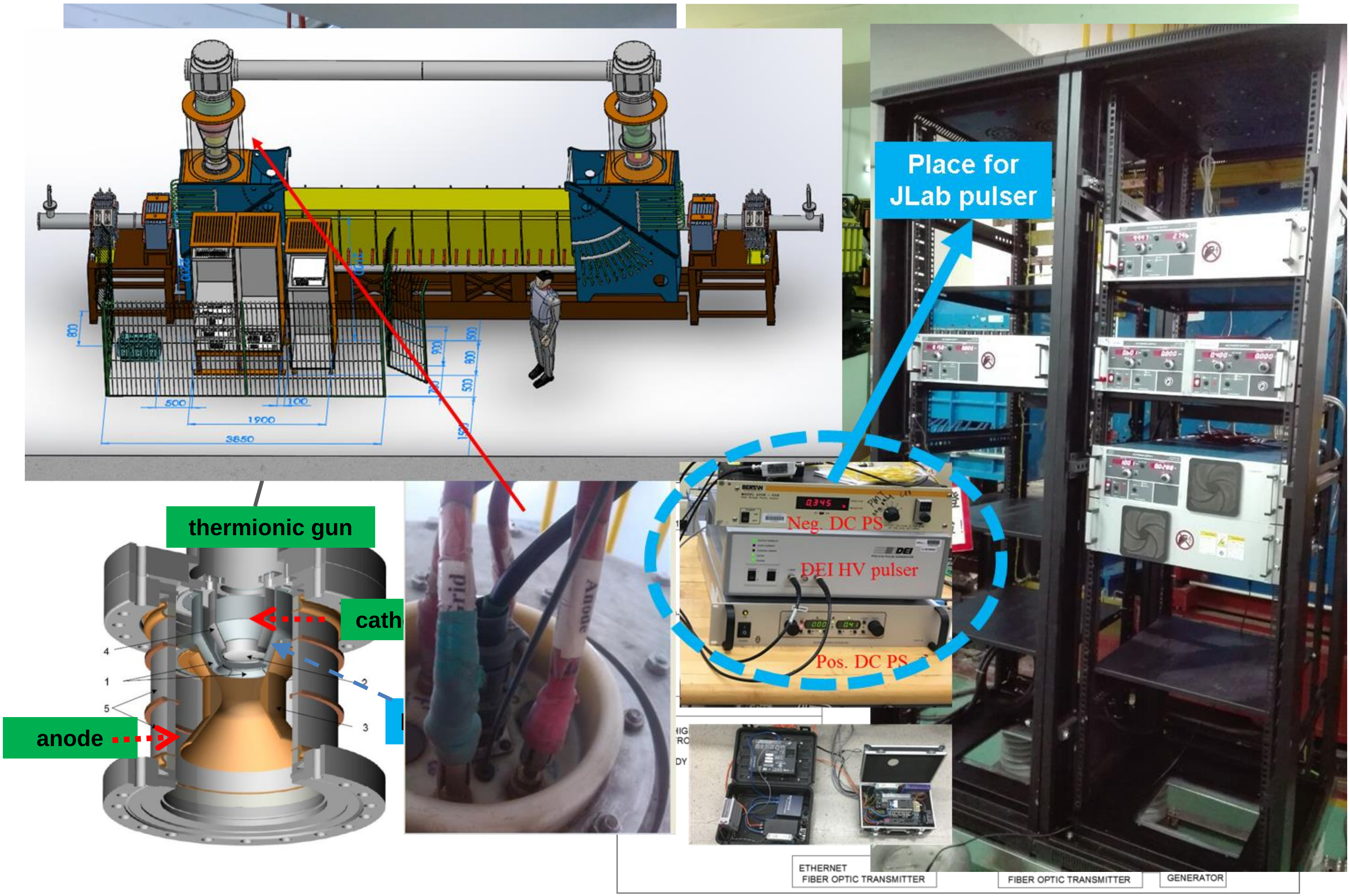
1. Nuclear Inst. and Methods in Phys. Research, A 902 (2018) 219-227.
2. doi:10.18429/JACoW-IPAC2018-TUPAL069
3. doi:10.18429/JACoW-COOL2017-TUP15
4. PHYSICAL REVIEW ACCELERATORS AND BEAMS 21, 023501 (2018)

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 ($\Delta p/p$ = ±0.15 %)		**150** ($\Delta p/p$ =±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 ($n \times kV$)	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



Experiment Parameters and Data Taken in 2017/2018

ION RING	**IMP (CSRm ring**			
	2017	**2018**		
specieses	12C6+	86Kr25+	12C6+	
bunch charge		204.20		pC
charge per nucleon	0.5	0.2907	0.5	
kinetic energy per nucleon	7.0	5.00753	19.0	MeV/u
beta	0.121	0.103	0.198	
gamma	1.007	1.005	1.020	
revolution frequency	225.907	191.372	368.687	kHz
Harmonic Number	2	2	2	
Vrf	1200	600	1200	V
RF frequency	451.814	382.744	737.374	kHz
synchrotron frequency	813.824	440.214	798.167	Hz
Resonant or Broadband Schottky Picku	**IMP (CSRm coole)**			
	Plus Minus 0.5MHz			
Schottky spectrum center frequency	5.8736	2.2976	5.8736	MHz
harmonic number	26	12	15	
p number	0.00010	0.00593	0.93113	
Electron Cooler	**IMP (SC35 coole)**			
kinetic energy	3.81	2.7271	10.35	keV
electron pulse edge width	0.035	0.721	0.058	rad
dI/dt	2.64	0.11	2.64	mA/ns
Cooling section length	3.4	3.4	3.4	m
Electron kick δE per turn	0.306	0.010	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	575.0	371.0	V
maximum pulsed peak current at revolution frequency	177.36	177.36	110.91	mA
maximum pulse grid voltage at bunch frequency	297.0	297.0	145.0	V
maximum pulsed peak current at bunch frequency	90.64	90.64	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

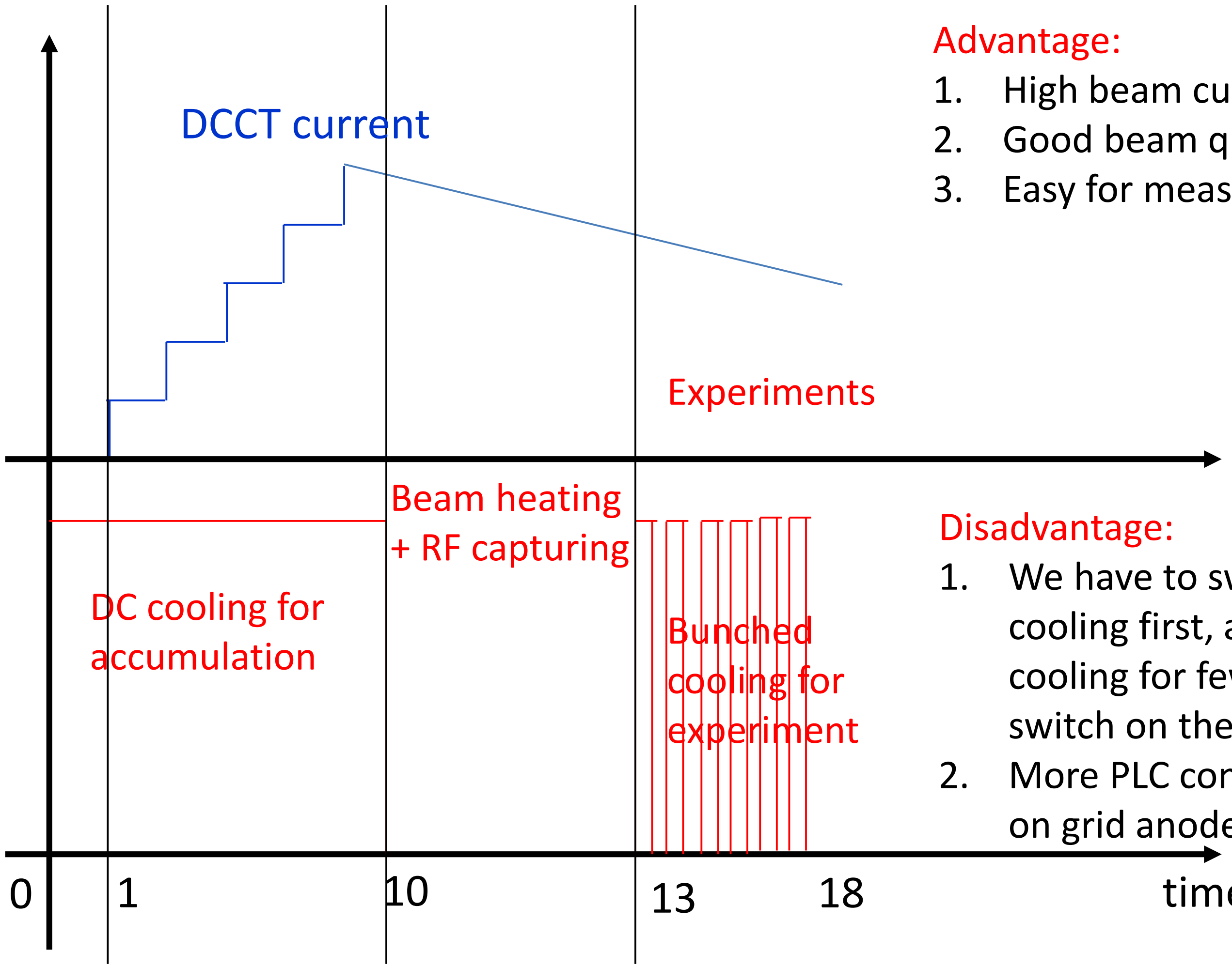
Experiment parameters

A lot of data taken at 2017 and 2018

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 5-7MeV/u [most experiment data taken in 2016/2017/2018 at this energy level]



Advantage:

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

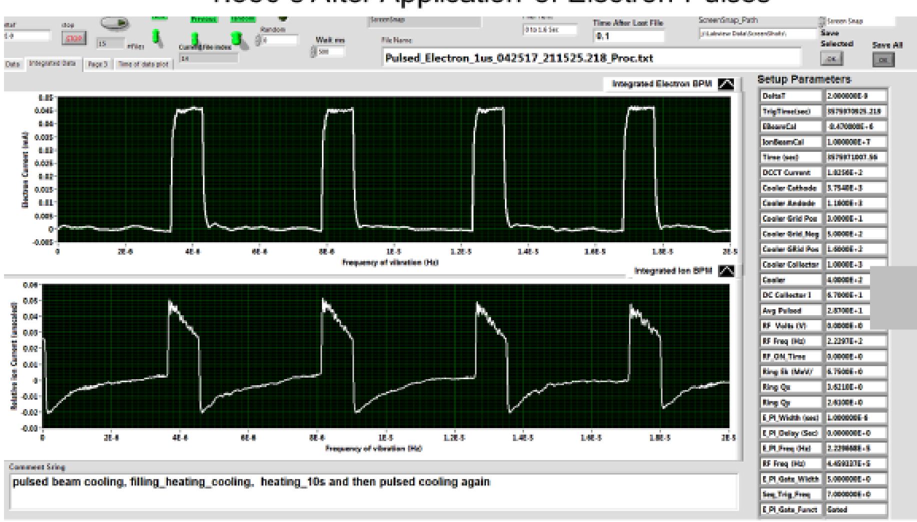
Disadvantage:

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

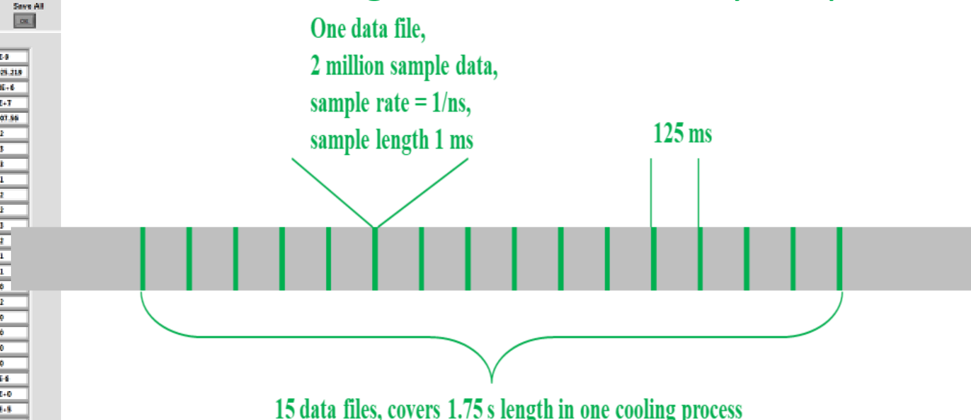
Beam Diagnostics at CSRm for Bunched Cooling Experiment

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(now R&S) spectrum analyzer
IPM	Measure the transverse cooling	Yes	EPICS

1.350 s After Application of Electron Pulses

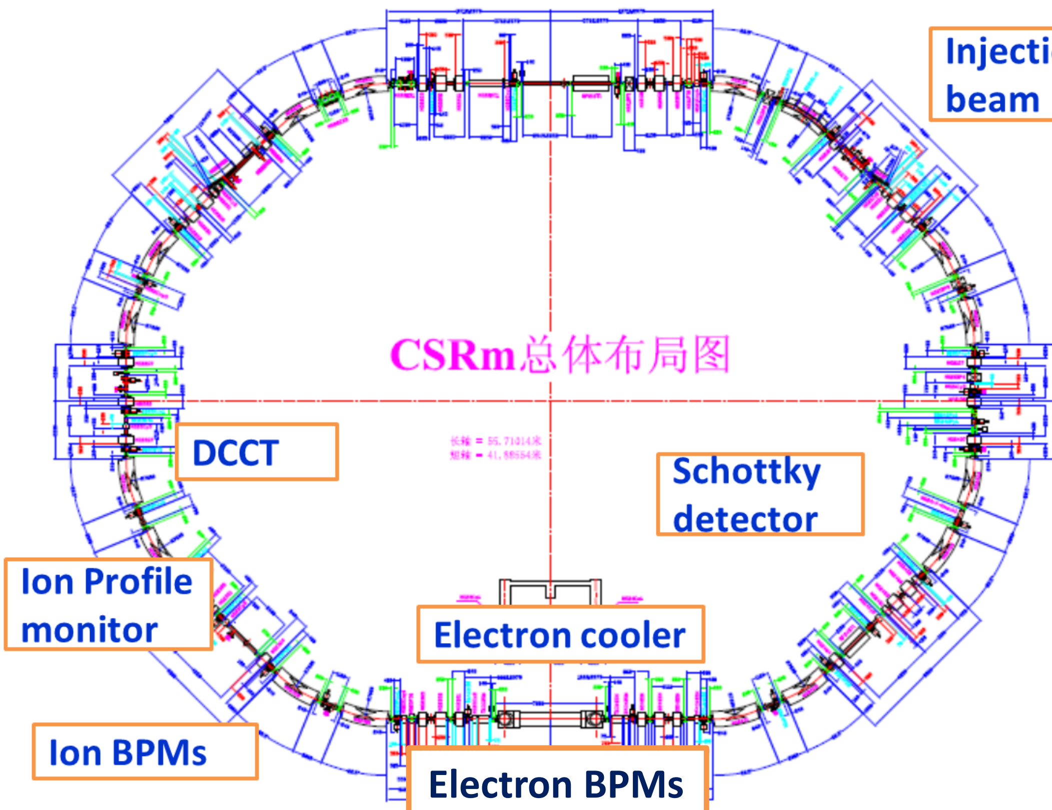


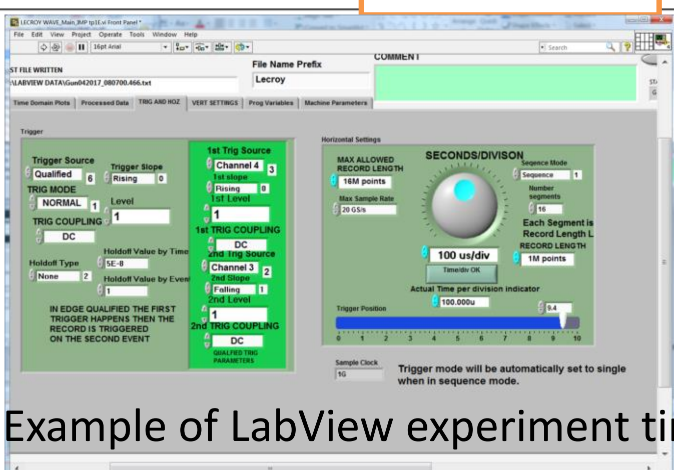
Data recording with JLab's LeCroy scope



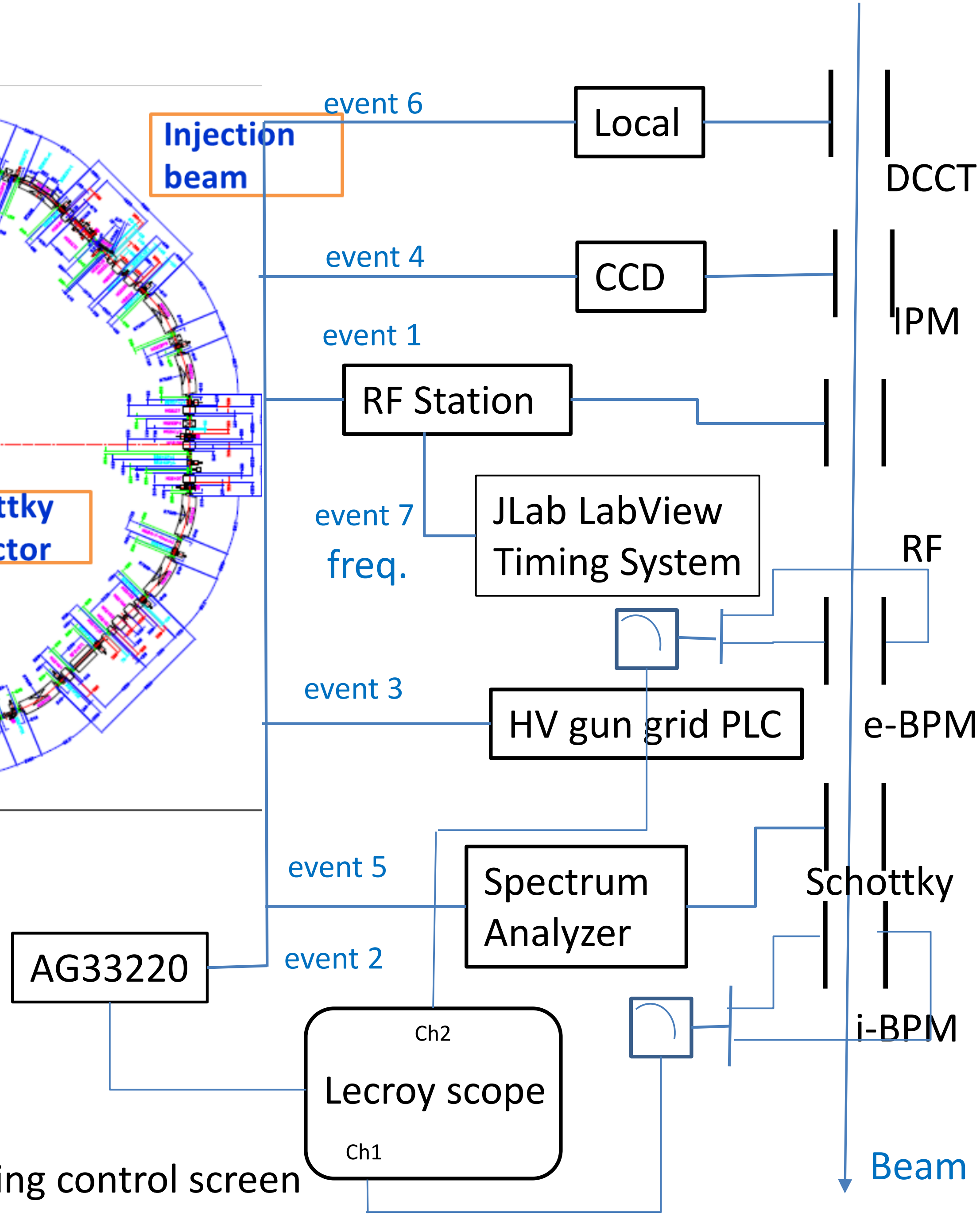
Possible IMP is using a new R&S scope

Beam diagnostic setups:

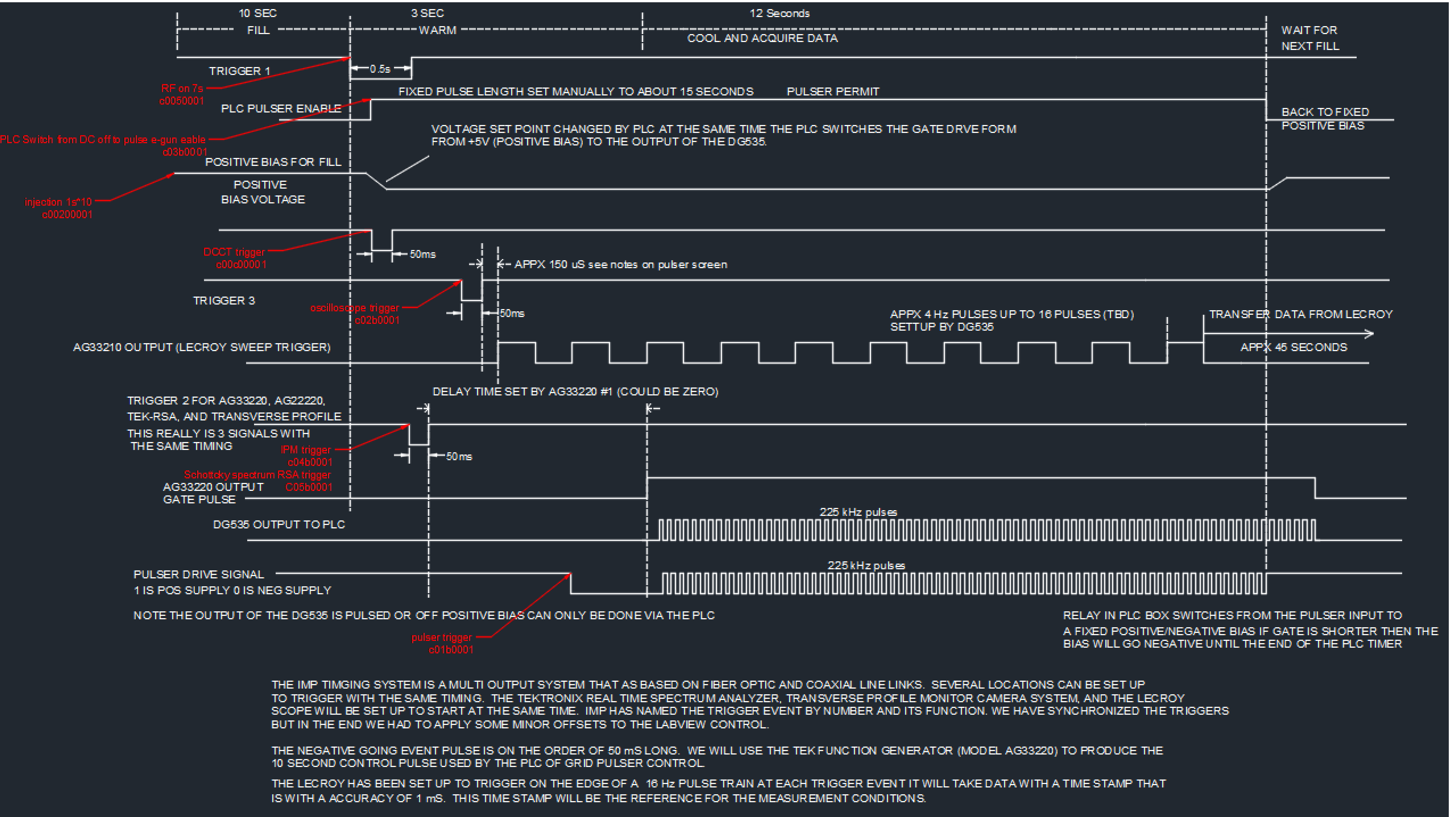




Example of LabView experiment timing control screen

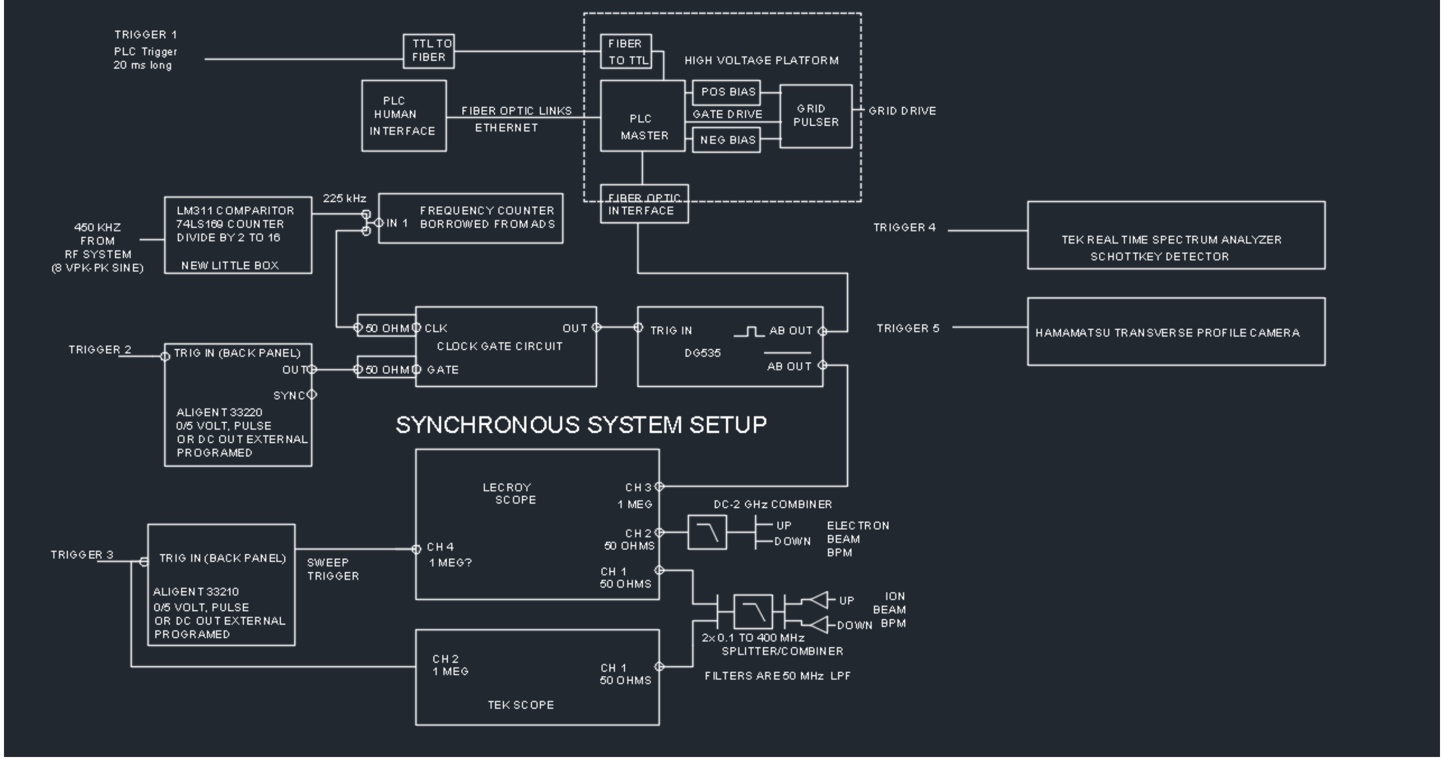


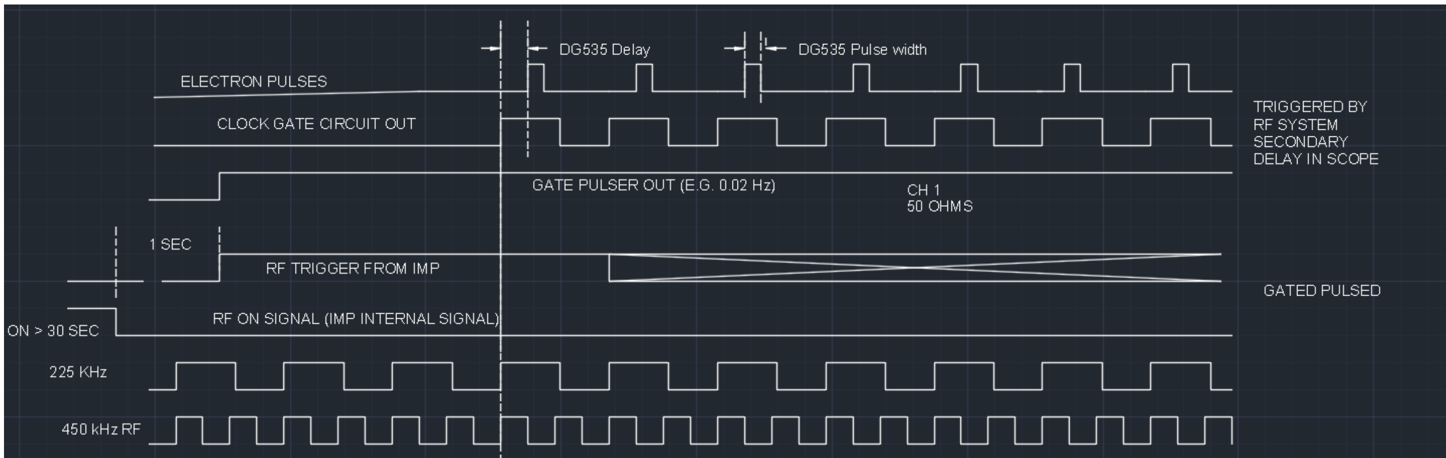
Global Timing and Local Triggering Logics for the BPM Data Capturing within One Filling Time of CSRm



GLOBAL TIMING FOR PLC, AND PULSERS

Ion/Electron Beam Synchronization Setup



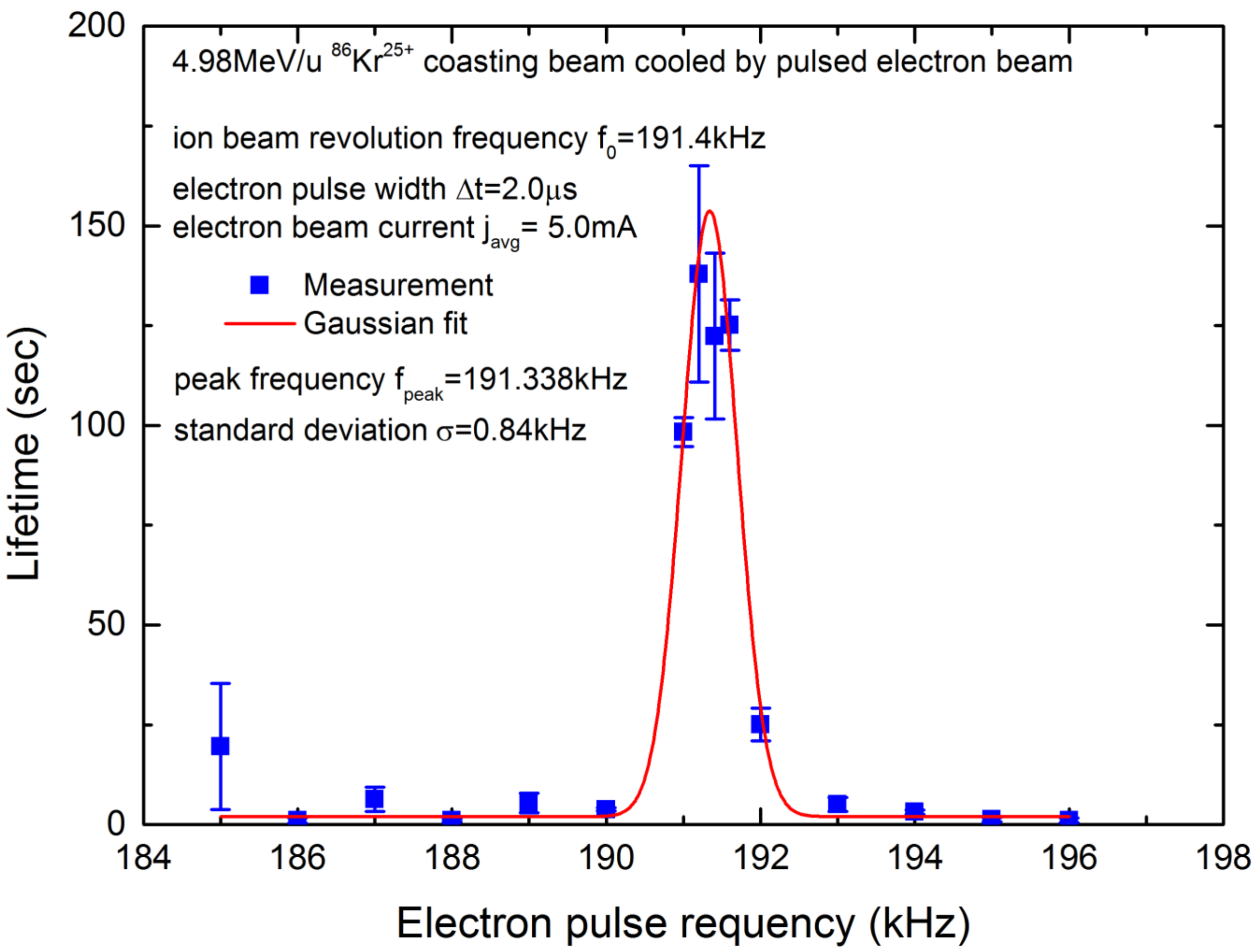


TIMING FOR CLOCK GATE CIRCUIT AND

➢ Experiment results

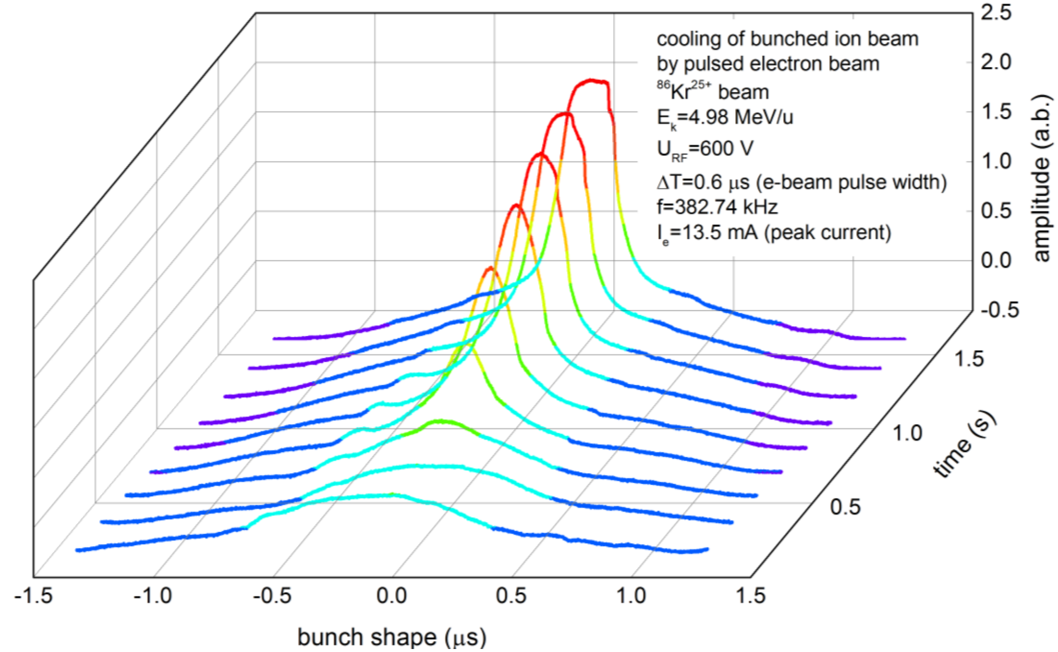
■ **Synchronization**

The repetition frequency of electron pulse **must be matched to** the ion beam revolution frequency



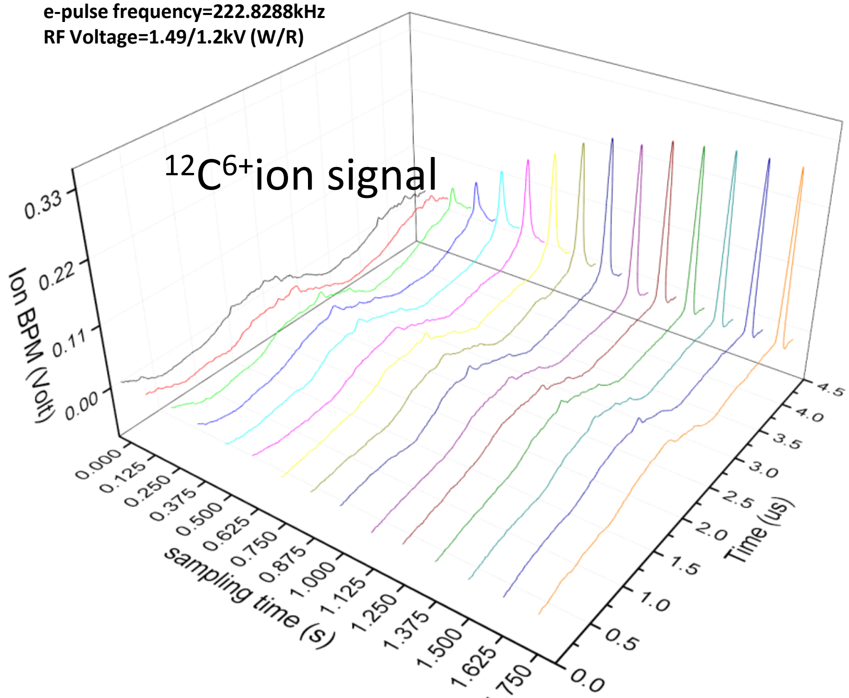
2017/2018 data analysis demonstrated the bunched beam cooling feature

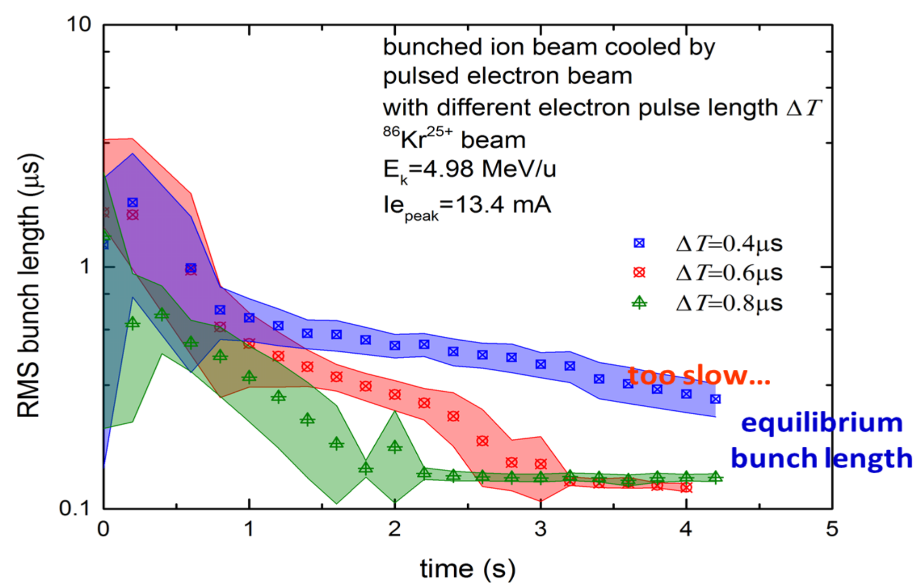
- BPM/IPM data from Dec, 2018 experiment have possible RF amplifier saturation effects
- Both BPM and IPM have double Gaussian distributions



DCCT ion current=43.78uA
e energy=3.74keV
e DC collector current=67.2mA
e average pulsed current=19.3mA
RF Frequency=445.6577kHz
e-pulse width=1.0us
e-pulse frequency=222.8288kHz
RF Voltage=1.49/1.2kV (W/R)

BPM April, 2017 data

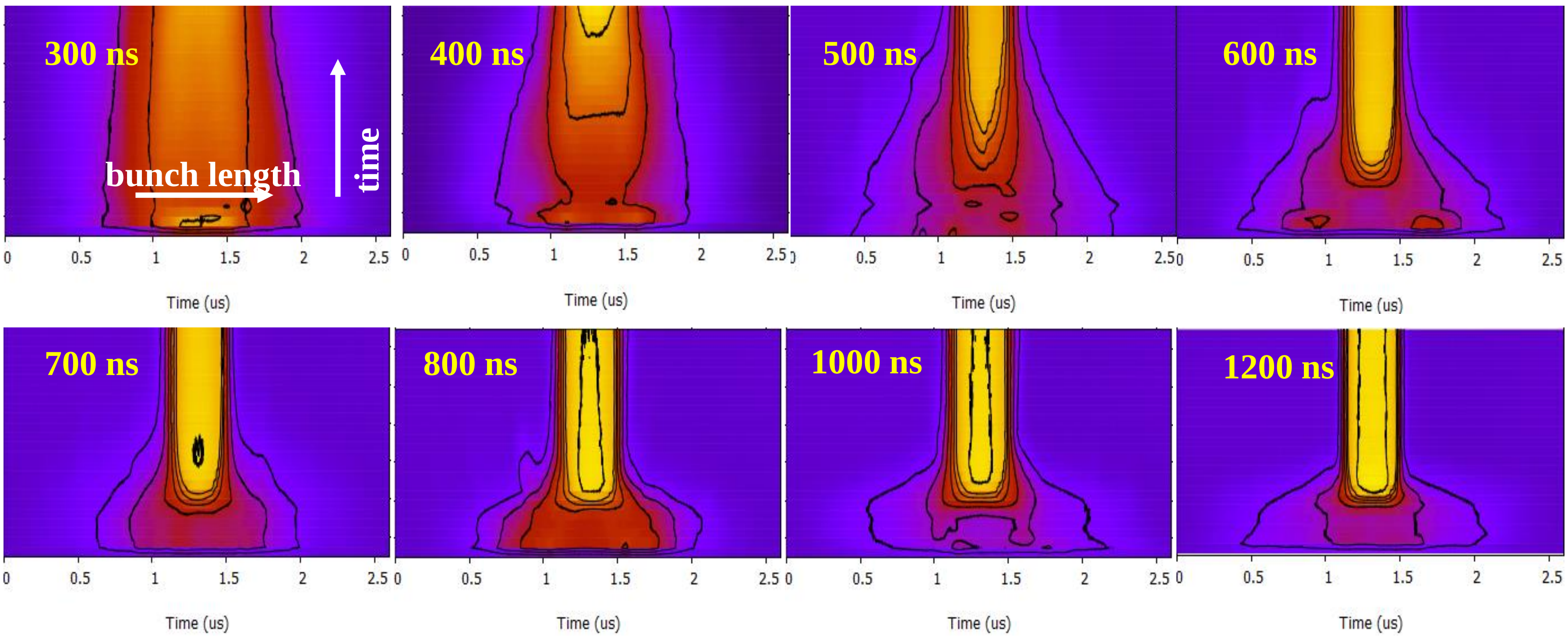




➢ Experiment results

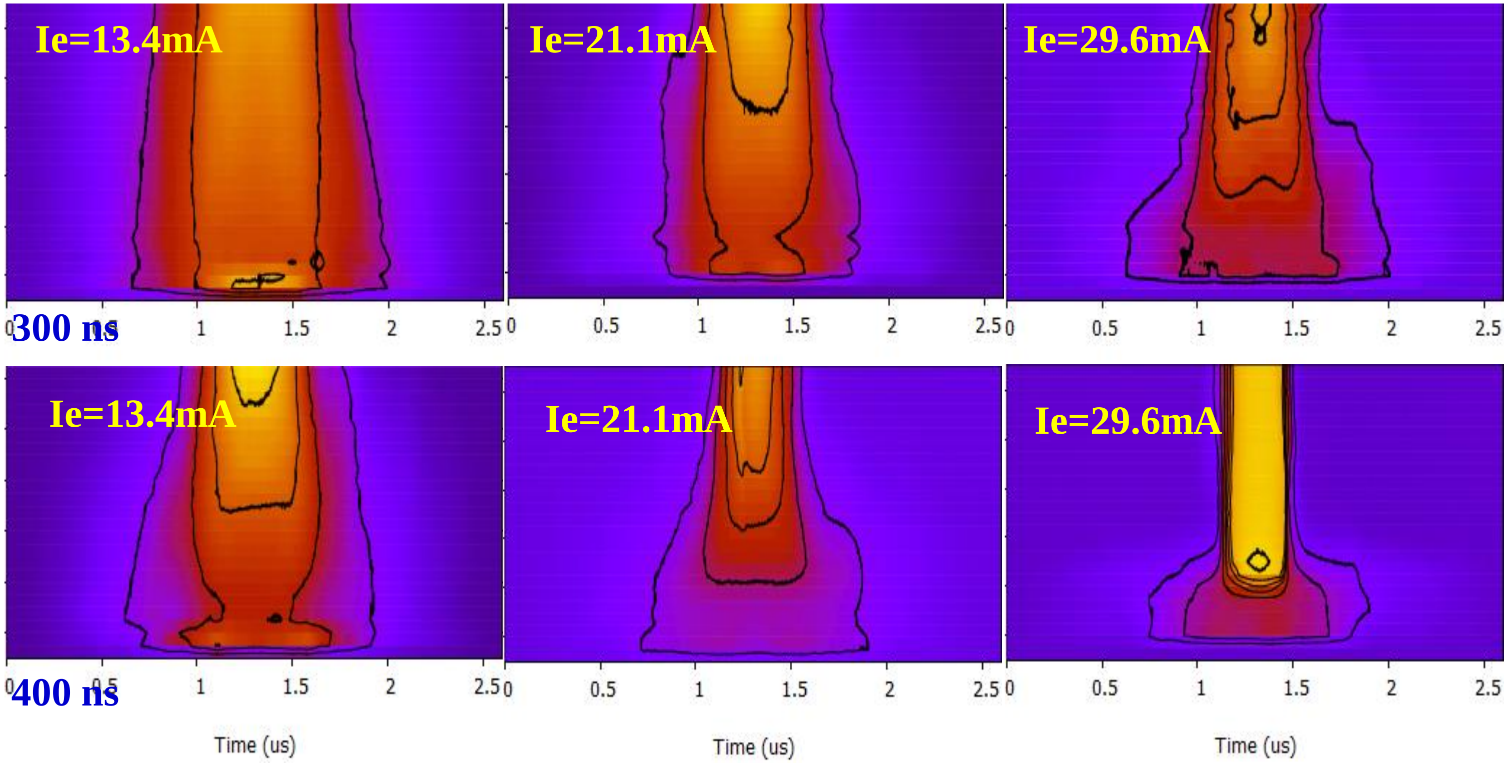
The cooling process with different electron pulse length

- It is observed that the cooling is **faster with larger e-beam pulse length** (the electron peak current is a constant)



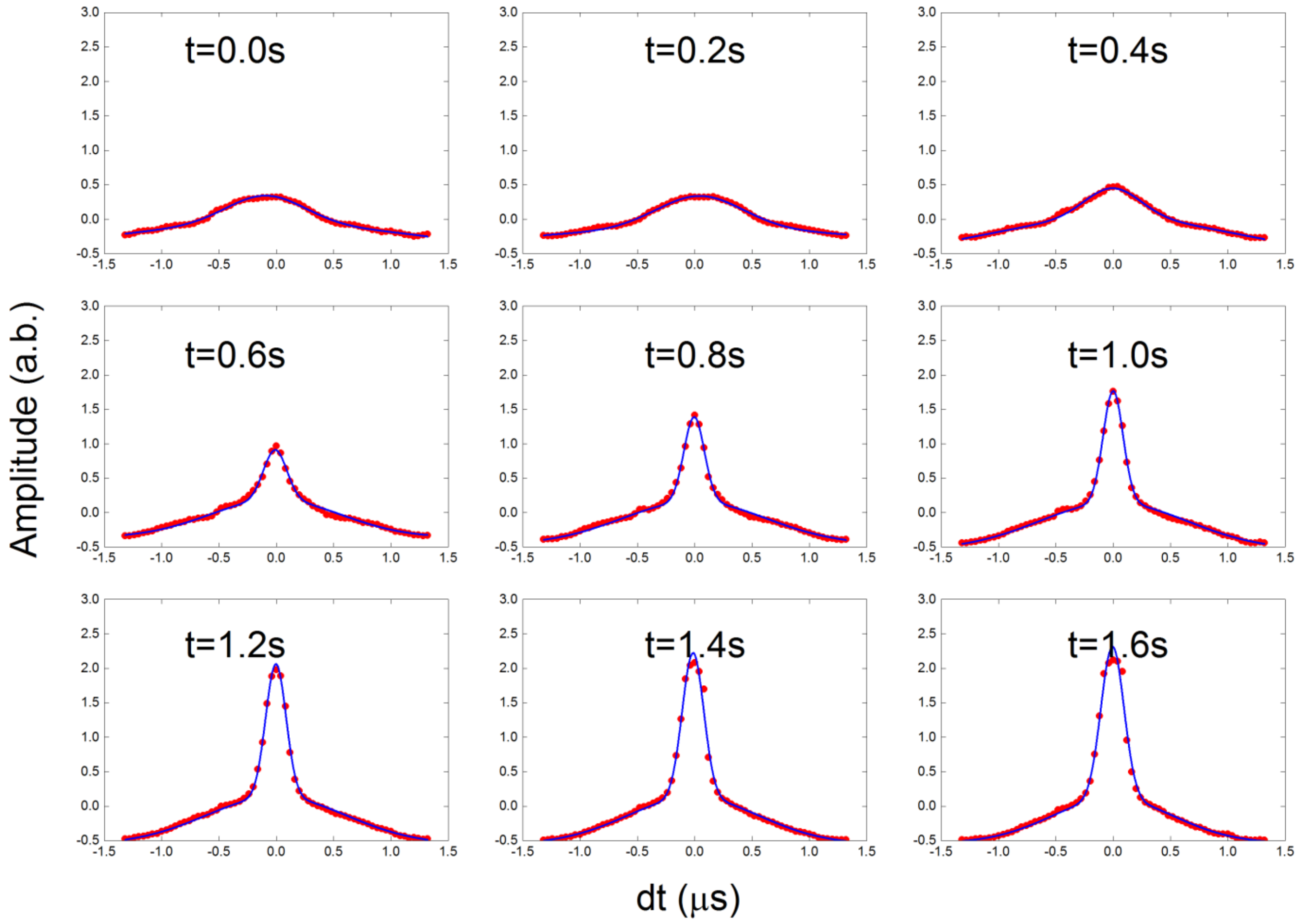
The cooling process with different electron peak current

- It is also observed that the cooling is **faster with high e-beam peak current** (the electron pulse length is a constant)

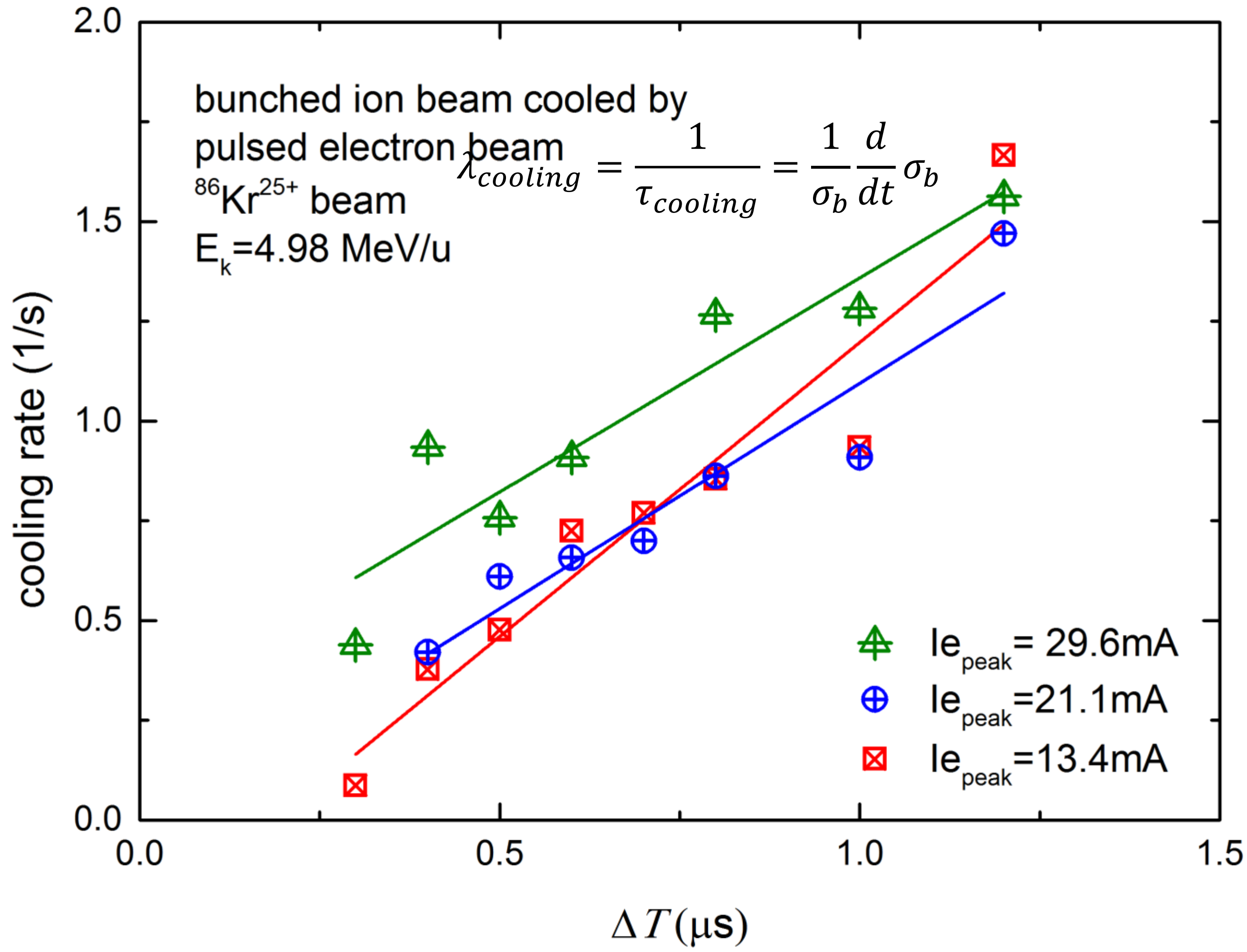


The measured longitudinal beam shape can be fitted by **Bi-Gaussian distribution**

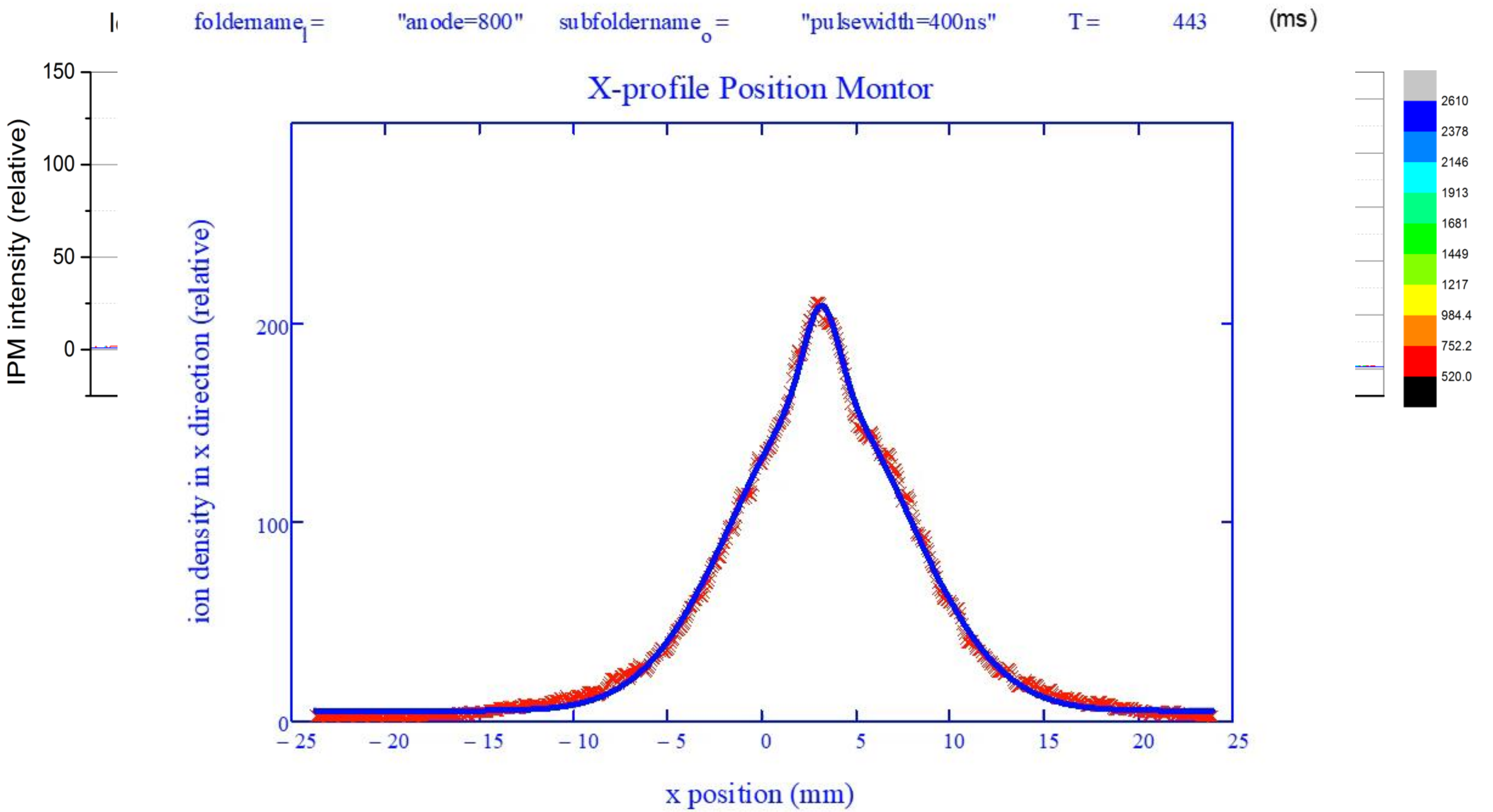
$$y = \frac{\Gamma_c}{\sqrt{2\pi}} \frac{1}{\sigma_c} \exp\left(-\frac{(t-t_0)^2}{2\sigma_c^2}\right) + \frac{\Gamma_t}{\sqrt{2\pi}} \frac{1}{\sigma_t} \exp\left(-\frac{(t-t_0)^2}{2\sigma_t^2}\right) + \delta \quad \rightarrow \quad \sigma = \frac{S_c\sigma_c + S_t\sigma_t}{S_c + S_t}$$



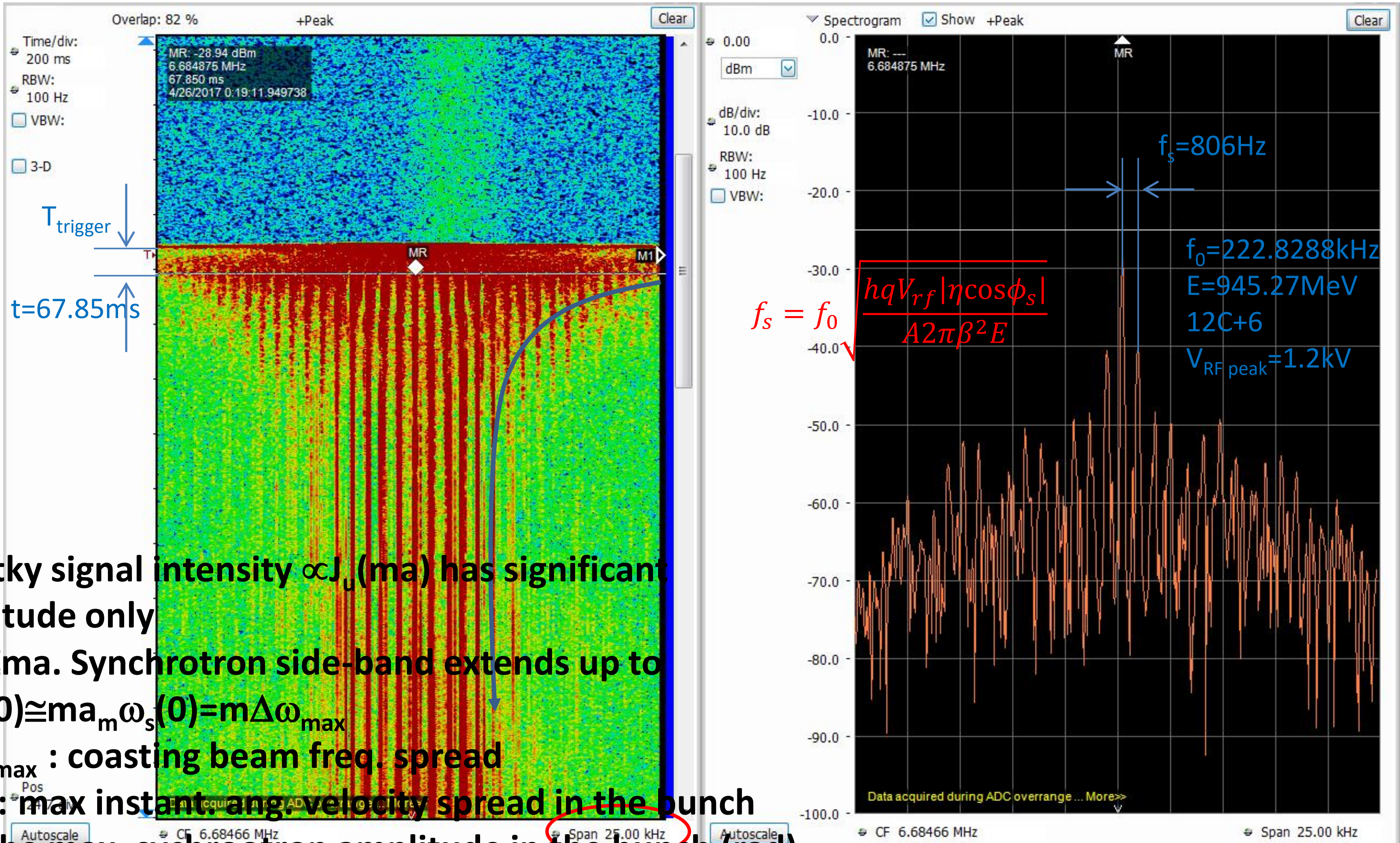
➢ The cooling rate **increases** with increasing of **the electron pulse length** and **the e-beam peak current**.



➢ The transverse beam cooling effect was observed by IPM detector.



Schottky signal analysis: cooling rate τ_{cool} and dp/p estimation



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

Schottky signal intensity $\propto J_u(ma)$ has significant magnitude only for $\mu \leq ma$. Synchrotron side-band extends up to $\mu_m\omega_s(0) \cong ma_m\omega_s(0) = m\Delta\omega_{max}$

$m\,\Delta\omega_{max}$: coasting beam freq. spread

$\Delta\omega_{max}$: max instant. ang. velocity spread in the bunch

a_m is the max. sychrootron amplitude in the bunch (rad)

Schottcky Signal_Large.mp4

frequency

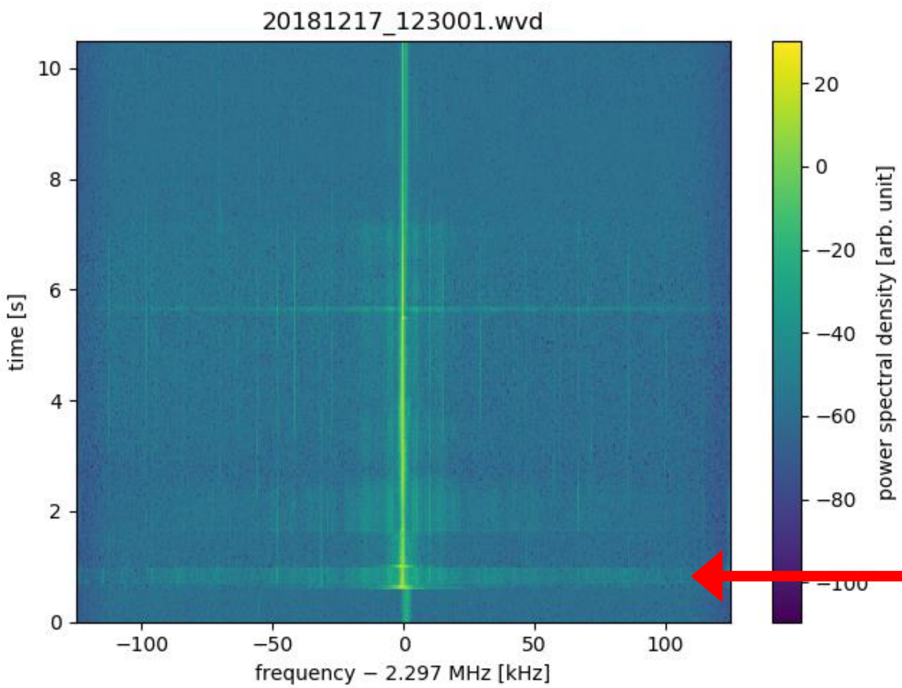
time

Schottky movie to play

- 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

Power spectral density – 2D
Dec. 2018's data

- Full time span, frequency resolution 25 Hz, time resolution 0.04 s



Full time span shows interesting times to look at in more detail, in the absence of other info about the measurement

These spectra look similar for the 5 sample data sets available to us

Look at 1D slices here, over time range ~0.5 to 1 s

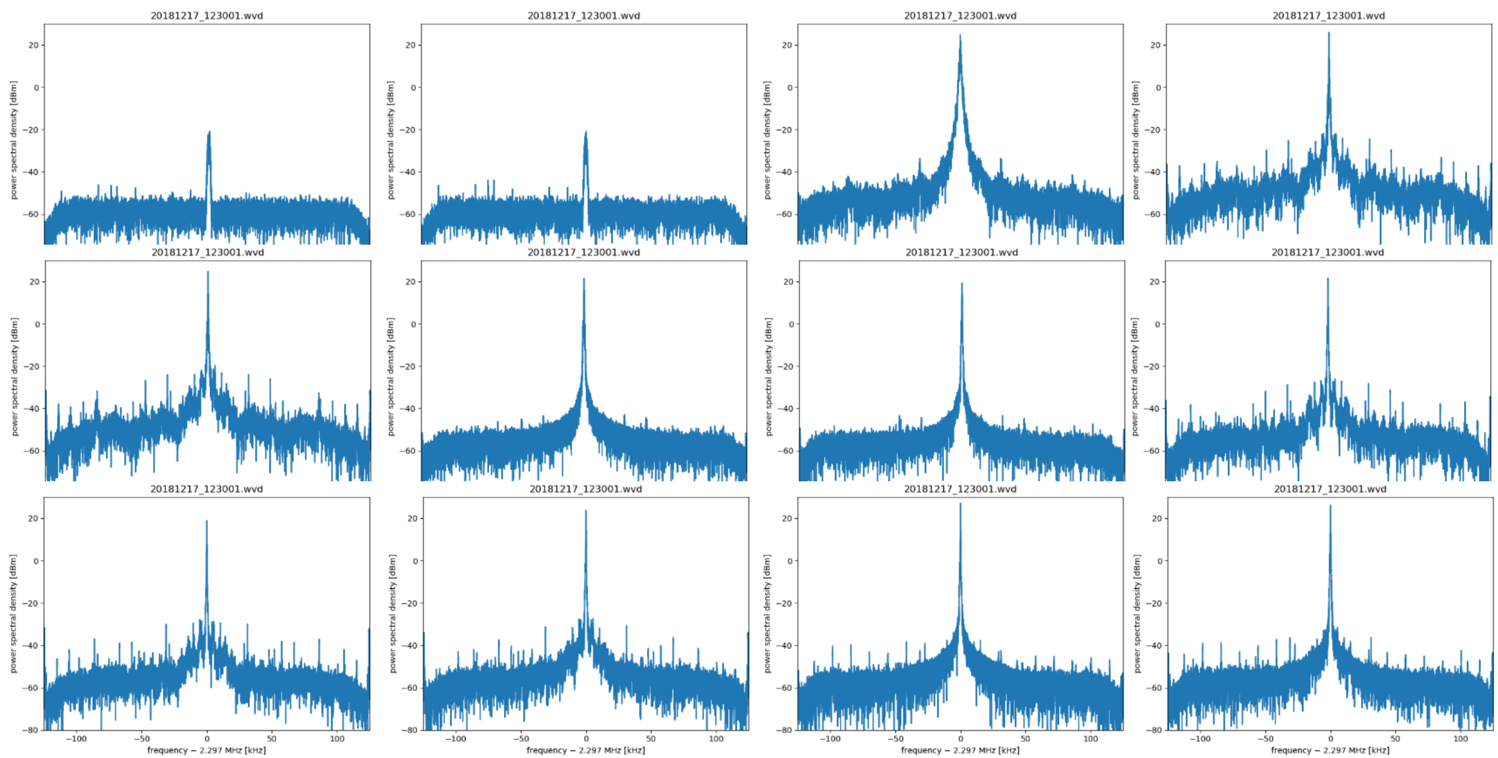
Power spectral density – 1D slices

Δt=0.04 s
t_0=0.52 s
Full frequency span

t=0.52-0.64 s

t=0.68-0.80 s

t=0.84-0.96 s



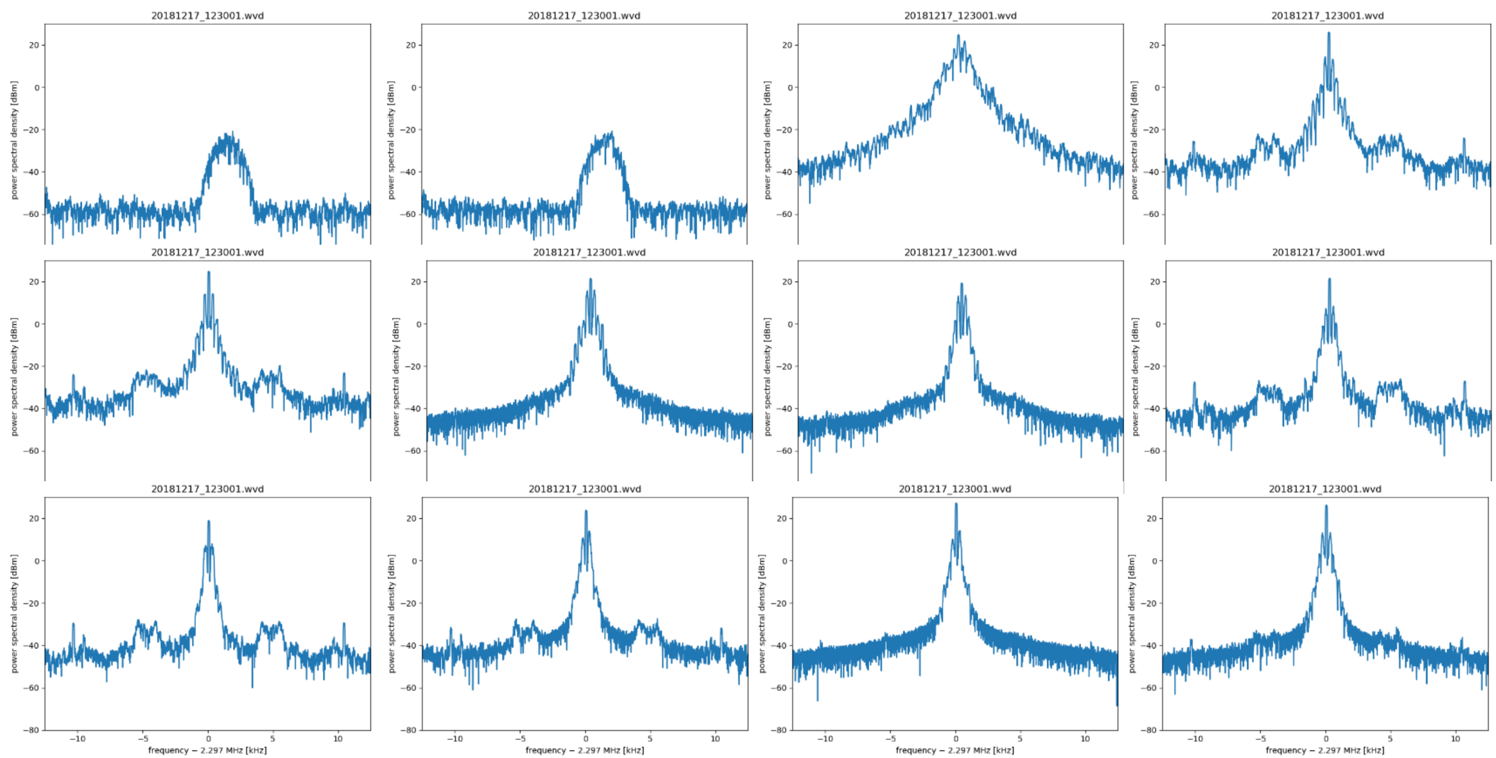
Power spectral density – 1D slices

Δt=0.04 s
t_0=0.52 s
25 kHz span

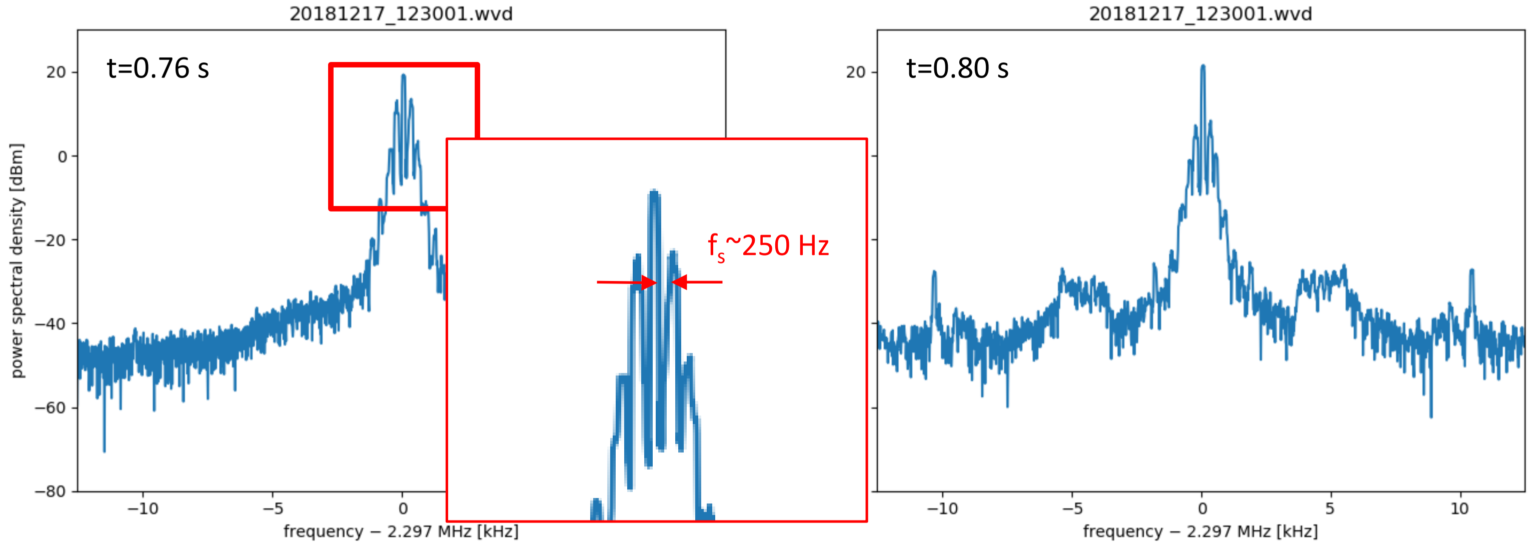
t=0.52-0.64 s

t=0.68-0.80 s

t=0.84-0.96 s



Power spectral density – 1D slices



- Calculated f_s~400 Hz does not match with observed f_s~250 Hz
- No clear evidence of sidebands associated with transverse Schottky signals, expected as repeats of longitudinal structure

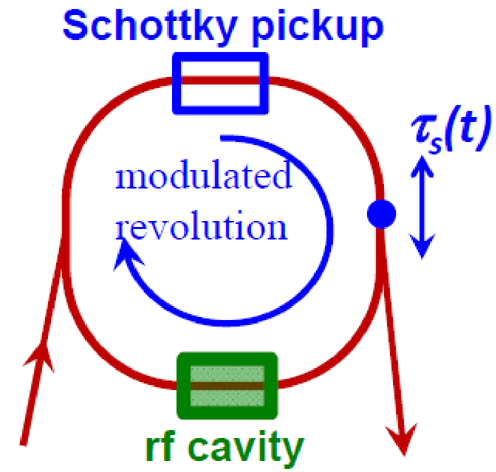
Bunched Beam: Longitudinal Schottky Spectrum for a single Particle

Single particle of a bunched beam → modulation of arrival by synchrotron oscillation:

Synchrotron frequency $f_s = Q_s \cdot f_0$

$Q_s << 1$ synchrotron tune i.e. long. oscillations per turn

$$\tau_s(t) = \hat{\tau}_s \cdot \cos(2\pi f_s t + \psi)$$



Modification of coasting beam case for a frequency modulation:

$$I_1(t) = ef_0 + 2ef_0 \sum_{h=0}^{\infty} \cos\{2\pi h f_0 [t + \hat{\tau}_s \cdot \cos(2\pi f_s t + \psi)]\}$$

Each harmonics h comprises of lower and upper sidebands:

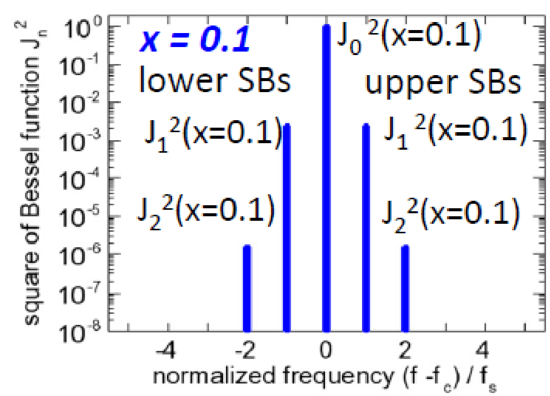
$$\sum_{p=-\infty}^{\infty} J_p(2\pi h f_0 \hat{\tau}_s) \cdot \cos(2\pi h f_0 t + 2\pi p f_s t + p\psi)$$

For ***each*** revolution harmonics h the longitudinal is split

- Central peak at hf_0 with height $J_0(2\pi \cdot hf_0 \cdot \hat{\tau}_s)$
- Satellites at $hf_0 \pm pf_s$ with height $J_p(2\pi \cdot hf_0 \cdot \hat{\tau}_s)$

Note:

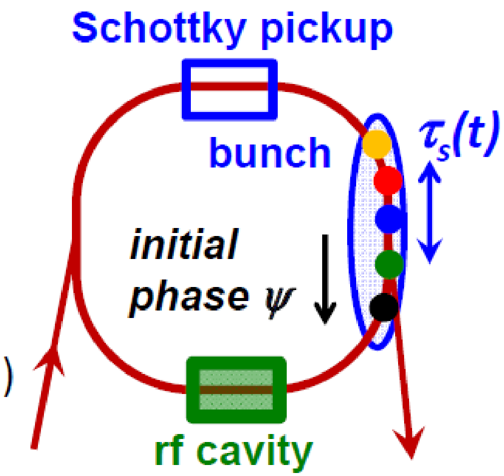
- The argument of Bessel functions contains amplitude of synchrotron oscillation $\hat{\tau}_s$ & harmonics h
- Distance of sidebands are independent on harmonics h



Bunched Beam: Longitudinal Schottky Spectrum for many Particles

Particles have different amplitudes $\hat{\tau}_s$ and initial phases ψ

$\Rightarrow$ **averaging over initial parameters for *n = 1…N* particles:**



Results:

- **Central peak *p = 0*:** No initial phase for single particles

  $U_0(t) \propto J_0(2\pi \cdot hf_0 \cdot \hat{\tau}) \cdot \cos(2\pi hf_0 t)$

  $\Rightarrow$ **Total power $P_{tot}(p = 0) \propto N^2$**

  i.e. contribution from 1…***N*** particles add up **coherently**

  $\Rightarrow$ **Width: $\sigma_{p=0} = 0$** (ideally without power supplier ripples etc.)

  Remark: This signal part is used in regular BPMs

- **Satellites *p* ≠ *0*:** initial phases ψ appearing

  $U_p(t) \propto J_p(2\pi \cdot hf_0 \cdot \hat{\tau}) \cdot \cos(2\pi hf_0 t + 2\pi p f_s t + p\psi)$

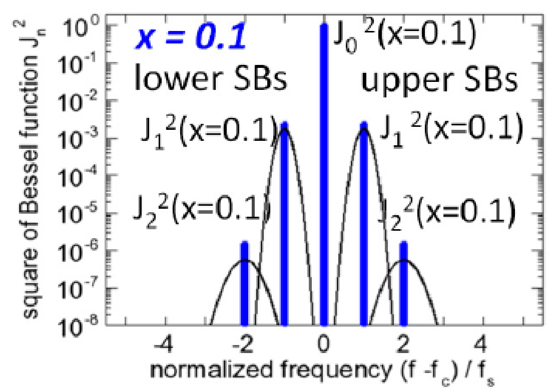
  $\Rightarrow$ **Total power $P_{tot}(p \neq 0) \propto N$**

  i.e. contribution from 1…***N*** particles add up **incoherently**

  $\Rightarrow$ **Width: $\sigma_{p\neq 0} \propto p \cdot \Delta f_s$** lines getting wider

  due to mom. spread $\Delta p / p_0$ &

  possible spread of synchrotron frequency Δf_s



Example for scaling of power:

If ***N* = *10*^{10}** *then* $P_{tot}(p = 0) \approx 100\text{dB} \cdot P_{tot}(p \neq 0)$

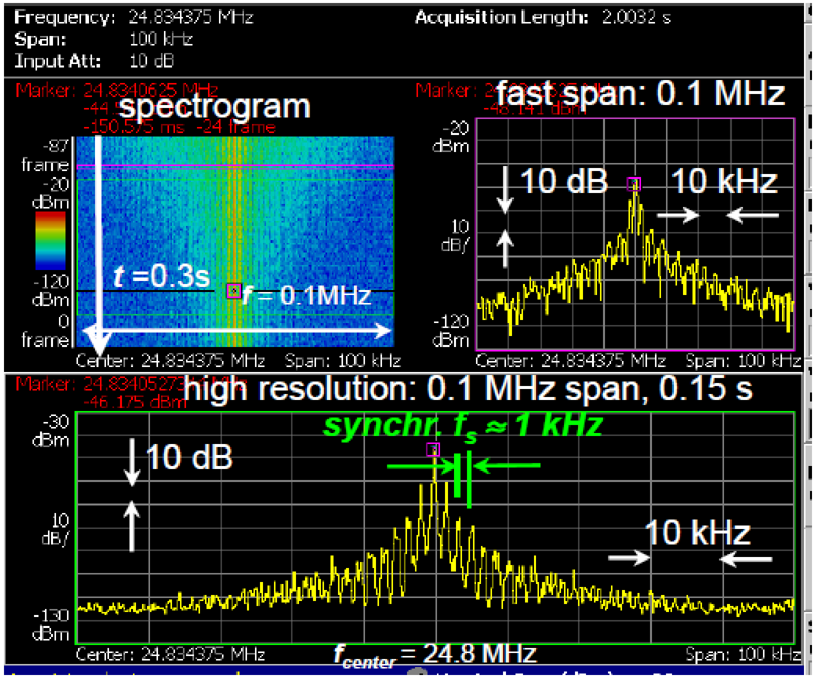
Remarks: The central peak is coherent $P_{tot}(p = 0) \propto N^2$

$\Rightarrow$ applying a **stringent** definition this is **not** a Schottky line

Example of longitudinal Schottky Analysis for a bunched Beam

Example: **Bunched** beam at GSI synchrotron

Beam: Injection E_{kin} = 11. 4 MeV/u harm. h = 120



Application for 'regular' beams:

- Determination of synchrotron frequency f_s
- Determination of momentum spread:
  - envelop does **not** represent directly coasting beam
    $\Rightarrow$ **not** directly usable for daily operation
  - but can be extracted with detailed analysis due to the theorem $\sum_{p=-\infty}^{\infty} J_p(x) = 1$ for all x
    $\Rightarrow$ for each band h: $\int P_{bunch} df = \int P_{coasting} df$

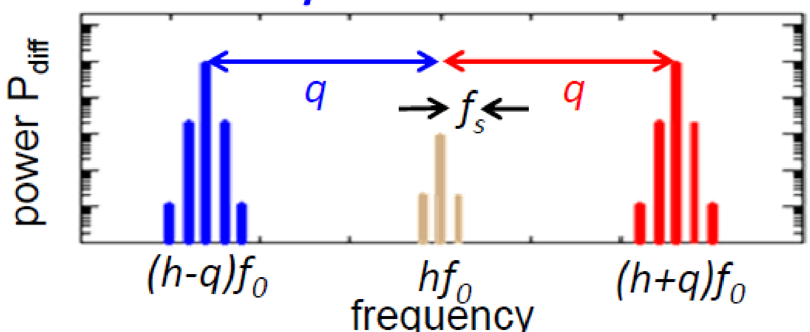
Application for intense beams:

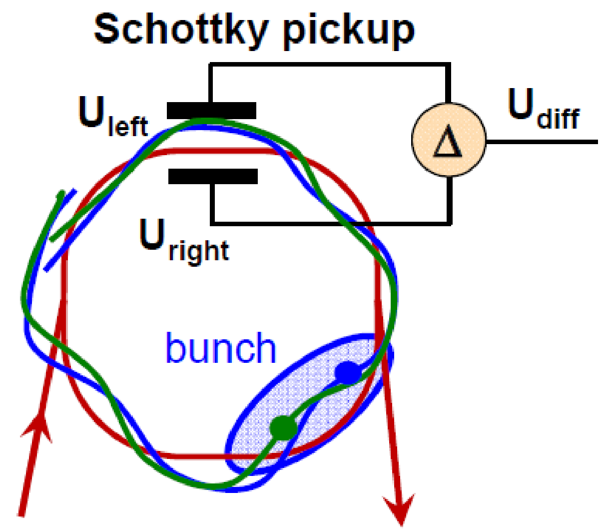
- The sidebands reflect the distribution $P(f_s)$ of the synchrotron freq. due to their incoherent nature
  see e.g. E. Shaposhnikova et al., HB'10, p. 363 (2010) & PAC'09, p. 3531 (2009), V. Balbecov et al., EPAC'04, p. 791 (2004)
- However, the spectrum is significantly deformed amplitude $\hat{\tau}_s$ dependent synchrotron freq. $f_s(\hat{\tau}_s)$
  see e.g. O. Boine-Frankenheim, V. Kornilov., Phys. Rev. AB 12. 114201 (2009)

Transverse Schottky Analysis for bunched Beams

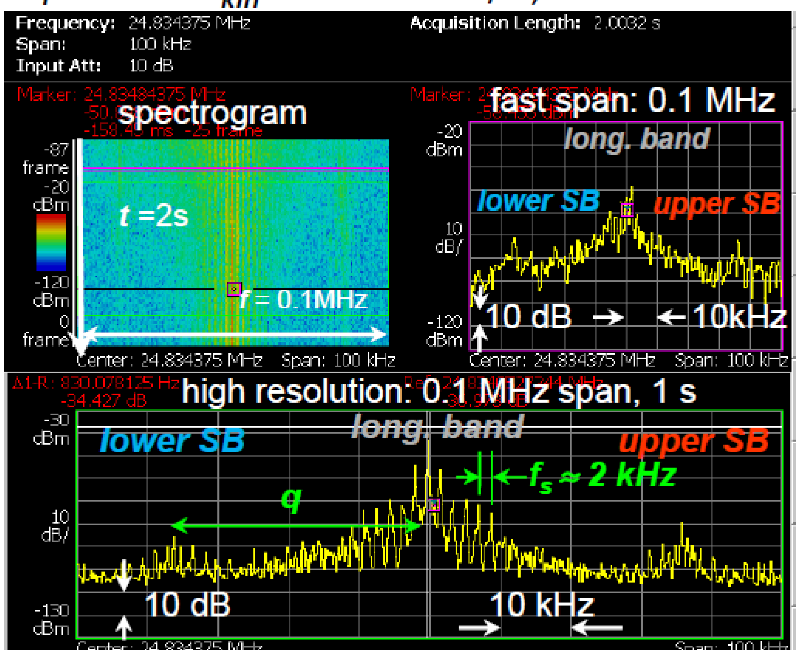
Transverse Schottky signals are understood as

- ➢ **amplitude modulation of the longitudinal signal**
- ➢ ***convolution by transverse sideband***





Example: GSI $\boldsymbol{E_{kin}}$ = 11.4 MeV/u, harmonics $\boldsymbol{h}$ = 119



Structure of spectrum:

- ➢ **Longitudinal** peak with synchrotron SB
  - central peak $P_0 \propto N^2$ called coherent
  - sidebands $P_p \propto N$ called incoherent
- ➢ **Transverse** peaks comprises of
  - replication of coherent long. structure
  - incoherent base might be visible

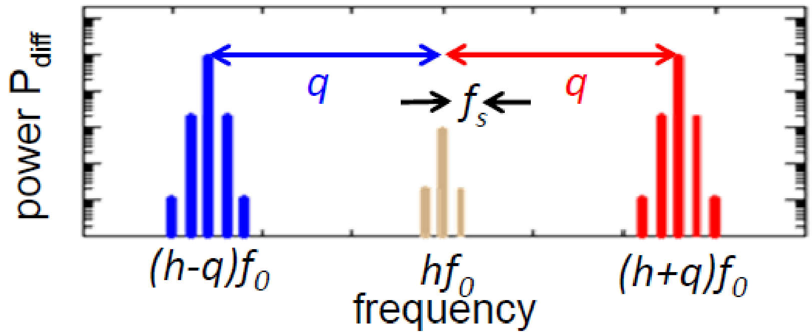
Remark: Spectrum can be described by lengthy formula see e.g. S. Chattopadhay, CERN 84-11 (1984)

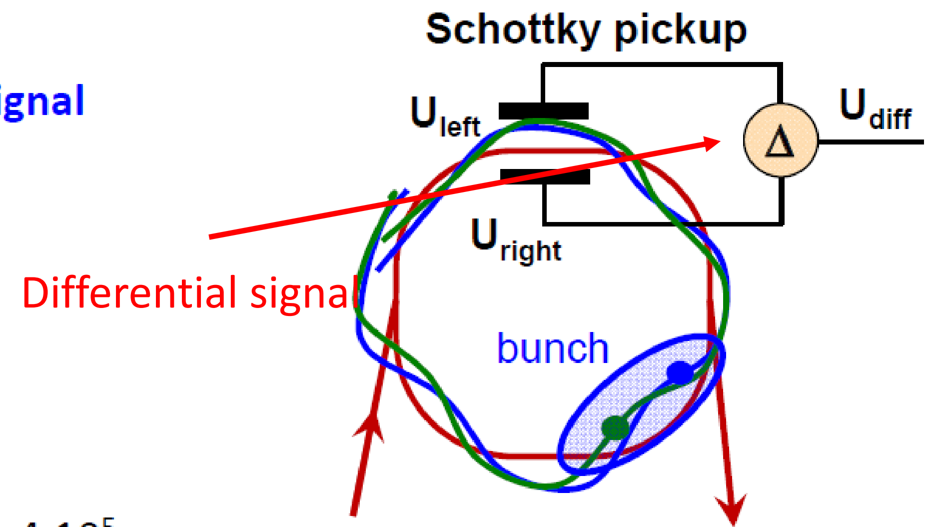
Remark: Height of long. band depends geometrical center of the beam in the pick-up

Transverse Schottky Analysis for bunched Beams

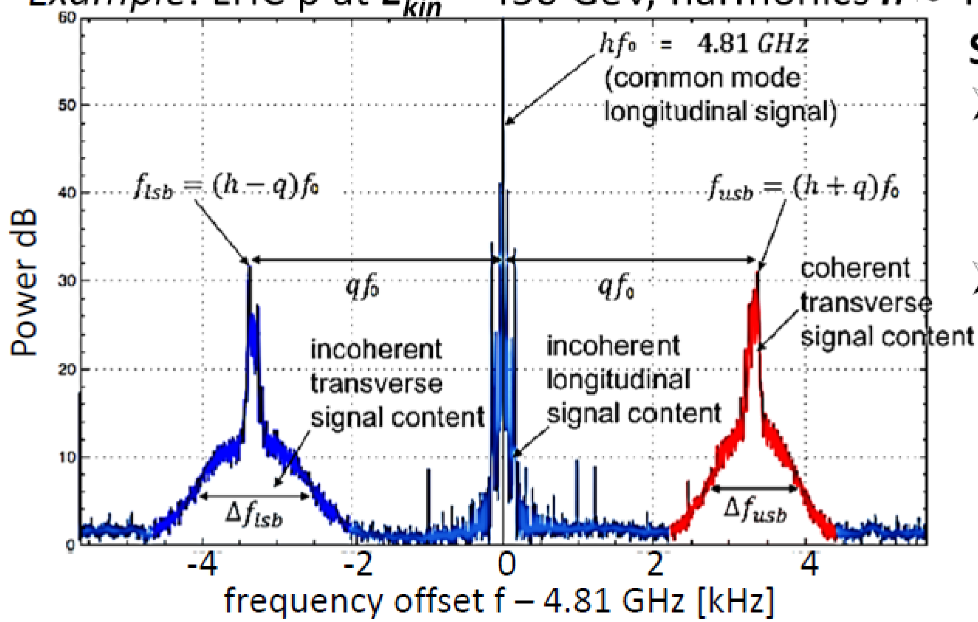
Transverse Schottky signals are understood as

- **amplitude modulation of the longitudinal signal**
- ***convolution by transverse sideband***





Example: LHC p at E_{kin} = 450 GeV, harmonics $h \approx 4 \cdot 10^5$



Structure of spectrum (LHC f_s < 150 Hz):

- **Longitudinal** peak with synchrotron SB
  - central peak $P_0 \propto N^2$ called coherent
  - sidebands $P_p \propto N$ called incoherent
- **Transverse** peaks comprises of
  - replication of coherent long. structure
  - incoherent base
    dominated by chromatic tune spread

$$\boxed{\Delta f_h^{\pm} = \eta \frac{\Delta p}{p_0} \cdot f_0 \left(h \pm q \pm \frac{\xi}{\eta} Q_0 \right)}$$

M. Wendt et al. IBIC'16, p. 453 (2016), M. Betz et al., NIMA submitted

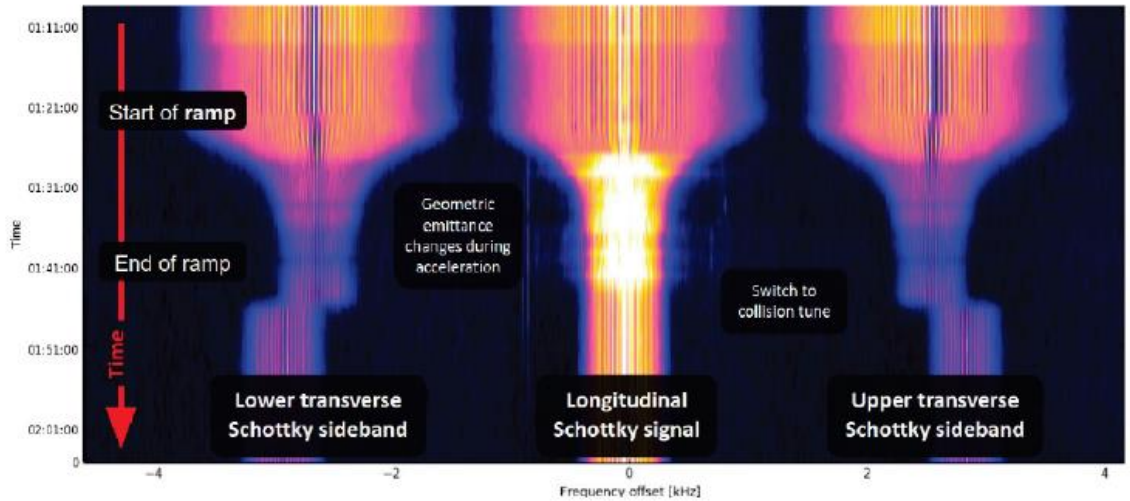
Transverse Schottky Analysis for bunched Beams at LHC

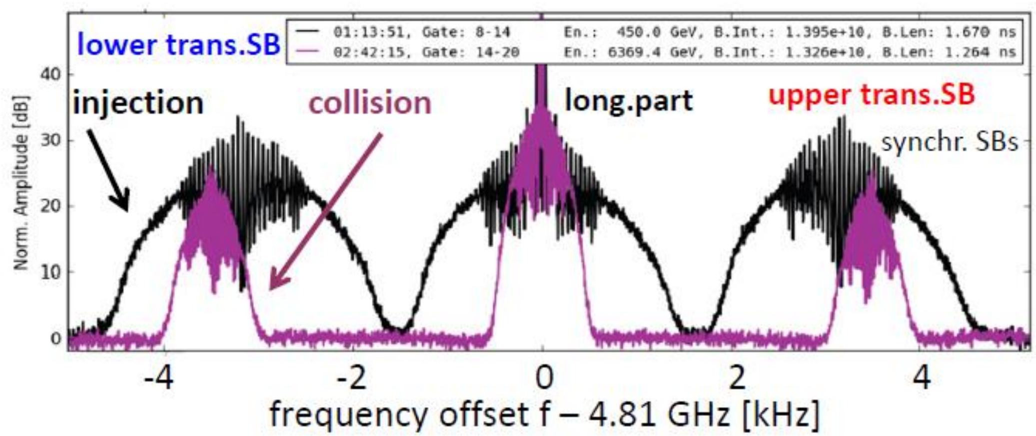
Schottky spectrogram during LHC ramp and collision:

The interesting information is in the ***in****coherent part of the spectrum (i.e. like for coasting beams)*

- **Longitudinal part**
  - ***Width:*** → momentum spread
    momentum spread decreases
- **Transverse part**
  - **Center:** → tune
    shift for collision setting
  - **Width**: → chromaticity
    difference of lower & upper SB
  - **Integral** : → emittance
    reduction of geometric emittance

Example: LHC nominal filling with Pb^{82+}
→ acceleration & collisional optics within ≈ 50 min





M. Betz et al. IPAC'16, p. 226 (2016)

Deficiencies of obtained experimental data (2017/2018):

Ion BPM signal data:

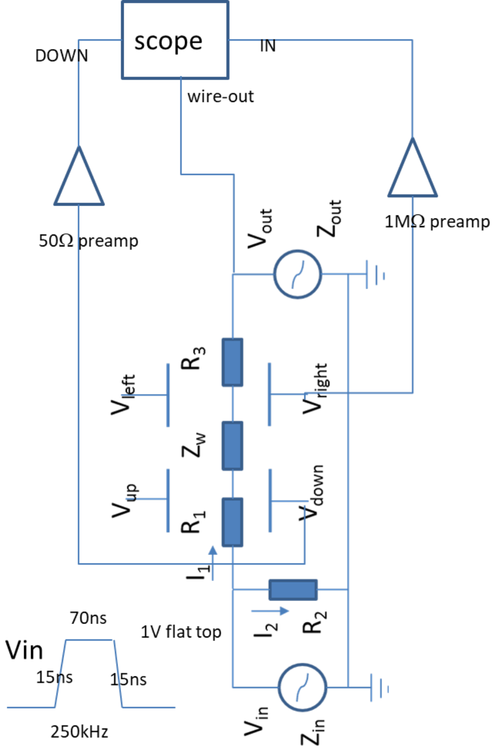
- From shoe-box type at CSRm with 50Ω input imp. Preamp. fcut~7.7MHz, so the BPM signal is a differential signal of ion pulse shape in 2017. Signal voltage integration includes noise buildup (with slope) After the slope correction, the signal at the pulse ends generated unphysical dips. The pulse distortion could be due to the external circuit capacitance or amp/cable mismatch
- Rebuild a new show-box BPM. Use 1MΩ preamps, so fcut drops to ~386Hz
- Did the bench RF measurement for the beam-to-signal transfer function by the wire-stretching technique
- No differential bunch signal anymore in 2018, but high Impedance amplifiers seem saturated at high beam signal

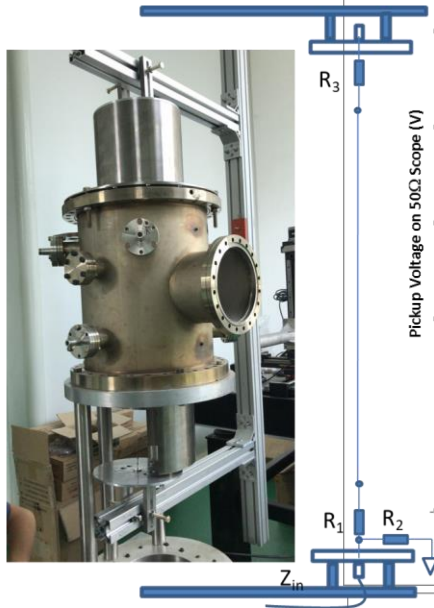
Schottky signal data:

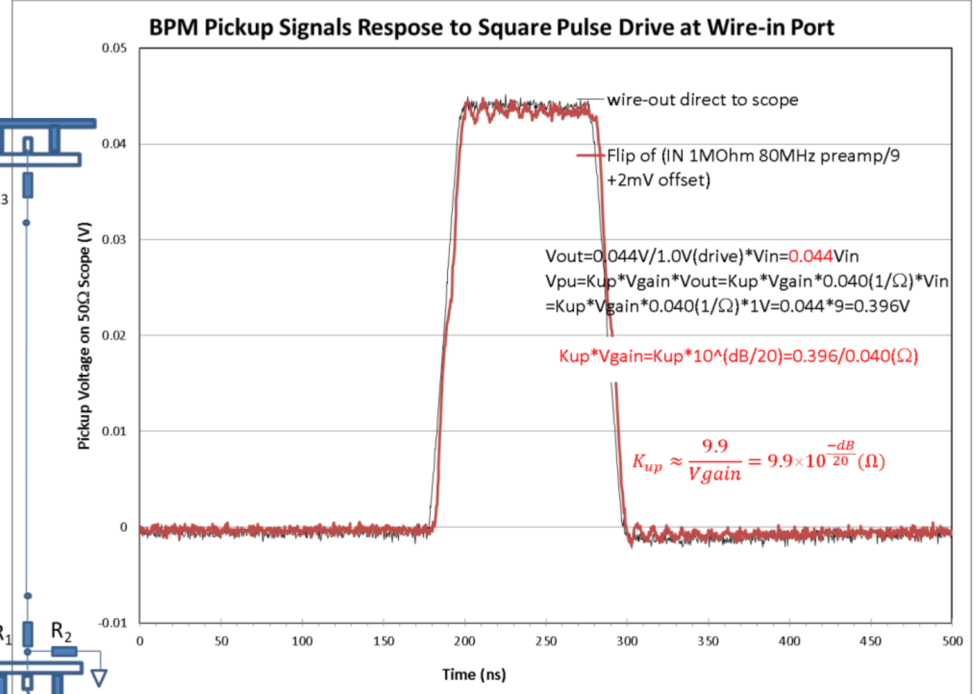
- 2017 Used RSA5100A (RSA385A) spectrum analyzer. IQ data obtained had a low sampling rate 48.8kS/s
- 2017 RBW=100Hz, spectrum resolution is limited to ~32Hz only even with a CFFT/ICFFT HPF/LPF reprocessing
- Build new Schottky device in 2018
- Use 50Ω amplifiers
- Uses R&S Spectrum Analyzer with .wvd data downloaded
- Too wide BW setup for the U/D sidebands recording

IPM signal data:

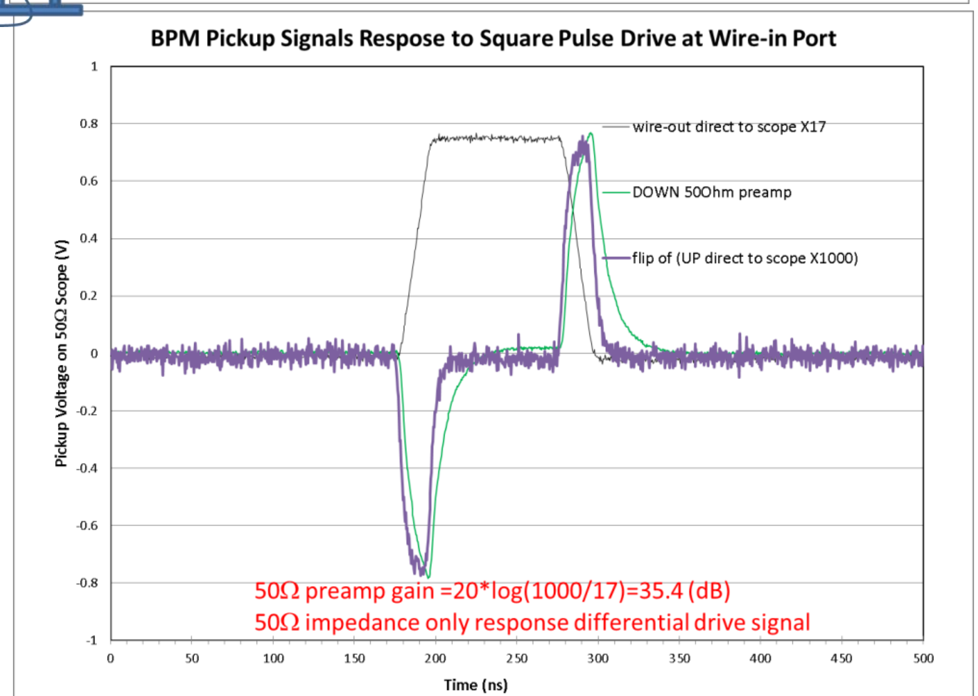
- Too slow data recording due to ionization
- Possible amplifier saturation



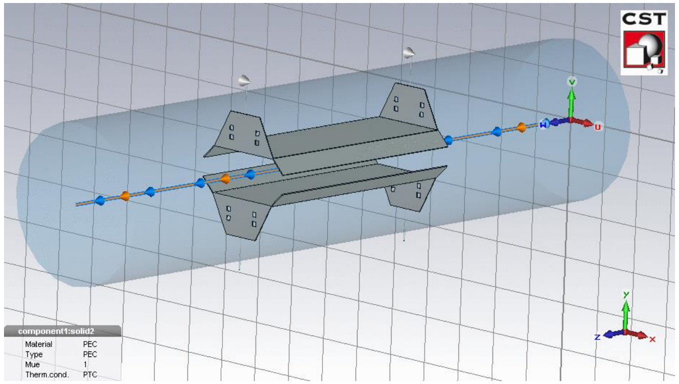


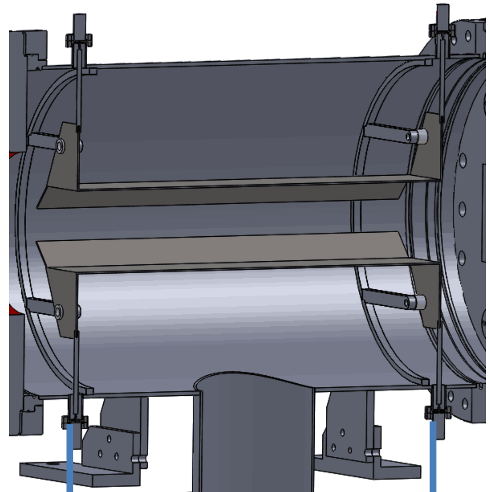


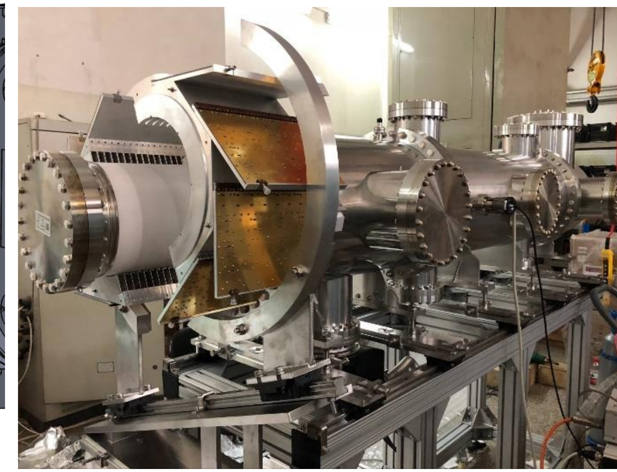
Vin=1V, 15ns rise/fall, 70ns flat top, 250kHz

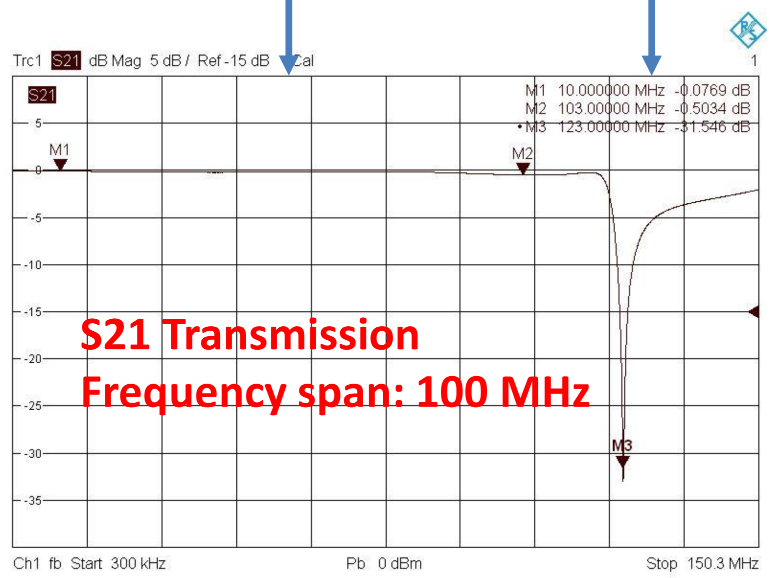


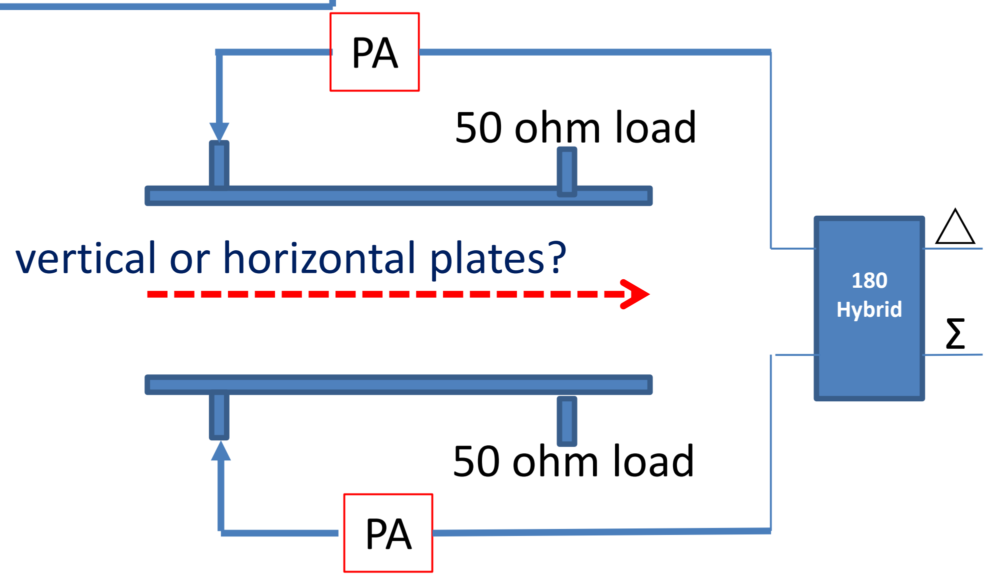
New Capacitive Pickup of Schottky Device





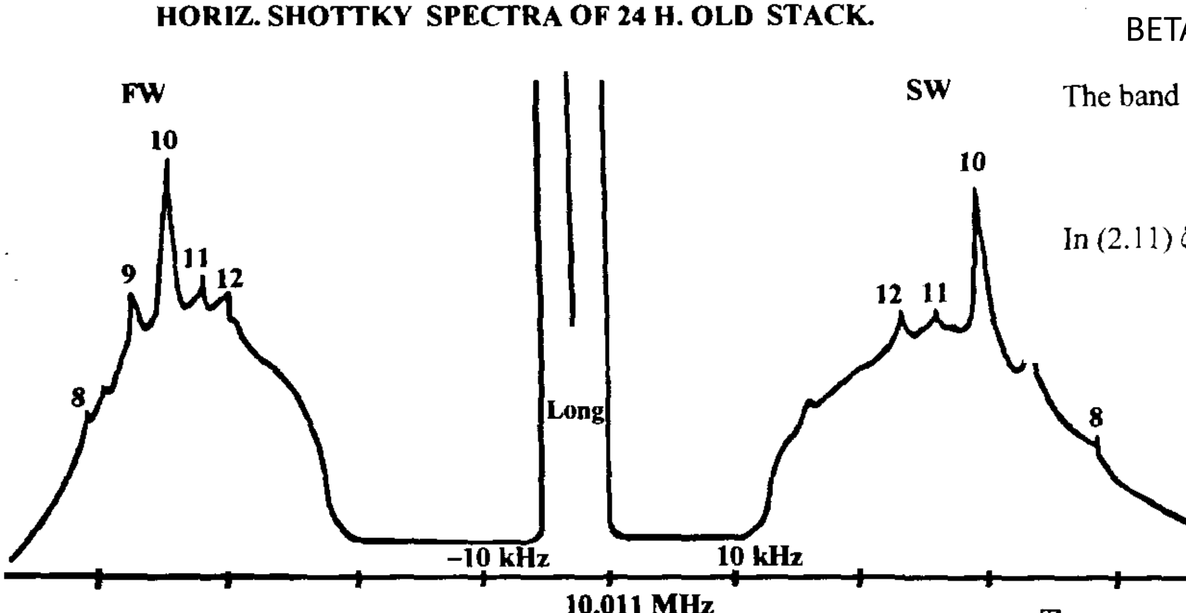






Homework on Challenges of Transverse Schottky Signals

D.Dinev, E9-2001-144
BETATRON TUNE MEASUREMENT



The band width is determined by:

$$\Delta f = f_0 \frac{\Delta p}{p}((n \pm q)\eta \pm Q\xi)$$

In (2.11) ζ denotes chromaticity which is defined trough:

$$\Delta q = \xi Q \frac{\Delta p}{p}$$

$$d_{rms} = e f_0 a_{rms} \sqrt{\frac{N}{2}}$$

Table 4
Lattice parameters of CSRm

Transition gamma	$\gamma_{tr} = 5.168$
Betatron tune values	$Q_x/Q_y = 2.63/2.61$
Natural chromaticity	$Q'_x/Q'_y = -3.05/-5.34$
Max. β-amplitude	$\beta_x/\beta_y = 10.4/17.5$ m (dipole)
	$\beta_x/\beta_y = 13.5/32.2$ m (quadruple)
Max. dispersion	$D_{max}(x) = 3.2$ m (dipole, $\beta_x = 10.4$ m)
	$D_{max}(x) = 4.6$ m (Quadruple, $\beta_x = 8.0$ m)
Injection section	$\beta_x = 10.0$ m, $D_x = 4.0$ m (septum)
	$\beta_x = 11.9$ m, $D_x = 3.9$ m (quadruple)
e-Cooler section	$\beta_x/\beta_y = 10.0/17.0$ m, $D_x = 0$
RF station section	$\beta_x/\beta_y = 10.0/6.4$ m, $D_x = 4.0$

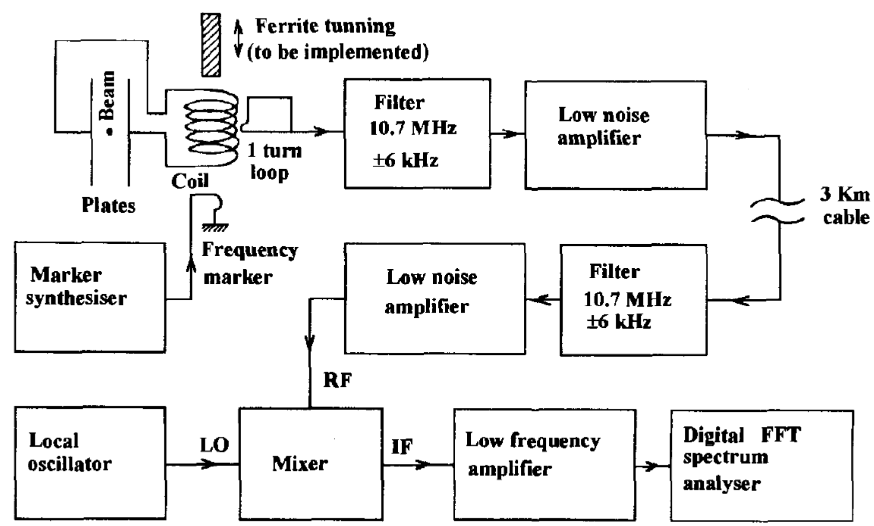


Figure 13. Block diagram of the electronic system of the CERN Schottky receiver - [10].

LHC 4.8 GHz Schottky: Electronics for triple Down Conversion

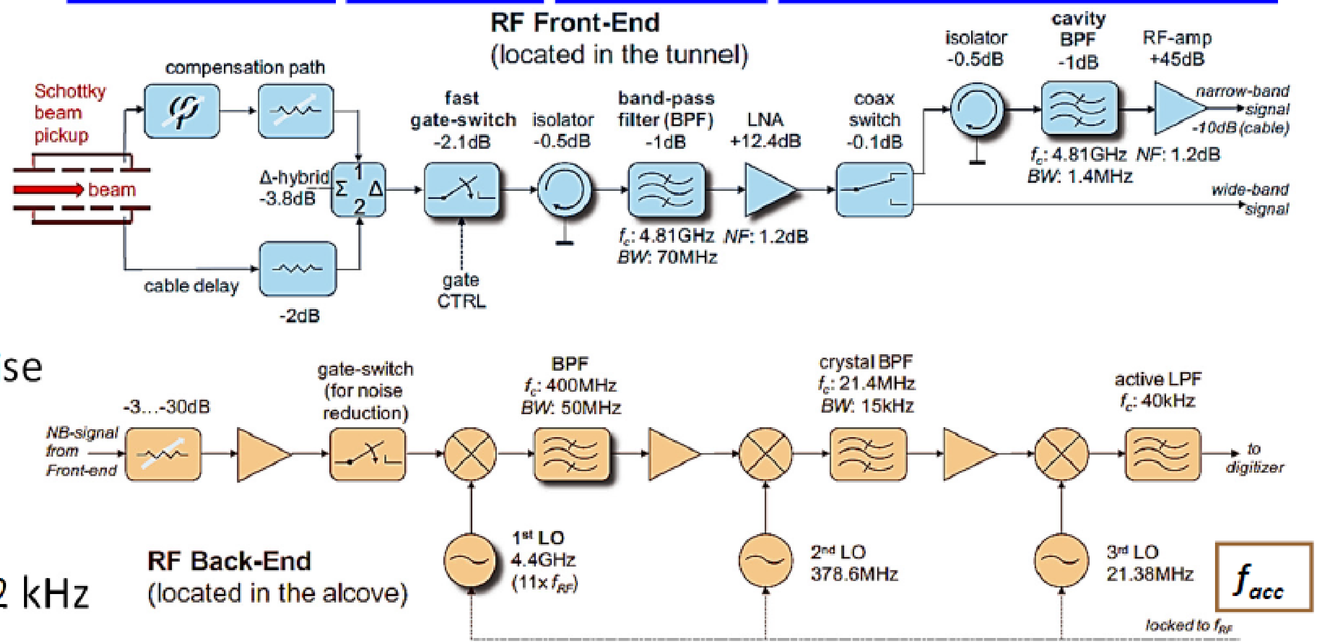
Challenge for bunched beam Schottky:
Suppression of broadband sum signal to prevent for saturation of electronics

Design considerations:

- Careful matching
- Switching
  during bunch passage
  switching time ≈ 1 ns
  ⇒ one bunch per turn
- Filtering of low signals
  without deformation
  to increase signal-to-noise
- Down-mixing
  locked to acc. rf
- ADC sampling with $4 \cdot f_0$
  revolution freq. f_0 = 11.2 kHz

Requirements: low noise & large dynamic range

matching part remote contr. | bunch switching | filter to f_c large BW | ampl. & filter to f_c small BW broadband part for check



matching part | mixing to 400 MHz | mixing to 21.4 MHz | mixing to 40 kHz | ADC $f_{sample}=4f_0$

M. Wendt et al. IBIC'16, p. 453 (2016), & M. Betz et al., NIM A submitted

Sweeping delay time A between electron and ion bunches with a frequency of synchrotron?

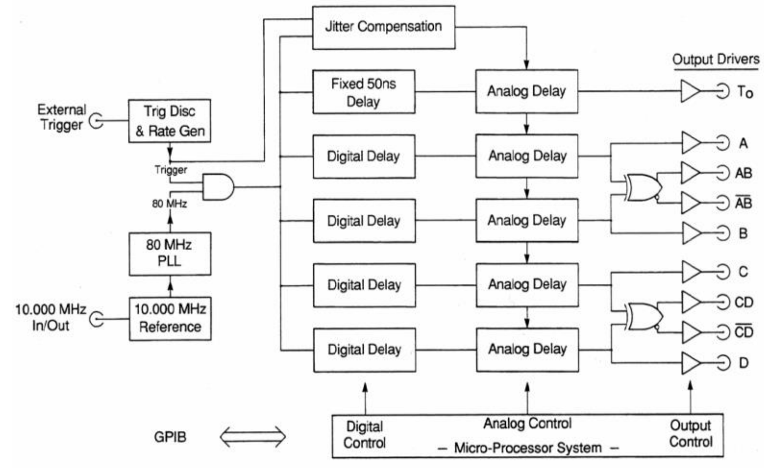


Figure - 6 DG535 Block Diagram

Need new Labview programming

DELAYS

DT i{,j,t}
Delay Time of channel i is set to t seconds relative to channel j. Example: DT 3,2,1.2E-6 will set B=A+0.000,001,200,000 seconds. The command DT 2,1,10.5 will set A=T0+10.500000000000 seconds. Setting delays shorter than 0 or longer than 999.999,999,999,995 seconds will set bit 2 of the Error Status Byte.

An efficient method to change a delay is to position the cursor under a digit (using the SC command) and then increment/decrement the digit (using the IC command).

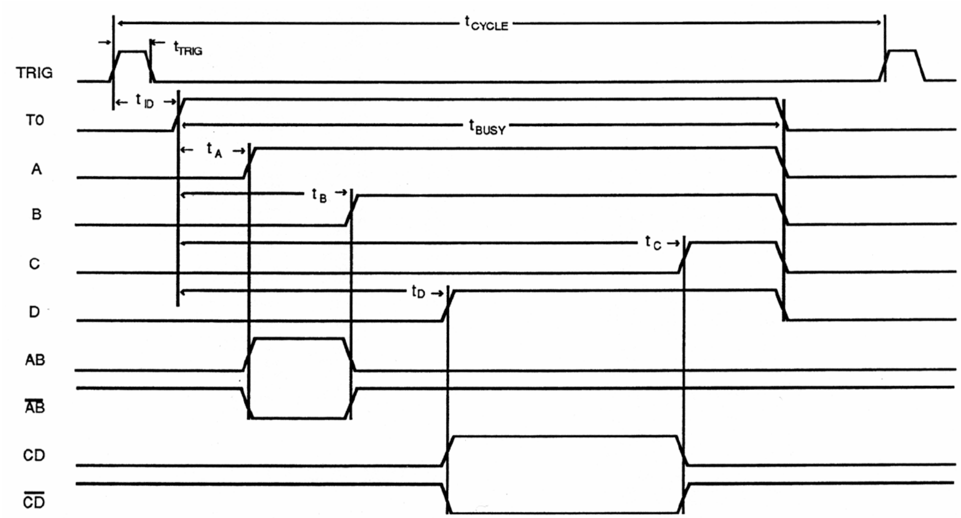
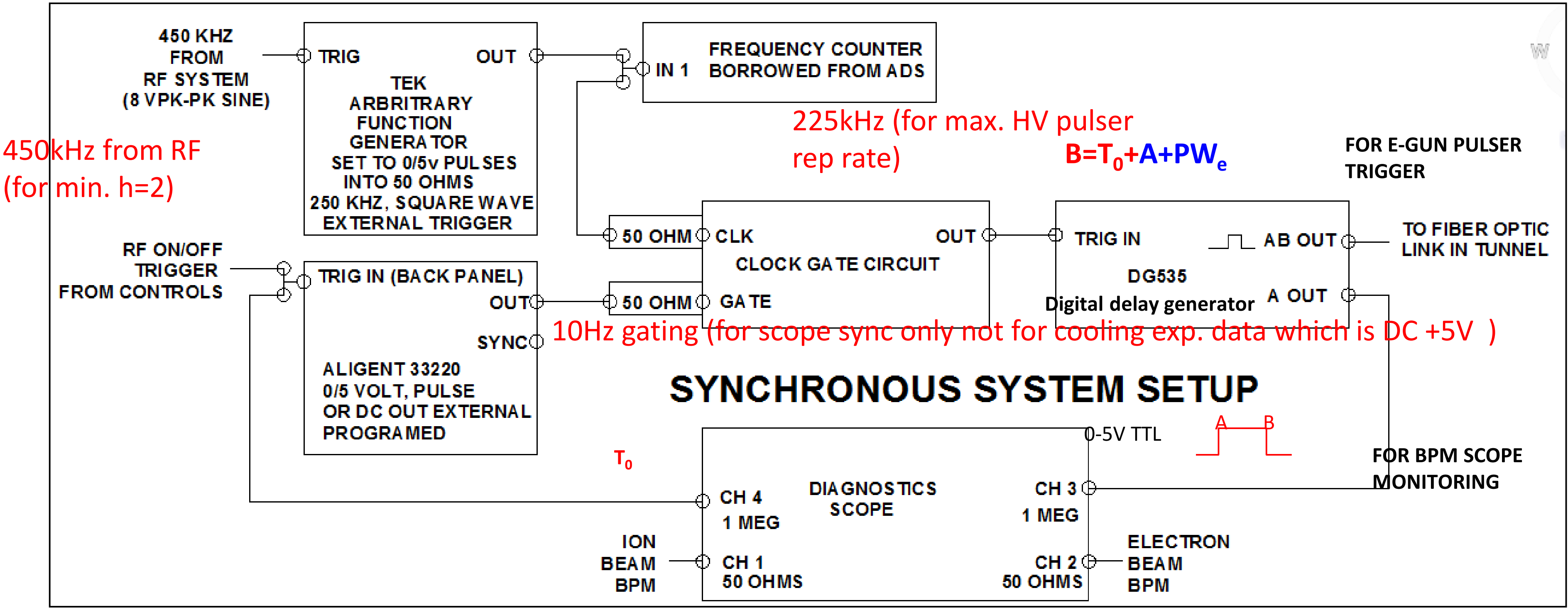


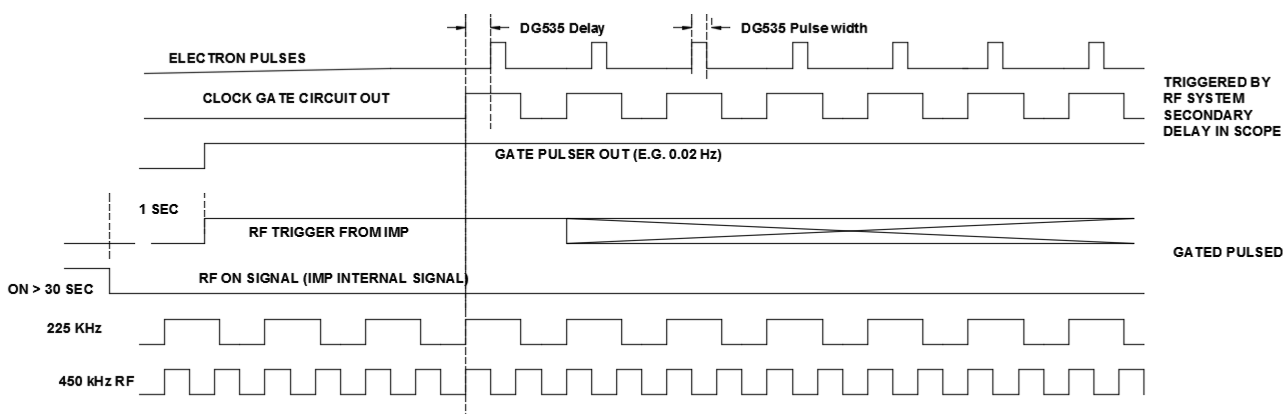
Figure - 7 DG535 Timing Diagram

IMP Pulsed E-Cooling Triggering Setup – Tom Powers, May 21, 2016

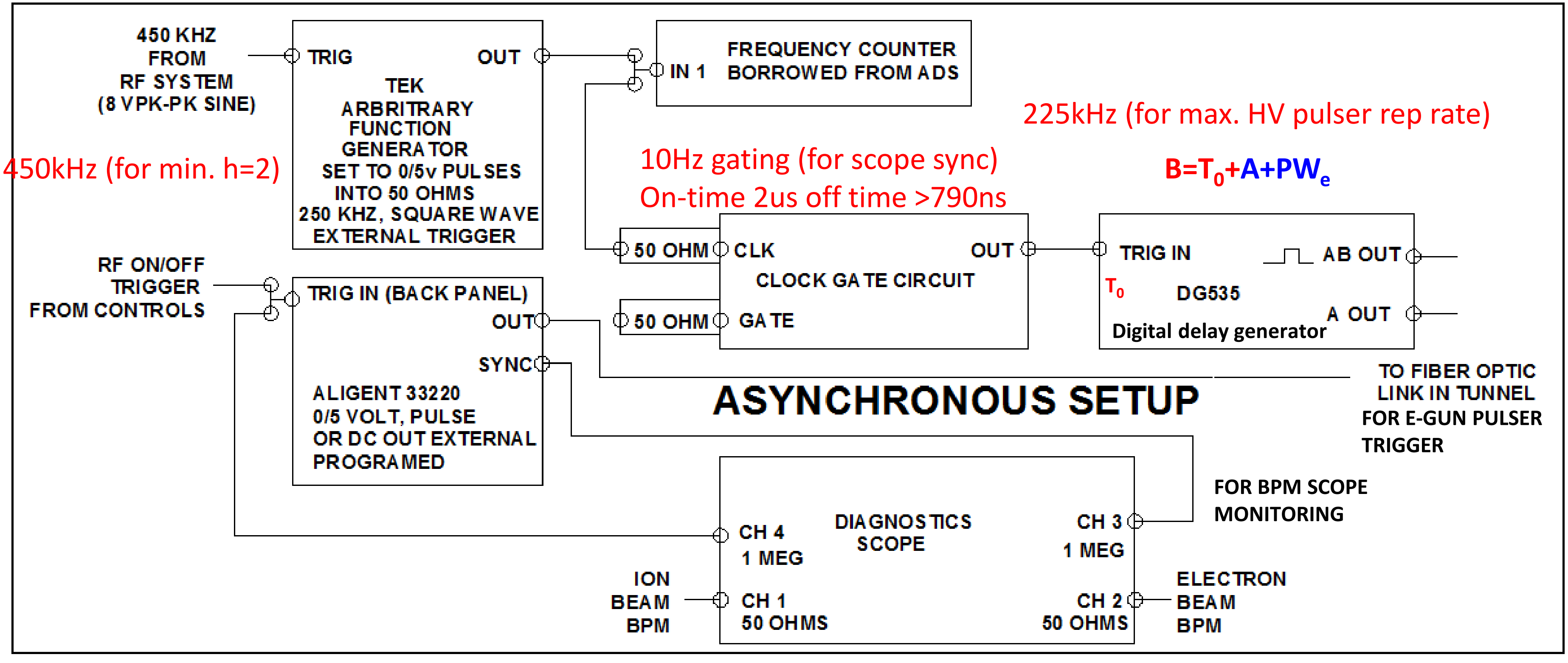


RF ON + wait (1sec) +T_0 (scope delay) on the traces of Labview data

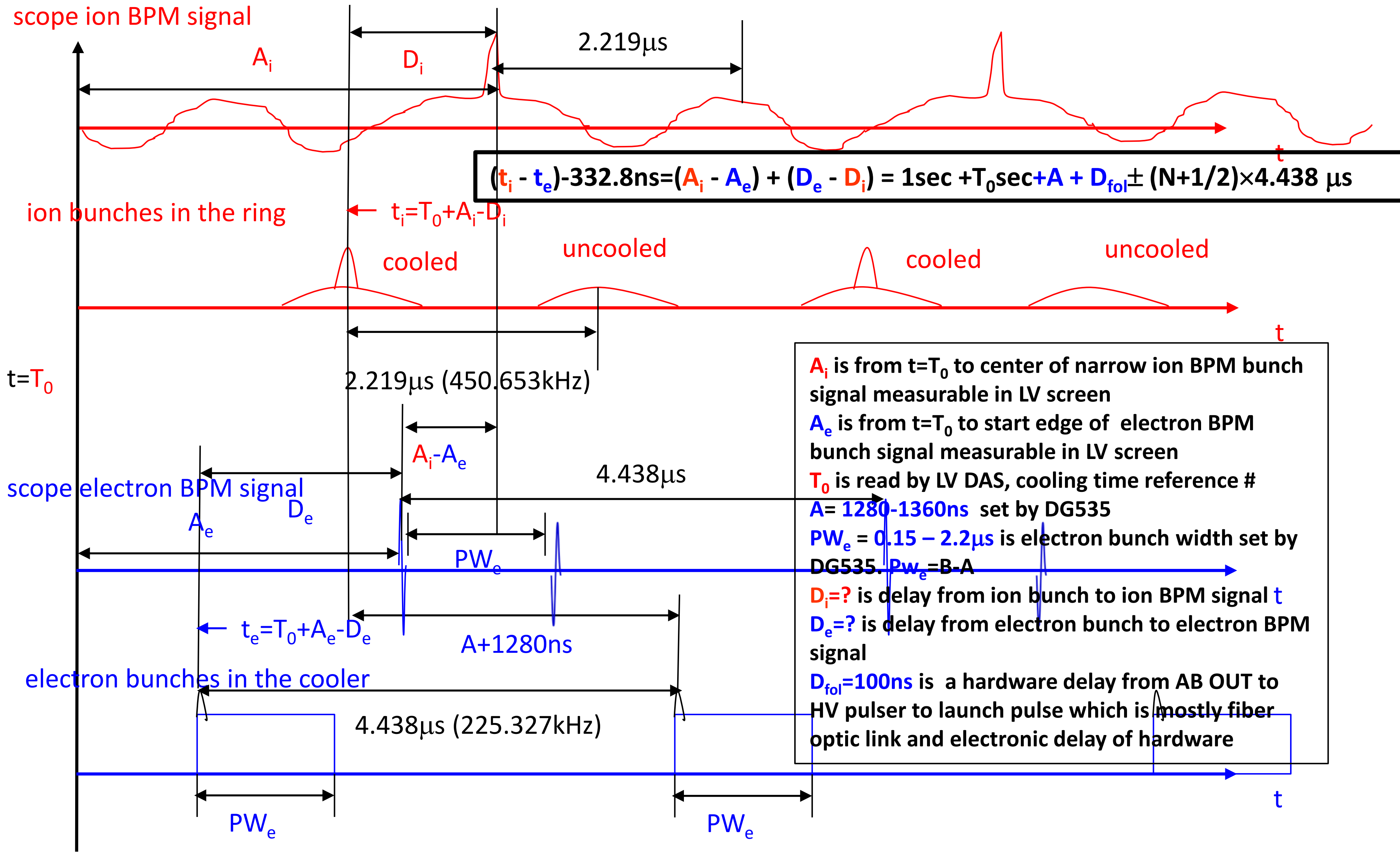
A=1280-1360ns is from T0 to AB OUT front edge



IMP Pulsed E-Cooling Triggering Setup, May 22, 2016



BPM Measurement Delay and Triggering and Display on LabView DAS



$$(t_i - t_e) - 332.8\text{ns} = (A_i - A_e) + (D_e - D_i) = 1\text{sec} + T_0\text{sec} + A + D_{fol} \pm (N+1/2)\times 4.438\ \mu s$$

A_i is from $t=T_0$ to center of narrow ion BPM bunch signal measurable in LV screen
A_e is from $t=T_0$ to start edge of electron BPM bunch signal measurable in LV screen
T_0 is read by LV DAS, cooling time reference #
A= 1280-1360ns set by DG535
PW_e = 0.15 – 2.2μs is electron bunch width set by DG535. Pw_e=B-A
D_i=? is delay from ion bunch to ion BPM signal t
D_e=? is delay from electron bunch to electron BPM signal
D_{fol}=100ns is a hardware delay from AB OUT to HV pulser to launch pulse which is mostly fiber optic link and electronic delay of hardware

BPM Measurement Delay and Triggering and Display on LabView DAS

$$(t_i - t_e) - 332.8\text{ns} = (A_i - A_e) + (D_e - D_i) = 1\text{sec} + T_0\text{sec} + A + D_{fol} \pm (N+1/2)\times 4.438\ \mu\text{s}$$

A_i is from $t=T_0$ to center of narrow ion BPM bunch signal measurable in LV screen

A_e is from $t=T_0$ to start edge of electron BPM bunch signal measurable in LV screen

T_0 is read by LV DAS, cooling time reference #

A= 1280-1360ns set by DG535

PW_e = 0.15 – 2.2μs is electron bunch width set by DG535. Pw_e=B-A

D_i=? is delay from ion bunch to ion BPM signal

D_e=? is delay from electron bunch to electron BPM signal

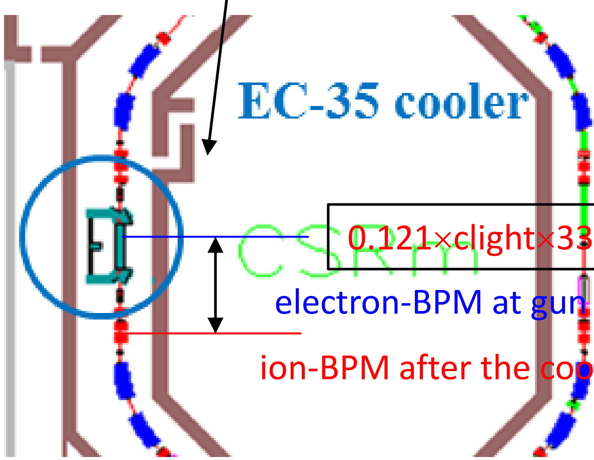
D_{fol}=? is a hardware delay from AB OUT to HV pulser to launch pulse which is mostly fiber optic link and electronic delay of hardware

$$(t_i - t_e) = \frac{PW_e}{2} \quad \text{or}$$

$$A_i - A_e = \frac{PW_e}{2} - 332.8ns - (D_e - D_i)$$

when electron bunch center aligns with ion bunch center

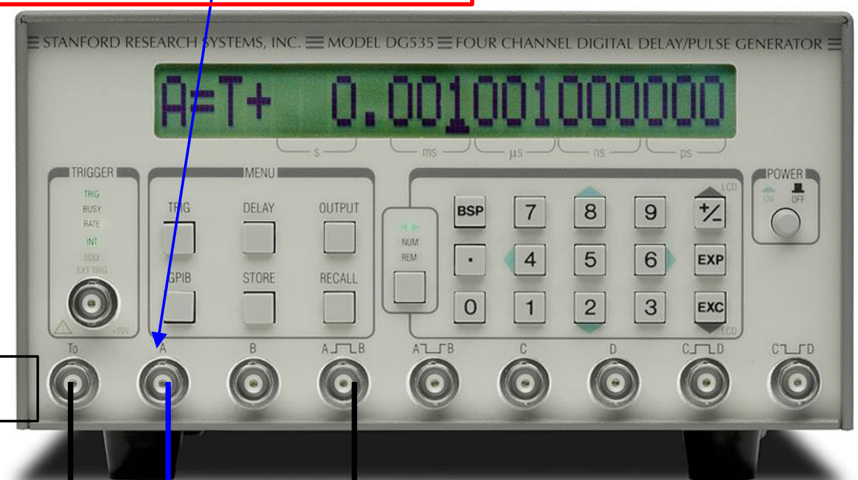
A is the delay (1280-1360) ns set up by DG535 from AB OUT (front edge) to the HV pulser to fire the electron bunch front edge



0.121×clight×332.8ns=12.072m

electron-BPM at gun position

ion-BPM after the cooler position



T_0 A AB OUT

Summary:

1. Bunched electron beam cooling 12C+6 ion beam at 7MeV/u in 2017 and 85Kr25+ at 5MeV/u in 2018 have 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
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, IPM and Schottky signals strongly support these evidences but obtained data so far lacks of calibrations and possible amplifier signal saturation which had affected measurement accuracies for a further quantitatively benchmark for the JESPEC simulation codes and better quality of publication.
6. Beam instrumentation improvement both in hardware and software has been carried out since 2018 experiment but missed JLab team to cross-check the data quality so as we missed the Schottky signal spectrum resolution. Big challenge to transverse Schottky signal processing (down converting) on bunched ion beam.
7. Balance core and tail cooling rates to reduce the double Gaussian distributions on the bunched beam cooling is an ultimate goal of next experiment in Dec. 2019
8. Uncertainties of travel on beam schedule, visa application and DOE approval processes