Coherent electron Cooling Experiment - Physics

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ICFA Mini-Workshop CeC 2019

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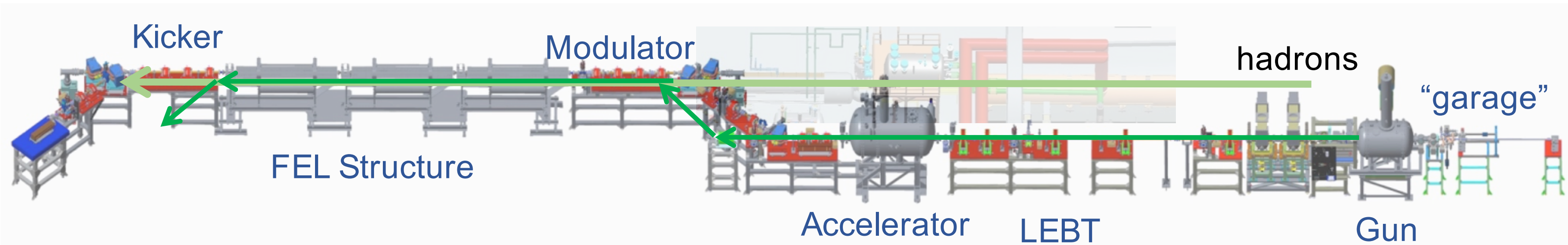
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Outline

- Project overview
- Accelerator performance
- Experiments with FEL-based system
- Run19 results
- Future plans
- Conclusions

Coherent Electron Cooling Proof-of-Principle Experiment



The goal of the experiment is to demonstrate longitudinal cooling of a single Au^{+79} bunch in the Relativistic Heavy Ion Collider.

The circulating hadron beam imprints its distribution on the electron bunch in the modulator section. The longitudinal charge modulation is amplified in the free-electron laser structure comprising three helical permanent magnet wigglers with a_w=0.5. The electrical field accelerates and/or decelerates hadrons in the kicker section.

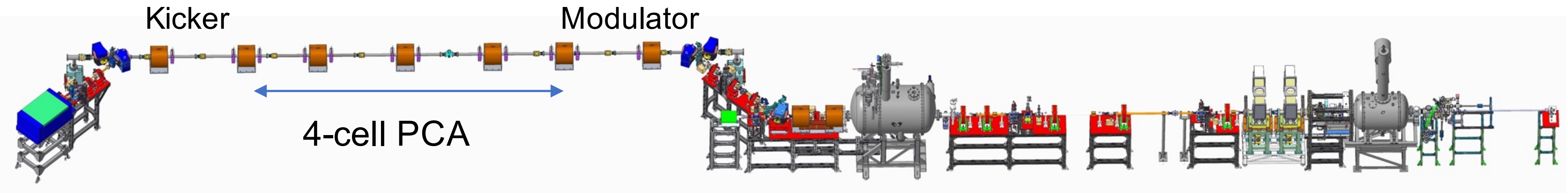
Required electron beam parameters

- Normalized emittance < 5 mm mrad
- Relative energy spread $\sigma_E/E < 10^{-3}$
- Bunch charge 500 pC – 1.5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10-50 psec
- Peak current > 75 A
- Kinetic energy 14.5 MeV
- IR FEL wavelength 30 microns

Hadron beam parameters

- Energy 27 GeV/u
- Intensity 10^9 hadrons/bunch (12 nC)
- R.m.s. bunch length 5 nsec
- Revolution frequency 78 kHz

PCA based CeC System

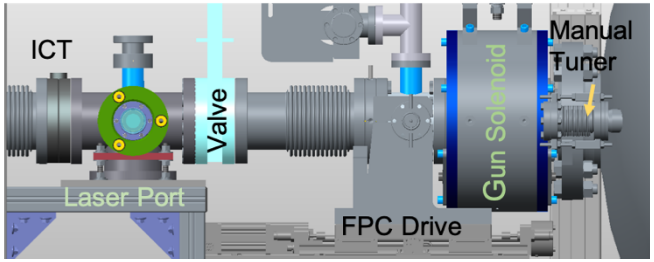


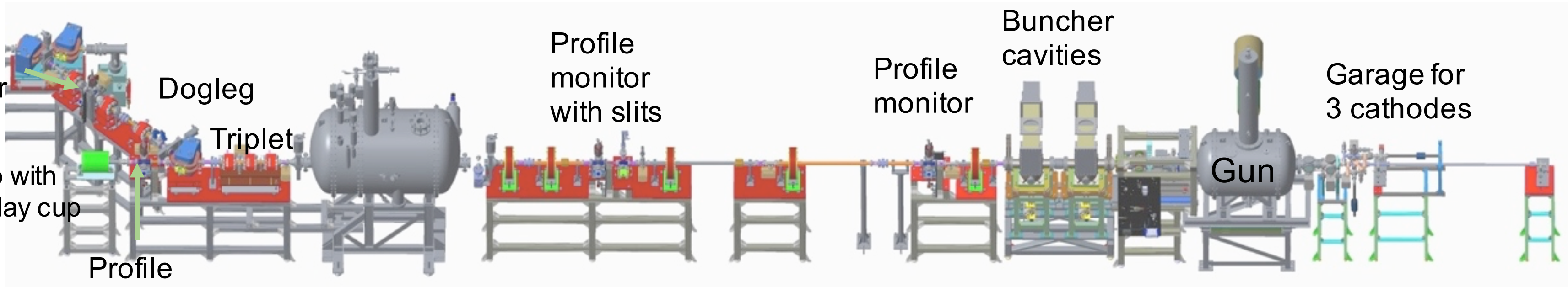
Required electron beam parameters

- Normalized emittance < 5 mm mrad
- Relative energy spread $\sigma_E/E < 10^{-3}$
- Bunch charge 0.5 – 1.5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10 – 25 psec
- Peak current 50-100 A
- Kinetic energy 14.5 MeV

- Mechanical design of new CeC system is completed
- We procured and commissioned new laser system with controllable pulse structure
- All new vacuum chambers with beam diagnostics are built
- All supports are built and installed
- All solenoids are designed, manufactured, delivered and undergo magnetic measurements
- Assembly of the plasma-cascade based CeC can be completed during this year's RHIC shut-down

Accelerator System





- 113 MHz SRF gun with CsK_2Sb photocathode. Cathode operation – weeks.
- 532 nm drive laser
- Two 500 MHz copper cavities for ballistic compression to the required peak current
- 704 MHz SRF accelerator cavity
- FEL structure with three helical undulators and three phase shifters
- 6 solenoids, 16 quadrupoles, and three dipoles

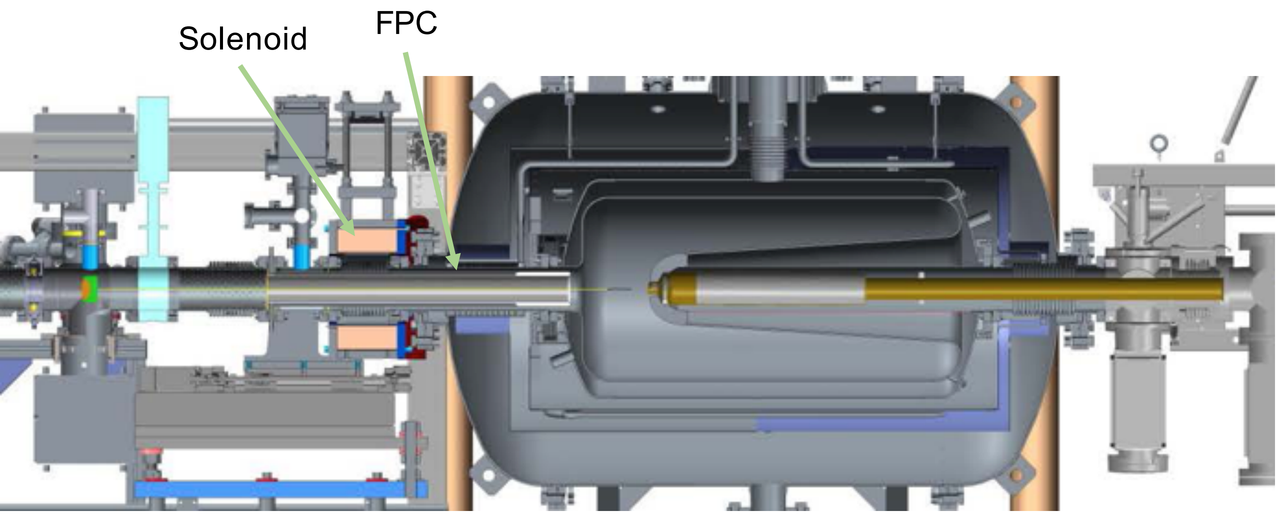
Demonstrated electron beam parameters

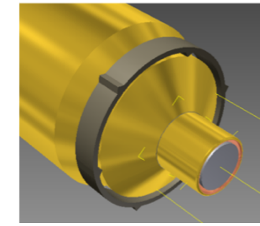
- Normalized emittance 3 – 4 mm mrad
- Relative energy spread $\sigma_E/E < 3 \times 10^{-4}$
- Bunch charge 0.03 – 10.7 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10 – 500 psec
- Kinetic energy 14.5 MeV

Challenges

- Gun axis is tilted by 11.1±0.1 mrad
- Buncher cavities generate time-dependent transvers kick
- Linac axis is 3 mm lower than median plane

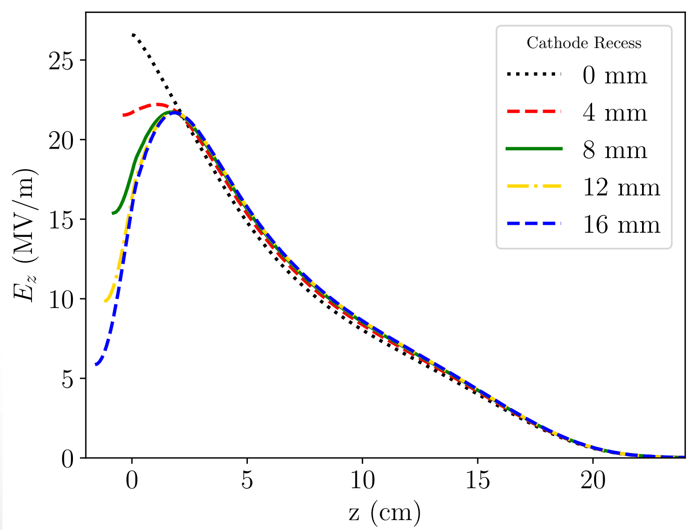
113 MHz RF Gun

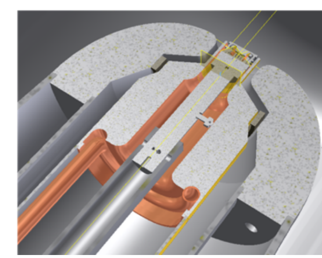




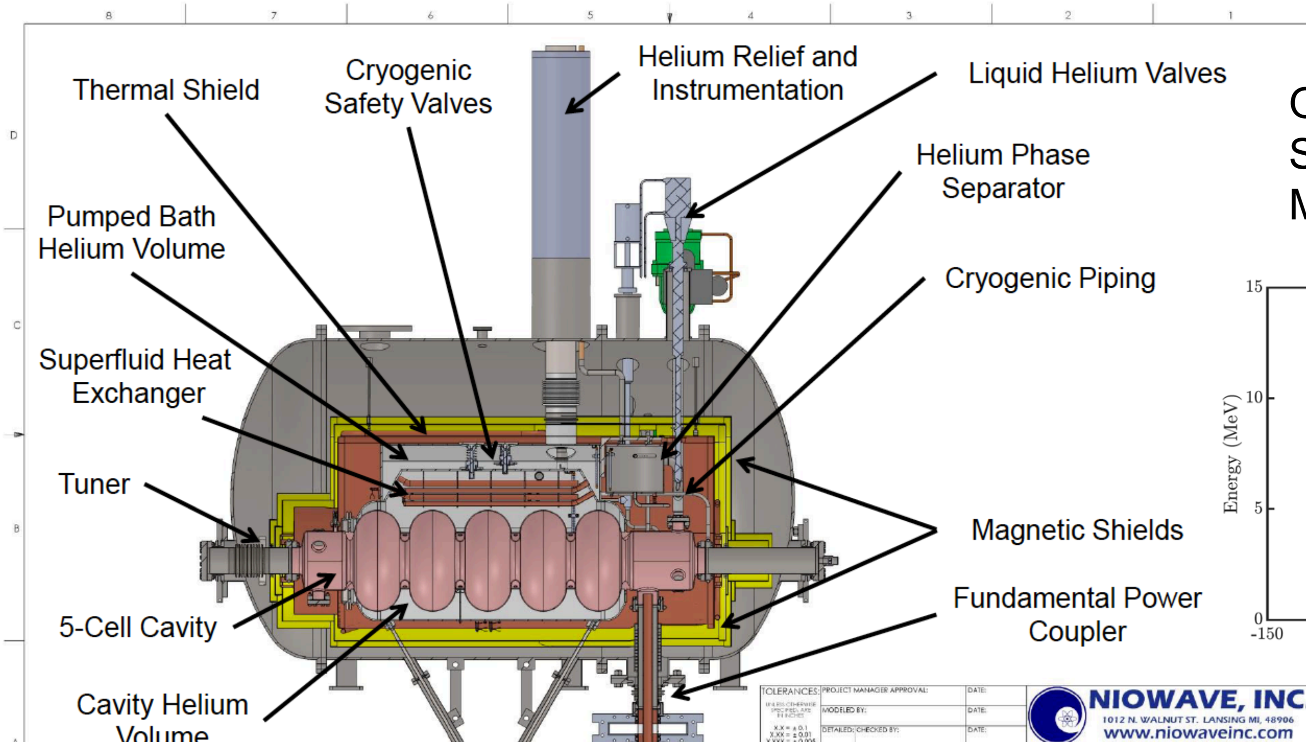
Challenges
- Strong multipacting barrier at 30-40 kV
- Dependence of the cavity frequency on coupling
- Location of the cathode puck vs nose is not fixed

- Quarter wave design
- Operates at 4.2ºK
- Cathode is at room temperature
- Stalk serves as field pick-up
- Manual coarse tuners
- FPC serves as fine tuner
- Maximal CW voltage 1.25 MV
- Maximal charge 10.7 nC

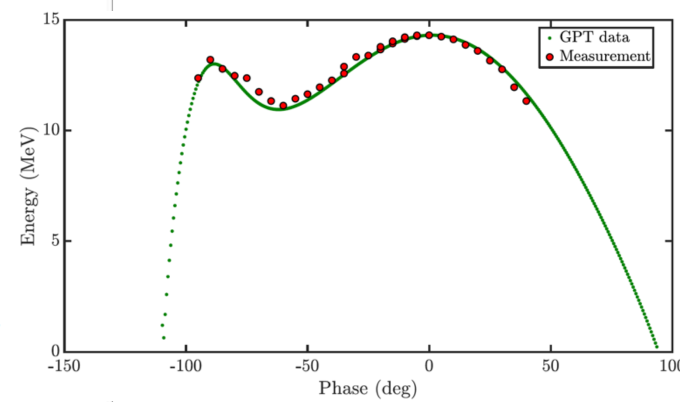


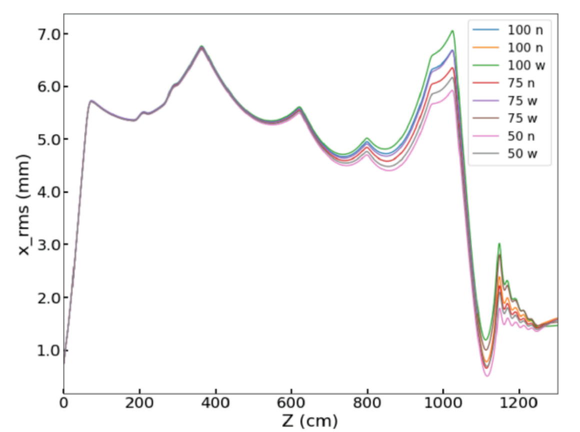


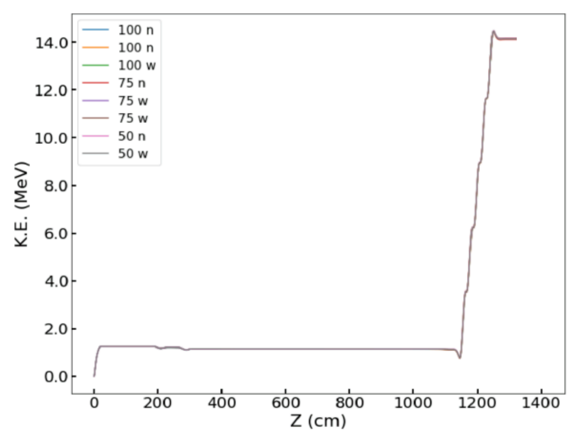
704 MHz SRF Linac



Operation temperature 2 ºK
Superfluid head exchanger
Maximal voltage – 13.5 MV

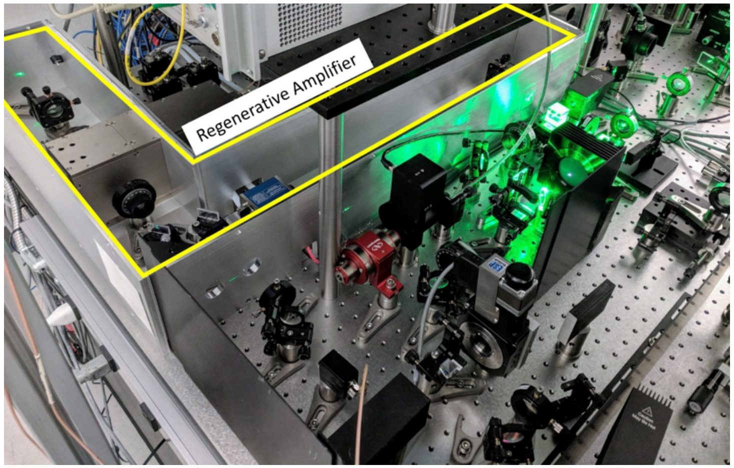


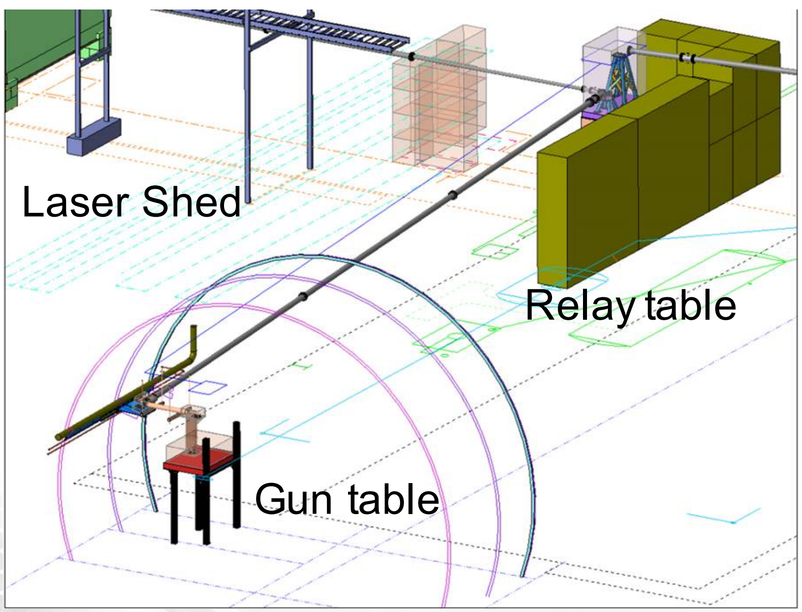




Very complicated beam dynamics in the first cell – beam is decelerated and strongly focused

Drive Laser





The seed laser with tunable longitudinal profile provides the input for the regenerative amplifier.

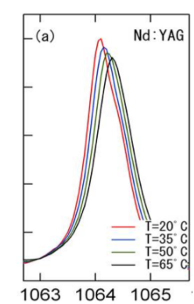
The regenerative amplifier has successfully suppressed the accumulation of nonlinear effects that caused the distortion of the temporal pulse profile which is crucial for CeC operations. In addition, the power fluctuations of the seed laser have been significantly mitigated.

The resulting excess power produced by the amplifier offers two additional advantages:

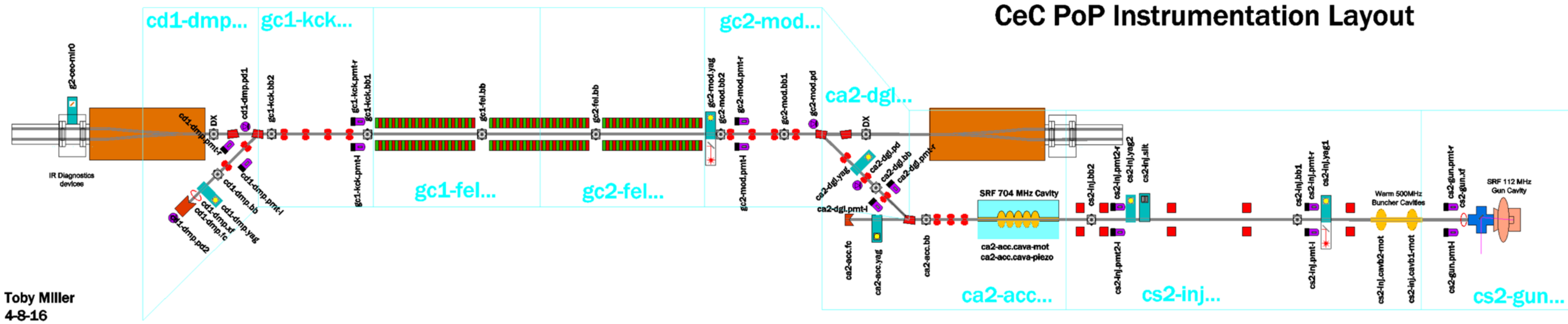
- the high available power allows for electron beam generation at a lower photocathode quantum efficiency
- the higher power allows for producing a significantly more uniform transverse intensity distribution on the photocathode due to overfilling of the aperture imaged onto the photocathode.

Challenges

- Pointing stability
- Pulse jitter
- Temperature drift of diode laser causes two lines generation and hence charge modulation at high frequencies



Instrumentation

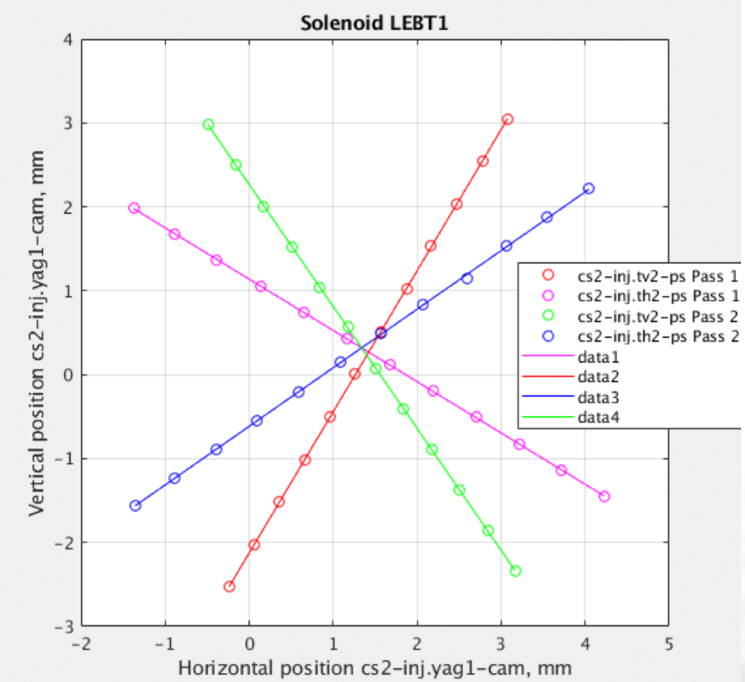


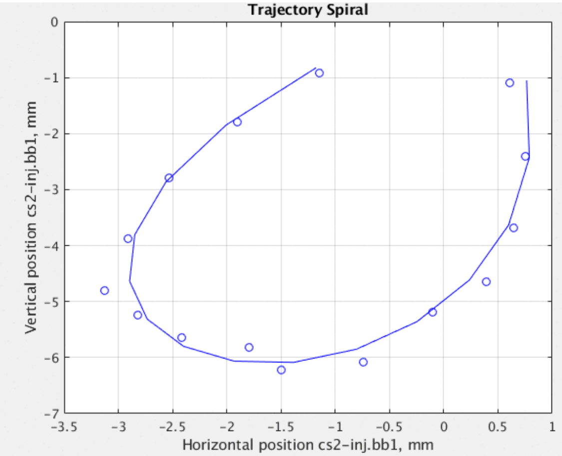
- Two integrating current transformers by Bergoz
- Two beam dumps with incorporated Faraday cups
- Fifteen single pass BPMs by Instrumentation Technologies (11 tuned to 500 MHz, 1 tuned to 352 MHz, 3 tuned to 9.37 MHz)
- 15-mm diameter buttons BPM pick-ups designed at BNL and manufactured by MPF
- Six profile monitors with YAG:Ce screens
- Set of slits for emittance measurement
- IR diagnostics (sensors, monochromator, iris for profile scan)
- 4 GHz Teledyne LeCroy WR640Zi oscilloscope
- PMT based beam loss monitors (JLab development)
- RHIC instrumentation for hadrons (orbit, tunes, profiles, …)
- No longitudinal beam profile diagnostics

Beam Parameters Measurement with Solenoid

- Energy measurement is based on the rotation of the betatron motion by solenoid
- Beam is steered by a trim before the solenoid and position is measured with a signal from downstream BPM or profile monitor
- Tilt angle gives beam energy with accuracy better then 1%
- For trajectory measurement solenoid is treated as sequence of the "hard-edge" short solenoids (from the magnetic measurements).
- Transfer matrix is calculated for each solenoid current and beam position is measured. Beam trajectory vs solenoid axis is found as solution of the system of linear equation.

	Tilt Angle 1	Tilt Angle 2	Ekin, MeV
Horizontal scan	-31.1791	34.6539	1.2573
Vertical scan	59.0198	124.7918	1.2588





Measured Beam Trajectory

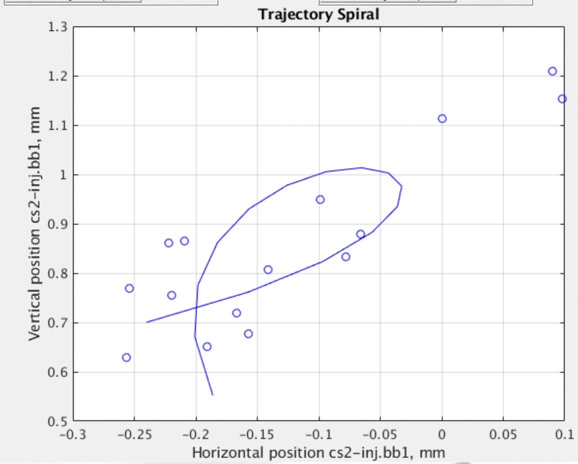
Sol X0, mm	-0.8467
Sol Y0, mm	-2.4286
Sol X ang, mrad	-0.8273
Sol Y ang, mrad	-3.3614
Xoffs, mm	-0.0145
Yoffs, mm	0.7138

	Current, A
cs2-inj.tv1-ps	0.4853
cs2-inj.th1-ps	0.1501
cs2-inj.tv2-ps	-1.4665
cs2-inj.th2-ps	1.0560

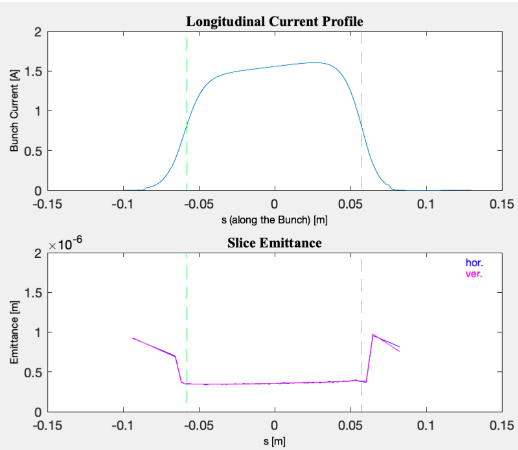
Corrected Beam Trajectory

Sol X0, mm	0.0841
Sol Y0, mm	0.1971
Sol X ang, mrad	-0.0478
Sol Y ang, mrad	0.1115
Xoffs, mm	-0.0872
Yoffs, mm	0.6721

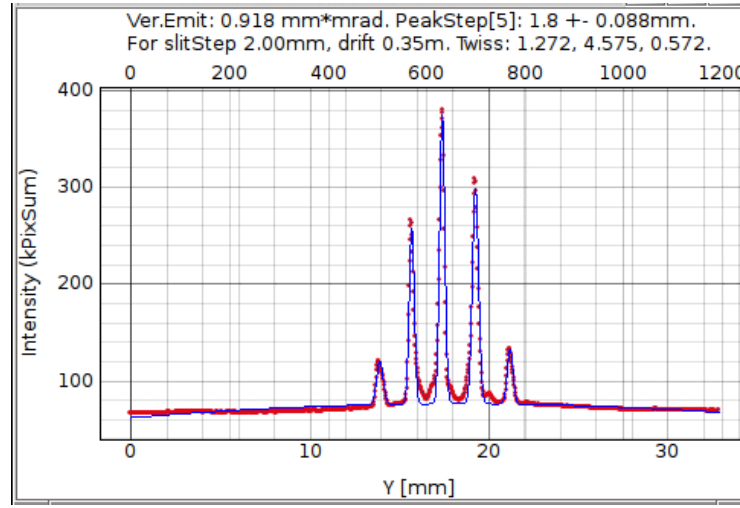
	Current, A
cs2-inj.tv1-ps	0.6424
cs2-inj.th1-ps	0.1997
cs2-inj.tv2-ps	-1.0198
cs2-inj.th2-ps	1.0944



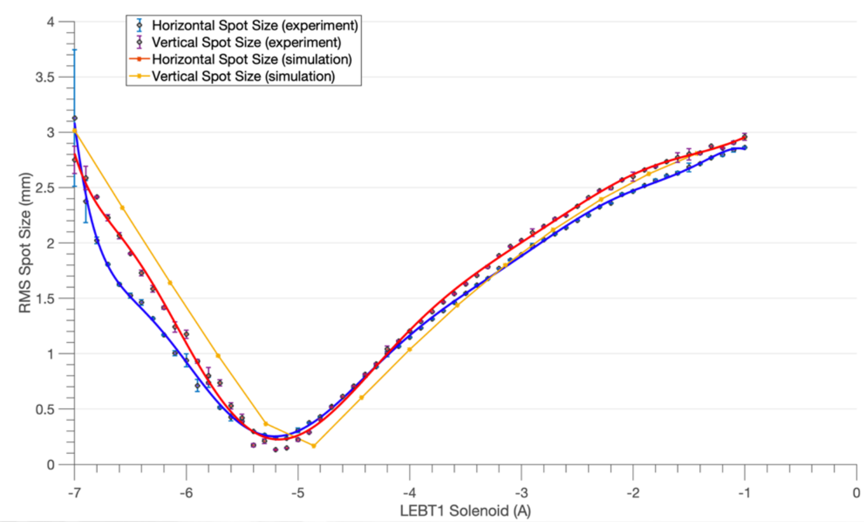
Emittance Measurement

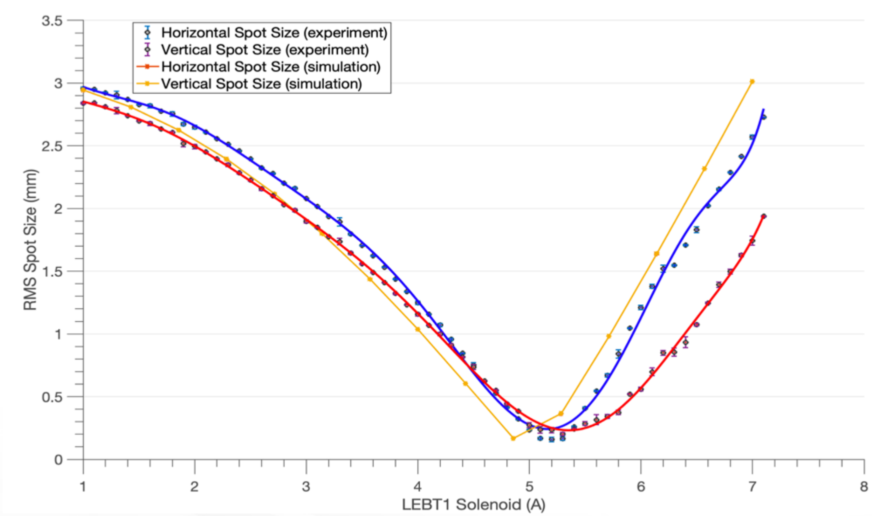


Gun energy: 1.25 MV
Laser spot on cathode r.m.s. size: 0.8mm (3.2 mm diameter)
Bunch charge: 600 pC
Bunch length: 400 ps
Gun solenoid: 8.6 A
LEBT1 solenoid varied from -7 to -1 A (left) and 1 to 7 A (right)



Slits were used for measurement of the space charge dominated beam (1.5 nC bunch charge).

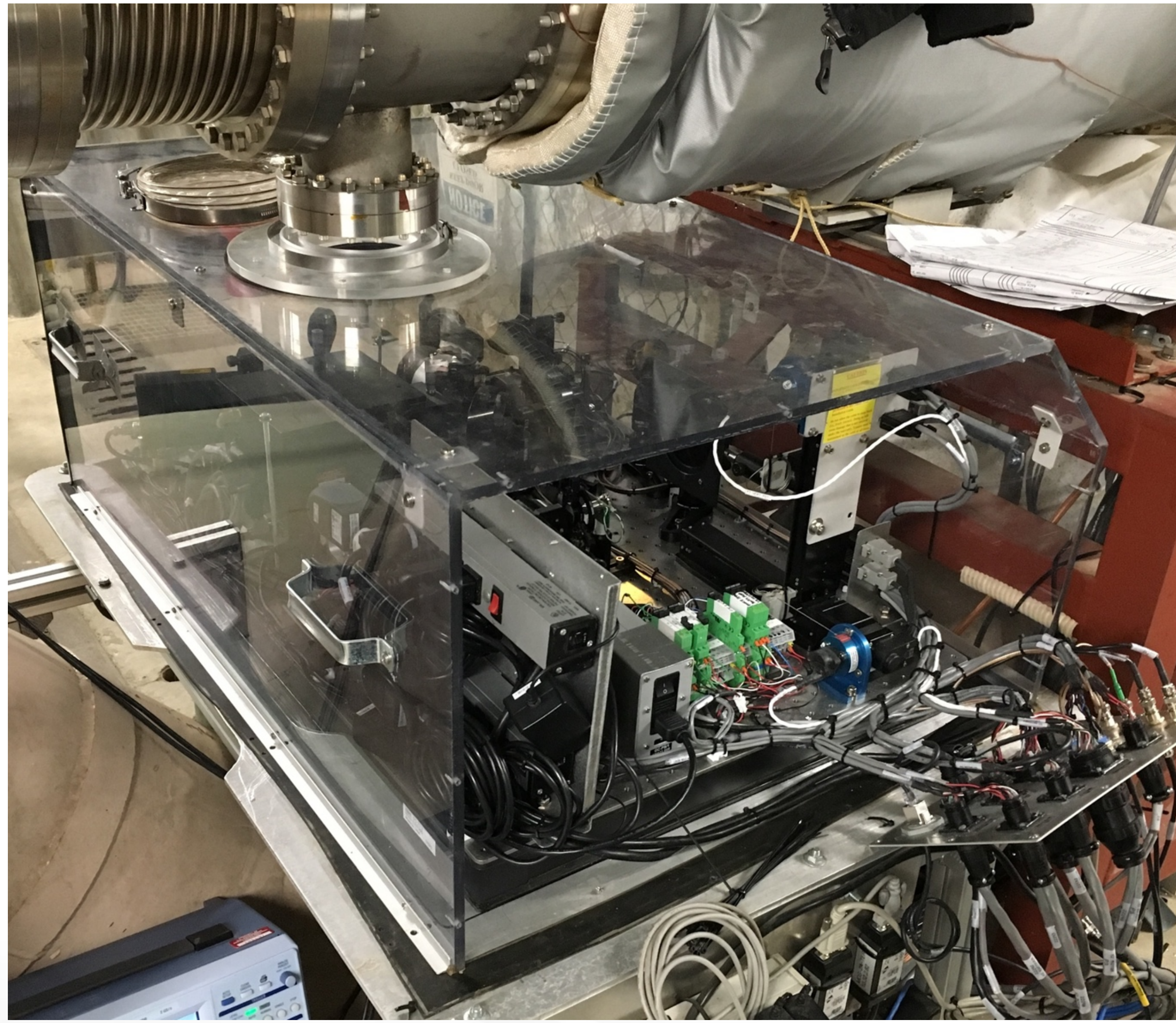




Projected normalized emittance - 0.57 mm mrad
Normalized core slice emittance - 0.35 mm mrad

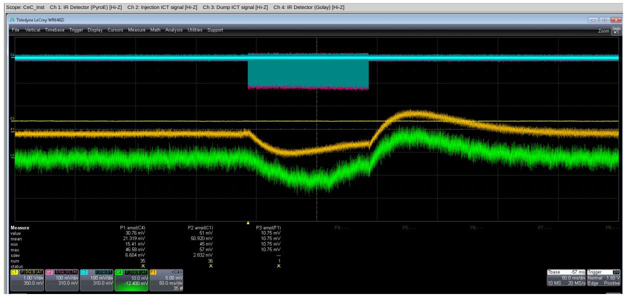
Infrared Diagnostics

- Insertable copper mirror
- ZnSe window was replaced with diamond window transparent at 30 microns
- Chopper
- Golay cell
- Pyroelectric detector
- Monochromator

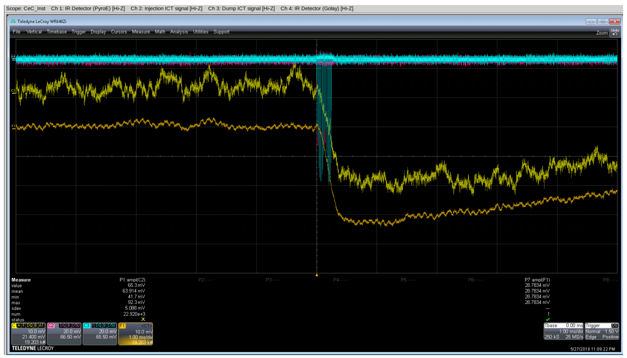


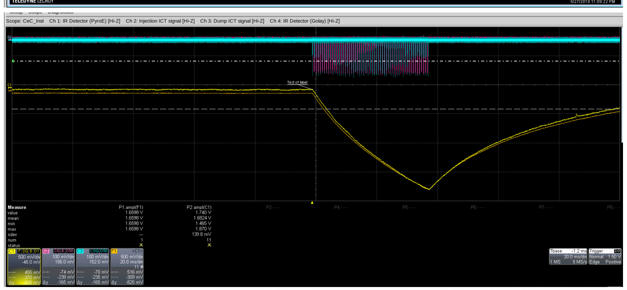
The power meters were intended to tune FEL (up to 6 orders of magnitude power level change). We expected 3-fold increase in power when electron beam intersects with hadrons.
Monochromator is used to measure FEL wavelength and precise measurement of the beam energy.

Infrared Diagnostics (2)

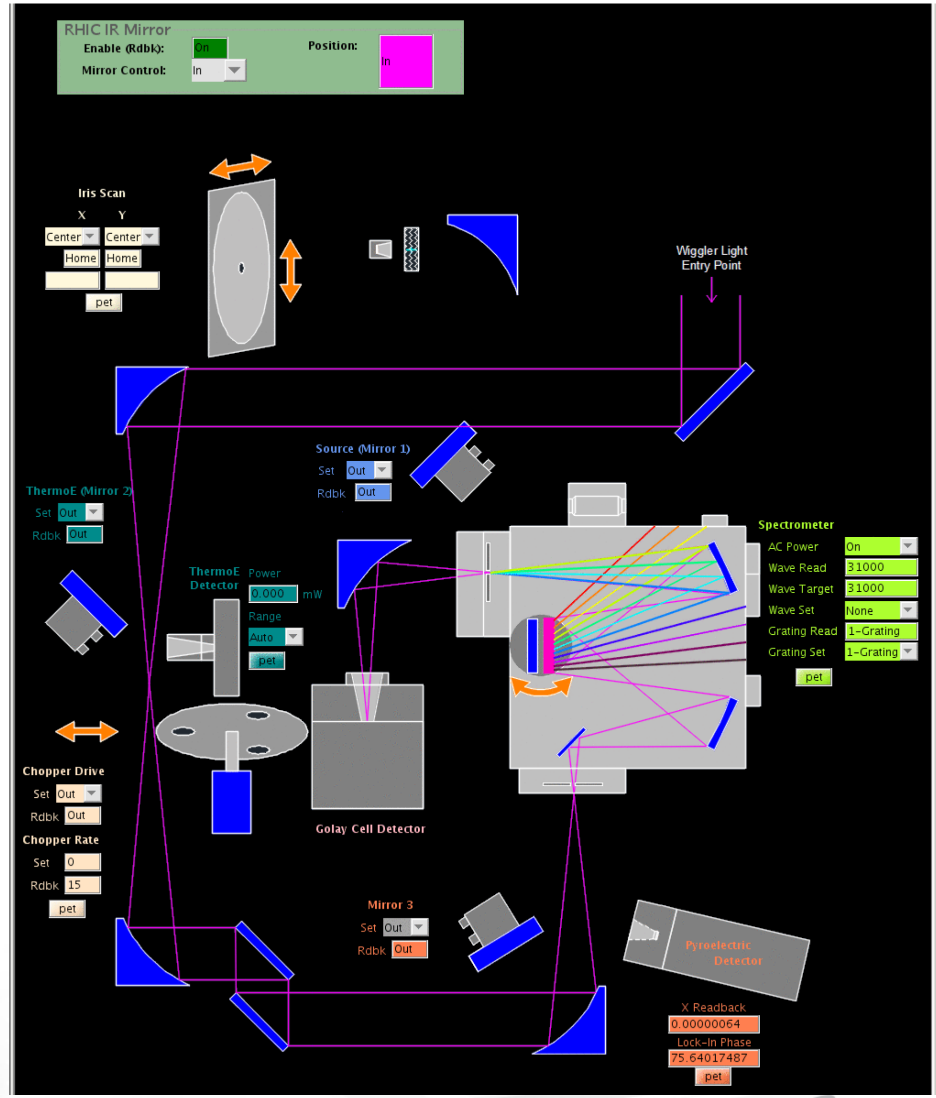


Golay cell signal (green)

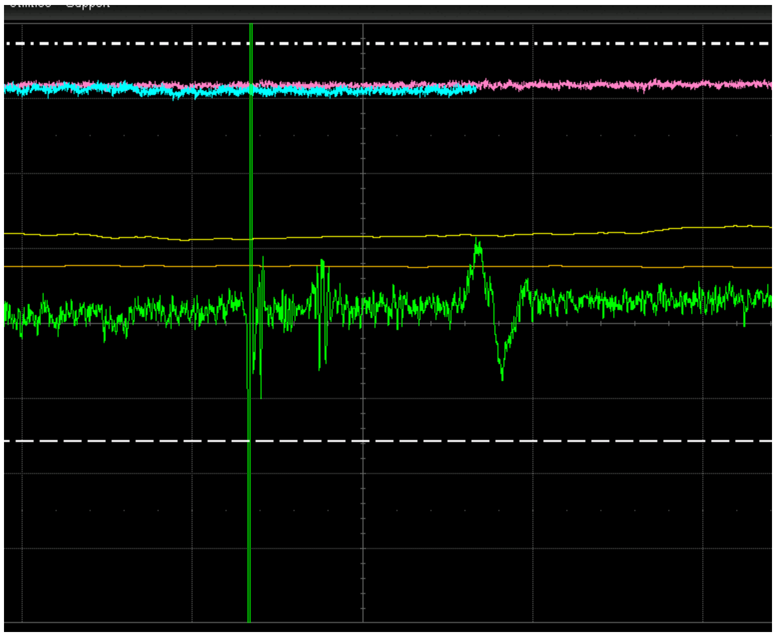




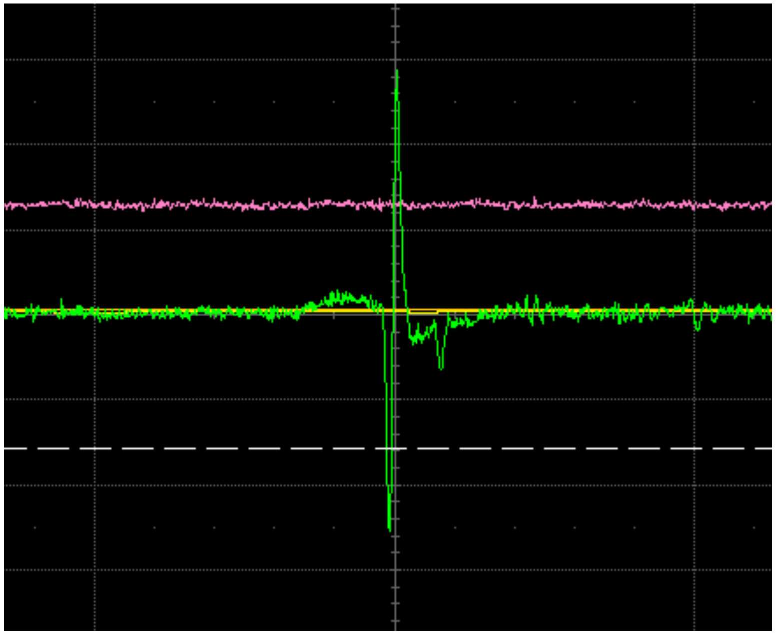
Pyroelectric detector signal (yellow)
ICTs signals are cyan and magenta



Synchronization of Hadron and Electron Bunches



No overlap (50 ns, 2 mV per division)

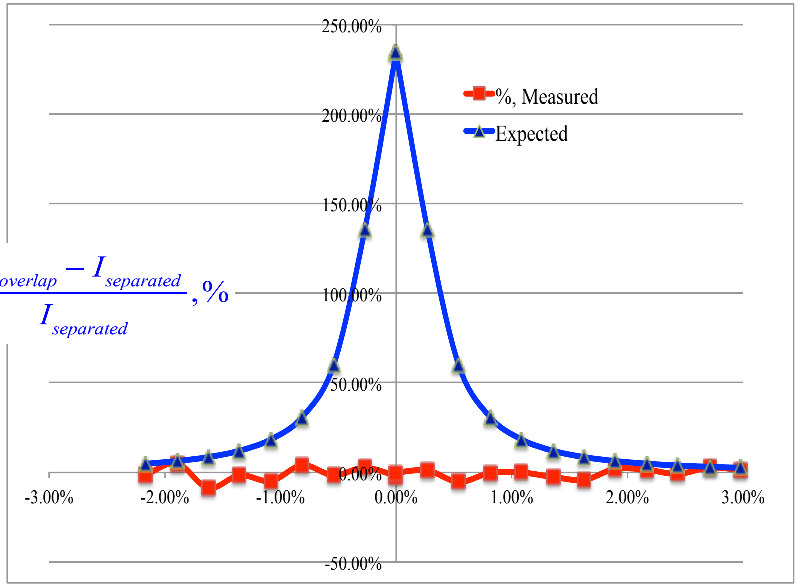


Overlap (20 ns, 10 mV per division)

Synchronization was achieved by observation of the signal from the BPM pick-up electrode in the FEL section.

Puzzle of the CeC Run 18

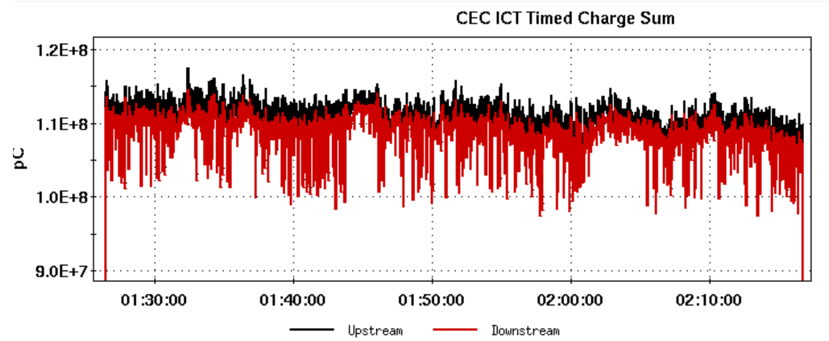
Search for ion's imprint

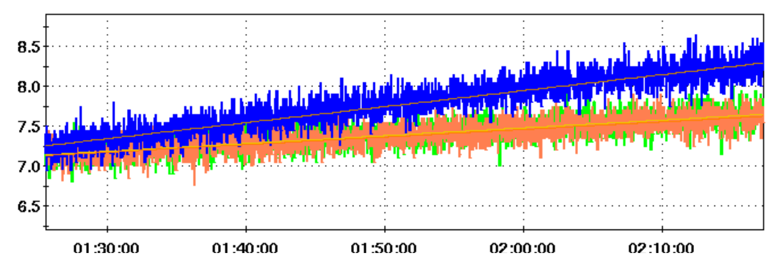


$$R = \frac{I_{overlap} - I_{separated}}{I_{separated}}, \%$$

Expected and measured relative change in the FEL signal with overlapping and separated beams. Each point corresponds to 16 or more cycles of 20 FEL power measurements for overlapped and separated beams. Data analysis indicate RMS error of 2%.

Top plot: electron beam current through the CeC ~ 110 μA or 1.4 nC per bunch at 78 kHz. Bottom plots: evolution of the bunch lengths for interacting (blue trace) and witness bunches (orange and green traces).

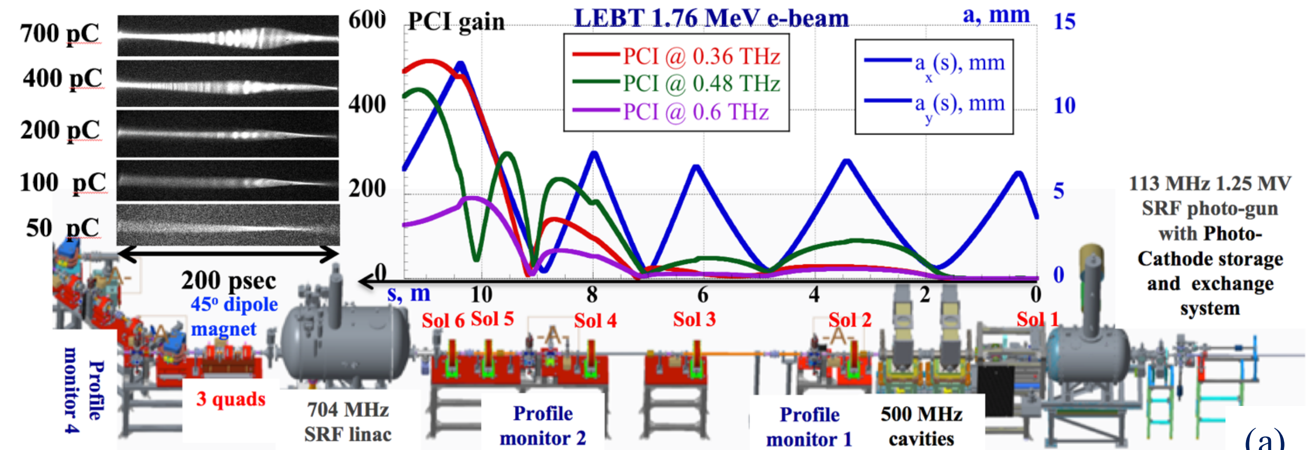


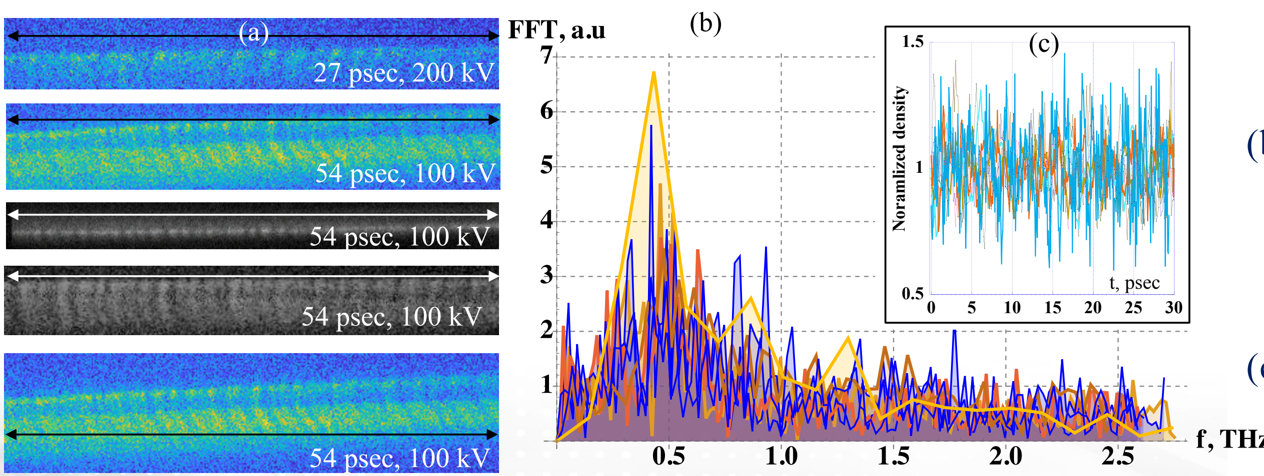


Heating of ion beam was occurring only with a perfect overlap of the beams and high FEL gain. Reducing the FEL gain eliminated the heating.

We have not observed growth of the FEL power due to the interactions with hadrons because of the beam instability due to PCI and/or overbunching

Uncompressed Bunch: Simulations and Experiment in September 2018





(a) Measured time profiles of 1.75 MeV electron bunches emerging from LEBT. Charge per bunch was from 0.45 nC to 0.7 nC;

(b) Seven overlapping spectra of measured bunch density modulation and PCI spectrum simulated by SPACE (slightly elevated yellow line);

(c) Clip shows a 30-psec fragment of seven measured relative density modulations.

Goals during Run 19

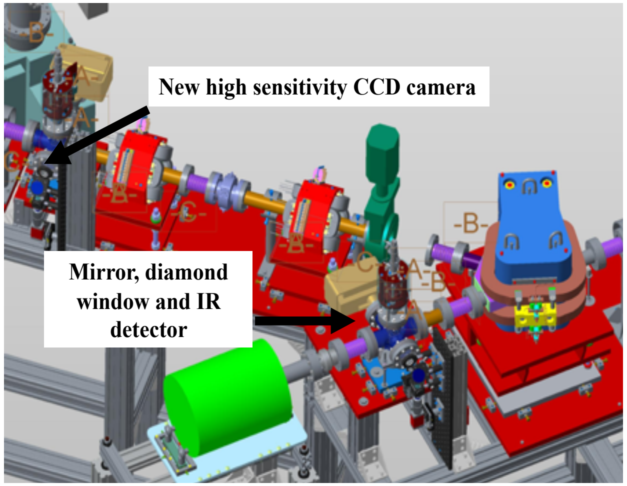
- Demonstrate generation of electron beam with beam parameters satisfying or exceeding requirements for CeC demonstration experiment

Parameter	Value
Relativistic factor, γ	28.5
Normalized beam emittance, mm mrad	≤ 5
Electron beam peak current, A	50-100
Relative energy spread	0.1%
Noise level at 10 THz/Poisson shot noise	~2 (<100*)

* minimal goal

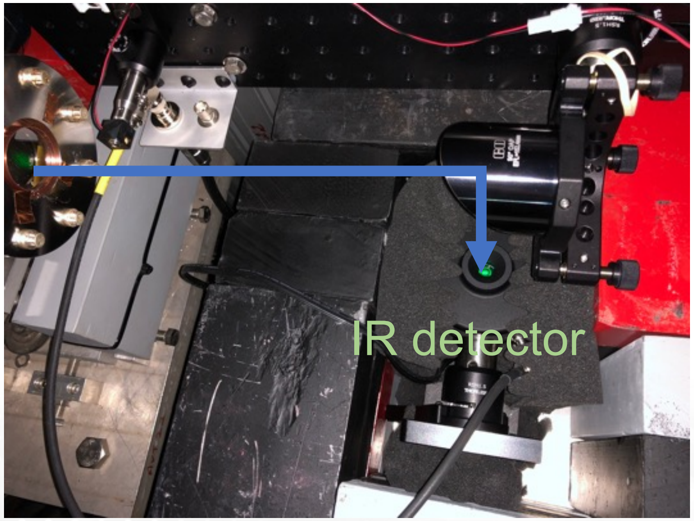
- Demonstrate control of newly discovered Plasma-Cascade Instability (PCI) and develop means of its suppression in the CeC accelerator ballistic compression beam-line

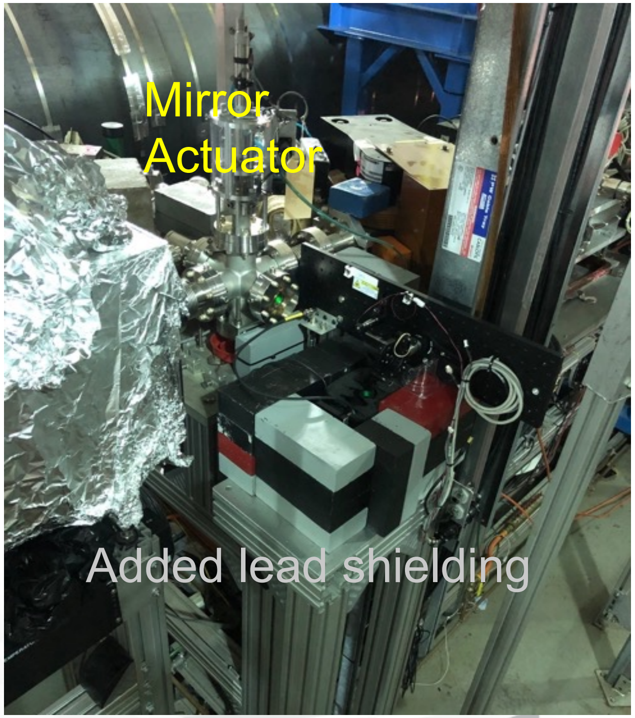
IR Diagnostics During Run19



- Utilized high-sensitivity CCD camera for the dogleg profile monitor
- YAG was removed from low-power dump profile monitor. Viewport was replaced with CVD diamond window. IR detector was installed. Mesh was installed to suppress THz radiation.

1” CVD diamond window covered with 1.4 mm x 1.4 mm metal mesh to suppress GHz radiation





SR Radiation and IR Detector Sensitivity

- IR power is measured by a very slow AC pyroelectric detector, which is calibrated for periodic 100 msec pulses separated by 100 msec: 2.12E6 V/J
- We cross-calibrated it for shorter 1.5 msec to 6.5 msec pulses (trains less then 600 bunches)
- We operated CeC accelerator short 100 to 500 bunch trains repeated typically with 10 Hz and used lock-in amplified. We cross-calibrated the lock-in amplifier output for such signal to be $(4\pm0.4)\cdot10^6$ V/J
- Power reaching the insertable the 1" Cu mirror was calculated using Igor-Pro for beam in a measured magnetic field of the 45-degree dipole operated at 140 A – it was is very good agreement (within 10%) with analytical estimations
- We expected that 1.4 mm x 1.4 mm metal mesh installed at he exit window has ~ 50% transparency
- With 50% reaching IR detector we expected 130 V/C/sec (30 μW/A) locking amplifier signal. With typical 1.5 μA beam current, we expected signal ~ 200 μV (~ 45 pW power)
- This expectations are in reasonable agreement with the measured level of radiation from relaxed beam

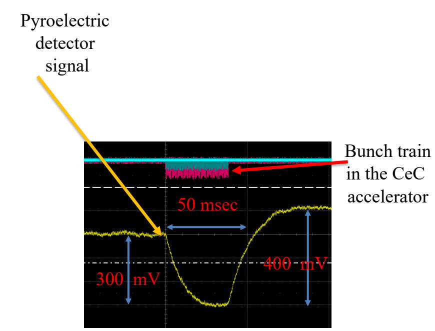
THZ-I-BNC

SPECIFICATIONS

	THZ5I-BL-BNC
MAX AVERAGE POWER	140 μW
EFFECTIVE APERTURE	5 mm Ø
INTEGRATED MODULE	Analog (BNC)
MEASUREMENT CAPABILITY	
Spectral Range [a]	
Frequency	0.1 - 30 THz
Wavelength	3000 - 10 μm
Max Measurable Power	140 μW
Noise Equivalent Power [b]	1.0 nW [1.0×10^{-9} W/(Hz)$^{1/2}$]
Rise Time (0-100%)	≤ 0.2s
Sensitivity (Typical) [b]	70 kV/W
Chopping Frequency	5 Hz (Required)

Pyroelectric detector

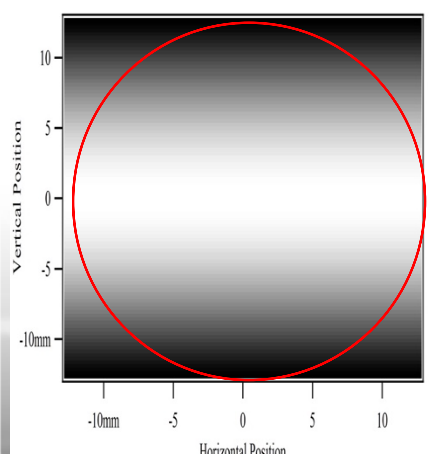
The range from 0.1 to 30 THz (10 μm – 3 mm)

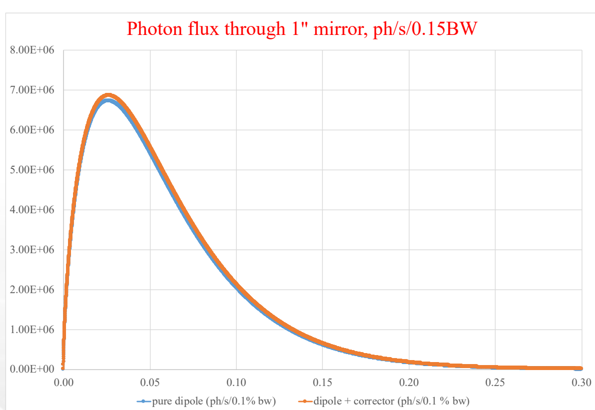


Response : 2.12 mV/nJ

Resolution of the system: ~0.1 nJ

Noise equivalent: 0.6 nW/Hz$^{1/2}$





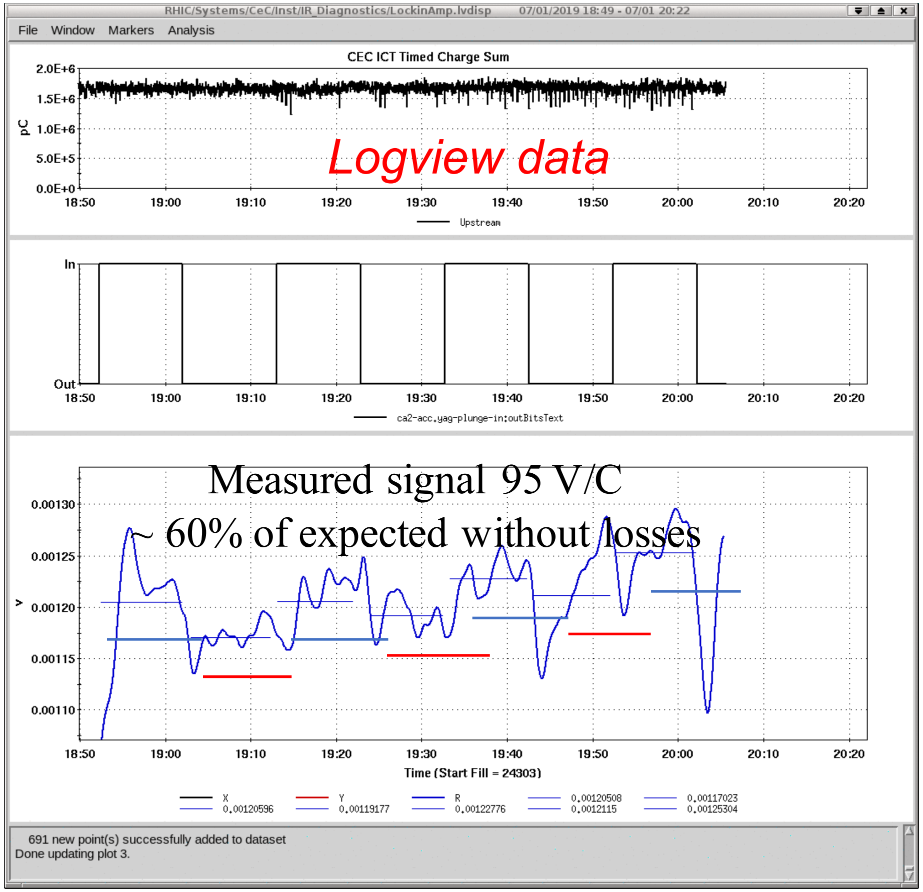
gentec-eo

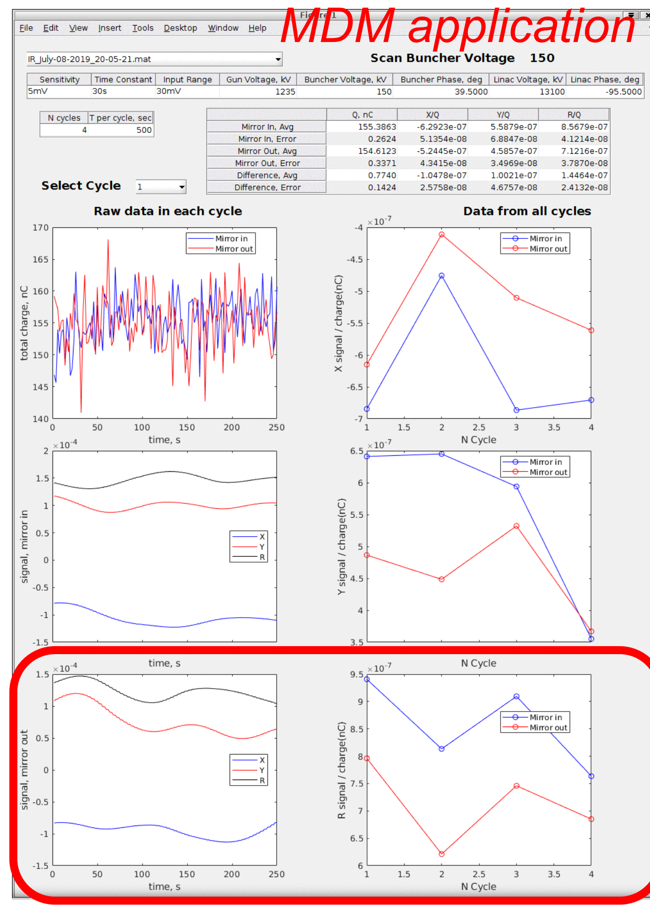
Certificate #:	506449-171103	Customer Name:	
Model Number:	THz5I-BL-BNC	Instrument ID:	
Head Serial Number:	506449	Date of Calibration:	
		Calibration Due Date:	
Cal. Procedure:	100-1025		

Calibration Data

Meaurement Parameter	Sensitivity		Into Load	Calibration Power	Rep.Rate
@ 633 nm	V/W	%	Ω	uw	Hz
Rv (P to P)	2.12E+05	± 2.1	NA	8.2	5
Rv (RMS)	6.91E+04	± 2.1	NA	8.2	5
					Hz

Shot Noise Level Measurements

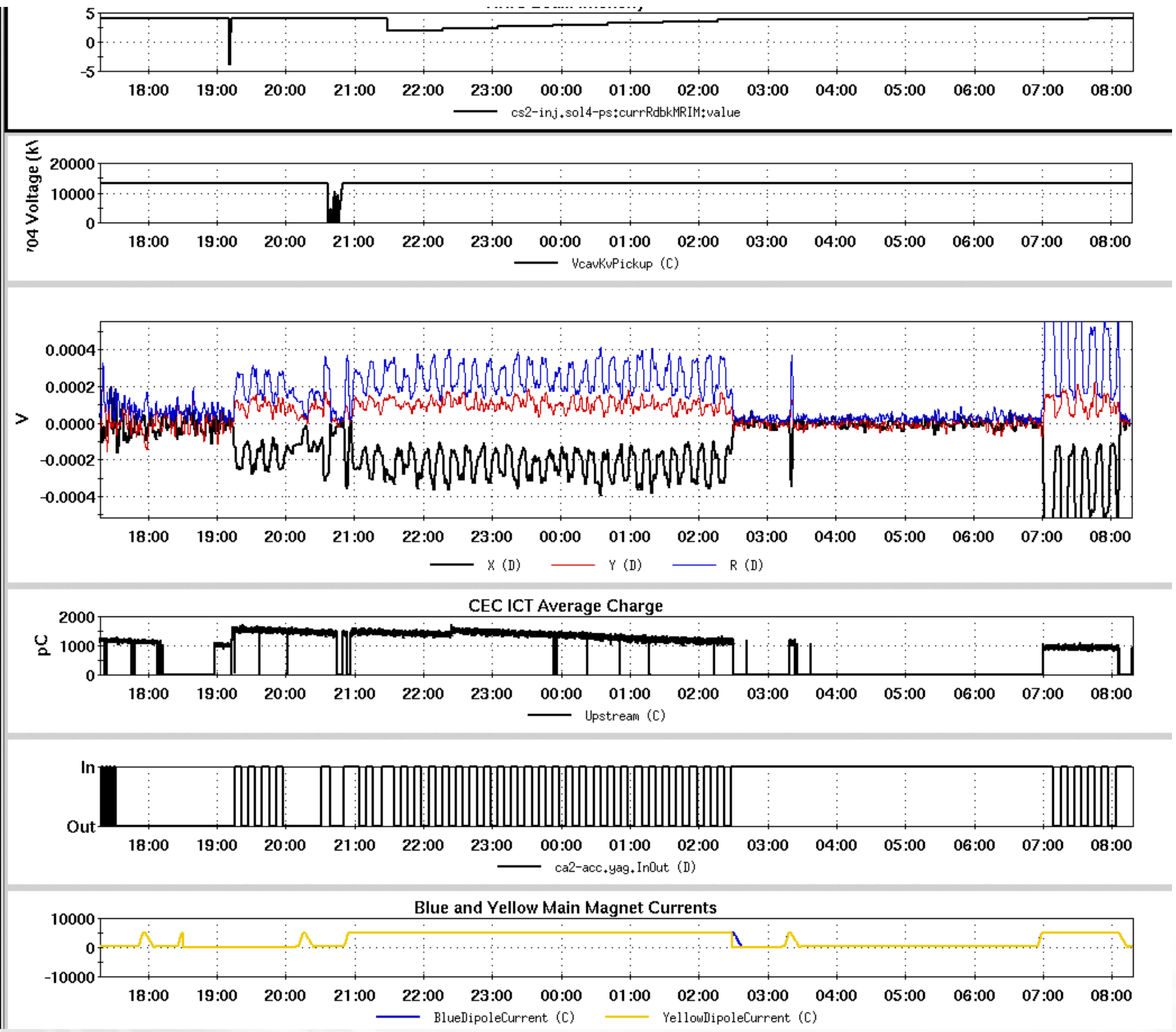


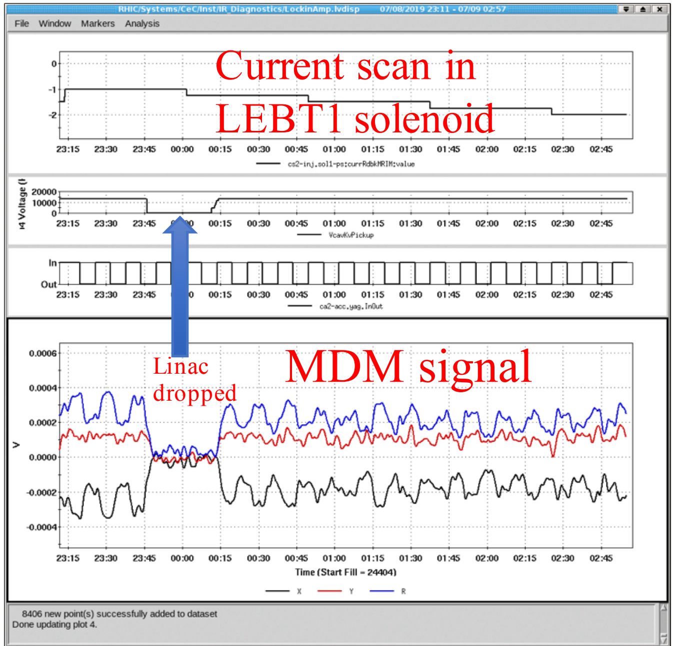


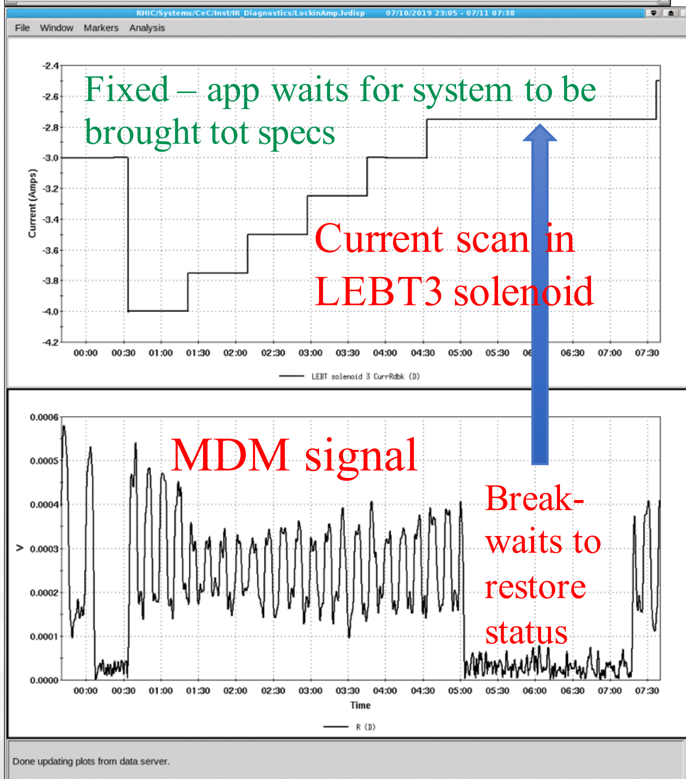
I = 105 V/C
Q = 100 V/C
R = 145 V/C

The measurements were performed for modestly (4-fold) compressed beam with 1.5 and 0.3 nC charges per bunch in relaxed LEBT lattice. Averaged over 4 long scans the lock-in amplifier MDM signal was **145 V/C (24 μW/A)** with RMS error of **15 V/C (3 μW/A).** This value is at 40% level of synchrotron radiation that reaches the Cu mirror.

Typical Long Scans

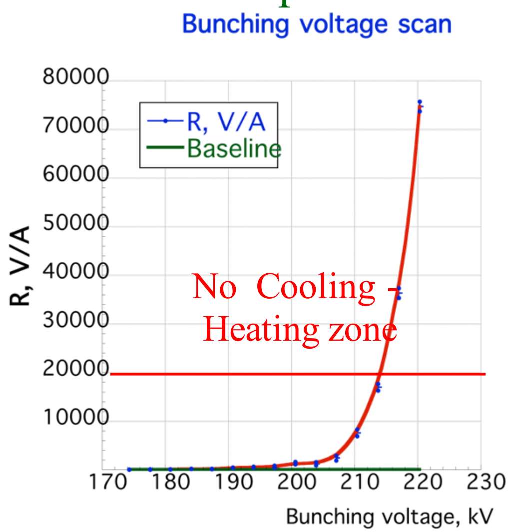


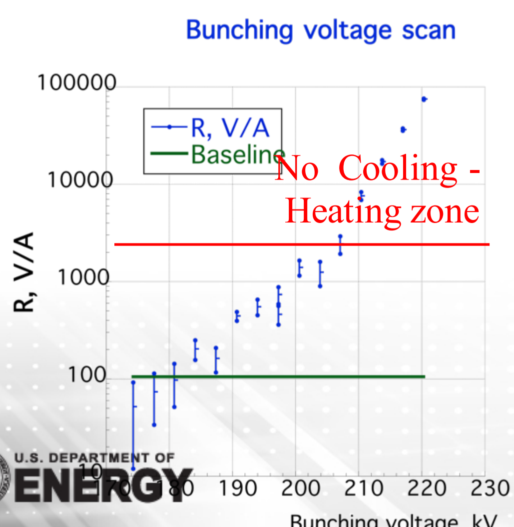




Dependence on the Bunching Voltage and Checking Run 18 Set-up

1.5 nc per bunch

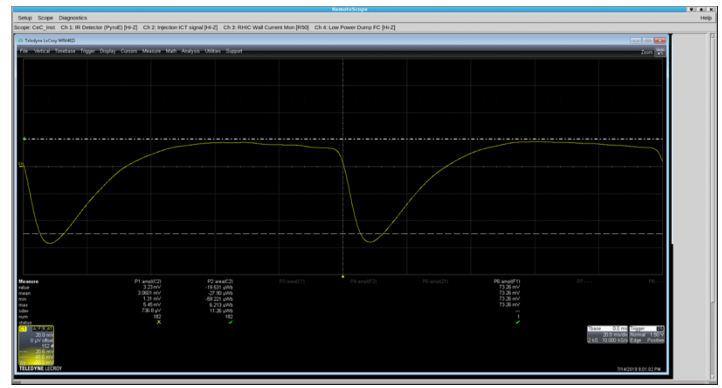


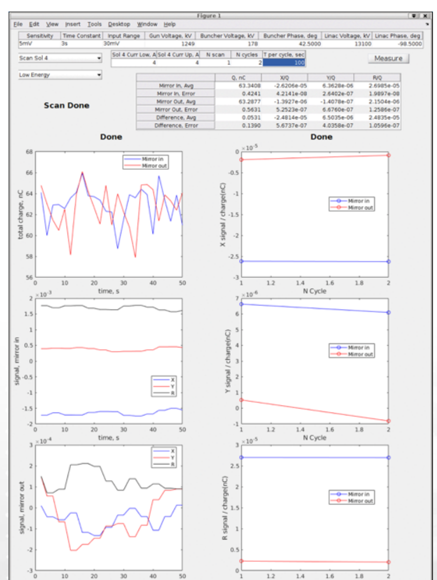


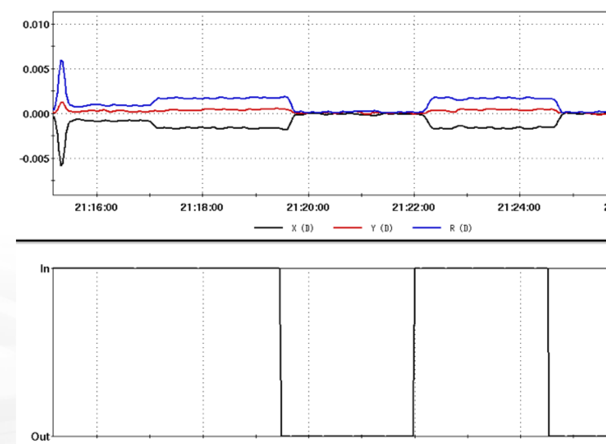
Run 18 lattice and beam: 0.6 nC per bunch

Large signal of 25,000 V/A ~ 250-fold above base line.

Can be seen both on scope and measured easily

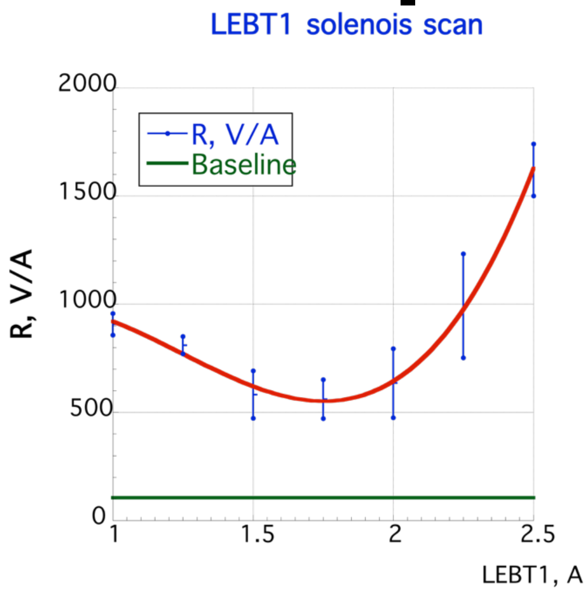


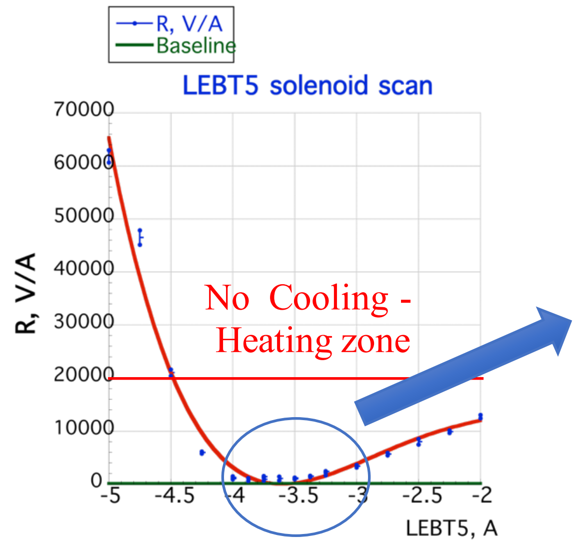


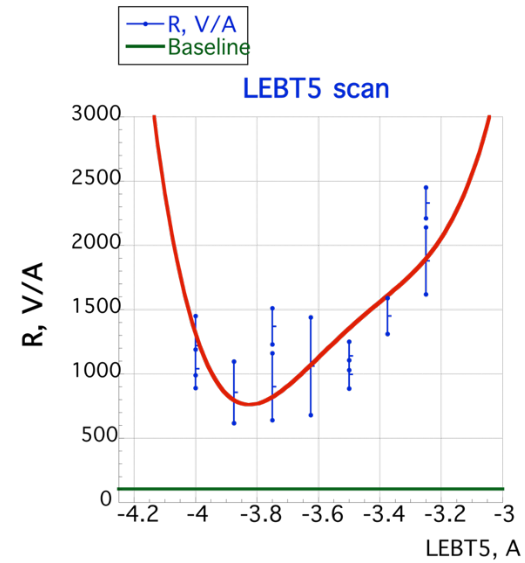


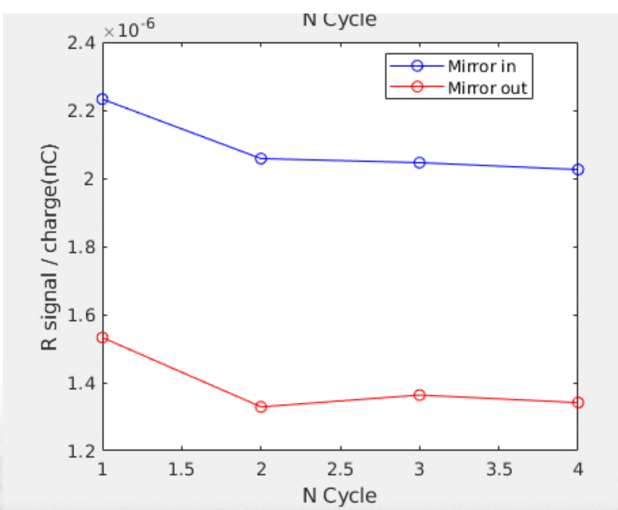
U.S. DEPARTMENT OF ENERGY

LEBT Optimization







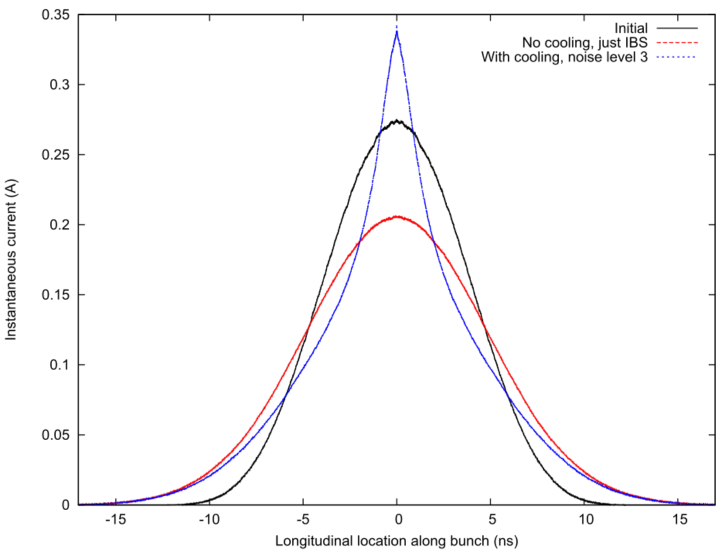


As a result of optimization we were able to achieve the FIR signal only factor two above shot noise level.

The optimized set-up has rather flat response of the noise on the variation of the solenoid current leaving sufficient headroom for optimizing other beam parameters.

Plans for PCA based CeC

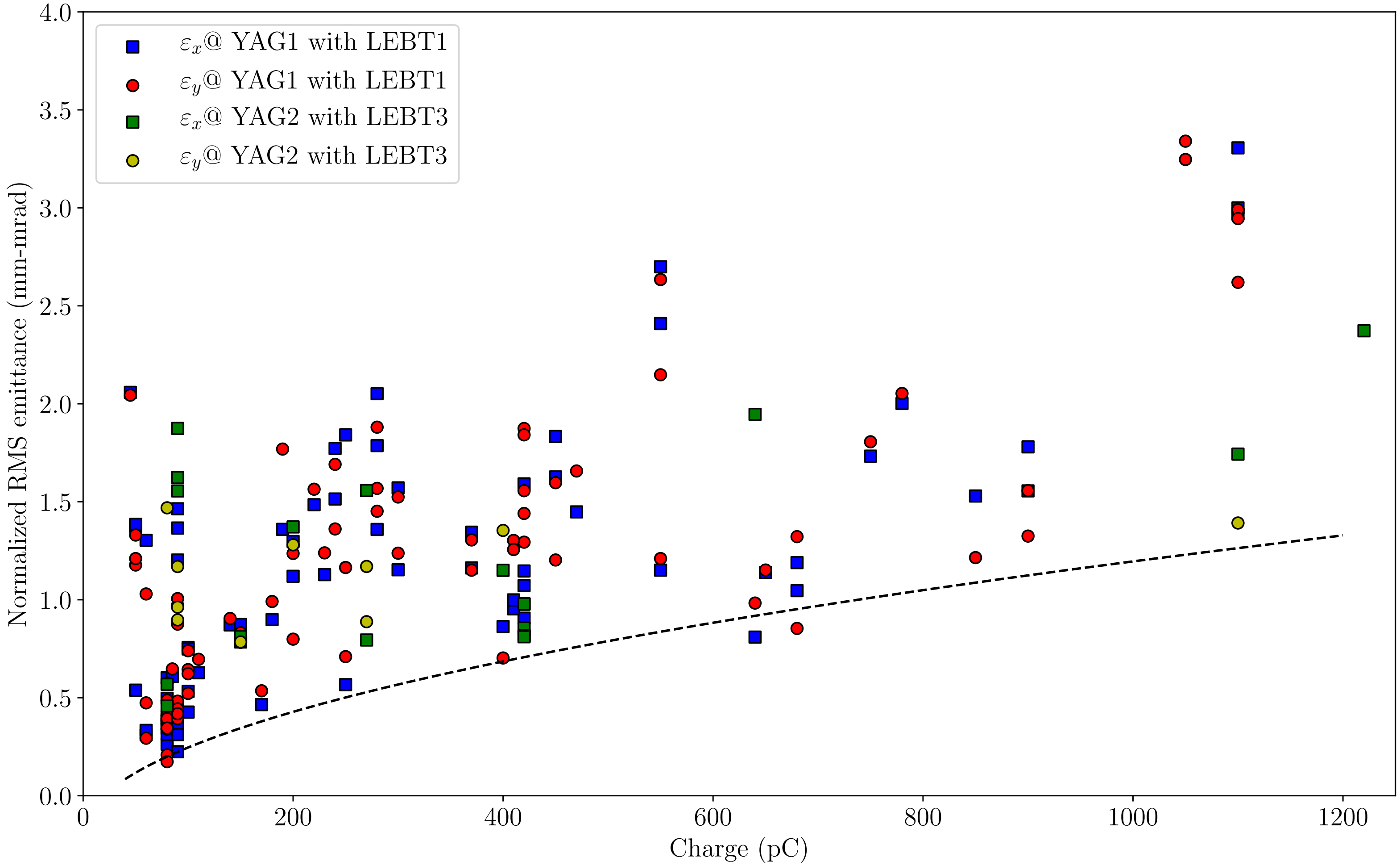
- Shutdown jobs
  - Install new elements into the common section
  - Add IR diagnostics: two sets – one after DX magnet, another at low power dump
- Run 20
  - Establish electron beam operation in the background mode in parallel with RHIC operation
  - Optimize electron beam parameters
  - Establish high-current operation and demonstrate interaction with hadrons circulating in RHIC
- Demonstrate longitudinal cooling during Run 21
- Perform cooling experiments including transverse and/or 3D cooling during Run 22



Conclusions

- Accelerator delivered the beam with parameters suitable for the CeC PoP experiment
  - Electron normalized emittance as low as 0.3 mm mrad was measured
  - Relative energy spread 3×10^{-4} was demonstrated
- Two new methods for measuring beam trajectory vs. solenoid axis (position and angle) and energy utilizing solenoid were developed
- We were unable to demonstrate the imprint of the hadrons on the electron beam due to the discovered plasma cascade instability and/or overbunching
- The development of the PCI was experimentally confirmed in the dedicated studies and methods for it suppression were developed
- The PCA based CeC system will be tested during Runs 20-22

Results of Emittance Measurements



Hadron Beam Instrumentation

- Three 9-MHz tuned BPMs for monitoring position in the common section (trajectory should coincide within 100 microns)
- RHIC instrumentation: BPMs, wall current monitor, tune and emittance measurement systems
- Signal from the pick-up electrode for overlapping electron and hadrons beams