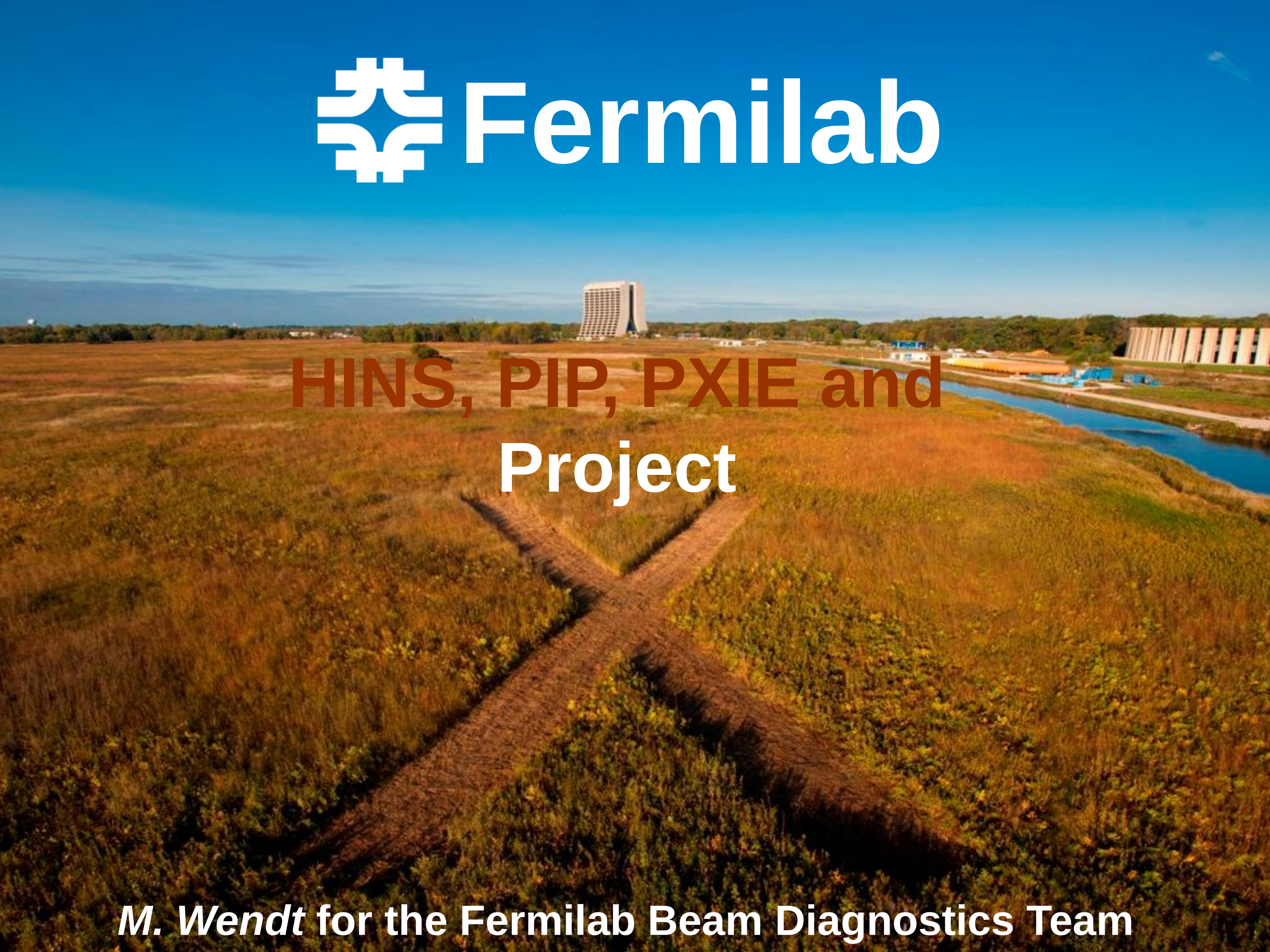


Fermilab

HINS, PIP, PXIE and Project X

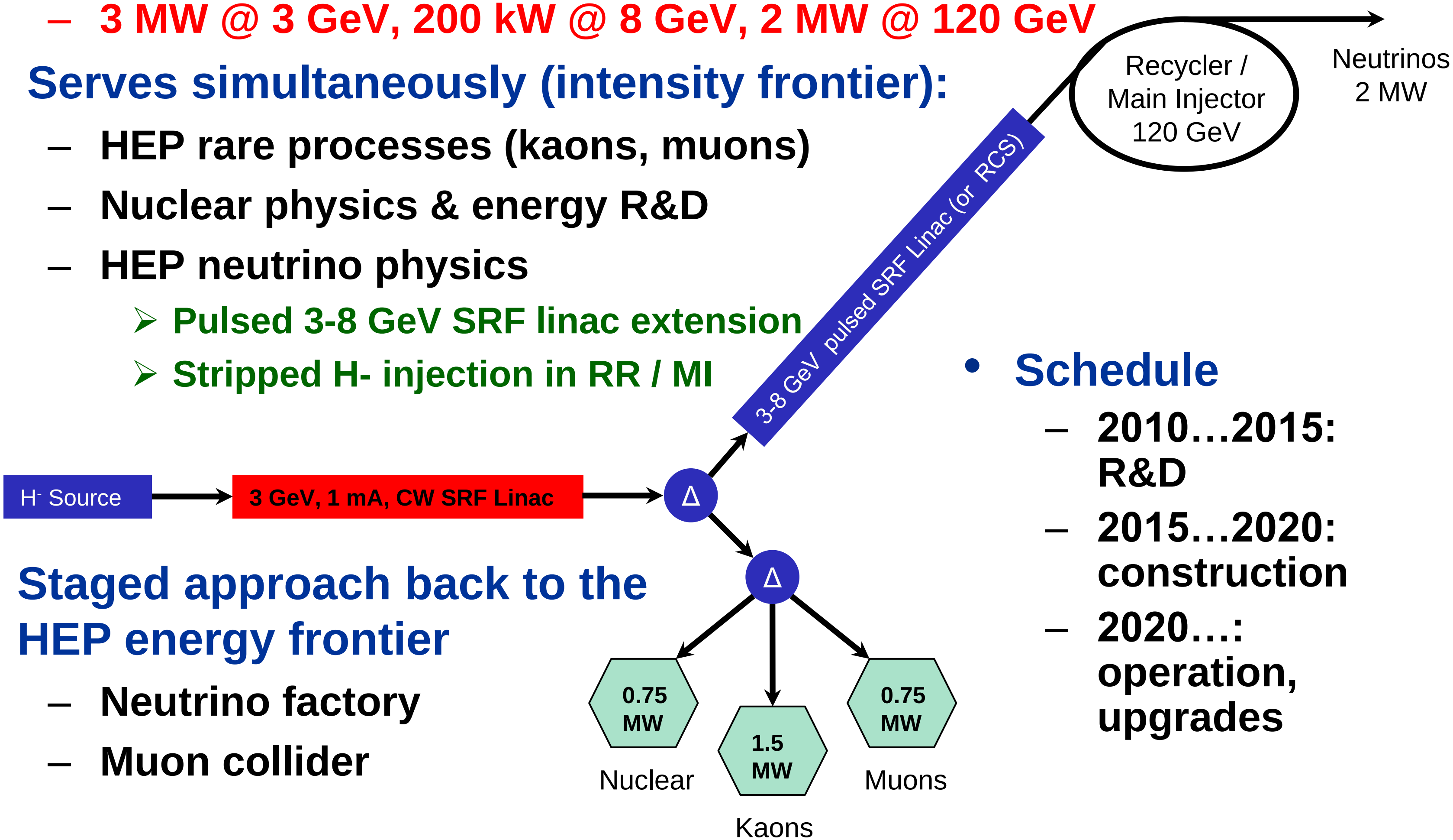
M. Wendt **for the Fermilab Beam Diagnostics Team**

Outline

- Project X
- HINS Beam Studies
- BPM Read-out for HINS an PIP
- What is PXIE?
- Optional: TOF Measurements

Reference Design

- **Stable since more than a year, delivers simultaneously:**
  - **3 MW @ 3 GeV, 200 kW @ 8 GeV, 2 MW @ 120 GeV**
- **Serves simultaneously (intensity frontier):**
  - **HEP rare processes (kaons, muons)**
  - **Nuclear physics & energy R&D**
  - **HEP neutrino physics**
    - **Pulsed 3-8 GeV SRF linac extension**
    - **Stripped H- injection in RR / MI**

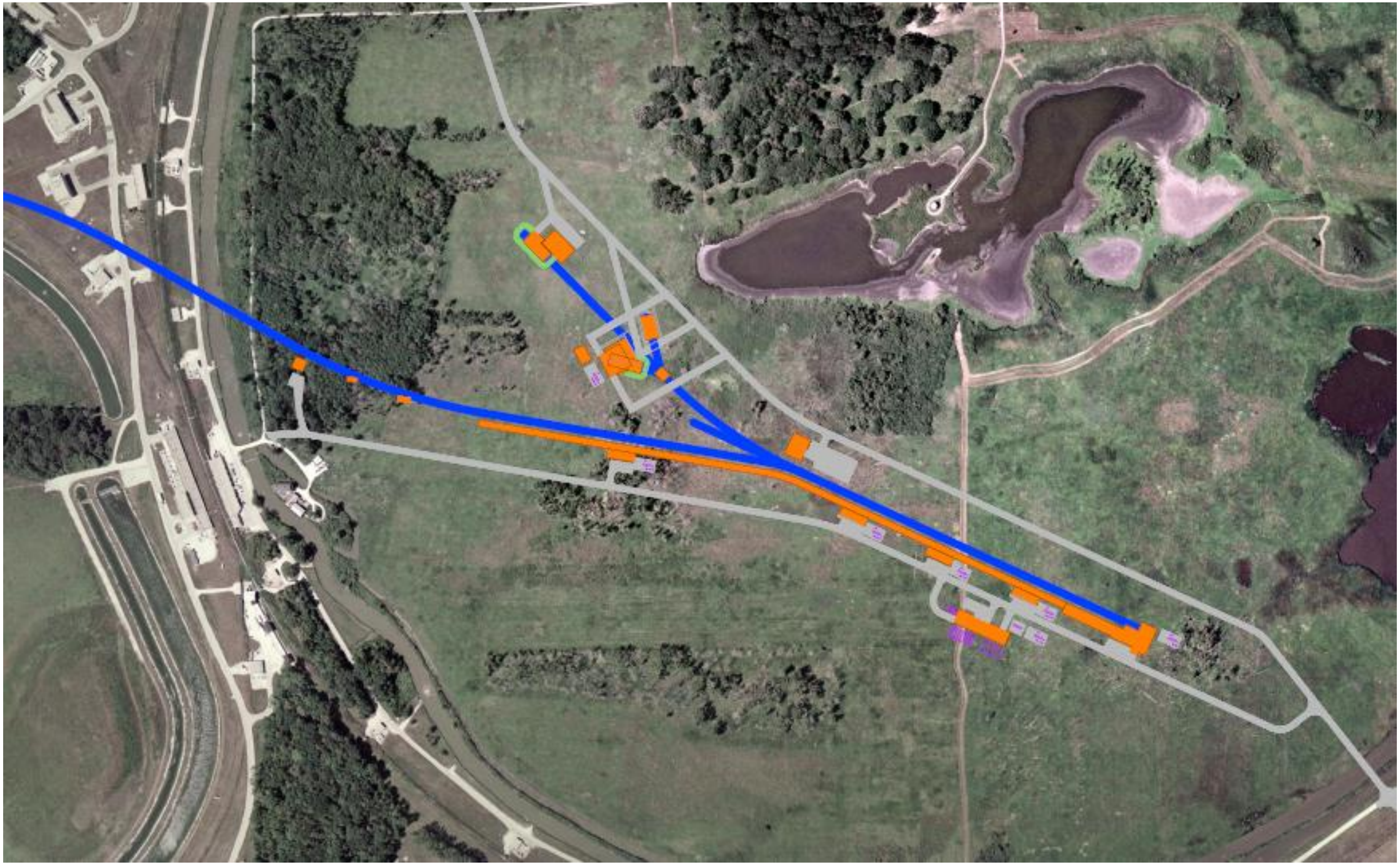


- **Schedule**
  - **2010…2015: R&D**
  - **2015…2020: construction**
  - **2020…: operation, upgrades**

- **Staged approach back to the HEP energy frontier**
  - **Neutrino factory**
  - **Muon collider**

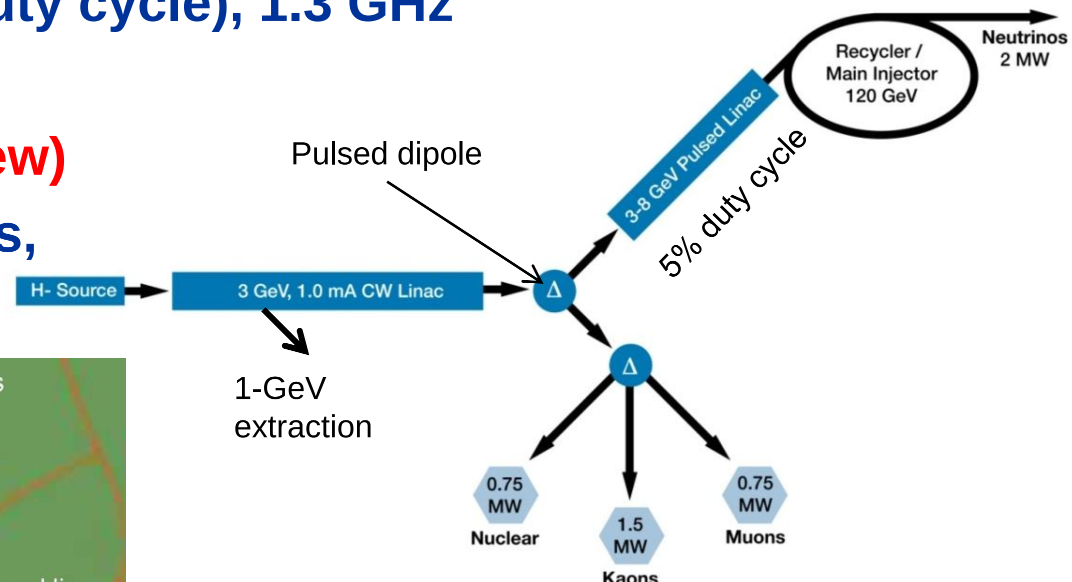
Project X

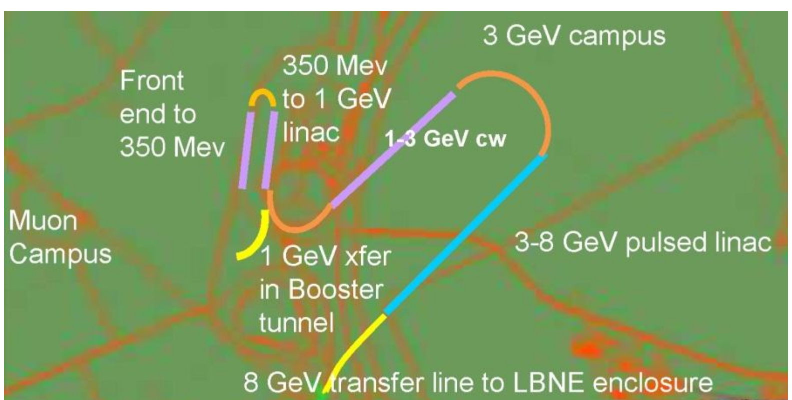
Reference Design



Accelerator Scope & Staging

- Warm CW front end 162.5 MHz, 5 mA (H- ion source, RFQ, MEBT, chopper)
- 3-GeV CW SCRF linac (162.5, 325, 650 MHz), 1-mA ave. beam current
- Transverse beam splitter for 3-GeV experiments
- 3-8 GeV: pulsed linac (5% duty cycle), 1.3 GHz
- Recycler and MI upgrades
- 1-GeV extraction section (new)
- Various beam transport lines, including targets (new)





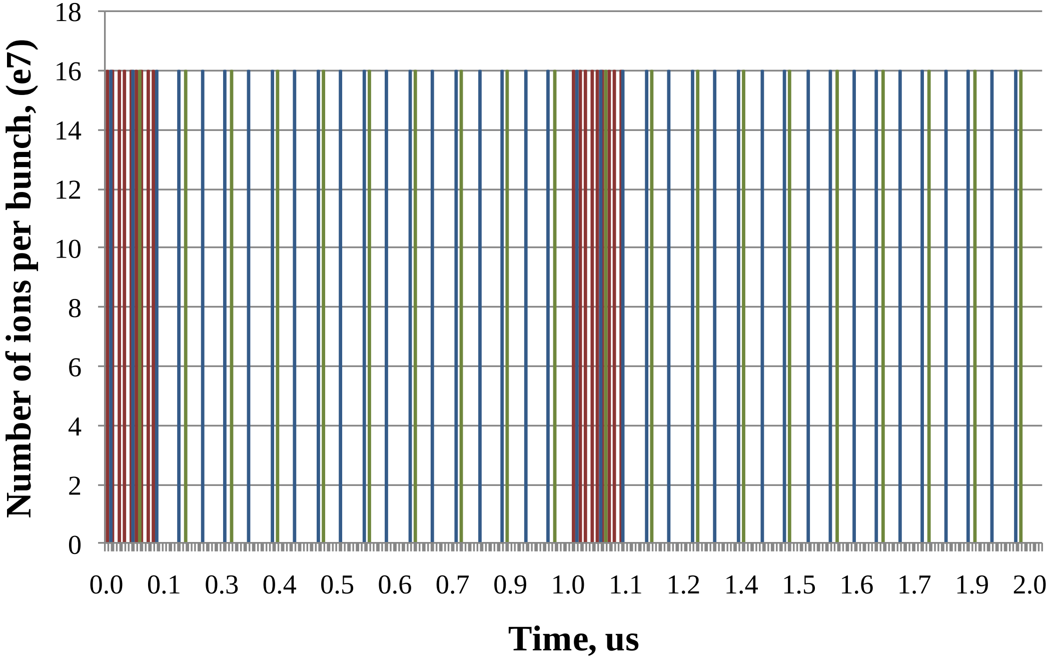
Beam Chopping

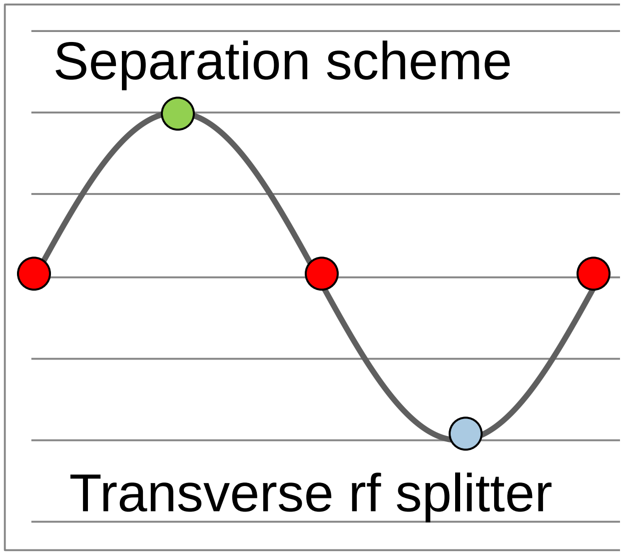
<u>1 μsec period at 3 GeV</u>

Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz	700 kW
Kaon pulses (16e7) 20.3 MHz	1540 kW
Nuclear pulses (16e7) 10.15 MHz	770 kW

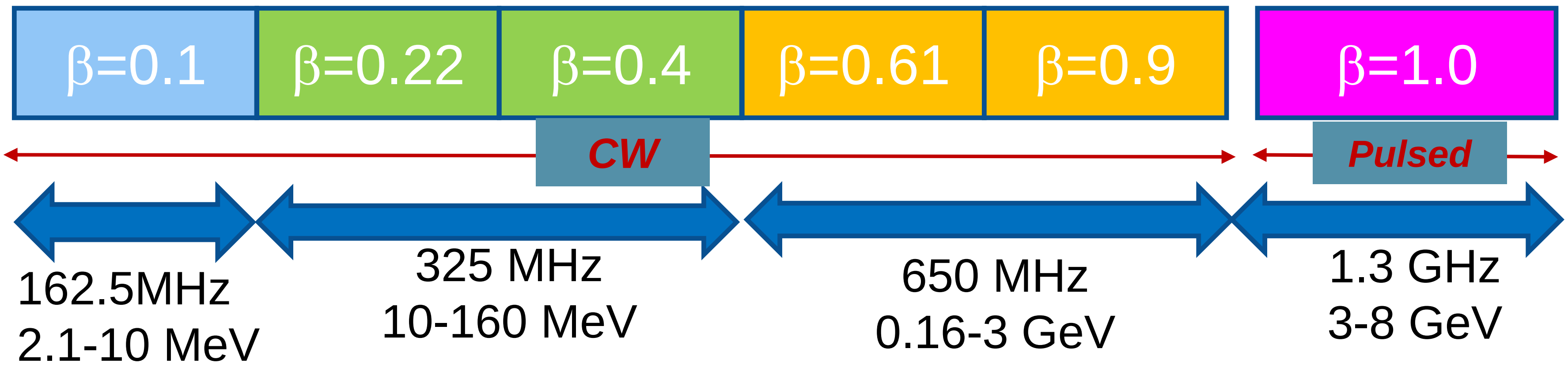
Ion source and RFQ operate at 4.2 mA

~75% of bunches are chopped at 2.5 MeV after RFQ



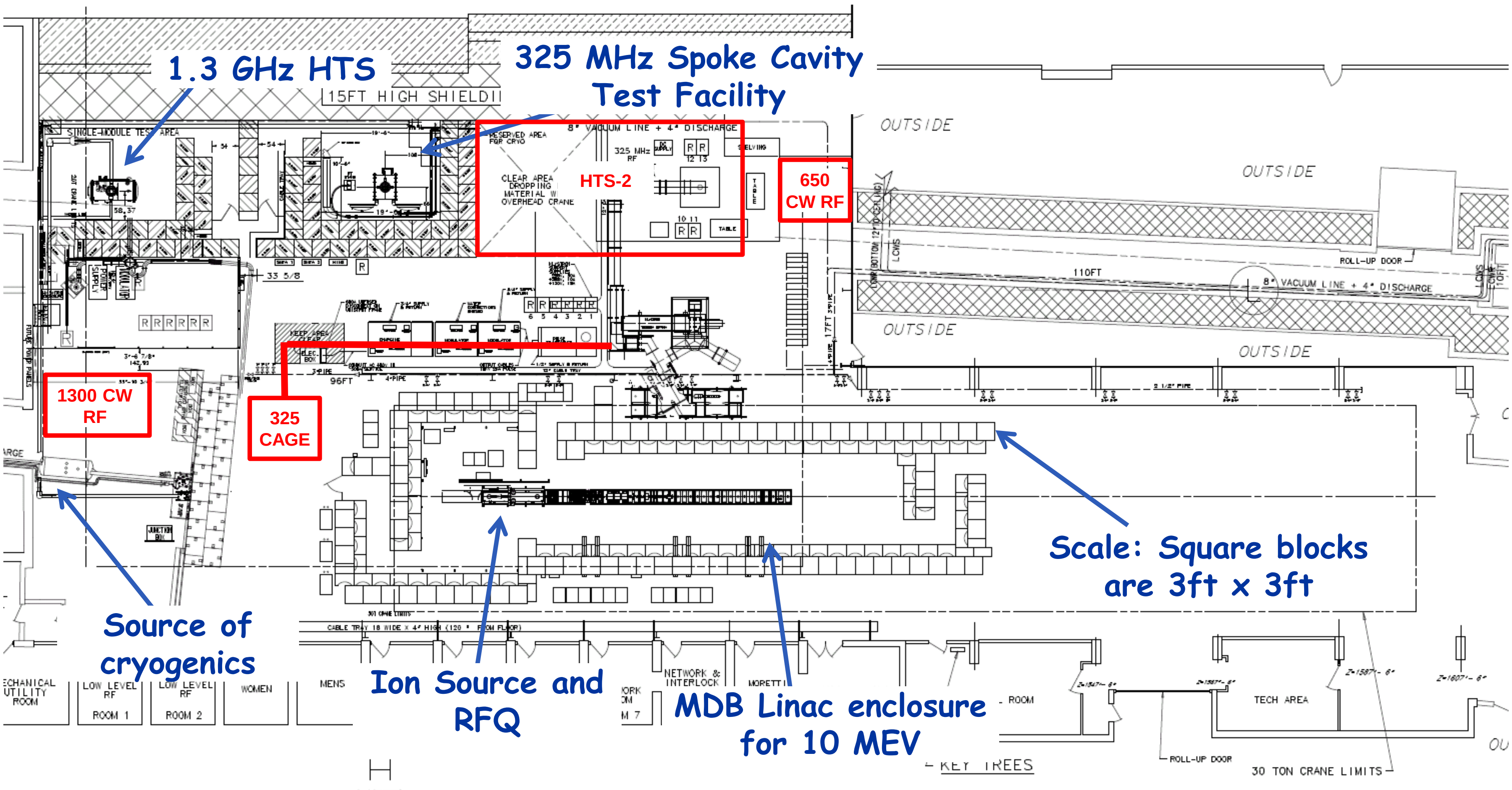


SRF Technology Map



Section	**Freq**	**Energy (MeV)**	**Cav/mag/CM**	**Type**
HWR (β_G=0.1)	162.5	2.1-10	9 /6/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/8/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

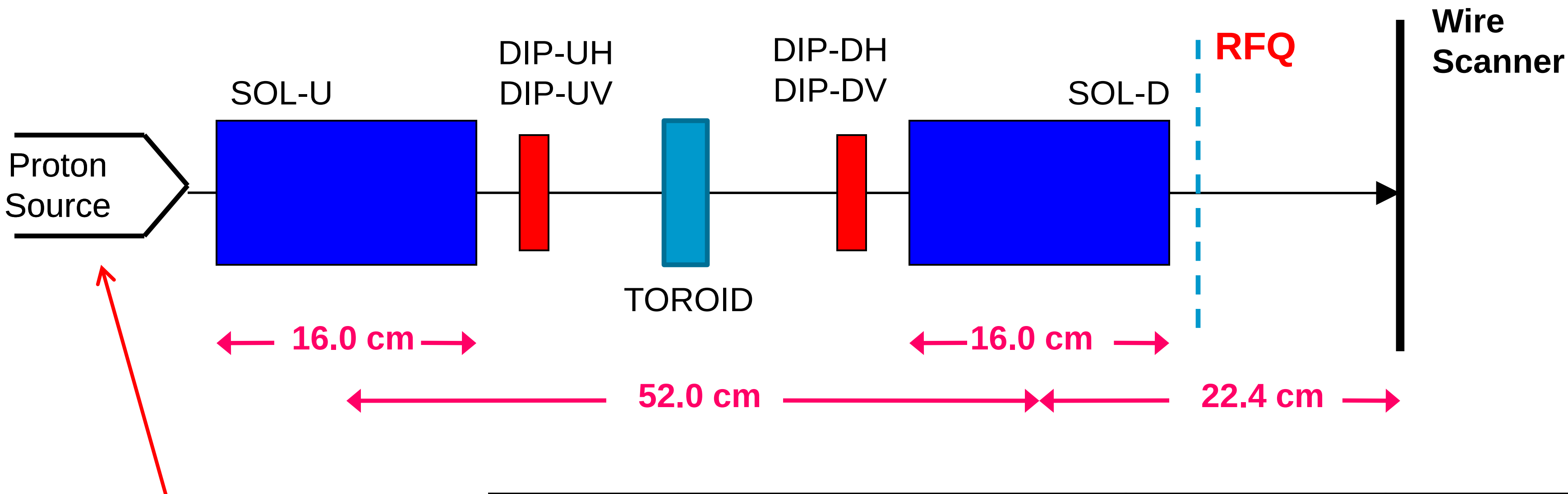
MDB Test Facility Layout



HINS Beam Parameters

	Proposed	Actual	
Particle	H+ then H-	H+ (then H- ??)	
Nominal Bunch Frequency/Spacing	325 3.1	325 3.1	MHz nsec
Pulse Length	3 @ 2.5 Hz 1 @ 10 Hz	1 @ 0.2 Hz 0.1 @ 1 Hz	msec
Average Pulse Current	~ 20 (source)	~ 20 (H, 2H+, 3H+) ~8 (RFQ - H)	mA
Pulse Rep. Rate	2.5/10	0.2/1	Hz
Beam Energy	Up to 10	2.5 to 3.0	MeV

HINS Proton Source and LEBT



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

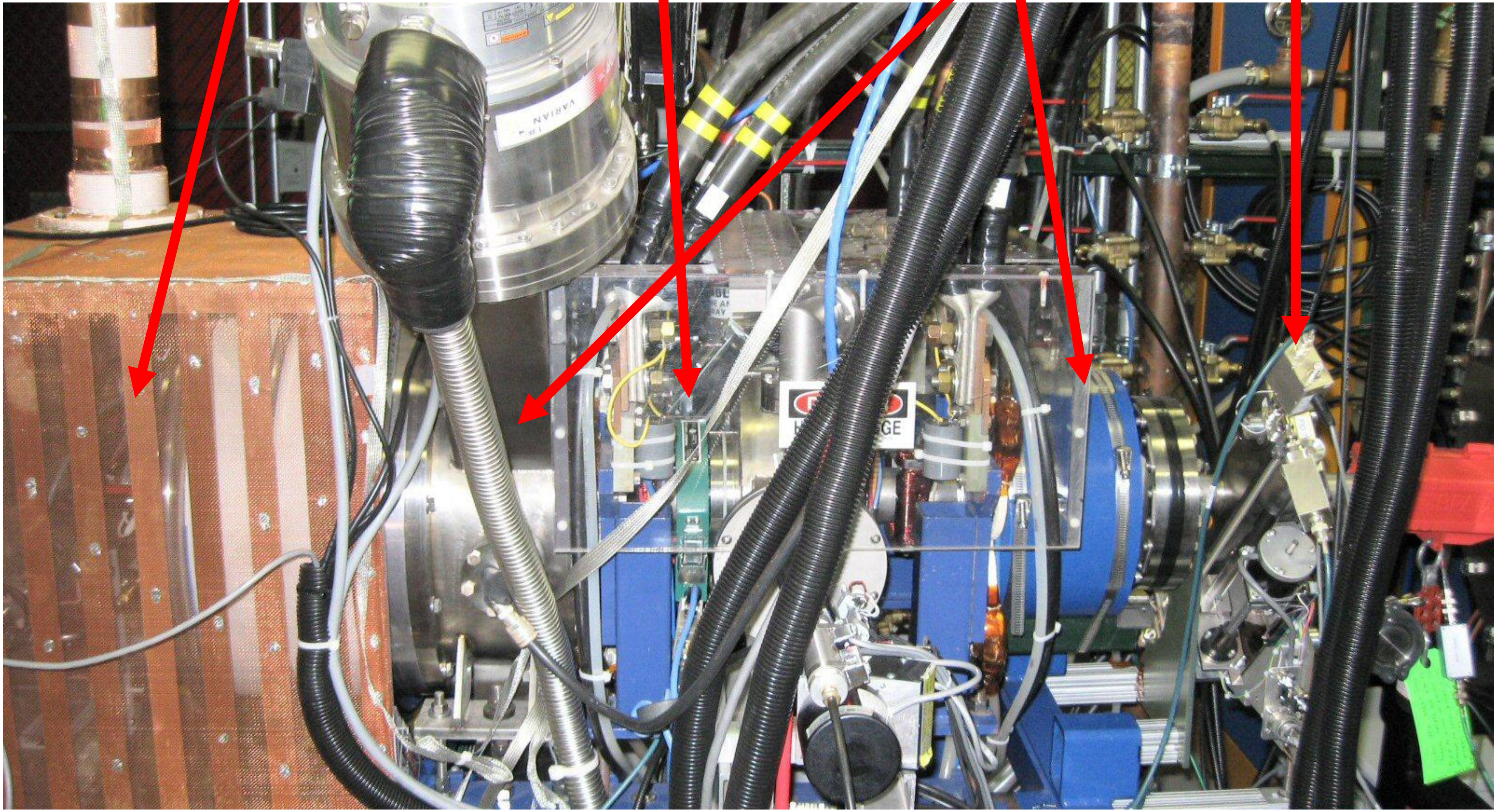
HINS LEBT Beam Characterization

Proton Source

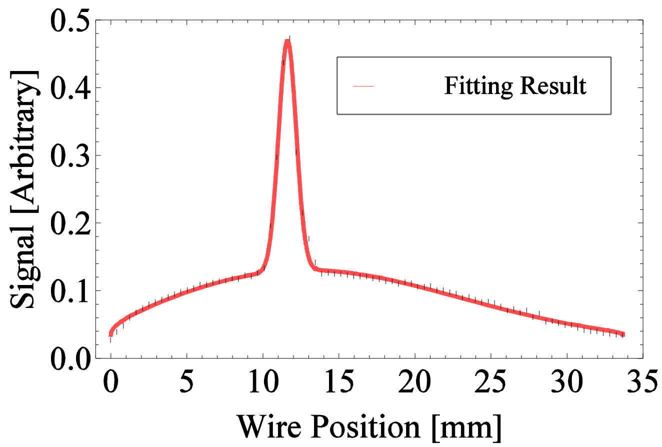
Toroid

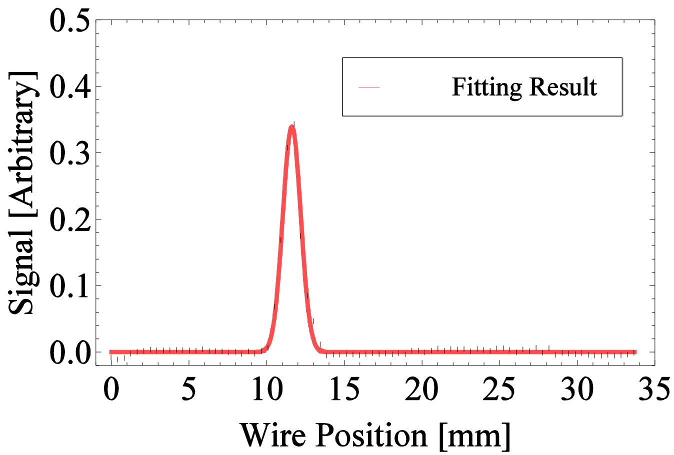
Focusing Solenoids

Wire Scanner

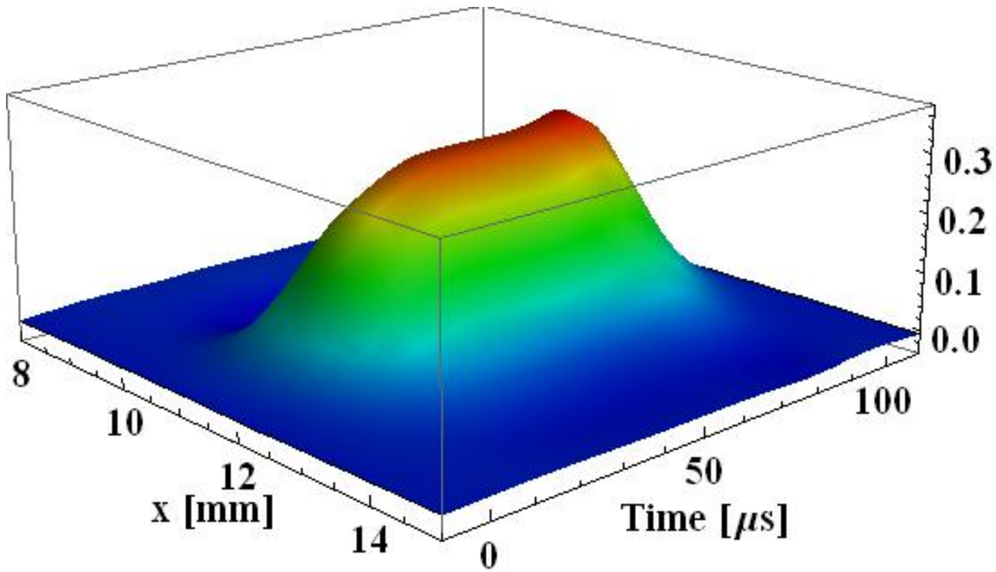


A Typical Wire Scan (LEBT)



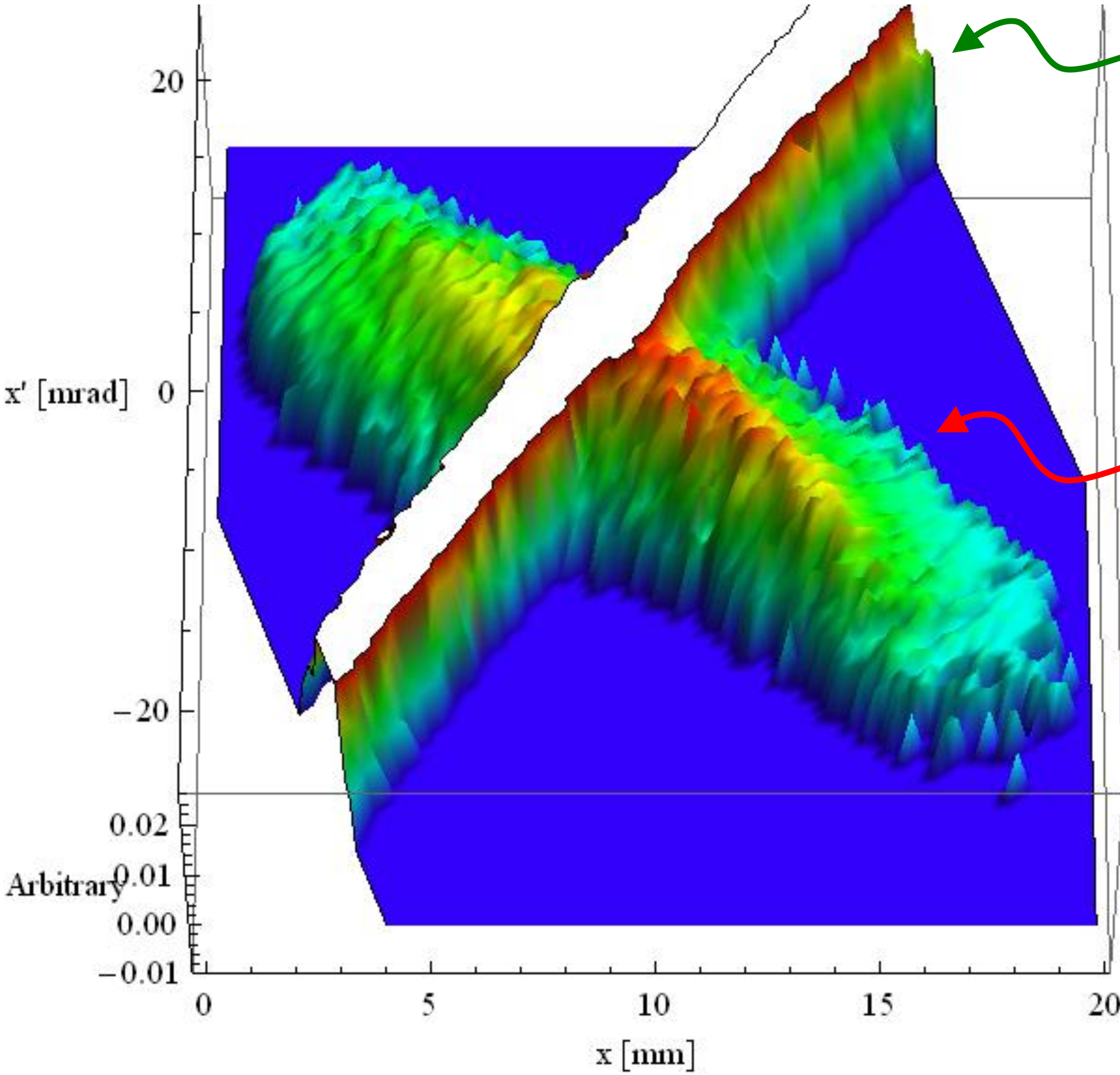


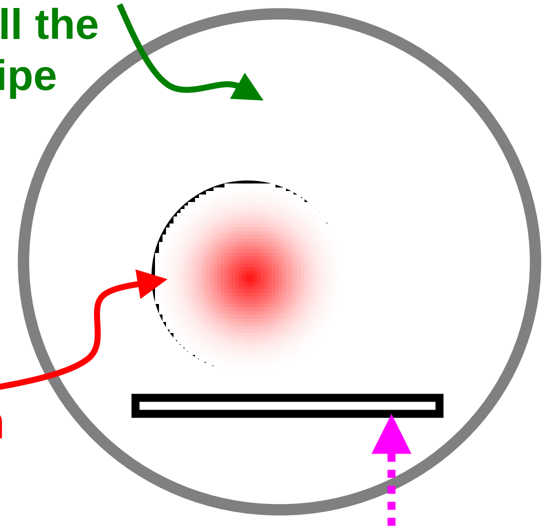
Signal with background subtracted.



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

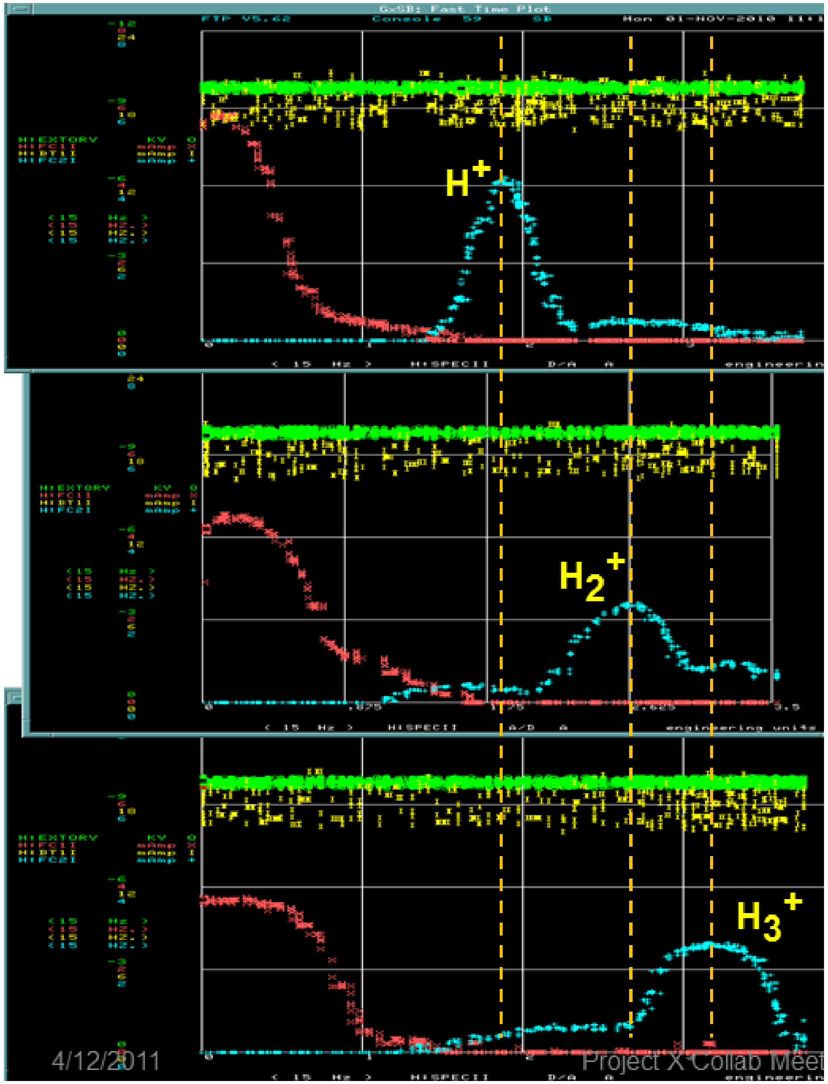
Project X Slit-WS Emittance Measurement

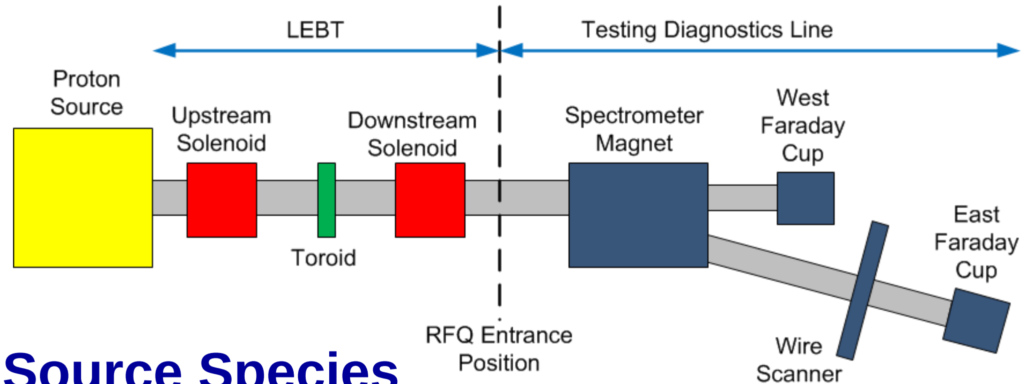




Background signal outweighs proton signal.

Species from the Proton Source





Source Species

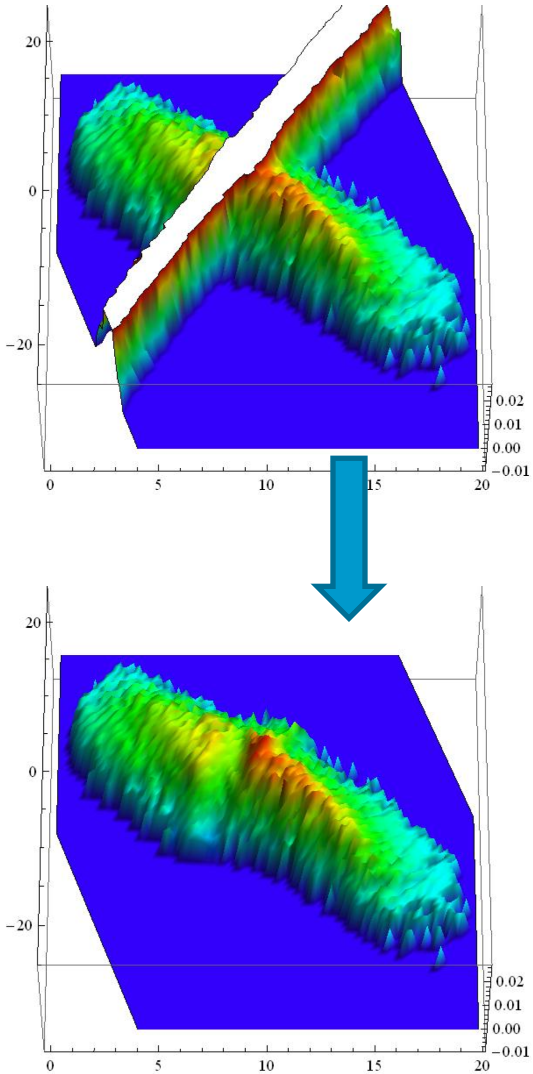
Green – Source Extractor Voltage
Yellow – LEBT Toroid Current
Red – Straight ahead Faraday Cup
Blue – Spectrometer Faraday Cup (bend)

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

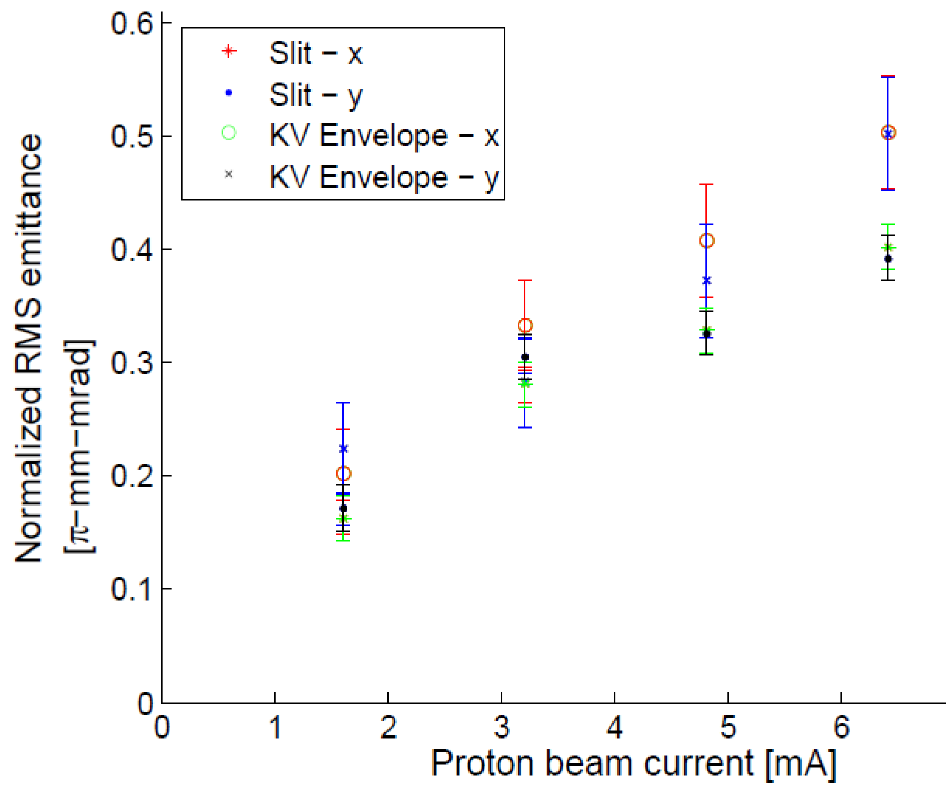
~ 40% Protons
~ 30% H2+
~ 30% H3+

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

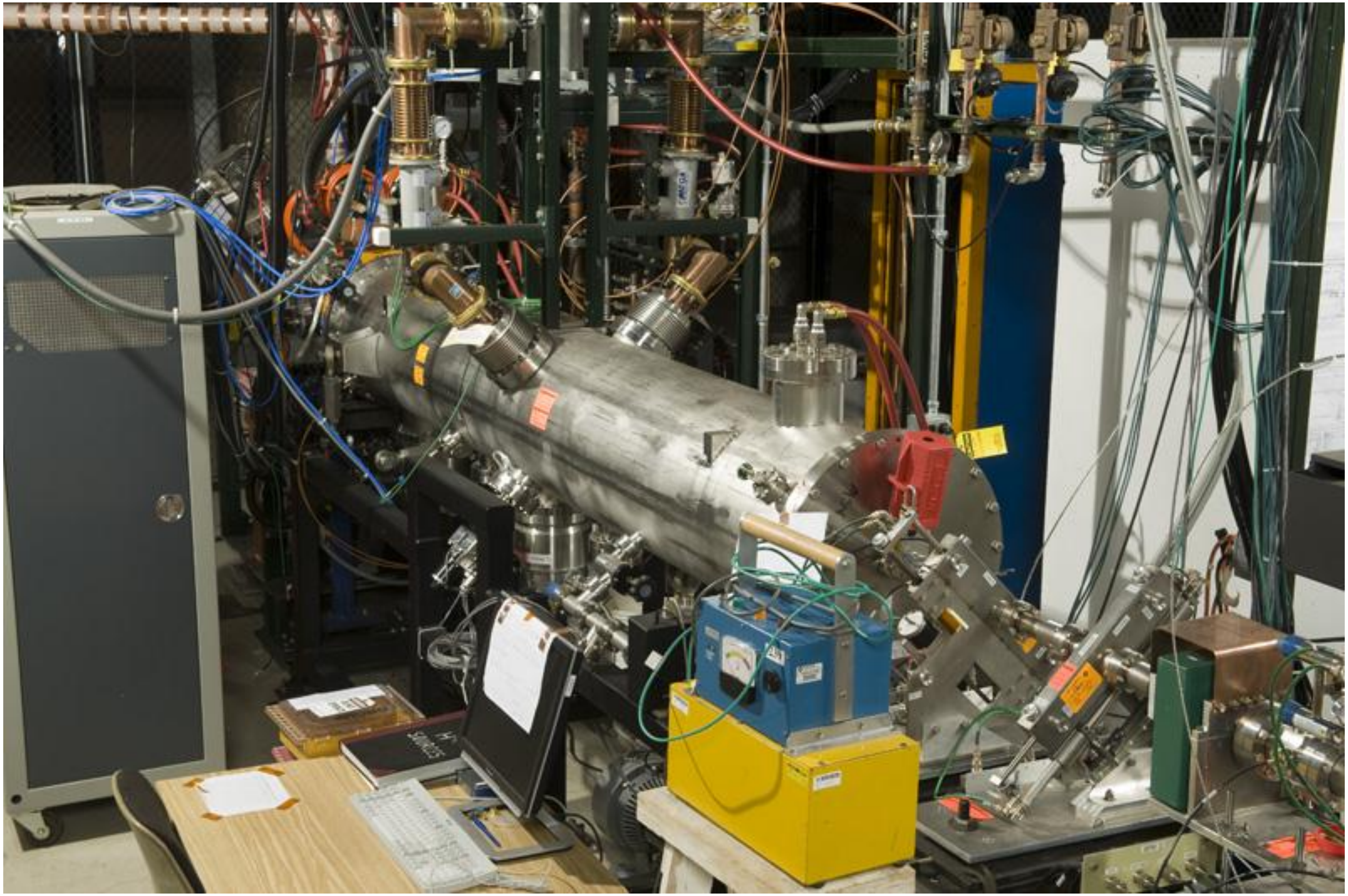
Phase Space Cleaning



Source Emittance
Slit & Solenoid Scans



HINS 325 MHz Pulsed RFQ

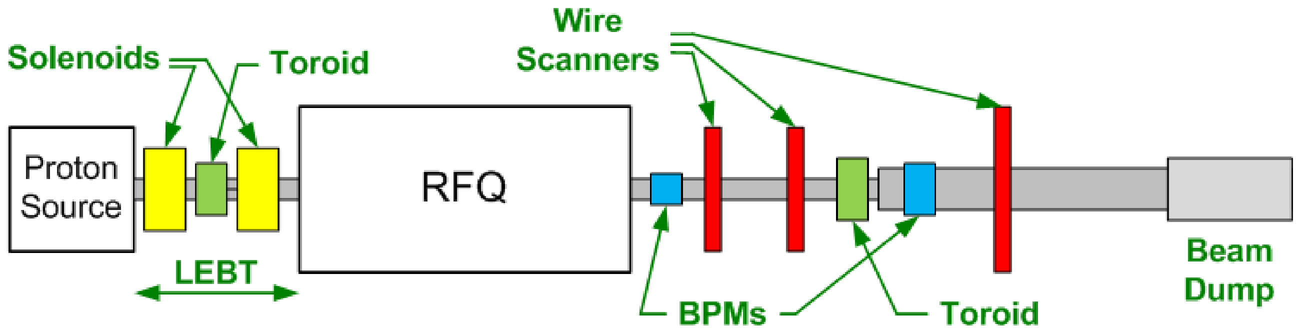


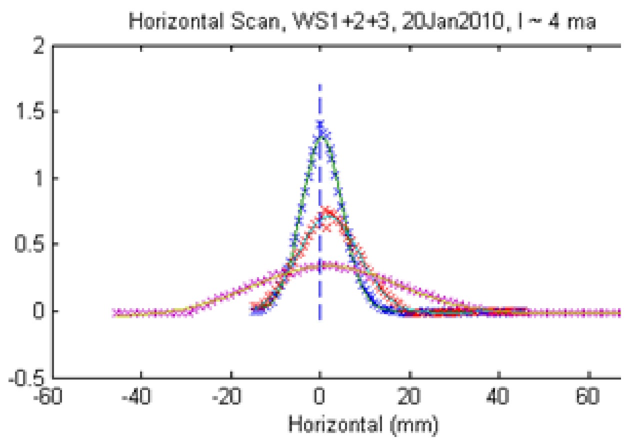
Initial RFQ Beam Measurements

RFQ design:

- 2.5 MeV
- 325 MHz
- Peak power up to 450 KW
- 1 ms pulses at 10 Hz

RFQ suffered from detuning problems and water leaks → 50 μs pulses at 1 Hz





Profile Sigmas and Integrals ; I ~ 4 mA

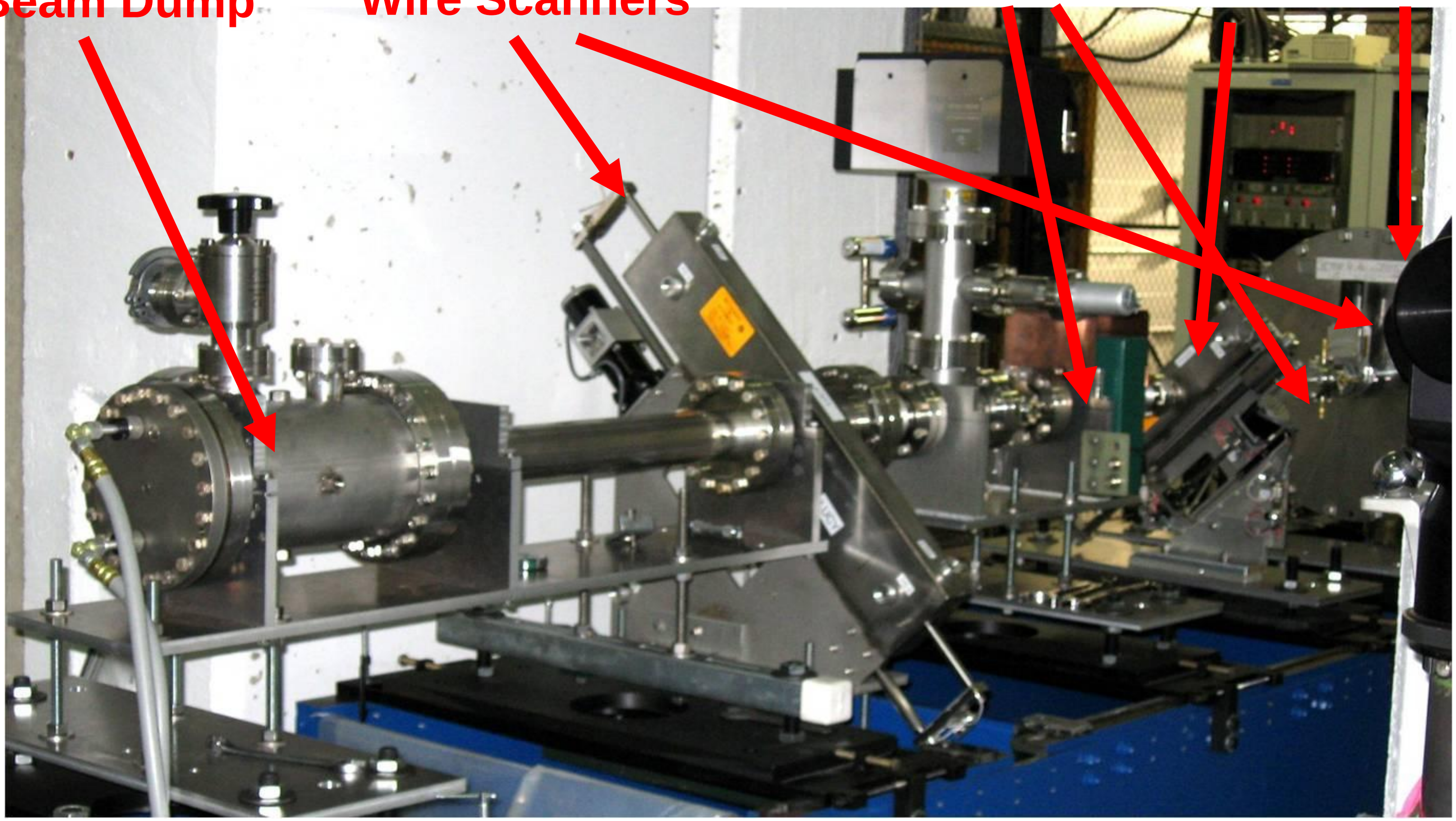
Sigmas	Horizontal	Vertical	Diagonal
Scanner 1	4.5 mm	4.2 mm	4.3 mm
Scanner 2	7.0 mm	6.8 mm	6.2 mm
Scanner 3	16.2 mm	13.2 mm	13.4 mm

Integrals	Horizontal	Vertical	Diagonal
Scanner 1	14.8 V*mm	14.9 V*mm	14.7 V*mm
Scanner 2	11.8 V*mm	10.5 V*mm	10.2 V*mm
Scanner 3	11.6 V*mm	10.1 V*mm	10.7 V*mm

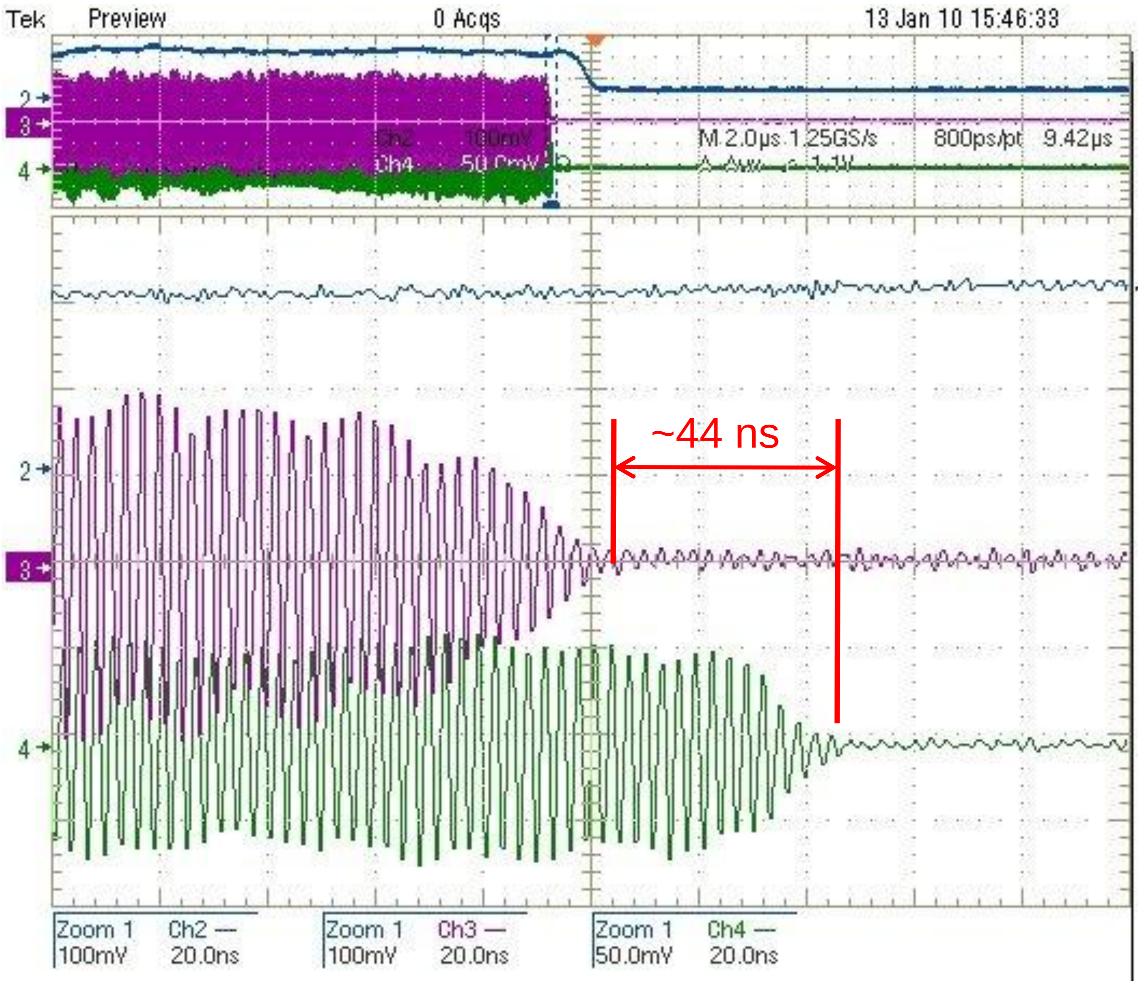
Beam loss after first wire scanner → need focusing

Initial RFQ Beam Diagnostics

The HINS linac was equipped with a reconfigurable, movable diagnostics station at the end of the linac



RFQ Energy Measurement by TOF



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

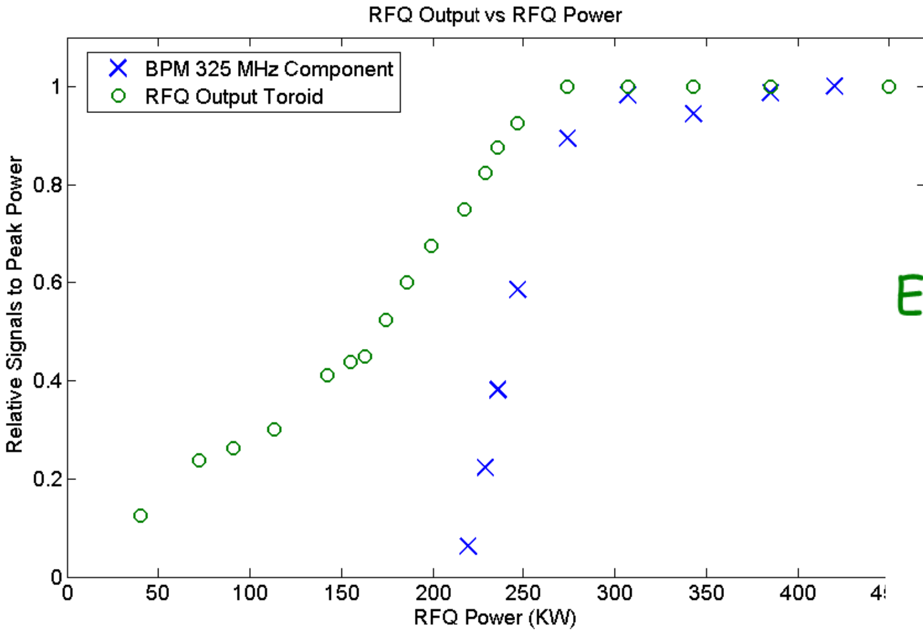
Upper display: 2 μsec/div

Lower display: 20 nsec/div

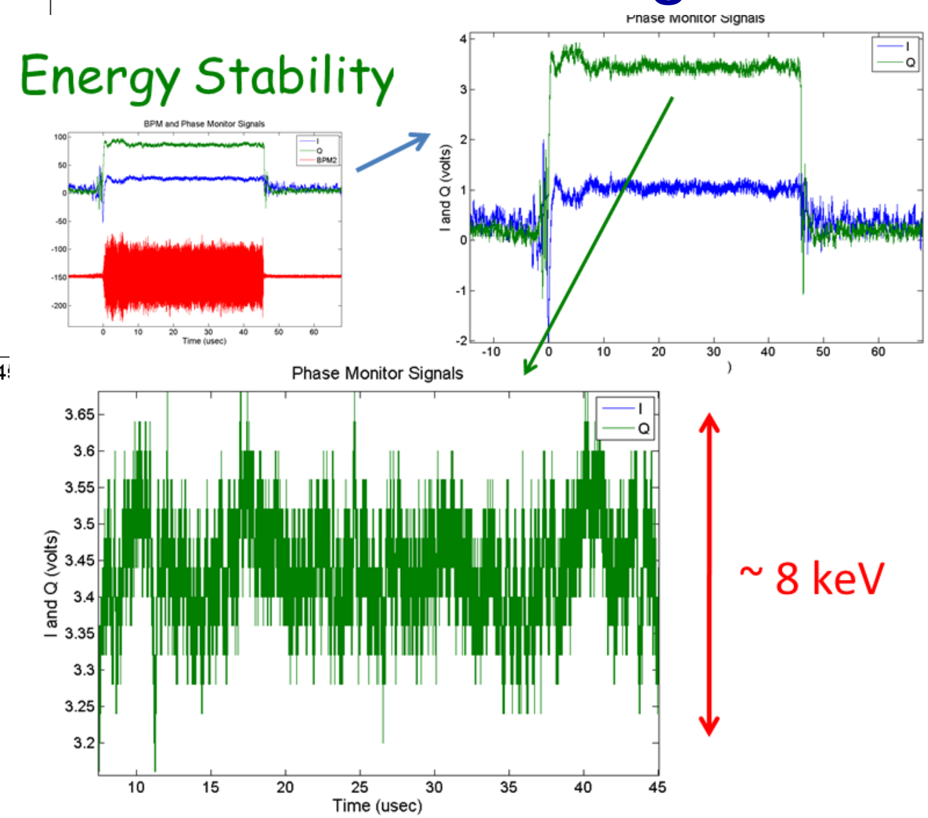
Lower display shows the 44 ns delay expected for transit of 2.5 MeV beam between the BPM two buttons separated by 0.96 meters

Beam current is about 3 mA

RFQ Stability



Phase variation from time-of-flight



Relative RFQ output beam vs. RF Power

Next Iteration of RFQ Beam Measurements

- **Initial measurements suffered from RFQ water leak problems**
  - **RFQ limited to 50 μsec pulses**
  - **RFQ has been repaired and reinstalled at the Meson test facility**

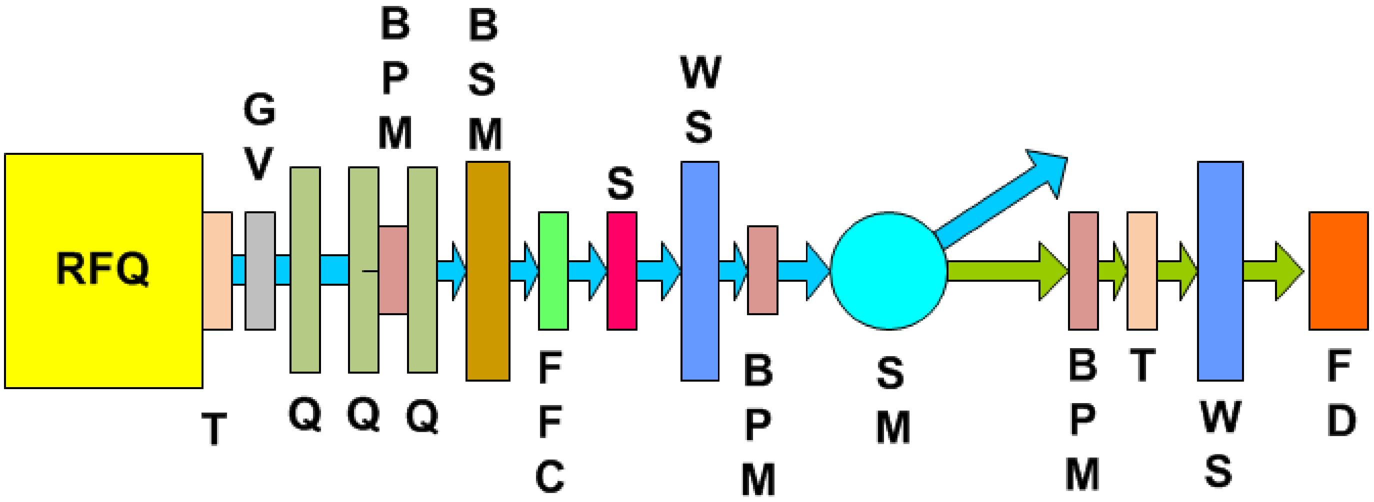
- **Initial RFQ measurements suffered many issues**
  - **No transverse focusing → Quadrupoles added**
  - **No longitudinal measurements → FFC and BSM**
  - **No transverse emittance measurements → Quad-Wire, Slit-Wire**
  - **Energy measurement was not precise → Spectrometer magnet**
  - **RFQ efficiency not accurately measured → Toroid at RFQ output**

- **New diagnostics line has been install**
  - **Reconfigurable, movable**
  - ***Space available for R&D projects***

Advanced HINS Diagnostics Line

T:	Toroid
GV:	Gate Value
Q:	Quadrupole
BPM:	Beam Position Monitor
WS:	Wire Scanner
S:	Horz and Vert Slits
BSM:	Bunch Shape Monitor (Longitudinal)
FFC:	Fast Faraday Cup
FD:	Faraday Cup/Dump
SM:	Spectrometer Magnet

RFQ Beam Diagnostics April 2011

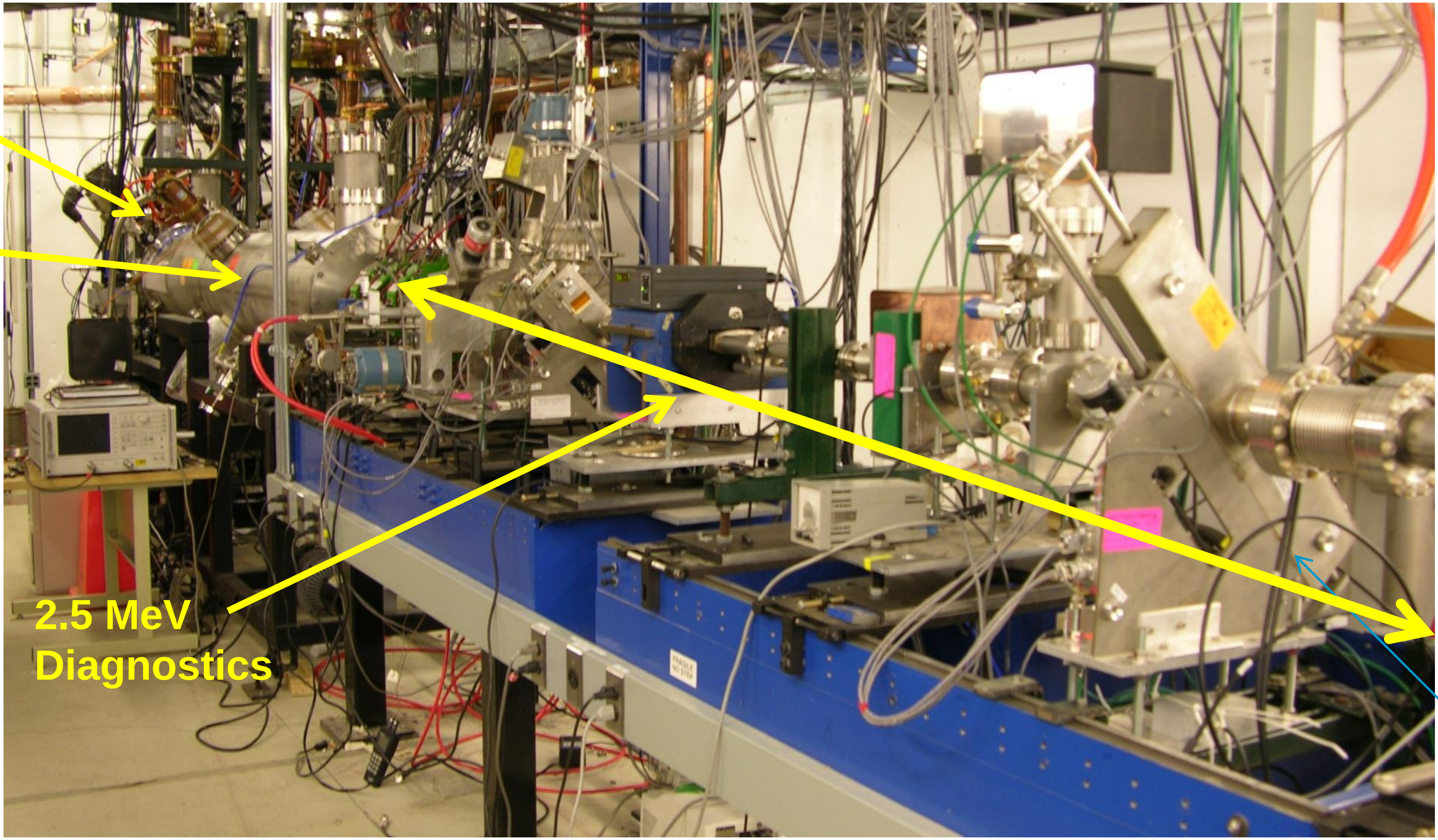


Project X

HINS Beamline

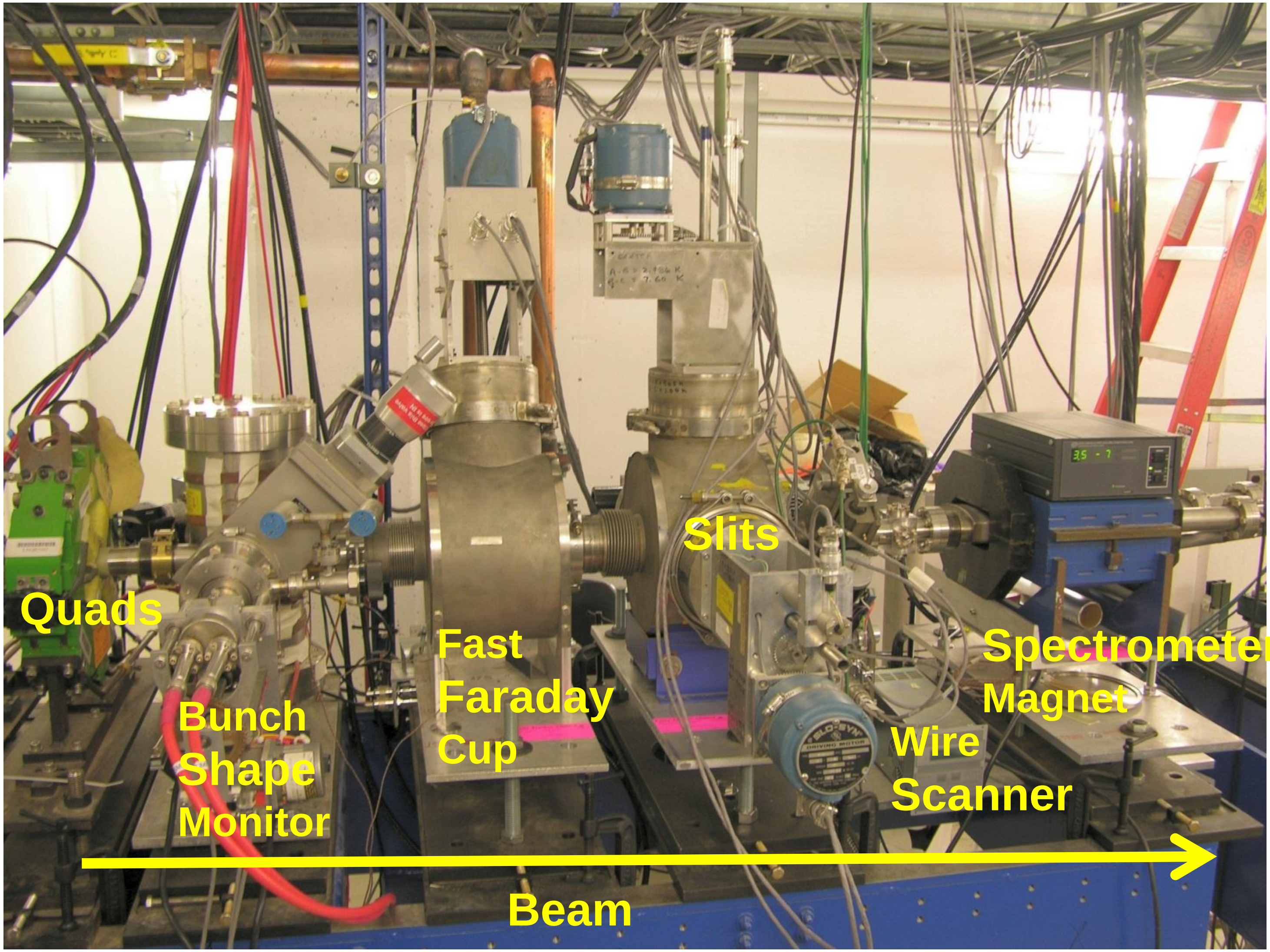
Source /LEBT

RFQ

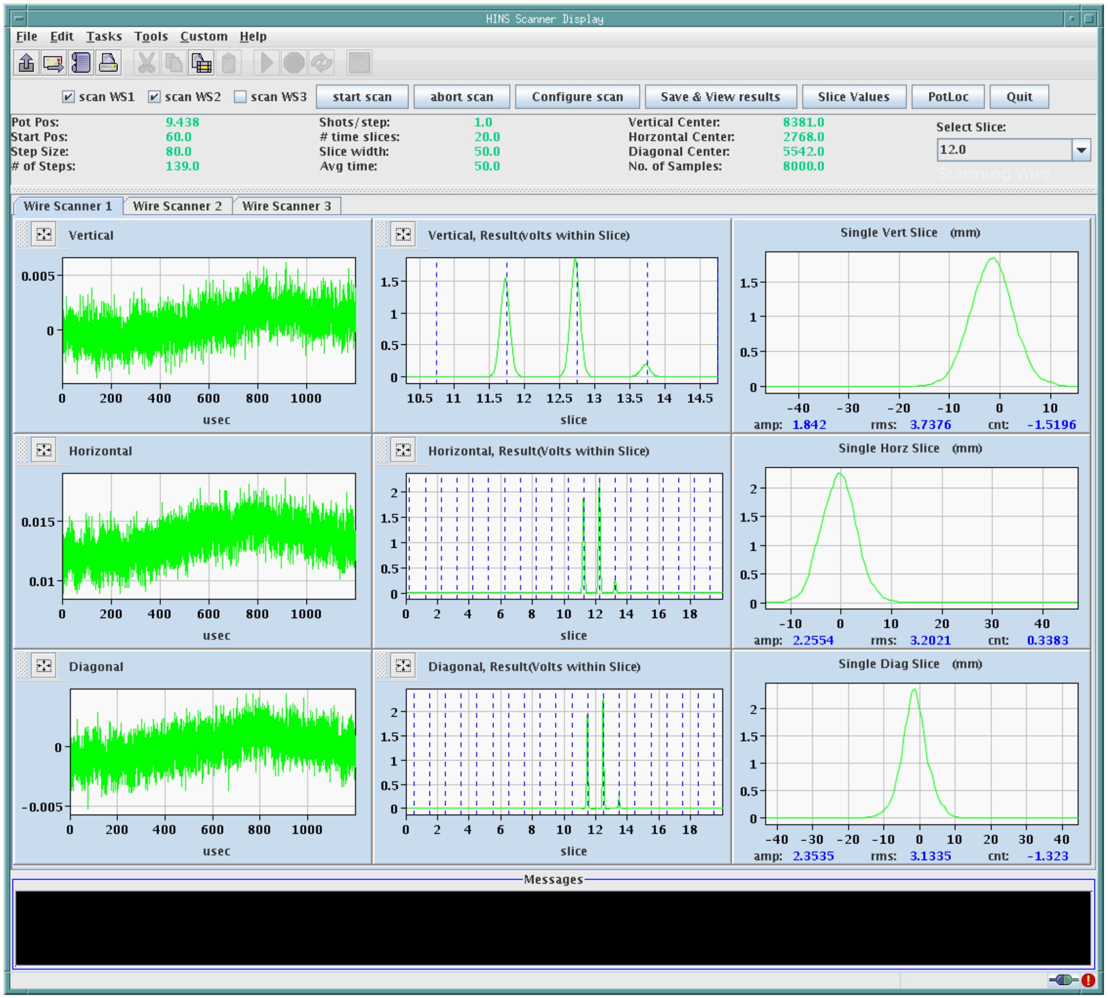


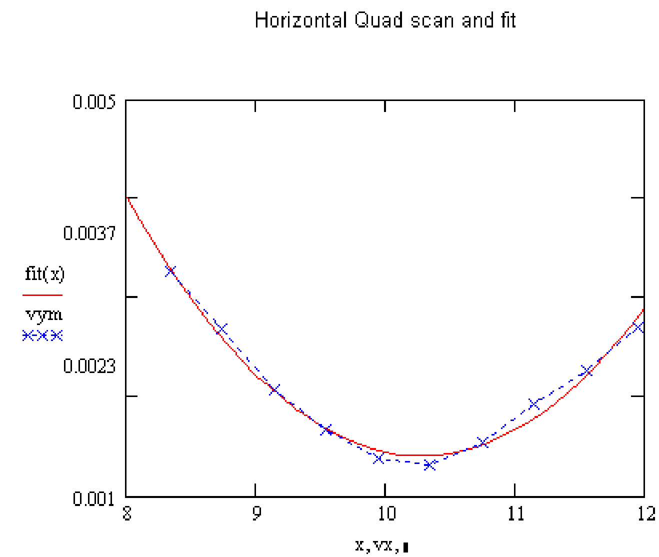
2.5 MeV Diagnostics

HINS MEBT Beam Diagnostics



Tr. Emittance from Quad Scans





the equation is sigma=.05452 - .01034k + 5.02791E-4k^2
setting the derivative to zero gives k0=10.283. Note this is the gradient at minimum

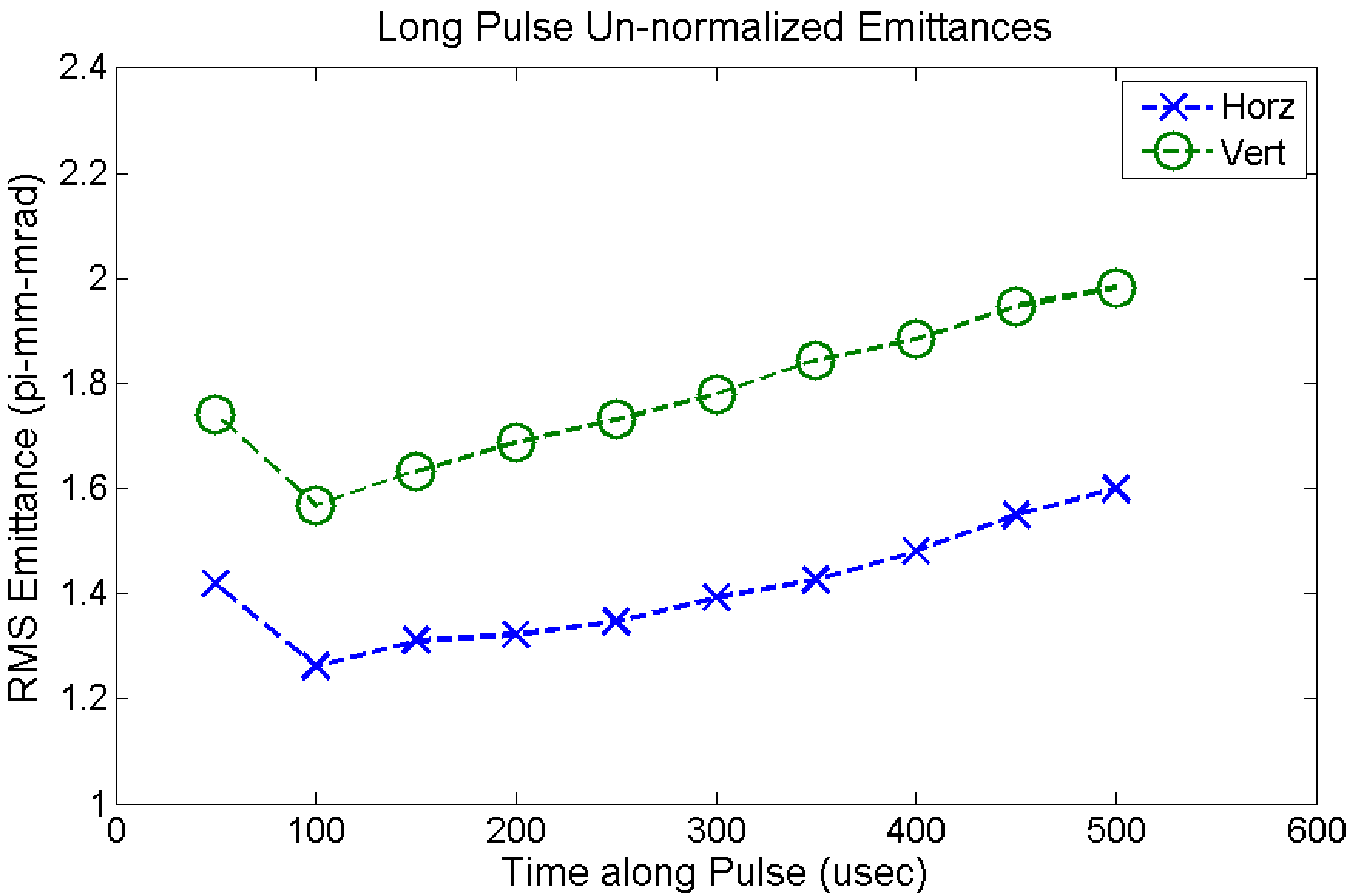
<u>Unnormalized emittance</u>

- 6 mA RFQ beam
- 100 usec pulses

H: 1.49 pi mm-mrad

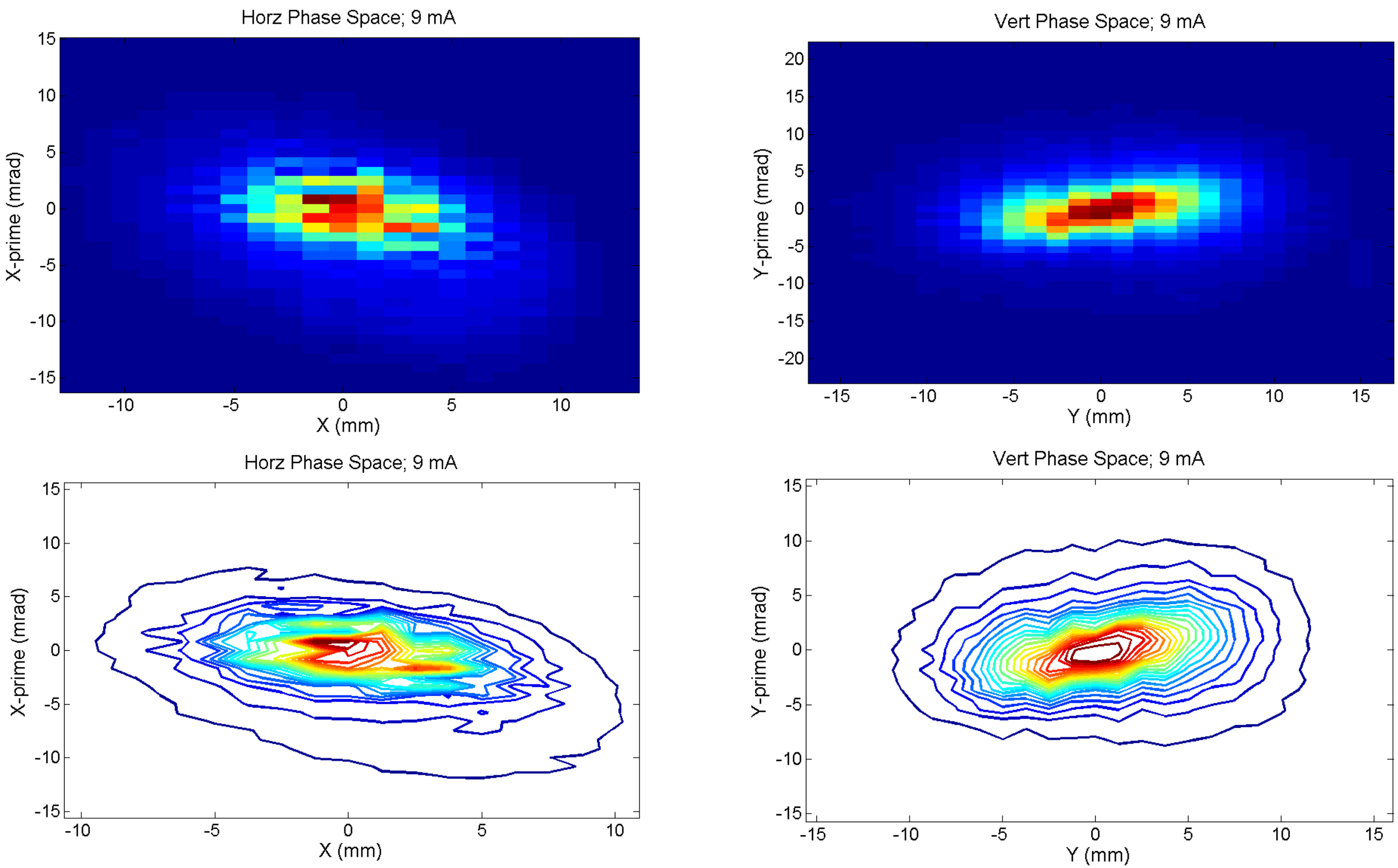
V: 1.88 pi mm-mrad

Emittance along 500 µsec Pulse – Quad Scan



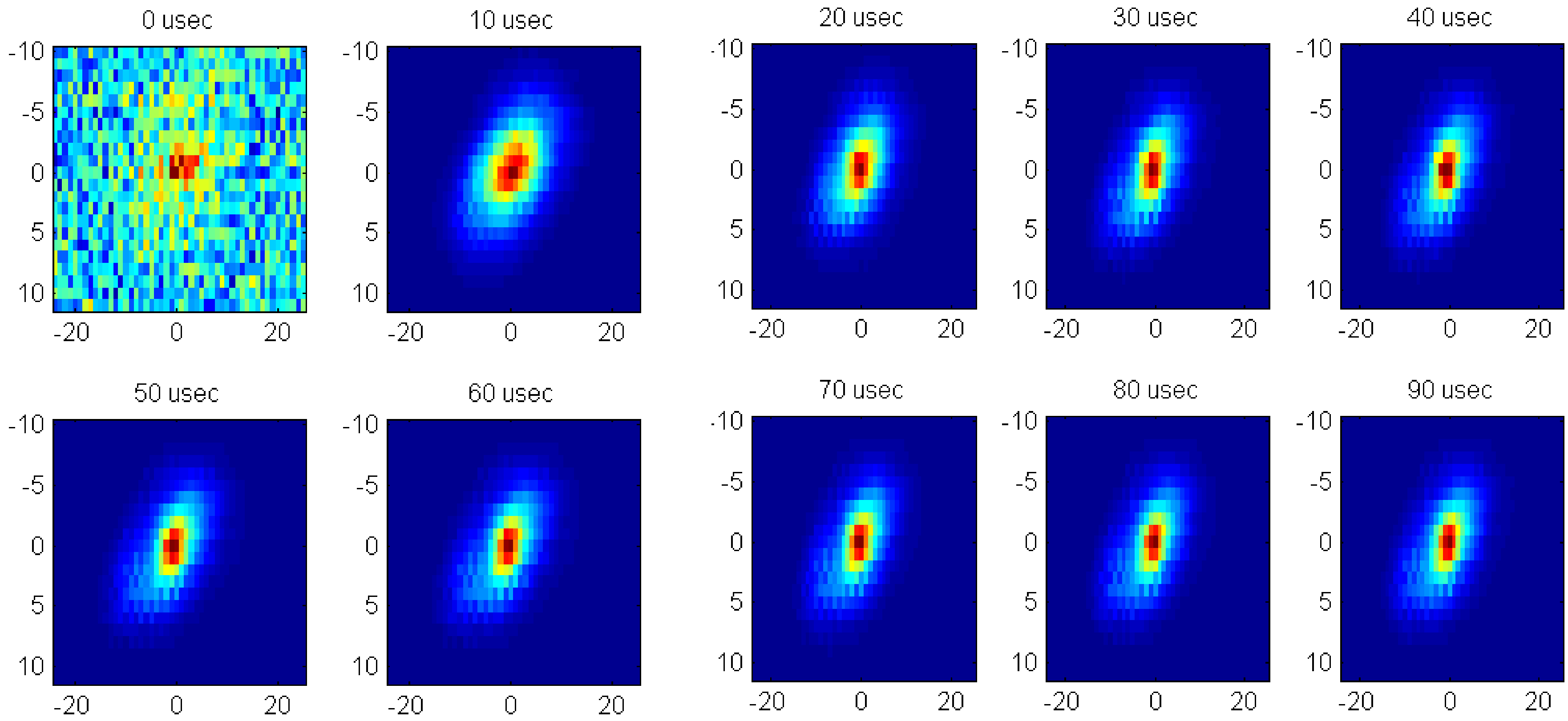
Phase Space Plots; 9 mA RFQ

HORIZONTAL



VERTICAL

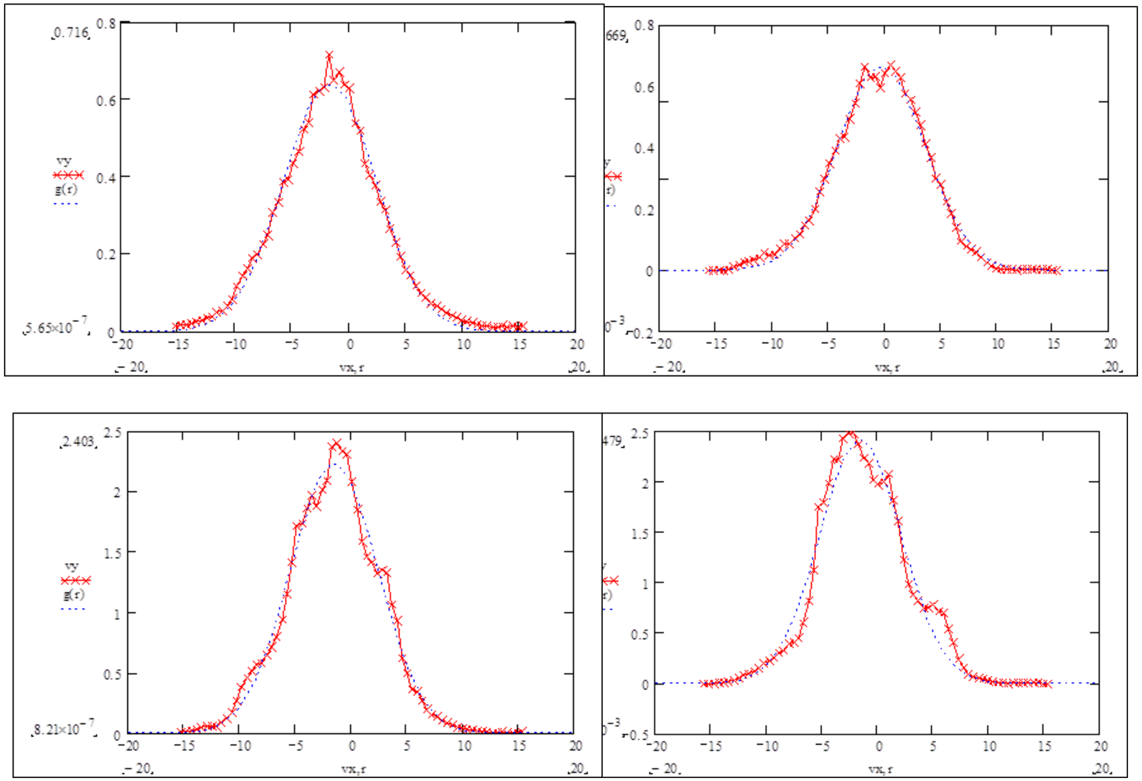
Hor. Phase Space along Pulse



- X – X' along beam pulse; arbitrary units
- 6 mA beam

Odd Transverse Shape Effects

Vertical | Horizontal



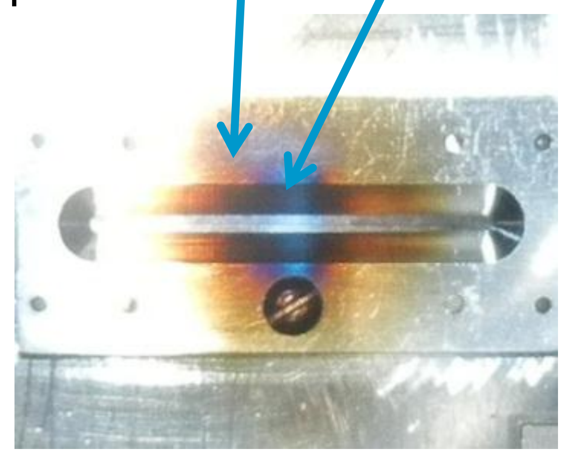
Front
of pulse

Back
of pulse

Halo?

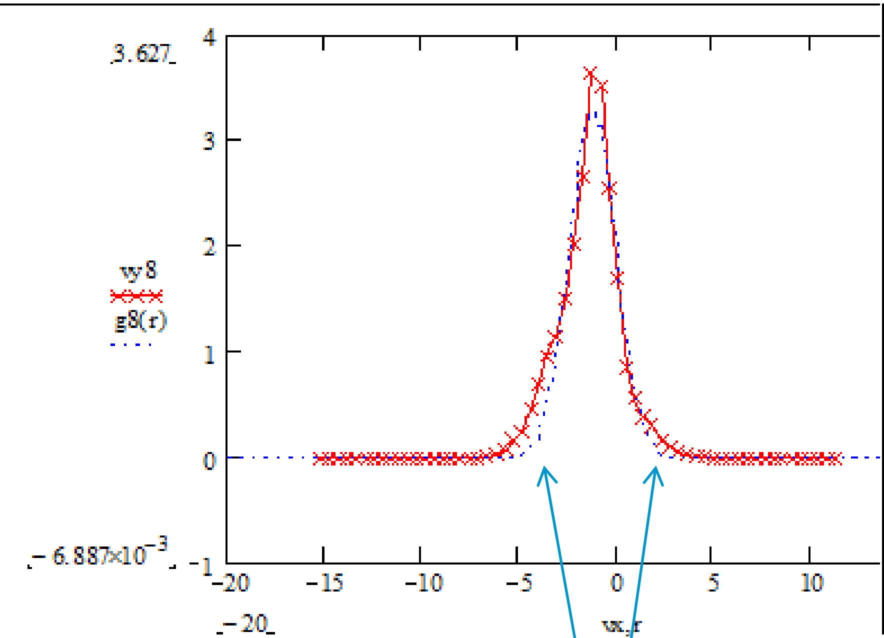
Main beam

Horz
Slit

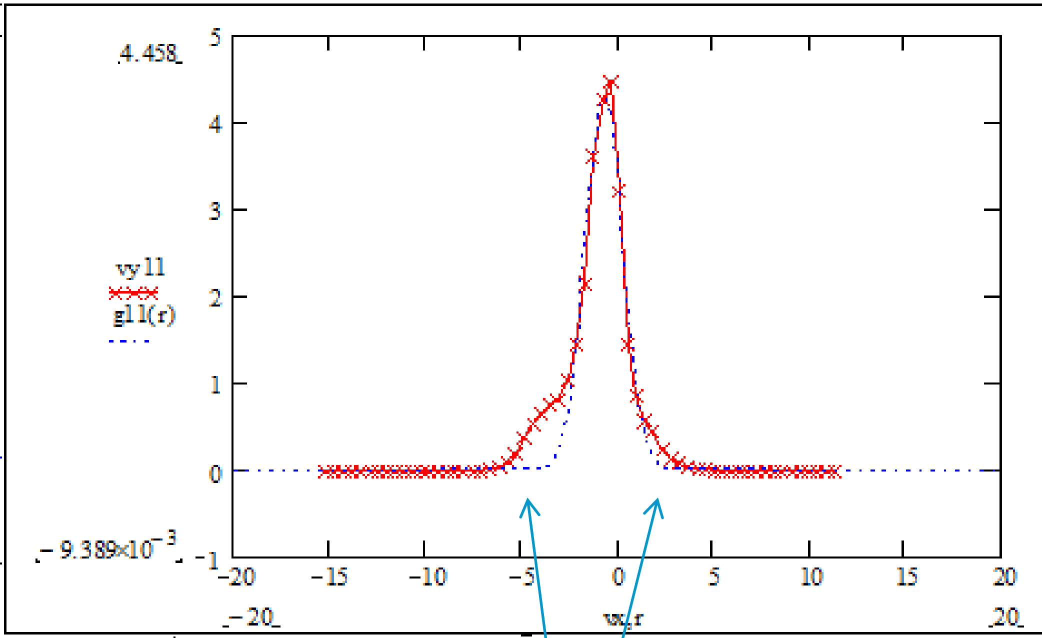


Hor. Shape at Minimum Focus at Wirescanner

Beginning of 100 usec pulse



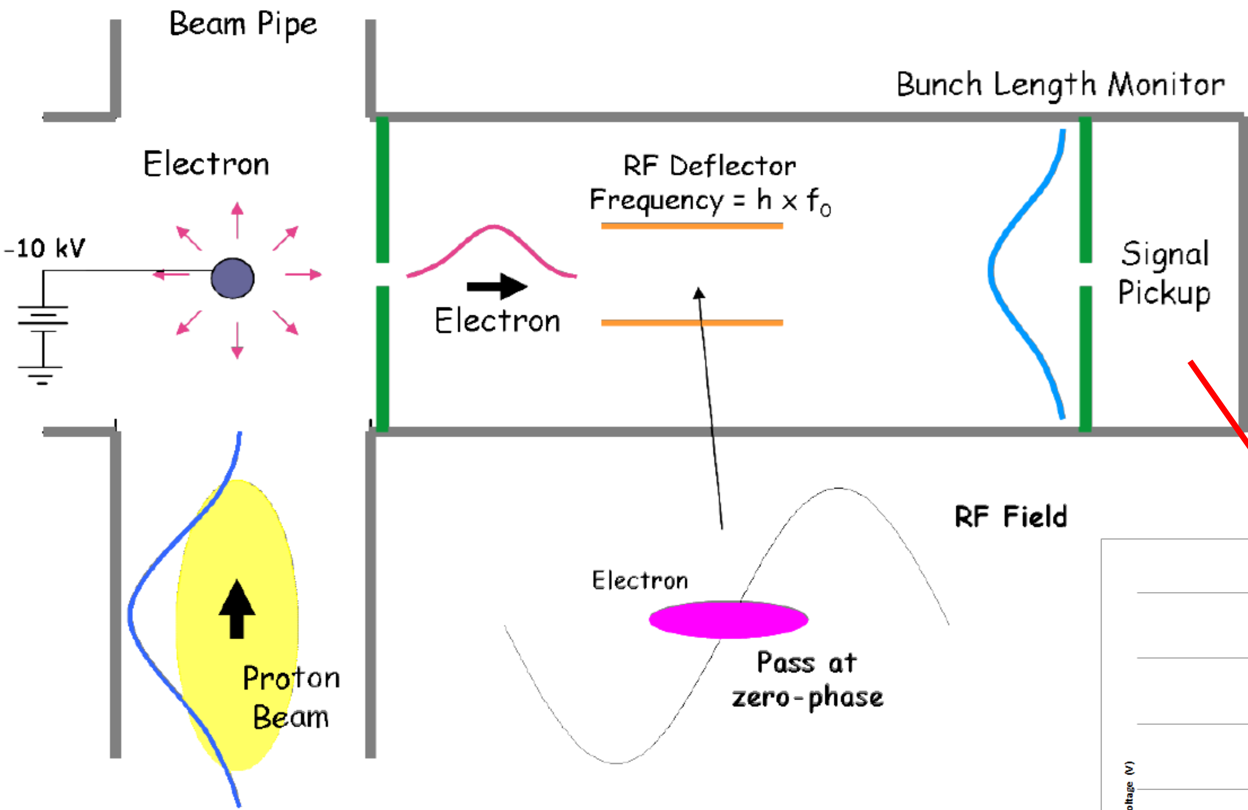
Middle of 100 usec pulse



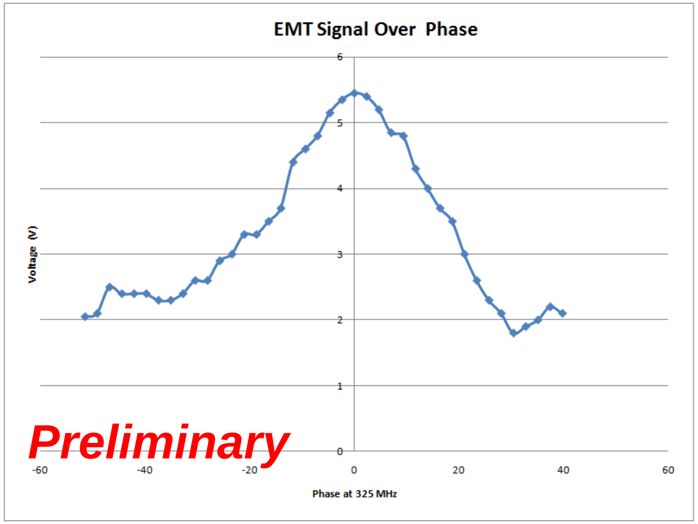
Background?

Background?

Longitudinal Bunch Shape Monitor



FWHM: (prelim)
~ 40^{o} @325 MHz
~ 340 ps

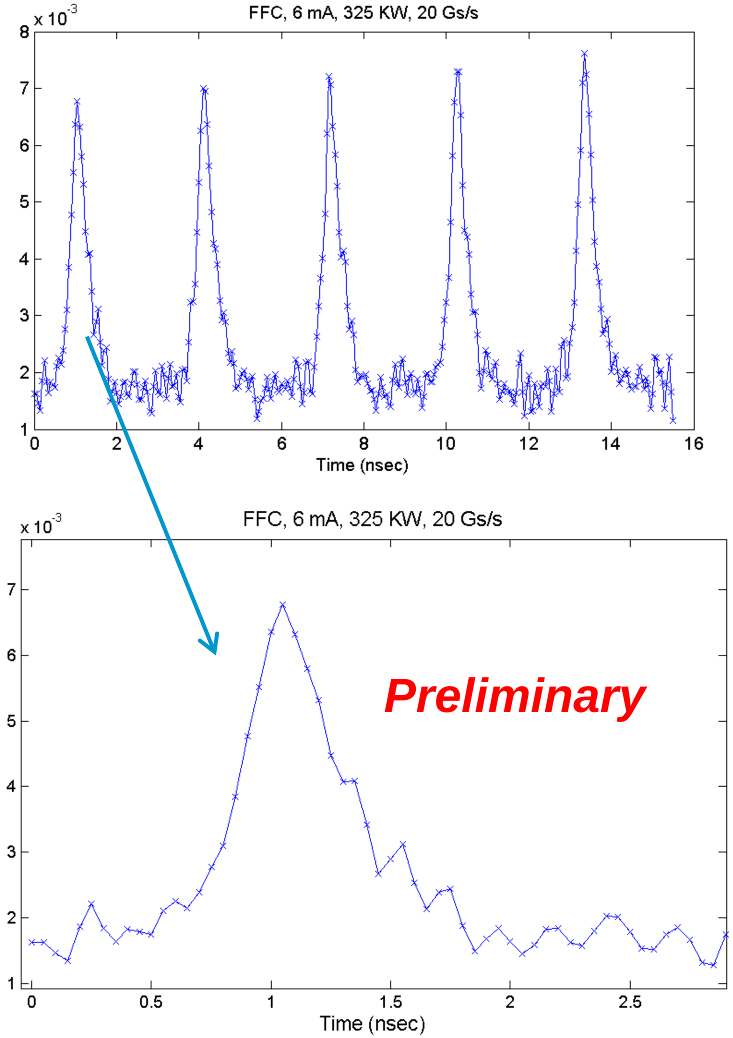


Translate time coordinate into space coordinate using RF deflector cavity

- like a streak camera

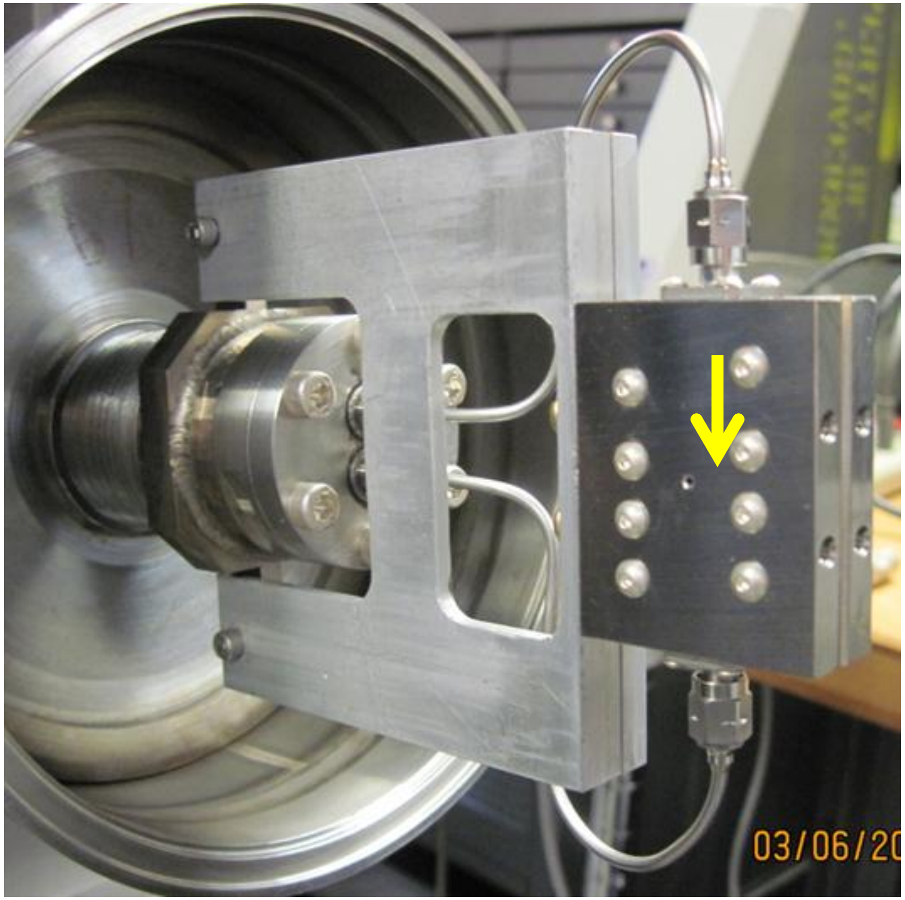
Systematics need to be understood for H- at low energy

Longitudinal Bunch Shape – Fast Faraday Cup (SNS)



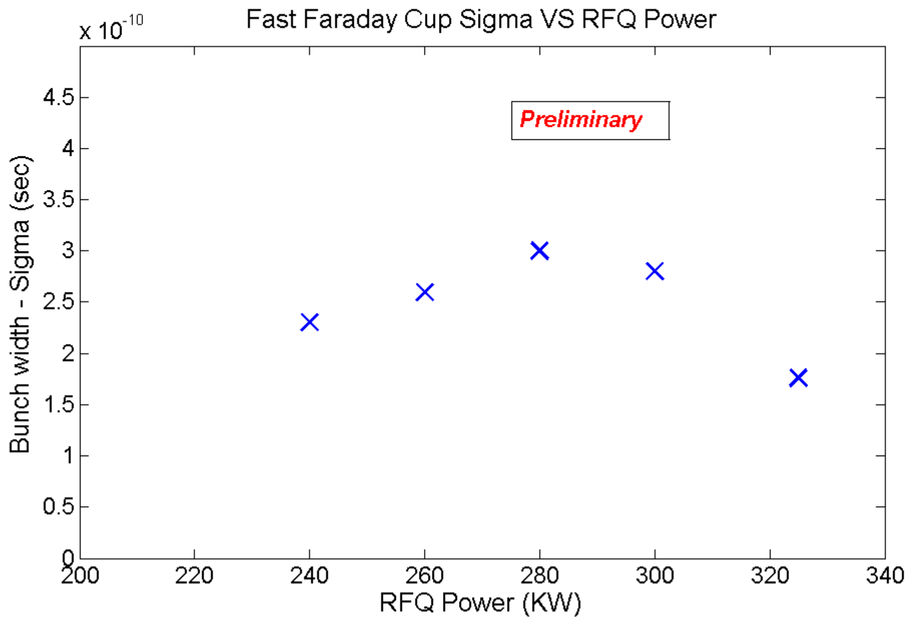
~ 12 GHz bandwidth

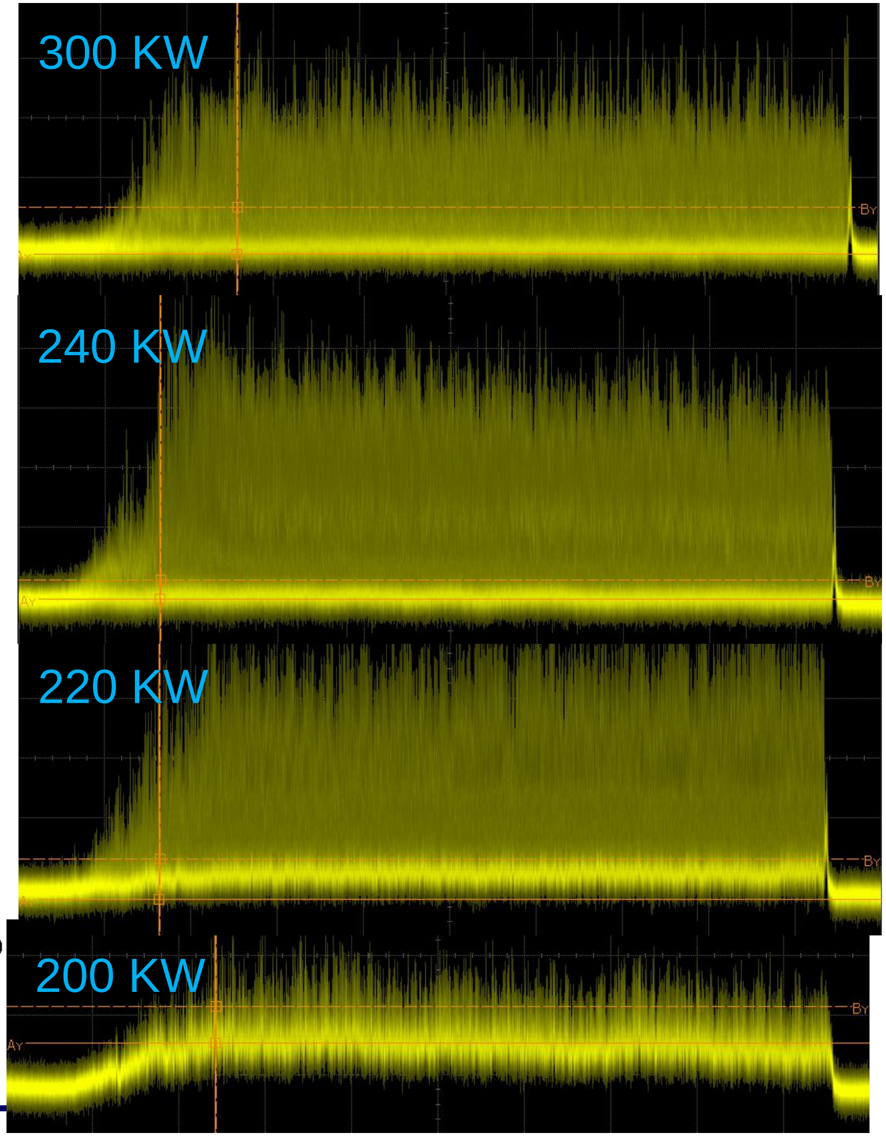
- Some limitations by signal cable



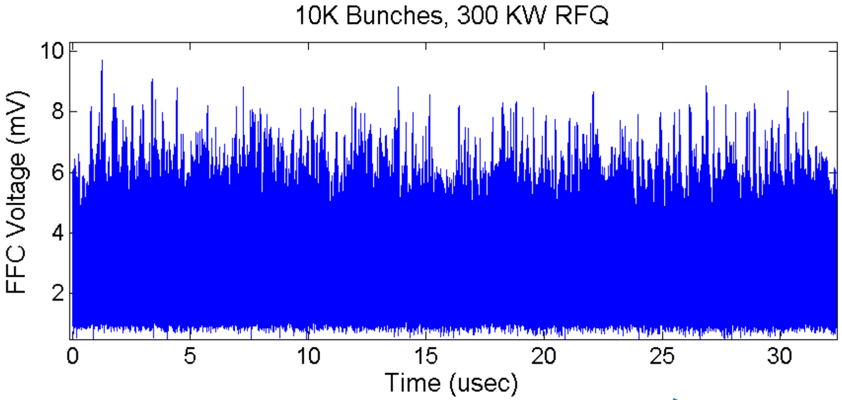
Longitudinal Shape VS RFQ Power

Feed fast Faraday Cup into high bandwidth scope (6 GHz ABW) to measure bunch shape.

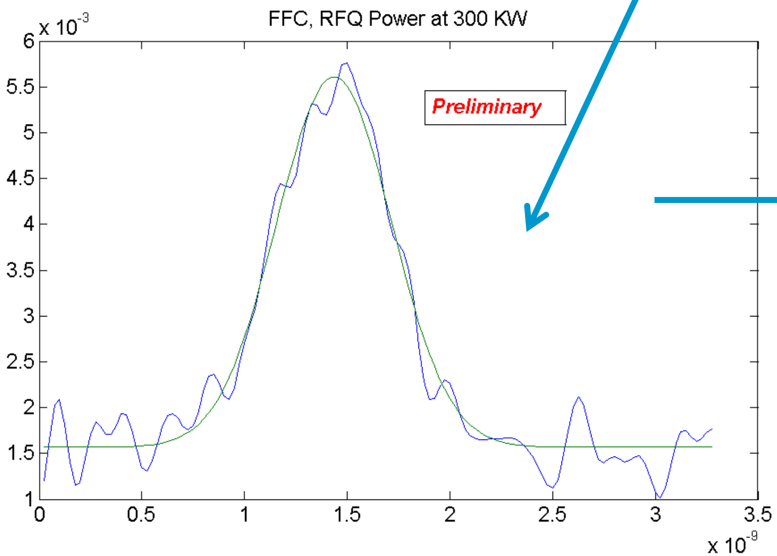


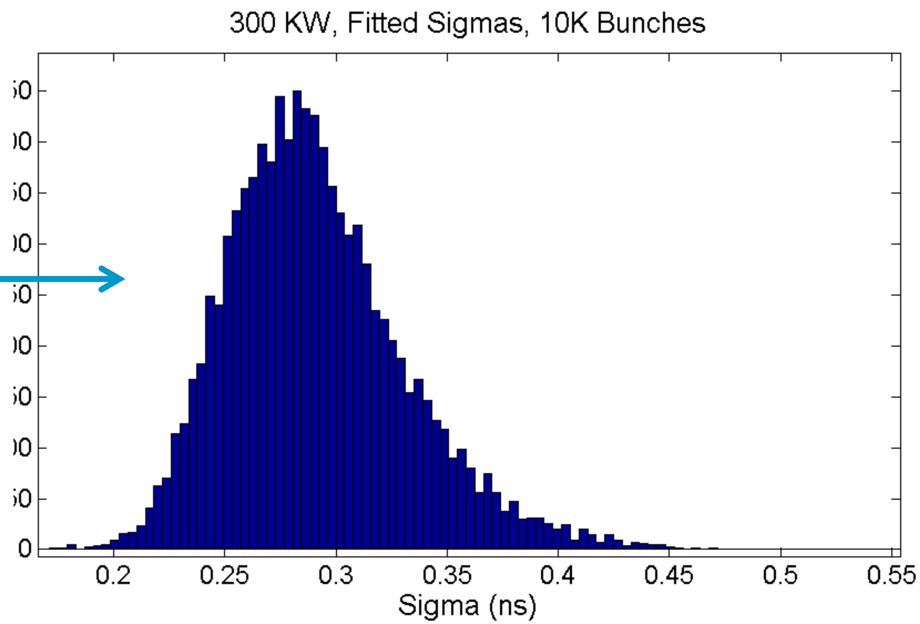


Bunch Shape Along Pulse



Fit individual bunches along pulse
- RFQ at 300 KW
- Histogram → ~ 0.28 ns sigma
- → 33 deg @ 325 MHz
- Need to deconvolve cable





Beam Diagnostic Projects for Project X

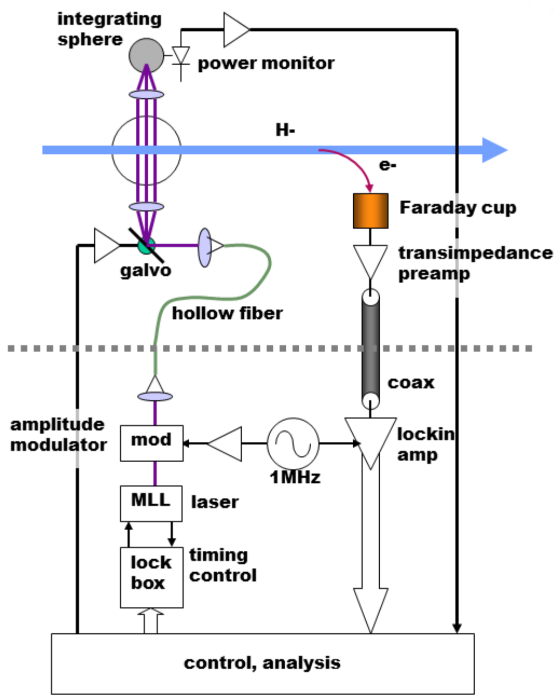
Transverse Diagnostics
- Laser Transverse Profile Monitor*
- Ionization Profile Monitors
- Electron Wire Transverse Profile Monitor – with SNS

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

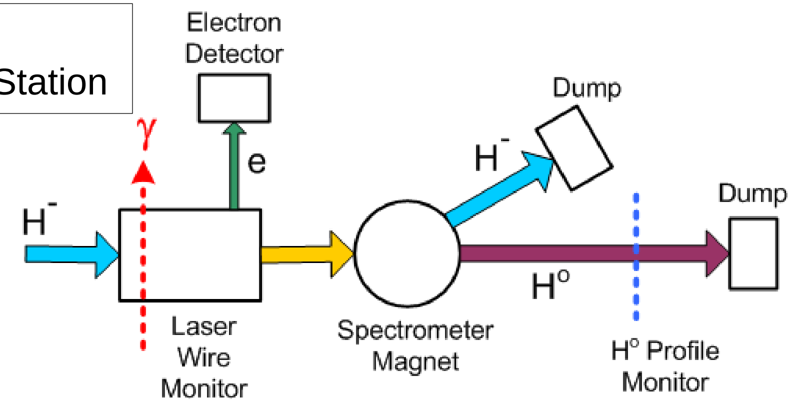
Halo Monitoring – transverse and longitudinal
- Vibrating wire* - *from Bergoz Instrumentation*
- Laser wire* - with LBNL

MEBT Emittance station
- Slit-collector*
- Laser Slit*

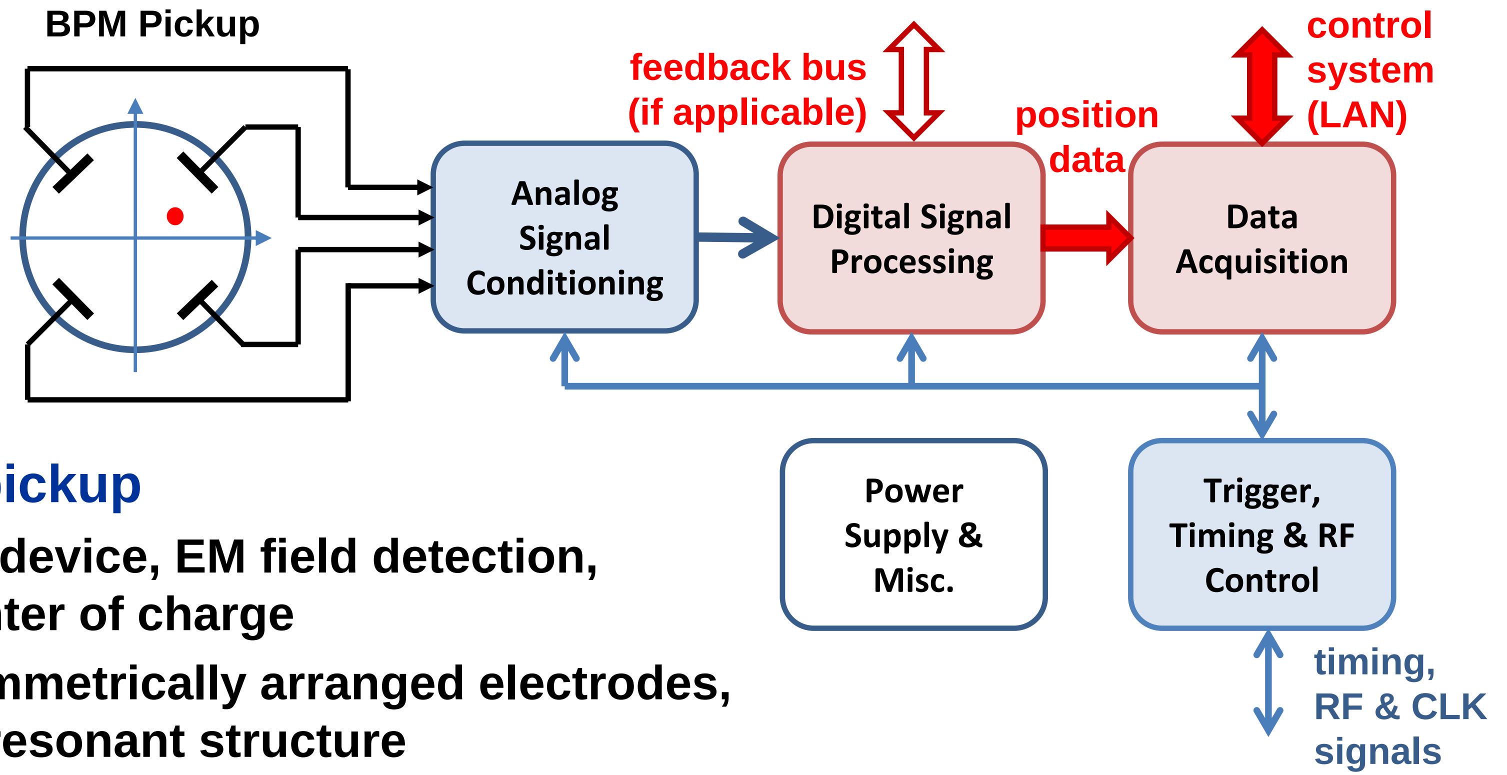
** Project X related instrumentation to be tested at HINS*



Laser Wire Emittance Station

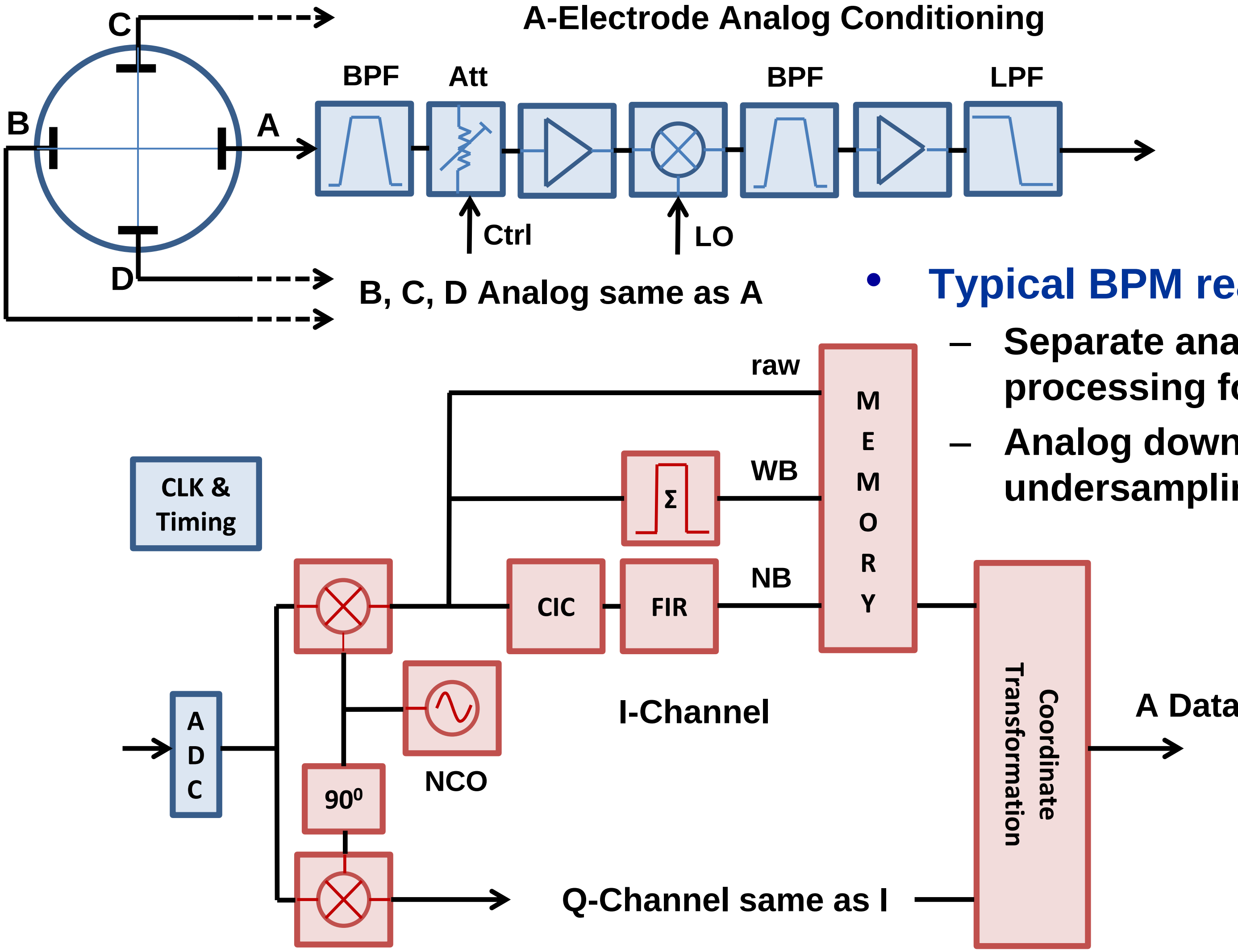


BPM Technology



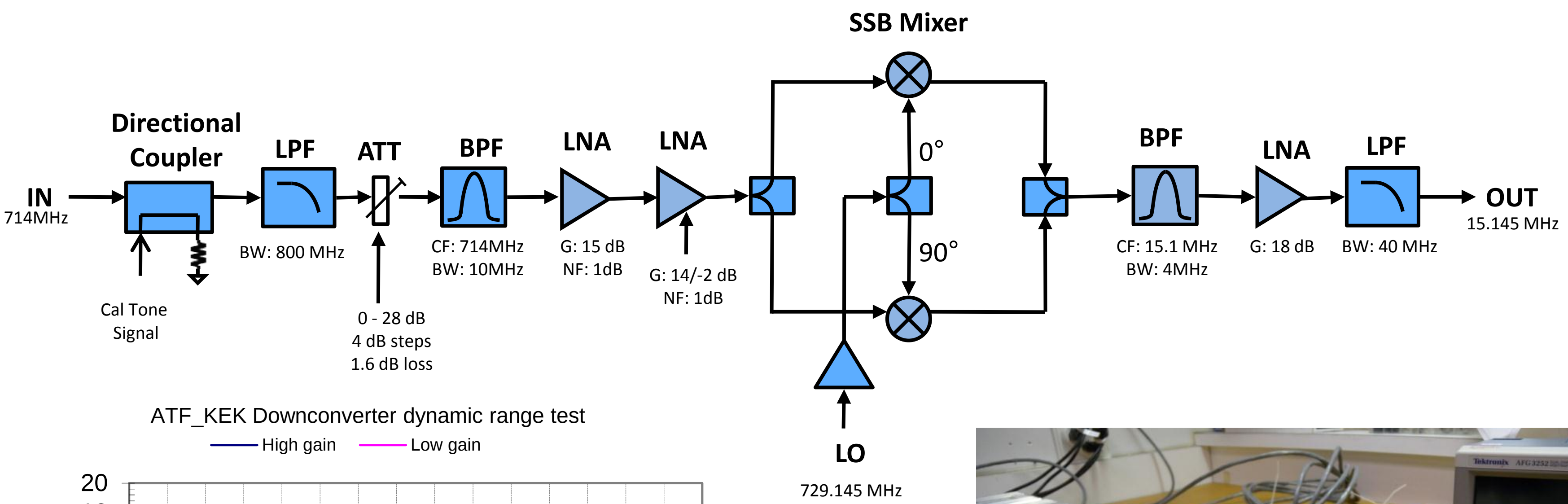
- **BPM pickup**
  - RF device, EM field detection, center of charge
  - Symmetrically arranged electrodes, or resonant structure
- **Read-out electronics**
  - Analog signal conditioning
  - Signal sampling (ADC)
  - Digital signal processing
  - Data acquisition and control system interface
  - Trigger, CLK & timing signals

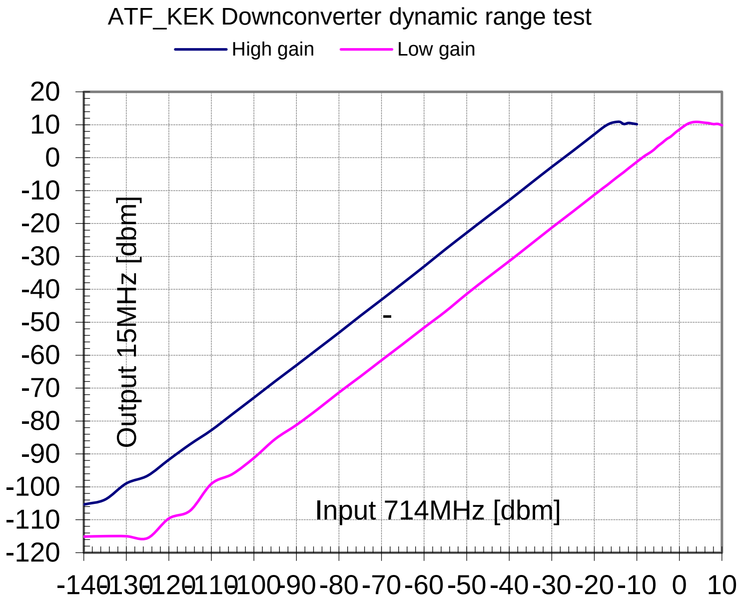
Read-out Electronics



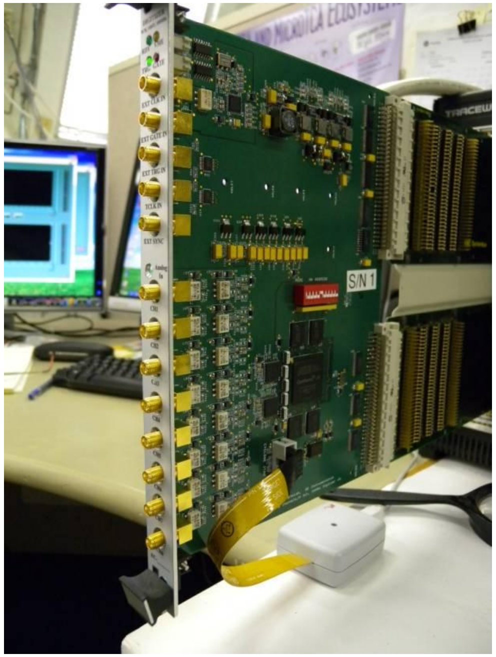
- **Typical BPM read-out scheme**
  - Separate analog signal processing for the channels
  - Analog down-converter if undersampling is not applicable.

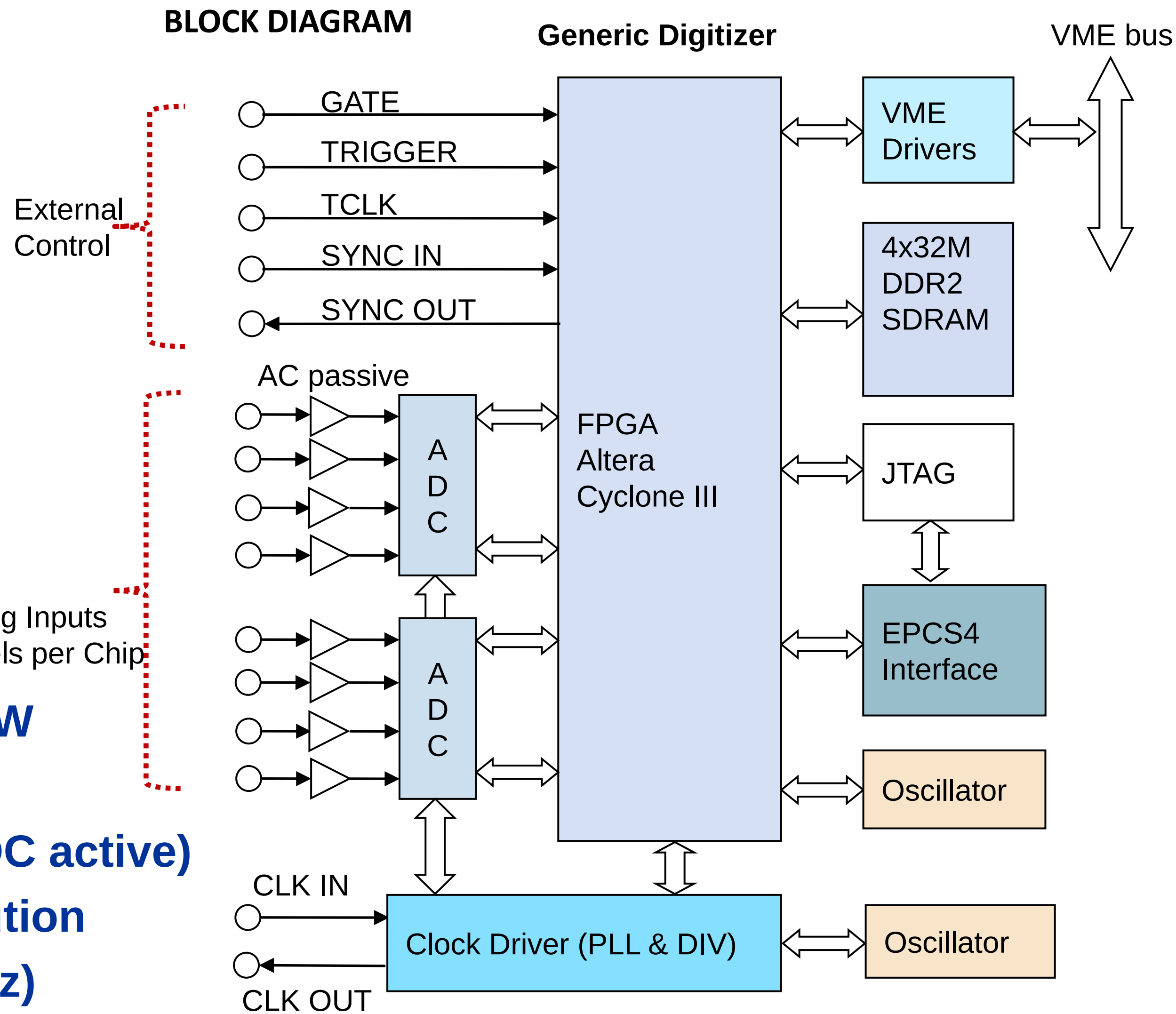
BPM Read-out Hardware: Analog





BPM Read-out Hardware: Digital

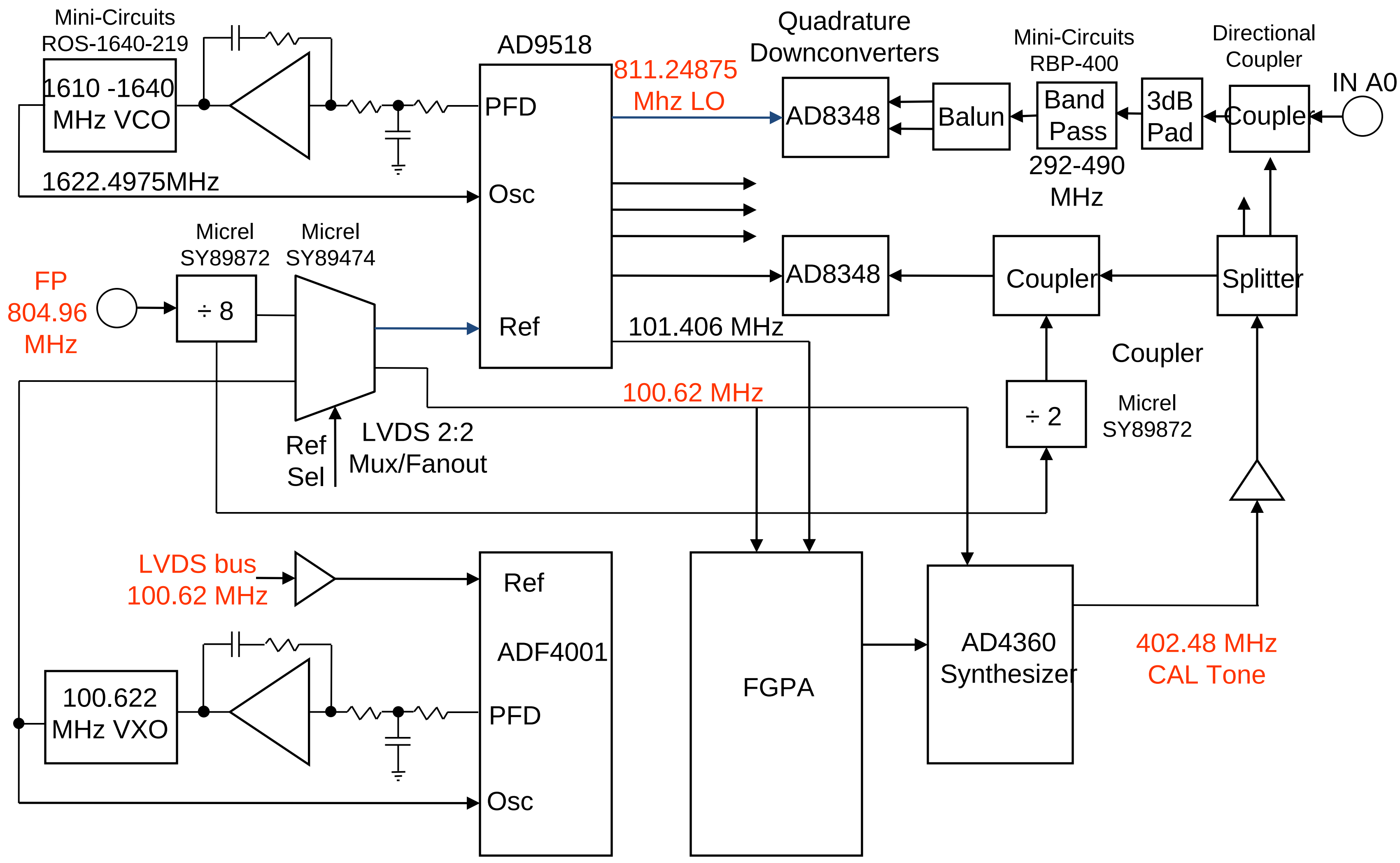




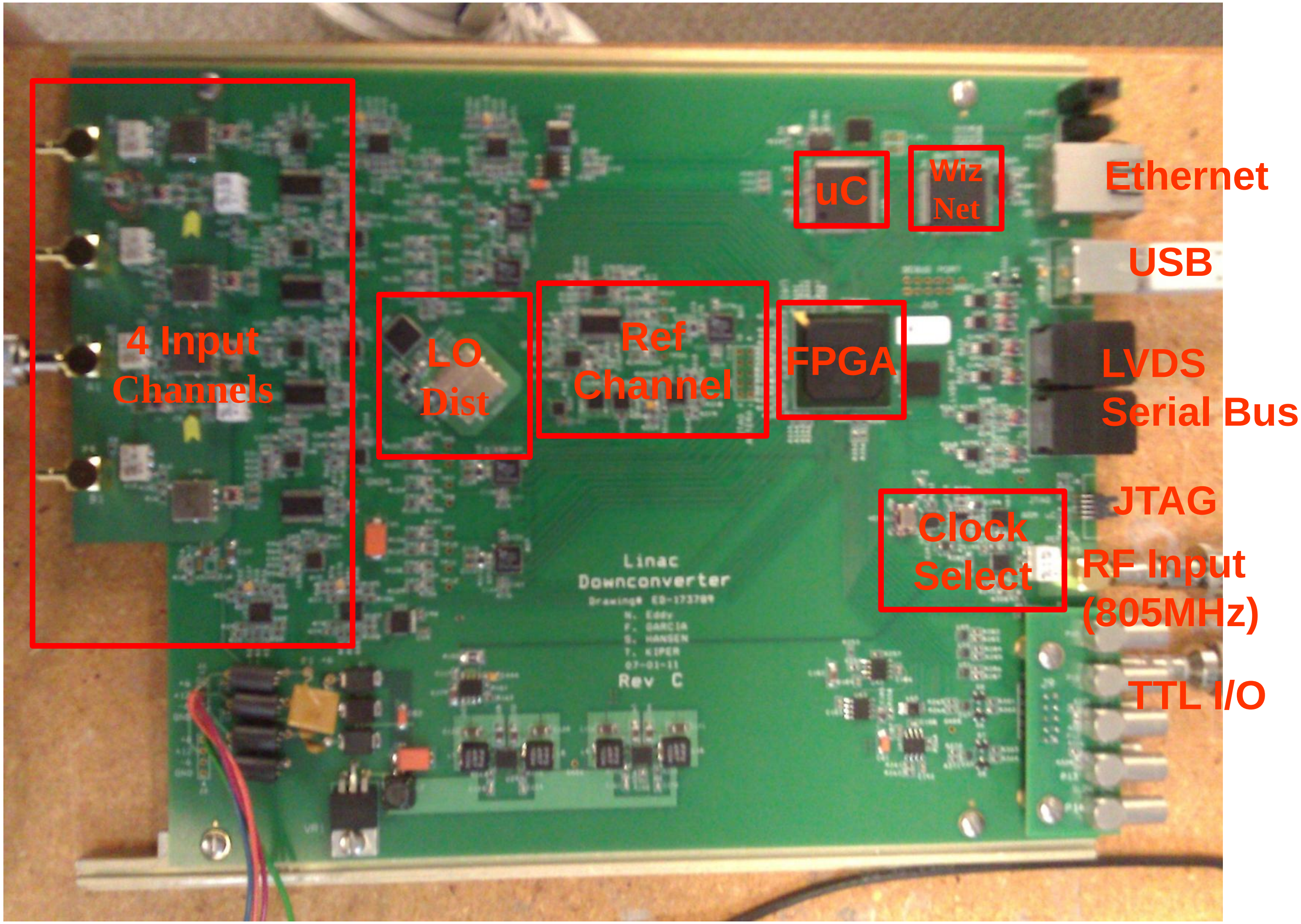
- **125 MSPS, 500 MHz BW**
- **4-ch serial ADC chips**
- **8-ch, AC passive (or DC active)**
- **PLL/VCO CLK distribution**
- **SNR > 72 dB (@50 MHz)**

Linac BPM Electronics

Base band is set to 22.5° per ADC sample at 50.31Msps



NIM BPM Hardware



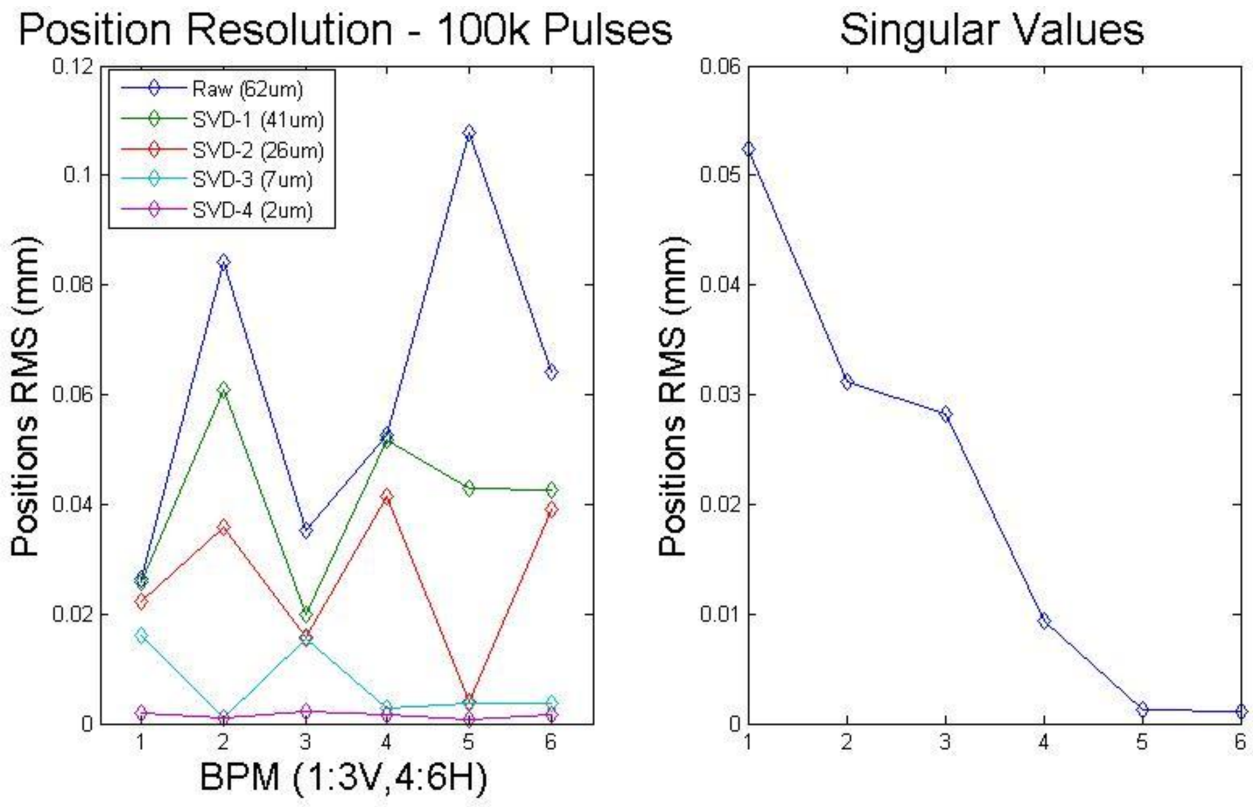
Linac BPM Read-out Electronics

- Analog Quadrature Downcoverter – AD8348
  - Provide from 0-40db variable gain
- ADC – LTC2265
  - 12 bits @ 805MHz/16 = 50.3MHz
- FPGA – Altera Cyclone III
  - Can provide all needed DSP
- uController – Stelaris LM3S5B
  - 32 bit ARM processor, operating at 80MHz
- Ethernet – Wiznet W5300
  - 16 bit providing ~4MB/s BW
- Custom LVDS Serial Data Bus
  - 25MHz providing ~2.5MB/s data transfer
  - Can be sped up if needed
- Fully configurable within the FPGA
  - Linac Clock Event
  - External Trigger (TTL)
  - Delay & Acquisition Window
  - Beam Search – *Implemented and working*
- Provide average Position, Intensity, & Relative Phase over each beam pulse for every BPM @15Hz
  - Beam pulse varies from few µsec up to ~40usec
- Provide "waveform" data for select BPMs @15Hz
  - Can select minimum of 1 BPM per crate
  - Average & decimate data rate by 16 to ~3MHz
    - IF frequency out of the Quad DC (remove distortions)

Timing Notes

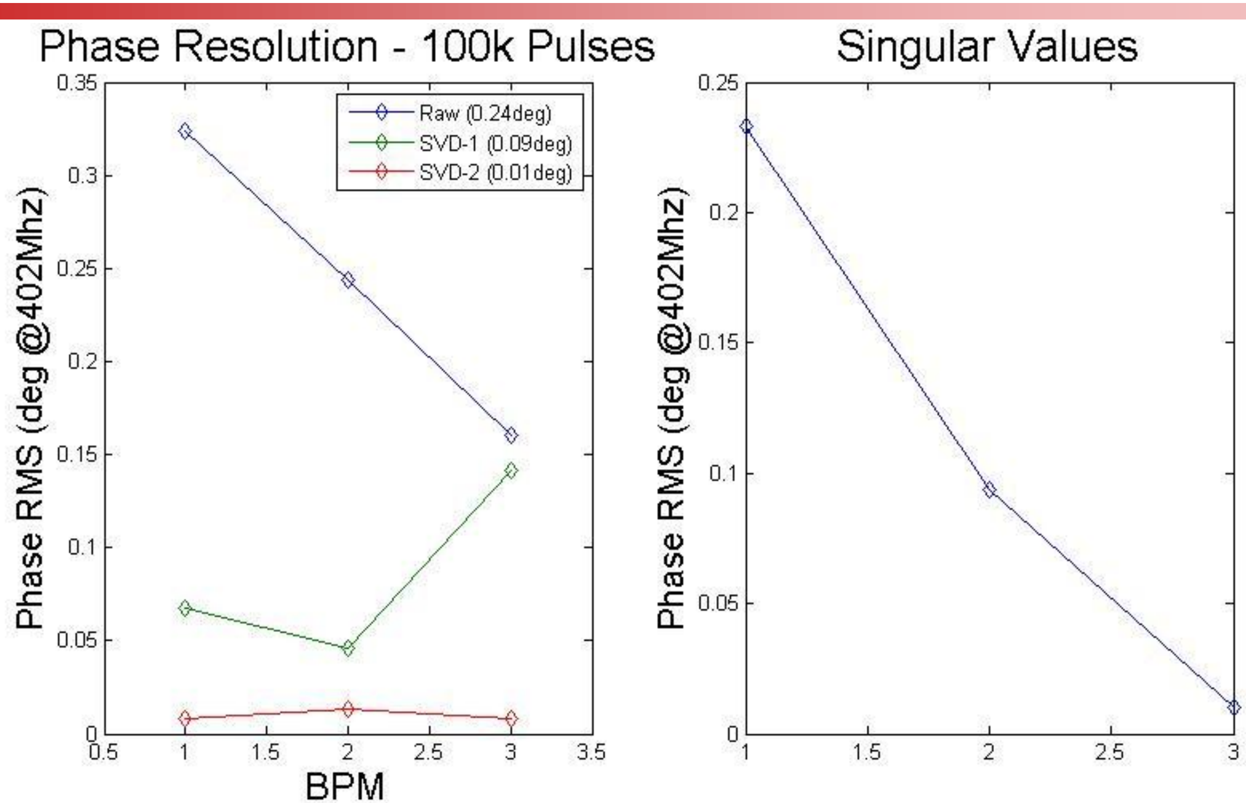
- All signals locked to Ref = 805Mhz
- ADC Clock = Ref/16
- IF = ADC Clock/16 = Ref/256
  - Pi/8 phase advance per adc sample
- Eff LO = Ref/2 + IF
- LO to Quad DC = 2*Eff LO
  - Generates I,Q on successive edges of LO input
- Cal = Ref/2

Prototypes: Position Resolution



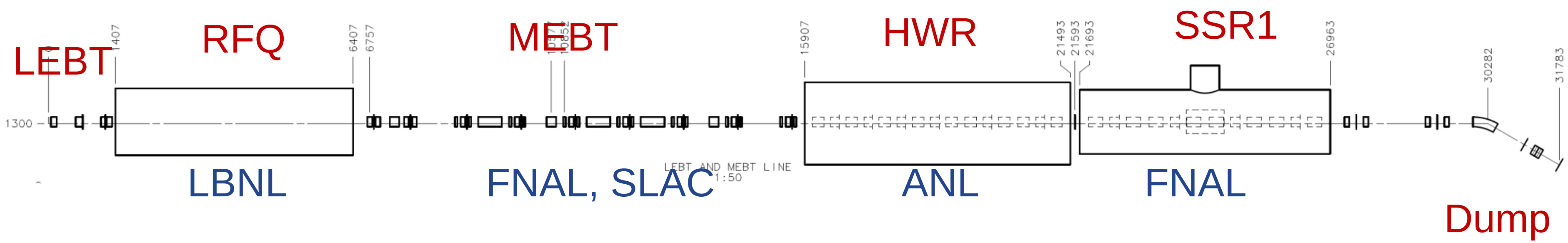
- SVD with only 6 position measurements (3H,3V)
  - Ideally expect up to 3 modes to correlate with initial trajectory & energy
  - With only 6 pickups, real noise sneaks into modes
- Conservative estimate resolution < 40um

Prototypes: Phase Resolution



- **Measured on 2nd Harmonic at 402Mhz**
- **Expect correlations from Beam & LO**
  - **SVD suffers from only 3 pickups…**
- **Estimate resolution < 0.1 degree at 402MHz**

PXIE Test Facility



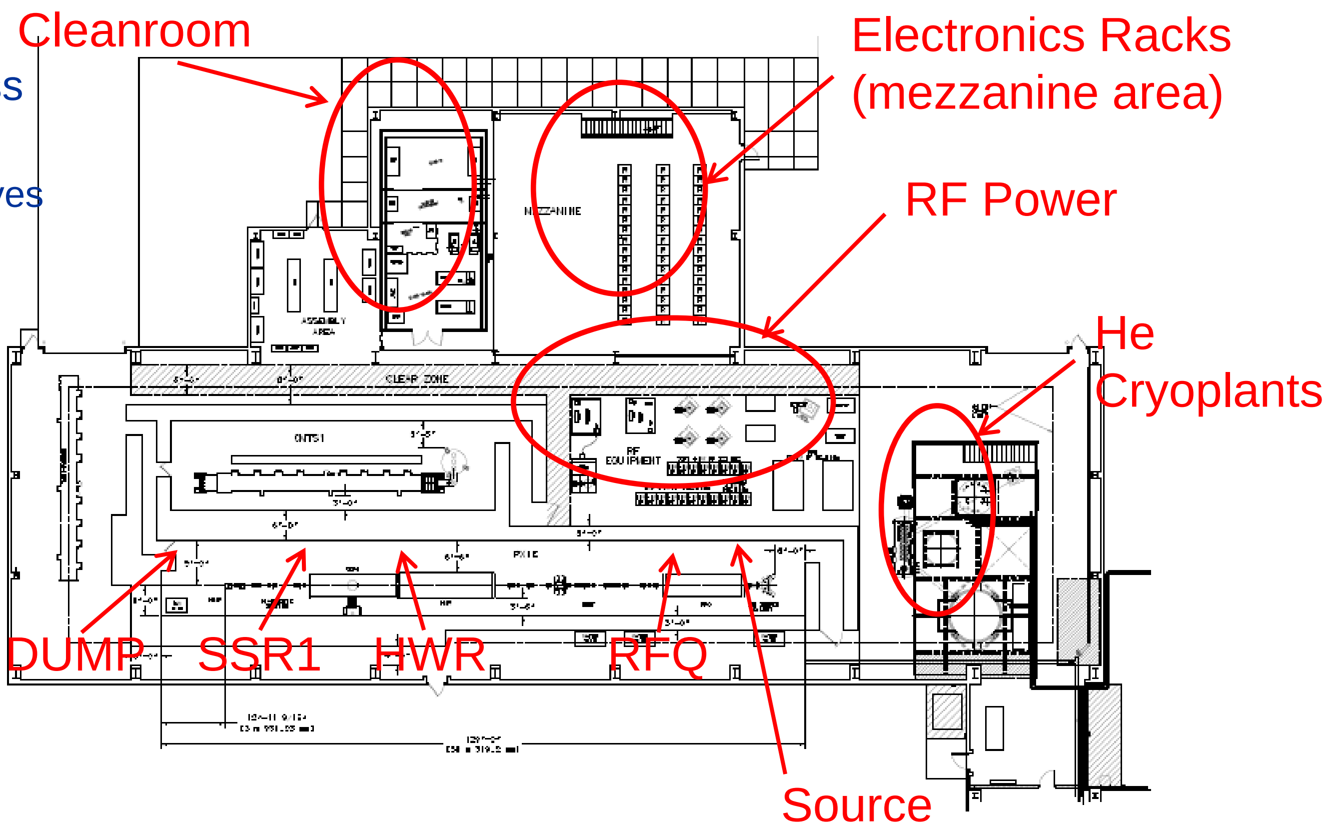
- **CW H- source delivering 5 mA at 30 keV**
- **LEBT with beam pre-chopping**
- **MEBT with integrated broadband chopper and beam absorbers, capable to generate arbitrary bunch patters at 162.5 MHz, while disposing 4 mA average beam current**
- **Low beta SRF cryomodules capable of accelerating 1 mA to 15 MeV**
- **Beam dump capable of accommodating 1 mA at 15 MeV (15 kW) for extended operation periods.**
- **Associated beam diagnostics, utilities and shielding.**

PXIE at CMTF

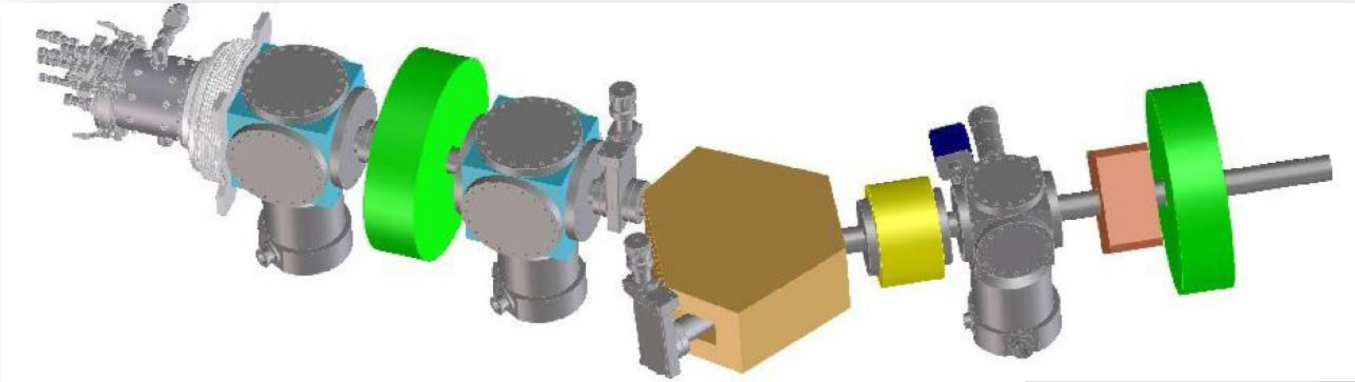
Layout is iterative process

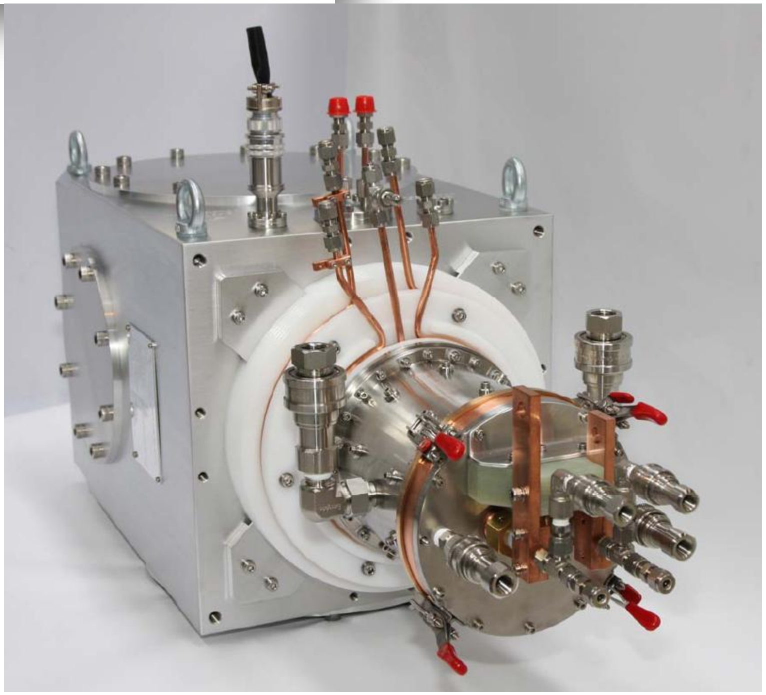
Identify:

- Sizes of components/caves
- Special requirements
- Safety considerations
  - Life and Rad
- Optimize placement
  - Cable length
  - Ease of access
  - Distance to cryo
  - Min. penetrations
- Iterate as required



PXIE Ion Source & LEBT





- **Provides 30-keV beam transport from the Ion Source to the RFQ**
  - **chopper**
  - **diagnostics**

PXIE CW 162.5 MHz RFQ

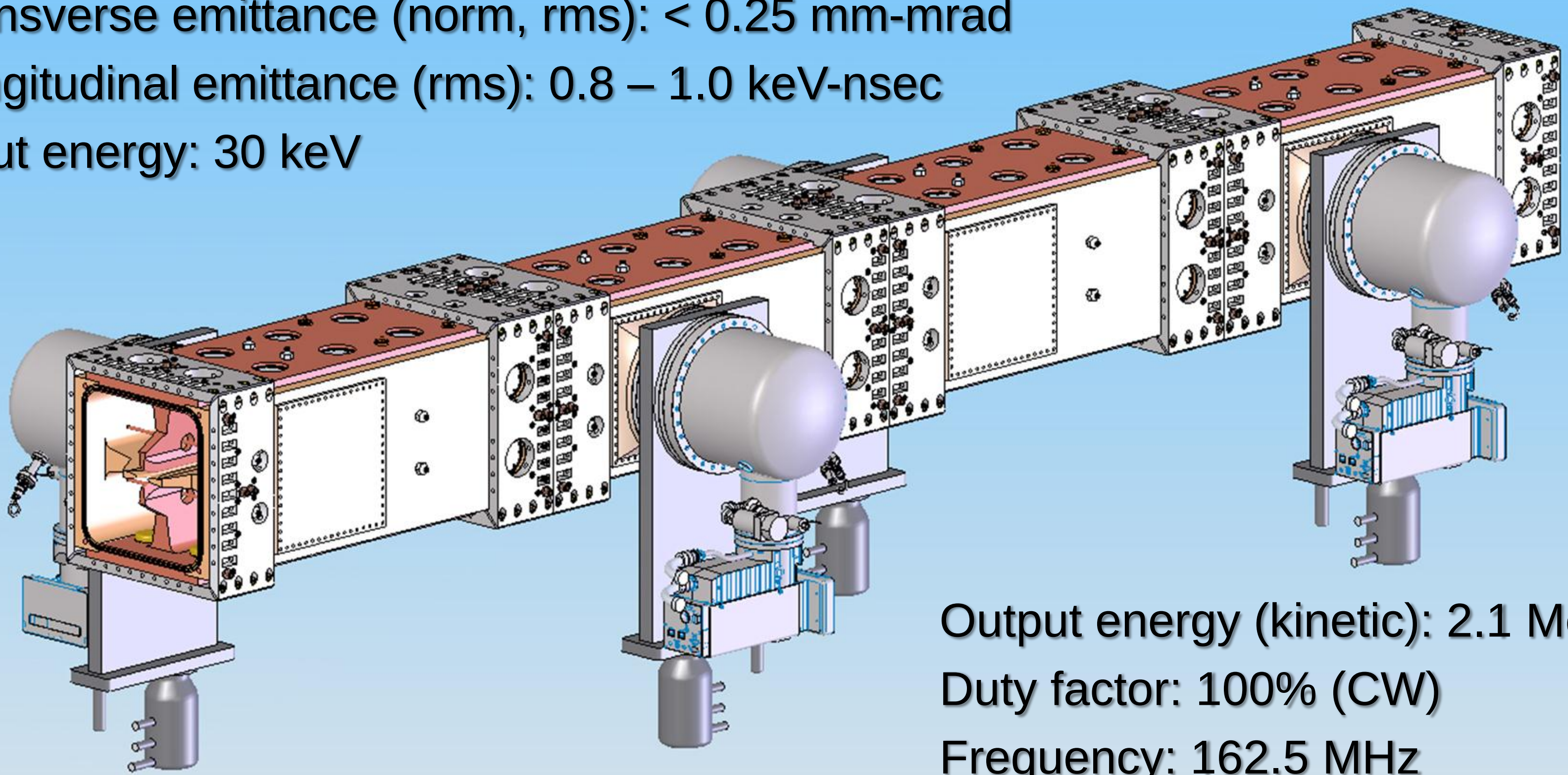
Ion type: H-

Beam current: 5 mA (nominal); 1 – 10 mA

Transverse emittance (norm, rms): < 0.25 mm-mrad

Longitudinal emittance (rms): 0.8 – 1.0 keV-nsec

Input energy: 30 keV



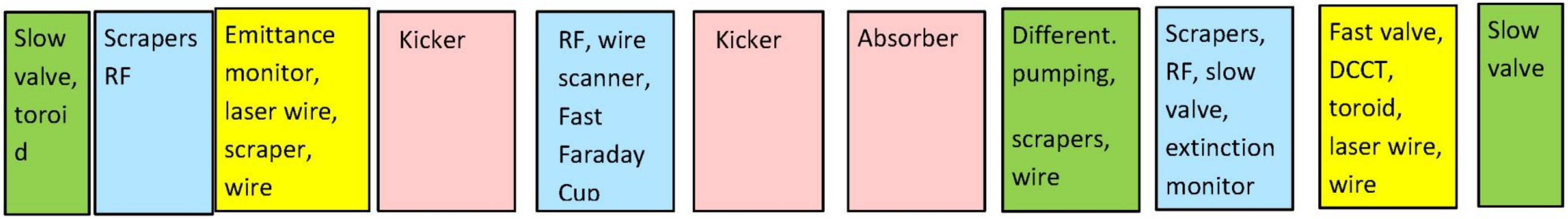
Output energy (kinetic): 2.1 MeV

Duty factor: 100% (CW)

Frequency: 162.5 MHz

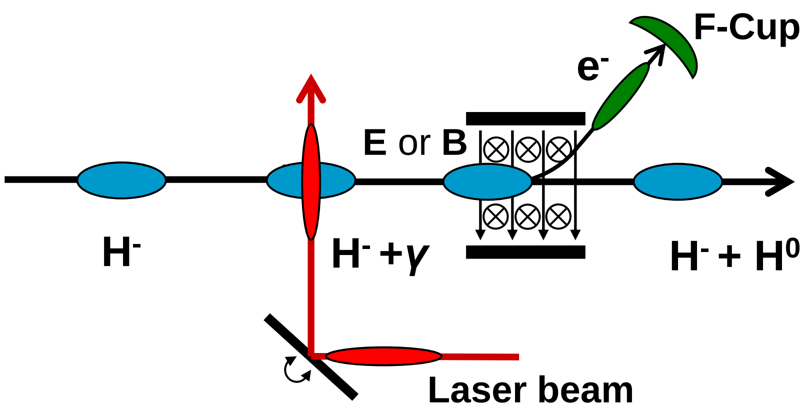
Length: ~4.4 m

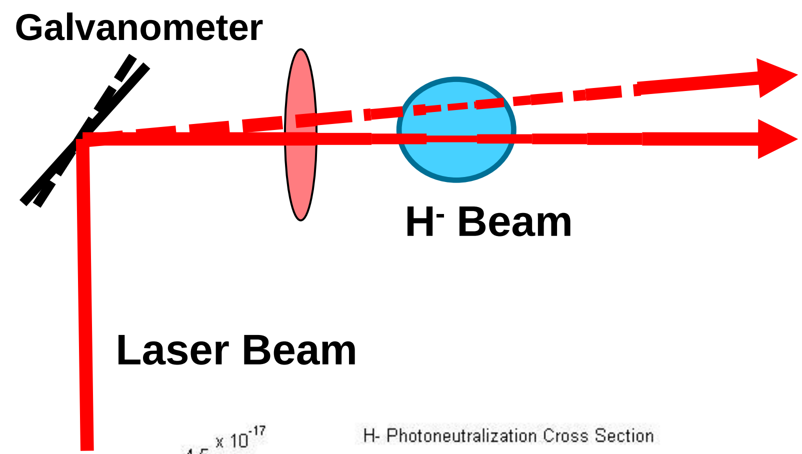
PXIE MEBT Beam Diagnostics



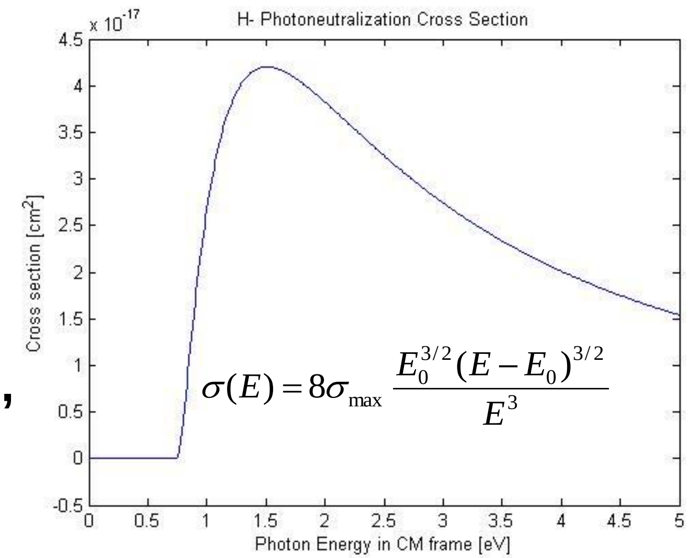
- **BPMs in each triplet or doublet (3D positions)**
  - **Draft of specifications**
- **A set of beam diagnostics to characterize the RFQ beam**
  - **Toroid, emittance monitor, laser wire(s), wire scanner, fast F-cup**
  - **Scarpers a halo diagnostics**
- **A set of diagnostics to characterize the beam towards the HWR**
  - **Toroid, DCCT(?), laser wire(s), wire scanner, extinction monitor**
  - **Scrapers as halo diagnostics**

Laser Wire for H- Beams

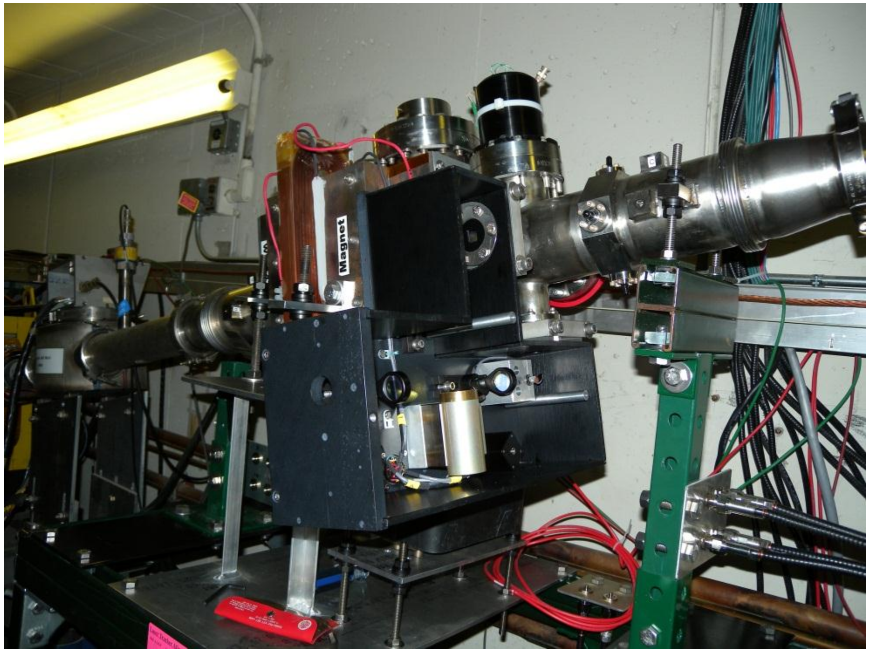


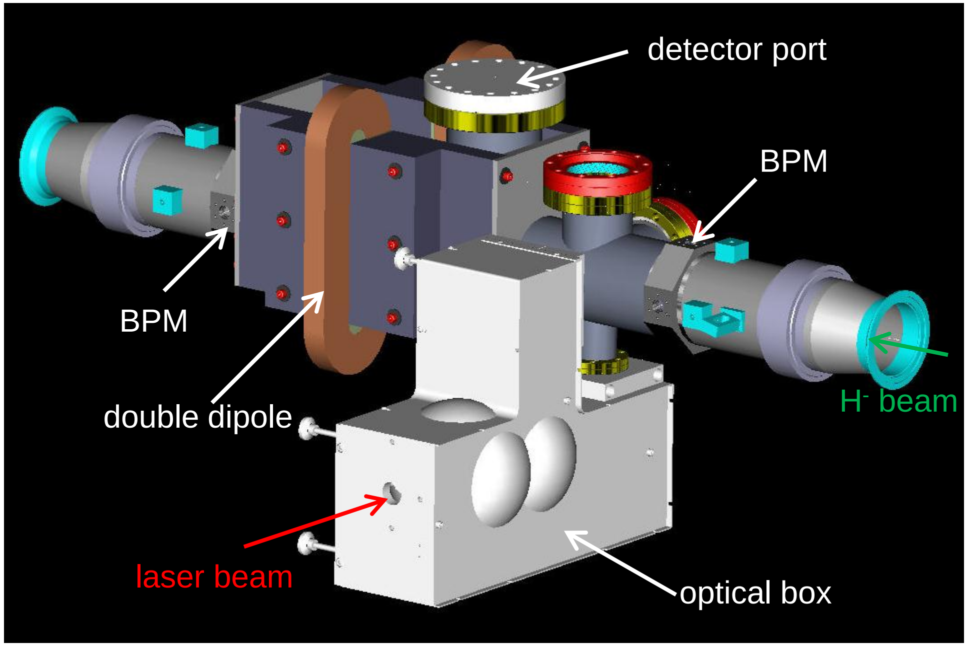


- **H- neutralization by photo-detachment**
  - **Cross-section $\sigma_{max} \approx 4.2 \times 10^{-17} cm^2$**
  - **Electron binding $E_0 = 0.7543$ eV**
- **Typical HINS / PX MEBT parameters**
  - **E_{beam} = 2.5 MeV, Nd:YAG laser 1064 nm, 90^0 angle, -> $\sigma \approx 3.66 \times 10^{-17}$ cm^2**
  - **Requires laser energy ~ 10-30 mJ**

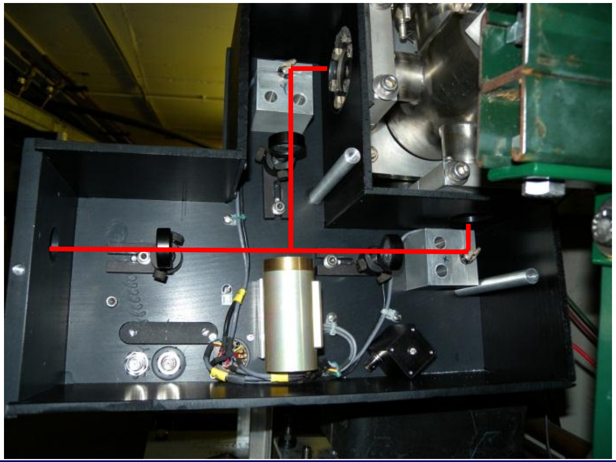


Laser Wire (400 MeV H^-)



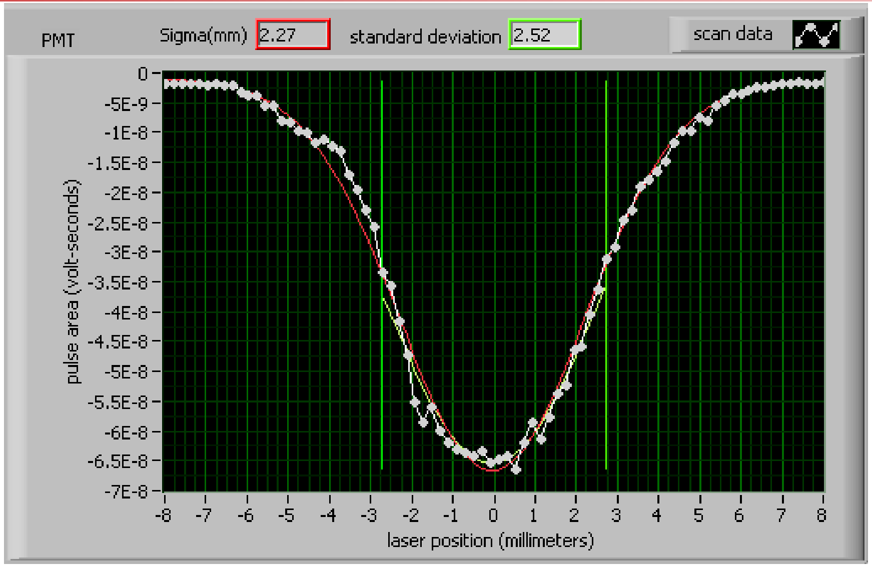


- **Laser Profile Monitor details**
  - Q-switch laser
  - Laser energy: 50 mJoule
  - Wavelength: 1064 nm
  - Pulse length: 9 nsec
  - Fast rotating mirrors (±4^0 / 100 µsec)
  - e^- detector: scintillator & PMT

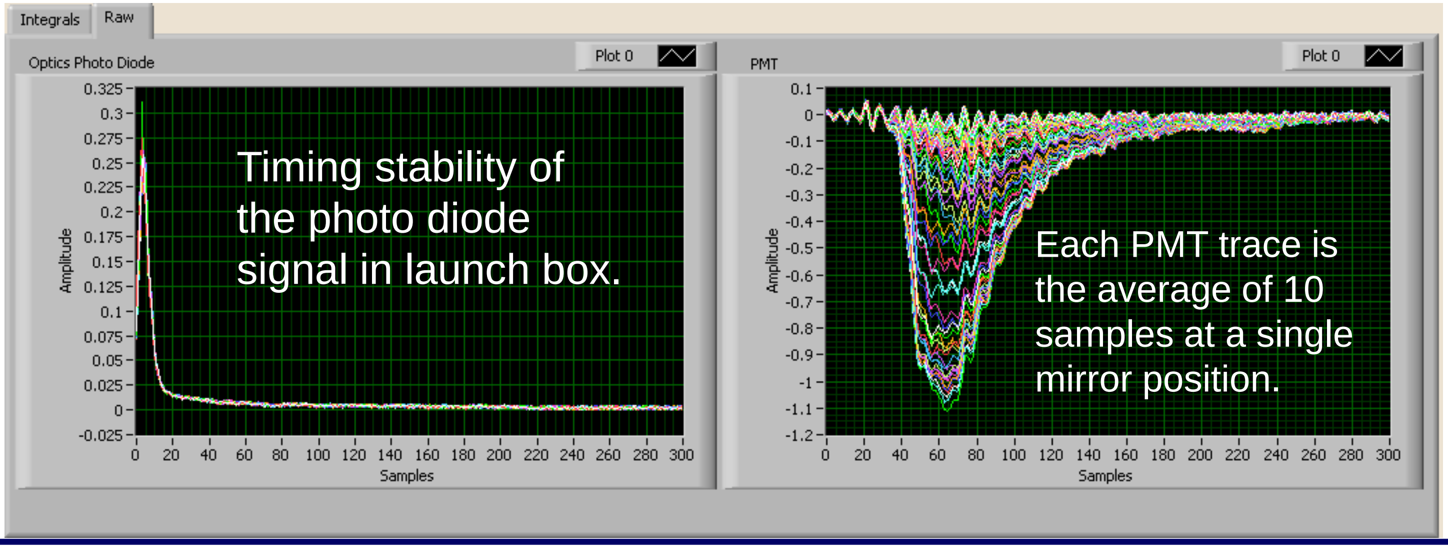


Laser Wire: First Results

Profile created from 10 Laser pulses at each of 80 mirror positions across the beam.
System acquires data at 15Hz, Linac Cycle rate.



Profile created by integrating the area of the raw PMT Signal

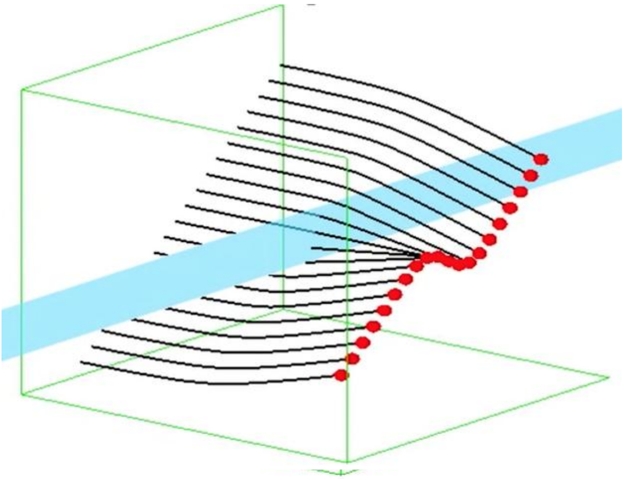


Electron-Beam Scanner

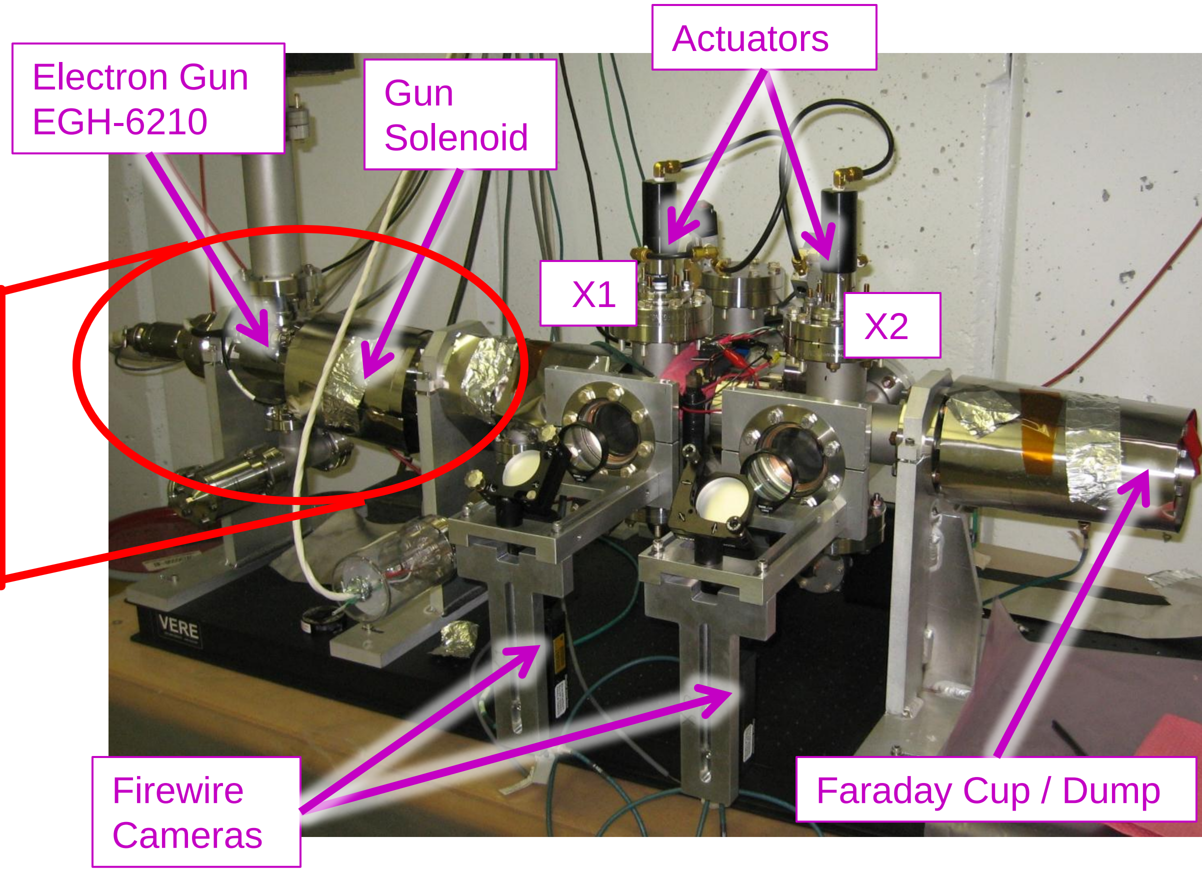
- **Non-intrusive profile measurement of high intensity p-beams**
  - **SNS / Fermilab R&D collaboration for Project X, beams in MI**
  - **Evaluate measurement techniques for available electron gun**
  - **Setup simulation**
- **Look at the deflected projection of a tilted sheet of electrons due to the proton beam charge**
  - **Neglect magnetic field (small displacement of projection)**
  - **Assume path of electrons is straight (they are almost straight)**
  - **Assume net electron energy change is zero (if symmetric)**
  - **Proton bunch length >> electron scan**

$$\rightarrow \quad \frac{d\theta_0(x)}{dx} = \int_L \frac{e}{mv^2} \frac{\delta(x,y)}{\varepsilon_0} dy$$

i.e. take the derivative to get the profile



E-Beam Scanner Test Setup at NWA



Gun Parameters

Energy: 1 – 60 keV

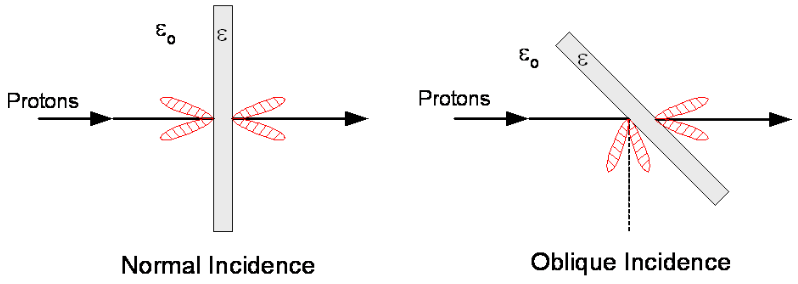
Current: 10 μA – 6 mA

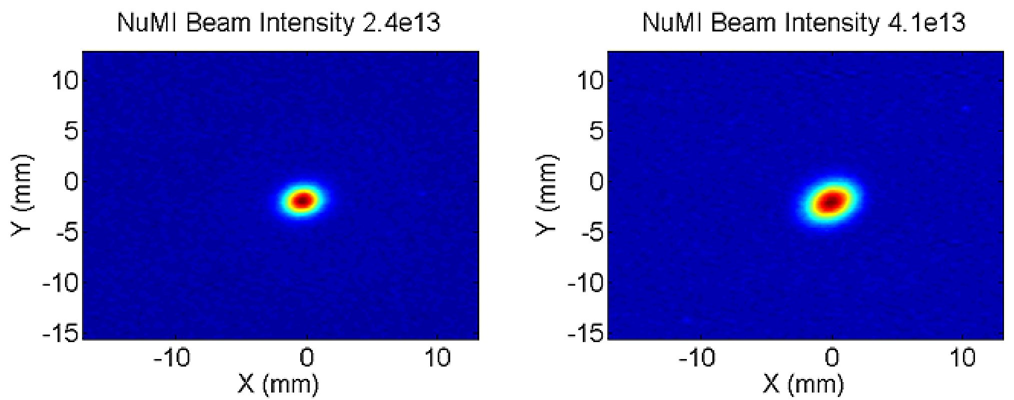
Spot size: 50 μm – 10 mm

Gateable: 2 μs – DC; 5 kHz max rate

Thank You!

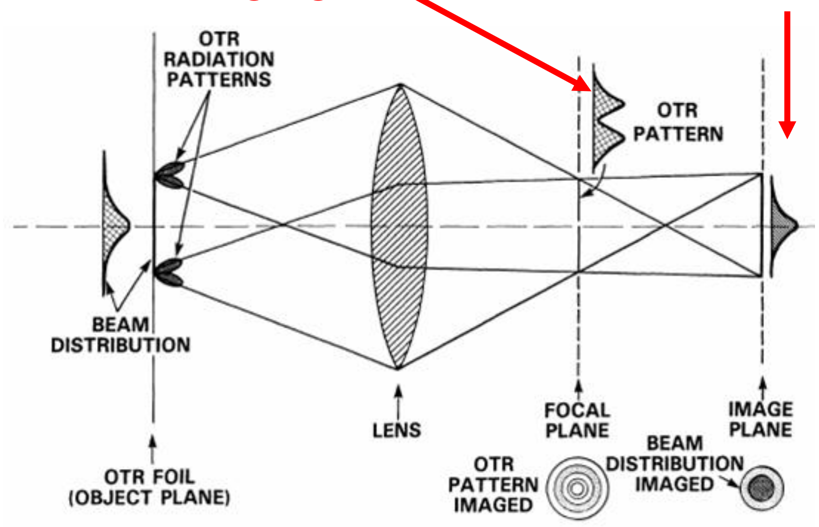
OTR with Protons

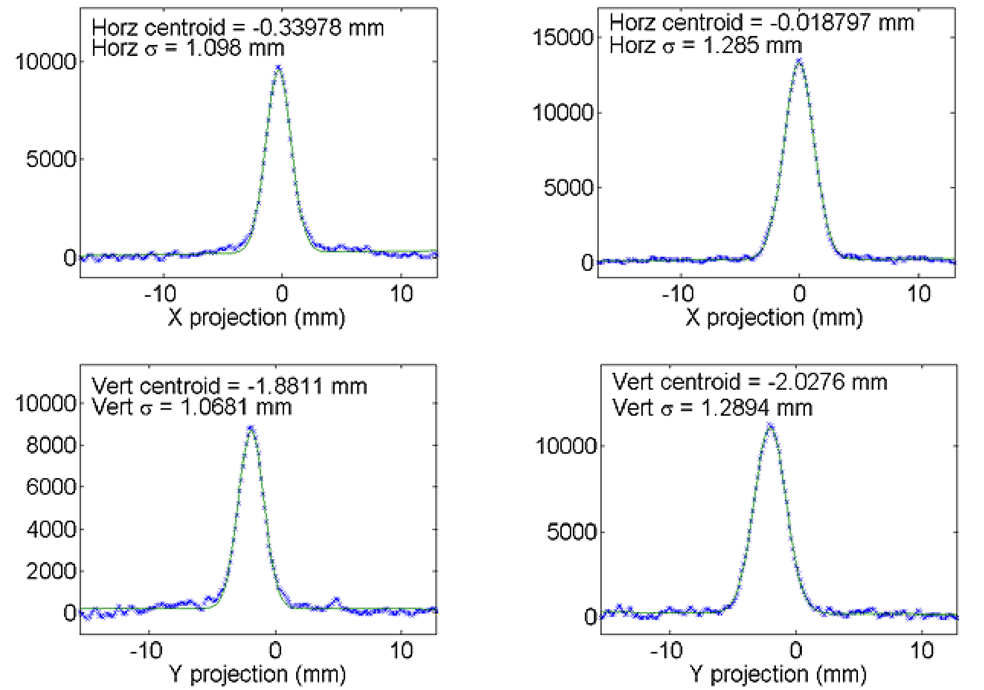




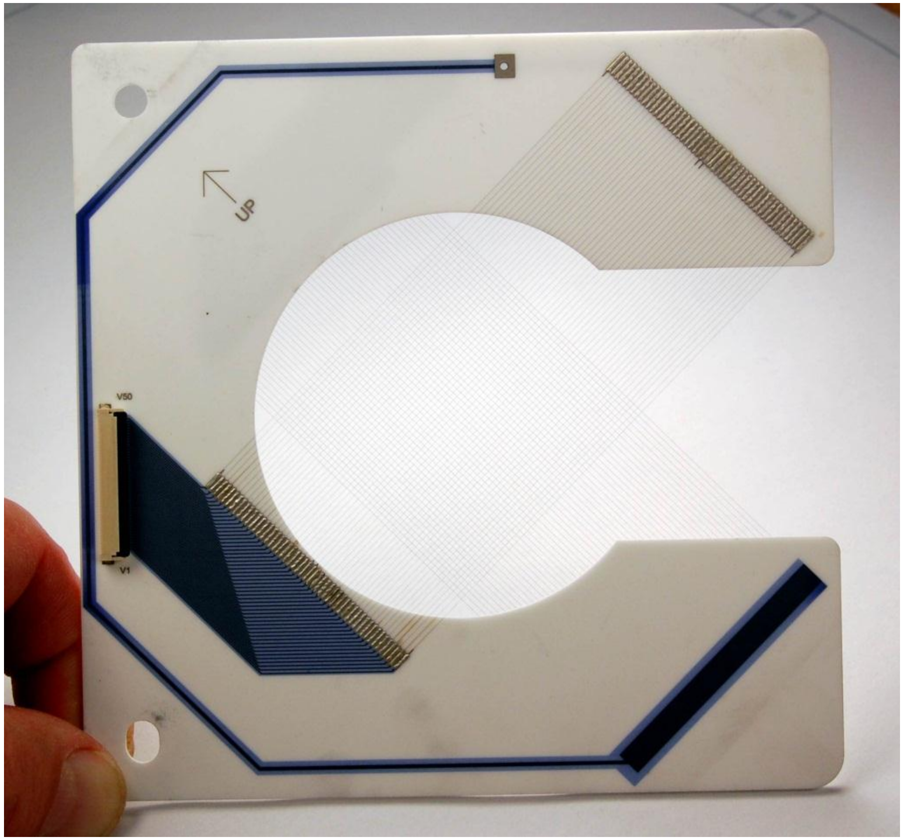
Far-field imaging

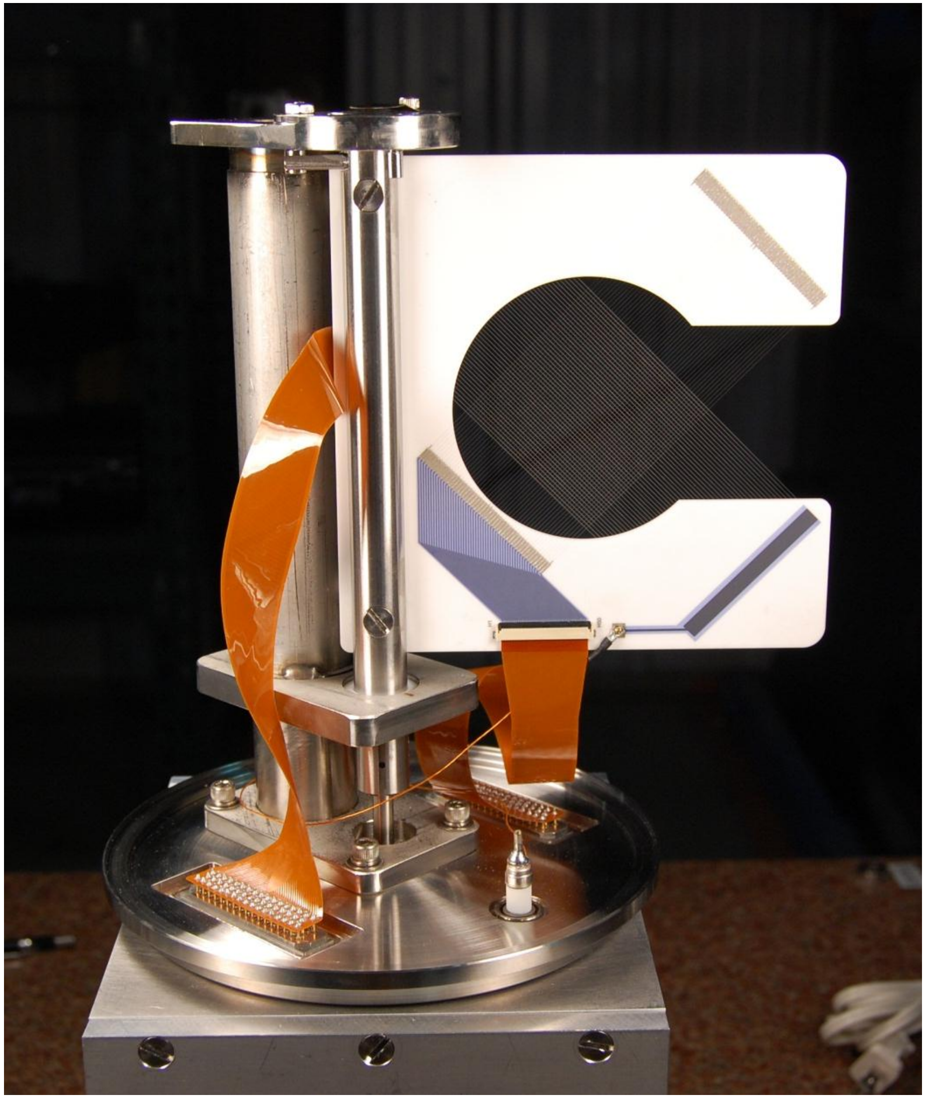
Near-field imaging





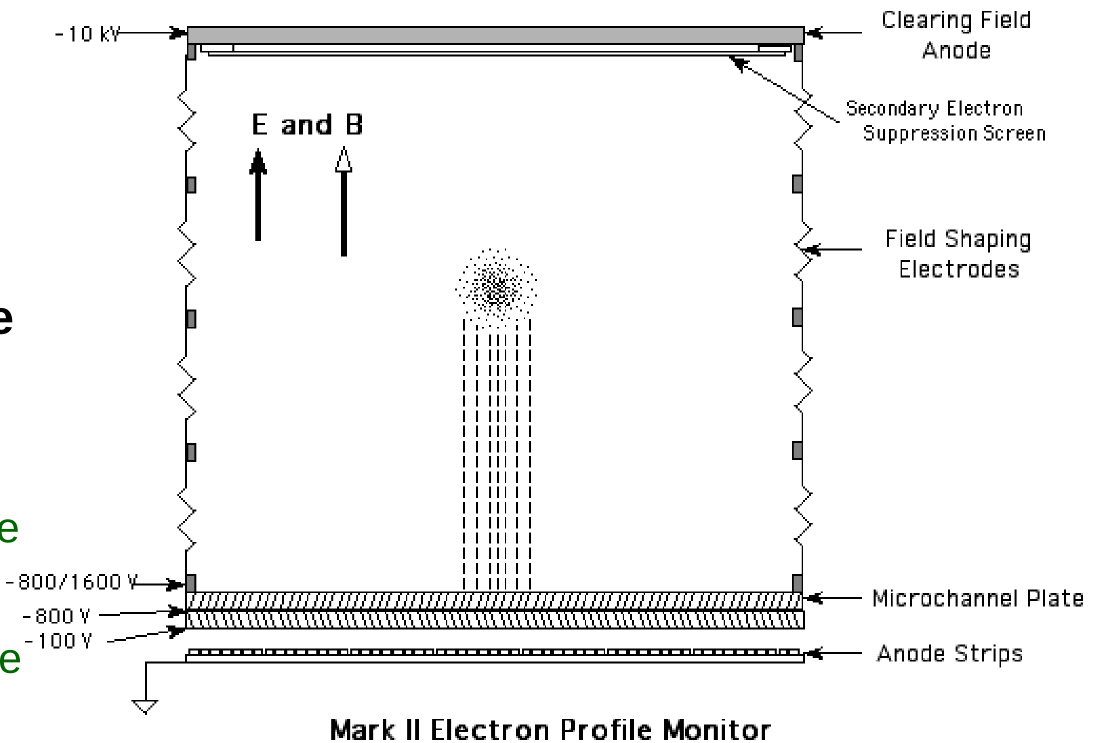
SEM Mulitwire





Project X Ionization Profile Monitor (IPM)

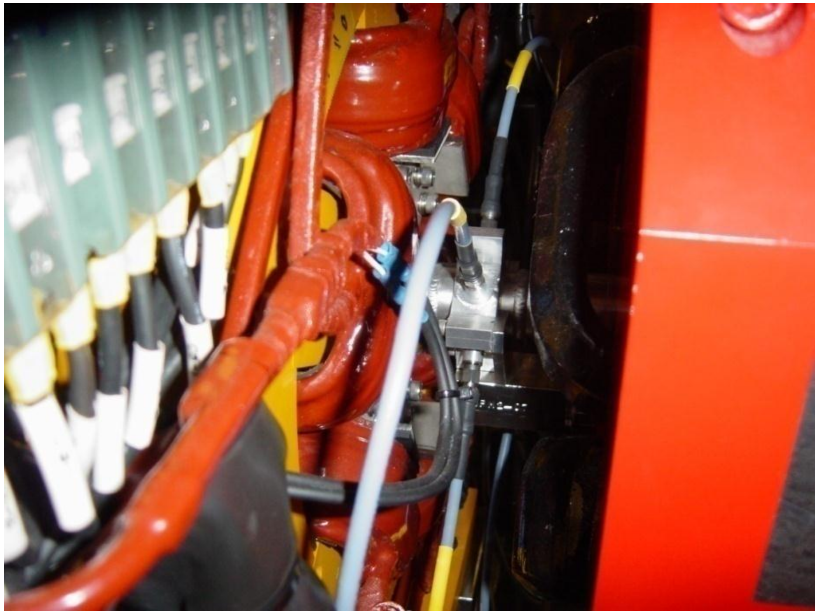
- **Based on the ionization of the residual gas**
  - **p or pbar collisions**
  - **Gas molecule -> ion + e**
- **Collect either**
  - **Ions**
    - Subject to space charge
  - **or Electrons**
    - Needs magnetic a guide field, such that the spin diameter < detector strip width



- **Used for turn-by-turn measurements**
  - **Booster: 2.25 – 1.5 μsec**
  - **MI: 11.1 μsec**
  - **TeV: 21 μsec (also single bunch)**

Button BPM

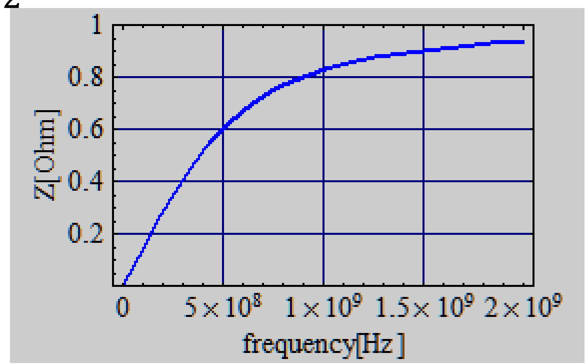
- **Commercial UHV RF button feedthroughs, made to specs**
  - **RF properties (numerical simulation)**
  - **Environmental requirements**
- **Compact construction**
- **Installation, tolerances, cabling**
- **Other button load impedance, than $R_0 = 50\ \Omega$?**



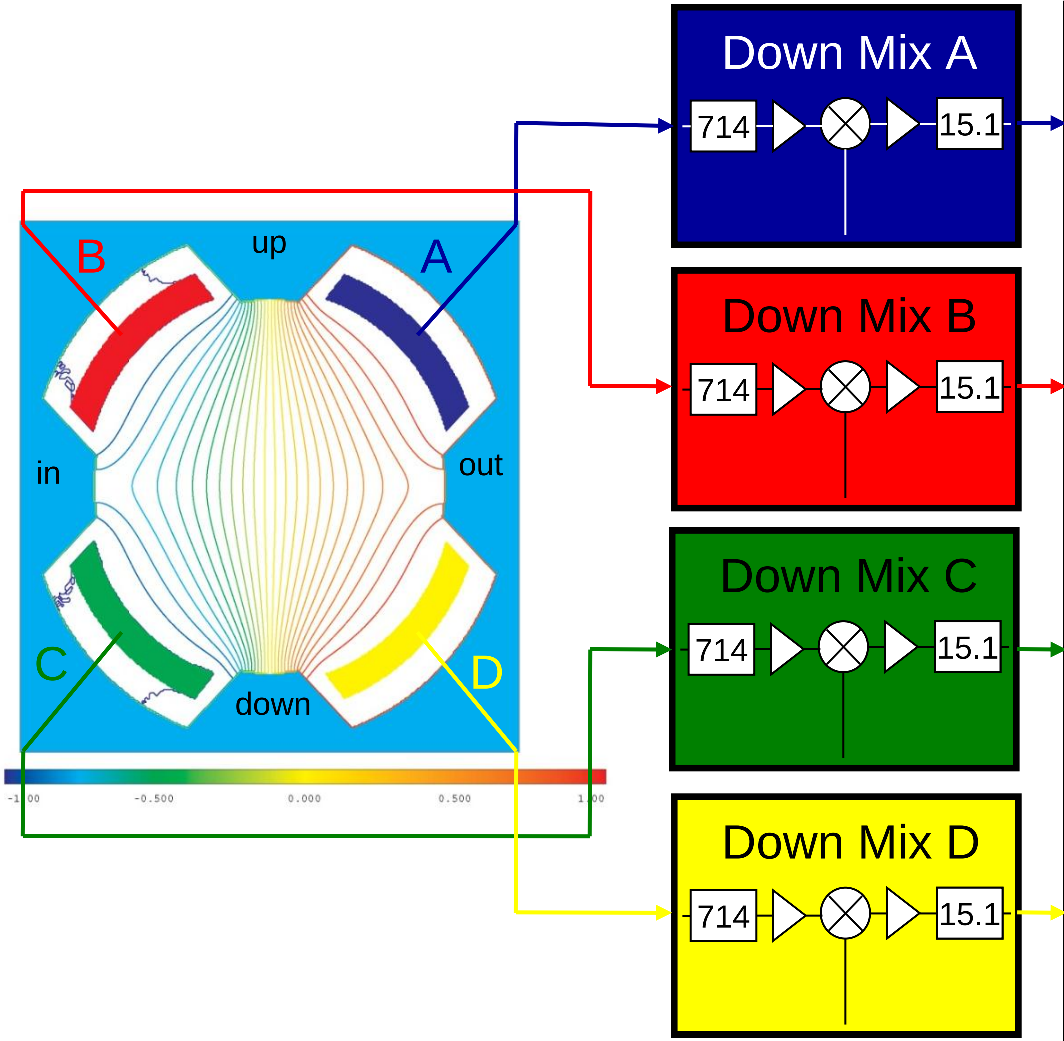
$$Z_{\text{button}}(\omega) = \phi\, R_0 \left(\frac{\omega_1}{\omega_2}\right) \frac{(\omega_1/\omega_2)}{1 + (\omega/\omega_1)^2}$$

$$\omega_1 = \frac{1}{R_0\, C_{\text{button}}} \qquad \omega_2 = \frac{v_{\text{beam}}}{2\, r_{\text{button}}}$$

$$\phi = \frac{r_{\text{button}}}{4\, R_{\text{pipe}}}$$



BPM Electronics Scheme (ATF DR)



Digital signal processing:

$$\phi_H = \frac{(A+D)-(B+C)}{A+B+C+D}$$

$$\phi_V = \frac{(A+B)-(C+D)}{A+B+C+D}$$

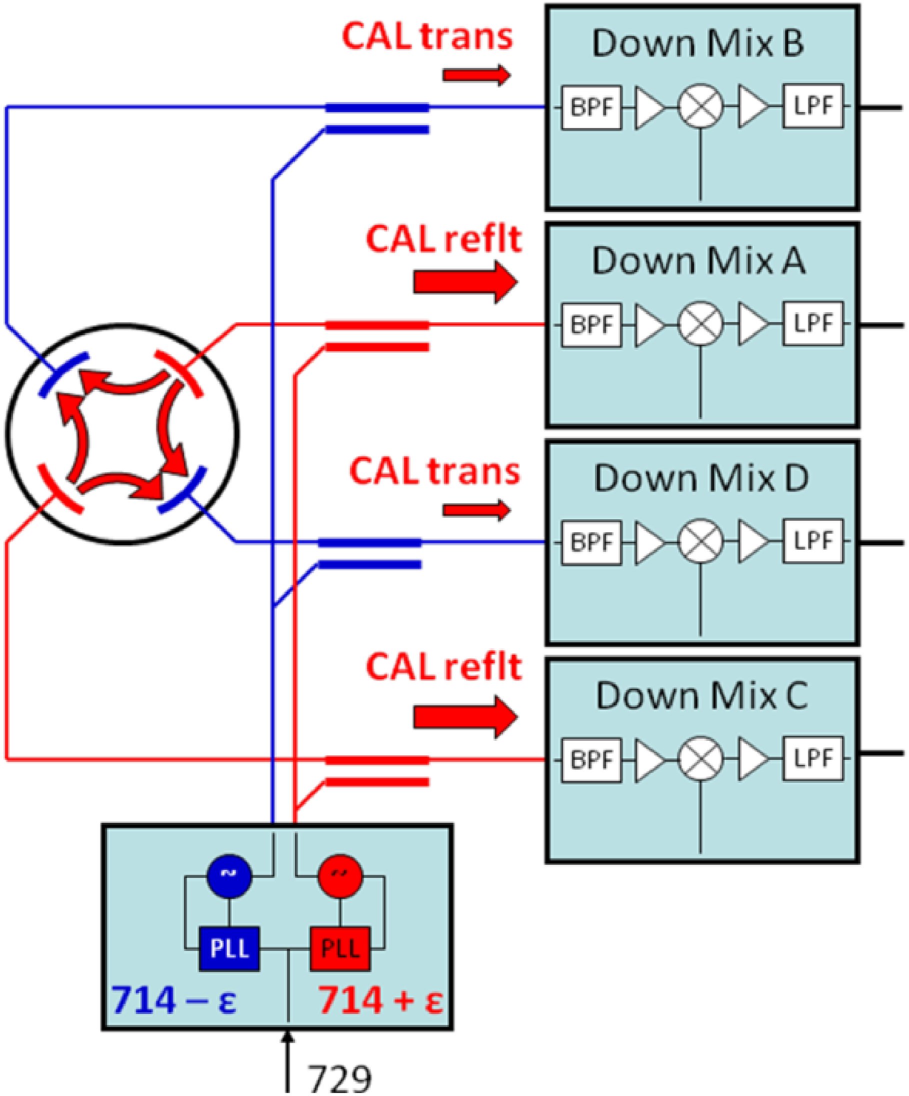
1D polynomial fit:

$$Pos\,[mm] = 9.35\phi + 1.00\phi^3 + 7.79\phi^5$$

(we now use a 7th order 2D fit)

0.1 dB gain error ≡ 27 µm offset error !

Automatic Gain Correction



- **Use calibration tone(s)**
  - **714+ε MHz, 714-ε MHz**
  - **Reflected and/or thru BPM calibration signal**
  - **Inside analog pass-band**
  - **Separate DDC in NB mode**
  - **Error & correction signals:**

$$X_{\mathrm{Err}} = \frac{A_{\mathrm{CAL}} + B_{\mathrm{CAL}} + C_{\mathrm{CAL}} + D_{\mathrm{CAL}}}{4\, X_{\mathrm{CAL}}}$$

$$X_{\mathrm{Corr}} = X_{\mathrm{raw}}\, X_{\mathrm{Err}} \qquad X: A, B, C, D$$

- **Advice:**
  - **Two calibration tones is not a good idea!**
    (use “ping-pong” calibration workaround)