Instrumentation Developments and Beam Studies for the Fermilab Proton Improvement Plan Linac Upgrade and New RFQ Front-End

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HB 2012 Workshop
Beijing

Outline

- Fermilab Proton Improvement Plan (PIP)
- Linac new RFQ-based front-end
  - Experiences with commissioning front-end
  - LEBT beam measurements
  - RFQ beam measurements (*mostly beam energy*)
  - *Complete set of measurement too long to present here*
- If there is time then present upgrade to linac BPM and Toroid electronics

Proton Improvement Plan (PIP)

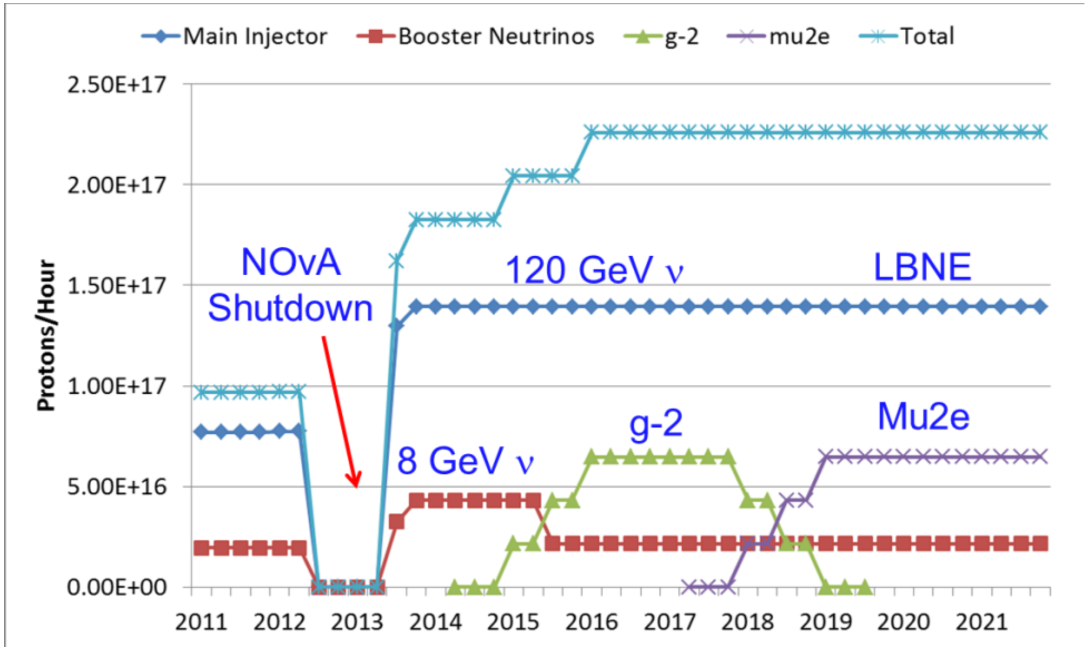
The goal of PIP is to enable Linac/Booster operation to:

- deliver 1.8E17 protons/hour (at 12 Hz) by mid-2013
- deliver 2.25E17 protons/hour (at 15 Hz) by 2016

while

- maintaining Linac/Booster availability > 85%
- and maintaining residual activation at acceptable levels

This is to ensure a useful operating life of the proton source to provide for the physics program through 2025.

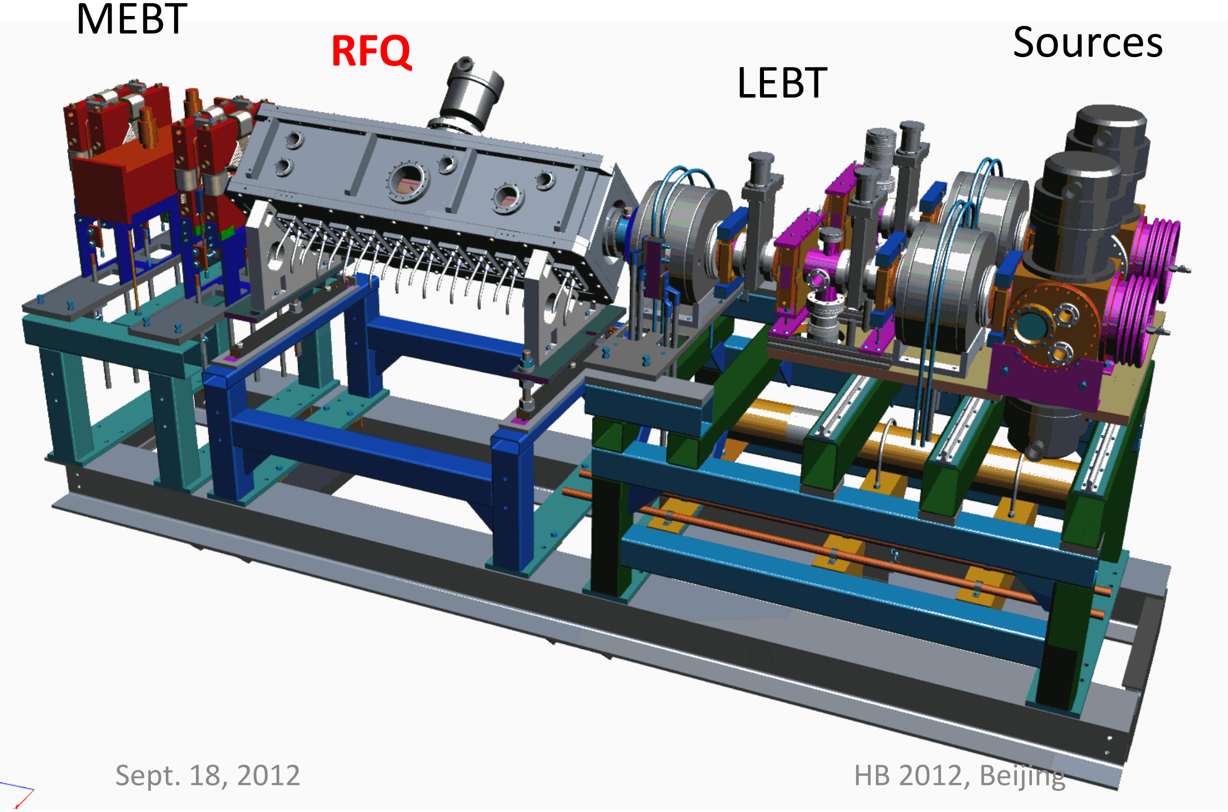


S. Henderson, Accelerator Advisor Committee, Nov 7-9, 2011

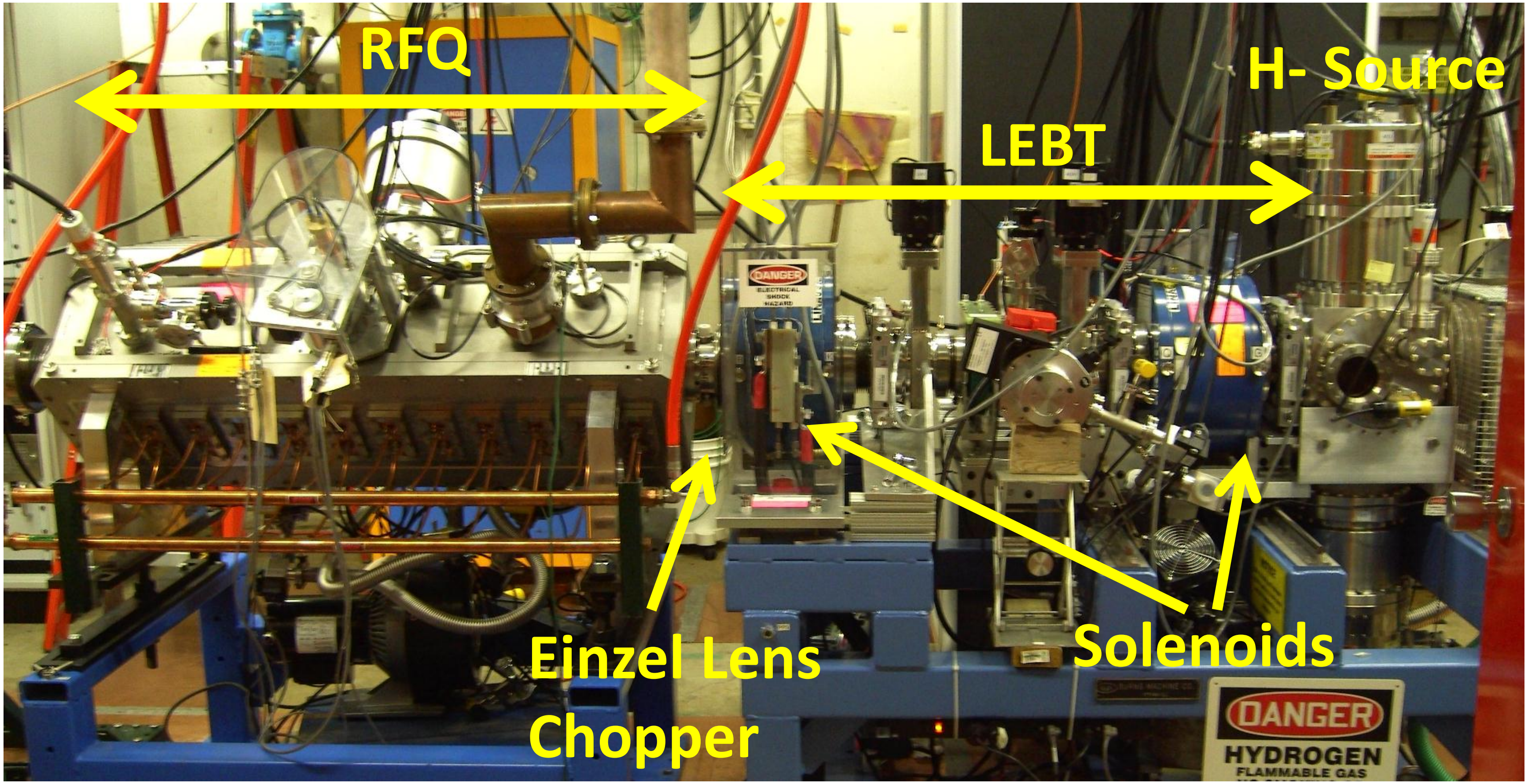
Fermilab PIP Front-End Upgrade

Upgrade Fermilab linac front-end :

- Replace present sources and Cockcroft-Walton
    - Liability; large source of down-time
- Dual H- sources – 65 mA @ 35 KeV
- New 201.25 MHz, 750 KeV, 4-rod RFQ



PIP New Front-End

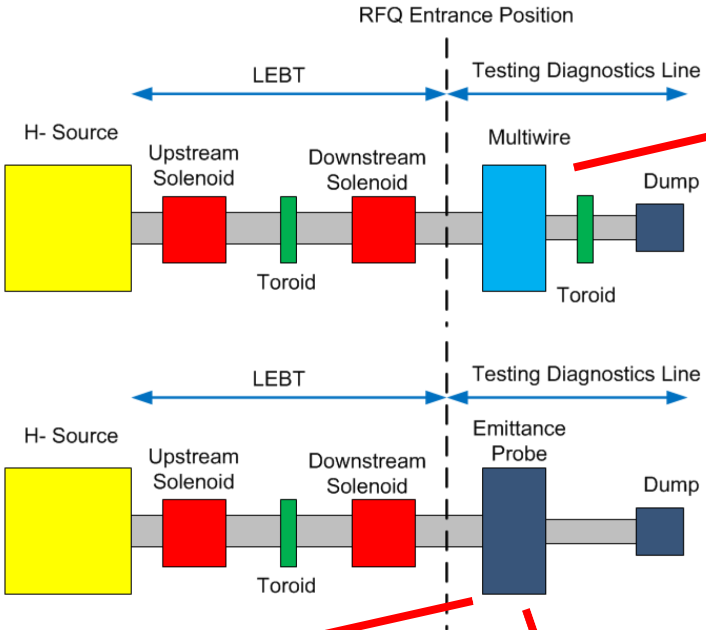


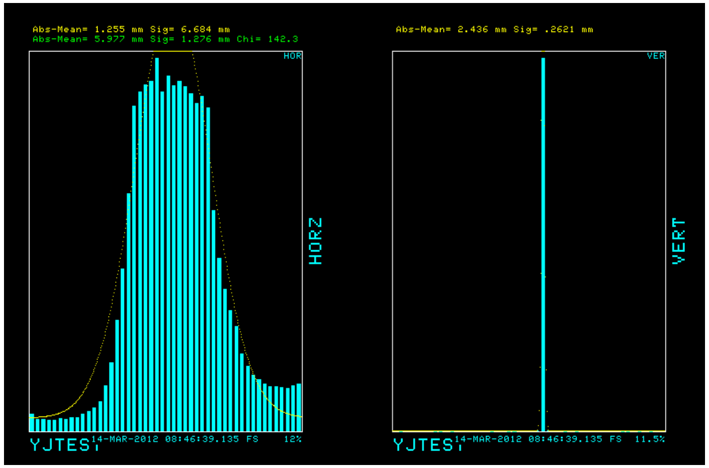
LEBT includes beam toroid and steering dipole magnets between solenoids.

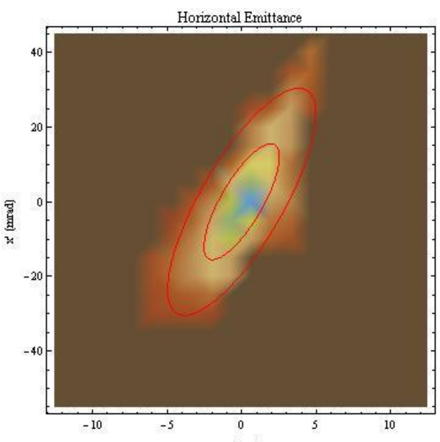
LEBT Commissioning

Measurement Setup !:
- Beam profile and beam position measurements at (near) RFQ entrance
- Beam transmission efficiency
- Transverse emittance from solenoid scan

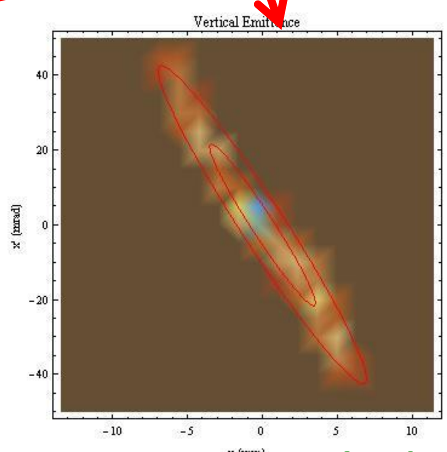
Measurements Setup 2:
- Beam transverse emittance at (near) RFQ entrance





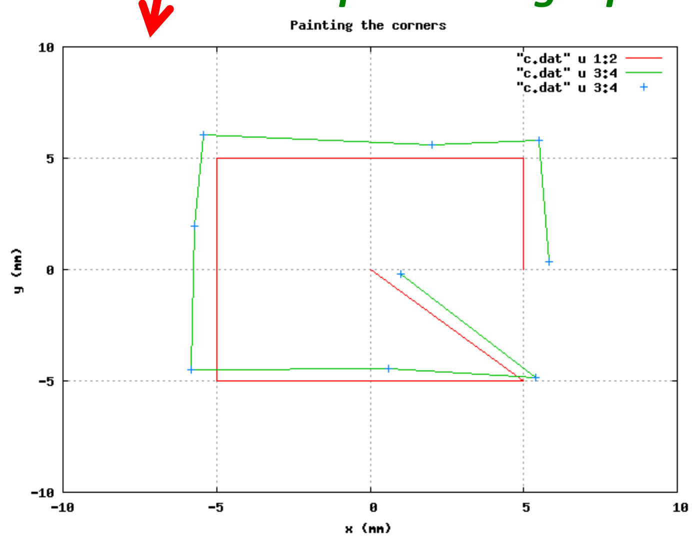


Horz: 0.21 pi-mm (1σ)

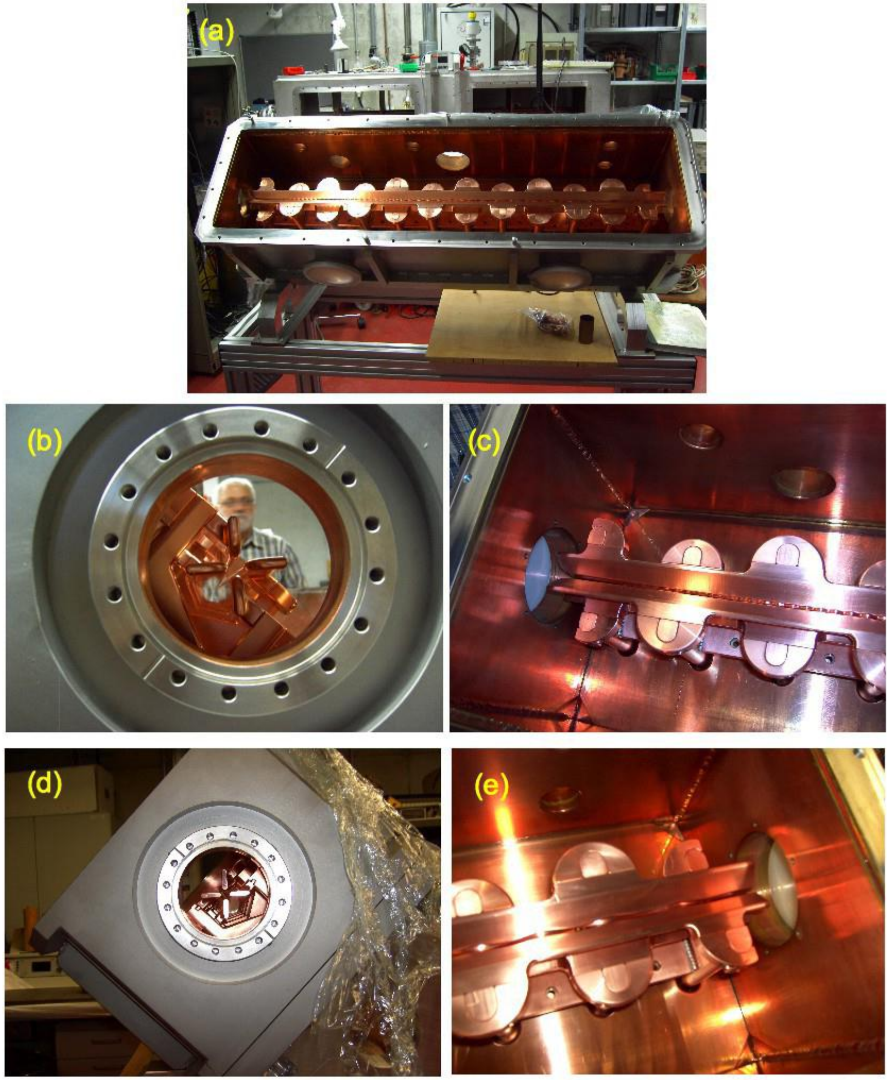


Vert: 0.17 pi-mm (1σ)

"Map" steering dipoles

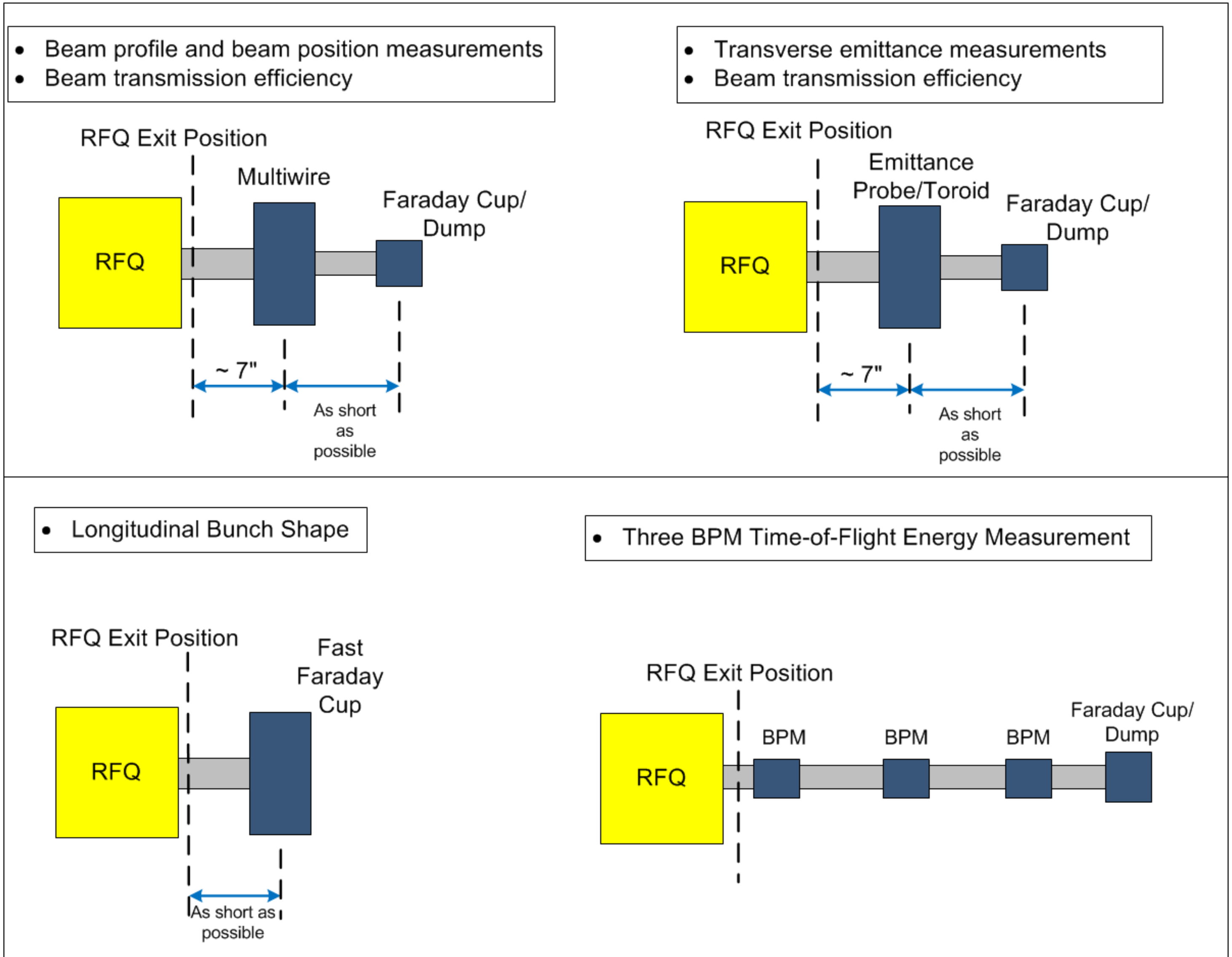


New 4-Rod RFQ



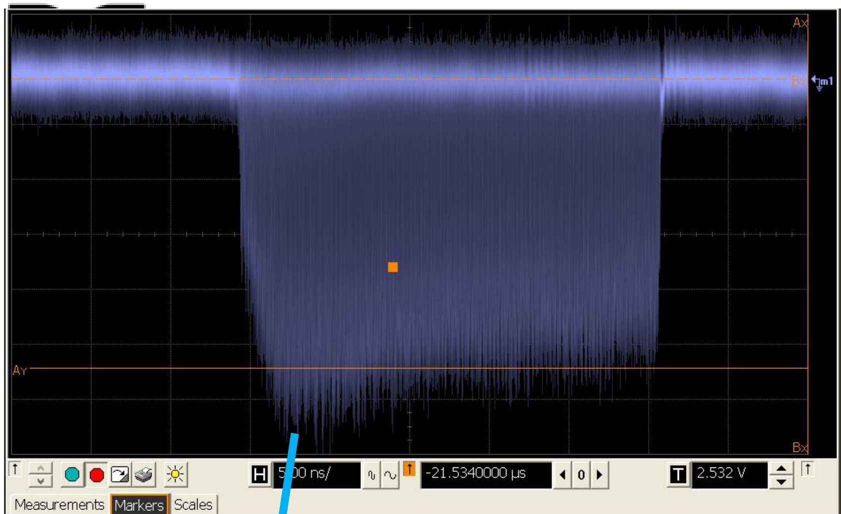
Parameter	Value	Units
Input Energy	35	keV
Output Energy	750	keV
Frequency	201.25	MHz
Length	102	cm
Duty Factor (80 μs, 15 Hz)	0.12	%
Design Current	60	mA
Transmission Efficiency	98	%

RFQ Commissioning Test Setups

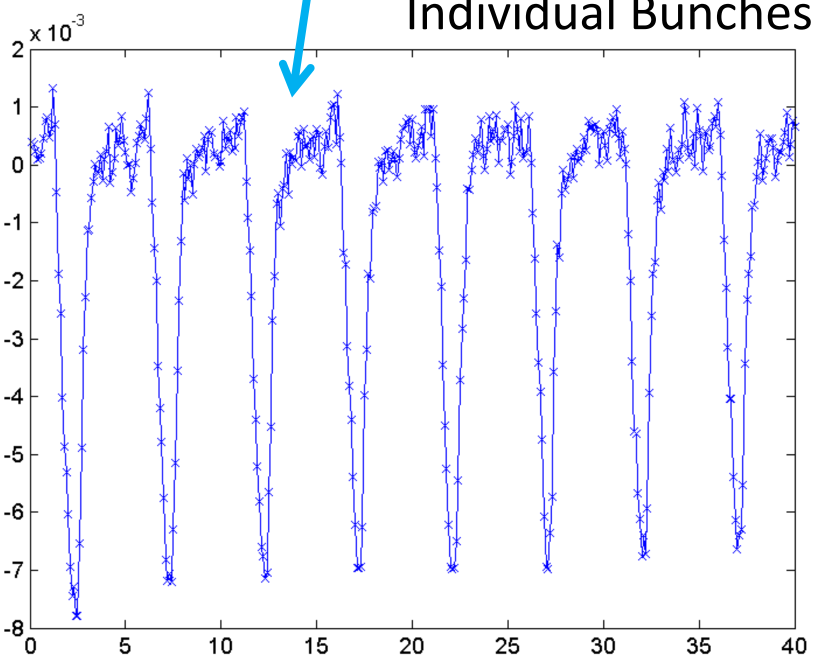


Longitudinal Bunch Shape – Fast Faraday Cup

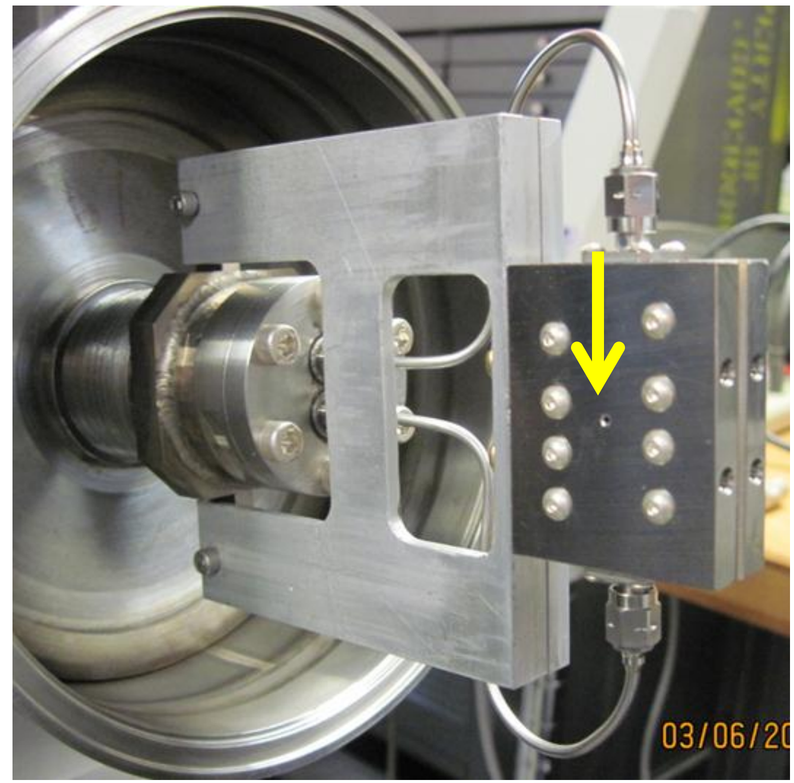
~ 100 μs Beam Pulse



Individual Bunches



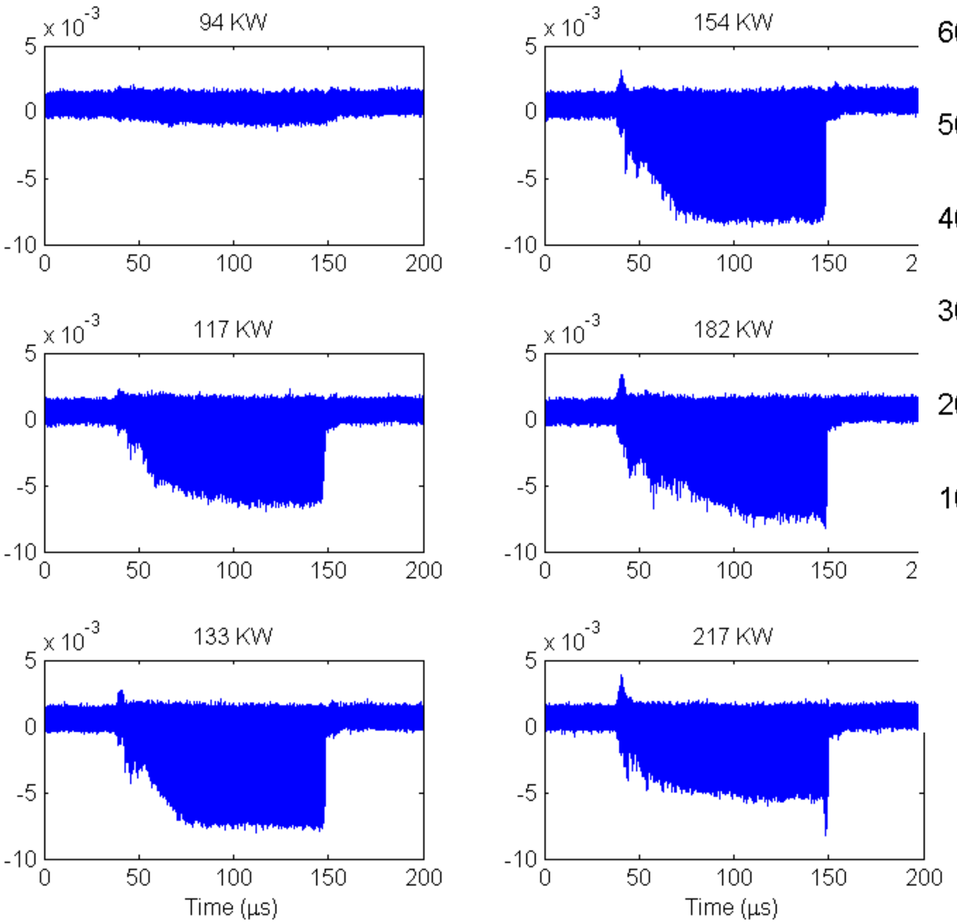
- Buried 50 Ω transmission time under ground plane
- Small aperture to all beam transmission
- High-Bandwidth → ~ 10 GHz

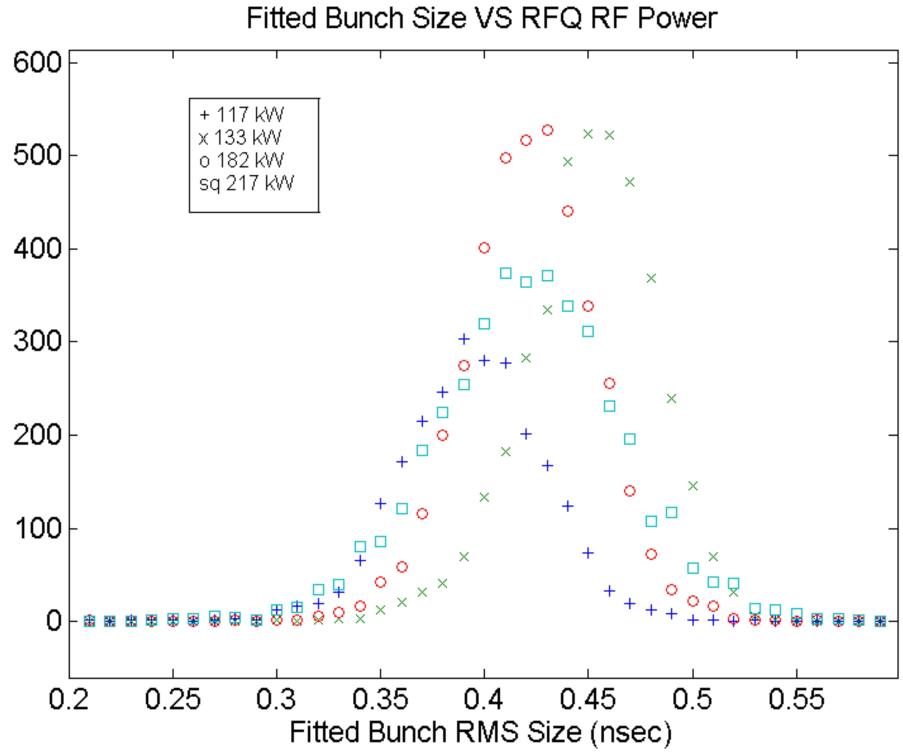


Courtesy of SNS

Bunching VS RFQ RF Power

At low power, beam is not bunched



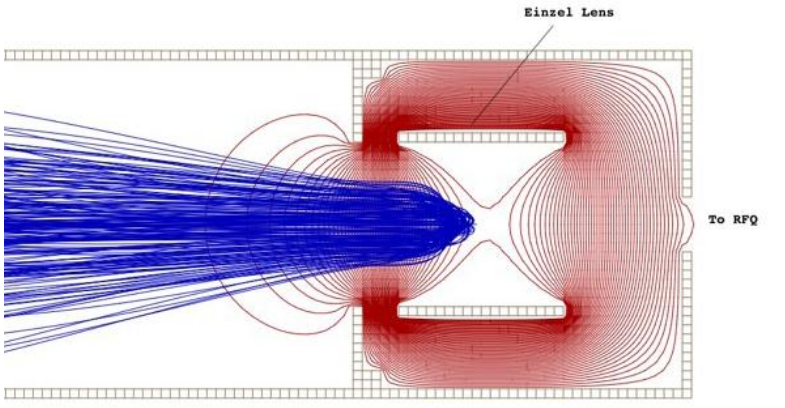


Fitted Bunch Length ~ 420 ps (rms)

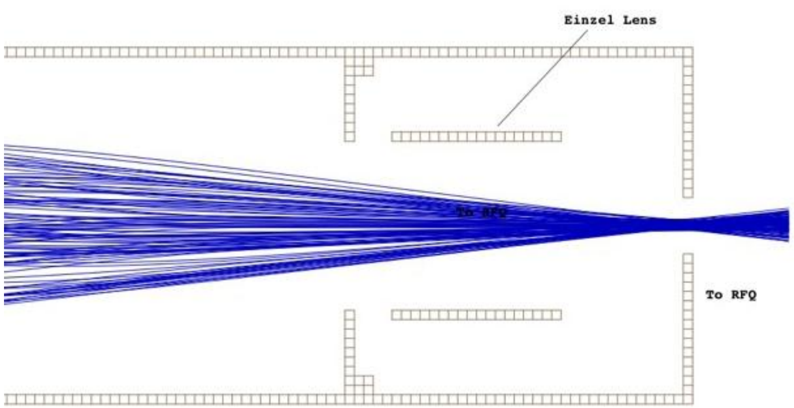
preliminary

Einzel Lens as Beam Chopper

Einzel lens located at end of LEBT before RFQ

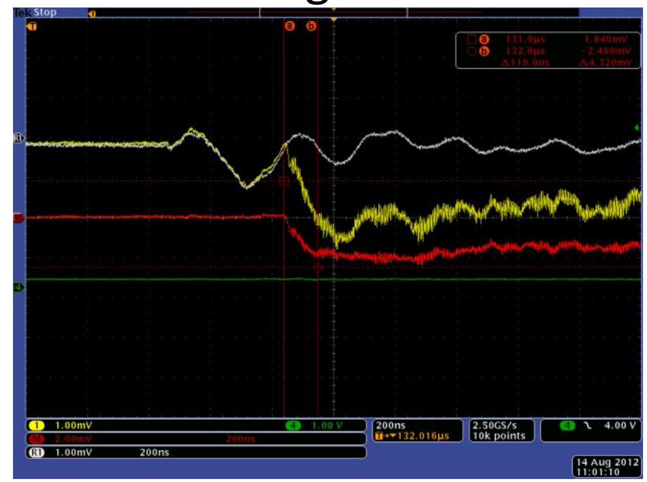


Einzel Lens On at -38kV



Einzel Lens Off

Rise and fall time of chopped beam edge ~ 100 ns



RFQ 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
   - Requires very, very low beam current on detector

First choice – Time-of-Flight

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

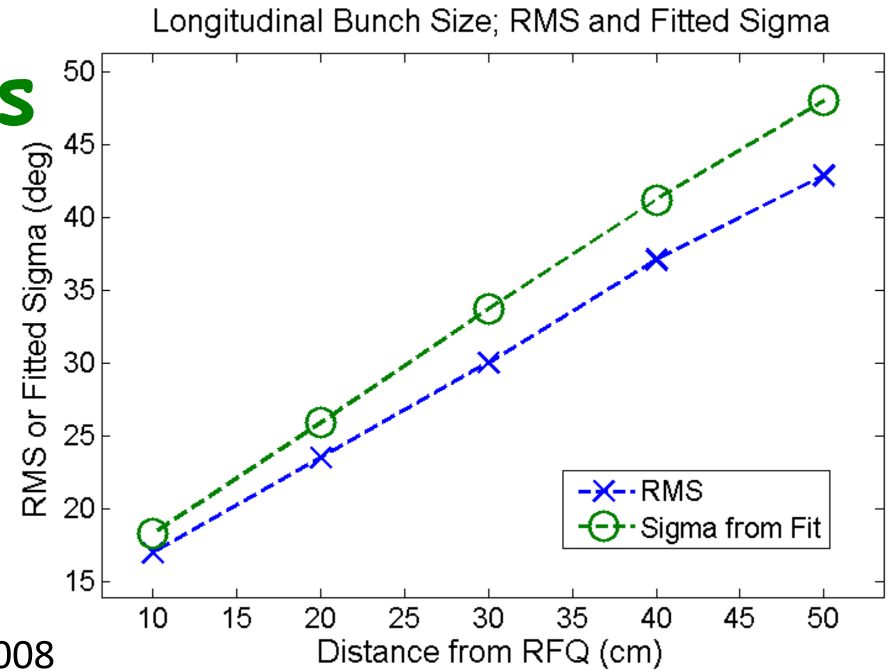
ToF Using 3-BPMs

Can define ToF as: ***N*(1/F_RF) + ΔΦ*** ($N*(1/F_{RF}) + \Delta\Phi$)

- 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

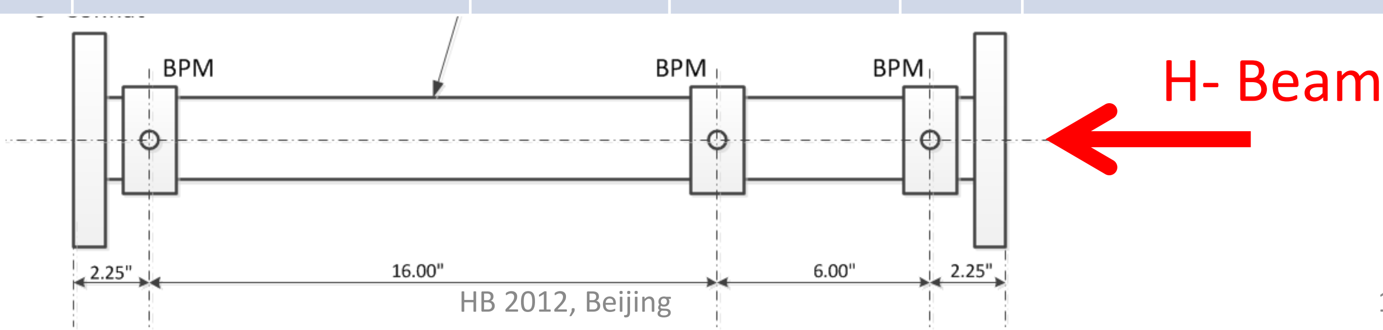


For 750 H- beam:

- 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?

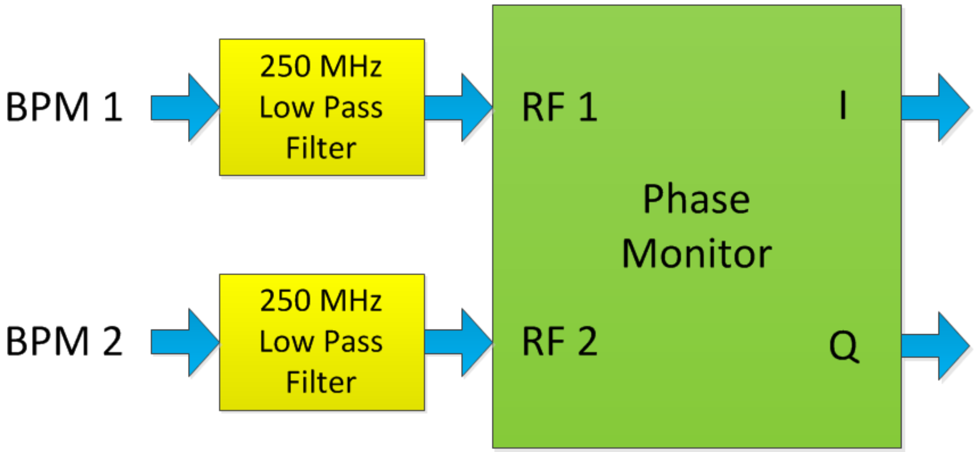
	dVel/dE ((m/s)/keV)	dE/dL (keV/mm)	dt/dE (ps/keV)	dE/dt (keV/ps)	dPhase/dE (deg/keV)	dE/dPhase (keV/deg)
BPM 1 to 2	7.983e3	9.846	-8.471	0.118	-0.613	-1.631
BPM 2 to 3	7.983e3	3.692	-22.589	0.044	-1.635	-0.612
BPM 1 to 3	7.983e3	2.685	-31.06	0.032	-2.248	-0.445

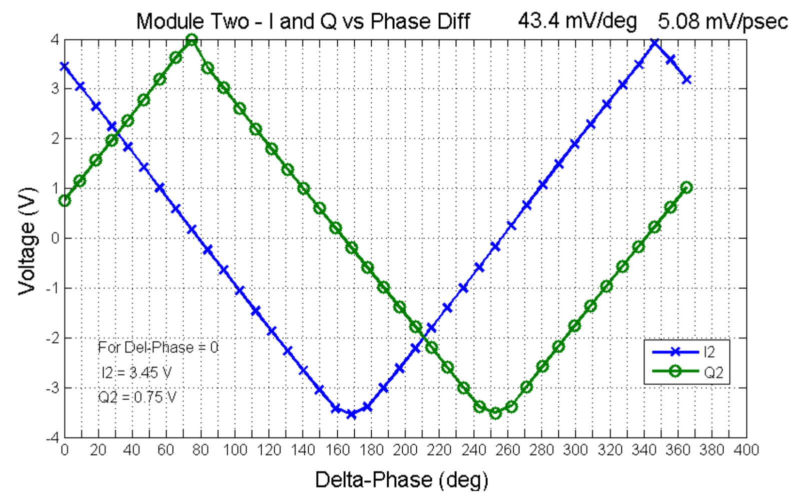
How much does the energy change if you pick the wrong number of RF cycles?

	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





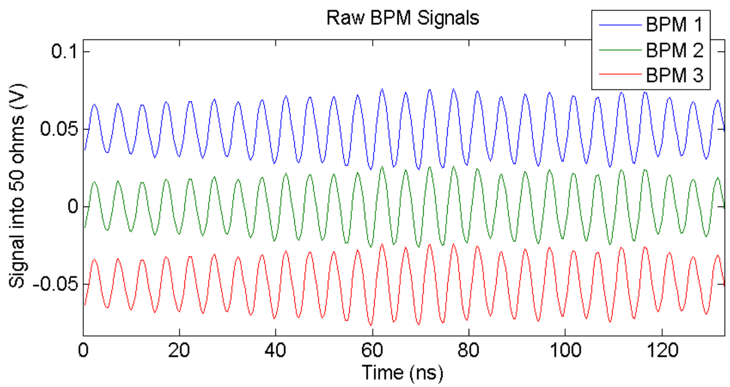
	Del-Phase (deg)	N0	ToF (ns)	Vel (m/s)	Beta	Gamma	Energy (KeV)
BPM 1 to 2	224	2	12.771	1.157e7	0.0386	1.0007	**701**
BPM 1 to 3	235	9	46.578	1.163e7	0.0388	1.0008	**708**

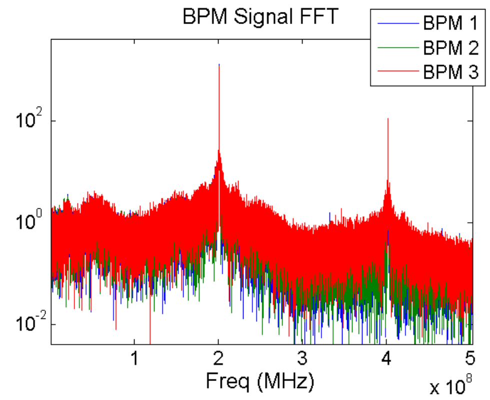
Energy ~ 7 % Low

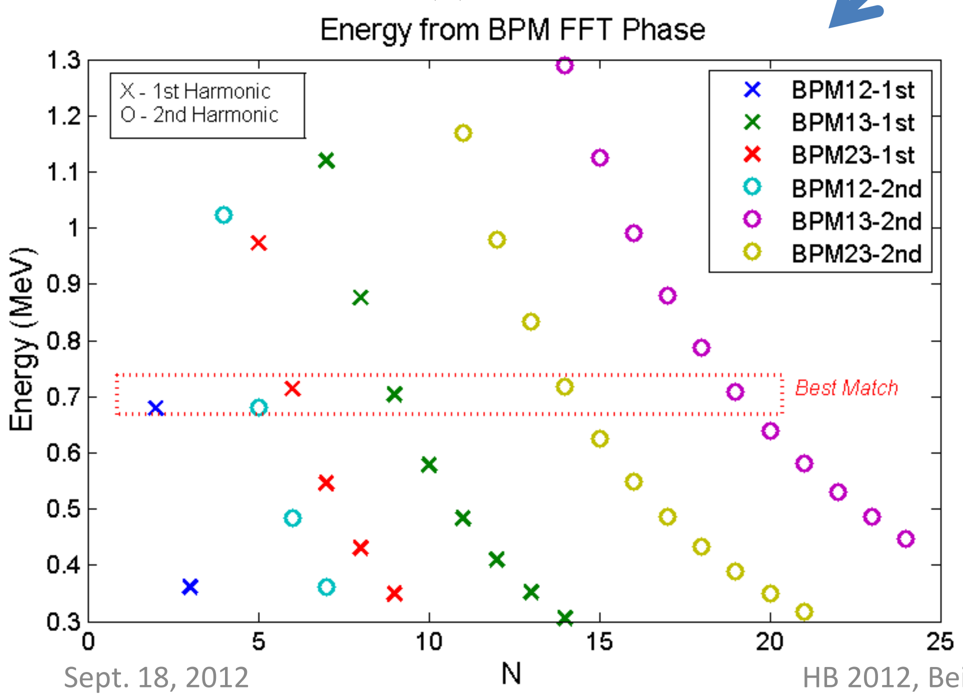
(2) Direct Scope Measurements

All three BPM signals into high-BW scope – *no filters, no phase monitor*

– Capture many bunches → FFT → unwrap phase from 201.25 MHz FFT



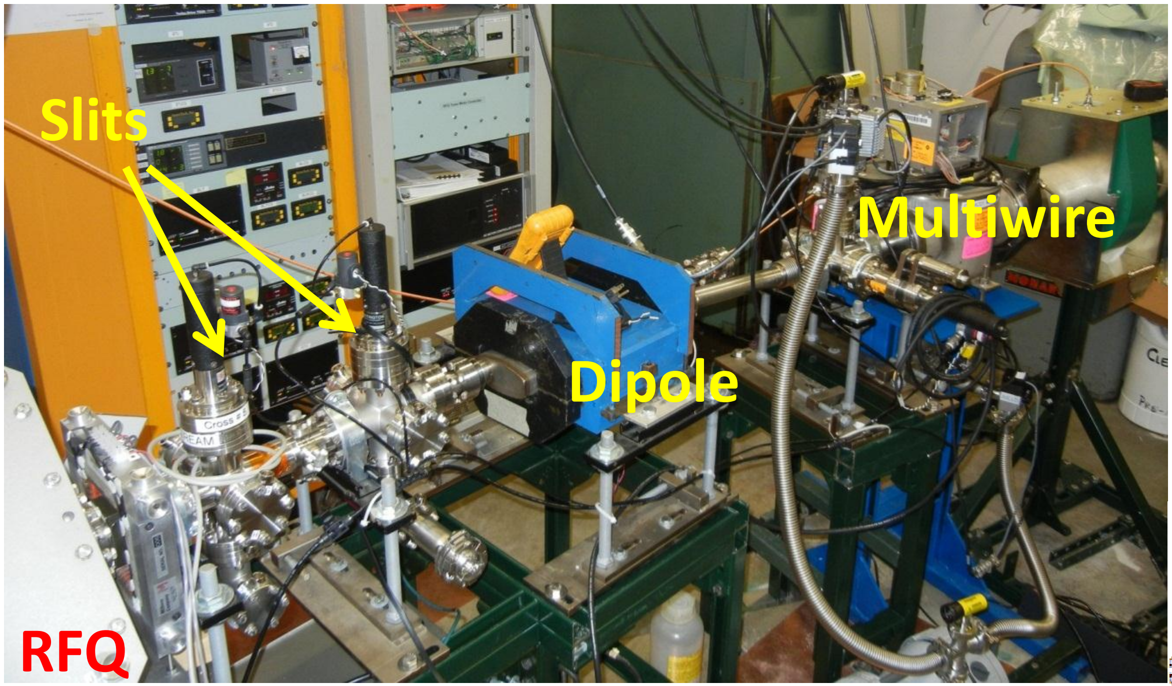


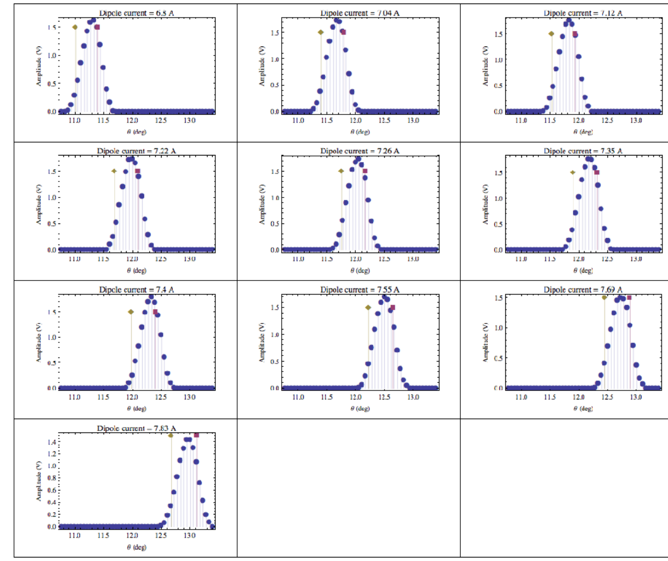


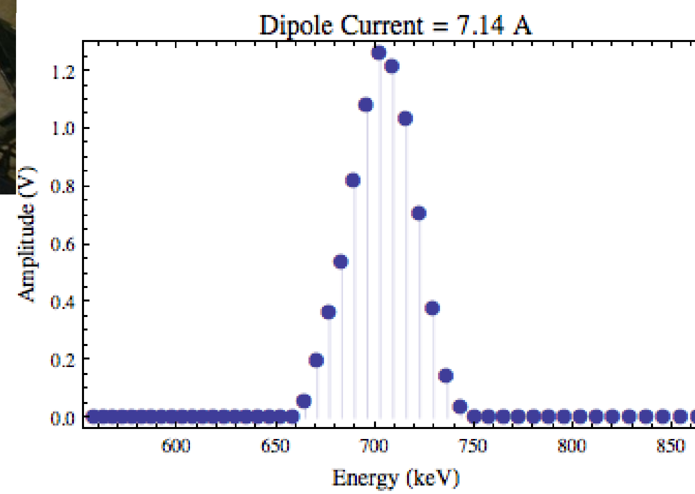
Energy still Low

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

Spectrometer Magnet Setup



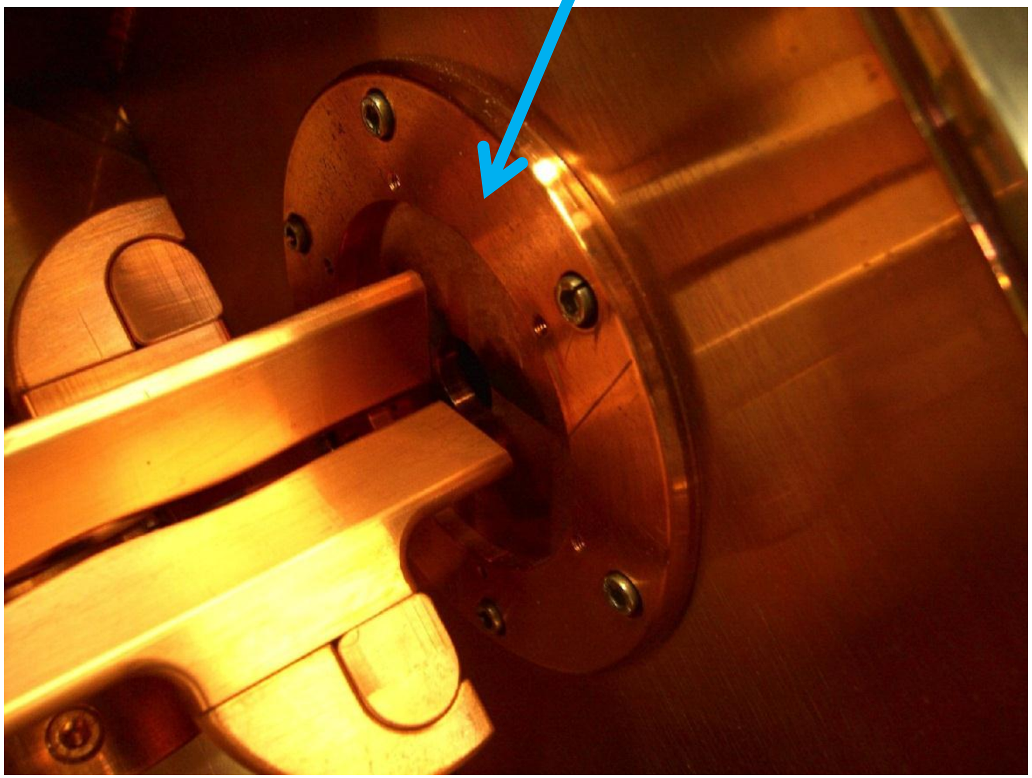




Spectrometer confirms energy:
701 +/- 1 keV

What is the Energy Problem?

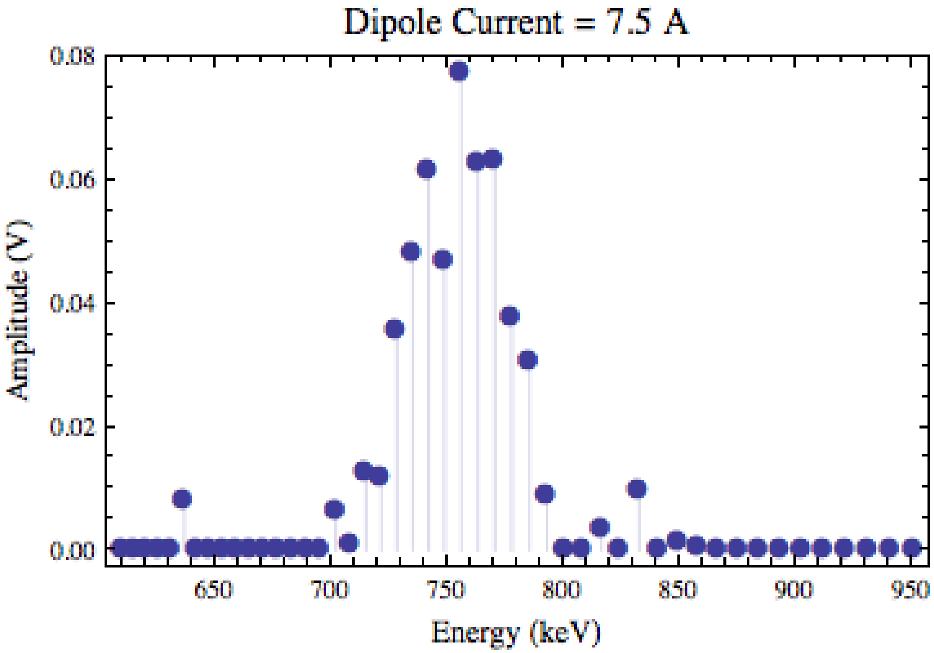
End plate inside RFQ



End plates in tank.
Their purpose is to:

- Keep RF in the RFQ tank
- Add capacitance to end of rods to help flatten the Ez fields in the transition region

Energy Solution? Remove End Plate



Energy now 756.5 +/- 0.5 keV

Linac BPM System Upgrade

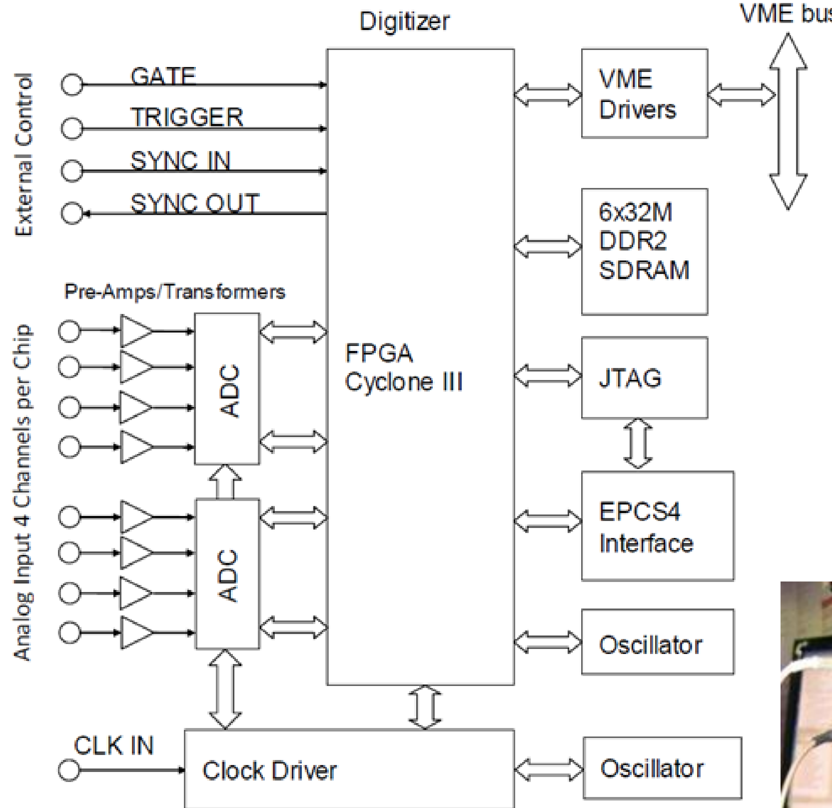
- Update existing RF electronics with Digital electronics
  - FPGA, ADC, Digital Signal Processing
  - Long term stability
  - Flexibility to modify system as needed
- No change to the BPM detectors or the cabling
- Implement calibration system to improve long-term stability
- Implement phase measurement for Time of Flight/Energy measurement
- *Provide average Position, Intensity, & Relative Phase over each beam pulse for every BPM @15Hz* – in ACNET via linac controls

Parameter	Minimum	Nominal	Maximum
Beam Intensity	5 mA	34 mA +/- 1 mA	60 mA
BPM Signal Amplitude			
BPM Signal Frequency		201.24 MHz	
Position Meas. Range		+/- 50 mm	
Position Rise Time			200 ns
Position Modulation BW	3 MHz		
Beam Pulse Duration	2.2 us	25 us	45 us
Sample Rate		5 MHz	
Position Resolution		0.1 mm	
Position Accuracy			
Long Term Position Stability		0.25 mm	

BPM Phase ~ 0.1 degrees @201MHz

Linac Toroid Upgrade

- Similar to BPMs, update existing electronics with digital electronics
  - 8 channel, 14 bit ADC, 125MSPS
  - FPGA Digital Signal Processing
    - Pulse integration
    - Baseline correction
    - Edge-detection
  - 15 Hz operation into ACNET
- Long term stability and flexibility



Summary

Fermilab has designed and tested a new H- injector front-end

- New dual-H- source, LEBT and RFQ
- RFQ energy issues corrected
- Installation of new front-end to occur during present shutdown
- Front-end measurements in future thesis

- Upgrade of linac BPM and toroid with new digital electronics proceeding during shutdown

Bottom line: Trust but Verify

Thanks and Acknowledgements

C. Y. Tan – Lead scientist for installation of new front-end

- D. Bollinger, P. Karns, B. Schupbach, K. Koch, A. Feld (Preacc group), P. Balakrishnan (summer student, MIT)
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- N. Eddy, N. Lui, A. Semenov (Instrumentation dept)
- And anyone whom I have inadvertently left out. Thanks!