TUOB01

Coherent electron Cooling Diagnostics: Design Principles and Demonstrated Performance

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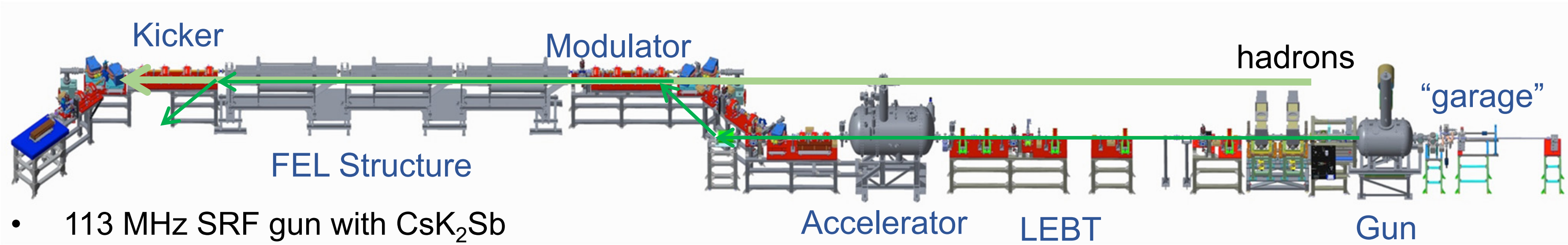
Outline

- Project overview
- Accelerator layout
- Diagnostics subsystems
- Applications
- Conclusion

Coherent Electron Cooling Proof-of-Principle Experiment



- 113 MHz SRF gun with CsK_2Sb photocathode
- 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

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. The electrical field accelerates and/or decelerates hadrons in the kicker section.

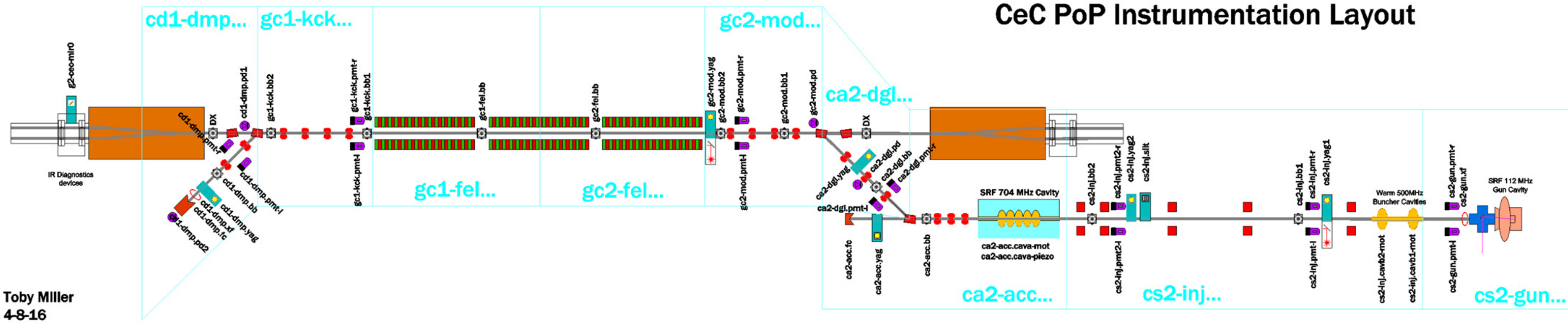
Electron beam parameters

- Normalized emittance < 5 mm mrad
- Bunch charge 50 pC – 5 nC
- Repetition rate 1 Hz – 78 kHz
- R.m.s. bunch length 10-500 psec
- Kinetic energy 14.5 (22) MeV
- IR FEL wavelength 30 (14) 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

Instrumentation



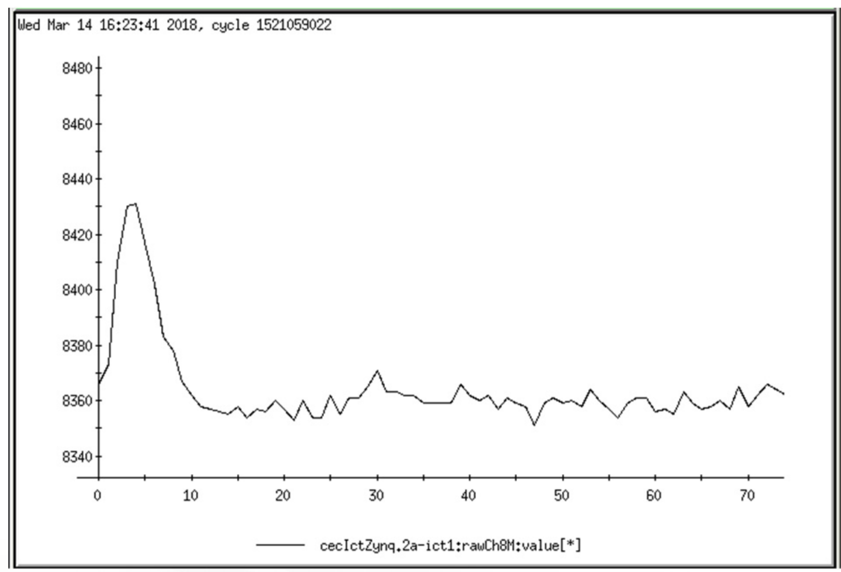
- Two integrating current transformers by Bergoz
- Two beam dumps with incorporated Faraday cups
- Fifteen single pass BPMs by Instrumentation Technologies (11 tuned to 500 MHz, 1 tuned to 352 MHz, 3 tuned to 9.37 MHz)
- 15-mm diameter buttons BPM pick-ups designed at BNL and manufactured by MPF
- Six 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, …)

Limited duration of the experiment led to choice of the already proven devices.

More detailed information can be found at MOPA09 (this conference)

Current Measurement System

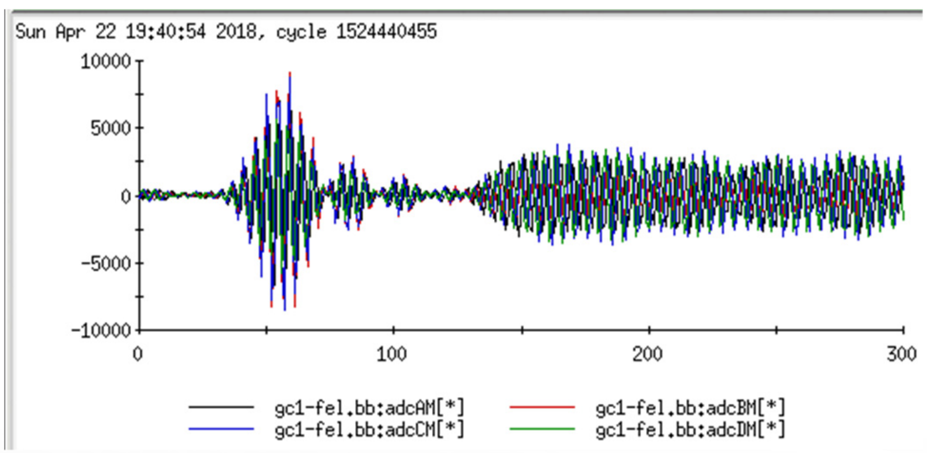
- Based on the in-flange integrating current transformers by Bergoz
- Signal processing of the both ICTs performed in the FPGA with self-triggering on the slope of the signal from the gun ICT to suppress low-frequency noise
- The dump ICT signal is processed each time bunch from the gun is detected
- If difference between the sum of the gun charge and dump charge exceeds threshold, signal is send to MPS (the required response time is few tens microseconds)



We have replaced gun ICT with arbitrary shape aperture option to avoid charge accumulation on the inner surface of the ceramic break. The dump ICT was also replaced due to the damage by the beam.

Beam Position Monitors

All units are Libera Single Pass E.
350 and 500 MHz units for measuring electron position.
9 MHz units for measuring hadrons.
Instrumentation Technologies modified firmware to accommodate for long trains.
Third order polynomial fit was used for position calculations.
The specified noise level of few microns is well below 10% of beam size.



Having ability for setting acquisition window facilitated us to operate in parallel with RHIC store even with short hadron bunches.

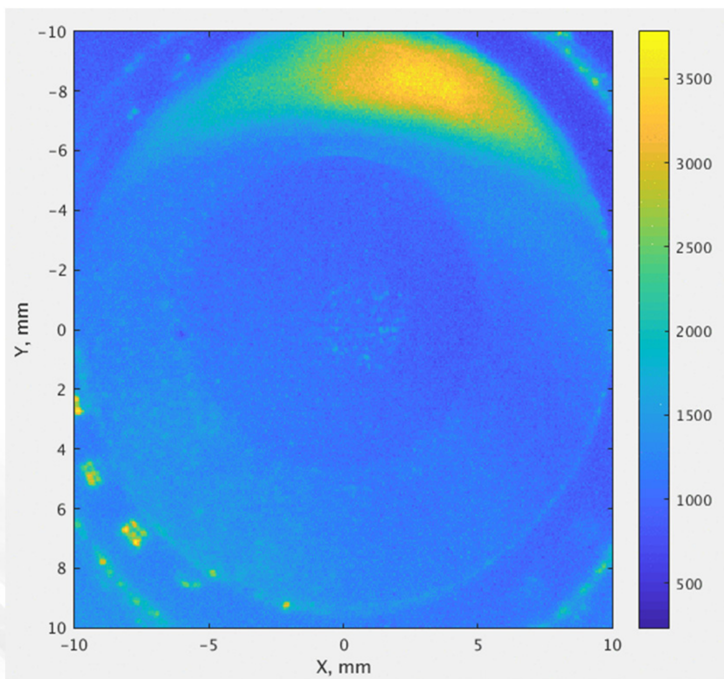
Long hadron bunches do not have 500 MHz content. Shorter and low charge electron bunches induce very low signal into the hadrons BPMs tuned to 9 MHz.

Photocathodes Diagnostics

- QE monitoring system in the garage
- Laser power meter
- Laser beam size and position control

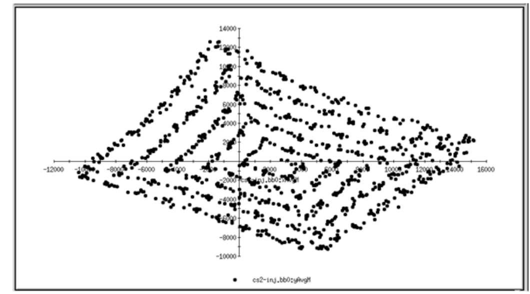
Camera image of the inserted cathode

Application screenshot of the laser spot on the 12-mm diameter active area

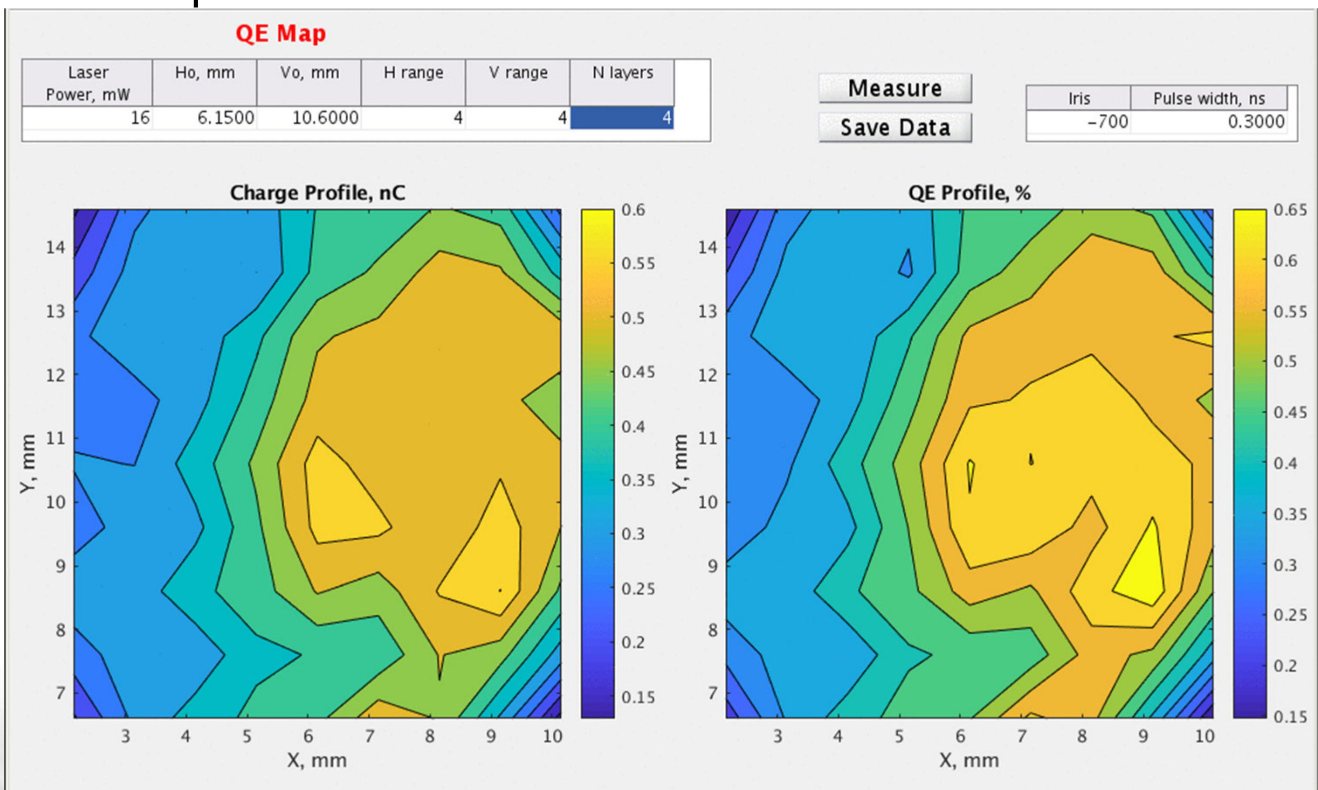


Photocathode QE Map

- Full 532 nm laser power (78 kHz) is measured prior the scan (up to few tens of mW)
- Small number of pulses is used (1-10)
- Laser spot is moved by two translation stages giving parallel displacement of the laser beam



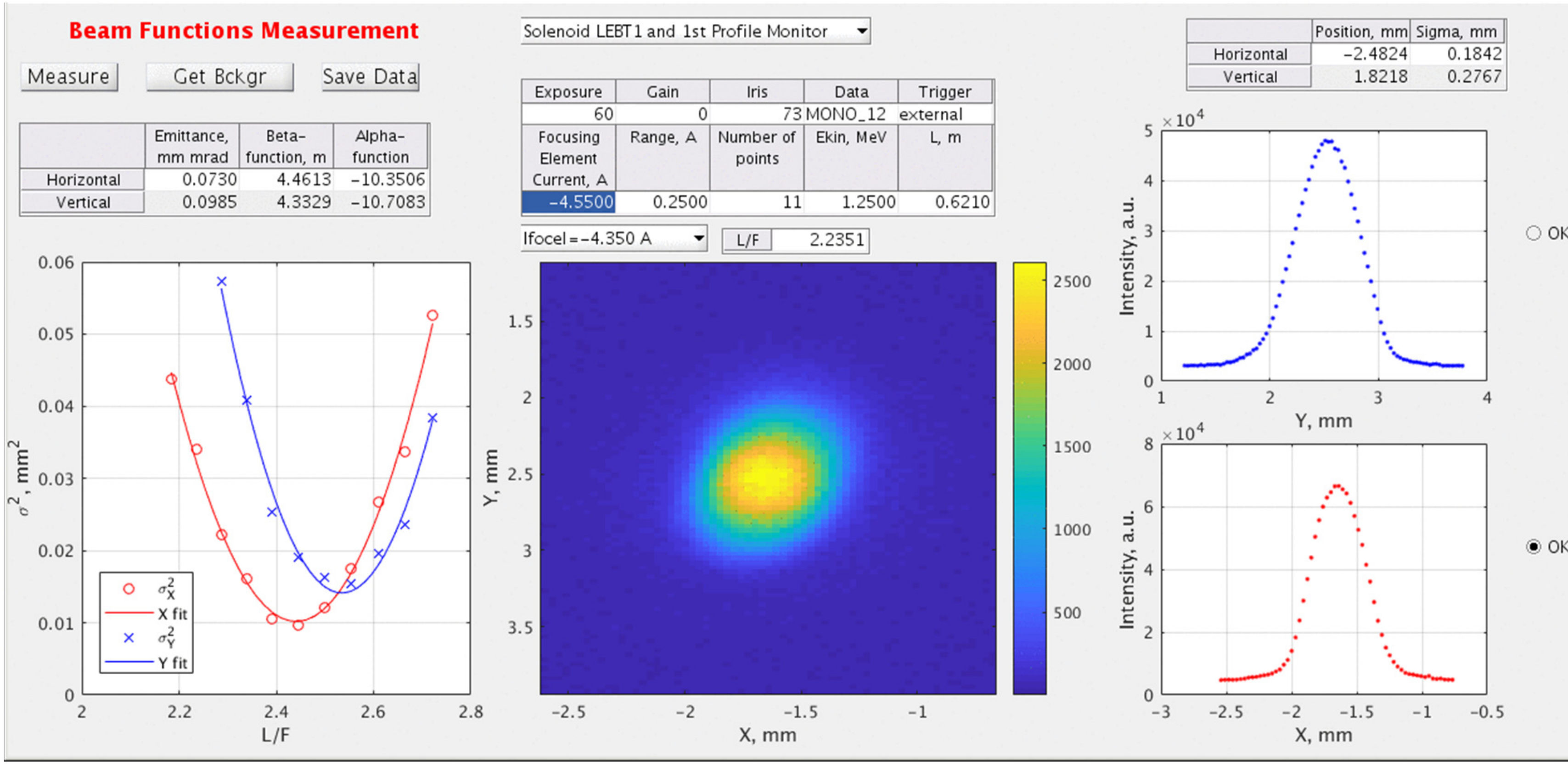
Electron beam position during QE map scan. The tilt is due to the rotation of the beam motion by the gun solenoid.



Machine Protection System

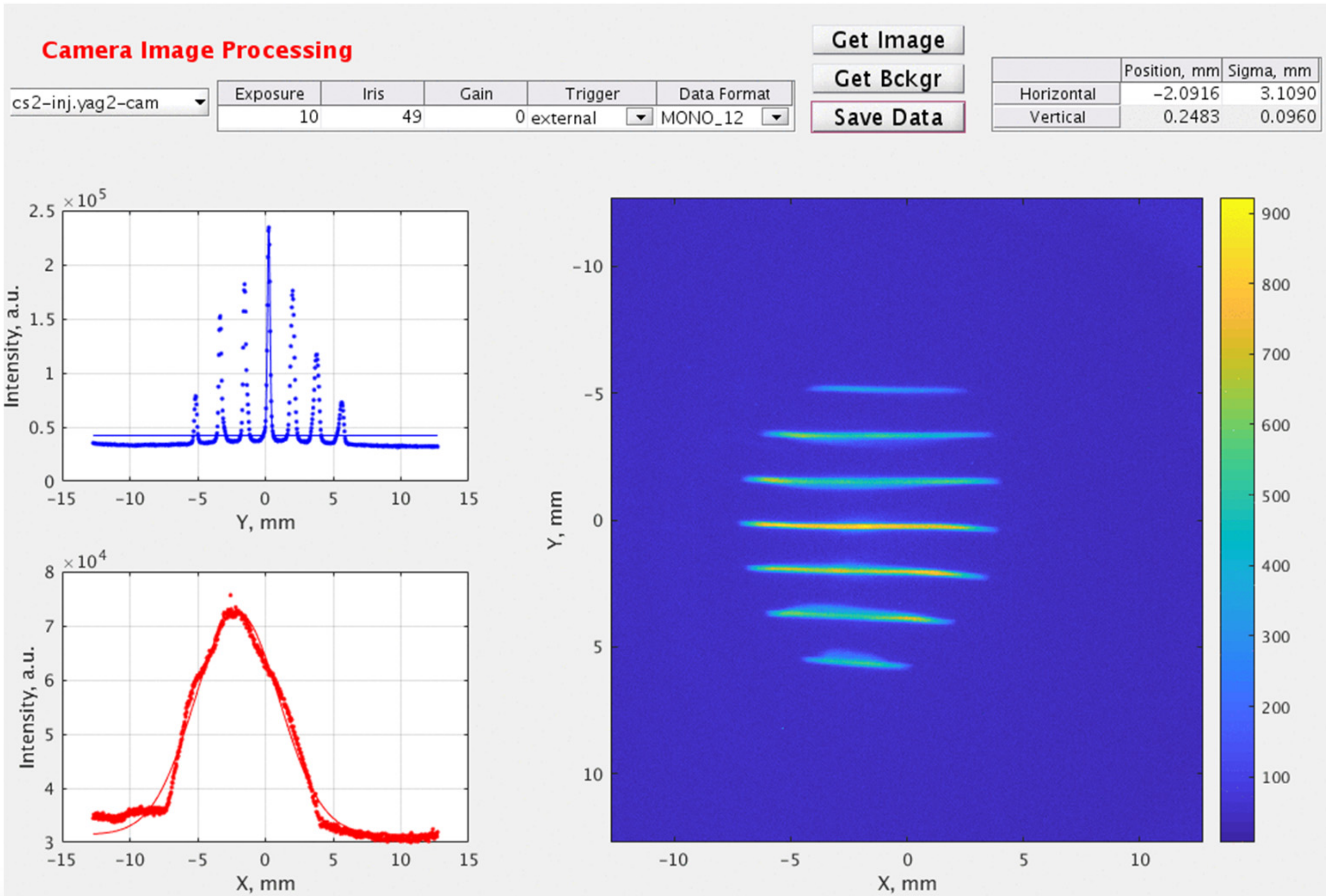
- Beam current from the gun and into the high-power dump
- Beam position
- Intercepting diagnostics and vacuum valves position
- MPS closes laser shutter and Pockels cell if conditions are not safe
- If gun current exceeds high limit the gun RF is also inhibited
- RF cavities (vacuum, air and water flow, cryogenics status, systems compliance)
- Stand-alone laser MPS

Emittance and Beam Functions Measurements



The strength of a focusing element (solenoid or quadrupole) is varied and beam size is measured. Operator can choose either r.m.s. or Gaussian fit for size measurement.
The requirement for the normalized emittance was better than 5 mm mrad with typical value of 3 mm mrad.

Emittance Measurement with Slits



Slits were used for measurement of the space charge dominated beam. It was found that solenoid scan gives similar results.

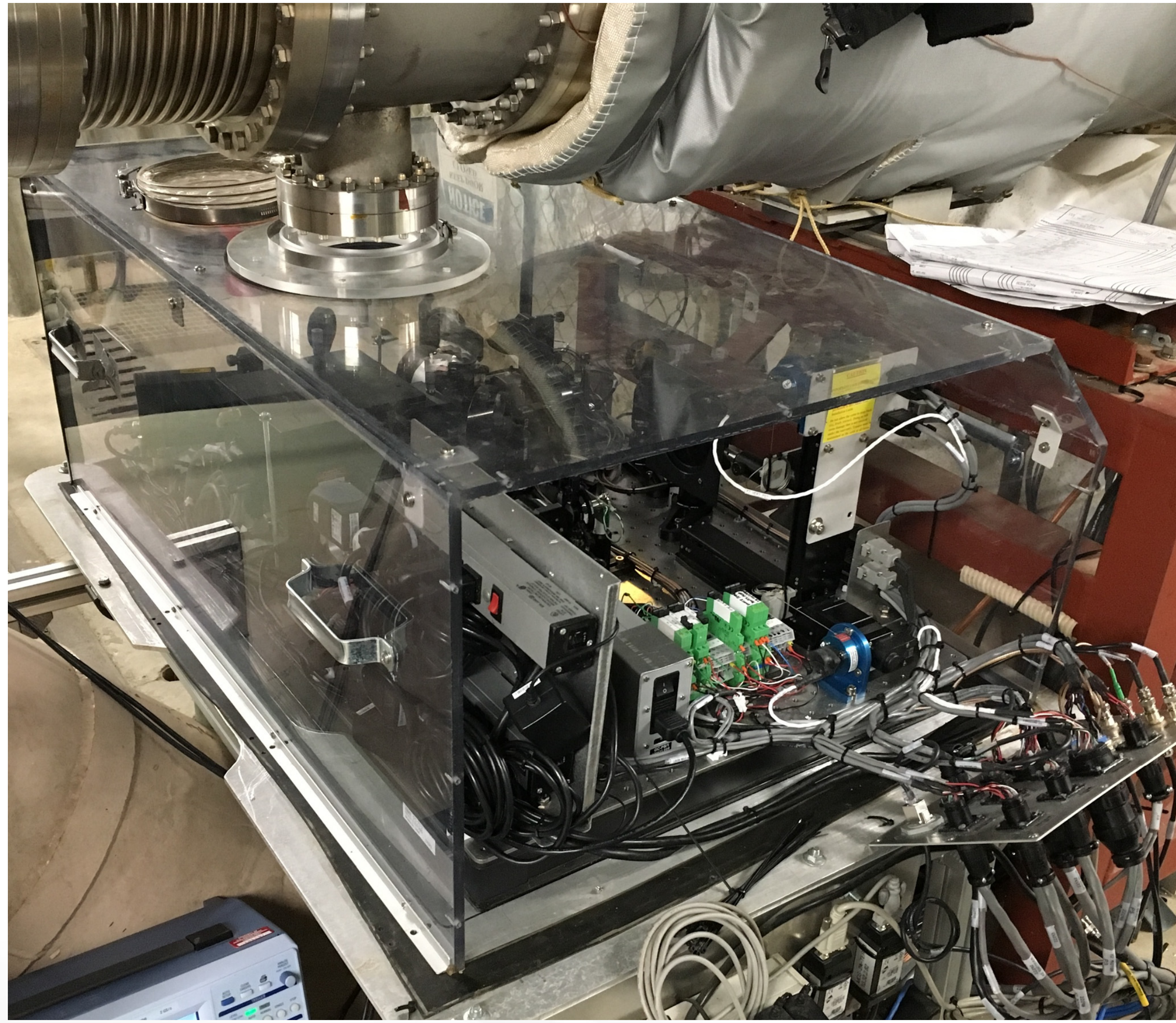
Best measured normalized emittance 0.3 mm mrad

IPAC’17, K. Mihara, Emittance Measurements and Simulations in 112 MHz Super-Conducting RF Electron Gun With CsK_2Sb Photo-Cathode

Infrared Diagnostics

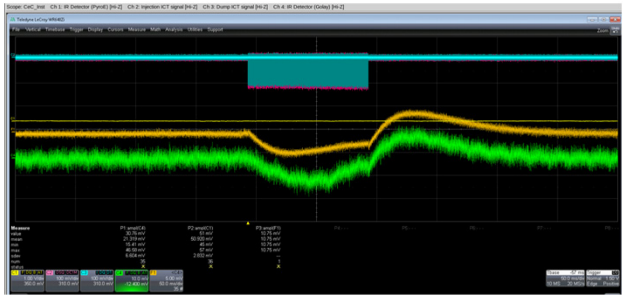
- Insertable copper mirror
- ZnSe window was replaced with diamond window transparent at 30 microns
- Chopper
- Golay cell
- Pyroelectric detector
- Monochromator

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.

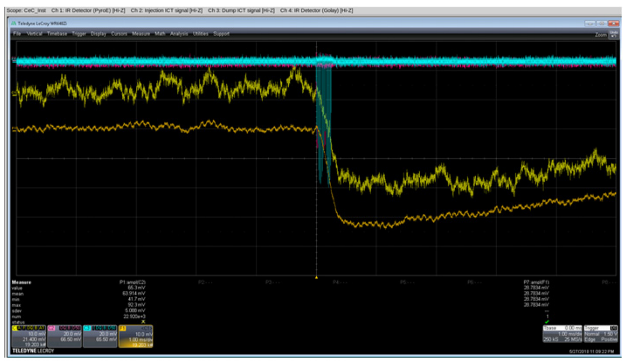


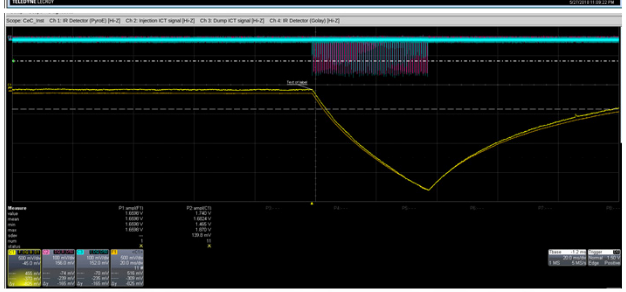
Mechanical vibrations, induced by the chopper located nearby of the detector, were modulating background radiation and therefore made chopper not useful

Infrared Diagnostics (2)

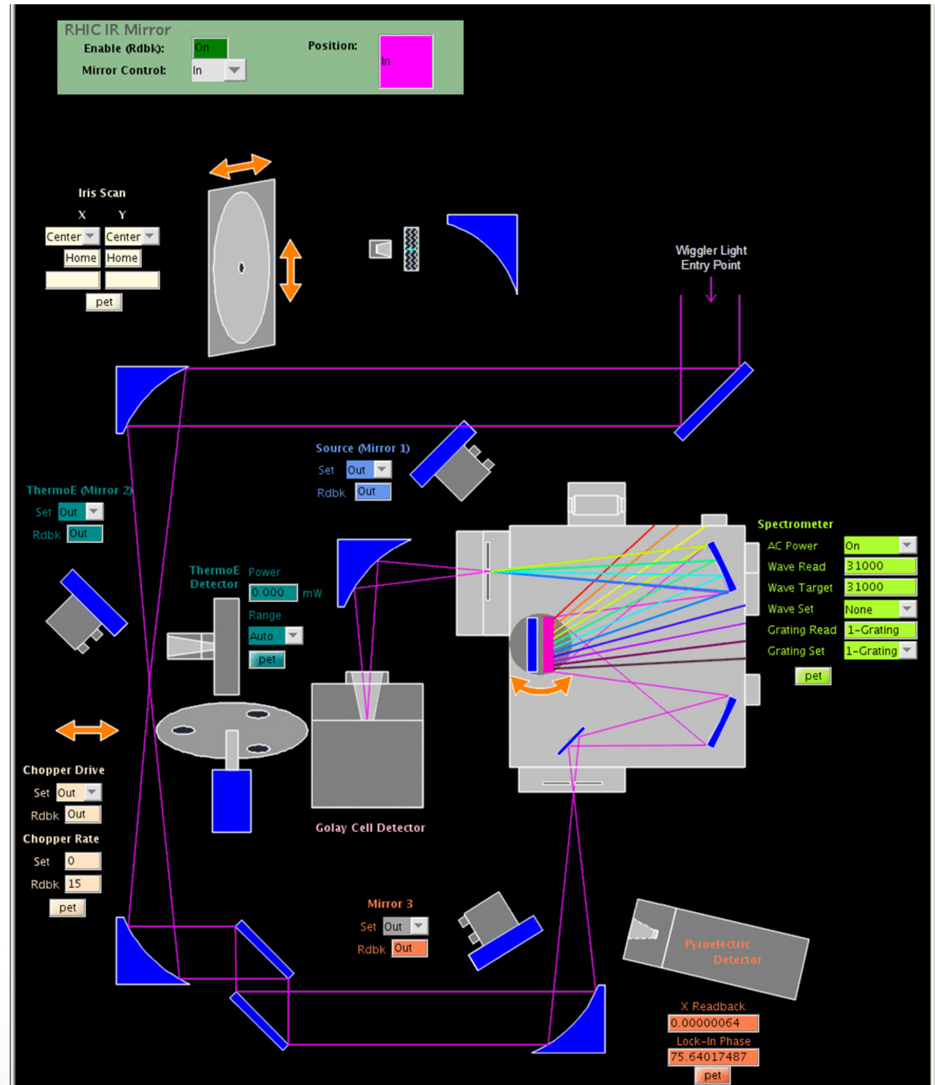


Golay cell signal (green)





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



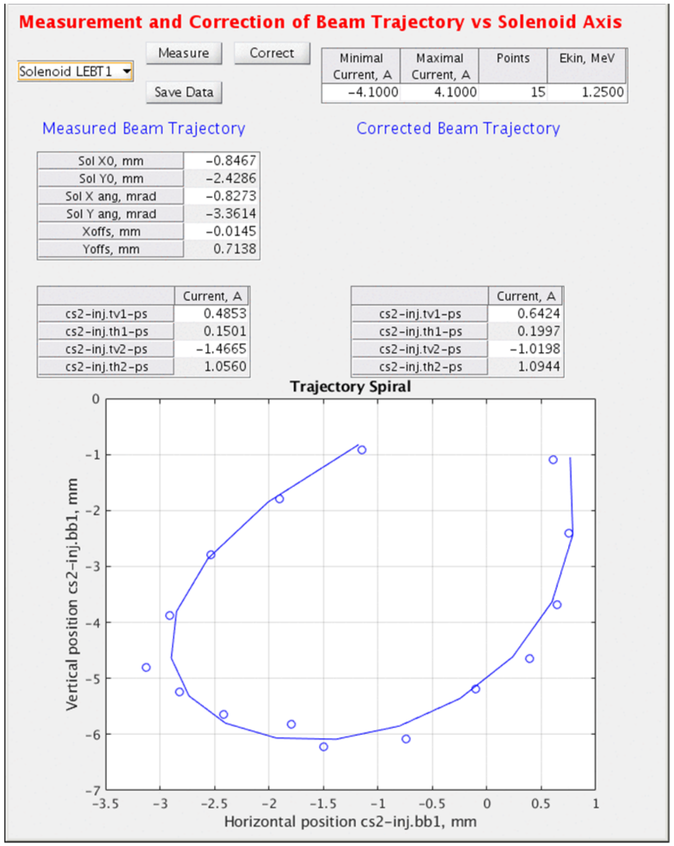
See poster MOPA09 for more information

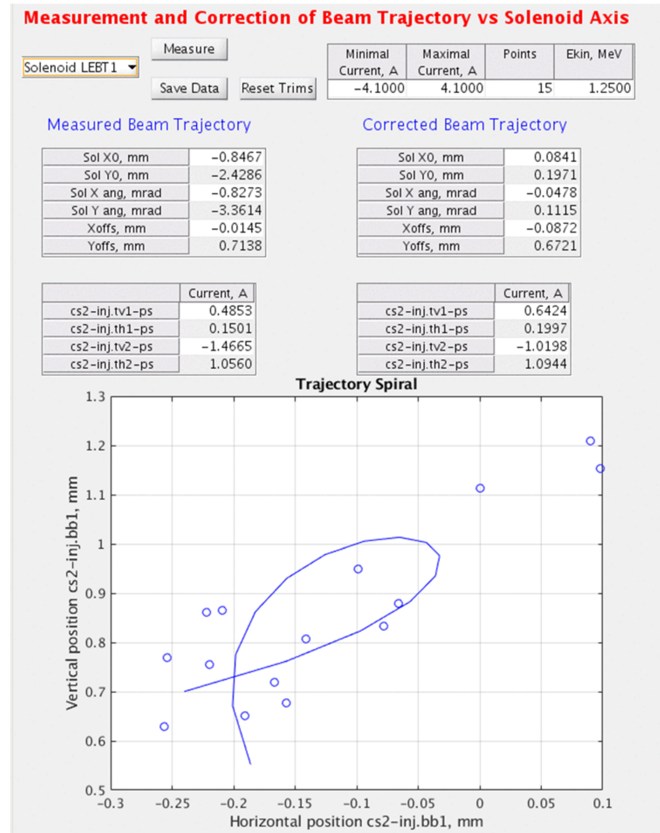
Hadron Beam Instrumentation

- 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

Beam Based Alignment of Solenoids

IBIC 2018
Shanghai China





- 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

$$\begin{pmatrix} x_1 \\ y_1 \\ \vdots \end{pmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & 1 & 0 \\ S_{21} & S_{22} & S_{23} & S_{24} & 0 & 1 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{pmatrix} x_{sol} \\ y_{sol} \\ x'_{sol} \\ y'_{sol} \\ x_{bpm} \\ y_{bpm} \end{pmatrix}$$

See IBIC’17, I. Pinayev et al., Beam Based Alignment of Solenoid

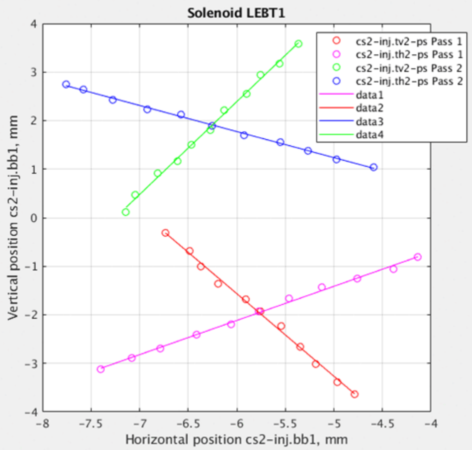
Beam Energy Measurement with Solenoid

- 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%

Solenoid LEBT1 | Measure

Solenoid Current, A	Htrim I, A	H range, A	Vtrim I,A	V range, A	Points
-4.1000	1.3543	0.5000	-1.0095	0.5000	11
4.1000	1.3543	0.5000	-1.0095	0.5000	11

	Tilt 1	Tilt 2	Ekin, MeV
Horizontal scan	35.1472	-28.2648	1.1868
Vertical scan	120.4389	62.3912	1.3301



$$\begin{pmatrix}\tilde{x}\\ \tilde{x}'\\ \tilde{y}\\ \tilde{y}'\end{pmatrix} = M_{rot}M_f \begin{pmatrix}x\\ x'\\ y\\ y'\end{pmatrix}$$

$$M_{rot} = \begin{pmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & -\sin\theta & 0 & \cos\theta \end{pmatrix}$$

$$\theta = \int eB_{\parallel}(s)/2p\, ds$$

$$M_f = \begin{pmatrix} \cos\theta & \sin\theta/k & 0 & 0 \\ -k\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta/k \\ 0 & 0 & -k\sin\theta & \cos\theta \end{pmatrix}$$

Injector Energy Measurement | Measure | Get Bckgr

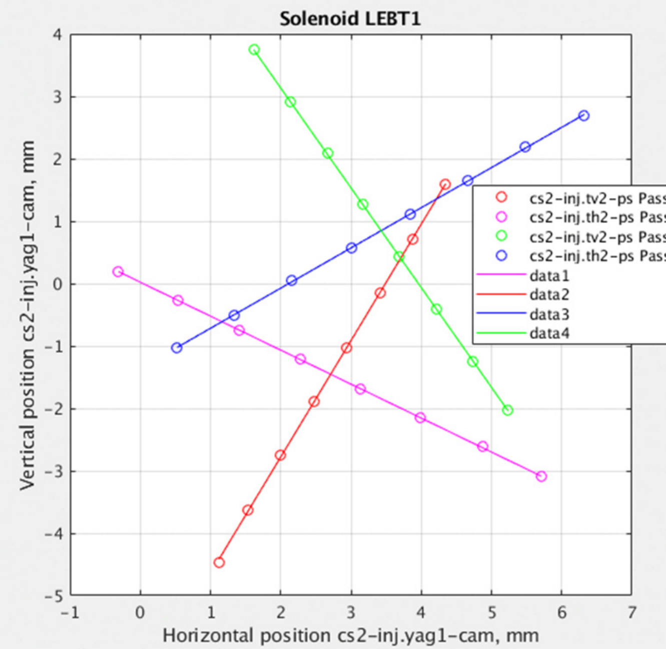
Solenoid LEBT1

Exposure	Gain	Iris	Data	Trigger
10	0	74	MONO_12	external

Solenoid Current, A	Htrim I, A	H range, A	Vtrim I,A	V range, A	Points
4.1000	1.3543	1.5000	-1.0095	1.5000	8
-4.1000	1.3543	1.5000	-1.0095	1.5000	8

	Tilt Angle 1	Tilt Angle 2	Ekin, MeV
Horizontal scan	-28.3257	32.5184	1.2523
Vertical scan	61.5619	122.2861	1.2555

Saturation



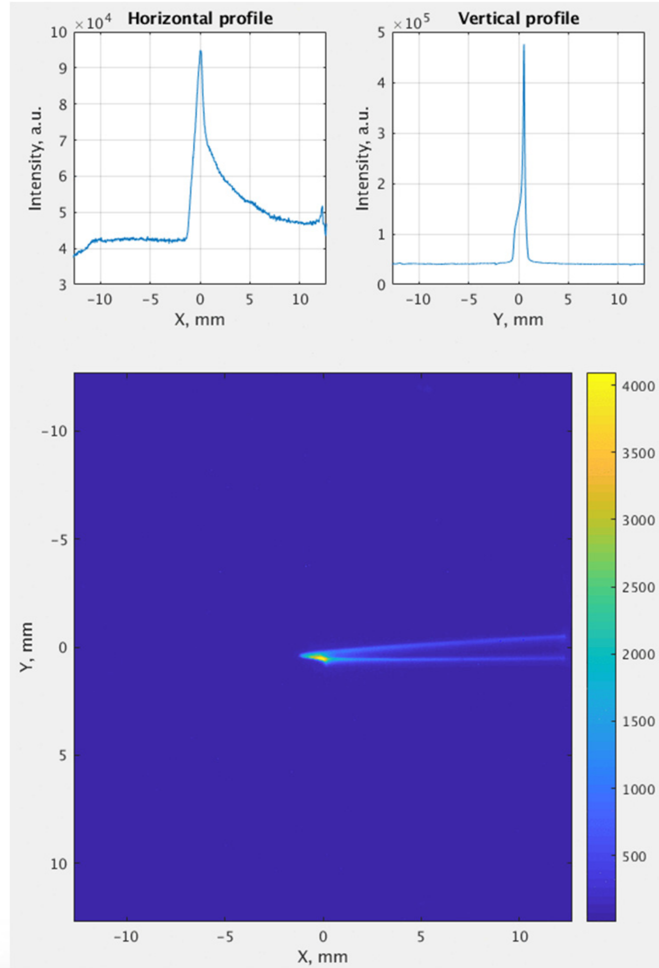
See IBIC'17, I. Pinayev et al., Measuring Beam Energy with Solenoid

Beam Energy Measurement with Dipole

Energy and energy spread of the electron beam were measured on the profile monitor after the first dipole before injection into the common section with RHIC.

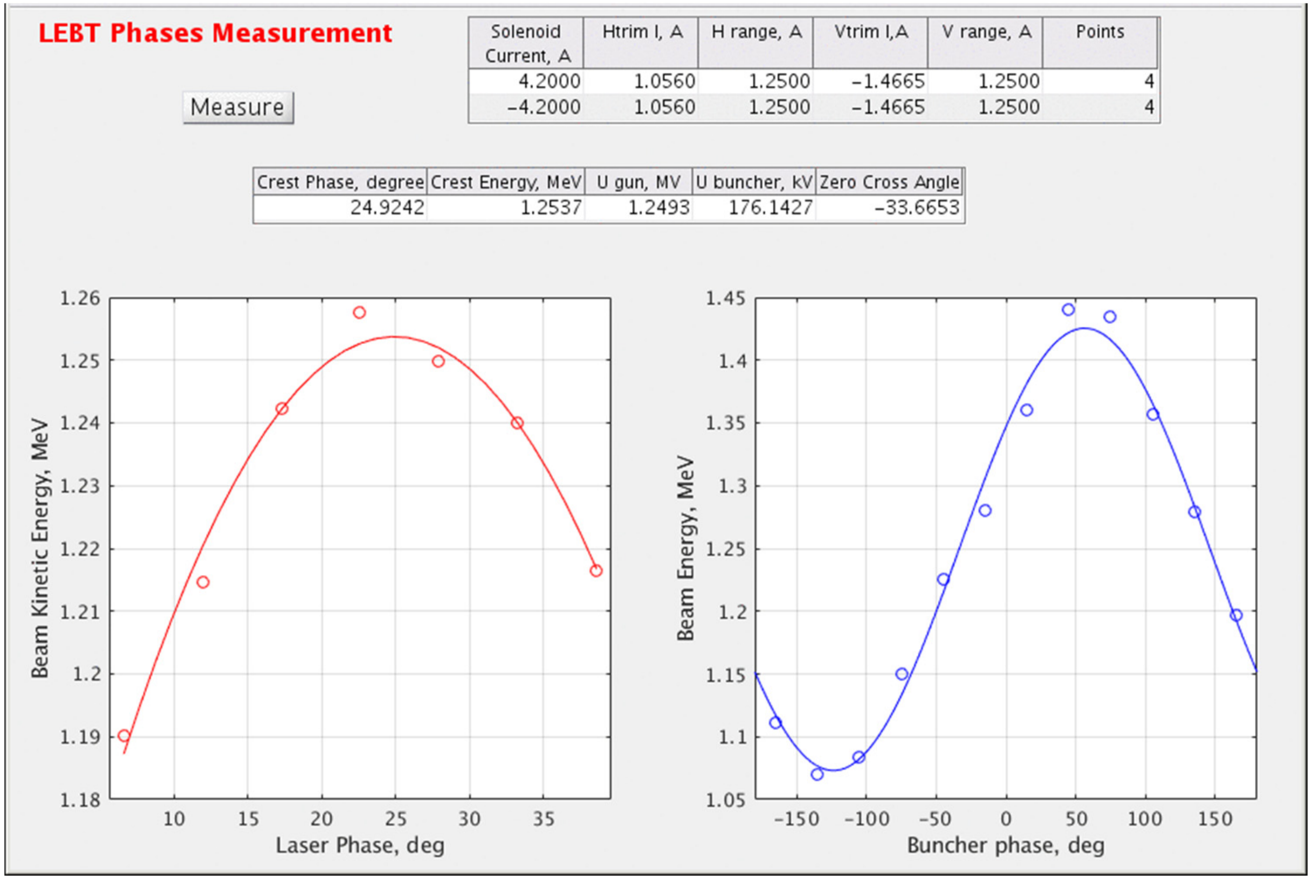
With quadrupoles off the dispersion at the location of the profile monitor is 1.3 m.

Dipole was used for coarse tuning. Fine tuning to $\Delta E/E=10^{-3}$ is done using FEL signal.



Beam shape on the profile monitor. Traces above show intensity projections.

Phasing of the RF Cavities



Correction for the final bunch length and RF frequency should be done

- The laser timing (phase) is changed and beam energy is measured. The phase of maximal energy is found.
- Buncher cavities voltage was fixed close to the operational level and full 360 degrees phase scan is done optimize beam compression

Hadron Beam Trajectory

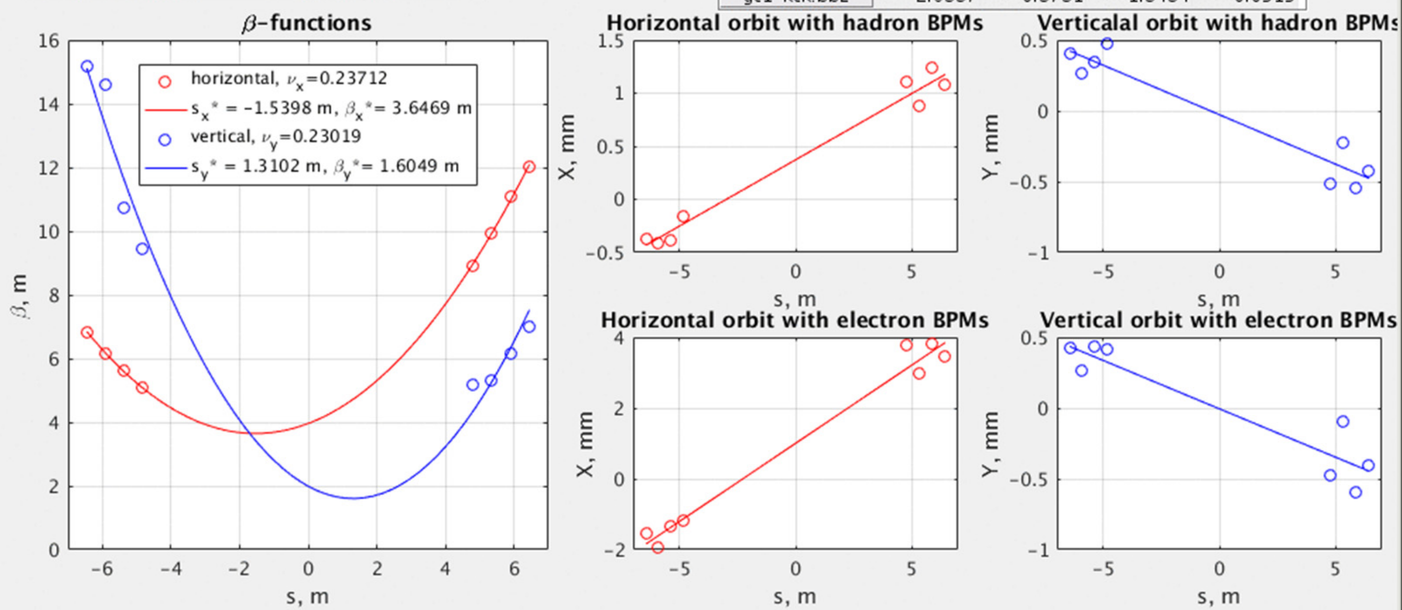
Common Section Orbit

Measure Save

	Xmeas, mm	Ymeas, mm	Xoffs, mm	Yoffs, mm
gc2-mod.bb1-y	-0.3166	-1.5118	0.0878	-1.9197
gc1-fel.bb-y	0.6698	0.3537	0.1329	0.4730
gc1-kck.bb2-y	0.3743	-0.4623	-0.8377	0.0350

	Xmeas, mm	Ymeas, mm	Xoffs, mm	Yoffs, mm
gc2-mod.bb1	0.1326	0.5073	1.8768	0.0873
gc2-mod.bb2	-0.4711	1.1275	0.5797	0.8148
gc2-fel.bb	0.9109	0.2805	0.5945	0.1792
gc1-fel.bb	1.3440	-0.0043	-0.2437	0.0911
gc1-kck.bb1	1.7787	-0.1312	-1.0803	0.1609
gc1-kck.bb2	2.6337	-0.3731	-1.3434	0.0919

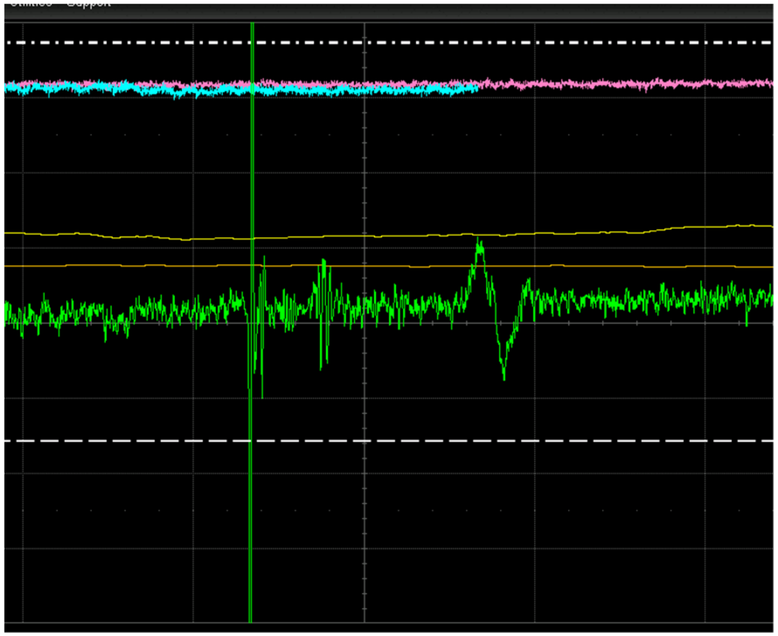
Imax, A	N	Number of points	B rho, T m
6.3000	15	60	727.7000



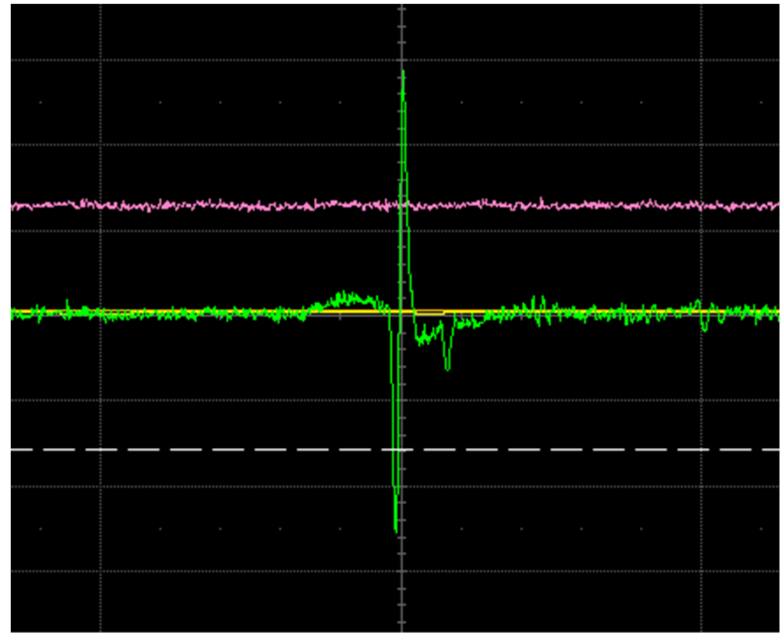
Quadrupoles in the common section were modulated and tune shift measured. From the BPM readings orbit offset from the quadrupole center is found.

We also utilized minimization orbit disturbance by modulated quadrupoles in the RHIC BPMs.

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.

Conclusions

- Utilized set of the diagnostics provided most of the required functionality (no electron bunch length measurement)
- We measured electron bunch charge from 30 pC to 4 nC and electron beam current based on the sum of the individual bunch charges
- The BPMs were capable to measure hadron and electron beam positions co-propagating in the same vacuum chamber
- Two new methods for measuring beam trajectory vs. solenoid axis (position and angle) and energy utilizing solenoid were developed
- Electron normalized emittance as low as 0.3 mm mrad was measured
- Relative energy spread better than 10^{-3} was demonstrated

Many thanks to

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