An Overview of Beam Instrumentation Results and Commissioning from the PIP-II Injector Test Accelerator at Fermilab

Vic Scarpine

IBIC 2017

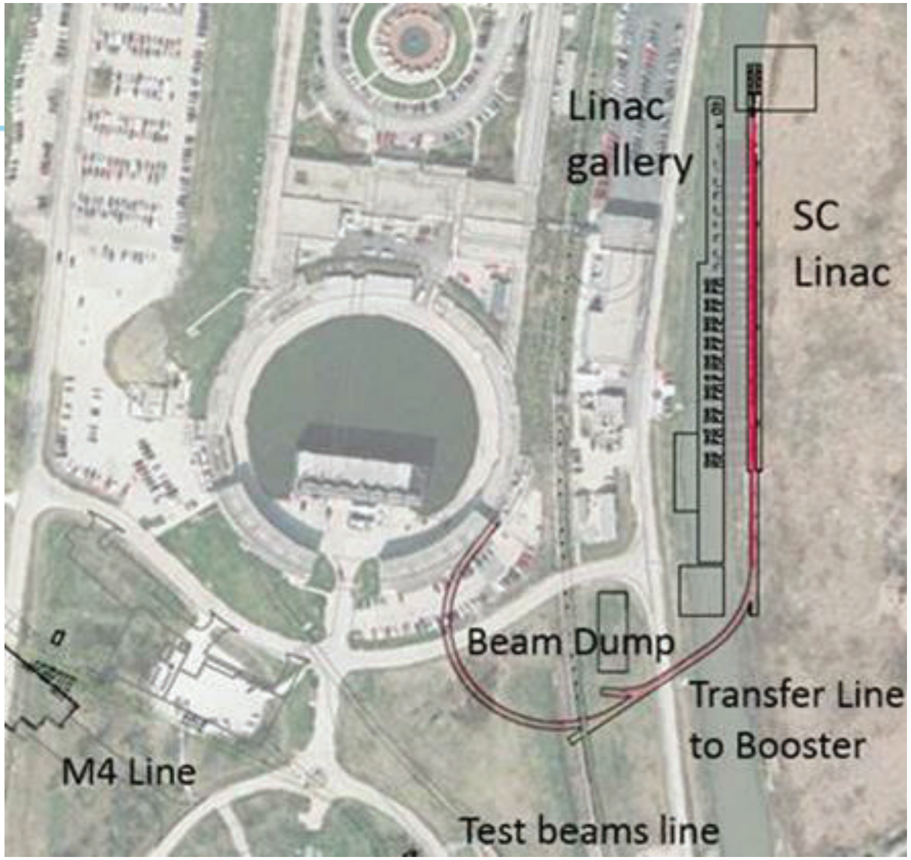
21 August 2017

Outline

- Proton Improvement Plan II (PIP-II)
- PIP-II Injector Test (PIP2IT)
- PIP2IT Layout and Diagnostics
  – LEBT
  – MEBT
- Challenges for PIP-II Beam Instrumentation

The PIP-II (Proton Improvement Plan II)

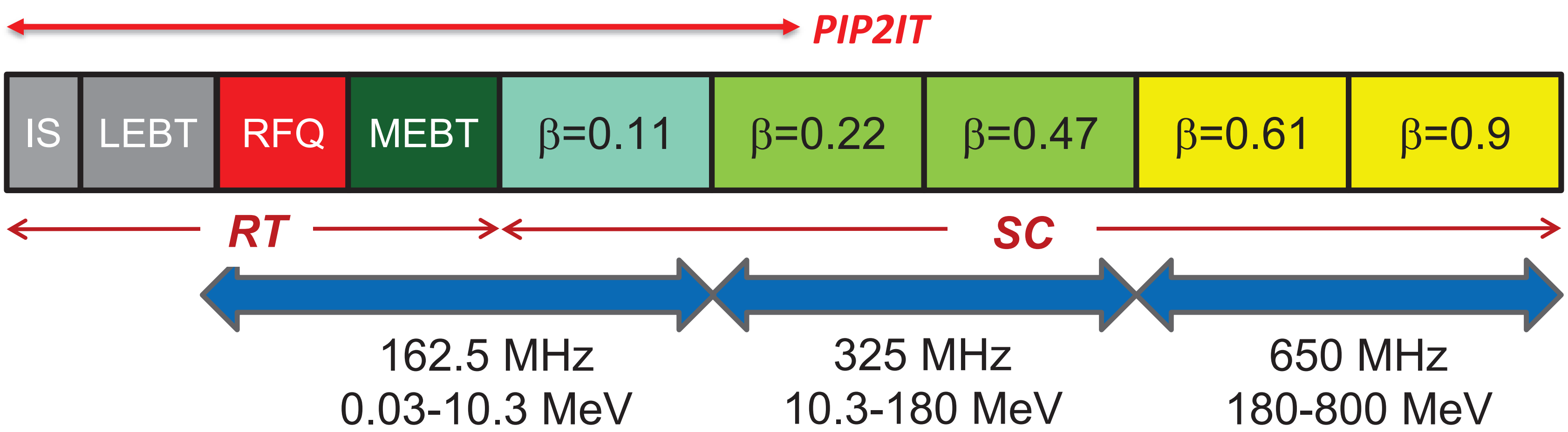
PIP-II is a proposed roadmap to upgrade existing proton accelerator complex at Fermilab. It is primarily based on construction of a 800 MeV superconducting linear accelerator that would be capable of operating in continuous wave (CW) mode.



PIP-II Linac High Level Performance Goals

Beam Energy	800 MeV
Beam Current (chopped)	2 mA
Pulse Length	0.54 ms
Pulse Repetition Rate	20 Hz
Upgrade Potential	CW

PIP-II Linac Technology Map



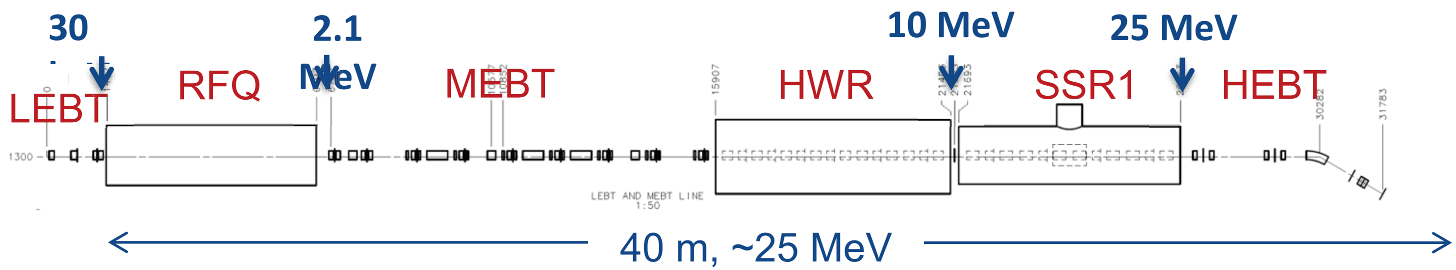
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_{opt}=0.65)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_{opt}=0.97)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

PIP-II Injector Test (PIP2IT) Accelerator

PIP2IT will perform an integrated system test of the room temperature front-end and the first two cryomodules of the proposed PIP-II accelerator

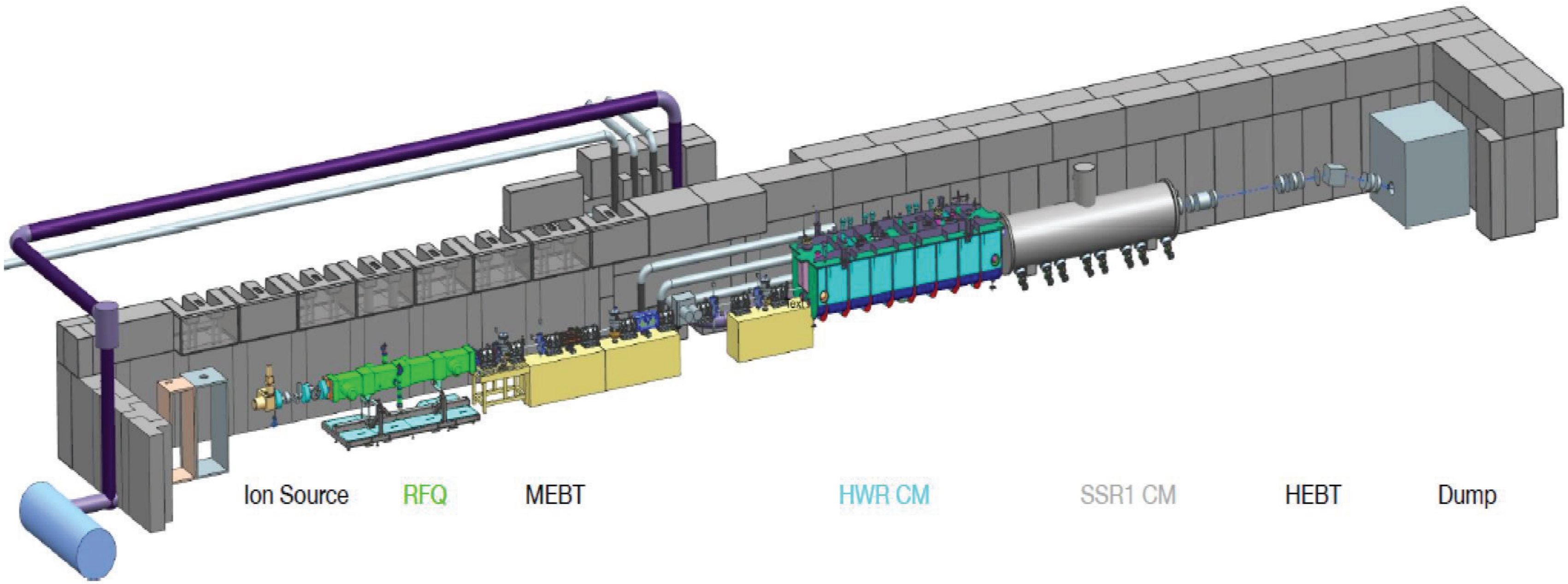


PIP2IT will address:

- LEBT pre-chopping
- CW 162.5 MHz, 2.1 MeV RFQ
- Validation of chopper performance
  - Bunch extinction, effective emittance growth
- MEBT beam absorber
  - Reliability and lifetime
- CW Operation
- Operation of HWR and SSR1 with beam
- Emittance preservation

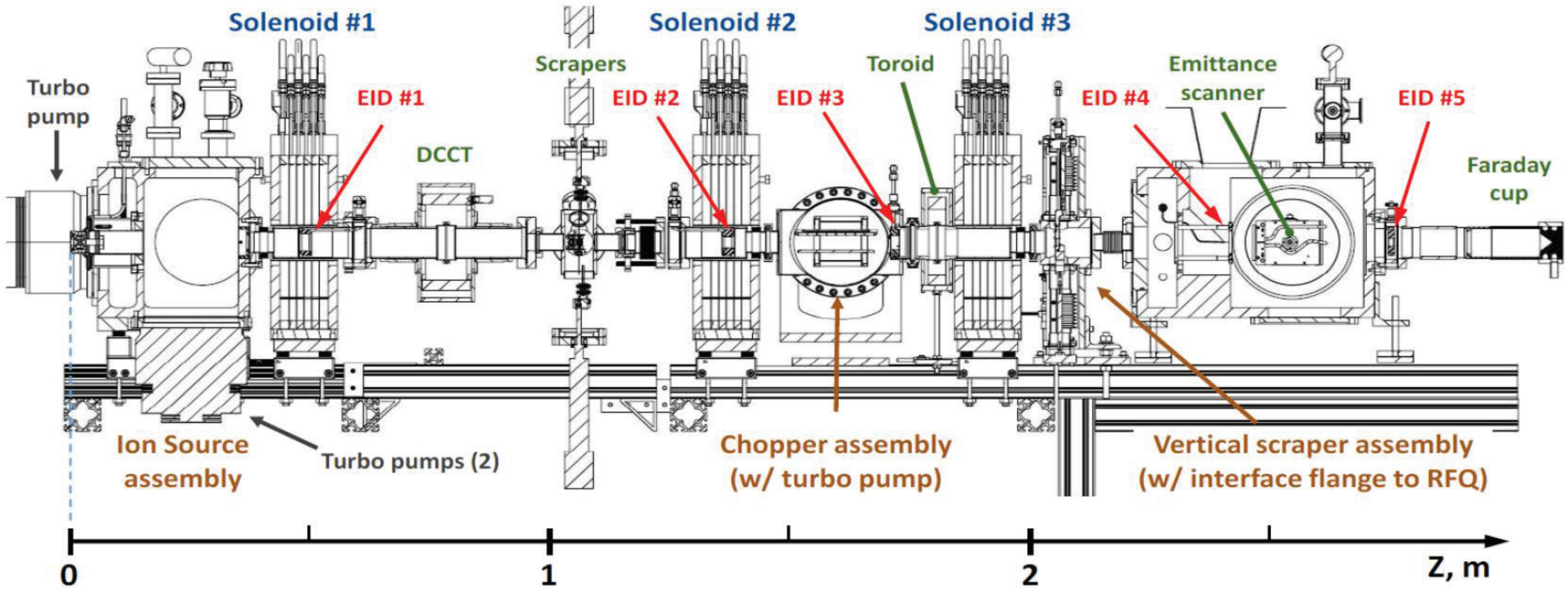
Parameter	Value	Unit
Beam kinetic energy, Min/Max	15/30	MeV
Average beam power	≤ 30	kW
Nominal ion source and RFQ current	5	mA
Average beam current (averaged over > 1μs)	1	mA
Maximum bunch intensity	1.9×10^{8}	
Minimum bunch spacing	6.2	ns
Relative residual charge of removed bunches	$< 10^{-4}$	
Beam loss of pass-through bunches	< 5%	
Nominal transverse emittance*	< 0.25	μm
Nominal longitudinal emittance*	< 1	eV-μs

Proposed PIP2IT Hardware Layout



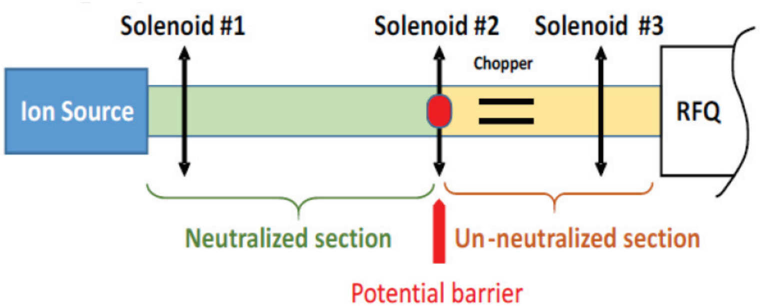
From left, ion source and LEBT, 4-vane RFQ, MEBT with bunch-by-bunch chopper, HWR cryomodule, SSR1 cryomodule, (6) HEBT and beam dump. At this time, ion source, LEBT, RFQ and part of MEBT have been installed and commissioned or under test.

PIP2IT Ion Source and LEBT Commissioning



LEBT Parameters

Parameter	Value	Unit
Kinetic energy	30	keV
Nominal/Maximum beam current, DC	5/10	mA
Output transverse emittance over 2-5 mA current range	< 0.18	µm
Typical pressure	$\sim 10^{-6}$	Torr
Chopping frequency, max	60	Hz
Pulse length	1-16600	µs



- Full neutralization upstream of Sol#2 and zero downstream
- Chopper between Sol#2 and #3

Hardware in action…

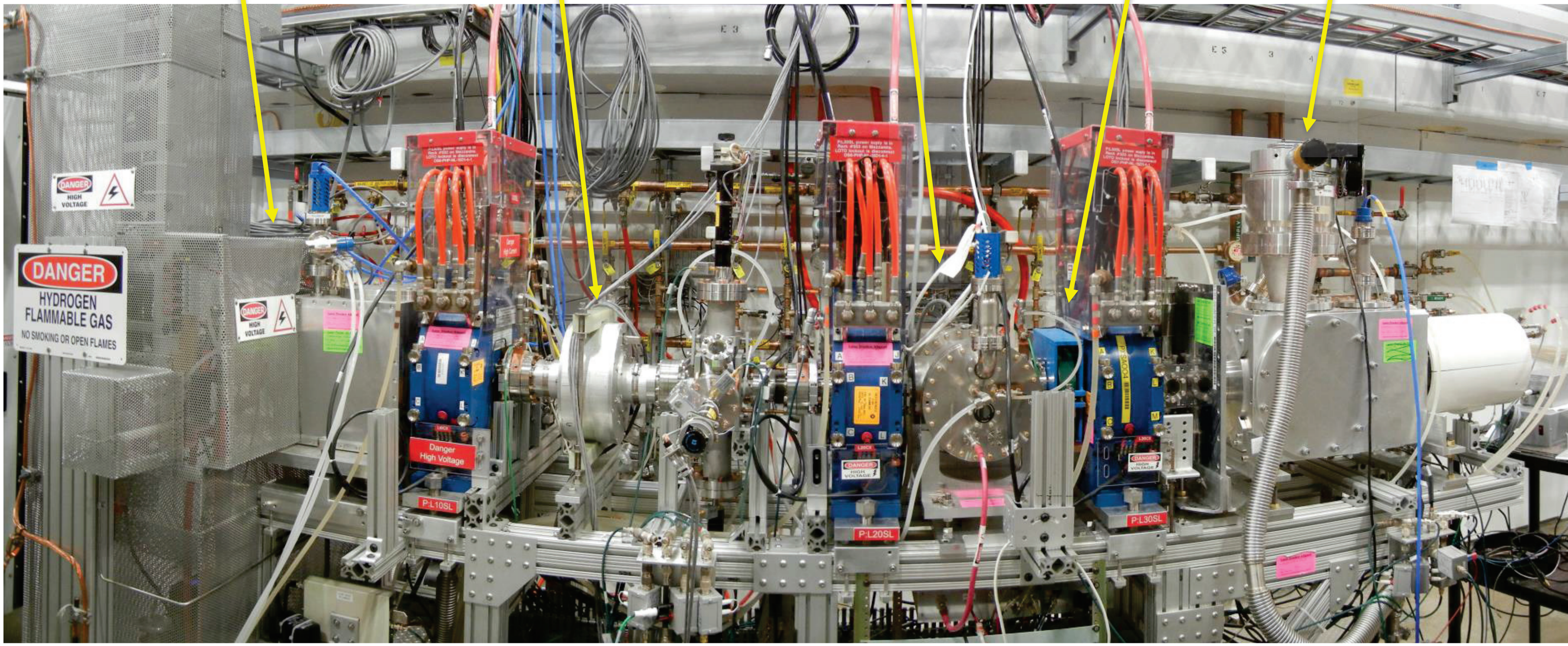
Emittance Scanner

Chopper

Source

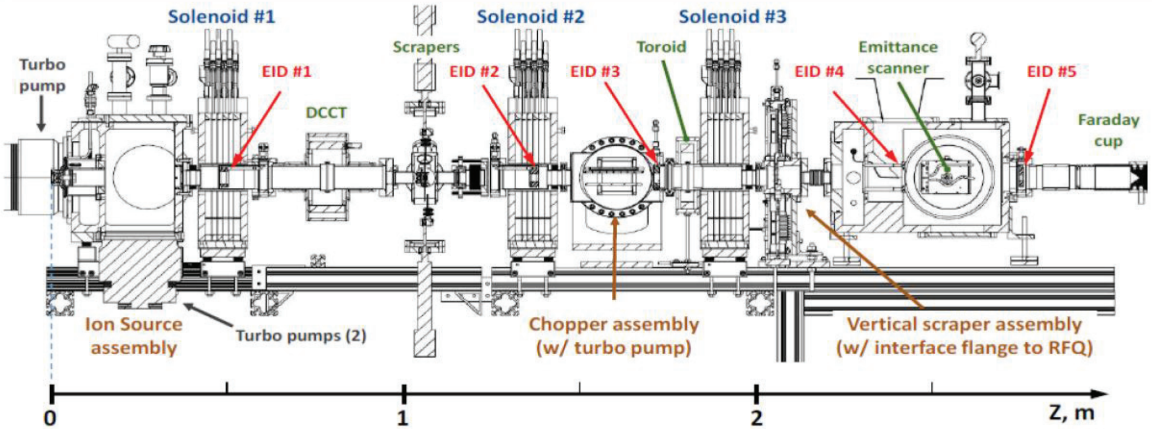
DCCT

Toroid

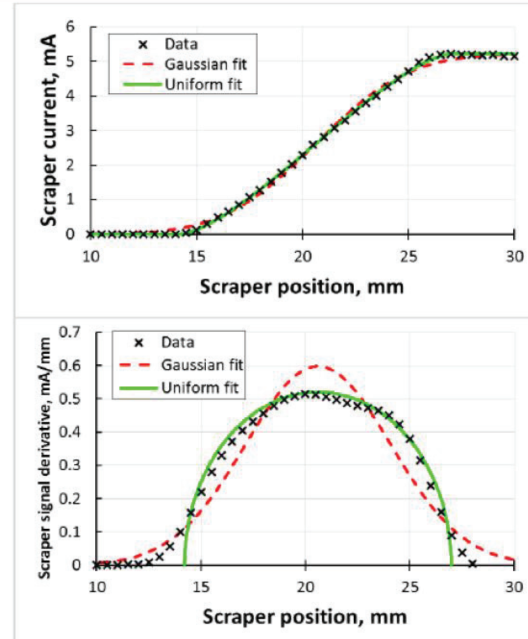


LEBT commissioning beamline

LEBT Diagnostics



- Beam current: DCCT, toroid (ACCT), Faraday Cup, EIDs
- Beam profile: scans with dipole correctors; scrapers
  - LEBT scraper (permanent)
  - Temporary scrapers
- Allison type emittance scanner
  - In several locations



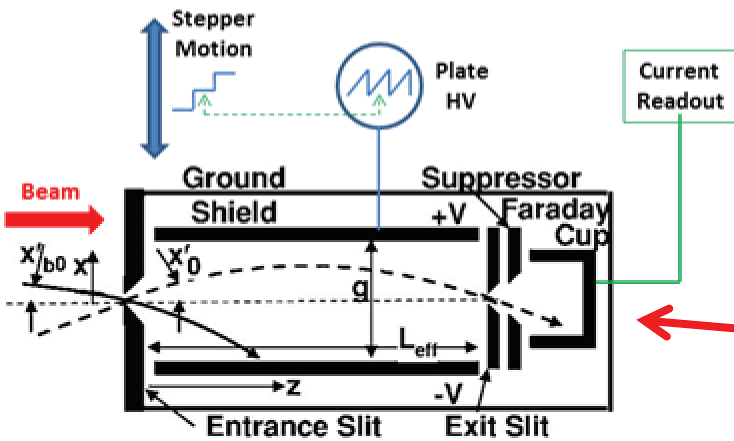
Horizontal beam size measurements with temporary scraper. (a) - current measured from the scraper plate as a function of the scraper position; (b) – density projection on the horizontal axis reconstructed as a derivative of the data in (a) over position. The data are recorded 1 ms from the front of a 1.5 ms modulator pulse.

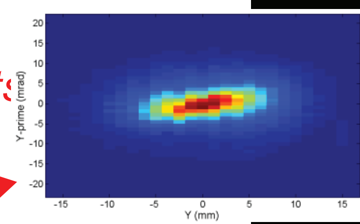
A. Shemyakin

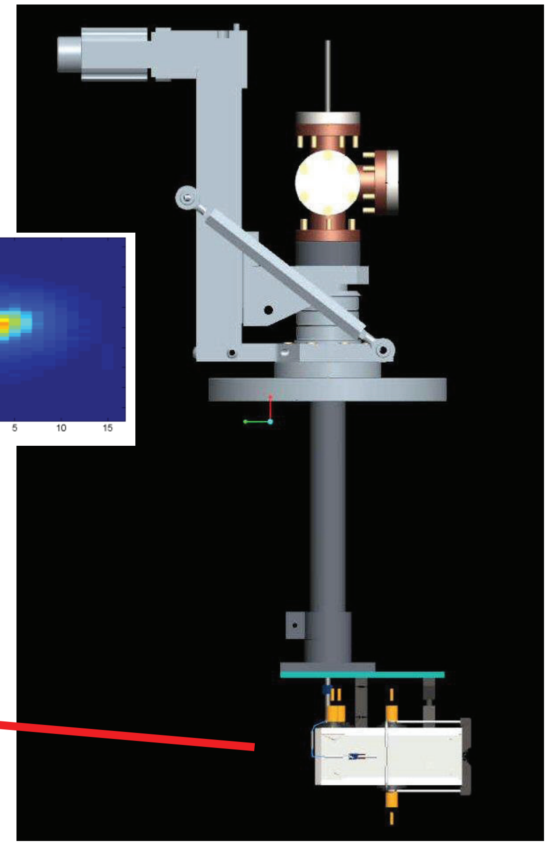
LEBT Allison Scanner for Source/LEBT Emittance Measurements

Water cooled Allison scanner – CW operation

- Developed in collaboration with SNS
- Adjustable entrance slits
- Status:
  - Installed in multiple locations in LEBT
  - *Over 1000 phase-space measurements*

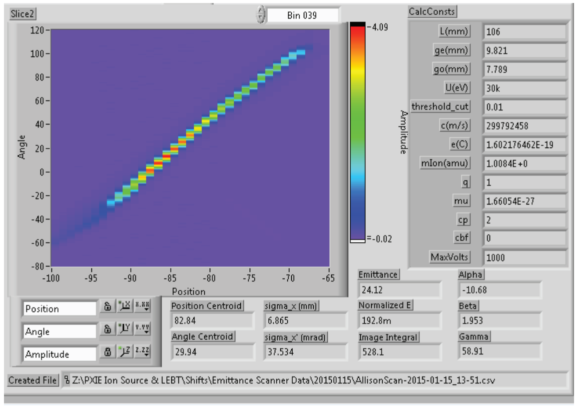






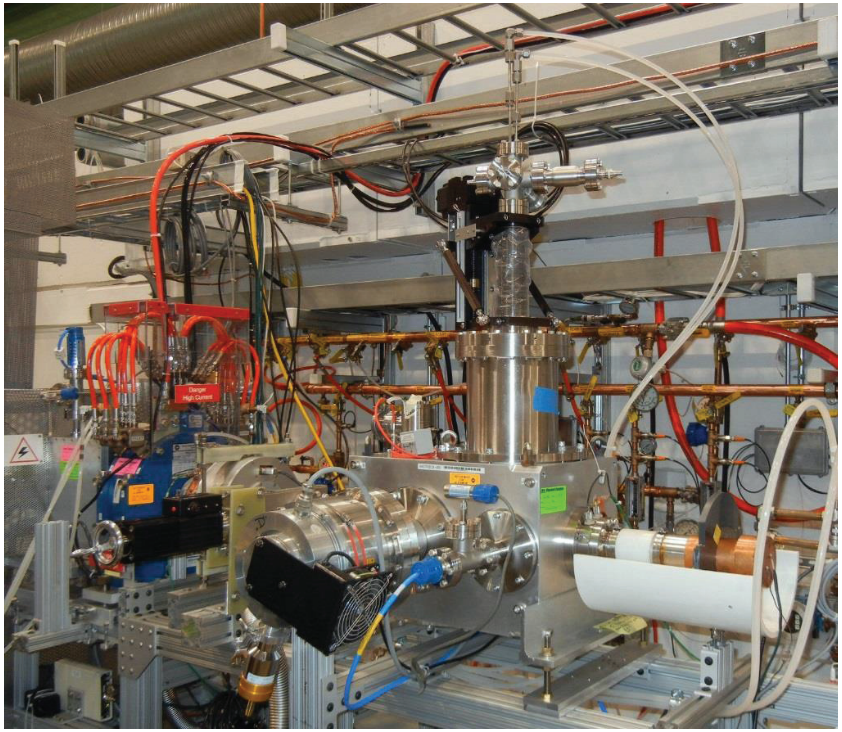
Initial LEBT Allison Scanner Installation

Labview-based DAQ and analysis software



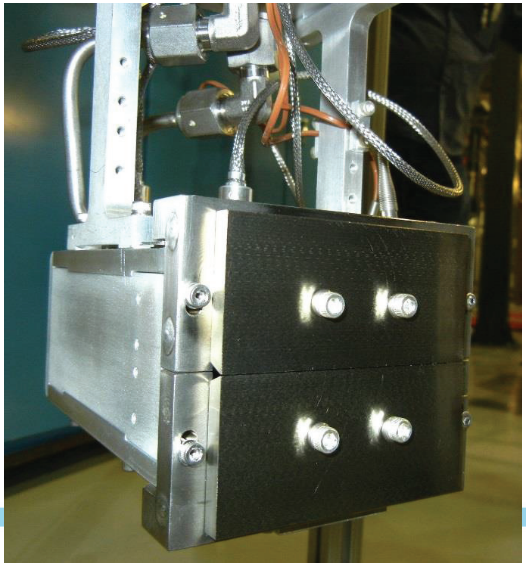
Courtesy of SNS

Installation after 1st Solenoid – May 2014



Operated in both vertical and horizontal orientations

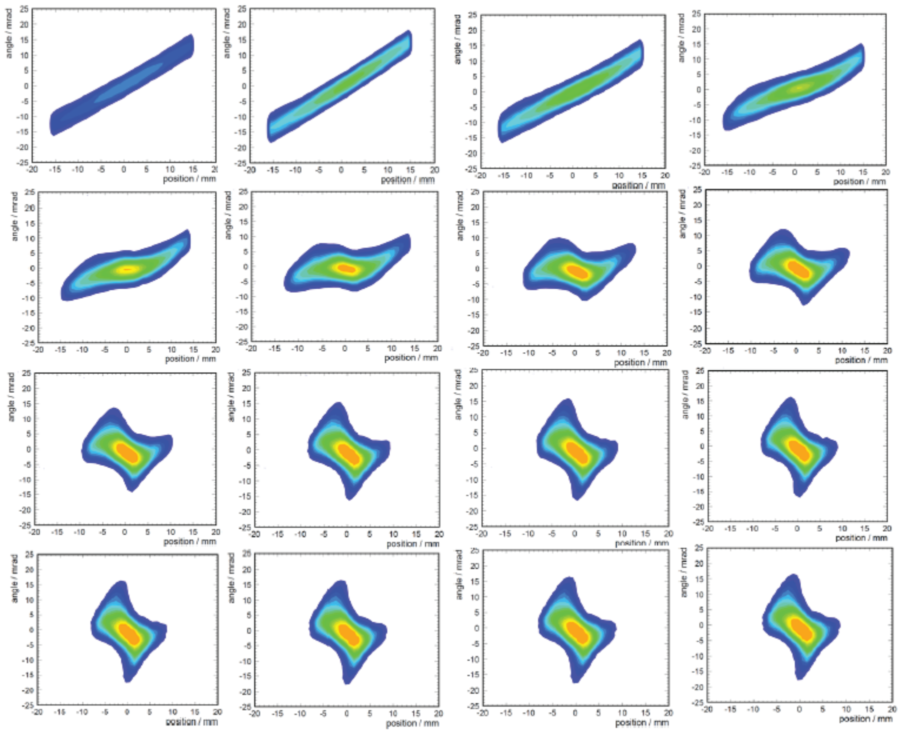
Front-slit made of TZM pressed against water-cooled blocks



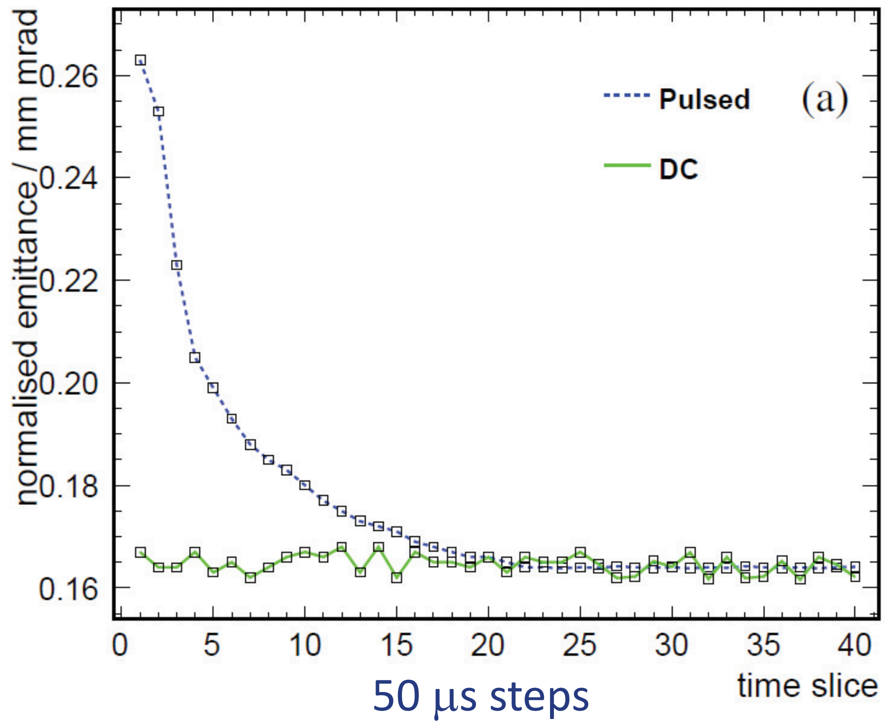
Electronics rack

Fermilab

LEBT Allison Scanner Measurements



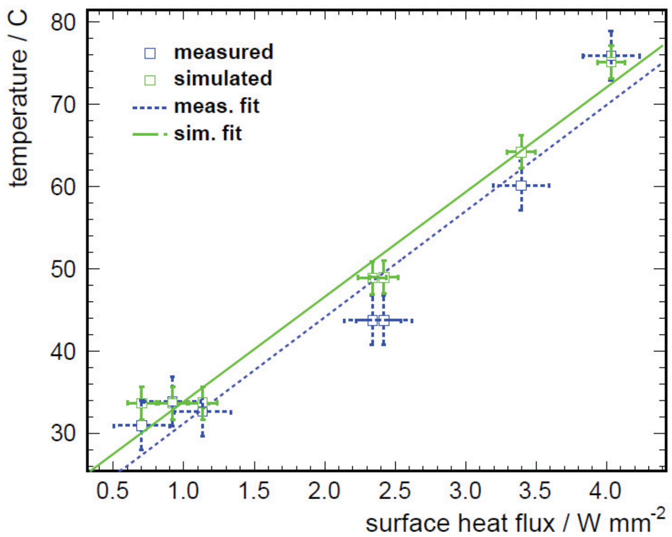
Evolution of phase space along 2 ms, 5 mA beam pulse for pulsed ion source beam.



Emittance evolution for ion source pulsed versus DC beam. Pulsed beam shows neutralization of H- beam.

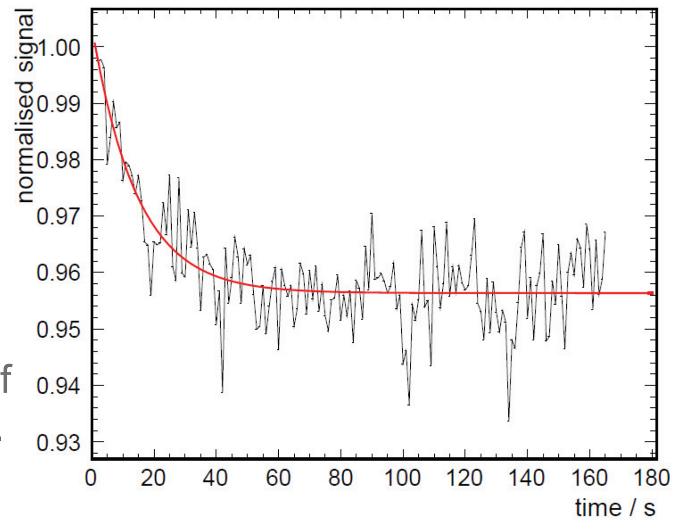
LEBT Allison Scanner Thermal Studies

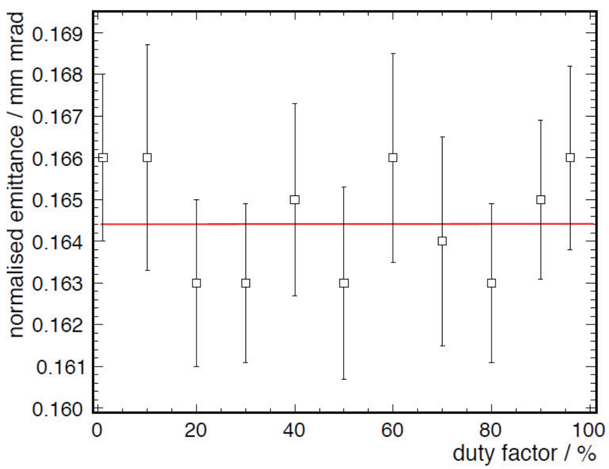
Effect of beam duty factor on emittance measurements



Measured and simulated front slit temperature versus surface heat flux

H- signal drop in emittance scanner due to thermal expansion of front slits for DC beam.





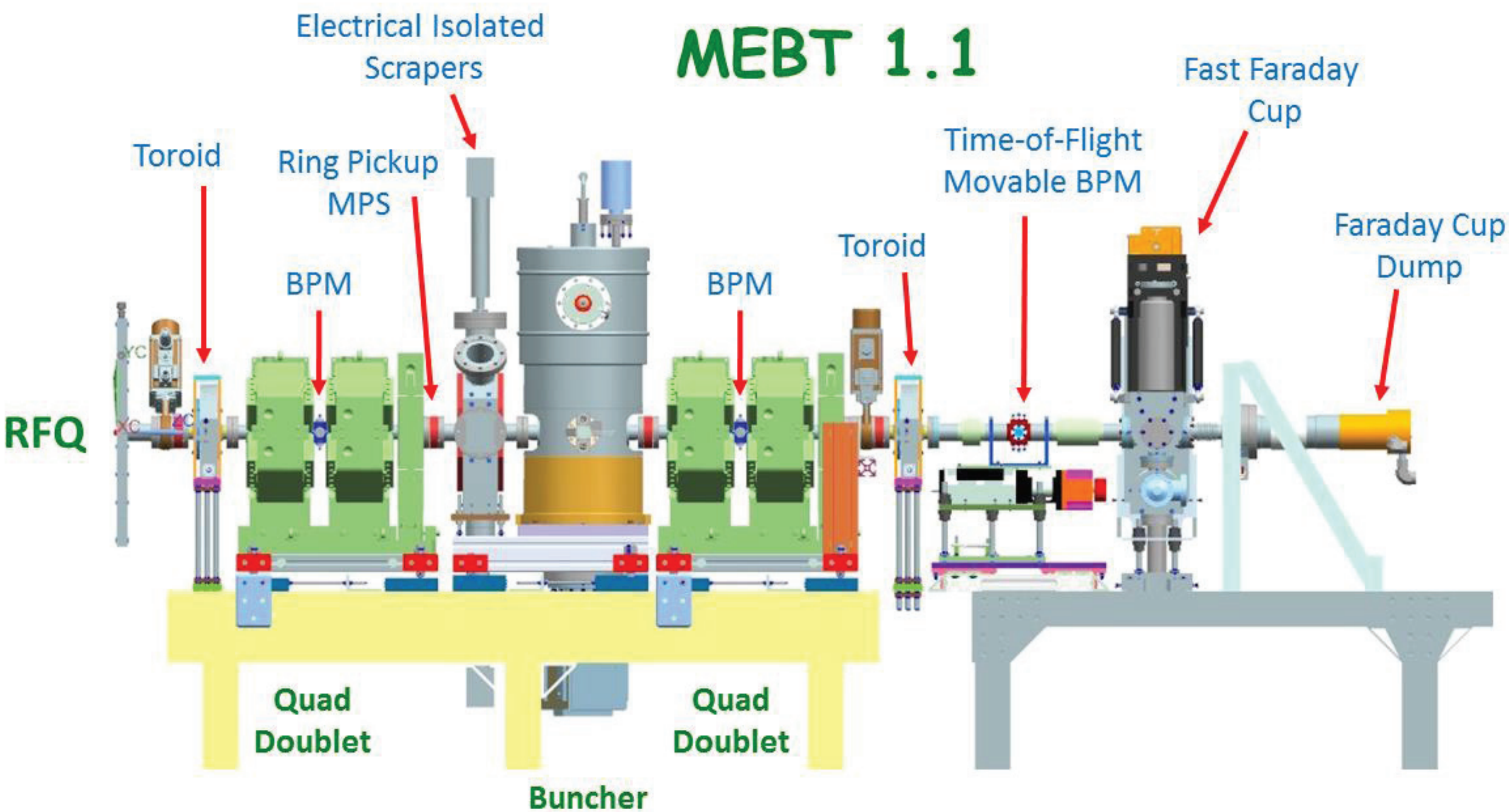
Normalized emittance versus beam duty factor

MEBT Beam Diagnostics

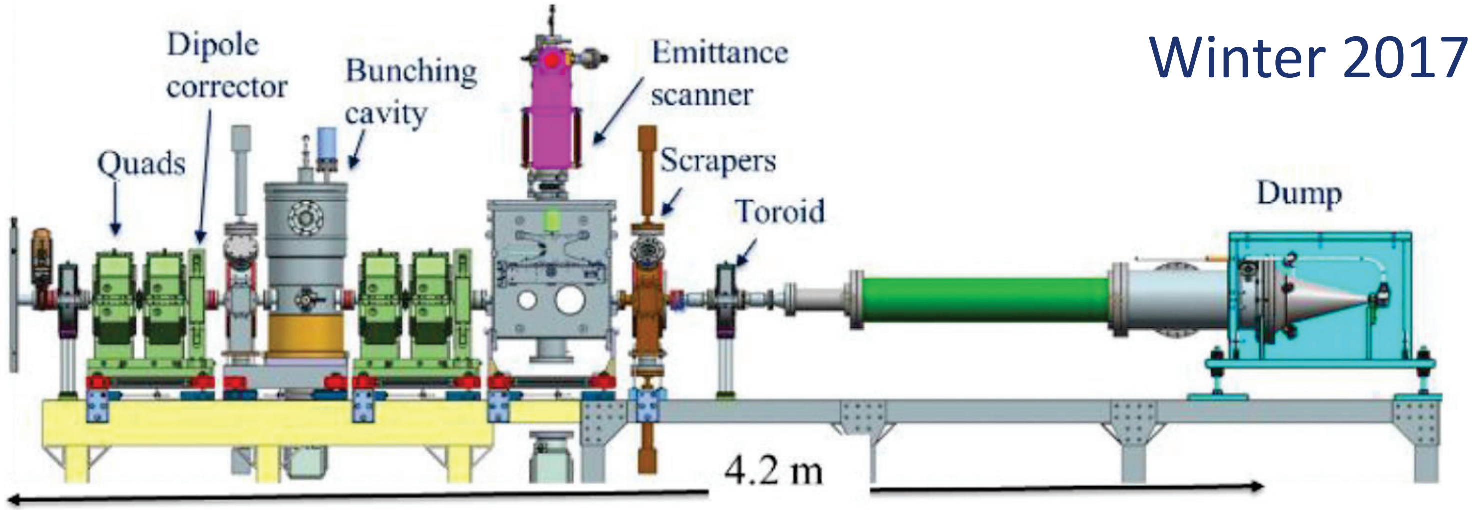
- Beam current measurements
  - Toroids, isolated beam dump, ring pickup, electrically isolated pickups (scrapers)
- Beam position and phase
  - Warm BPMs - installed in quadrupole doublets
- Beam transverse profiles
  - Electrically isolated beam scrapers
  - Laser profiler under development
- Beam energy
  - Time-of-flight via movable BPM
- Beam transverse emittance
  - Allison-style emittance scanner
- Longitudinal bunch shape
  - High-bandwidth Faraday Cup - > 6 GHz BW
  - Laser profiler under development

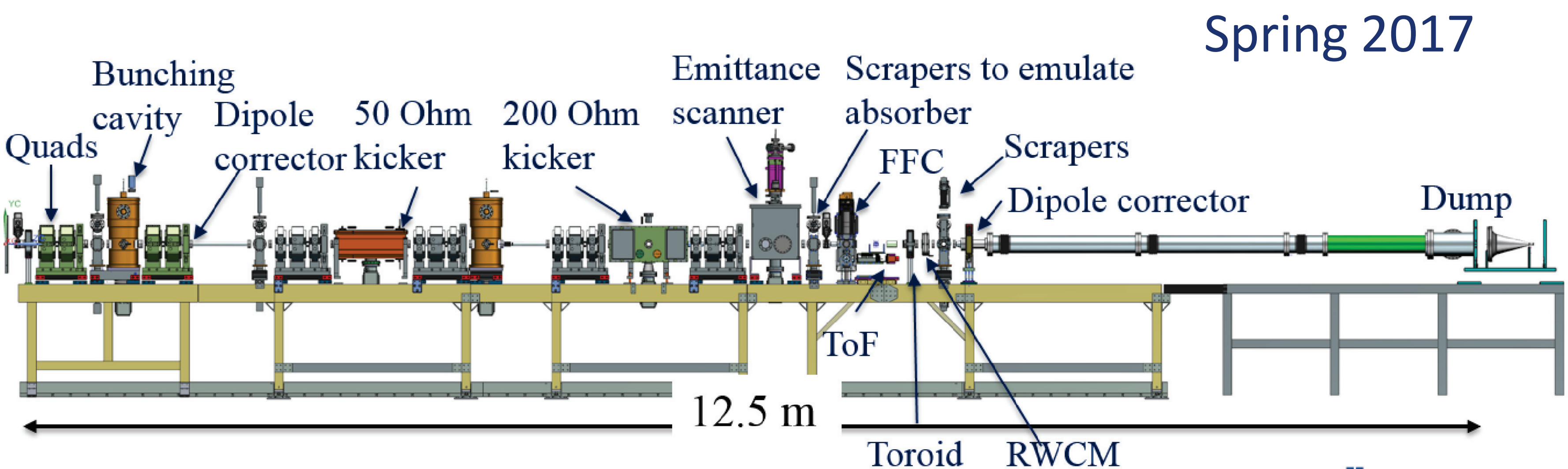
PXIE MEBT Instrumentation Development – Initial RFQ Commissioning

Spring 2016



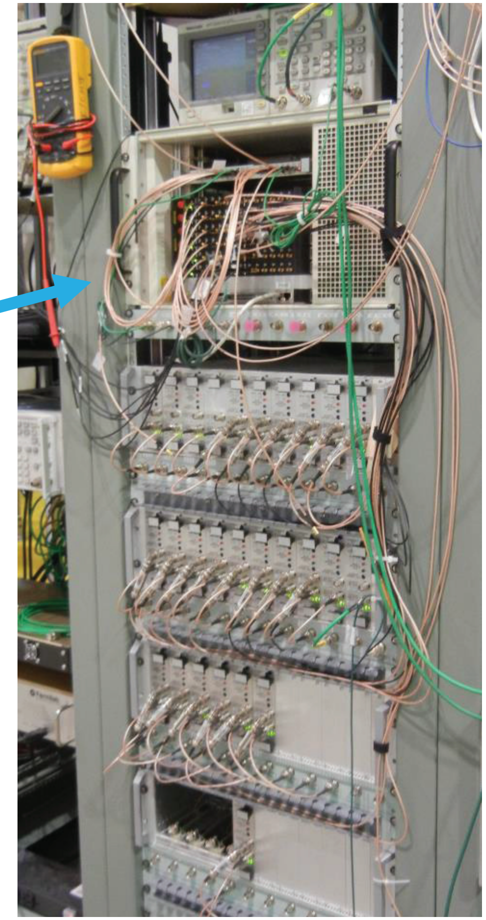
PIP2IT MEBT Commissioning Layouts

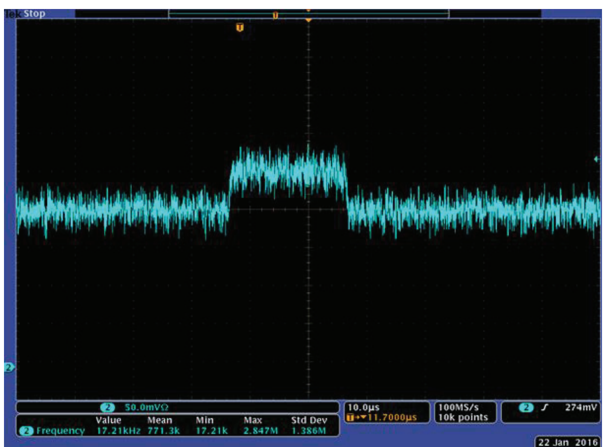




MEBT Beam Current Measurements

- *Toroids, Faraday cup dump, ring pickups and EIP(scrapers)*
- Utilize FPGA-based 8-channel, 125 MHz, 14 bit digitizer cards and analog transition/bias cards
  - Integrates with MPS
- Noise and systematic effects are an issue
  - Large gain on toroids
  - *Tight beam loss requirements for MPS*
- Electrically Isolated Pickups (EIP) - scrapers
  - Bias up to +100 volts

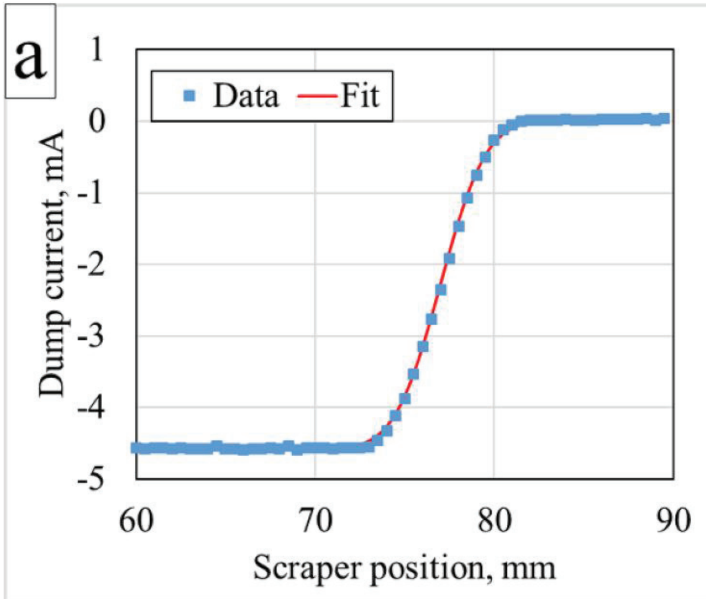


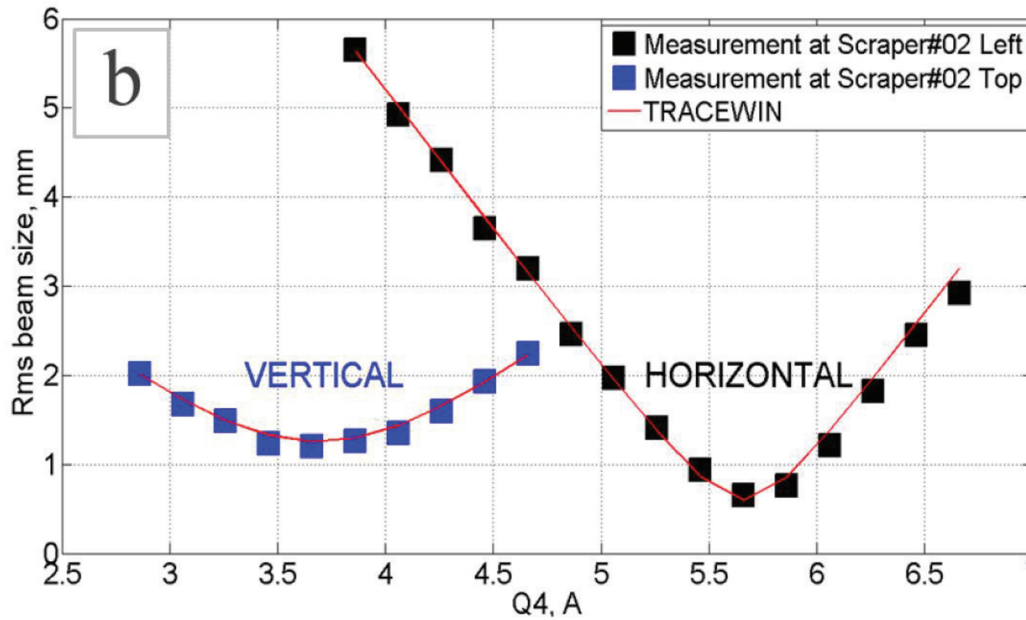


LEBT Toroid

- Calib signal
- 1 mA, 20 µs
- 50 mV signal
- 60 db gain

Beam Size Measurements via EIP (Scrapers)



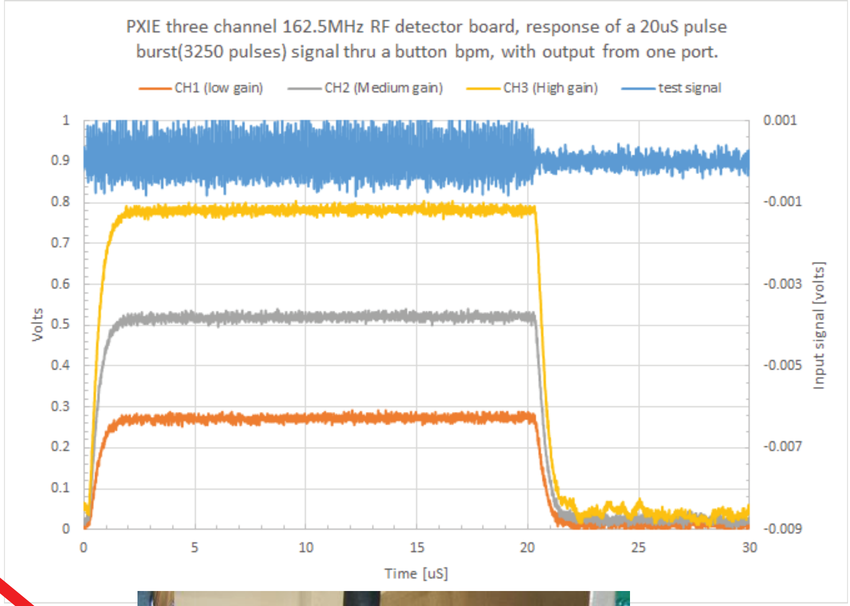


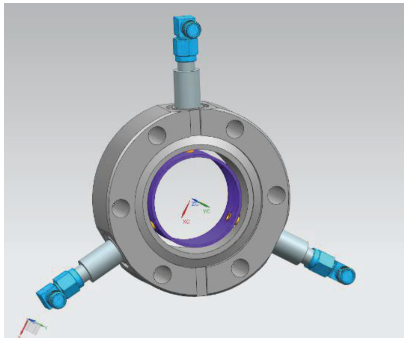
Beam size measurements with scrapers. **a**- currents of the dump as a function of the horizontal scraper position. The red line is a fit assuming the Gaussian beam distribution with rms width of 1.97 mm. Each data point is the average of ten 10-μs pulses. **b**- example of a quadrupole scan. Fitted emittances are 0.17 μm horizontal and 0.16 μm vertical (rms n). The data point at the quadrupole current of 5.06 A is deduced from the plot in (a).

Courtesy of A. Shemyakin

Ring Pickup – Beam current for Machine Protection

- Dedicated ring pickup to measure bunched-beam current for machine protection system
  - Wide bandwidth pickup but narrowband electronics
  - Simple analog circuit give rectified signal pulse
  - Installed in MEBT and studying performance with beam





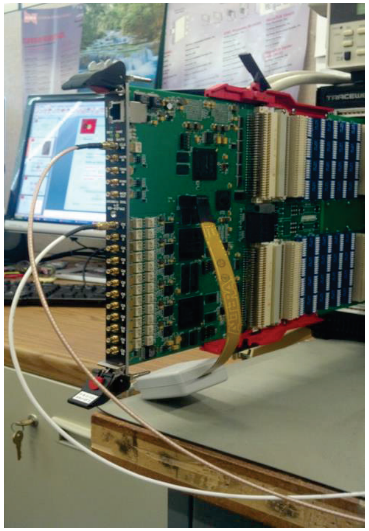
MEBT BPM Development

Requirements:

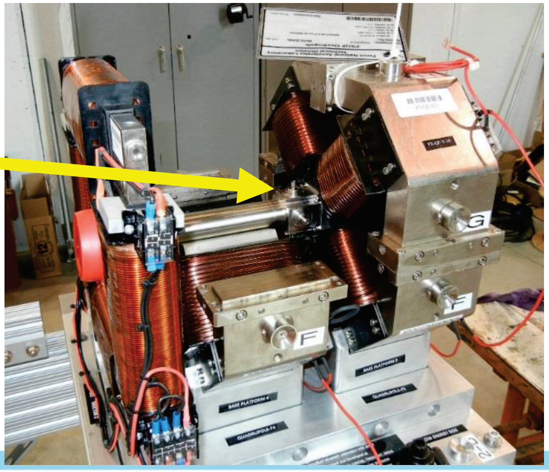
	Accuracy	Precision
Position, µm	10	30
Phase, degrees of 162.5 MHz	0.05	0.2
Relative intensity, %	1	3

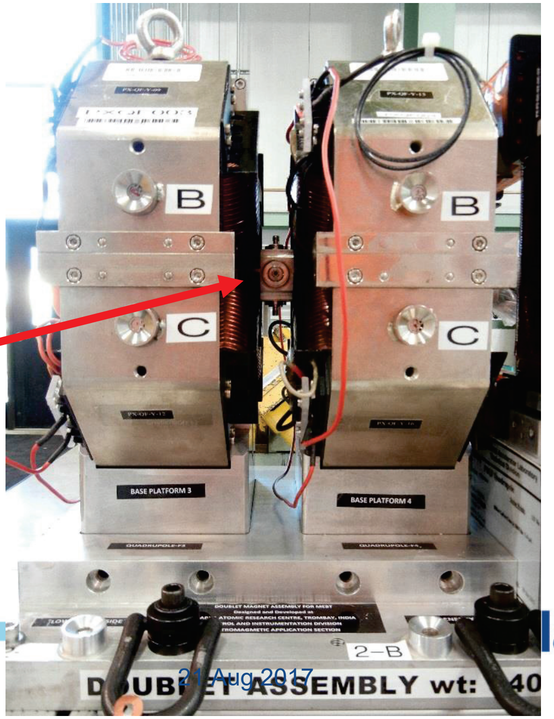
DAQ with FPGA-based electronics for CW and pulsed beam

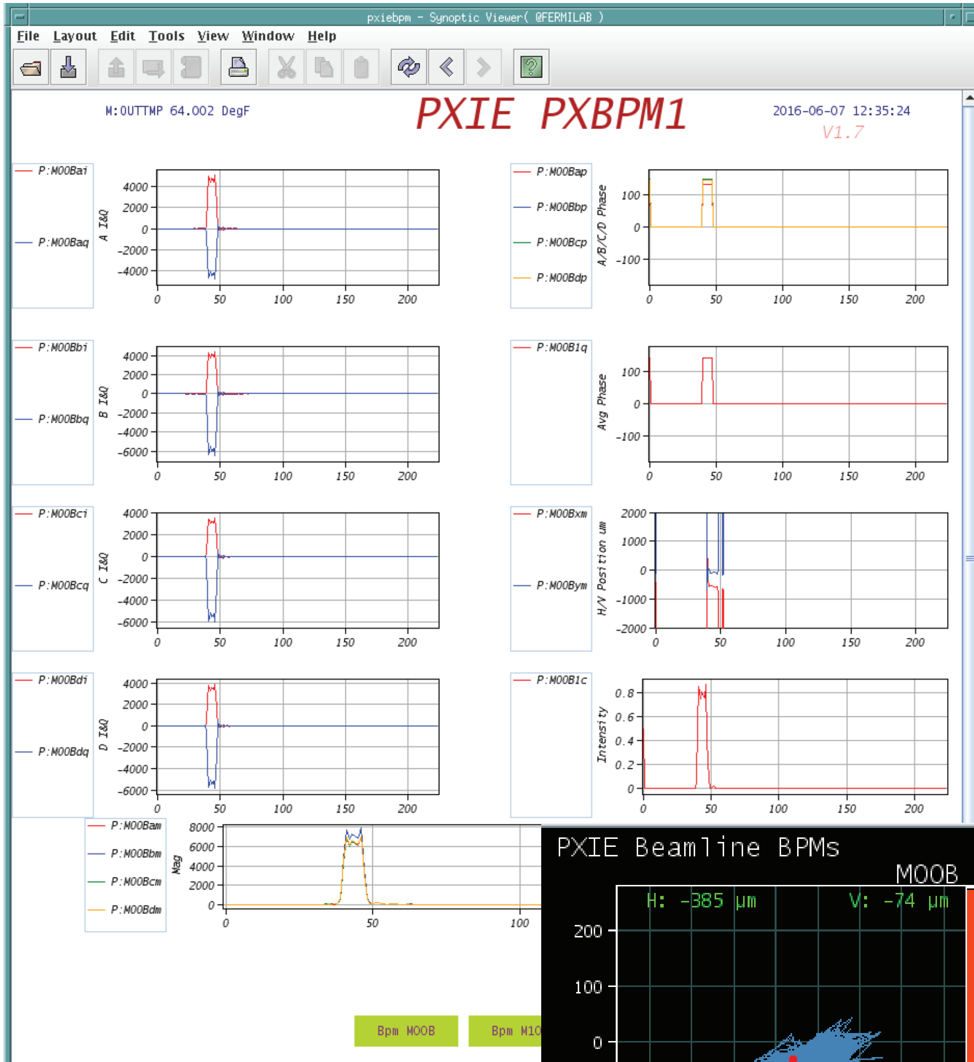
- 8 channel, 14 bit, 125 MSPS boards
- Analog filter & amp boards
  - Narrow-band filter → No bunch-by-bunch measurement capability
  - Use oscilloscopes in MEBT chopper region



4-buttom BPM

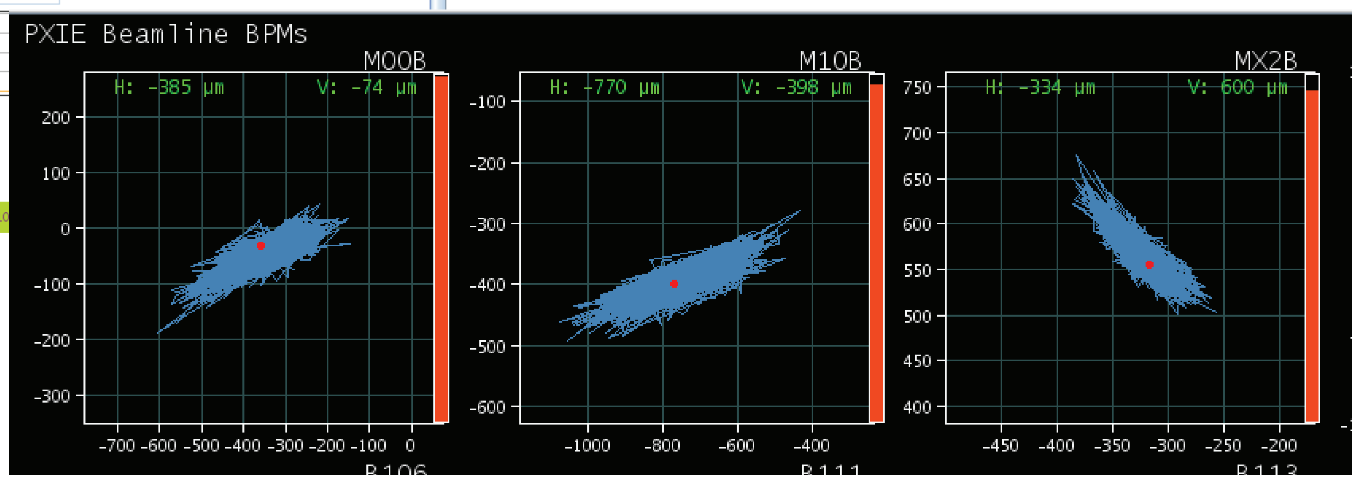






BPM Diagnostic Tools

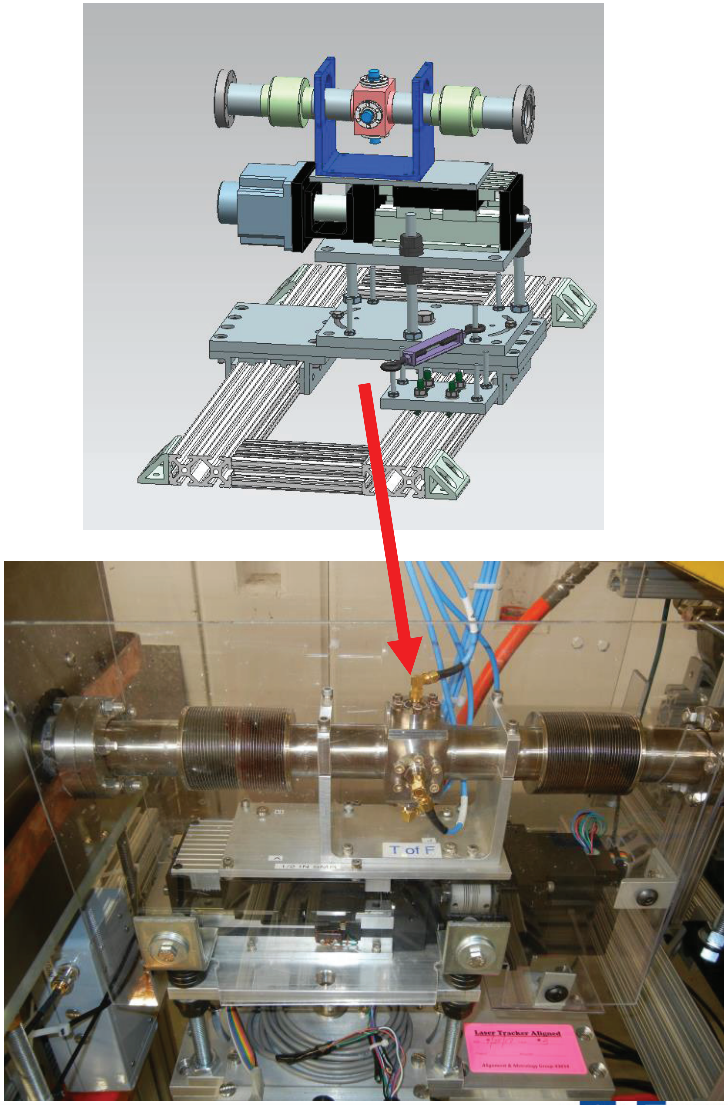
- *Preliminary position resolution of 3 μm*
- *Preliminary phase resolution of ~ 0.3 degrees*



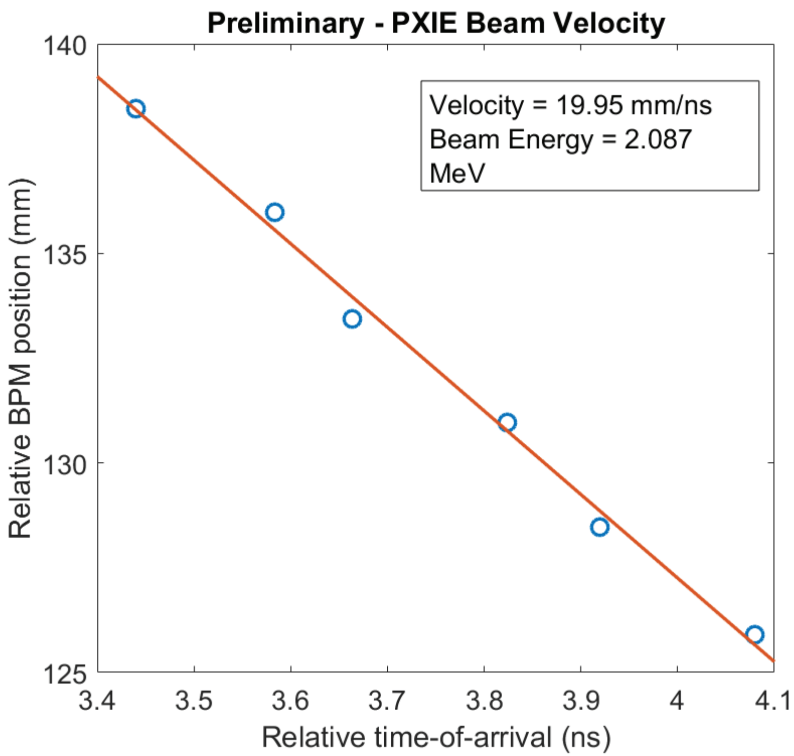
Beam Energy - Time of Flight (ToF) Movable BPM

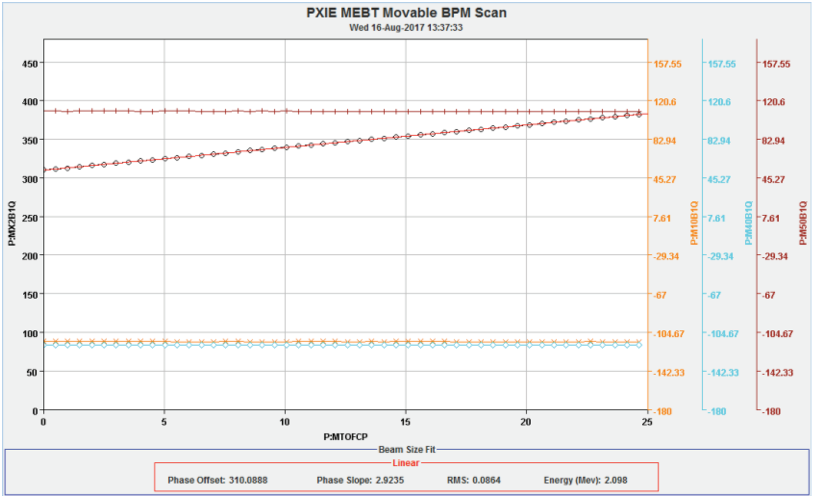
Measure beam velocity (energy) via ToF

- Utilize single movable BPM to minimize systematics
  - e.g. BPM response, bunch shape effects
- Use BPM on linear stage
  - ~ 1” of travel; ~10 μm resolution
  - Allows for “continuous” BPM phase measurements
  - MEBT energy resolution: ~0.3% @ 2.1 MeV



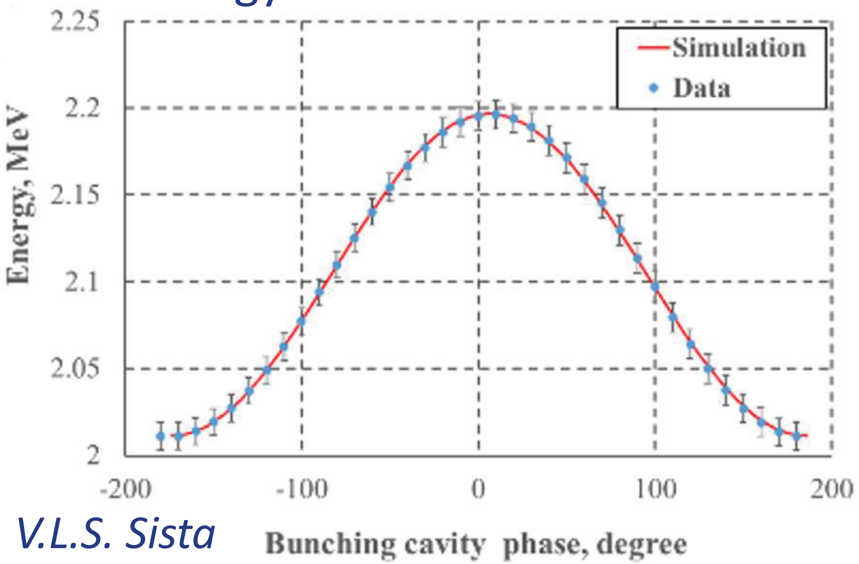
Beam Energy Measurements with ToF





Automated ToF energy display program

Beam energy versus MEBT buncher cavity



V.L.S. Sista

MEBT Allison-Style Emittance Scanner

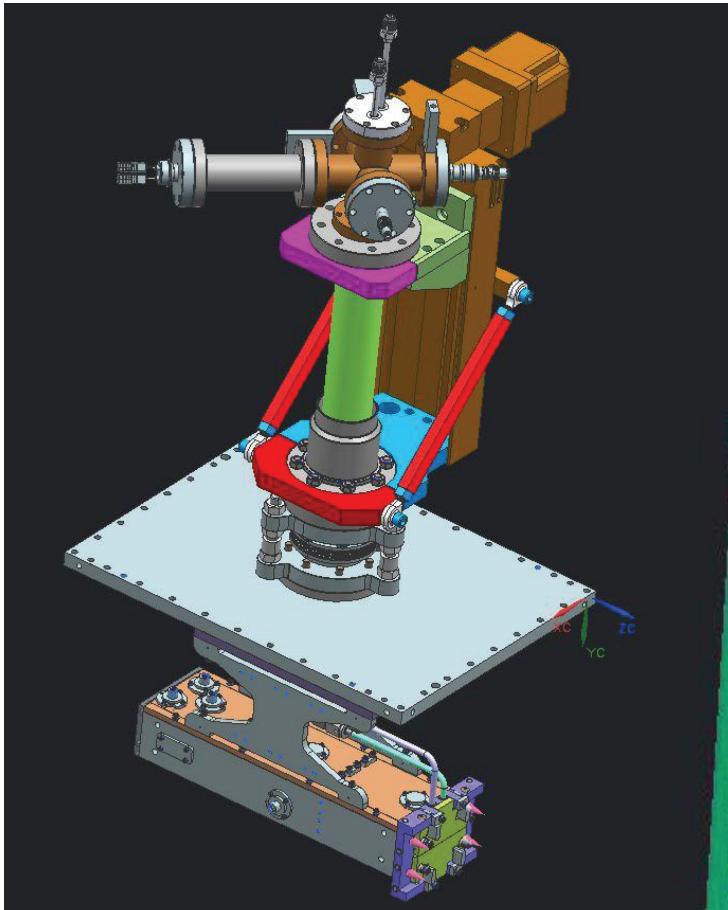
Parameter	LEBT	MEBT
Kinetic Energy	30 keV	2.1 MeV
Nominal Beam Current	5 mA	5 mA
Max/Min Beam Current	10 mA/0.5 mA	10 mA/0.5 mA
Nominal Beam radius (rms)	2.5 mm	2 mm
Max CW Beam Power	300 W	21 kW*
Nominal Max Beam Pulse	CW	20 μsec
Measurement X range (resolution)	$\pm$ 30 mm (100 μm)	$\pm$ 15 mm (25 μm)
Measurement X' range (resolution)	$\pm$ 80 mrad (0.5 mrad)	$\pm$ 12 mrad (0.25 mrad)
Signal Dynamic Range	10^3	10^3

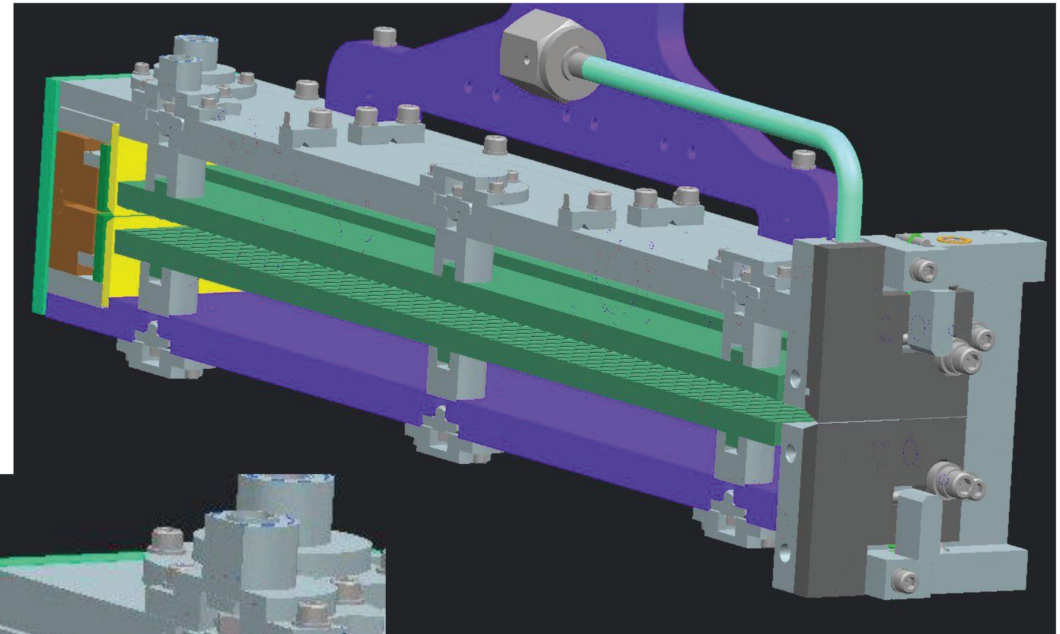
*Limit beam power to < 8 W/mm^2

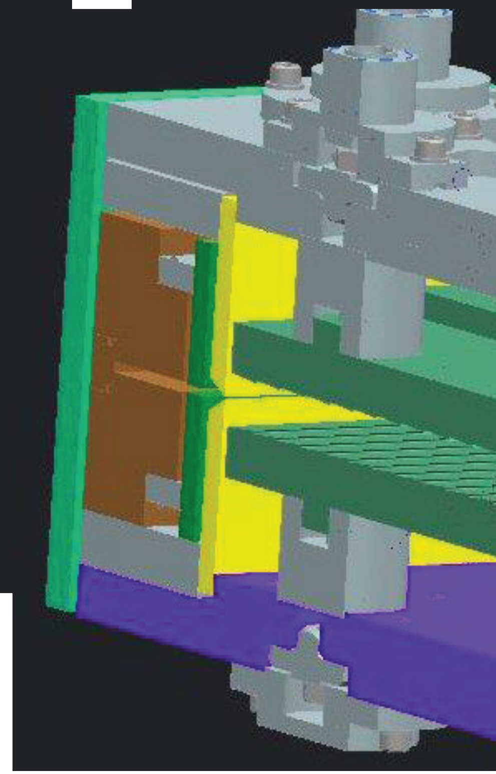
MEBT Allison Emittance Scanner Requirements

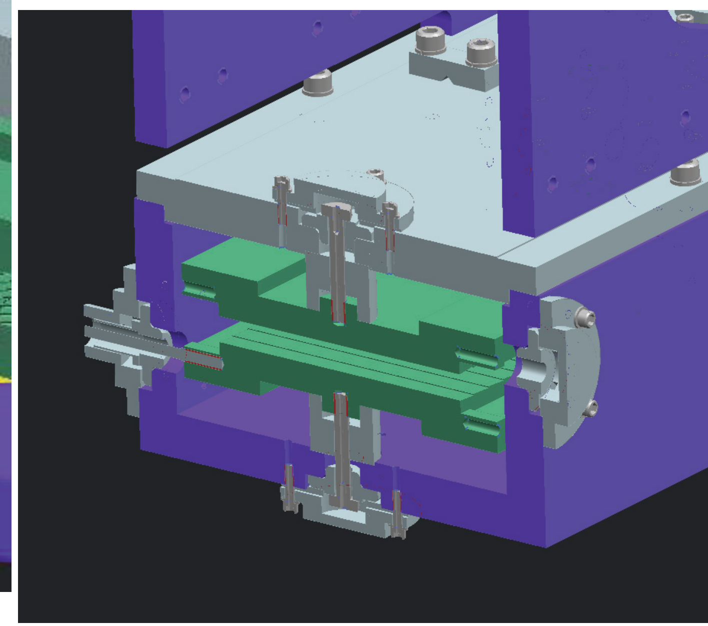
Parameter	Unit	Value
Motion and positioning		
Vertical range of measurement positions with respect to the beam line axis	mm	± 15
Absolute accuracy of vertical position of the sensor	mm	≤ 1
Reproducibility of vertical position	mm	≤ 0.1
Resolution of vertical position	mm	≤ 0.025
Sensor horizontal alignment with respect to beam line axis	mm	≤ 1
Sensor yaw alignment with respect to beam line axis	mR	10
MAES module pitch adjustment range	mR	± 35
MAES module pitch adjustment resolution	mR	1
MAES module pitch angle stability thru measurement region	mR	0.2
Scanner dimensions		
Scanner slit-to-slit distance	mm	320
HV deflector plate length	mm	300
Minimum HV deflector plate width	mm	> 40
Gap between teeth on HV plates	mm	5.5 ±0.2*
Angle of the teeth surface on HV plates	degree	> 2
Teeth depth	mm	≤ 0.5
Front slit gap	mm	0.2
Rear slit gap	mm	0.2
Front slit/Rear slit/HV plates axial alignment	mm	< 0.2
Electric		
HV amplitude on each plate	kV	-1 to +1
Time Slice Resolution	μS	1

MEBT Emittance Scanner

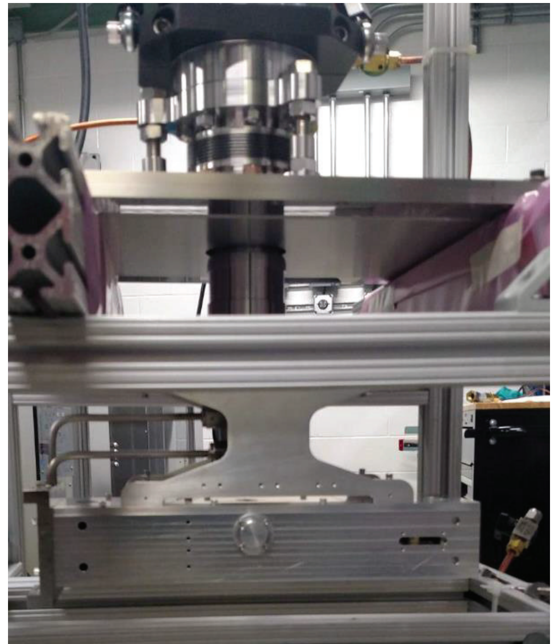


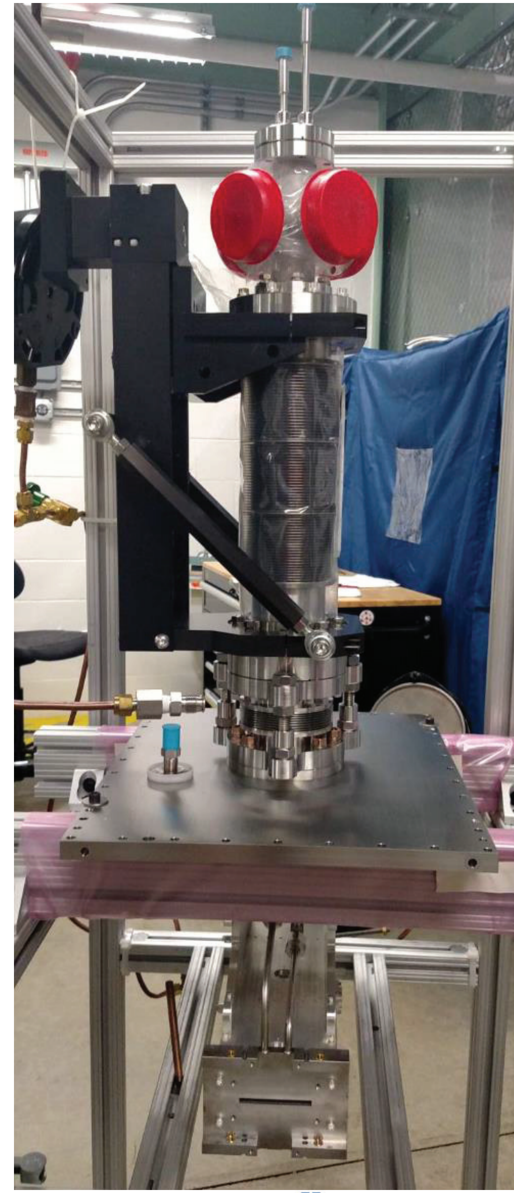


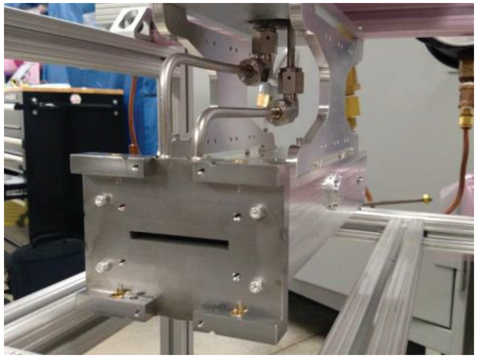


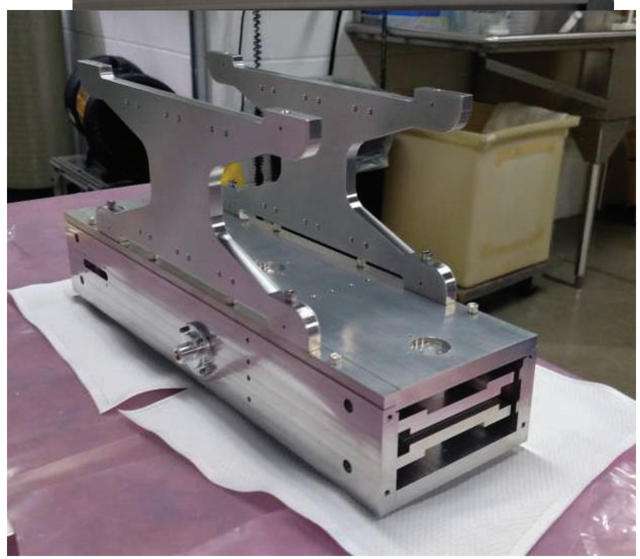


MEBT Allison Scanner Components

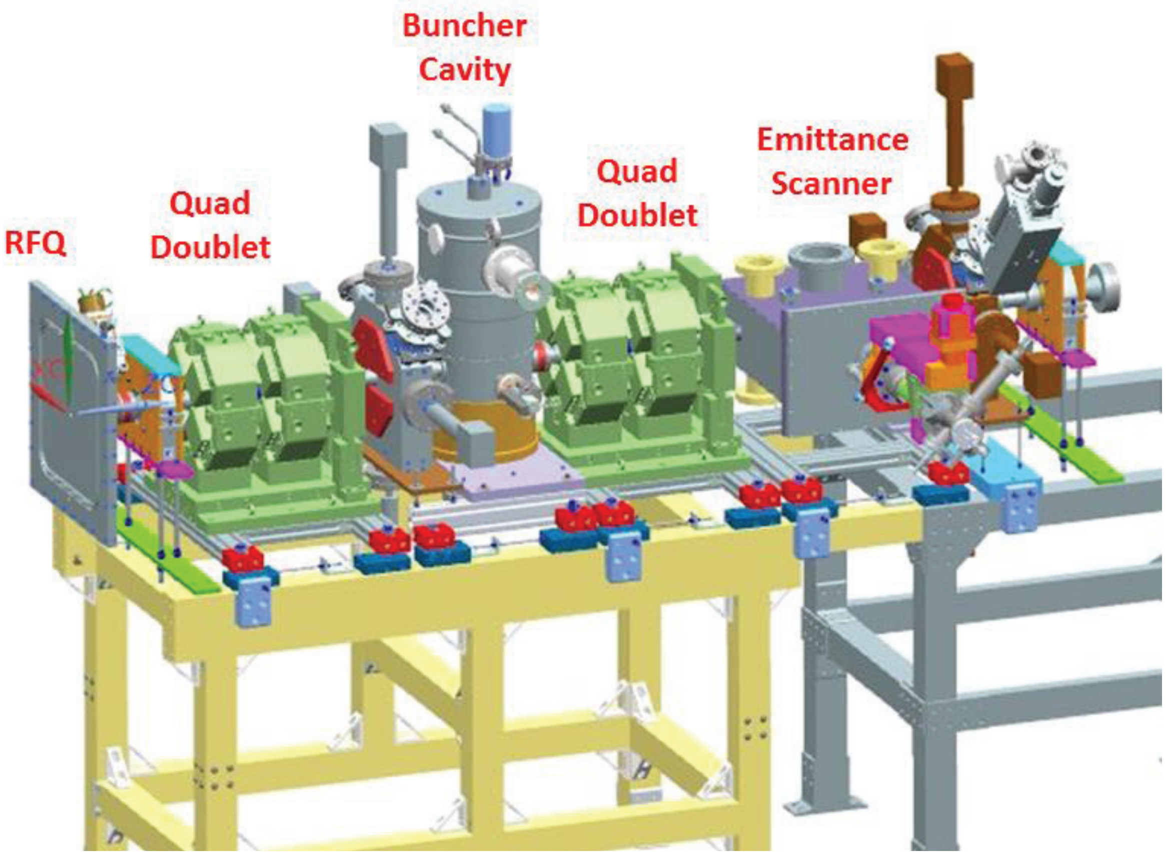


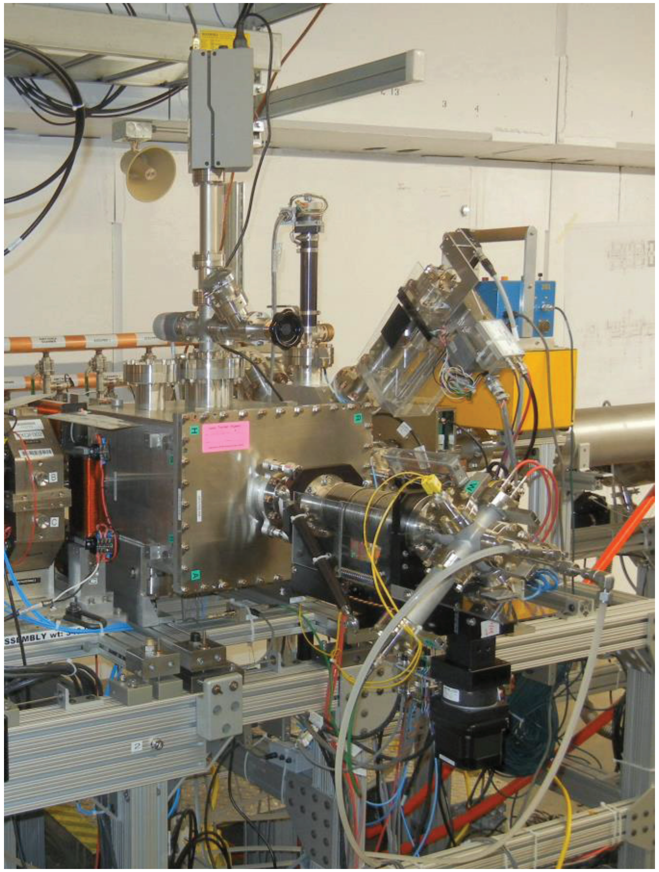






Emittance scanner in MEBT Beamline

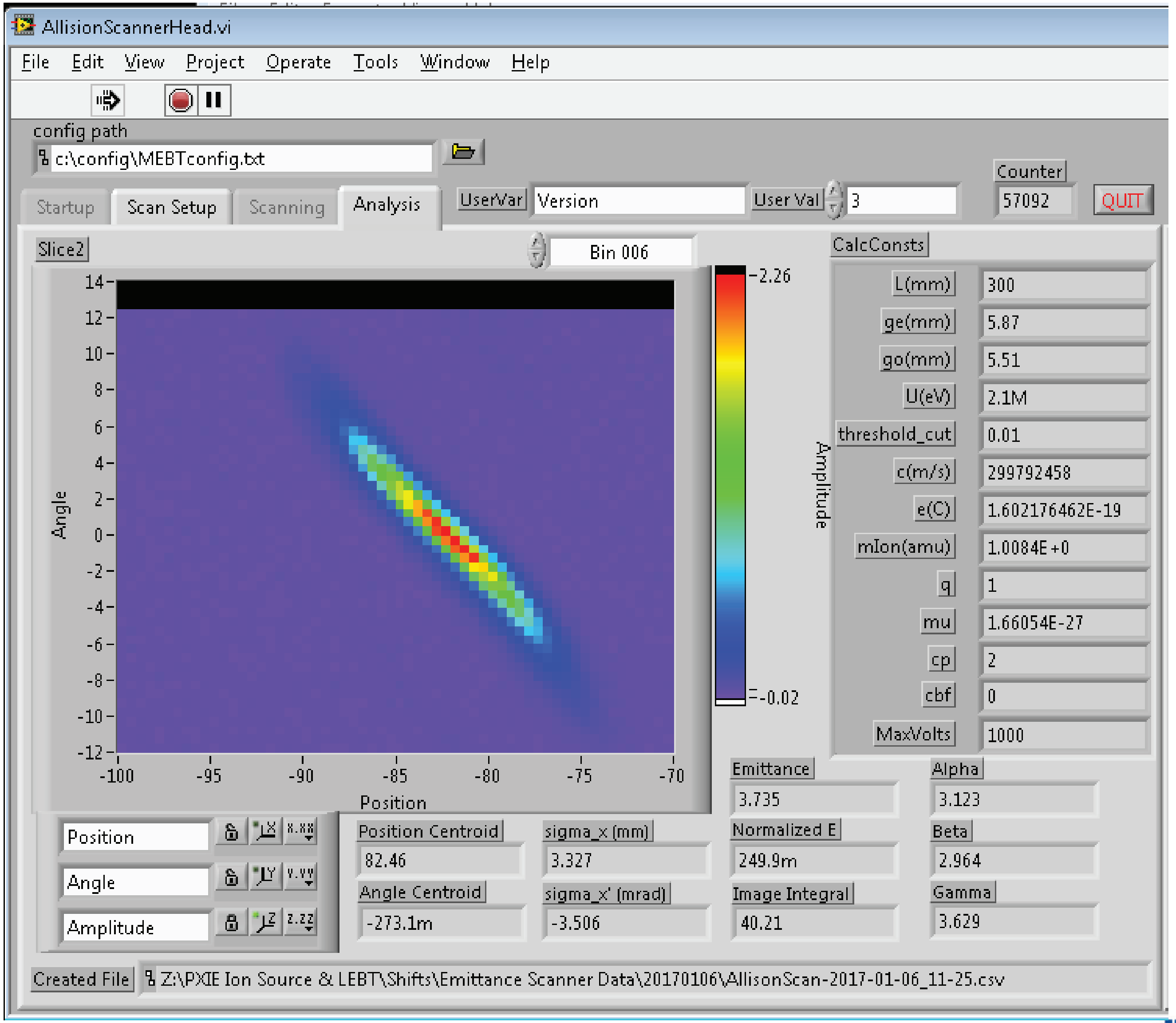




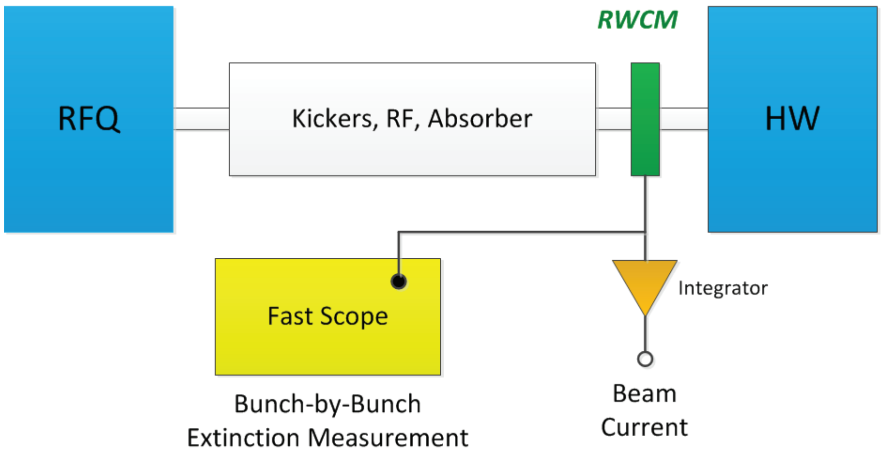
Installed in Dec 2016 for horizontal emittance measurements

- Rotate entire vacuum chamber for vertical measurements

First Beam Measurements Jan 6, 2017

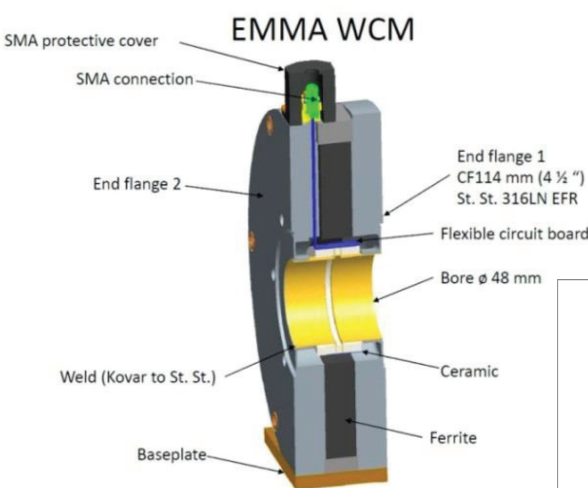


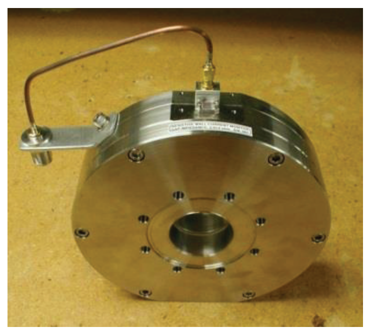
MEBT Chopper Extinction Measurement – Under Development

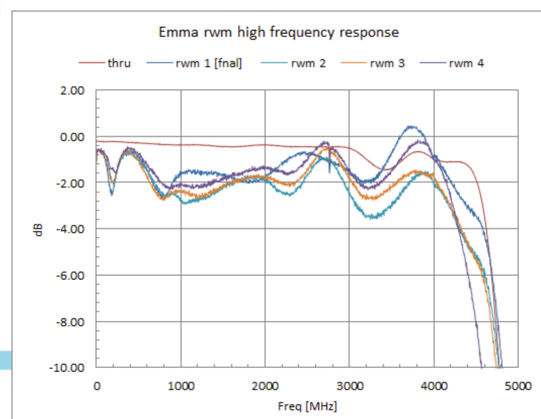


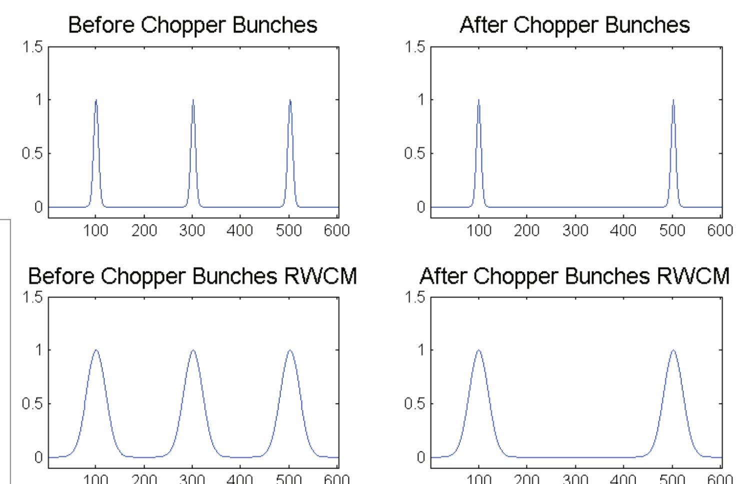
Use downstream Resistive Wall Current Monitors (RWCM)

- Extinction
  - Can average over many bunches or take a single shot measurement
  - Measurement BW < 1 Hz
  - Fits to bunch shape
  - Measure impact on adjacent bunches





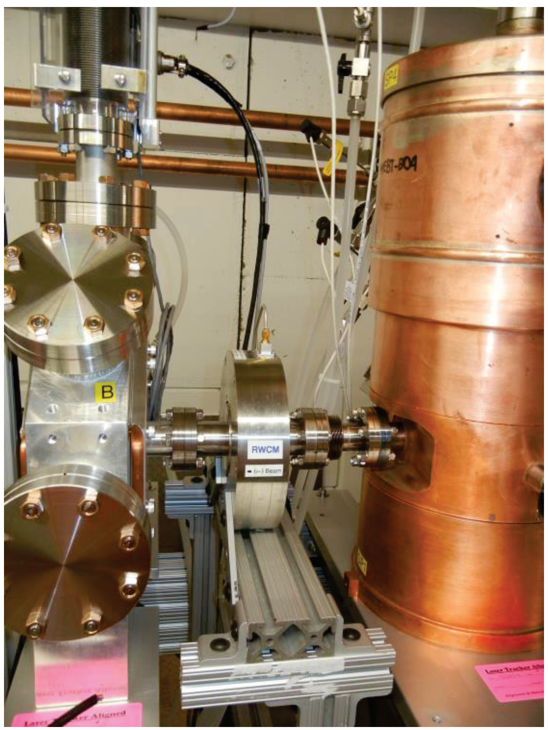




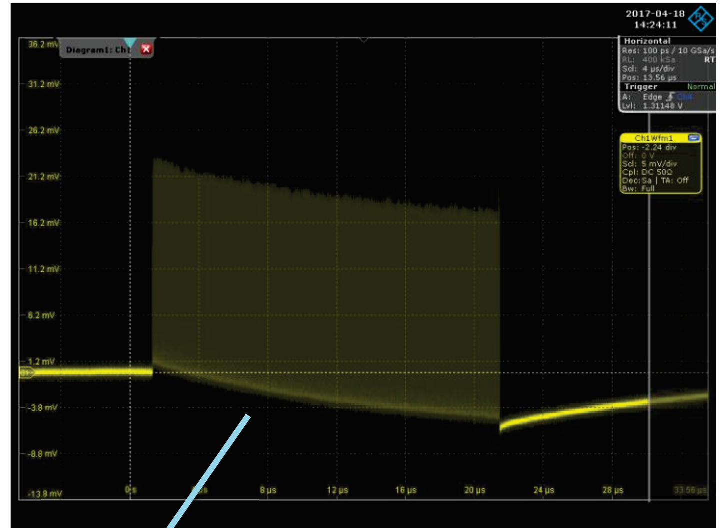
Initial RWCM MEBT Beam Measurements

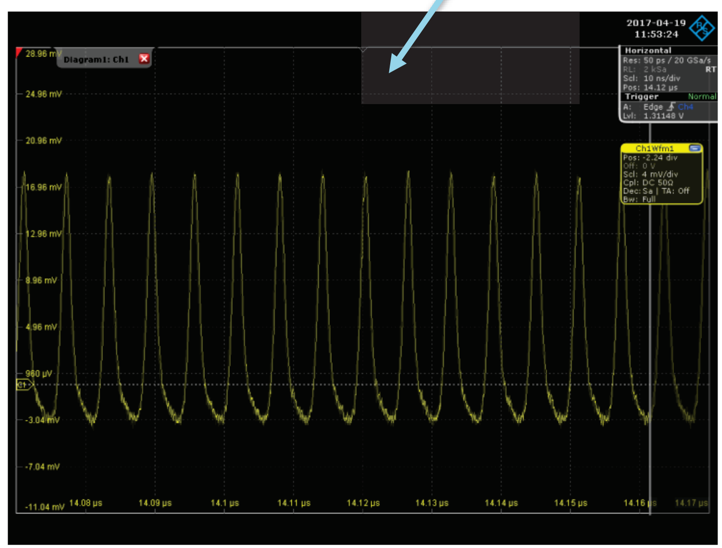
Installed 2” diameter RWCM into MEBT (spare from FAST)

- 12 kHz to 4 GHz
- Larger than 1 ¼” MEBT beampipe



5 mA, 20 us beam pulse





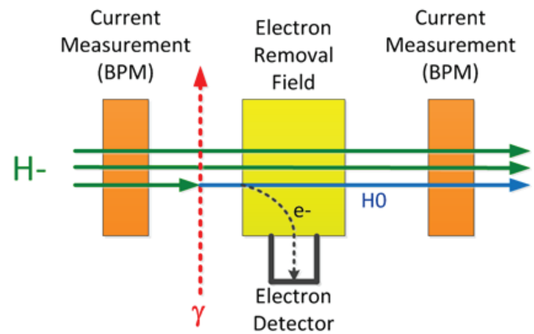
Non-adequate bunch separation

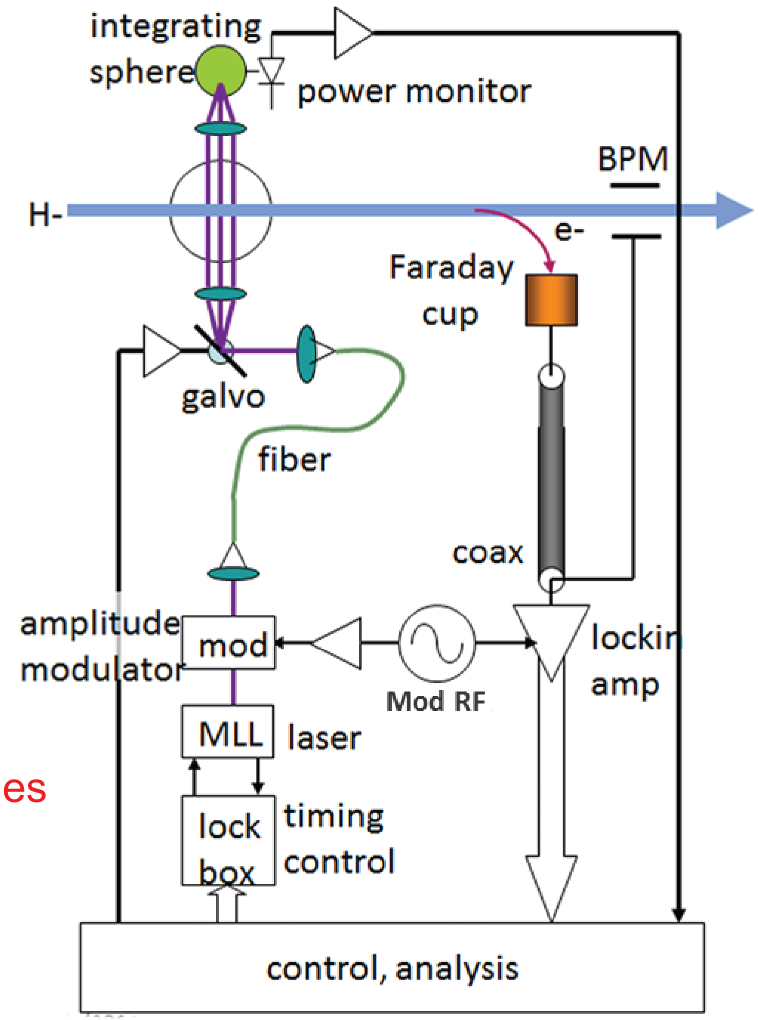
- Cable dispersion
- Low-velocity beam
- Large diameter
- RWCM

R&D – Laser Diagnostics Development – Low-power transverse (and longitudinal) laser wire for PIP-II

$H^{-} + \gamma \rightarrow H^{0} + e^{-}$

162.5 MHz, psec mode-locked laser (MML) used to measure both transverse and longitudinal profiles





- Laser rep-rate is locked to accelerator RF
- Amplitude modulate laser pulses
- Distribute modulated laser pulses via fibers
- Measure profiles by either:
  - Collection of electrons
  - Use BPM as reduced-beam pickup
    - Allows laser monitor to fit between cryomodules
- Narrow-band lock-in amp detects modulated signal

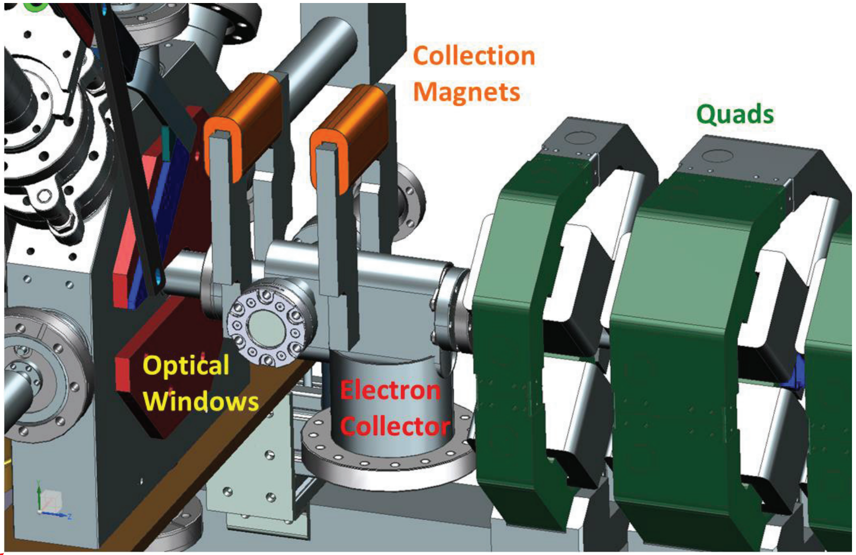
Prototype laser wire

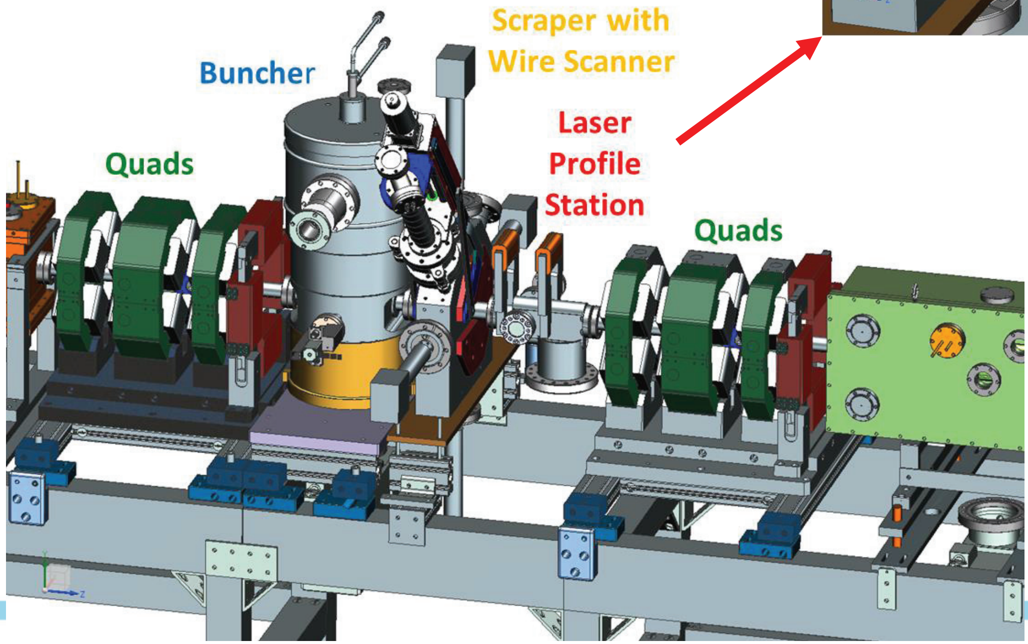
- Single plane measurement – vertical profiles
- Goal to test laser profiling at PIP2IT

R. Wilcox, LBNL

Prototype Laserwire Vacuum Chamber Design

- Design complete, starting construction
- Tight fit in MEBT
- Corrector/quad magnetic field interference issues
- Single plane measurement only – vertical profiles

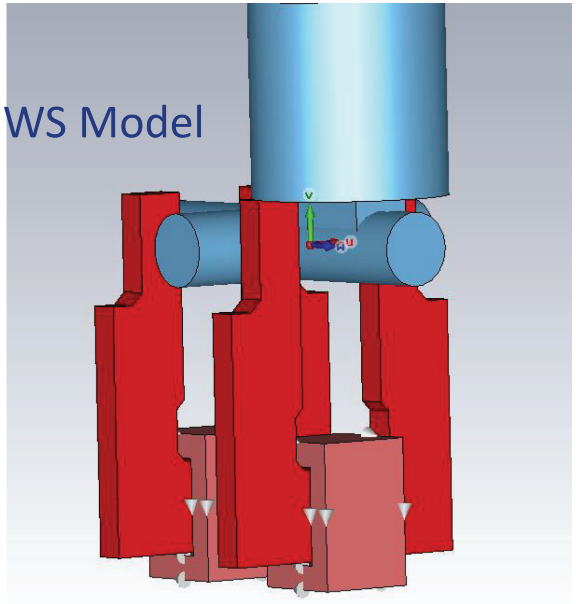




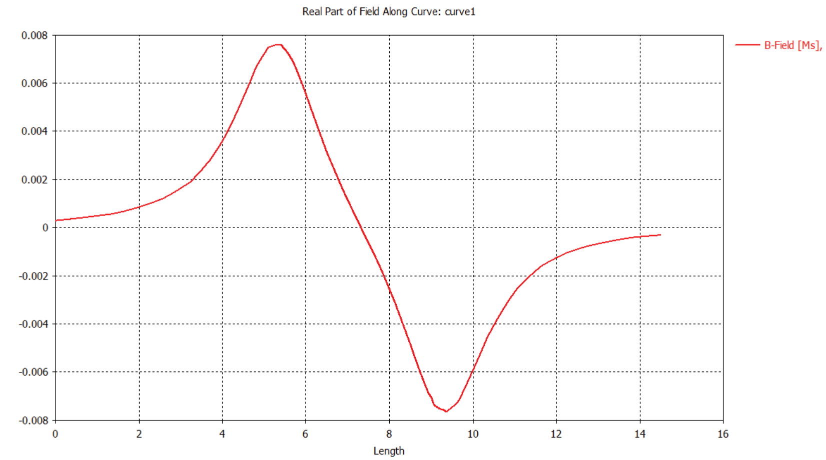
Laserwire Magnet Field Modeling

- *Magnet design and simulation critical*

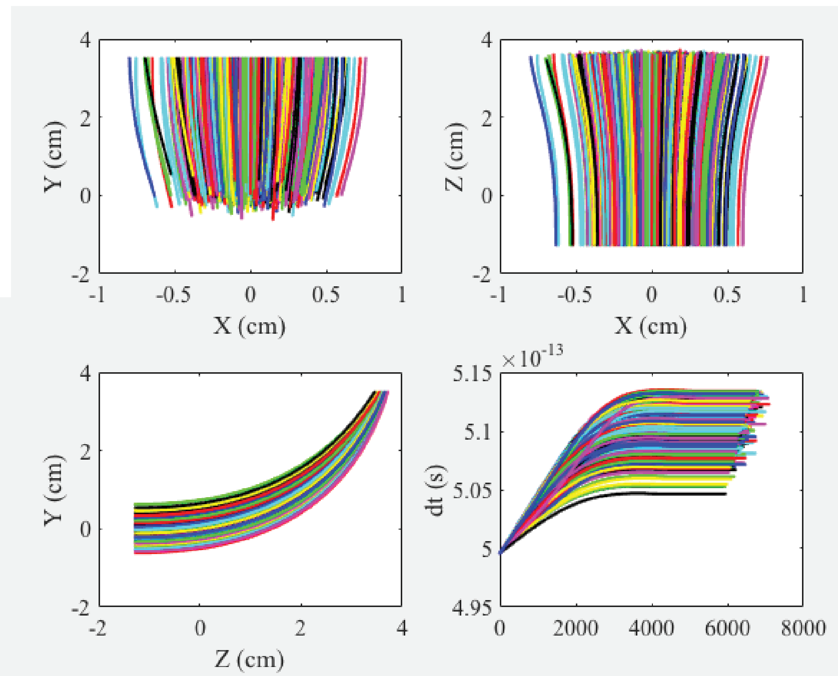
MWS Model



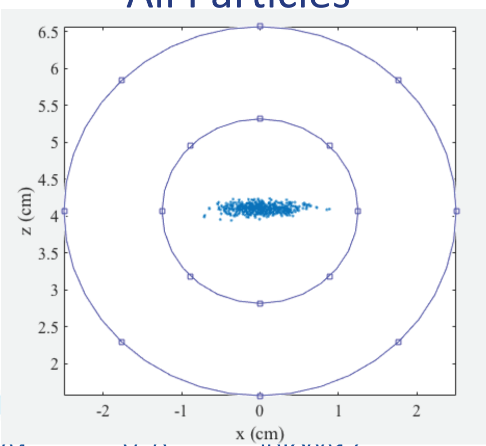
B-field
on axis



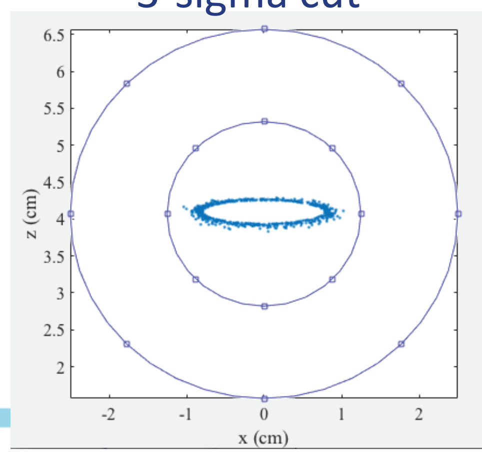
5 mA H-
2 mm rms



All Particles



3-sigma cut



Challenges for PIP-II and PIP2IT Beam Instrumentation

1. Beam loss at low-energy
   - Beam loss in LEBT, RFQ, MEBT and HWR does not escape
   - Internal beam loss monitoring with scrapers
   - Investigating diamond detectors
2. Longitudinal profiling
   - Bunch lengths as short as 4 ps difficult to measure in linac
   - Investigating:
     - Ultra-fast (fs) laser techniques with photo-ionization (i.e. laserwire)
     - OTR plus streak camera techniques
3. Fast, high-resolution differential beam current measurements for MPS
   - CW beam operation with slow loss requires high-resolution differential current measurements (10^{-3} or better)
   - Fast intense beam loss requires fast differential current measurements (~ few μs)
   - Investigating RWCM as a current device

Summary

- Commissioning of PIP2IT continues
  - Ion source and LEBT operational in pulsed and CW modes
  - RFQ and MEBT only operational in pulsed mode. Continue work for CW operation.
  - MEBT 50Ω and 200Ω kickers installed and under test
  - Plan to complete MEBT in 2017 and then start cryogenic and HWR and SSR1 cryomodule installation
- Beam instrumentation
  - Instrument commissioning continues
  - MEBT Allison emittance scanner successful and operational
  - Pulsed beam measurements mostly operational. CW beam measurements still being developed.
  - Laserwire profiling under development