Beam Diagnostics for Low Energy Proton and H^- Accelerators

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Outline

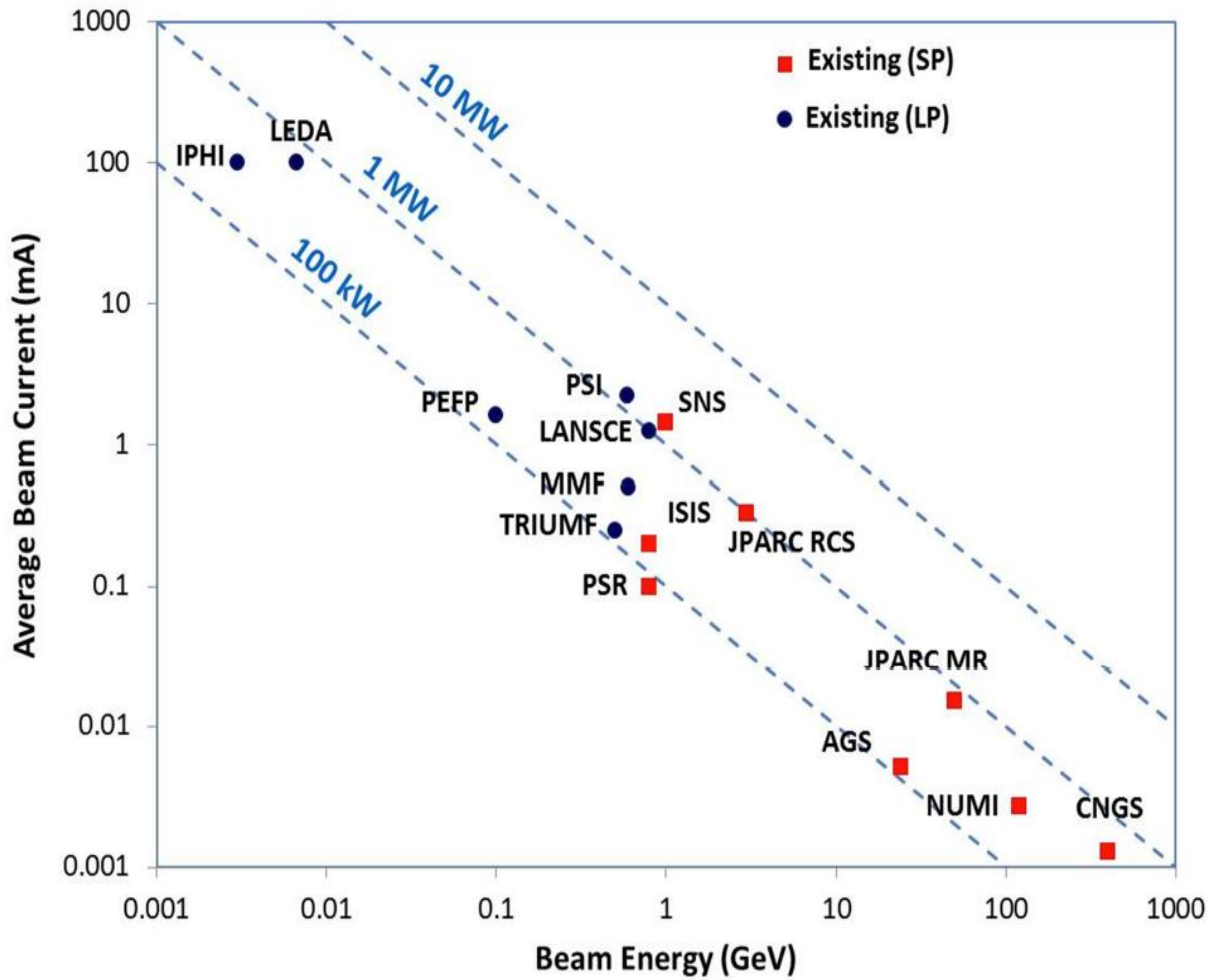
- High-power proton/H- accelerator future
- Generic accelerator front-ends
- Typical diagnostic instruments and measurements
- Specific measurement cases with front-end accelerators at Fermilab
  - HINS – High Intensity Neutrino Source
    - R&D Test Accelerator
  - PIP – Proton Improvement Plan
    - Upgrade to Fermilab Linac
  - PXIE – Project X Injector Study
    - Project X front-end test accelerator

Talk is not a laundry list of diagnostic instruments but more of a discussion of generic front-end with a few specific measurement cases

Existing Beam Power Landscape

"Intensity frontier" pushing proton/H- accelerators to higher beam powers:

- Neutrino physics
- Rare decay physics
- Accelerator driven systems (ADS)

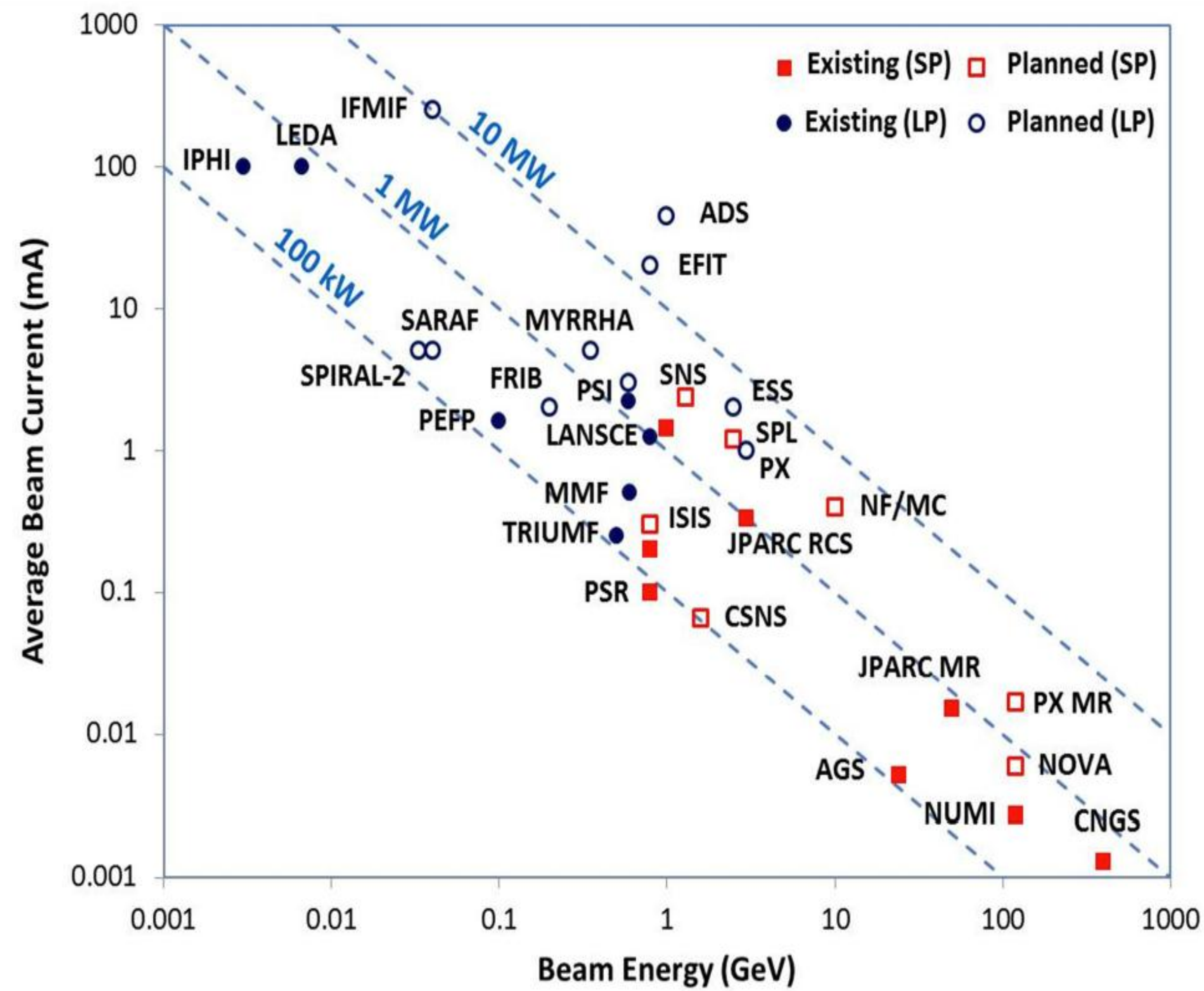


Future Beam Power Landscape

A “large” number of upgrades or new high power accelerators are on the horizon.

Drives diagnostics to be either:

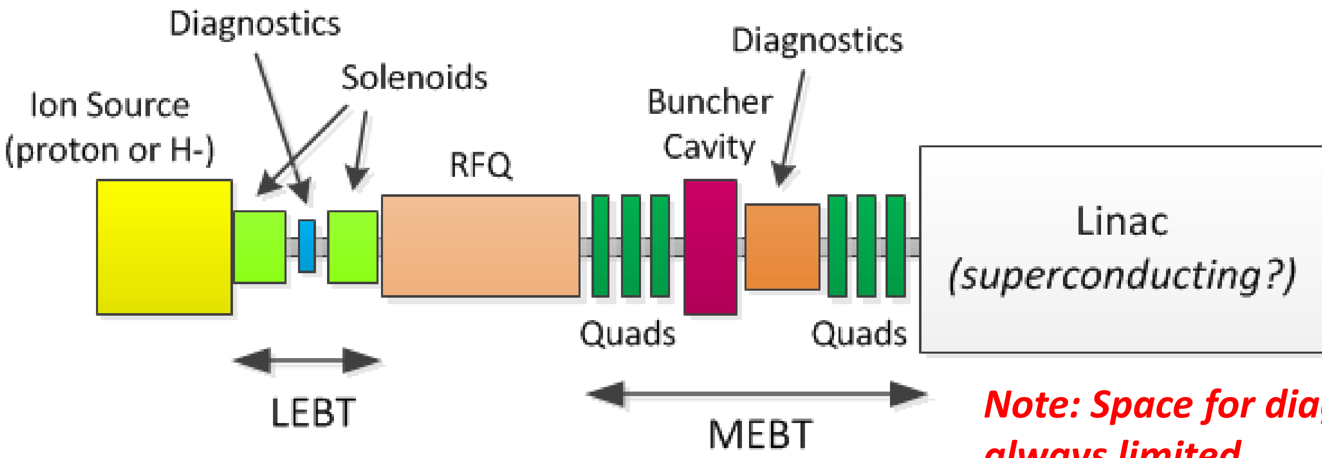
- *Non-intercepting*
  - Instrument survival and minimize beam loss
- *Reduced beam power operation*
  - Beam chopper



Challenges for High Power Proton/H- Accelerators

- *Producing high-quality beams in the injector system (high brightness, low halo) at high duty factor*
- Accelerating high beam currents to high energy
  - High-duty factor, high-power RF systems, structures and components; for RF efficiency and practicality, *SCRF is the technology of choice*
- Transporting high power beams while maintaining beamloss at a level where routine maintenance is possible (<1 Watt/m)
  - *Acceleration of beams from keVs to GeVs with little emittance growth, and minimization of halo growth*
  - Understanding and control of collective effects that have the potential to generate large-amplitude particles
  - Systems for stripping, collimation, low-loss extraction, machine protection
- Target systems capable of handling extreme power densities and extreme radiation environments (~ 1e5 Rem/hr beam off)

“Generic” Front-Ends



Issues:

- Low β
  - Particle field lines spread
- Multiple ion species

Note: Space for diagnostics always limited

	HINS	PIP	PXIE
Source	Proton (H- later)	H-	H-
Source Energy	50 KeV	35 KeV	30 KeV
Beam Current	up to 20 mA	up to 65 mA	5 mA LEBT, 1 mA linac
RFQ Energy	2.5 MeV	750 KeV	2.1 MeV
Pulse Rate	up to 10 Hz	15 Hz	CW
Pulse Length	3 @ 2.5 Hz 1 @ 10 Hz	100 μs	1 μs → infinite
RFQ RF Freq	325 MHz	201 MHz	162.5 MHZ

Functional Requirements

- *What beam measurements are required to meet the goals of the accelerator program?*
- Functional requirement guidelines should drive diagnostics
  - This is seldom the case
- "Operational" vs "Commissioning" Requirements
  - Operational Instrumentation required to monitor normal beam operations as well as identify potential problems
  - Commissioning instrumentation required to *characterize* beamline performance
    - Nominally a super-set of operational instrumentation
    - What defines a full set of beamline characteristics?
      - When does "operation" knowledge bleed over to "academic" interest
      - Few R&D front-ends to test diagnostics

"Typical" LEBT Diagnostics

What to measure and why?

- Stability of Ion Source (operational)
- Quality of beam entering RFQ (operational?)

Usual operational diagnostics:

- Beam current in LEBT → toroid, DCCT

Additional: *(some subset during commissioning)*

- Transverse beam profile at end of LEBT
  - Wire scanners/multi-wires
- Transverse emittance at source and RFQ entrance
  - Slit + wire scanner, Allison scanner (water cooled)
- Beam energy (not usually measured)
  - Time-of-flight, spectrometer
- Mapping of beam position at RFQ entrance versus solenoid settings
  - Steering of beam through solenoids
  - Wire scanner/multi-wire
  - Laser wires ($H^- + \gamma \rightarrow H^o + e^-$) – *see Y. Liu talk*
    - *Non-intercepting*

Note: At these beam energies (30-50 KeV), H-/proton deposited in < 1 μm of materials

- *Thermal issues important*

“Typical” MEBT Diagnostics

What to measure and why?

- Stability of RFQ beam
- Operation of MEBT
  - For example, operation of buncher cavities or MEBT chopper

Usual diagnostics:

- Beam current into and out of MEBT
  - Beam toroid. DCCT
- Beam position along MEBT
  - BPMs
- Bunch phase along MEBT *(to phase in any MEBT cavities)*
  - *BPMs*
- Transverse beam profile
  - Wire scanner, multi-wire, laser wire (H-), Ionization profile monitor, beam fluorescense
    - Non-intercepting

Additional: *(usually in commissioning):*

Transverse beam halo

- Wires, lasers (H-)?
- *good place for R&D*

Longitudinal beam profile

- Bunch Shape Monitor (BSM), lasers (H-)

Longitudinal beam halo

- BSM? Lasers (H-)?
- *good place for R&D*

Transverse emittance

- Slit + wires, quad or solenoid scans, laser emittance monitor?

Beam energy

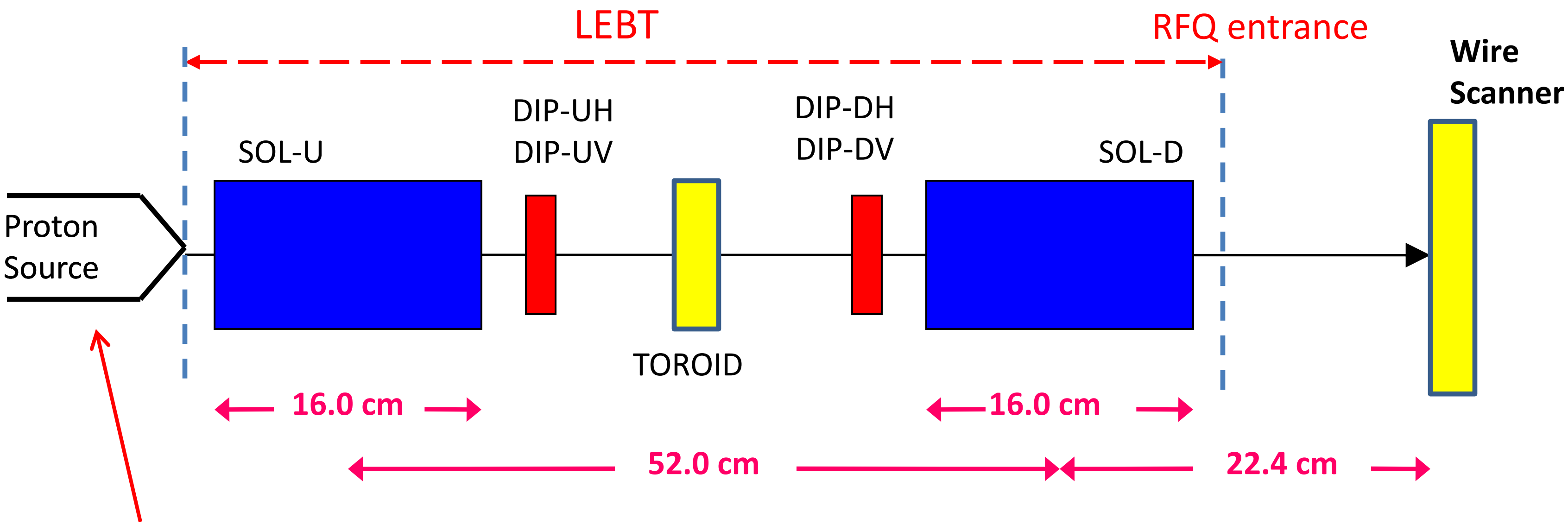
- Time-of-flight, spectrometer

Measurement Example

Fermilab High Intensity Neutrino Source (HINS)

Proton source and LEBT beam measurements

HINS Proton Source and LEBT Beam Measurements



Duo-plasmatron Proton Source	
Energy	50 keV
Peak Current	> 20 mA
Pulse	3 msec
Rep. rate	2.5 Hz

	Name	Current [Amp]	B [Gauss]
SOL-U	Upstream solenoid	850	7900
SOL-D	Downstream solenoid	850	7900
DIP-UH	Upstream horizontal dipole	3	100
DIP-UV	Upstream vertical dipole	3	100
DIP-DH	Downstream horizontal dipole	3	100
DIP-DV	Downstream vertical dipole	3	100

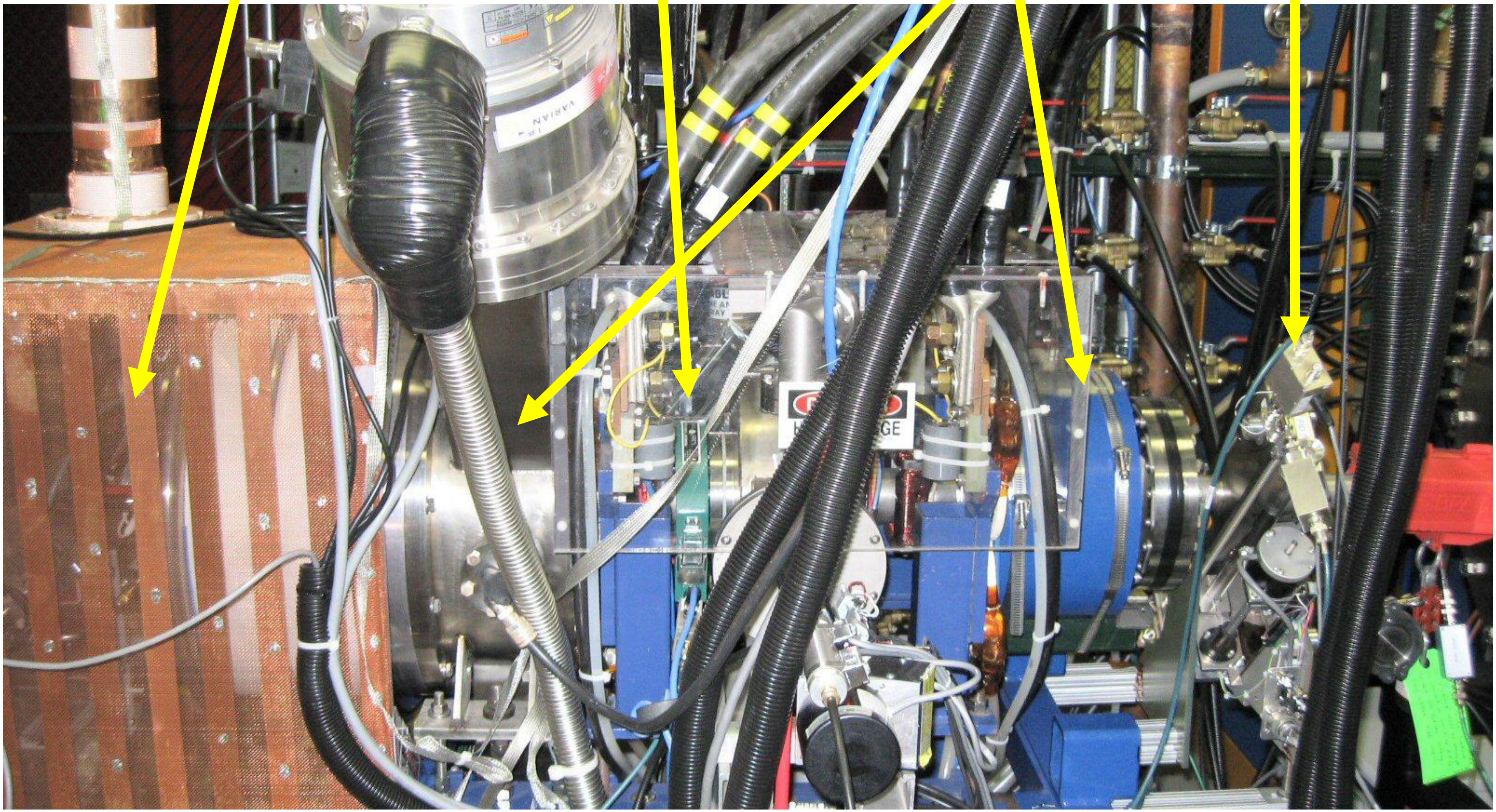
HINS LEBT Beam Measurement Setup

Proton Source

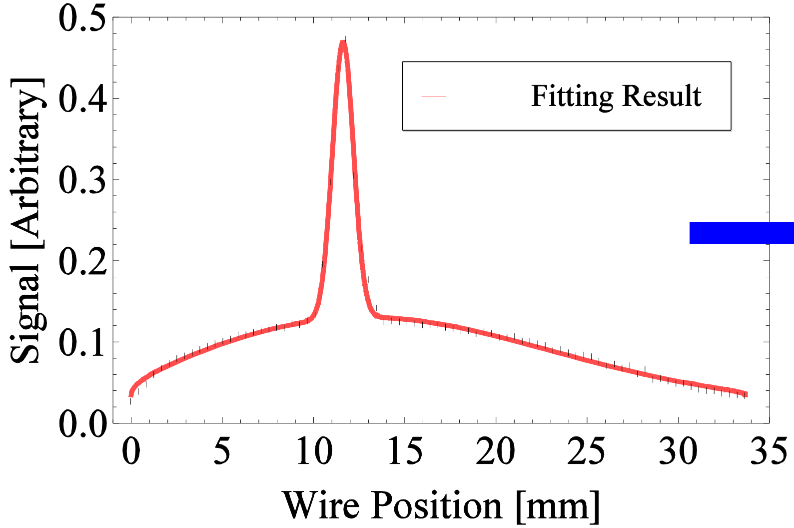
Toroid

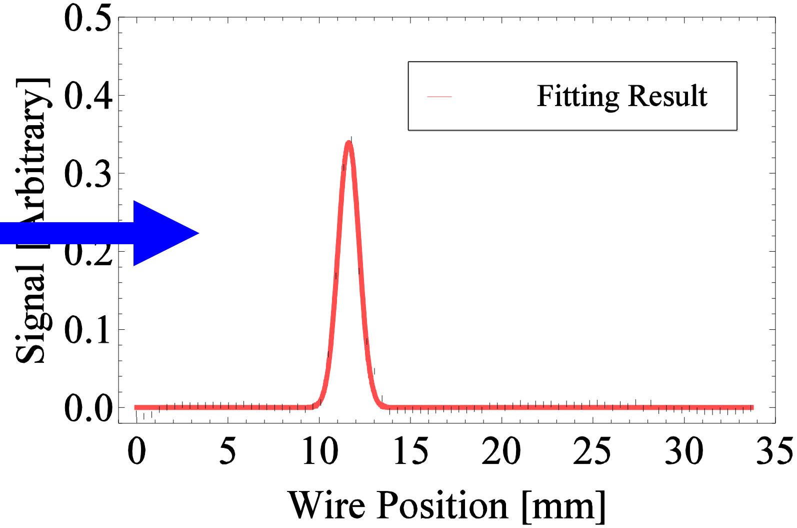
Focusing Solenoids

Wire Scanner

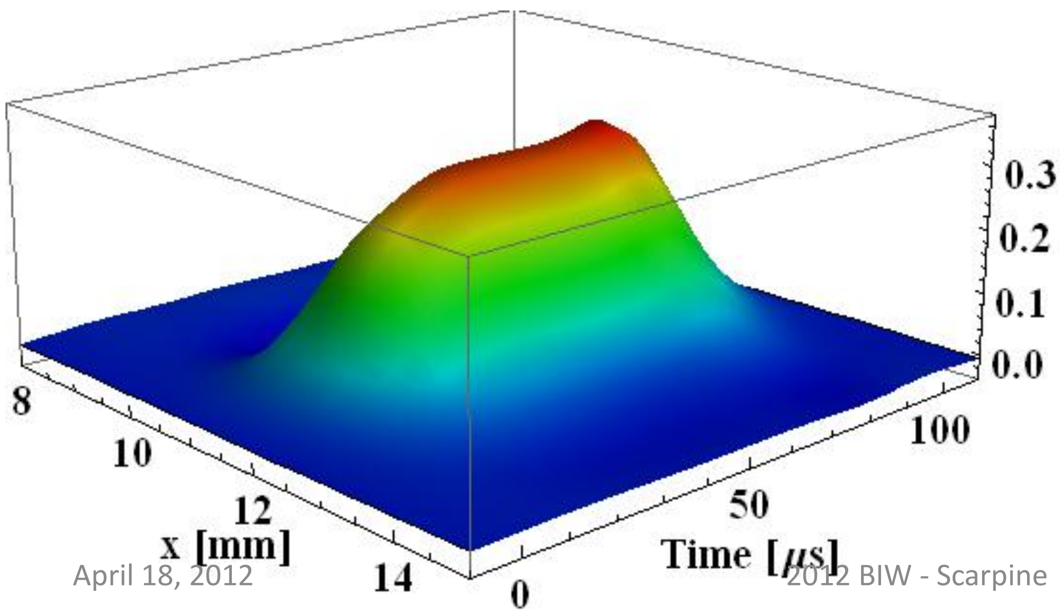


A Typical Wire Scan



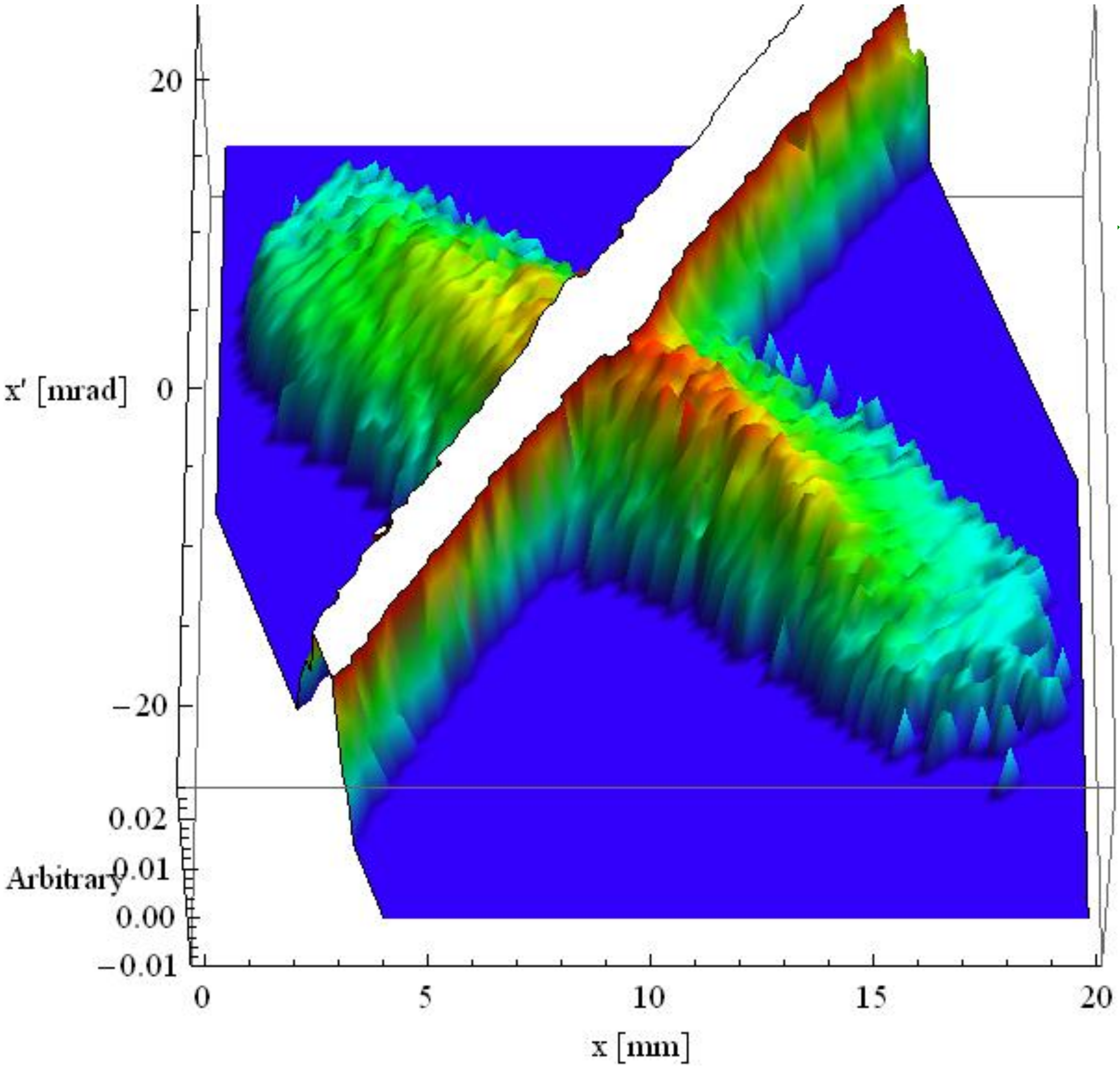


Signal with background subtracted.

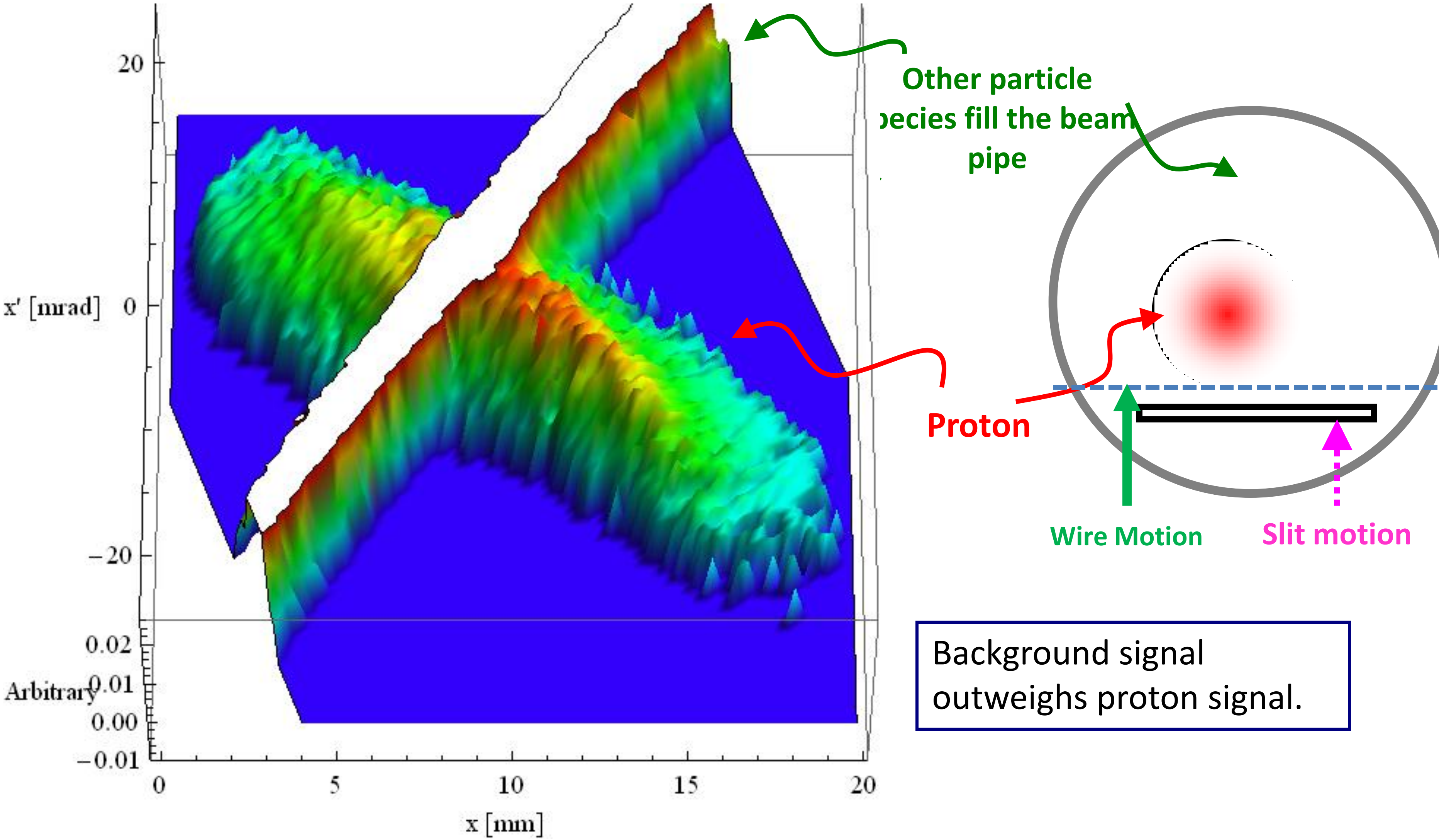


The time structure of a 100 μs pulse. The flattop is about 50 μs.

Proton Source Slit-WS Emittance Measurement



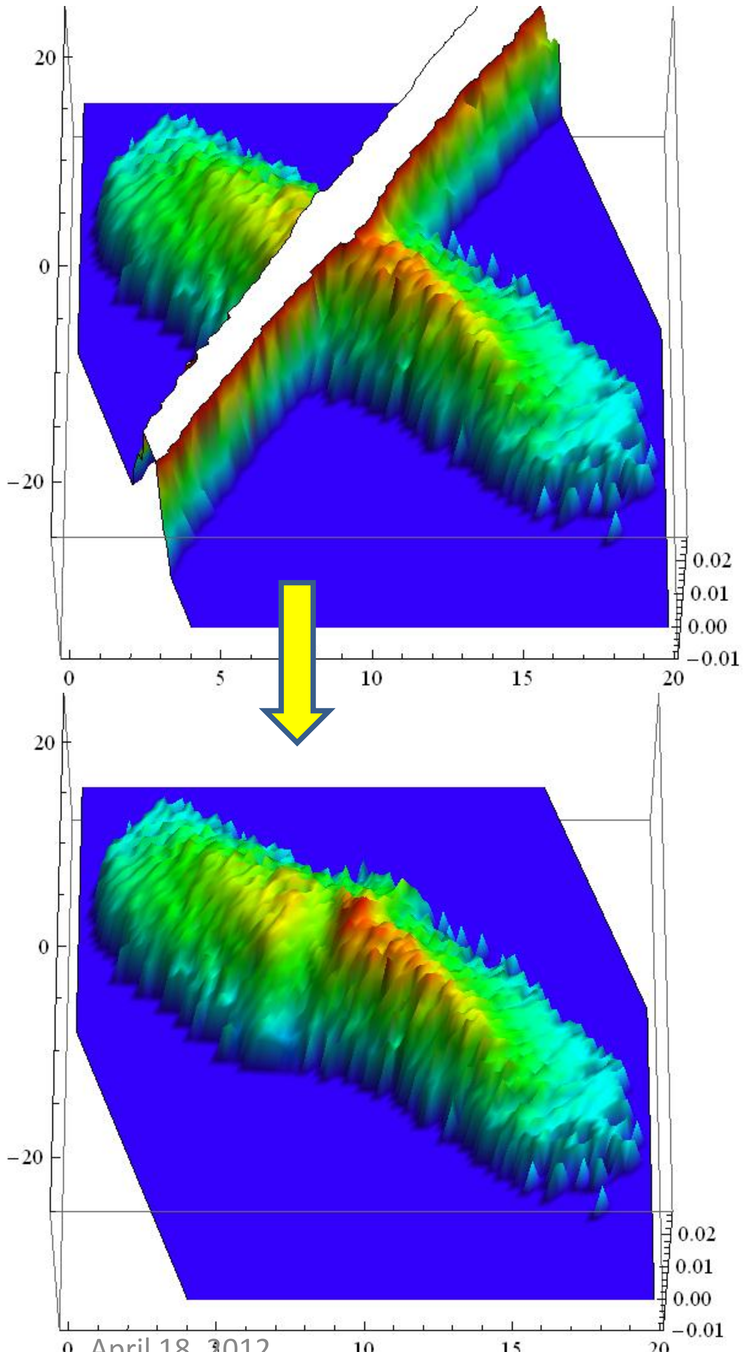
Proton Source Slit-WS Emittance Measurement



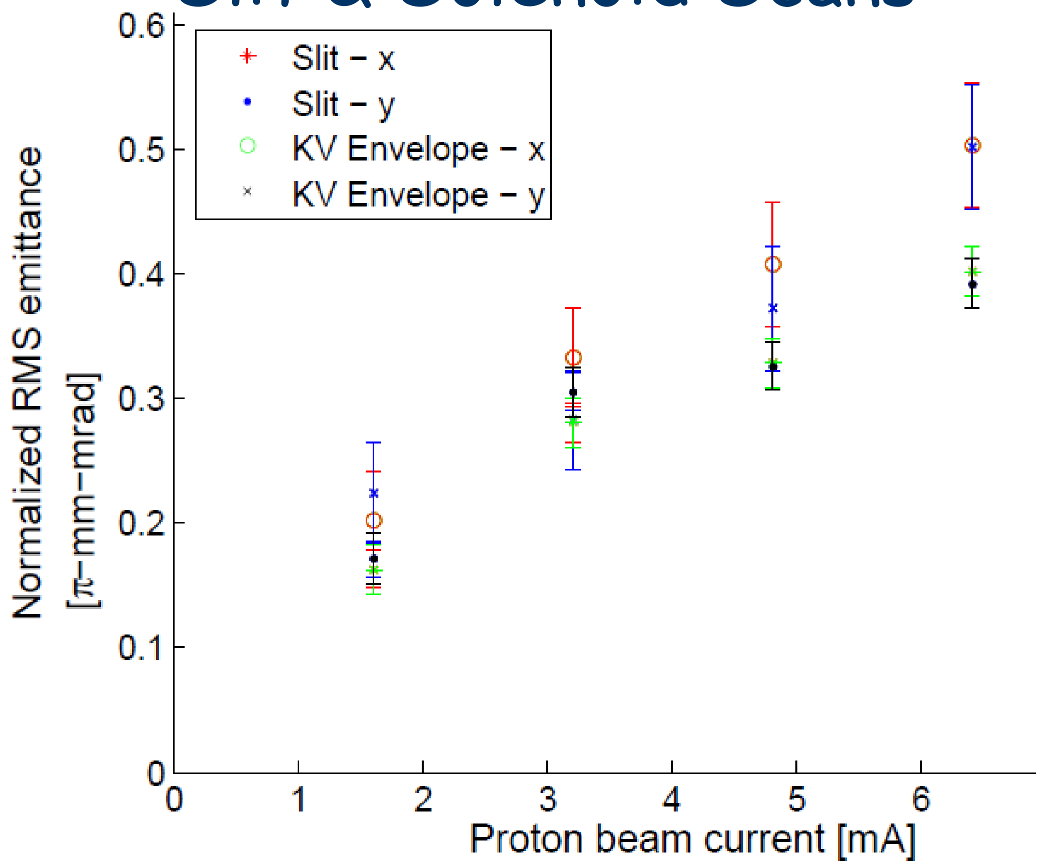
Background signal outweighs proton signal.

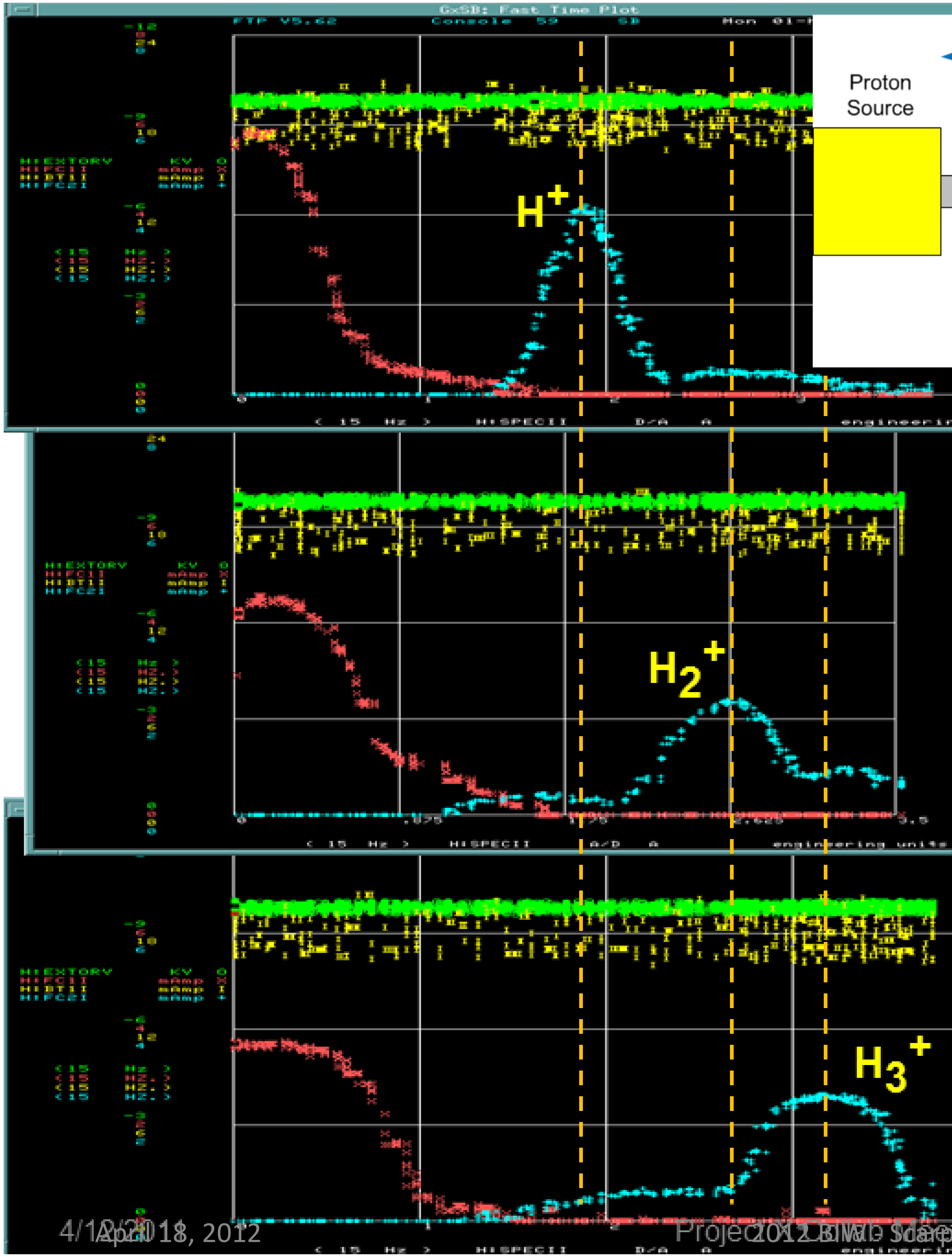
Phase Space Signal Cleaning

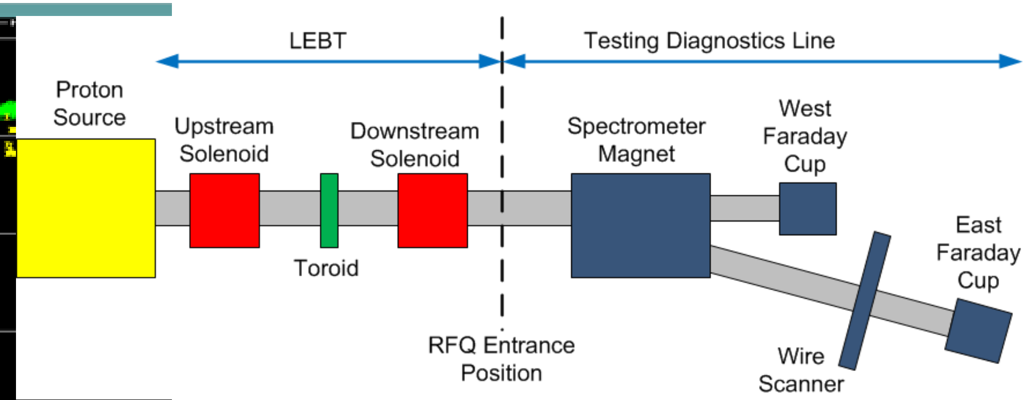
- Remove background thru image processing



Source Emittance from Slit & Solenoid Scans







Source Species

Green – Source Extractor Voltage

Yellow – LEBT Toroid Current

Red – Straight ahead Faraday Cup

Blue – Spectrometer Faraday Cup (bend)

- Downstream solenoid optimized for each species
- Upstream solenoid fixed at 470 A

~ 40% Protons

~ 30% H2+

~ 30% H3+

- ***As measured by LEBT toroid***

Measurement Example

Fermilab Proton Improvement Plan (PIP)

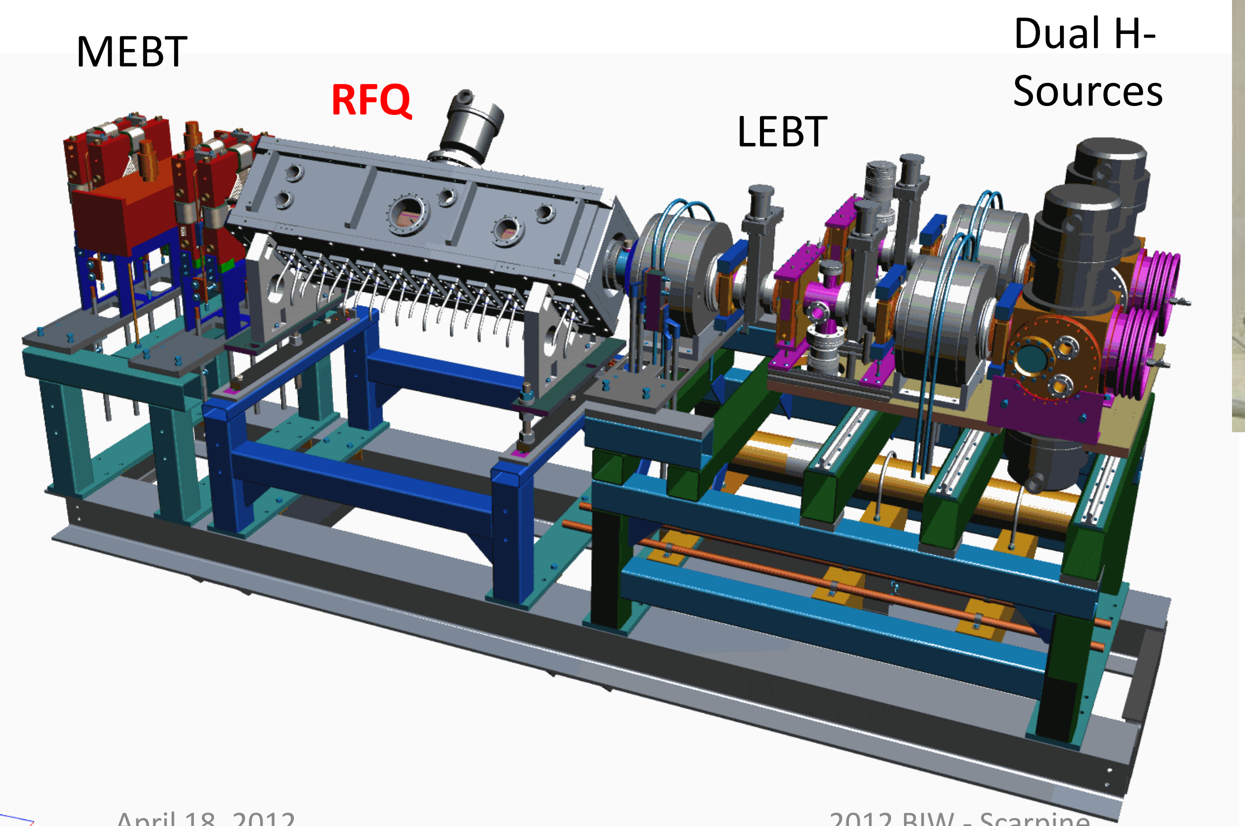
Upgrade to the Linac Front-End

RFQ Energy Measurement

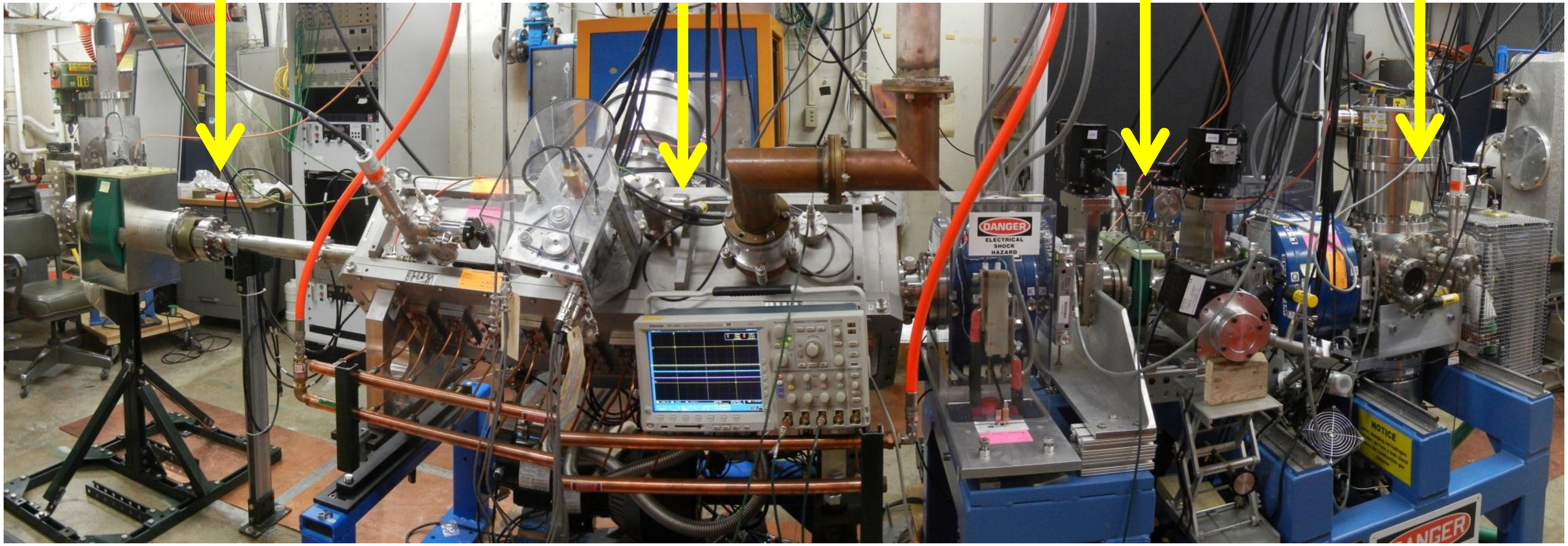
Fermilab PIP Front-End Upgrade

Upgrade Fermilab linac front-end :

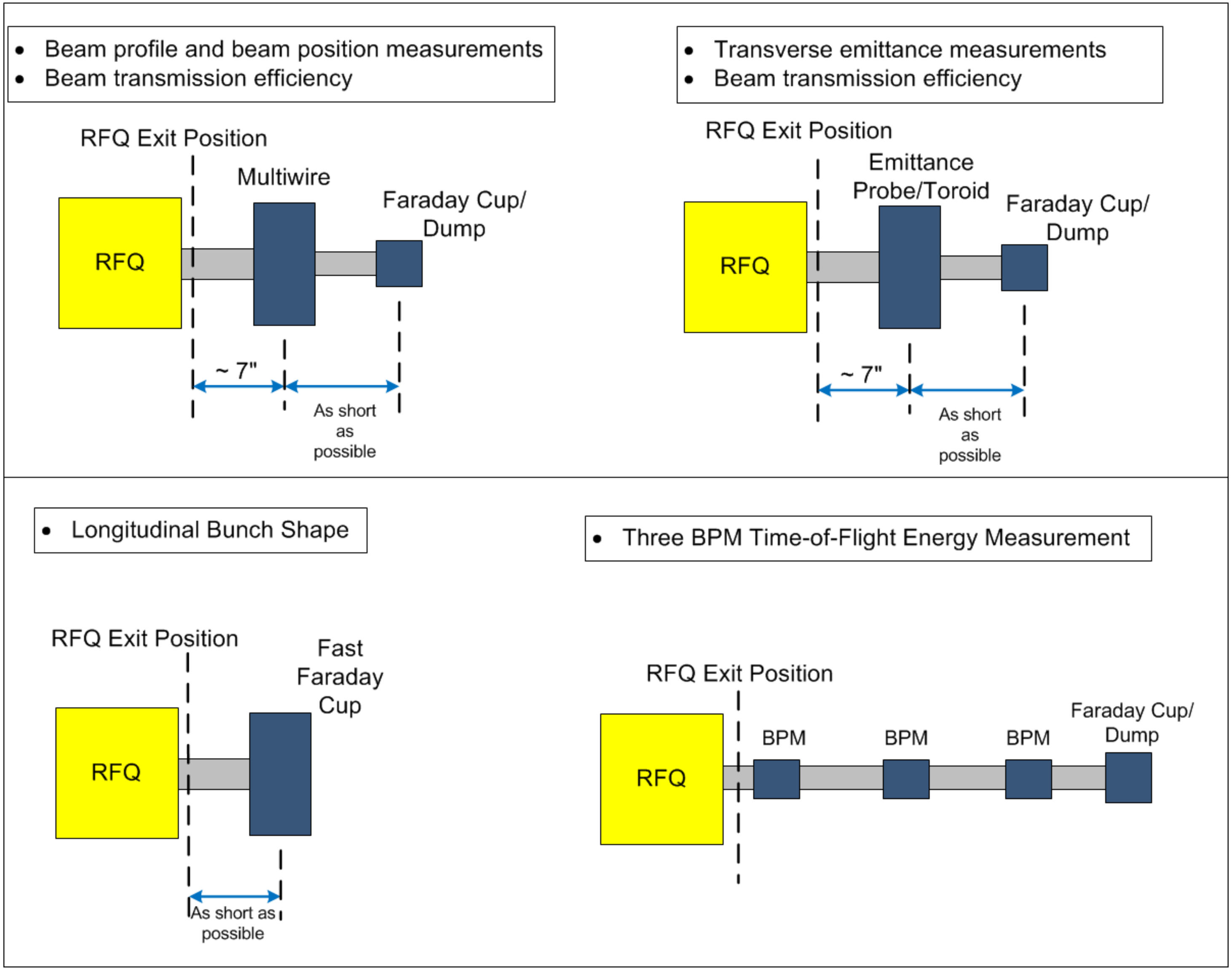
- Replace present sources and Cockcroft-Walton
- Dual H- sources – 65 mA @ 35 KeV
- New 201.25 MHz, 750 KeV, 4-rod RFQ



PIP Front-End



RFQ Commissioning Test Setups



Fermilab PIP Absolute Energy Measurements

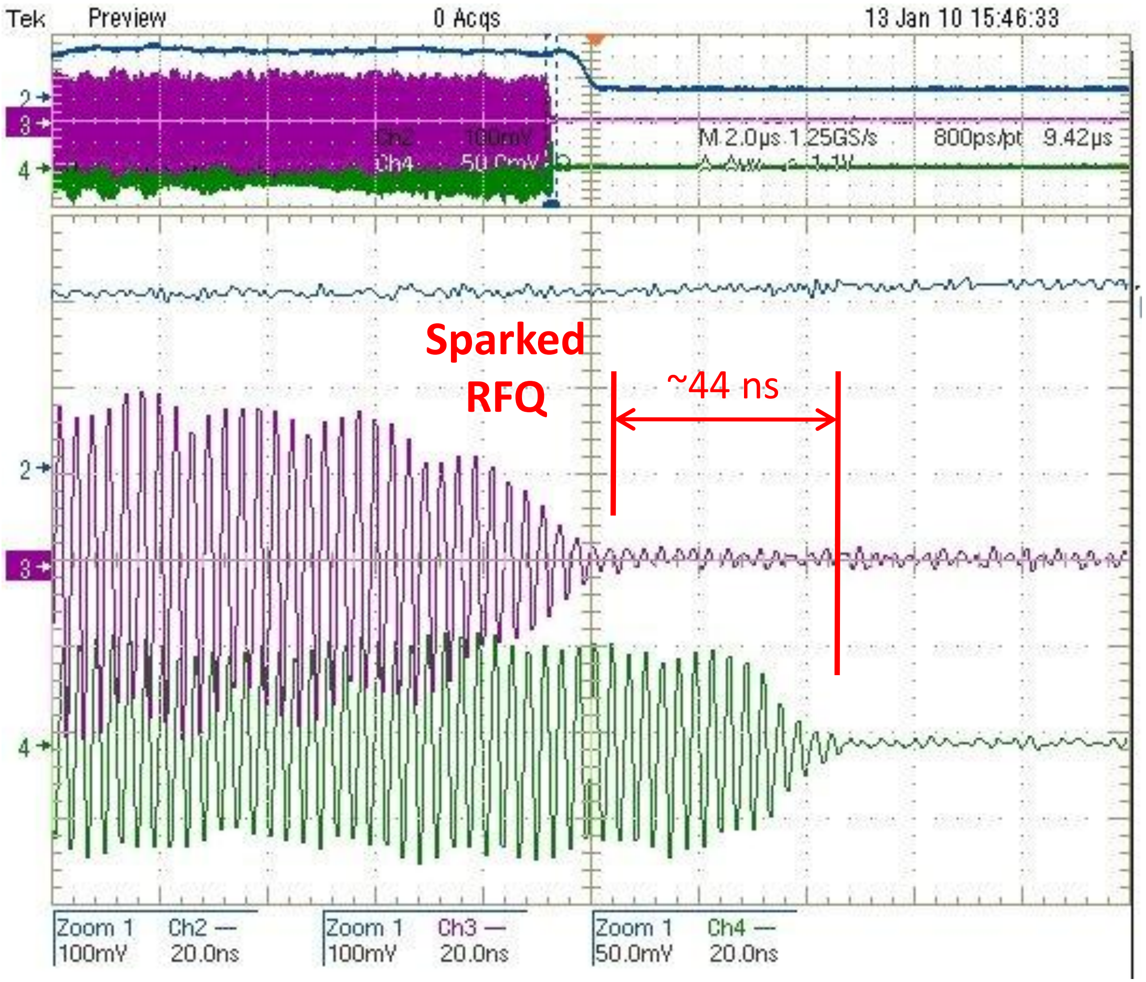
Which technique?

1. Energy spectrometer?
   - Fairly straight forward
   - Lots of pieces, complicated – magnetic field, beam alignment
2. Time of Flight (ToF)?
   - Simpler setup
   - Usually requires a sharp edge to get absolute energy
   - If velocity is constant then can infer absolute energy using multiple BPMs
3. Gas scattering system with solid-state detector

PIP choice – Time-of-Flight

- Two close BPMs for gross energy
- Two further apart BPMs for finer energy resolution

RFQ Energy Measurement by Time of Flight at HINS



Difficult without beam edge

Signals from toroid and two BPM buttons, all downstream of the RFQ

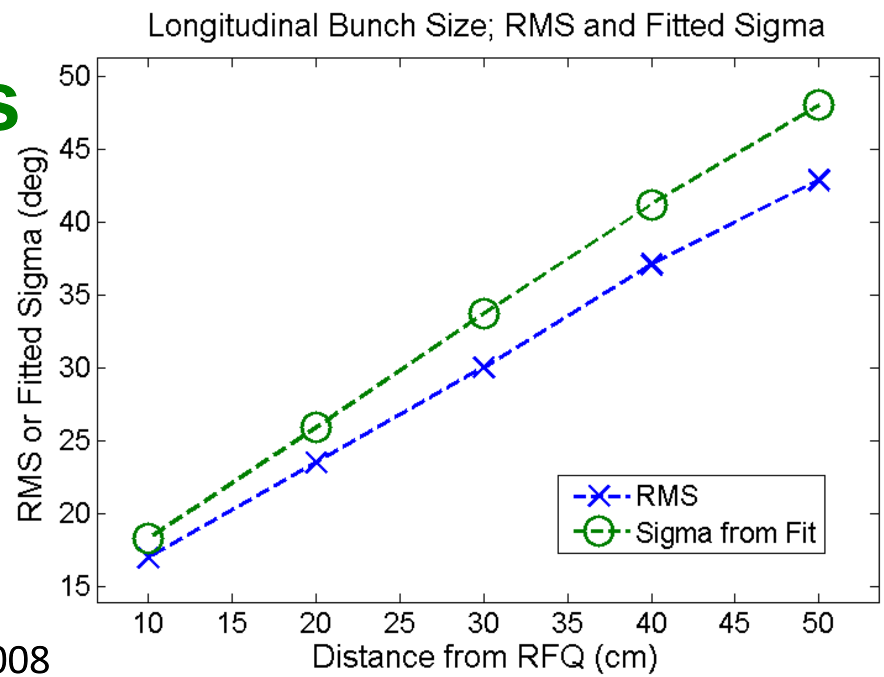
Upper display: 2 µsec/div

Lower display: 20 nsec/div

Lower display shows the 44 ns delay expected for transit of 2.5 MeV beam between the BPM two buttons separated by 0.96 meters

Beam current is about 3 mA

ToF Using 3-BPMs



Can define ToF as: ***N*(1/F$_{RF}$) + ΔΦ***

- Can measure $\Delta\phi$ accurately but can not directly measure N
- But can infer N if beam velocity constant and BPMs spaced correctly

What is BPM spacing?

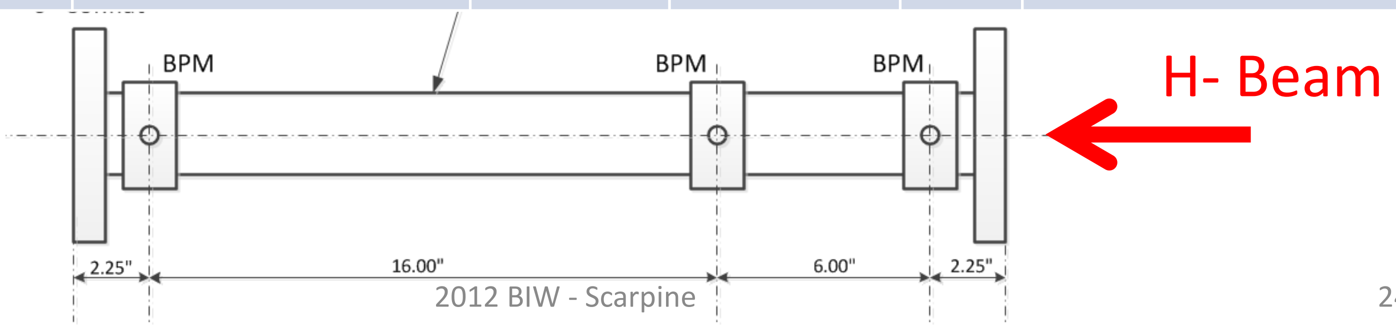
- – Can not go too far from RFQ because bunches decohere longitudinally

For 750 H- beam:

- Velocity = 1.198e7 m/s → β = 0.0400 → γ = 1.0008
- RF = 201.25 MHz → 1/RF = 4.969 ns

Predicted values

	BPM Separation	ToF (ns)	RF Cycles	N	$\Delta\phi$ (degrees)
1 to 2	6”	12.771	2.5734	2	206.43
2 to 3	16”	33.806	6.8035	6	289.27
1 to 3	22”	46.578	9.3895	9	138.77



Calculated Energy Sensitivities

How much does the energy change with length or time mis-measurement?

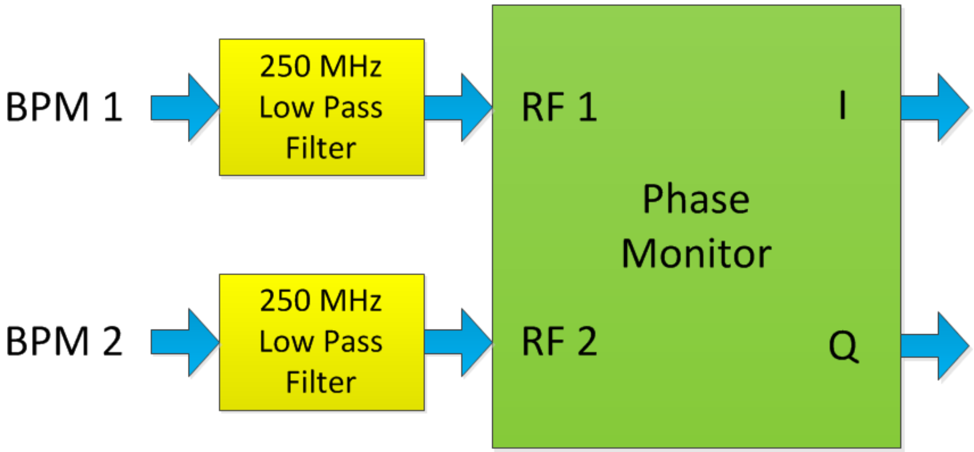
	dVel/dE ((m/s)/keV)	dE/dL (keV/mm)	dt/dE (ps/keV)	dE/dt (keV/ps)	dPhase/dE (deg/keV)	dE/dPhase (keV/deg)
BPM 1 to 2	7.983e3	9.846	-8.471	0.118	-0.613	-1.631
BPM 2 to 3	7.983e3	3.692	-22.589	0.044	-1.635	-0.612
BPM 1 to 3	7.983e3	2.685	-31.06	0.032	-2.248	-0.445

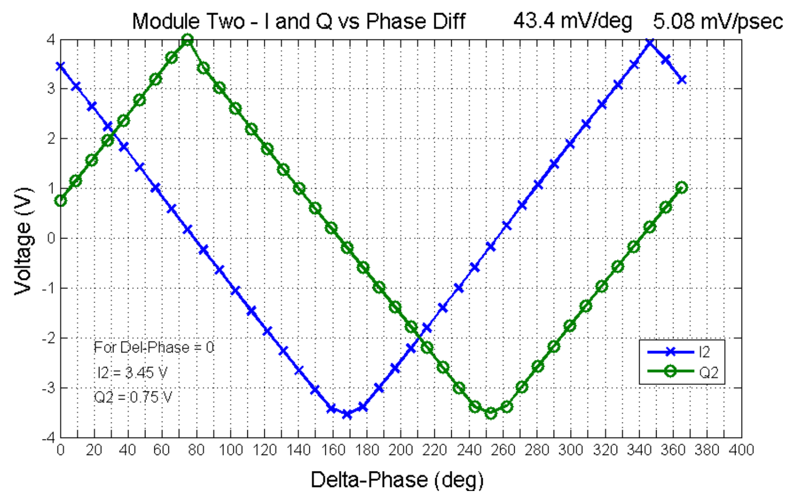
How much does the energy change if you pick the wrong number of RF cycles?

	N0	E @ N0 – 1	E @ N0	E @ N0 + 1
BPM 1 to 2	2	2016 KeV	750 KeV	389 KeV
BPM 2 to 3	6	1032 KeV	750 KeV	571 KeV
BPM 1 to 3	9	941 KeV	750 KeV	613 KeV

(1) ToF Using Phase Monitor

Feed BPM signals through low-pass filters into phase monitor

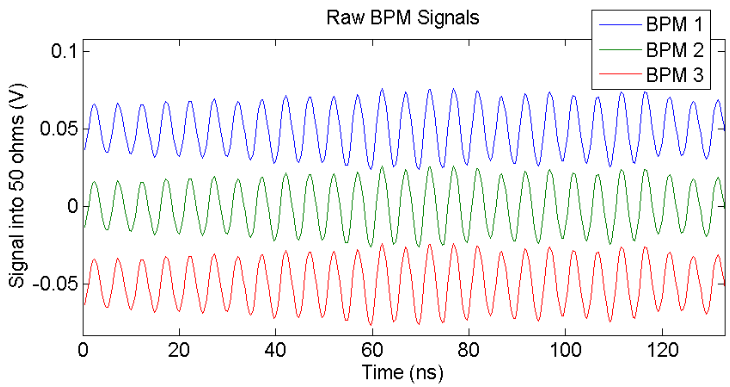


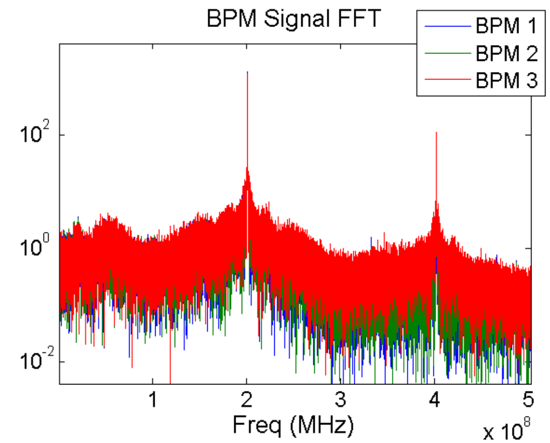


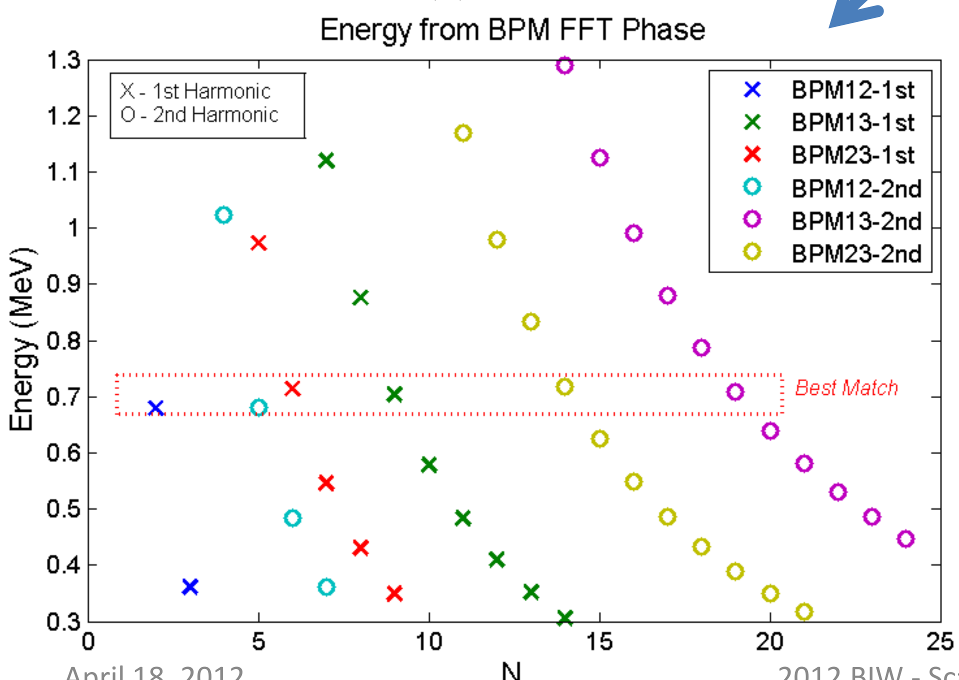
	Del-Phase (deg)	N0	ToF (ns)	Vel (m/s)	Beta	Gamma	Energy (KeV)
BPM 1 to 2	224	2	12.771	1.157e7	0.0386	1.0007	**701**
BPM 1 to 3	235	9	46.578	1.163e7	0.0388	1.0008	**708**

(2) Direct Scope Measurements

- All three BPM signals into high-BW scope – *no filters, no phase monitor*
  - Capture many bunches → FFT → unwrap phase from 201.25 MHz FFT

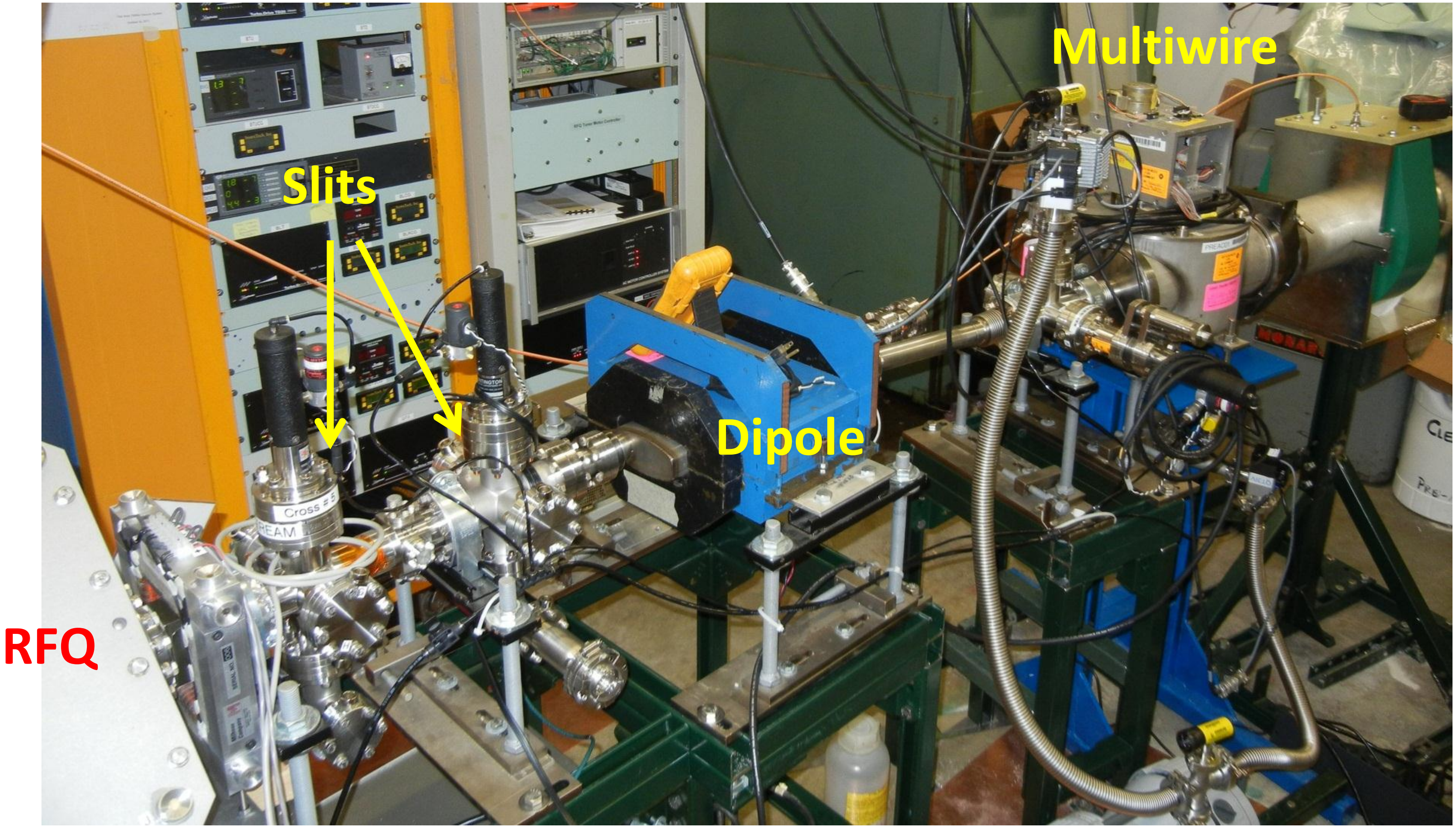






RFQ Power (KW)	Energy (BPM 1 to 2) keV	Energy (BPM 1 to 3) keV	Energy (BPM 2 to 3) keV
212	0.716	0.705	0.701
220	0.716	0.704	0.699
233	0.716	0.705	0.700
206	0.717	0.706	0.702
182	0.706	0.706	0.707
162	0.669	0.710	0.556

(3) Spectrometer Magnet Measurement *(preliminary)*



Preliminary RFQ Energy: 701 +/- 2 +/- 7 KeV

<u>Measurement Example</u>

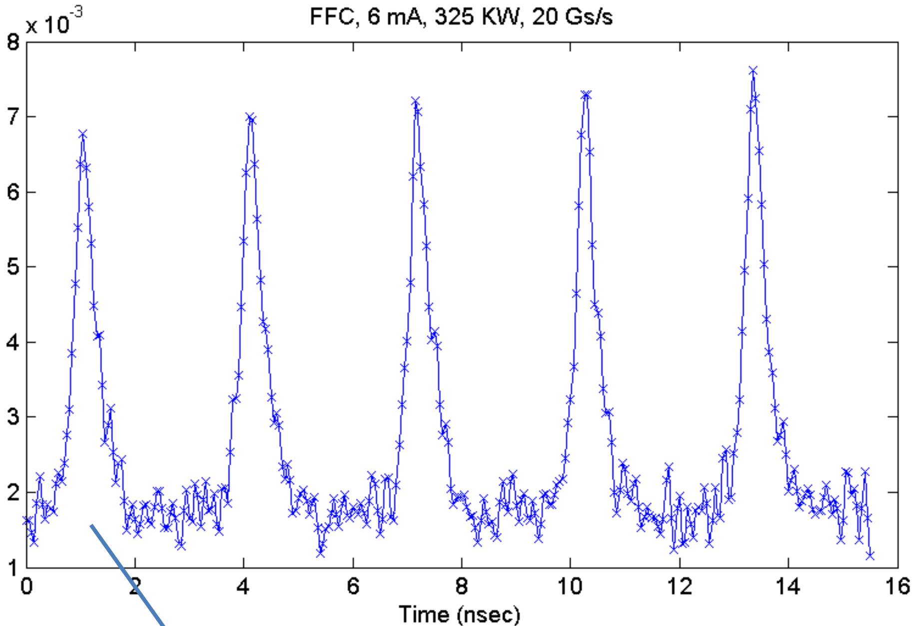
Fermilab High Intensity Neutrino Source (HINS)

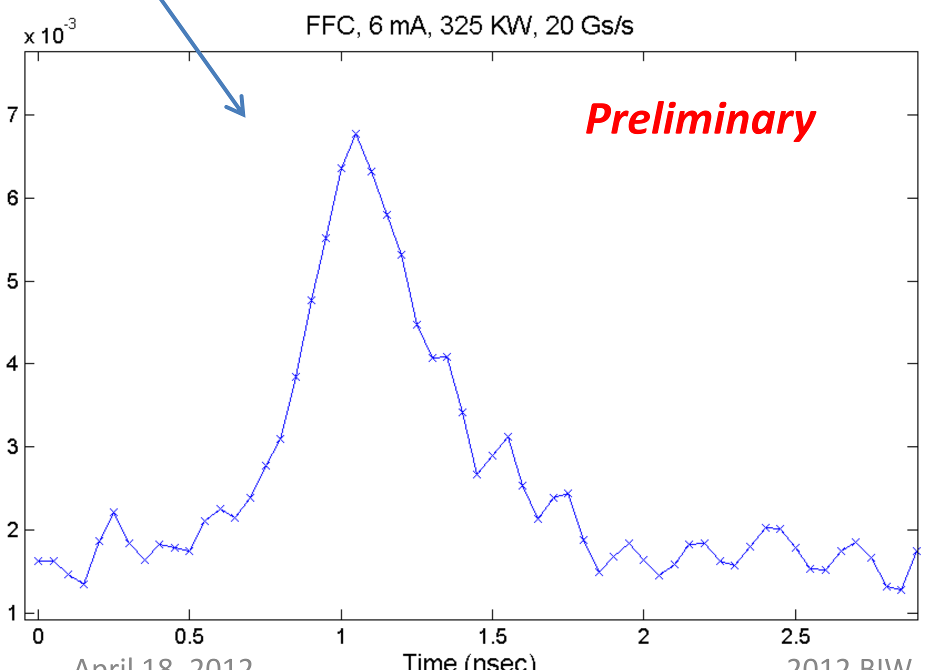
RFQ Beam Measurements of Longitudinal Bunch Shape from Fast Faraday Cup

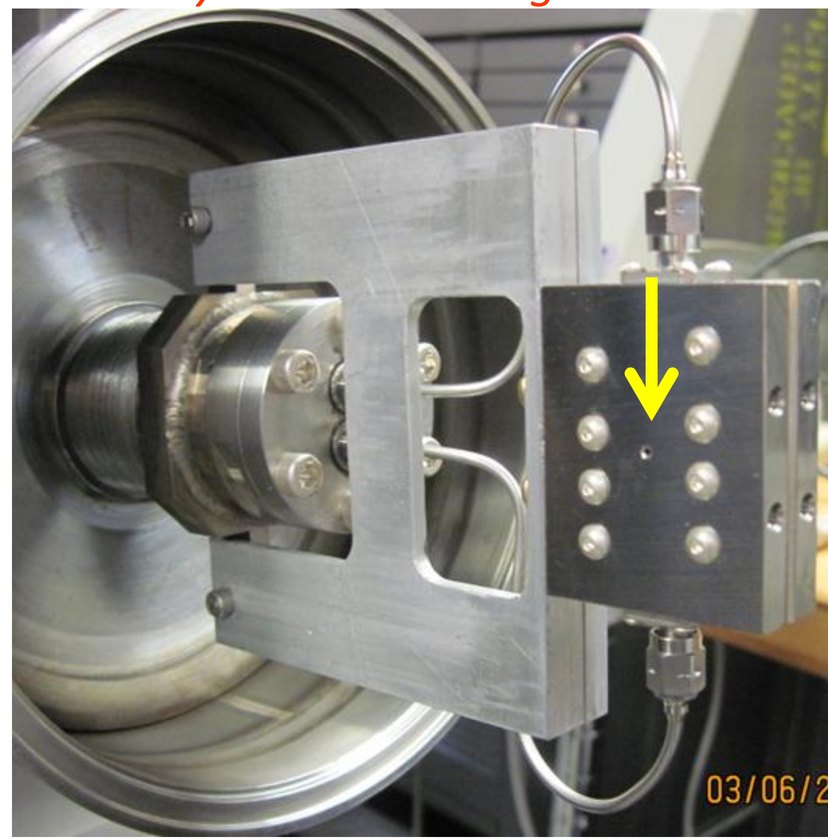
Longitudinal Bunch Shape – Fast Faraday Cup

- Buried 50 Ω transmission time under ground plane
- Small aperture to all beam transmission
- High-Bandwidth → ~ 10 GHz

Many thanks to Craig Deibel at SNS

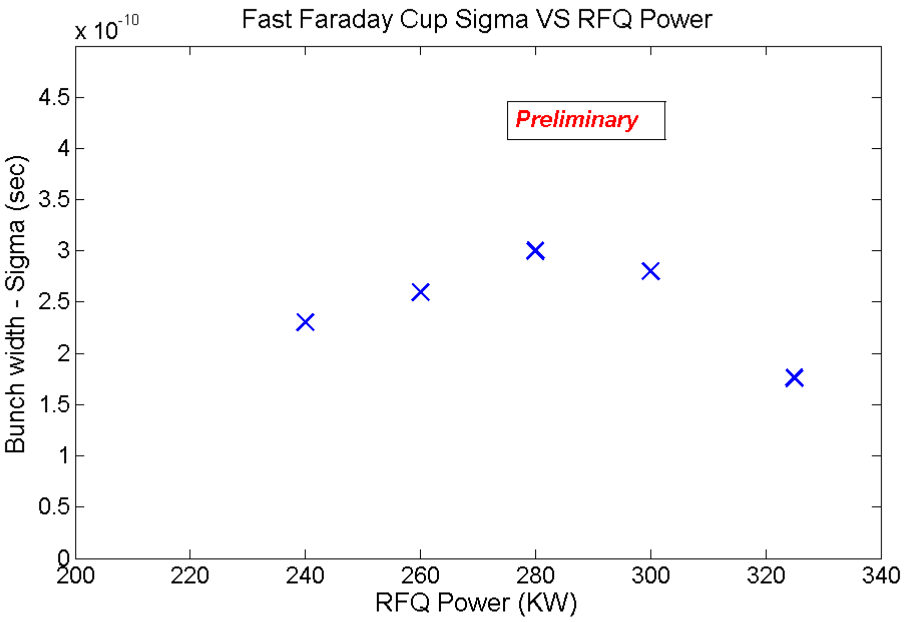


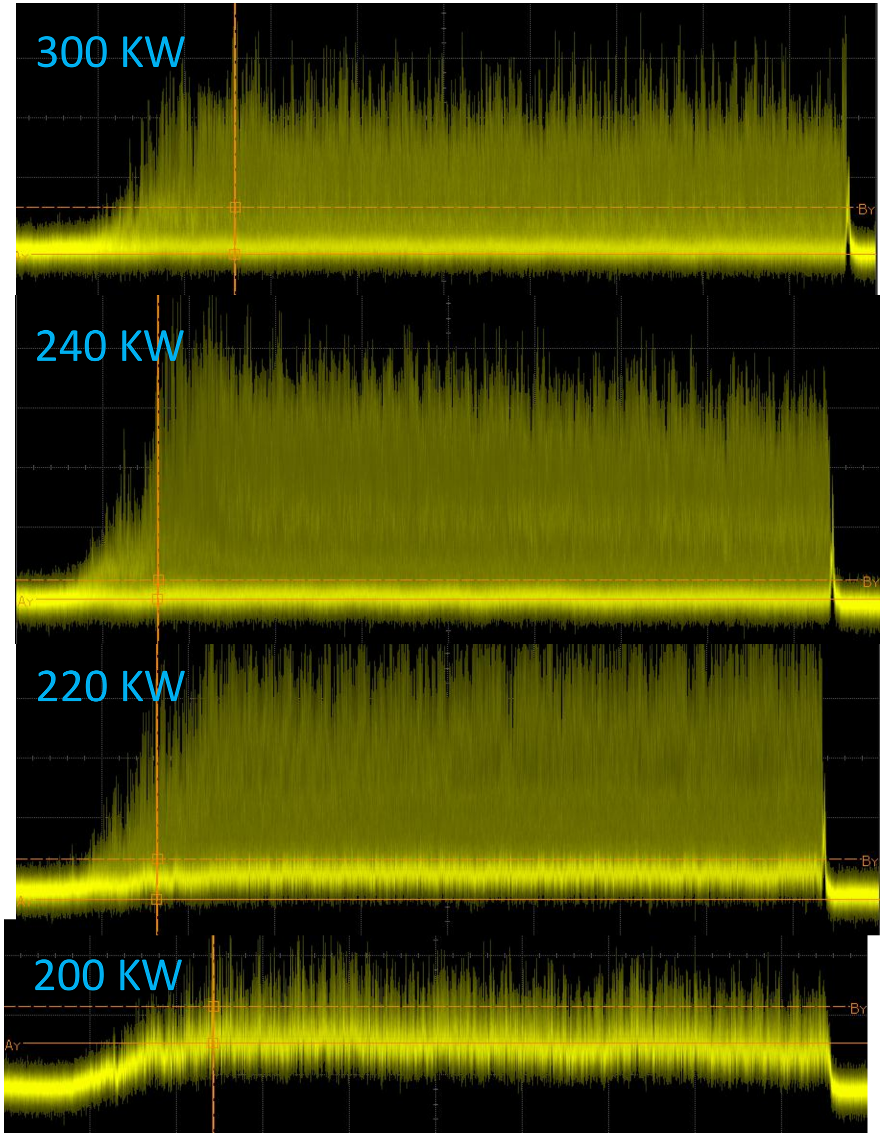




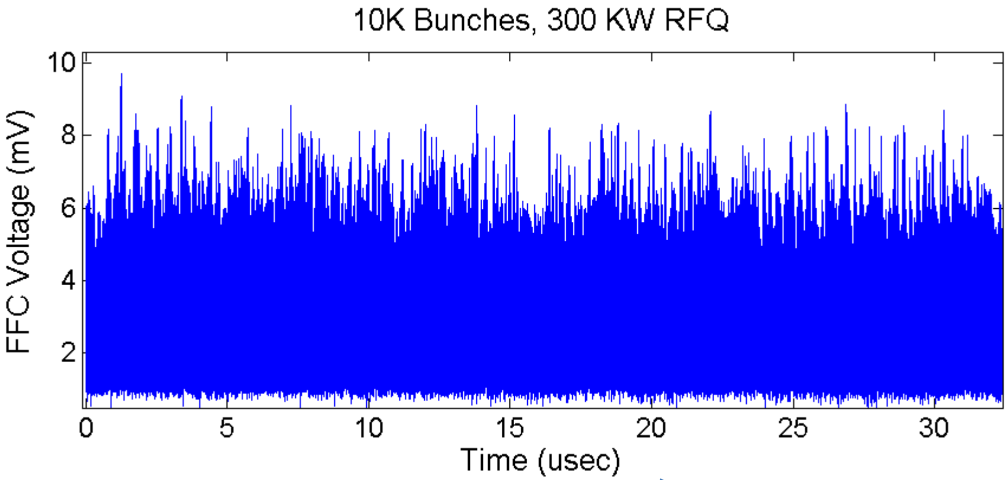
Longitudinal Shape VS RFQ Power

Feed fast Faraday Cup into high bandwidth scope to measure bunch shape.



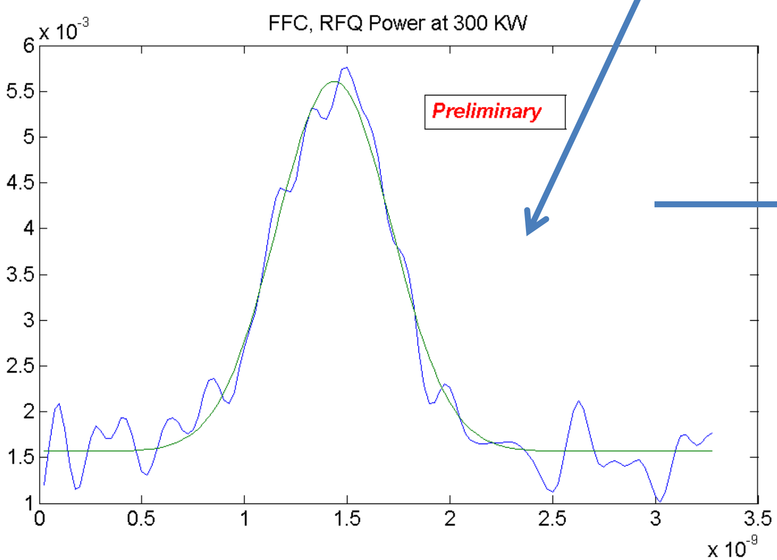


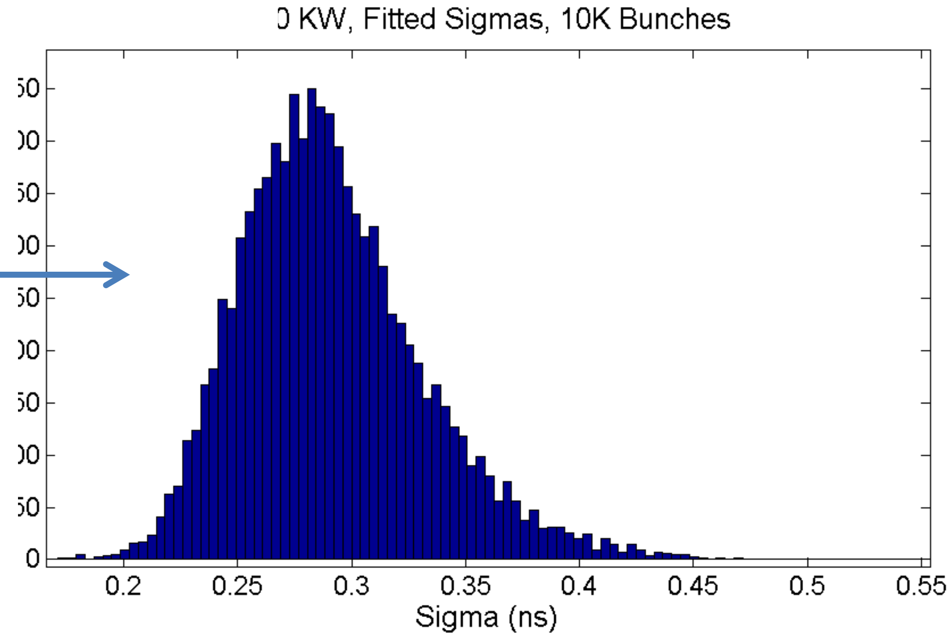
Bunch Shape Along Pulse



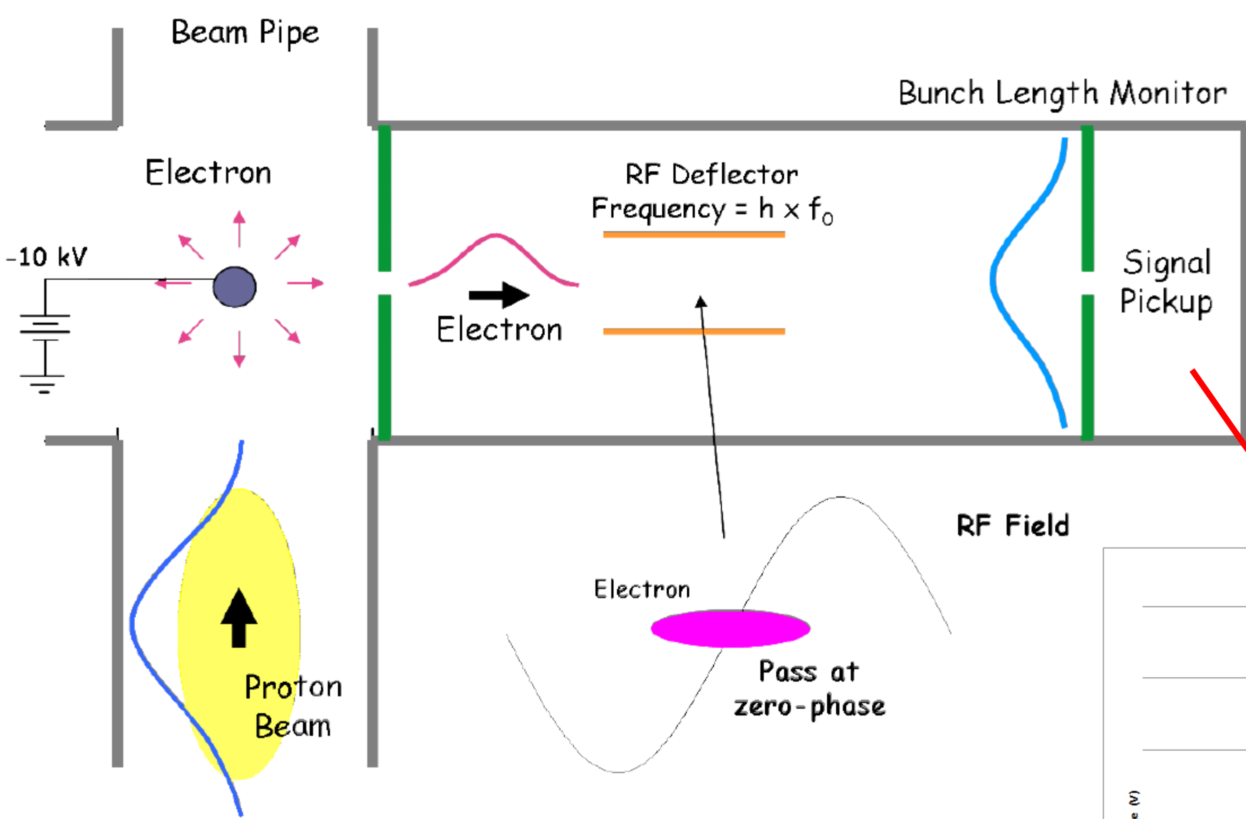
Fit individual bunches along pulse

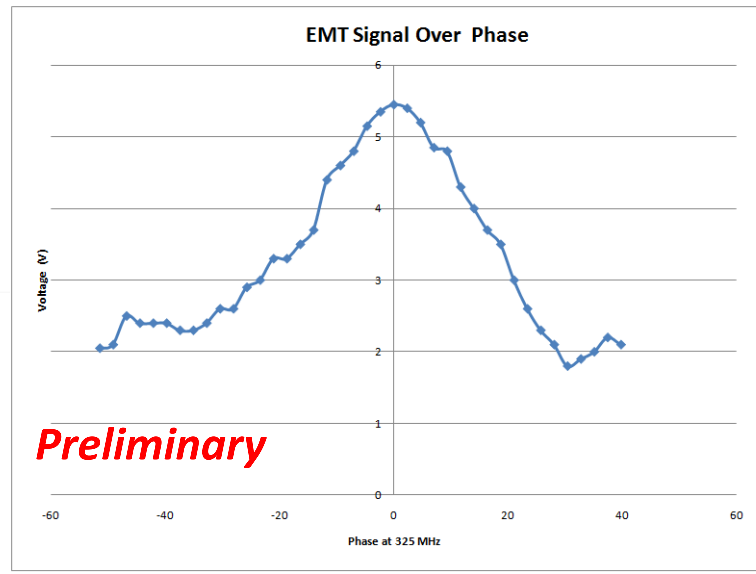
- RFQ at 300 KW
- Histogram → ~ 0.28 ns (1-σ)
- → 33 deg @ 325 MHz
- Still need to de-convolve cable dispersion





Longitudinal Bunch Shape Monitor (BSM)





Translate time coordinate into space coordinate using RF deflector cavity

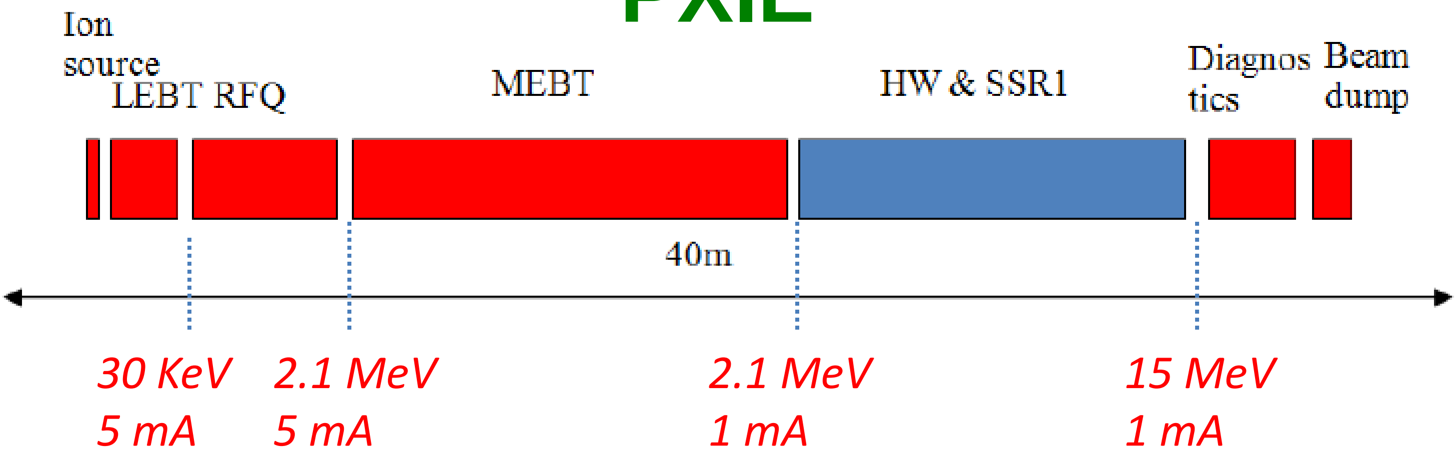
- like a streak camera

Systematics need to be understood for H- at low energy

- Electron space charge an issue
- X-ray version under development

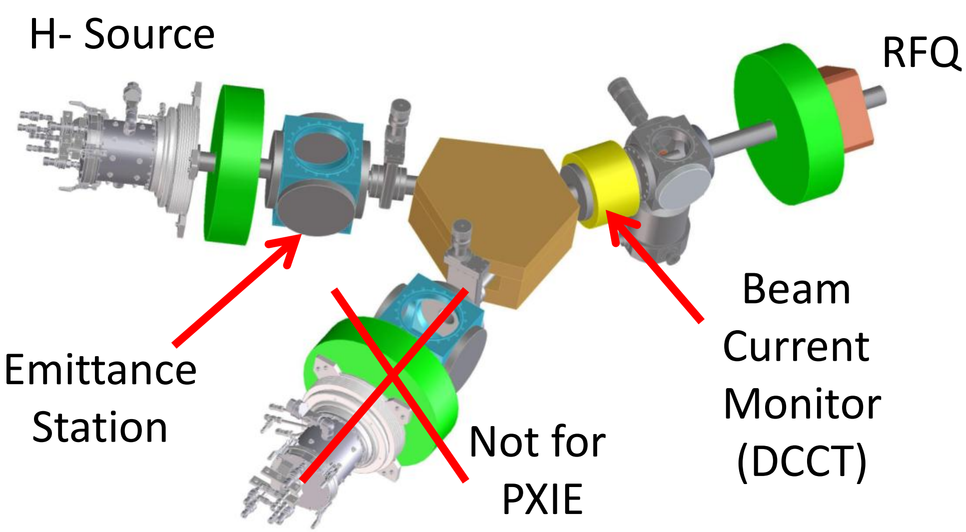
Fermilab Project X Injector Experiment (PXIE)

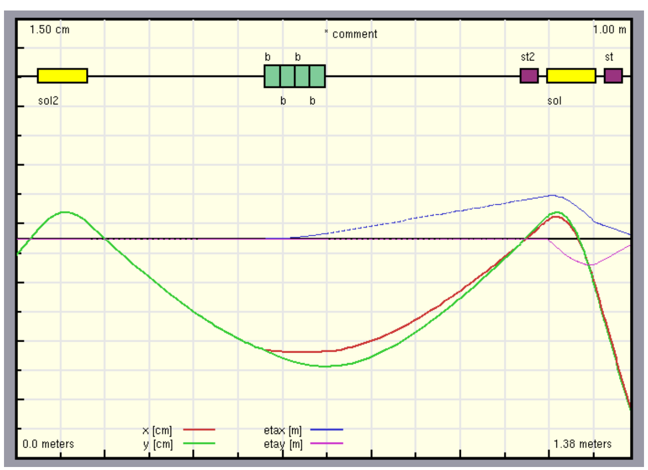
Project X Injector Experiment: PXIE



- CW H- source delivering 5 mA at 30 keV
- LEBT with beam pre-chopping
- CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
- MEBT with integrated wide band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of 4 mA average beam current
- Low beta superconducting cryomodules, starting at 2.1 MeV, capable of accelerating 1 mA to 15 MeV
- Beam dump capable of accommodating 1 mA at 15 MeV (15 kW) for extended periods.
- ***Associated beam diagnostics, utilities and shielding to support operation***

PXIE LEBT "Operational" Instrumentation





Working Parameters

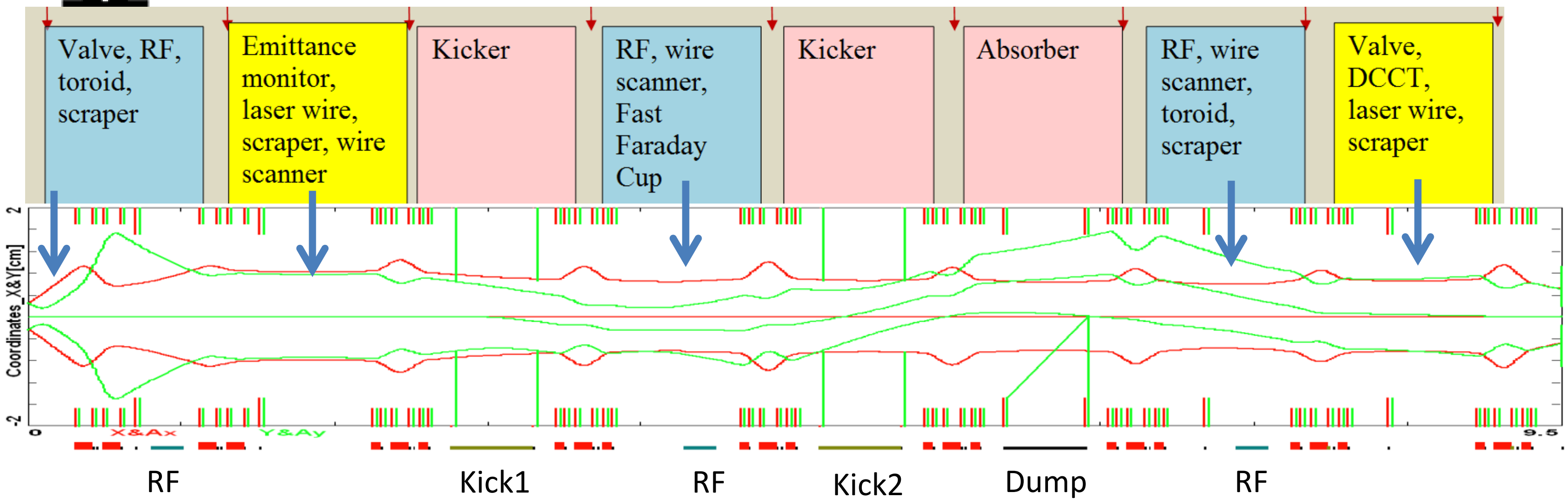
- One 30 KeV H- source for PXIE
- 5 mA DC beam
- Two solenoids
- Continuous beam only

Instrumentation

- One beam current monitor - DCCT
- Emittance station → two Allison-type scanners
  - ~ 150 watts beam power
  - Need water cooling for slits

- Full LEBT characterization before connection to RFQ

PXIE MEBT



- 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

MEBT Operational Beam Measurements: (red = CW)

- Transverse position - BPMs
- Bunch Phase – BPMs
- Beam Current – RWCM (resistive wall current monitor)
- Extinction - RWCM
- Transverse shape – wire scanners, laser wires
- Transverse emittance – slit/multiwire
- Longitudinal shape – water-cooled Fast Faraday Cup, X-ray BSM, laser wires
- Absorber Profiler – OTR Imager

Beam Diagnostic Projects for PXIE/Project X

Transverse Diagnostics

- Laser Transverse Profile Monitor*
- Ionization Profile Monitors
- Electron Wire Transverse Profile Monitor – with SNS

Longitudinal Diagnostics

- X-Ray Wire Longitudinal Profile Monitor*
- Laser Longitudinal Profile Monitor* - with LBNL
- Broadband Faraday-cup – with SNS*****

Halo Monitoring – transverse and longitudinal

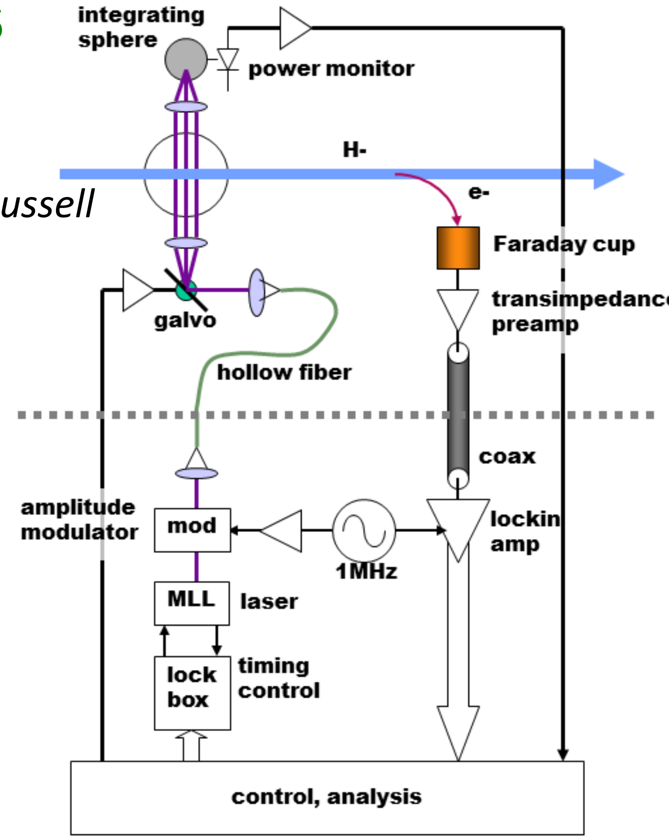
- Vibrating wire* - *from Bergoz Instrumentation*
- Laser wire* ?

MEBT Emittance station

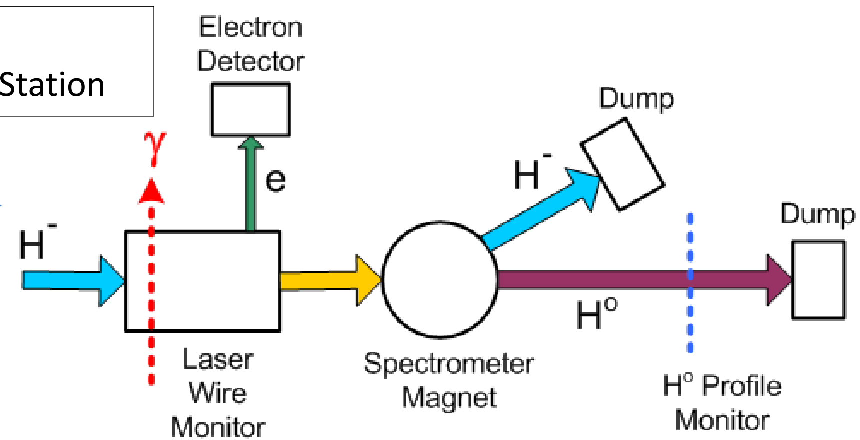
- Slit-collector*
- Laser Slit*

** Project X front-end related instrumentation*

Courtesy of Russell Wilcox, LBNL



Laser Wire Emittance Station



Summary

- Many upgraded or new proton/H- accelerators on the horizon
- Although many front-ends have a common layout, beam operating conditions can be completely different
  - This drives the requirements for beam diagnostics
- At these low β's, characterization of the beam at the front-end limit the performance of the rest of the linac
- Upcoming high-power linacs are placing stringent requirements on limiting beam interaction
  - This is driving "non-intercepting" instrumentation
  - Opening the door for new instrumentation including previously ruled out because of cost or complexity