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Beam Diagnostics at PXIE

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2015 PASI Workshop, Fermilab

Scope – PXIE and PIP-II

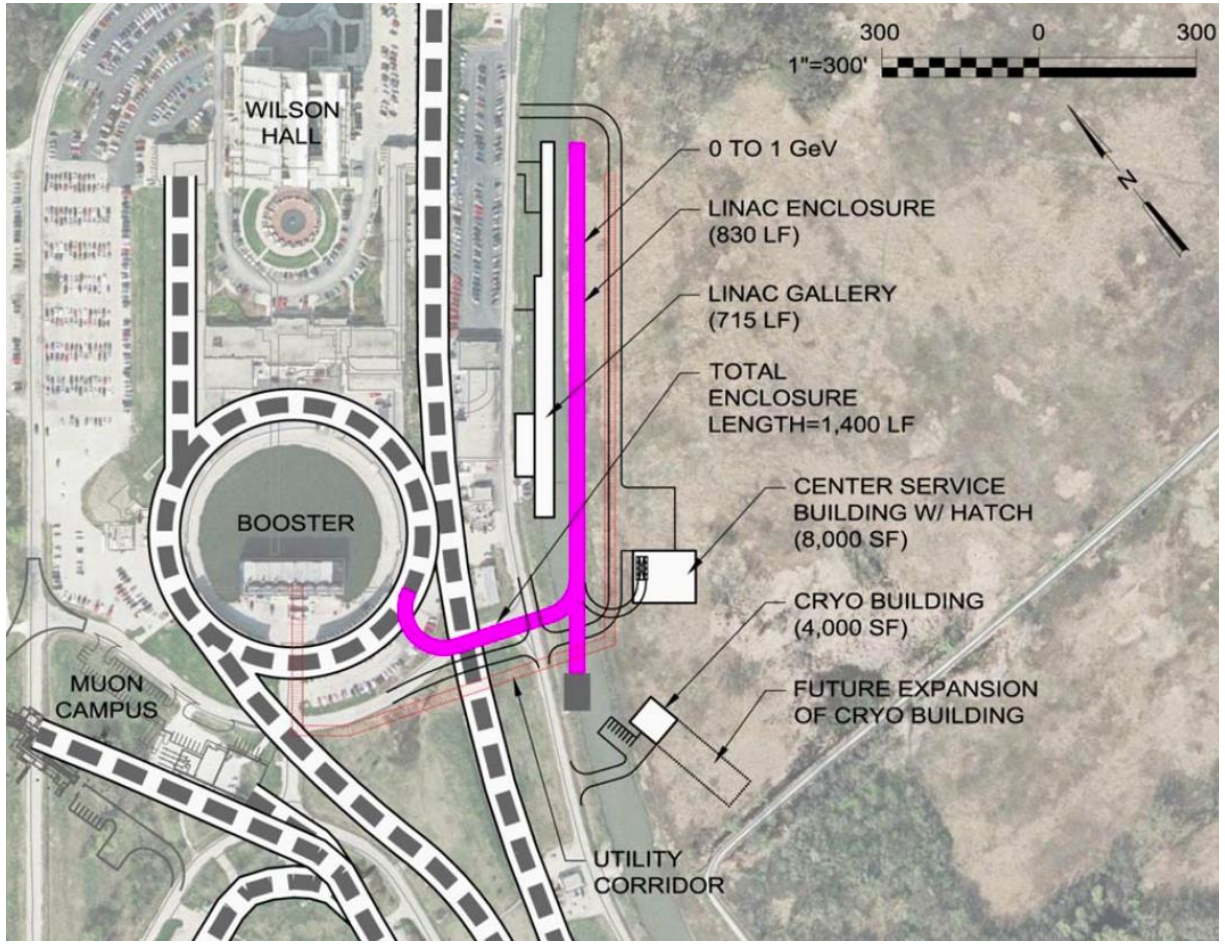
The scope of beam diagnostics are to identify and provide the instrumentation systems necessary to successful *commission*, characterize and operate PIP-II. PXIE is the prototype front-end of PIP-II.

- *Present focus is development of instrumentation for PXIE*
- *PIP-II focus on pulsed operation with an eye toward CW*
  - *Impact on instrumentation choices*

PXIE Accelerator instrumentation sections:

- Ion source & LEBT
- MEBT
- Superconducting linac – HWR, SSR1

See talks:
"High Power Proton Accelerators: PIP II & III" – E. Prebys
"Overview of PXIE" – L. Prost



PIP-II/PXIE Beam Diagnostic Measurements and Proposed Instruments

- Beam current
  - DCCTs, Toroids, High-Bandwidth Resistive Wall Current Monitors (RWCM), BPMs
- Beam transverse position
  - Warm and cold BPMs
- Beam energy
  - BPM phase, movable BPM (energy)
- Beam transverse profiles
  - Wire scanners, laser wires, IPM, electron beam profiler, isolated beam scrapers

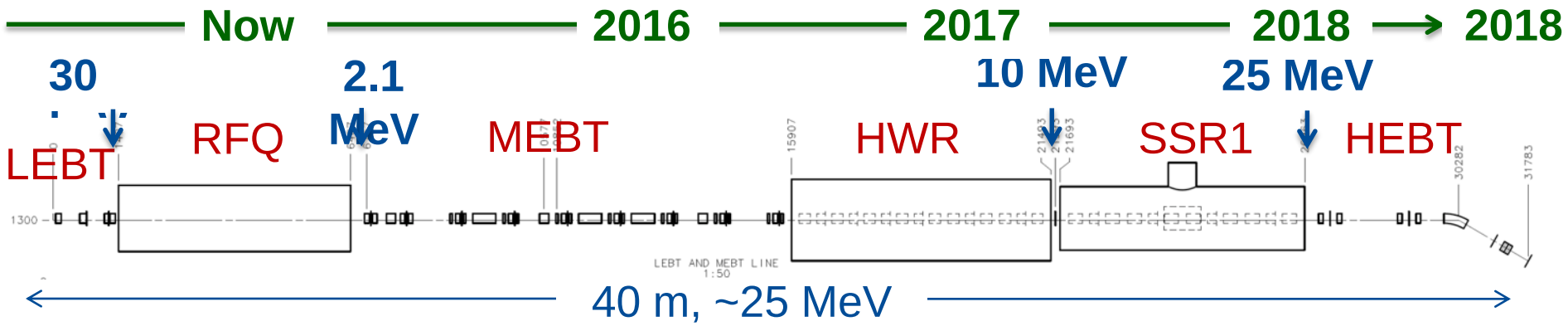
Large variety of instruments needed for PIP-II
- ***Develop many at PXIE***

- Beam transverse emittance
  - Allison scanner, slit-slit or slit-wire scanners, quadrupole scans
- Beam longitudinal profiles
  - Fast Faraday Cup, picosecond laser wires
- Beam halo
  - Vibrating wire, high-gain wires, laser wire, isolated apertures, diamond detectors
- Beam loss monitoring
  - Ion chambers, neutron detectors, diamond detector
- Chopped beam extinction efficiency
  - High-Bandwidth RWCM, single (few) particle detection

Green = developed or under development at PXIE

Orange = developed or tested at other Fermilab accelerators

PXIE (PIP-II Injector Experiment)



PXIE will address the address/measure the following:

- LEBT pre-chopping
- Validation of chopper performance
  - Bunch extinction, effective emittance growth
- MEBT beam absorber
  - Reliability and lifetime
- CW Operation of HWR
- Operation of SSR1 with beam
  - CW and pulsed operation
- Emittance preservation and beam halo formation through the front end

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

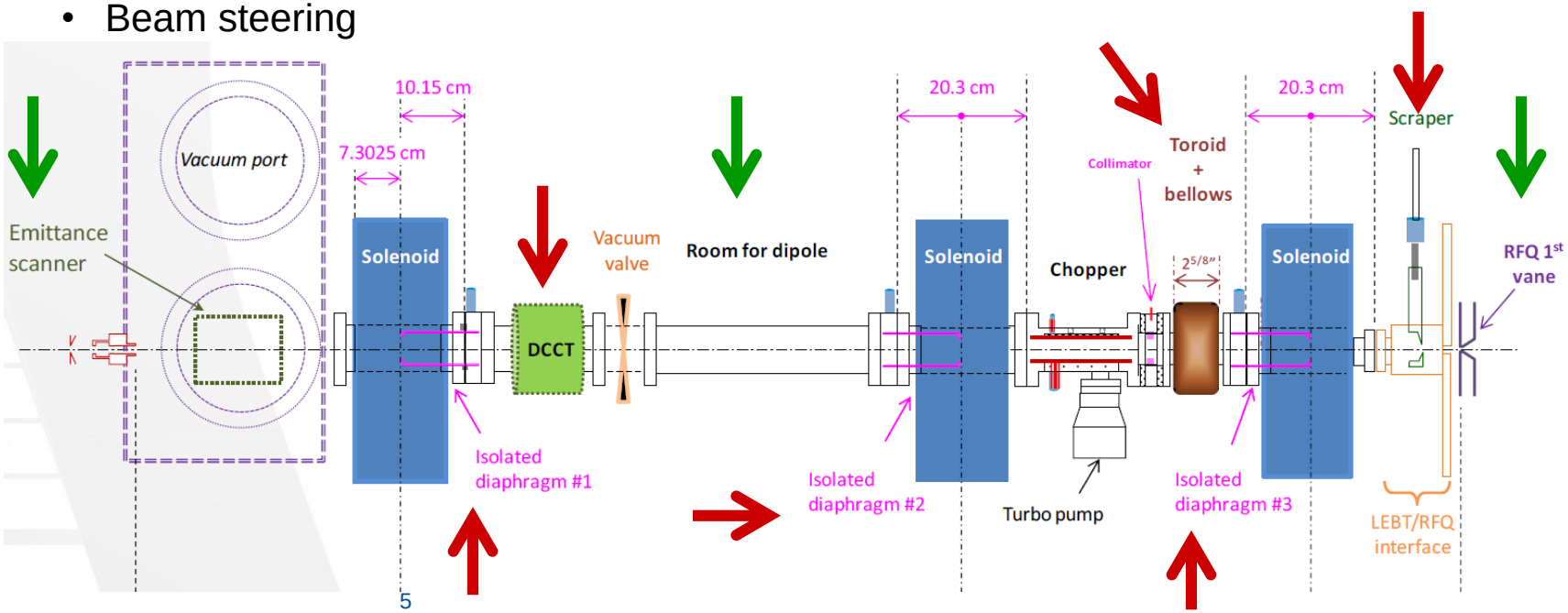
PXIE Source-LEBT Instrumentation

Beam Current

- DCCT
  - Unchopped Beam Current
- Toroid
  - Chopped Beam Current
- Isolated diaphragms
  - Beam tails
  - Beam steering

Beam Emittance

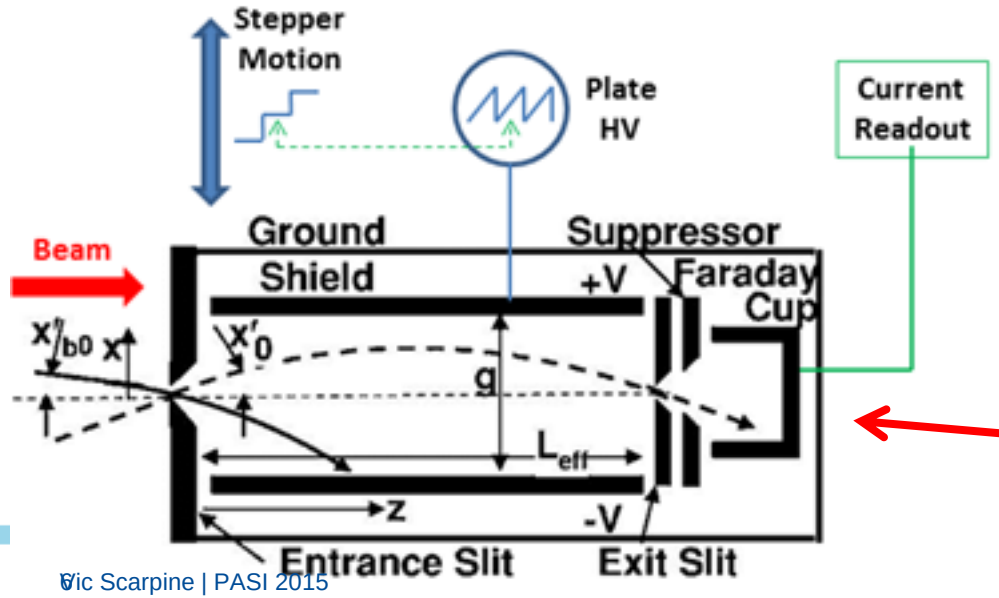
- Water-cooled Allison Scanner
  - Measurements at ion source
  - Measurements in LEBT during commissioning

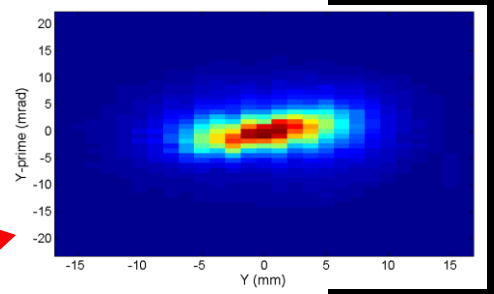


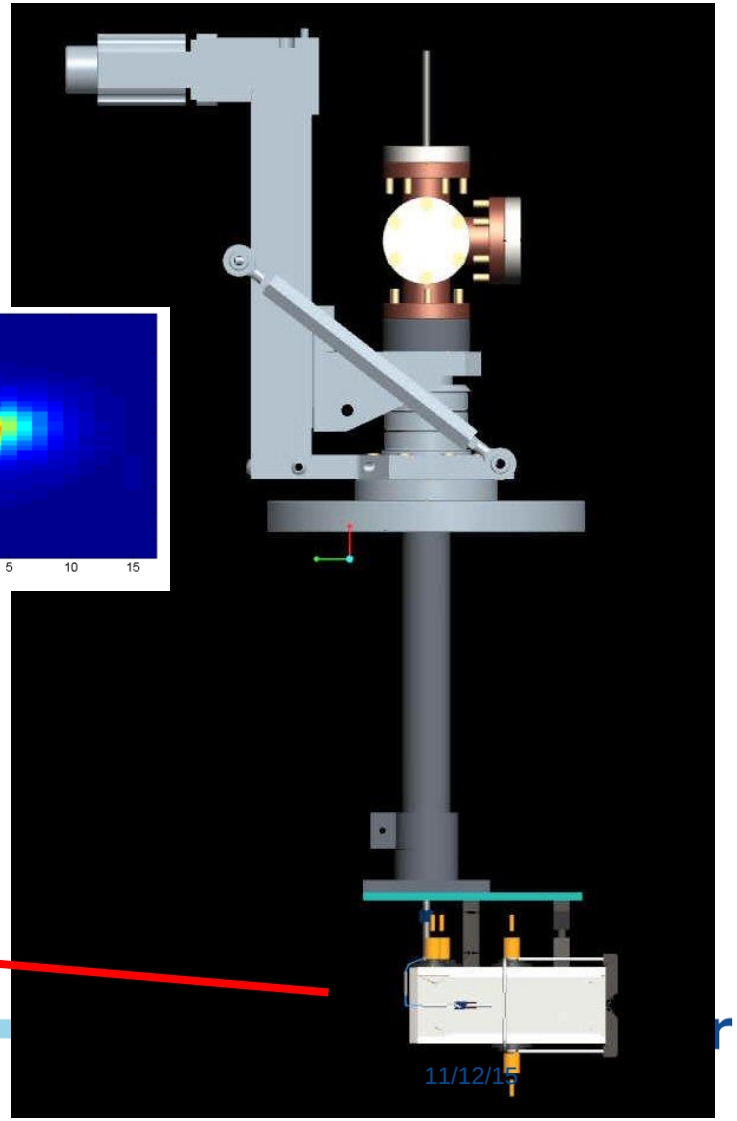
Allison Scanner for Source/LEBT Emittance Measurements

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*

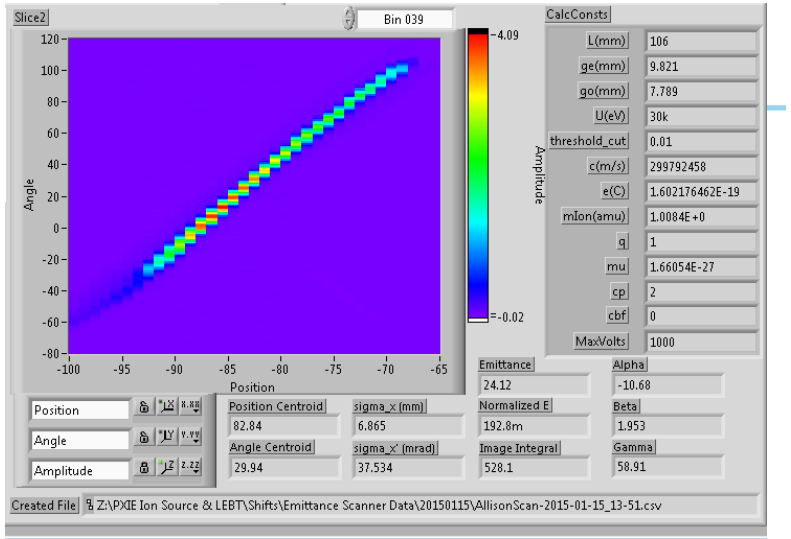




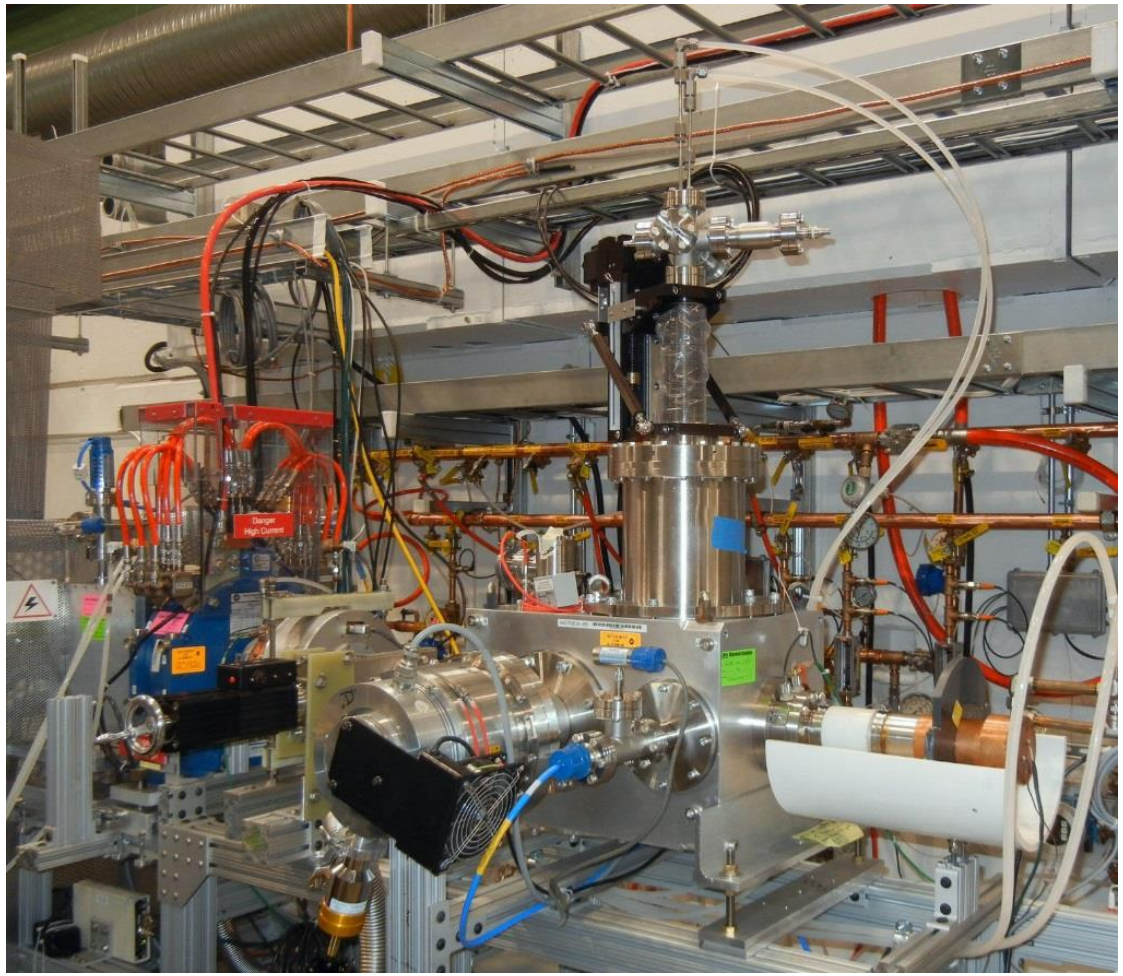


Allison Scanner Installation

Labview-based DAQ and analysis software

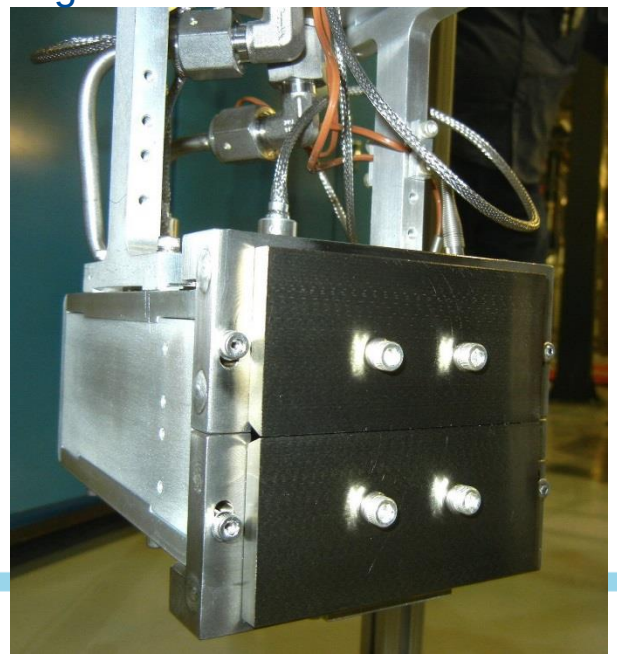


Installation after 1st Solenoid – May 2014



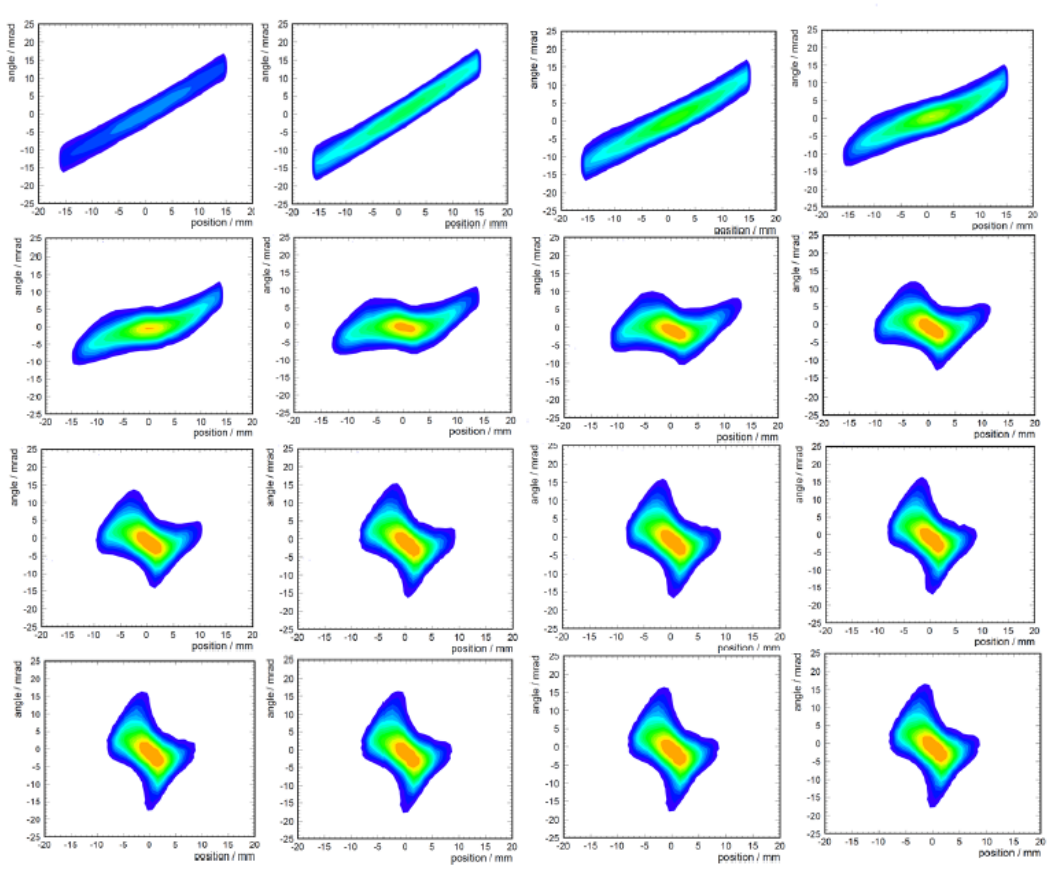
Operated in both vertical and horizontal orientations

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

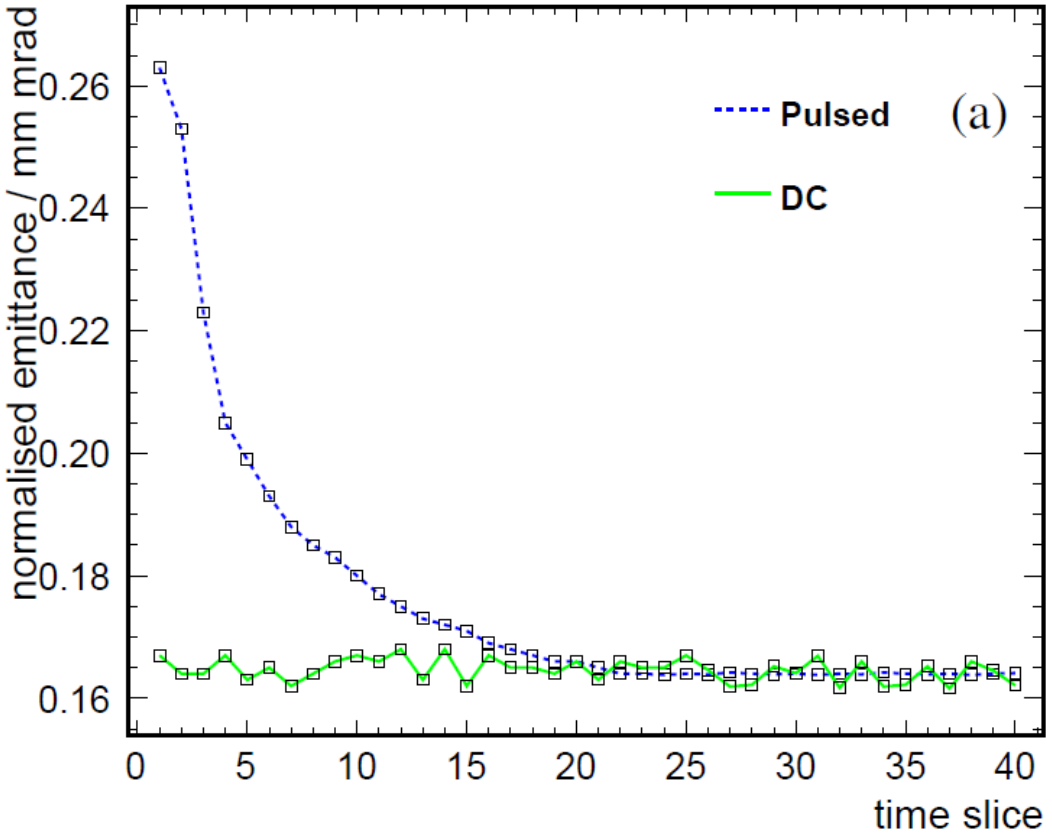


Electronics rack

Allison Scanner Measurements

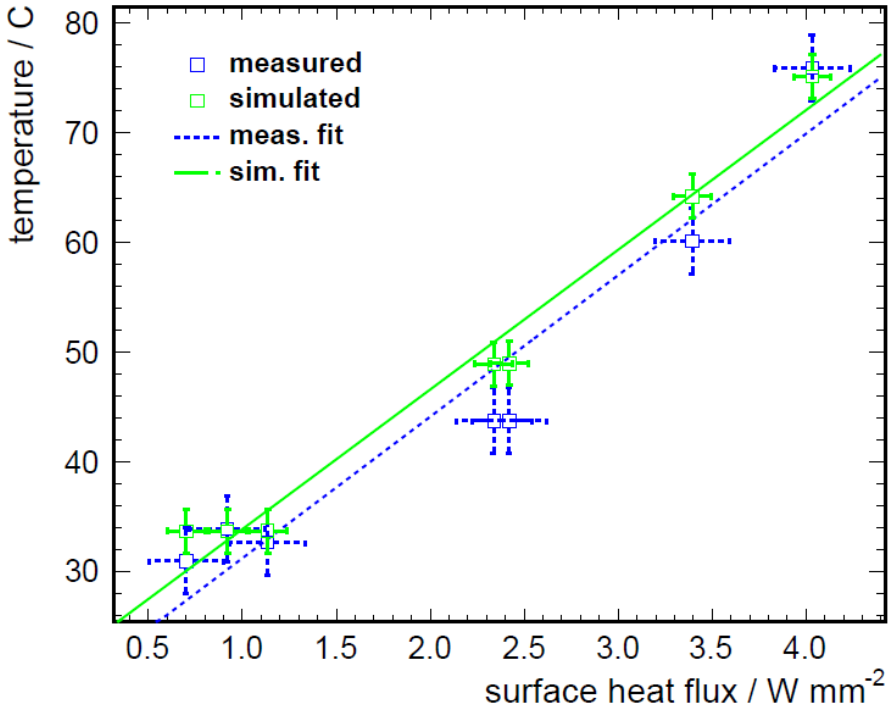


Evolution of phase space in 2 ms, 5 mA beam pulse



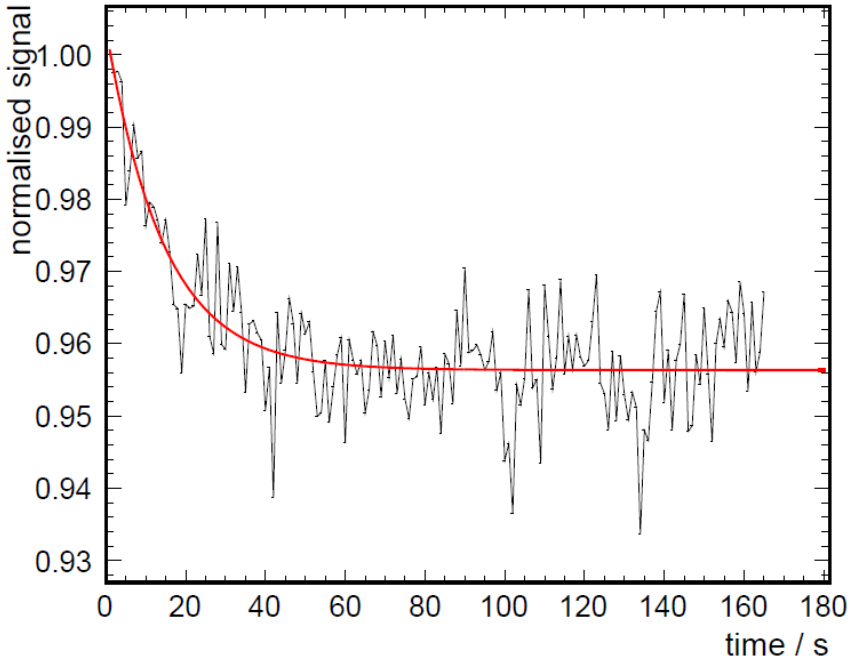
Emittance evolution for pulsed versus DC beam. Pulsed beam shows neutralization of H- beam.

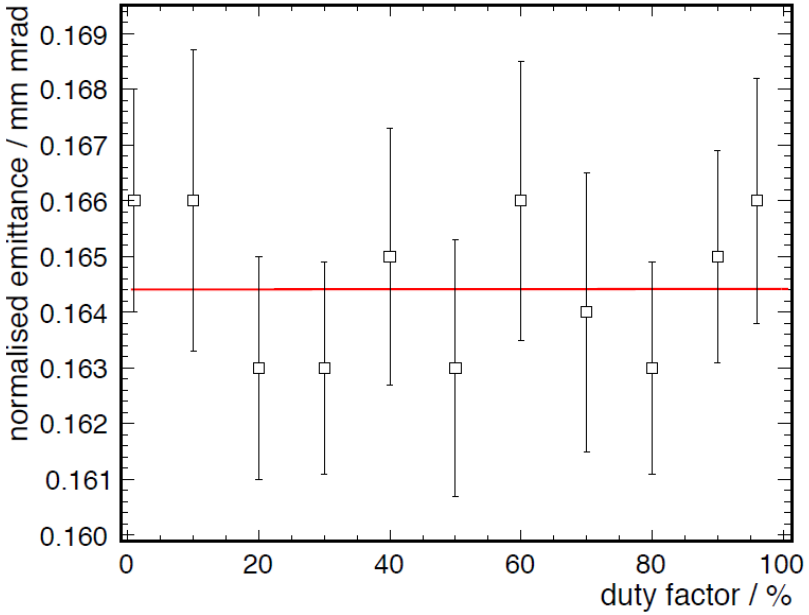
Allison Scanner Thermal Studies



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

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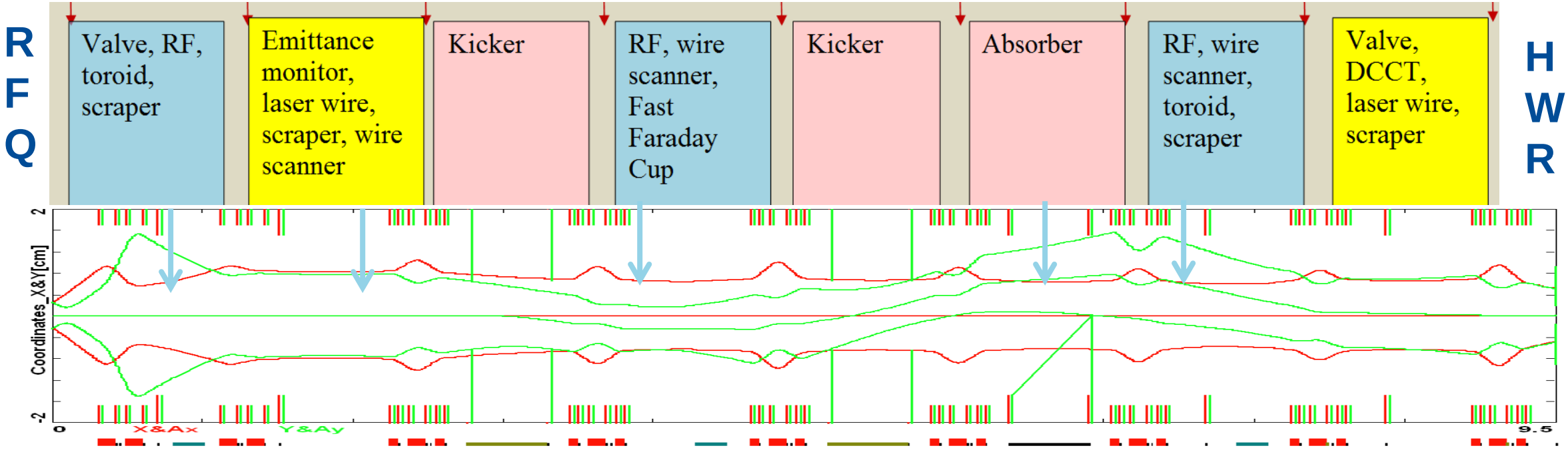
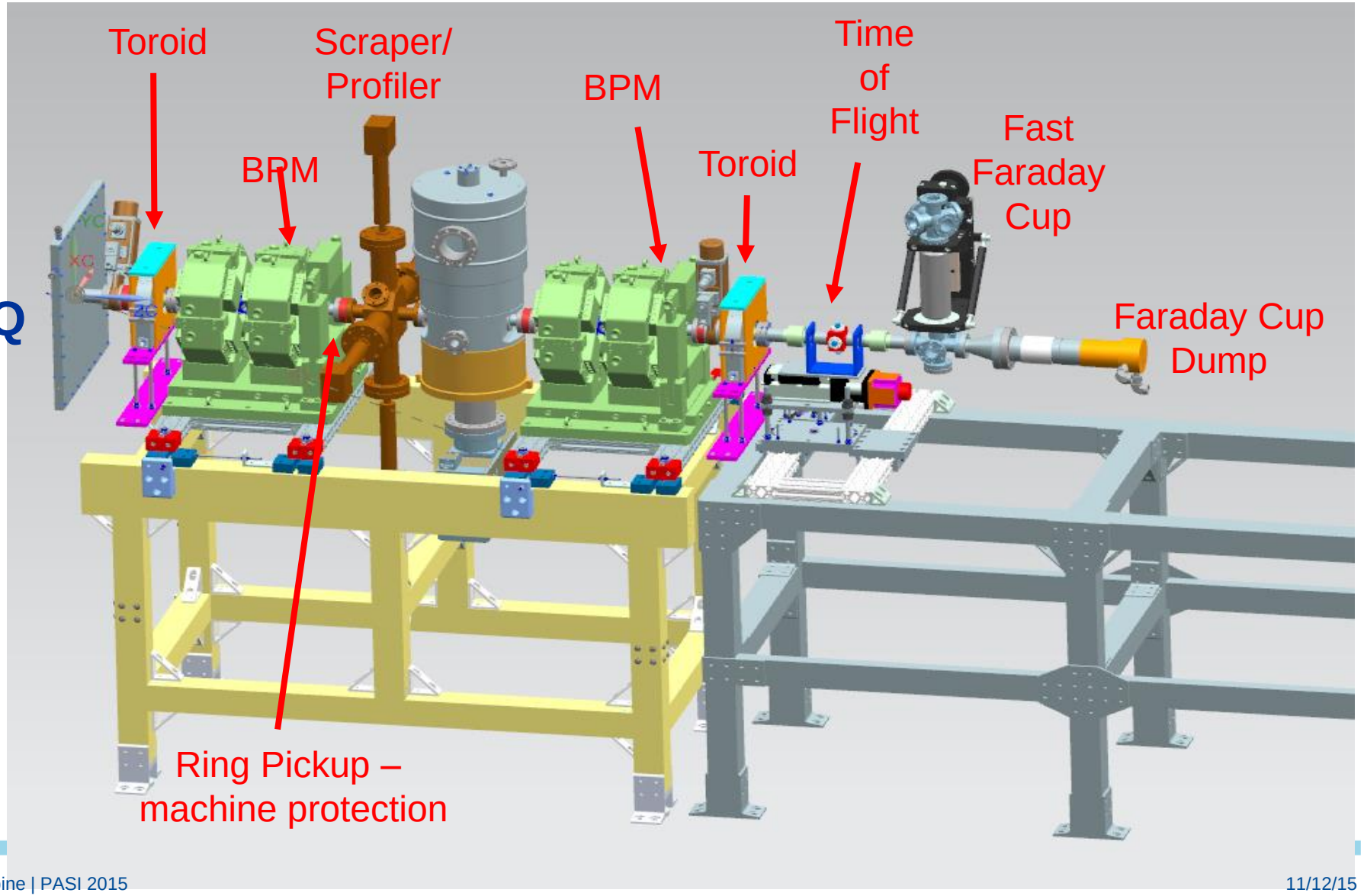
PXIE MEBT Block Diagram



- Ion type: H-
- Output energy: 2.1 MeV, same as input
- Max bunch freq: 162.5 MHz
- Operational beam current: 1 – 10 mA
- Nominal input beam current: 5 mA
- Particles per bunch: 1.8e8 nominal
- Bunch extinction: < 1e-4

Initial MEBT configuration showing beam diagnostics

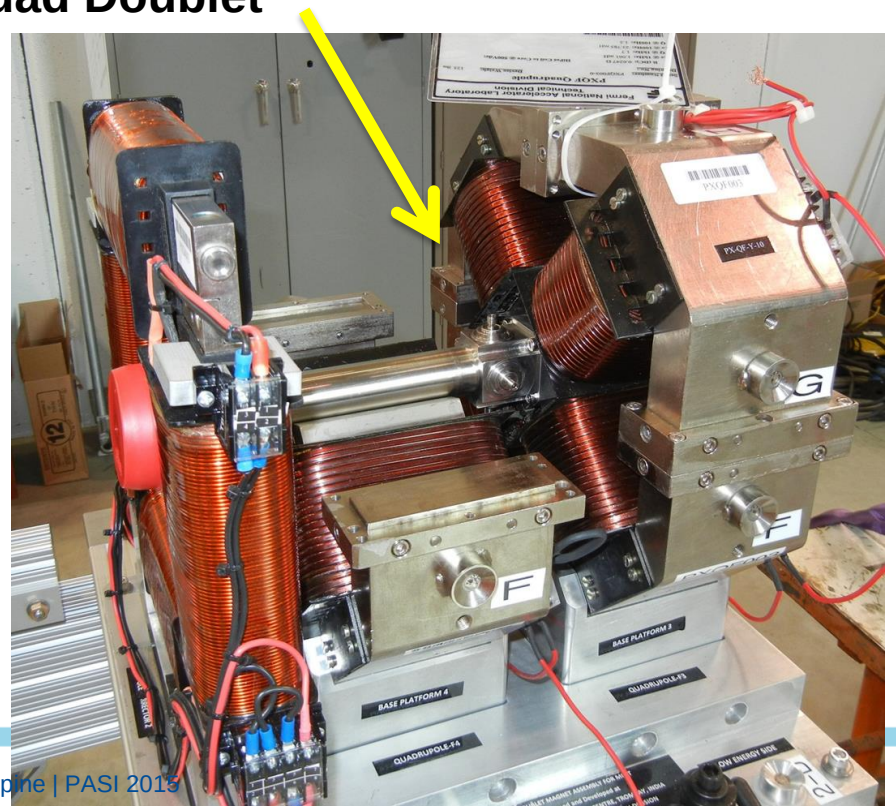


MEBT BPMs

Requirements:

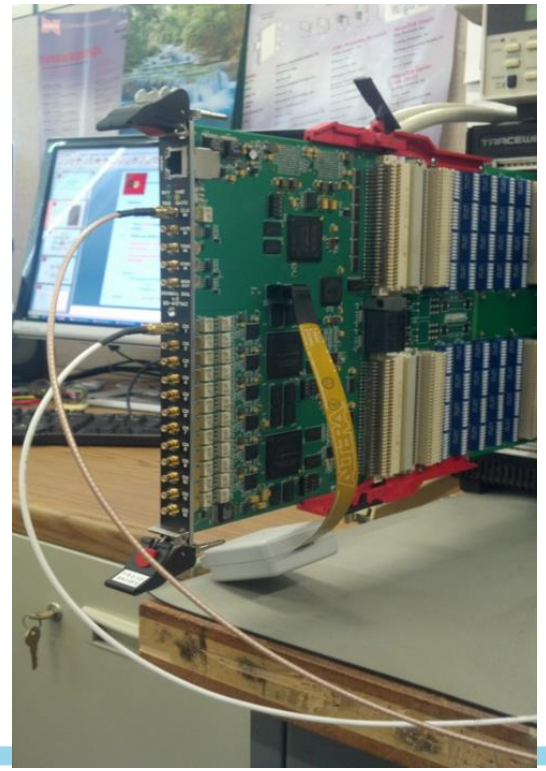
	Accuracy	Precision
Position, μm	10	30
Phase, degrees of 162.5 MHz	0.05	0.2
Relative intensity, %	1	3

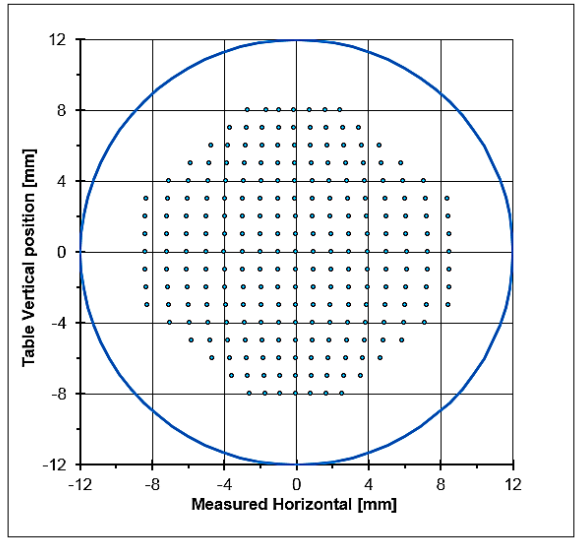
Four button Warm BPM in Quad Doublet



DAQ with FPGA-based electronics for CW and pulsed beam

- 12 channel boards
- 14 bits, 250 MSPS
- Different operational modes
- Adding lock-in synchronous signal detection capability
  - For laser wire development





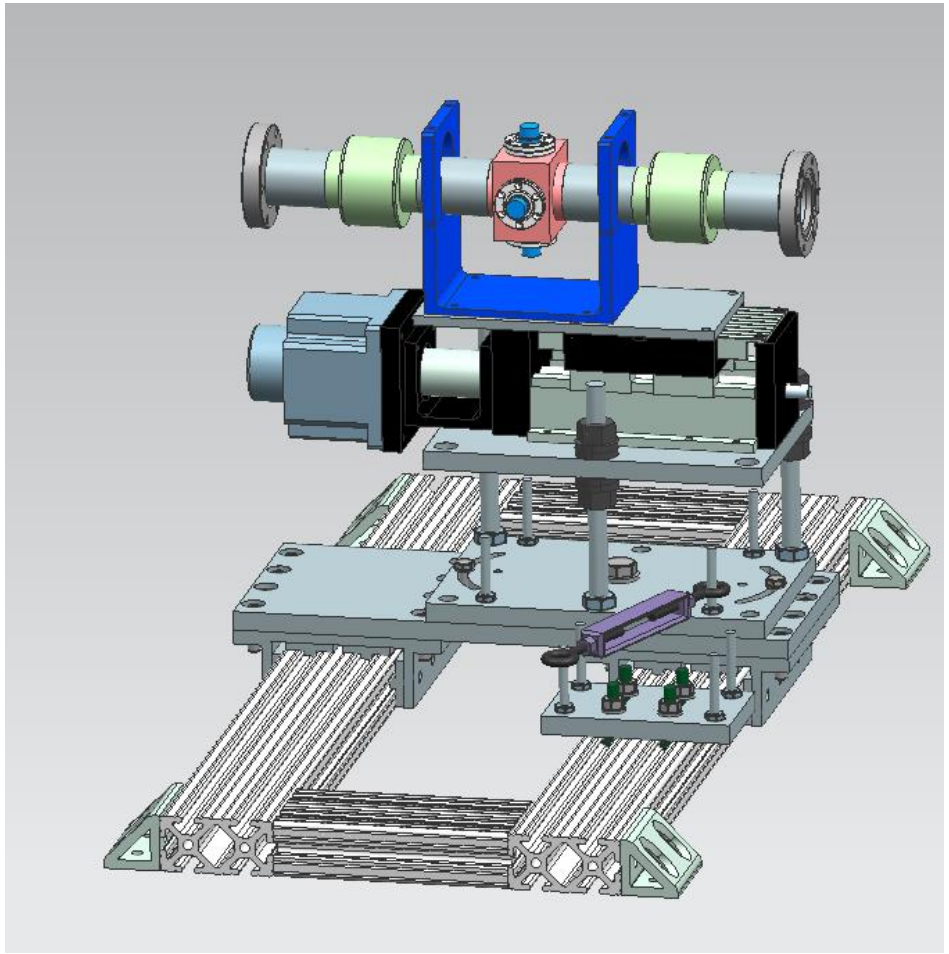
Stretched wire mapping

- Simulating low-β corrections

Time of Flight (ToF) Movable BPM

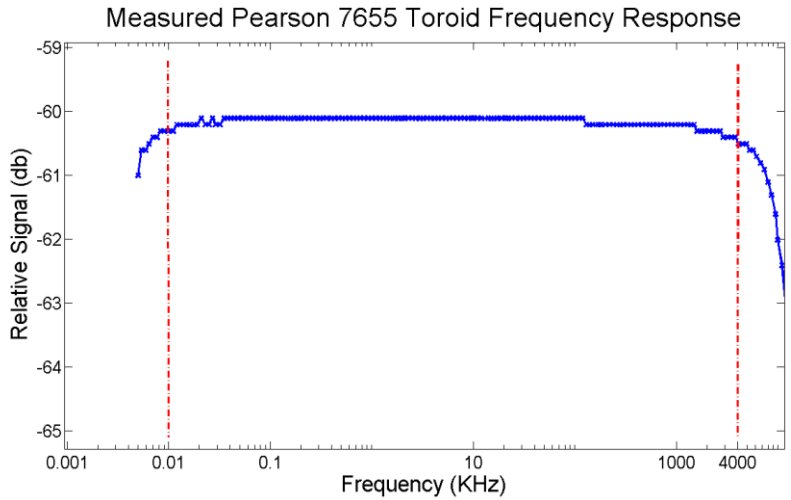
Measure beam velocity via ToF

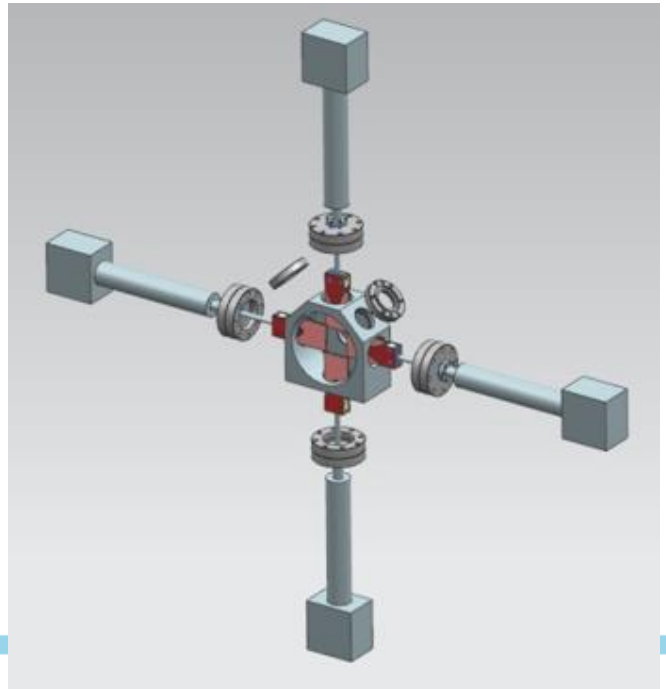
- Utilize movable BPM to minimize systematics
  - e.g. BPM response, bunch shape effects
- Use BPM on linear stage
  - ~ 1” of travel; ~10 μm resolution
  - Allows for “continuous” phase measurements
  - MEBT energy resolution: 0.1%
- Utilize ToF BPM to commission PXIE MEBT

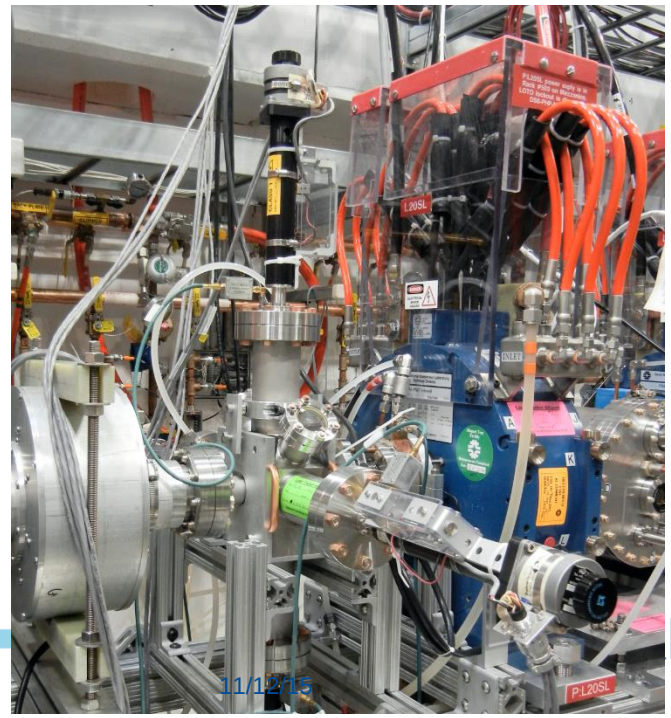


MEBT Beam Current and Profiles

- Faraday cup and two toroids
  - Pearson 7655 split toroids
    - Identical to LEBT toroid
  - Signal DAQ thru VME FPGA-based digitizers
- Beam profiles via scraper scans
  - Scrapers isolated and biased
  - Prototype scraper installed in LEBT
  - Signal DAQ thru VME FPGA-based digitizers
  - Profile reconstruction via Controls application



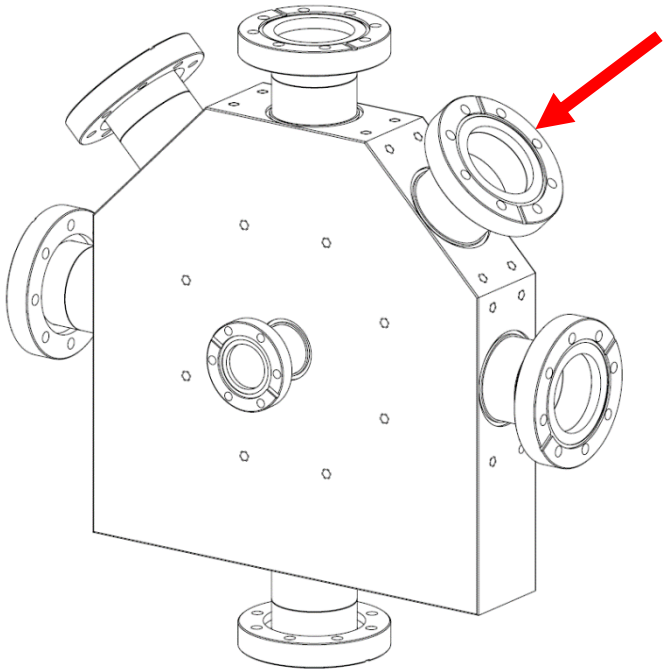


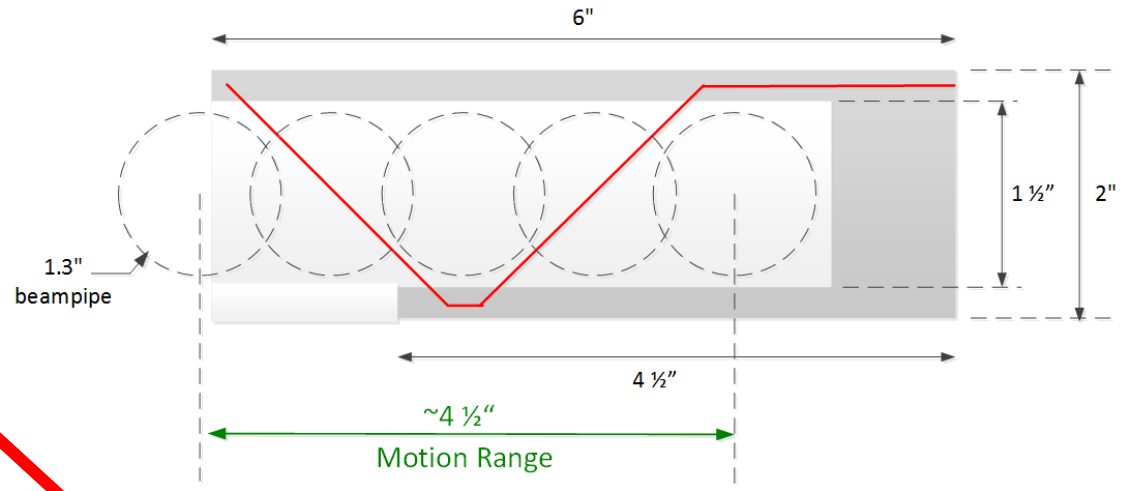


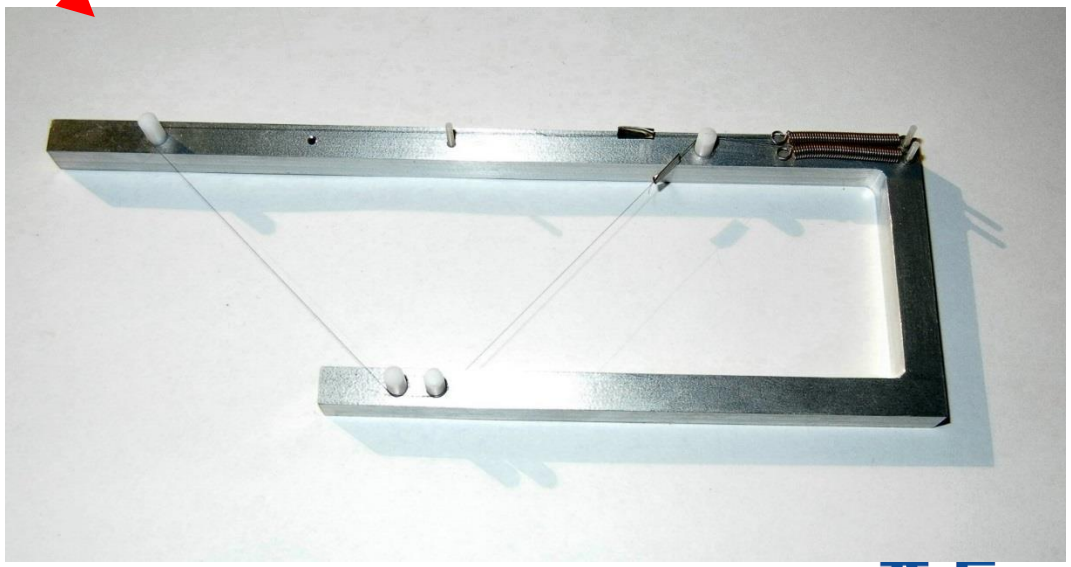
Prototyping Wire Scanner

Developing prototype wire scanner for profile measurements

- Test in diagonal port of MEBT scraper
- Constructed mock-up to test wire stretching and mounting issues

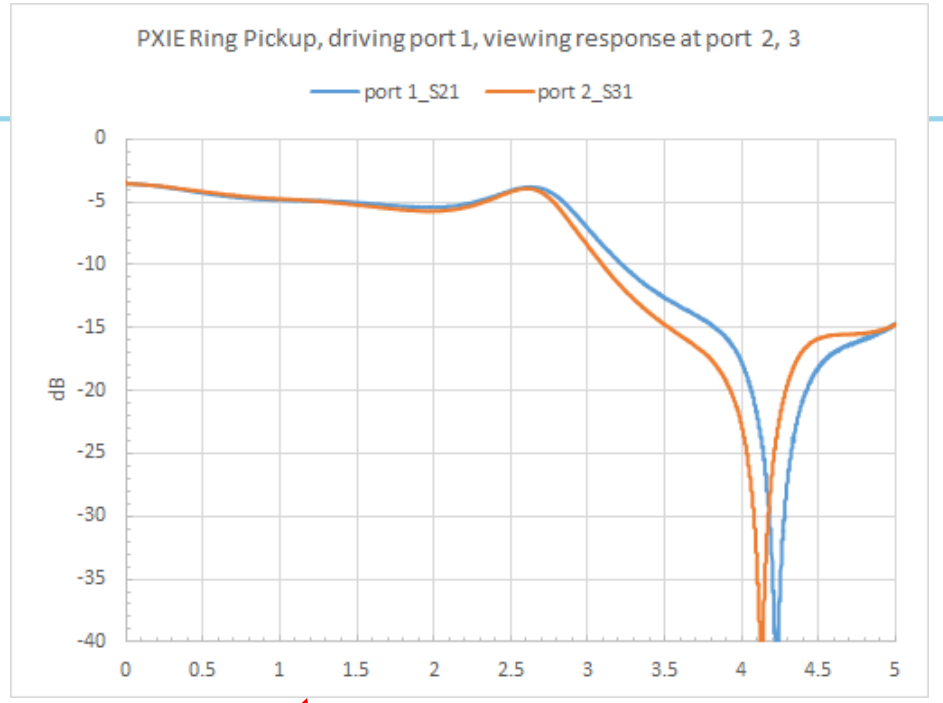


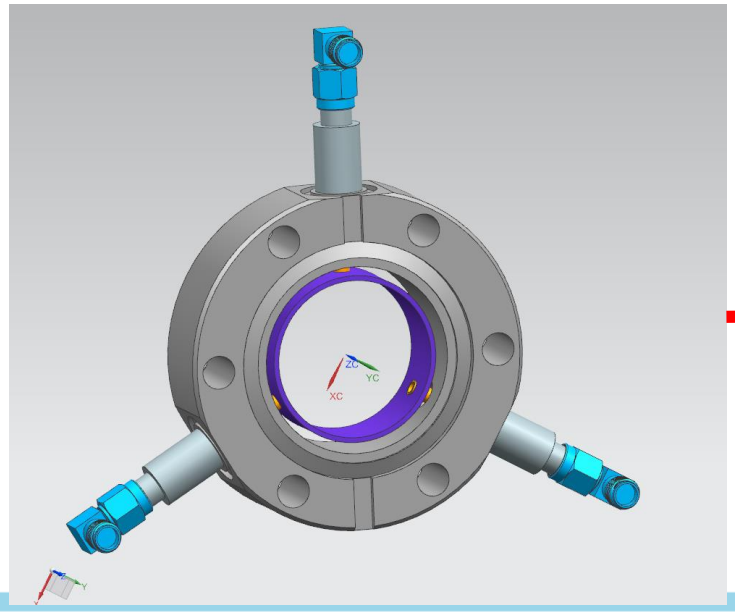




Ring Pickup - Machine Protection

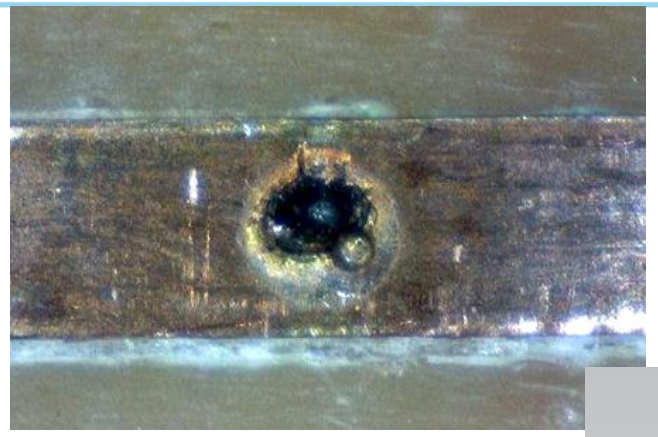
- Dedicated ring pickup to measure bunched-beam current
  - Wide bandwidth pickup
  - Independent of “standard” beam diagnostics
- Simple analog circuit to generate beam intensity



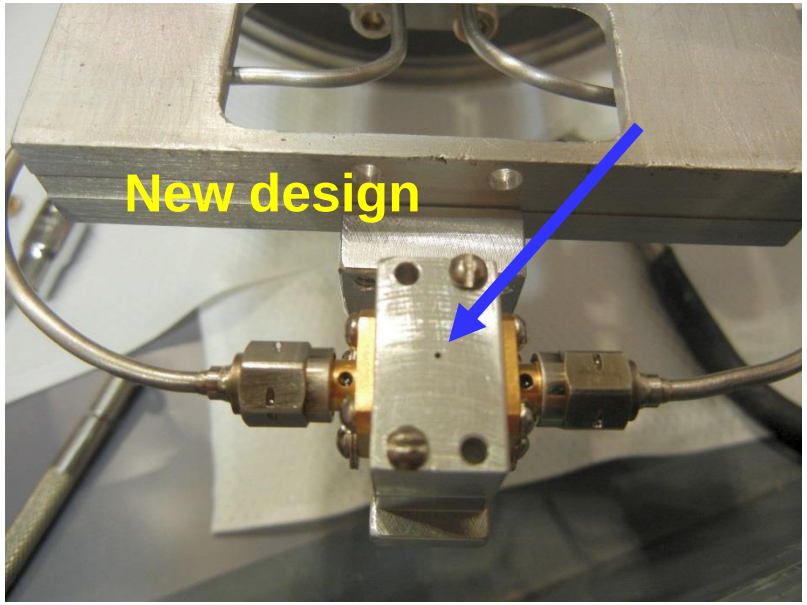


Bunch Length - New Fast Faraday Cup

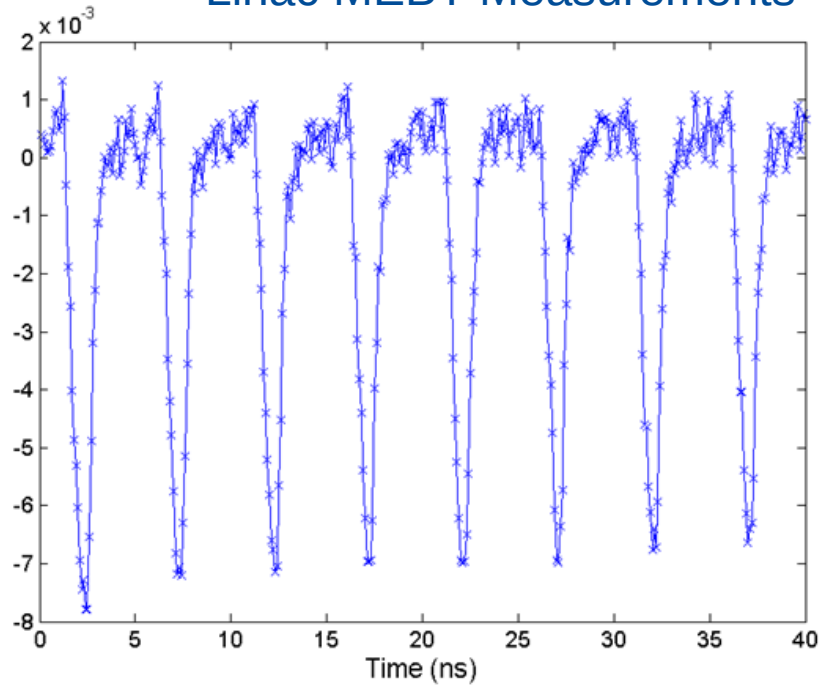
- Embedded 50 Ω stripline – initially designed by SNS
- High Bandwidth (> 6 GHz) – need scope DAQ
  - Beam damage at HINS (2.5 MeV protons)
  - We are redesigning with better thermal properties
- Old model tested at HINS and Linac
- Prototype new design tested in PXIE LEBT

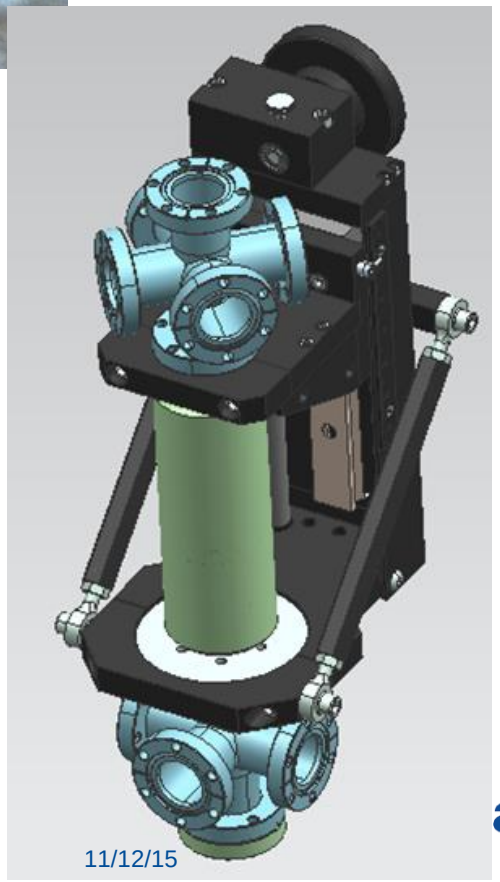


Old design - Damage with HINS beam
- 2.5 MeV protons
- 5 mA, 200 μs, 1 Hz

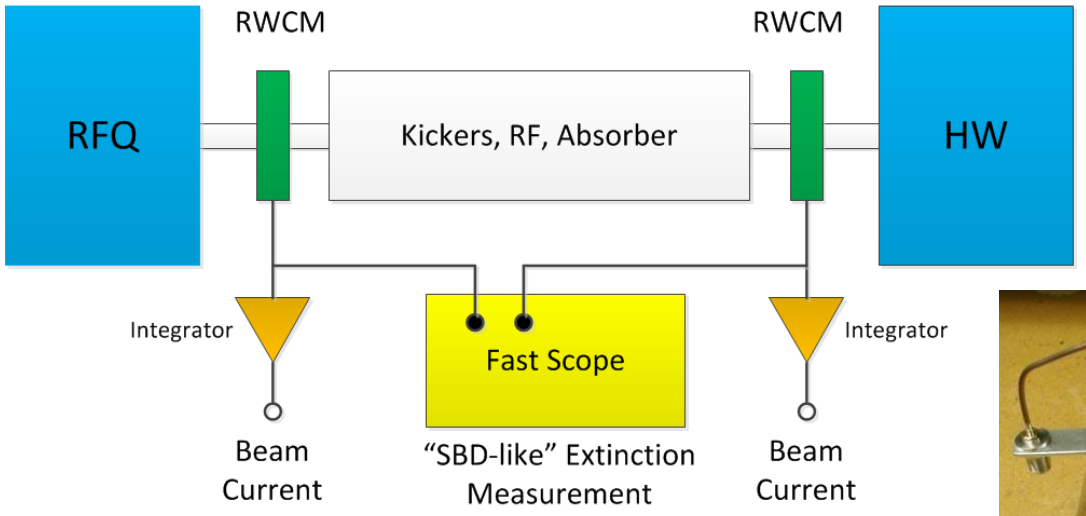


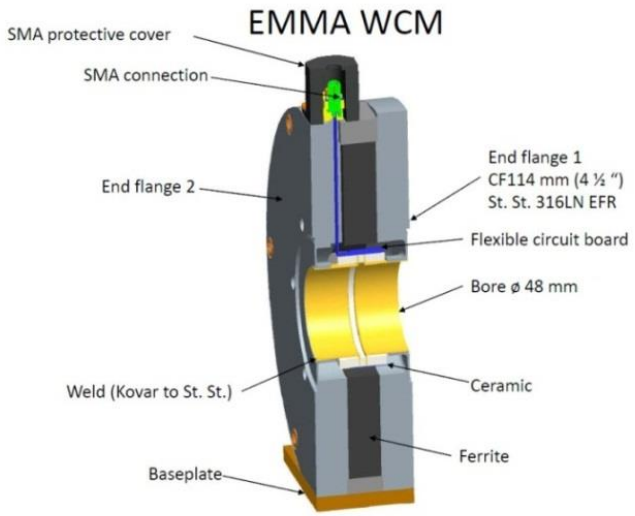
Linac MEBT Measurements

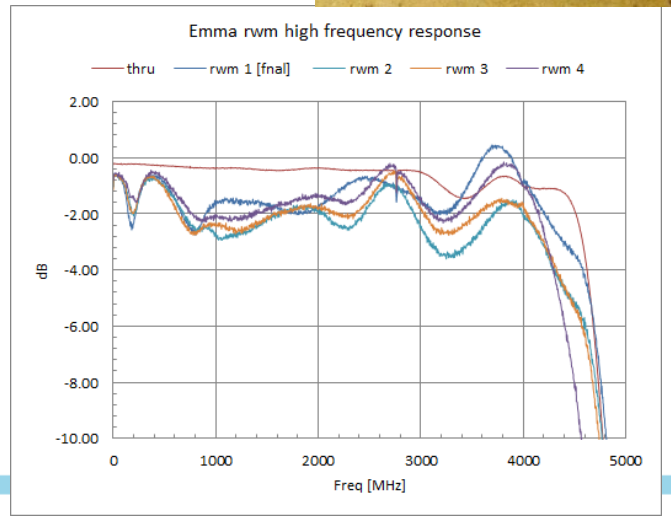




MEBT Chopper Extinction Measurement

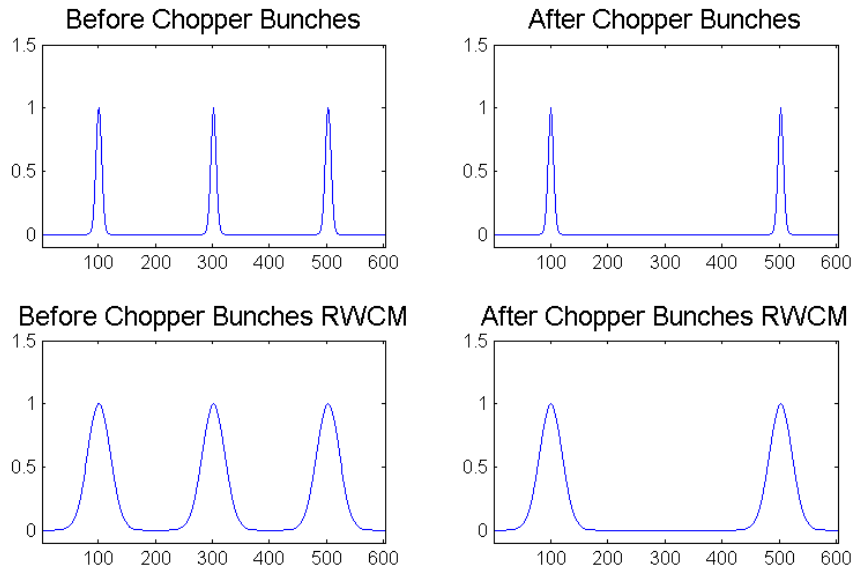






Use upstream and downstream Resistive Wall Current Monitors (RWCM)

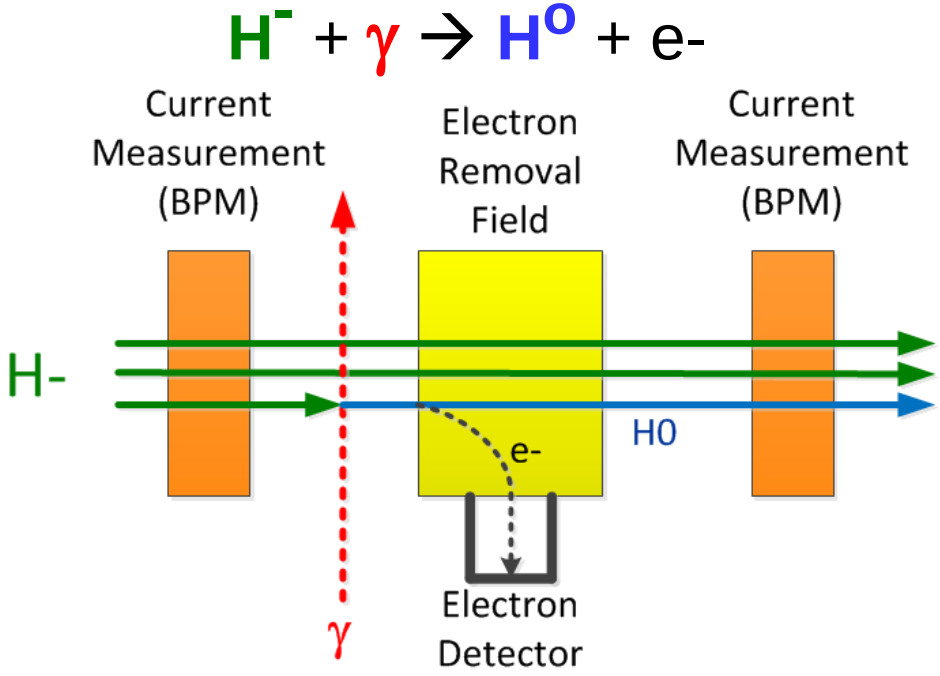
- Extinction -> 'SBD-like' monitor
  - Average over many bunches
  - < 1 Hz BW
  - Fits to bunch shape
  - Measure impact on adjacent bunches



Laser diagnostics R&D

History of laser diagnostics:

- Transverse profiling with high-power free-space laser and electron collection *operational* at SNS
- Longitudinal profiling using lower-power fiber delivery system and electron collection *demonstrated* at SNS
- Transverse profiling using high-power free-space laser and measurement of reduced beam current *demonstrated* at BNL
- Research goal to demonstrate *transverse and longitudinal* profiling using lower-power fiber lasers and reduced beam current technique



Primary Goal: Demonstrate both transverse and longitudinal profile measurements to a sensitivity of 1e-6 using low-power laser through fiber distribution and synchronized detection

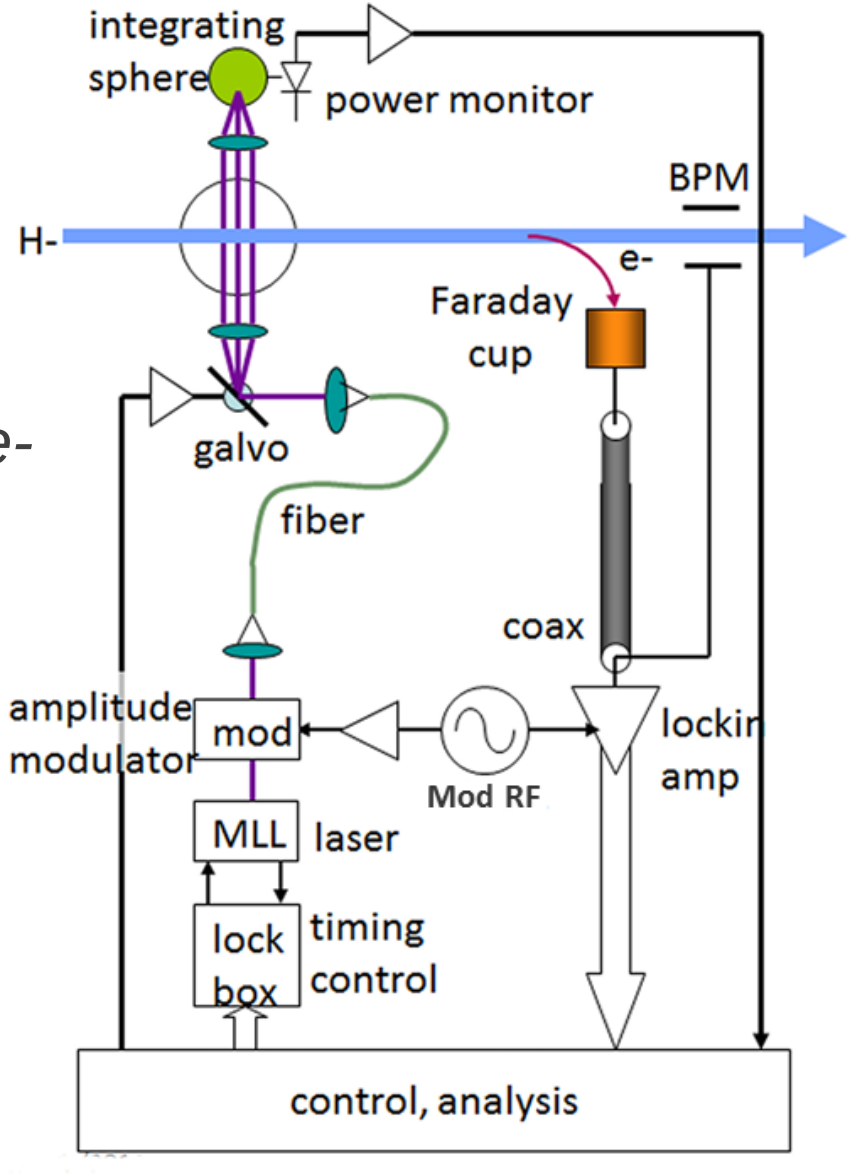
Secondary Goal: To understand any technology and systematic effects that would limit achieving primary goal

Laser Diagnostics R&D

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 intensity pickup
- Narrow-band lock-in amp detects modulated signal

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



R. Wilcox, LBNL

Questions:

- What are the noise issues?
- What are the power limits in the fiber?
- What signal-to-noise ratios and averaging times are practical?
- What are the accelerator systematics?

Status

- Test system at PXIE - infrastructure development underway
- Laser design/development underway
- System commissioning end of 2016

Summary

Fermilab

- PXIE LEBT beam instrumentation has been tested during initial source/LEBT beam commissioning
- Water-cooled LEBT Allison scanner has proved to be a key instrument
- PXIE MEBT instrumentation under various stages of development
  - Initial MEBT configuration focusing on commissioning of RFQ
- Operation with CW beam proving to be challenging
- PXIE provides an exceptional opportunity to develop beam diagnostic instrumentation for high-power H- beams