Beam Instrumentation for High-Intensity, Multi-GeV Superconducting Linacs

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ICFA-HB2010 Workshop
September 27 – October 1, 2010

Outline

- High Beam Power SRF Linacs
- Beam Diagnostics Issues in SRF Linacs
- Fermilab's "Project X"
- Beam Test Facilities at Fermilab
- First Beam Measurements
- Examples of Beam Diagnostics R&D
- Summary

High Power SRF Linacs

	SNS	SPL	ESS	Myrrha	Project X
E [GeV]	1,3	5	2.5	0.6	3
P [MW]	3	4	5	2.4	3
I_{pulse} [mA]	42	40	50	n/a	n/a
I_{ave} [mA]	2.5	0.8	2	4	1
duty factor [%]	6	2	4	CW	CW
pulse lenght [ms]	1	0.4	2	n/a	n/a
rep. frequency [Hz]	60	50	20	n/a	n/a

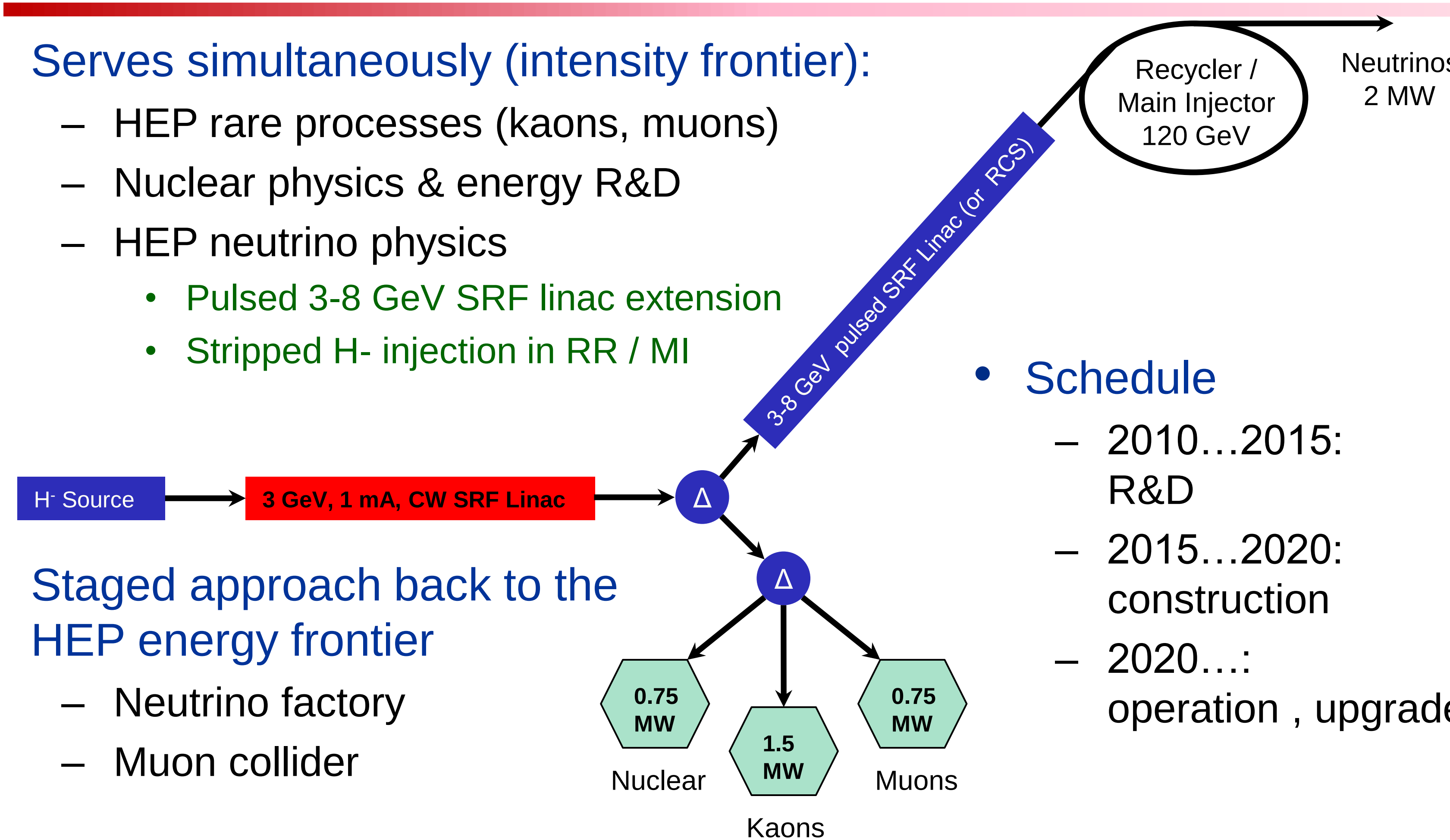
- Goals of existing and planned SRF proton / H- linacs
  not listed: J-PARC (not SRF yet), FRIB (heavy ions), and others(?)
- In common: High beam power!
  - Requires precise control, stability, and verification of the guide fields.

SRF Linac
Beam Diagnostics

- Essential beam instrumentation:
  - Beam trajectory
    - Beam position monitors (BPMs)
  - Beam phase, time-of-flight (TOF)
    - BPMs, WCMs, EO methods
  - Beam intensity
    - Toroid, wall current monitor (WCM)
  - Beam losses
    - BLM (ion chamber), TLM (*Heliax*)
  - Beam profile / emittance & halo
    - SEM (mulitwire), wire scanner, *Allison* scanner, slits, vibrating wire, laser diagnostics, e-beam scanner, IPM, etc.
  - Bunch profile & tails
    - *Feschenko* monitor, laser diagnostics, etc.
- SRF issues:
  - High beam power -> low losses
    - Rule of thumb: <1 W/m
    - Residual losses of invasive diagnostics
  - Requires non-invasive diagnostics
    - Cavities: cleanroom class 10
    - Contamination from dissociated wire material, etc.
  - Cryogenic temperatures
    - Avoid moving parts in the CM
  - Cryo-string sectioning
    - Warm diagnostics sections
  - In the cryo-modules (CM): just BPMs, no other beam diag.!

Fermilab's Project X: A Multi-MW Proton Source

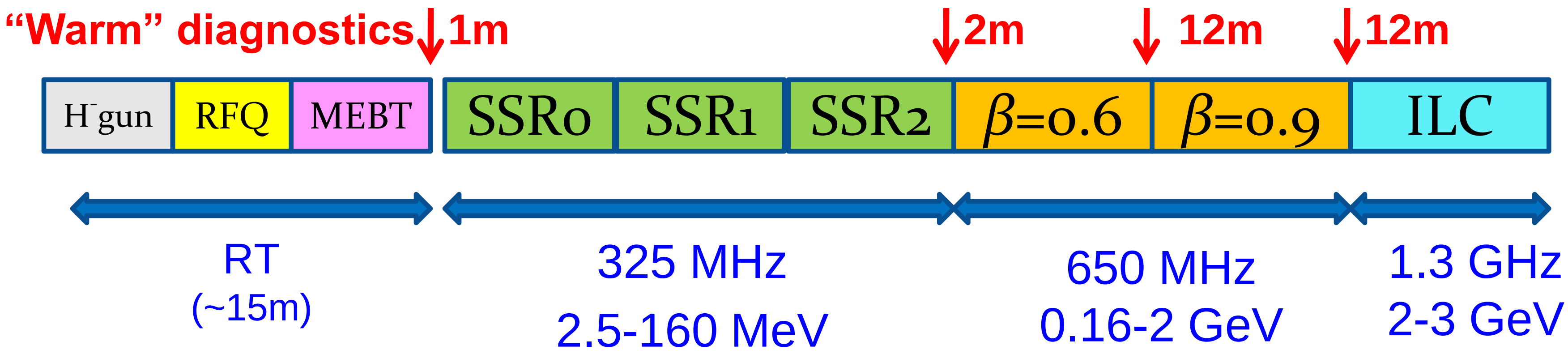
- Serves simultaneously (intensity frontier):
  - HEP rare processes (kaons, muons)
  - Nuclear physics & energy R&D
  - HEP neutrino physics
    - Pulsed 3-8 GeV SRF linac extension
    - Stripped H- injection in RR / MI



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

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

Project X SRF CW Linac Baseline Configuration



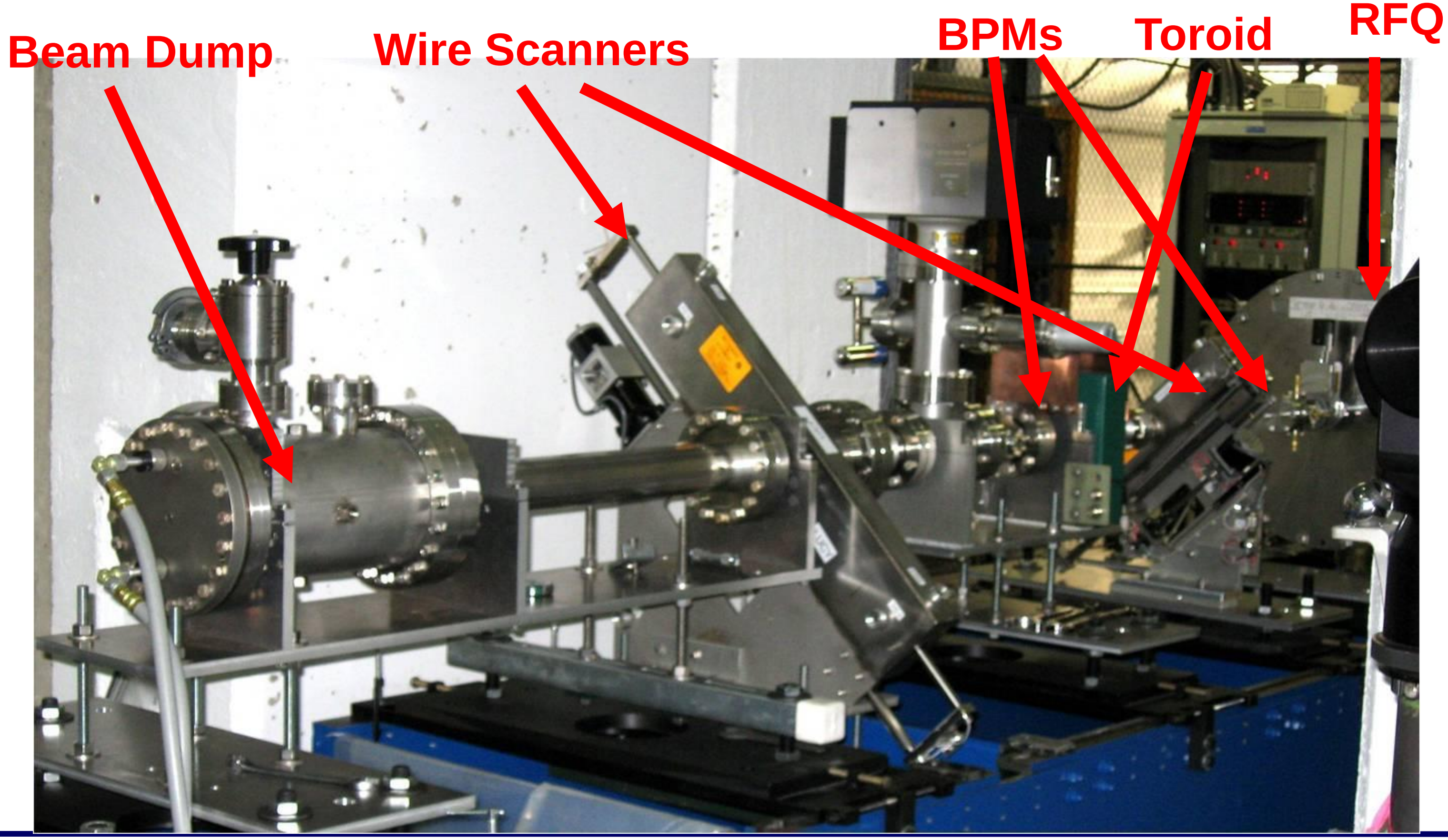
Section	Freq (MHz)	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	26 / 26 / 1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-32	18 / 18 / 2	SSR, solenoid
SSR2 (β_G=0.42)	325	32-160	44 / 24 / 4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-520	42 / 21 / 7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	520-2000	96 / 12 / 12	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	2000-3000	64 / 8 / 8	9-cell elliptical, quad

Project X
Beam Test Facilities

- ILC Test Accelerator (ILCTA)
  - Beam tests (electrons) of one or more ILC RF units, each consists out of 3 ILC//XFEL cryomodules, keeping eight 1.3 GHz β=1 elliptical TESLA-style cavities, plus quad package and cold button-style BPM.
  - Electron beam diagnostics, only partially applicable for Project X.
- Project X Test Accelerator (PXTA) –
  formally known as High Intensity Neutrino Source (HINS)
  - Beam tests (protons / H-) of a Project X "like" source
    - LEBT, RFQ, MEBT, 325 MHz SC spoke resonators, etc. up to some MeV
    - Ultra-broadband chopper
    - Beam optics, lattice optimization
    - Vector modulator concept (single klystron RF source on many cavities).
    - Various beam diagnostics

Movable Beam Diagnostics

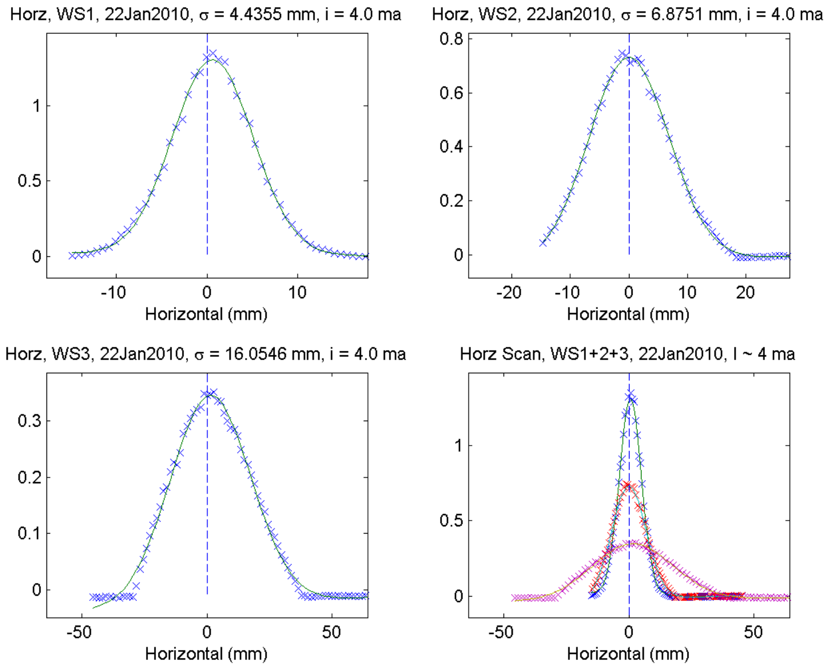
The PX test linac is equipped with a reconfigurable, movable diagnostics station at the end of the linac

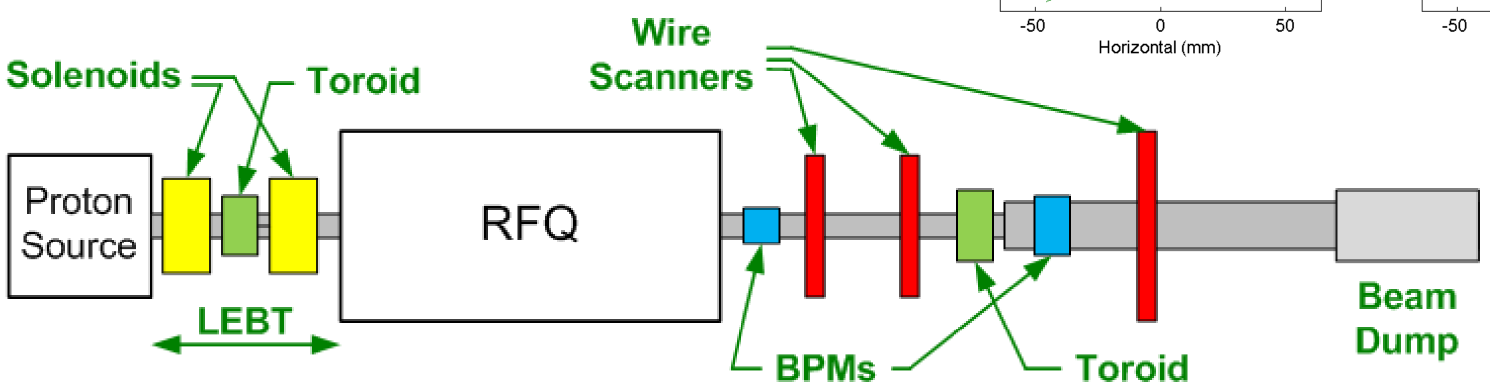


First Beam Measurements Transverse Beam Profiles

Project X

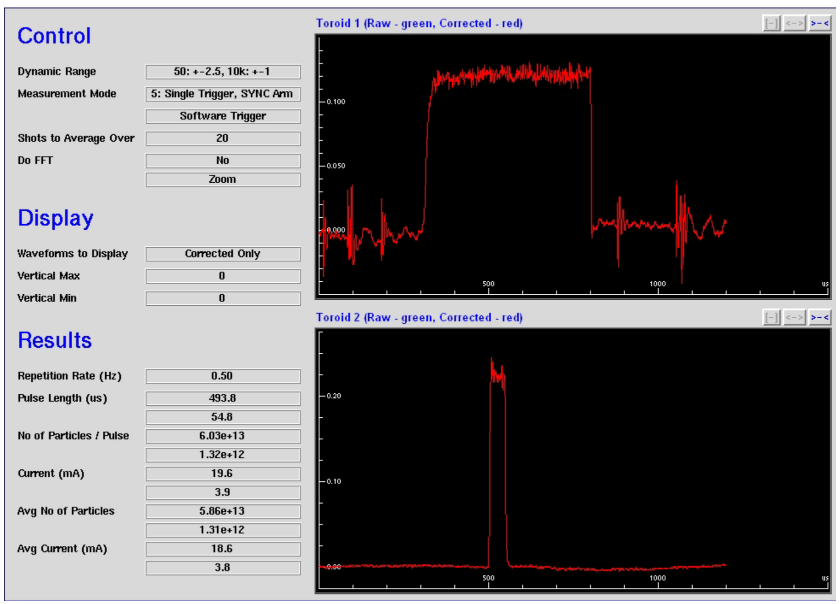
- Beam profiles at the RFQ output
  - 3 wire scanners
  - No focusing
  - Beam fills physical aperture



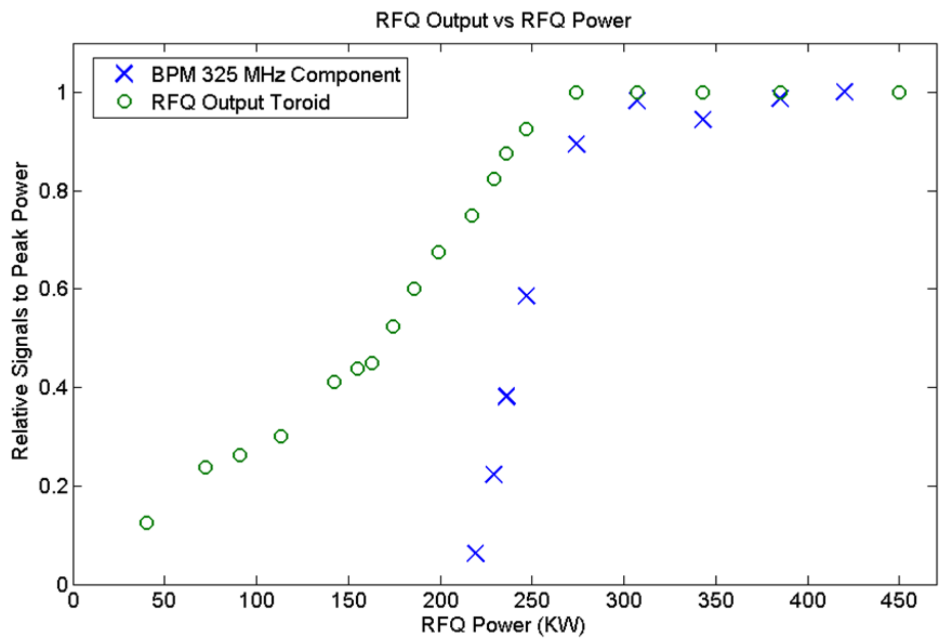


First Beam Measurements
Beam Intensity

- LEBT beam pulse
  - 18 mA (different charge states)
  - 500 μsec
- MEBT beam pulse
  - 4 mA (most H+), 50 μsec



RFQ Outputs VS RFQ Power

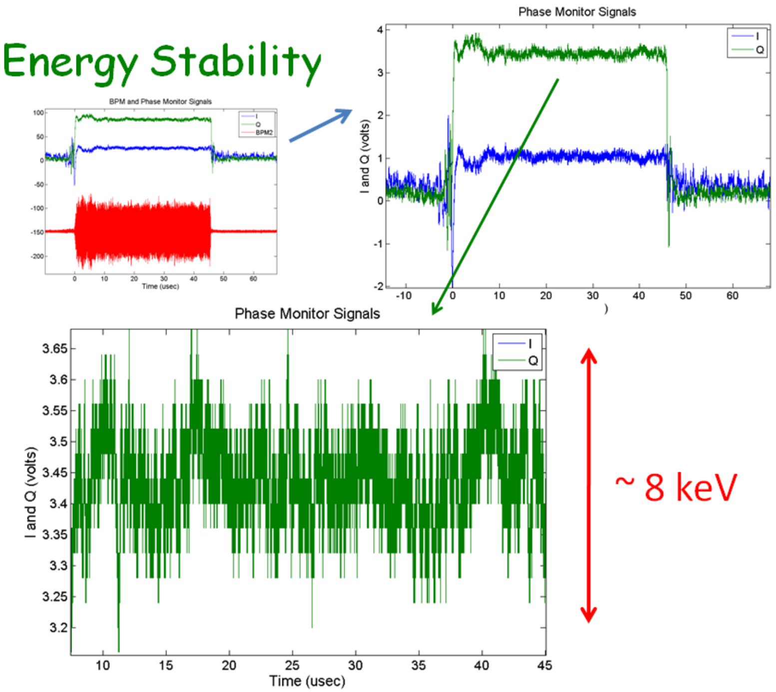


- RFQ bunched & unbunched beam
  - Toroir & BPM signal levels vs. RFQ RF power

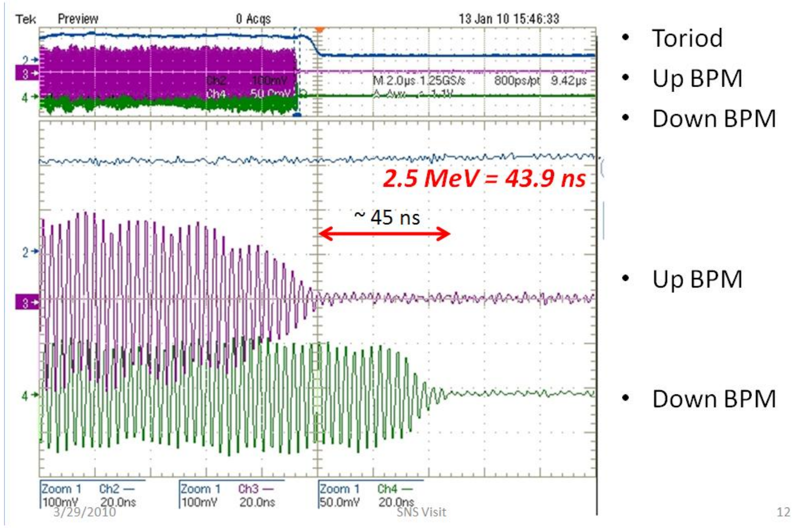
First Beam Measurements
Beam Energy

- Stability of the beam energy
  - Phase of BPMs I-Q signal
  - Q-signal tuned to 0^0: phase

Energy Stability



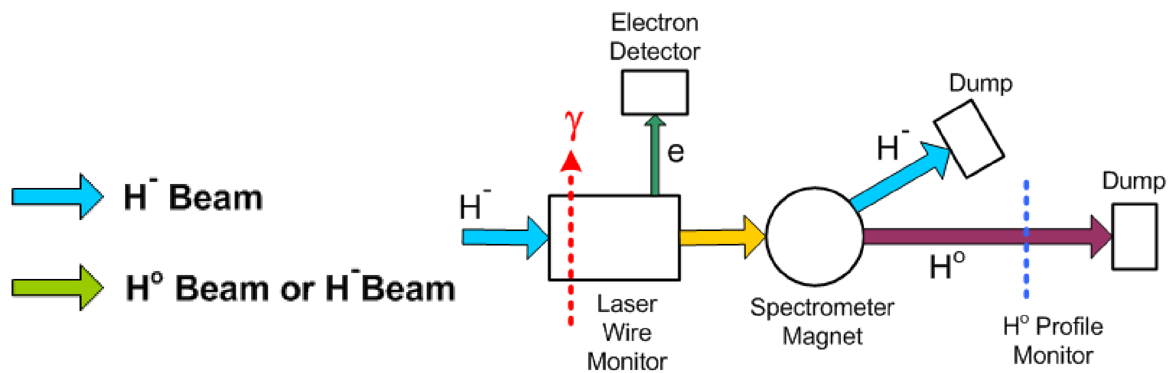
Time of Flight – Sparked RFQ

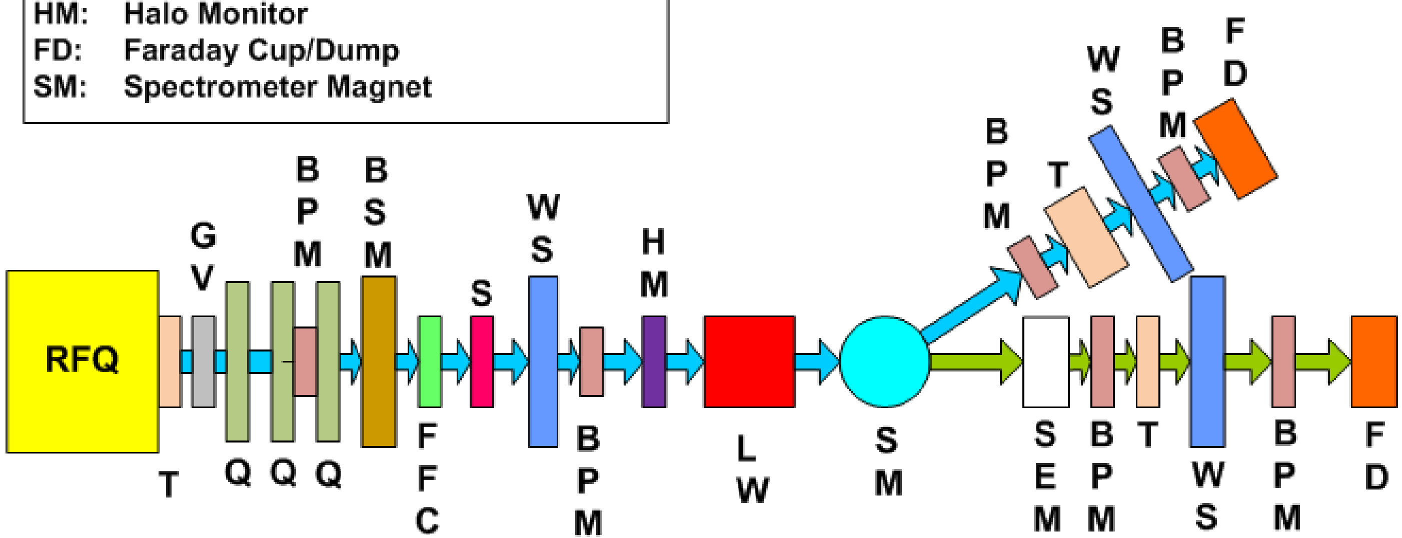


- MEBT beam energy: 2.5 MeV
  - TOF of the sparked RFQ between two button BPMs

Future Diagnostics Layout & Laser Emittance

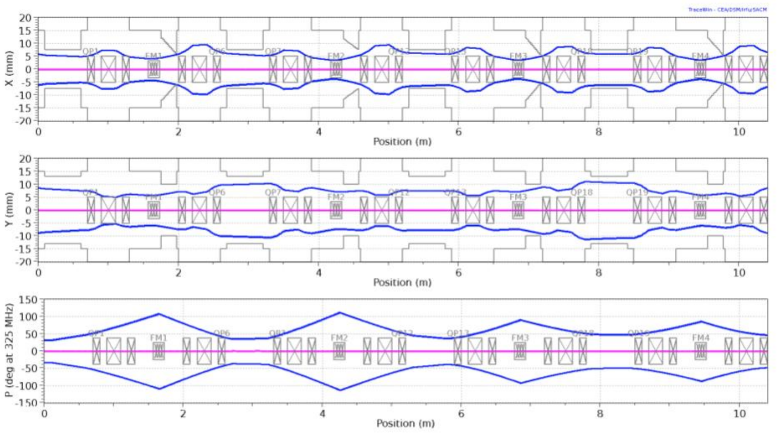
T: Toroid
GV: Gate Value
Q: Quadrupole
LW: Laser Wire
SEM: Secondary Emission Monitor
BPM: Beam Position Monitor
WS: Wire Scanner
S: Horz and Vert Slits
BSM: Bunch Shape Monitor (Longitudinal)
FFC: Fast Faraday Cup
HM: Halo Monitor
FD: Faraday Cup/Dump
SM: Spectrometer Magnet





Project X

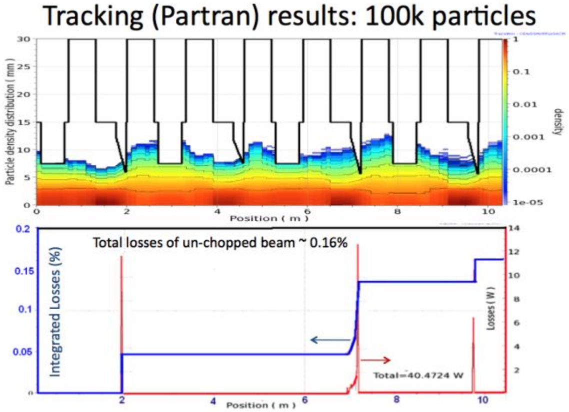
4-stage Chopper MEBT Lattice Optimization

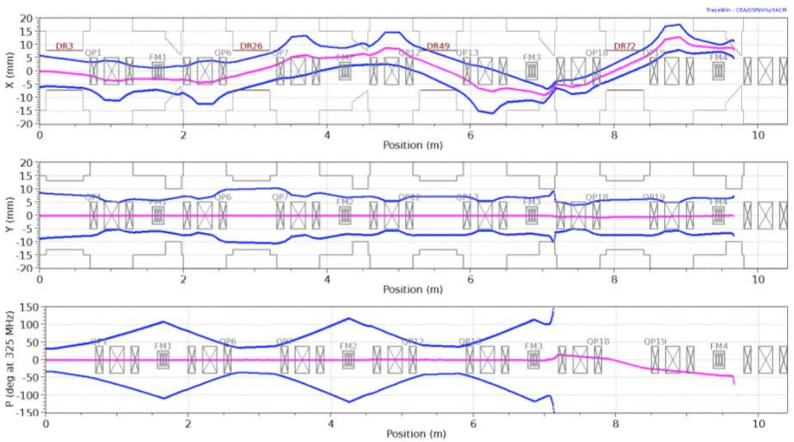


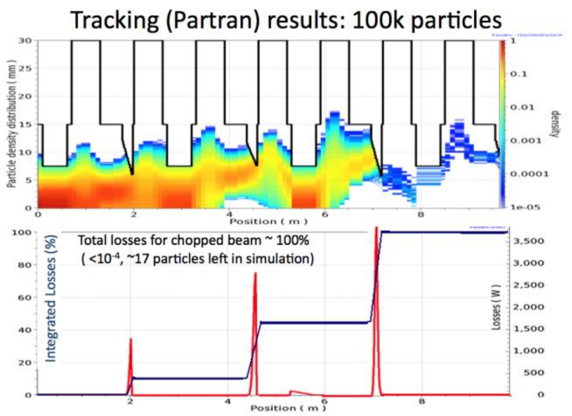
OFF

- Each kicker
  - 5 mrad
  - 750 volt
  - 0.5 m long
  - 150 mm gap
  - 1 nsec rise & fall time!
  - > 80 MHz rep. freq.

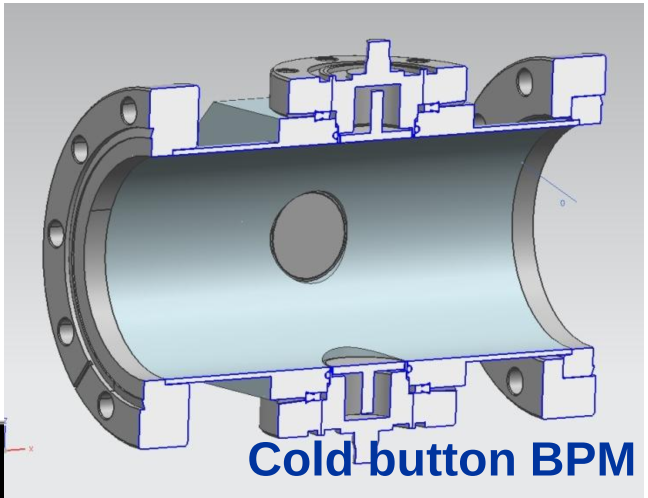
ON

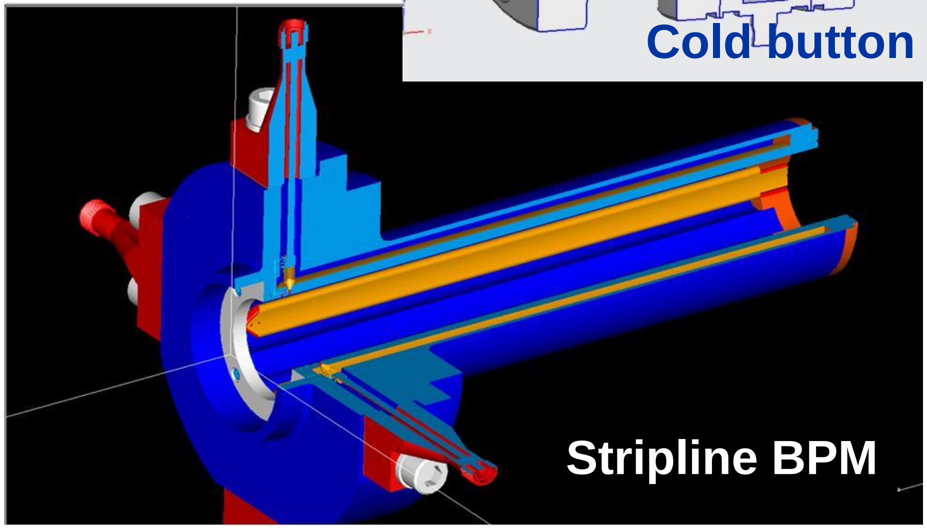


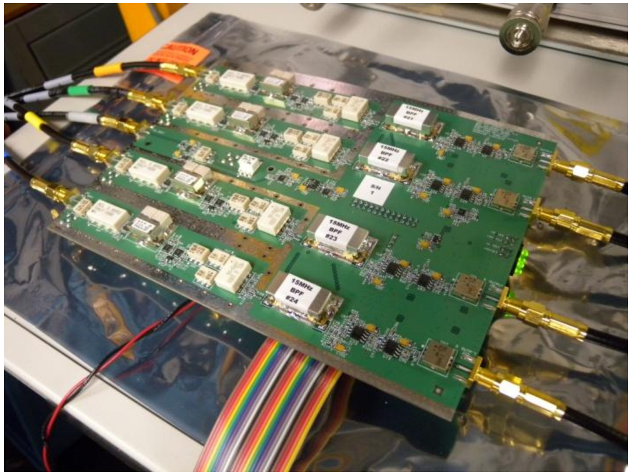




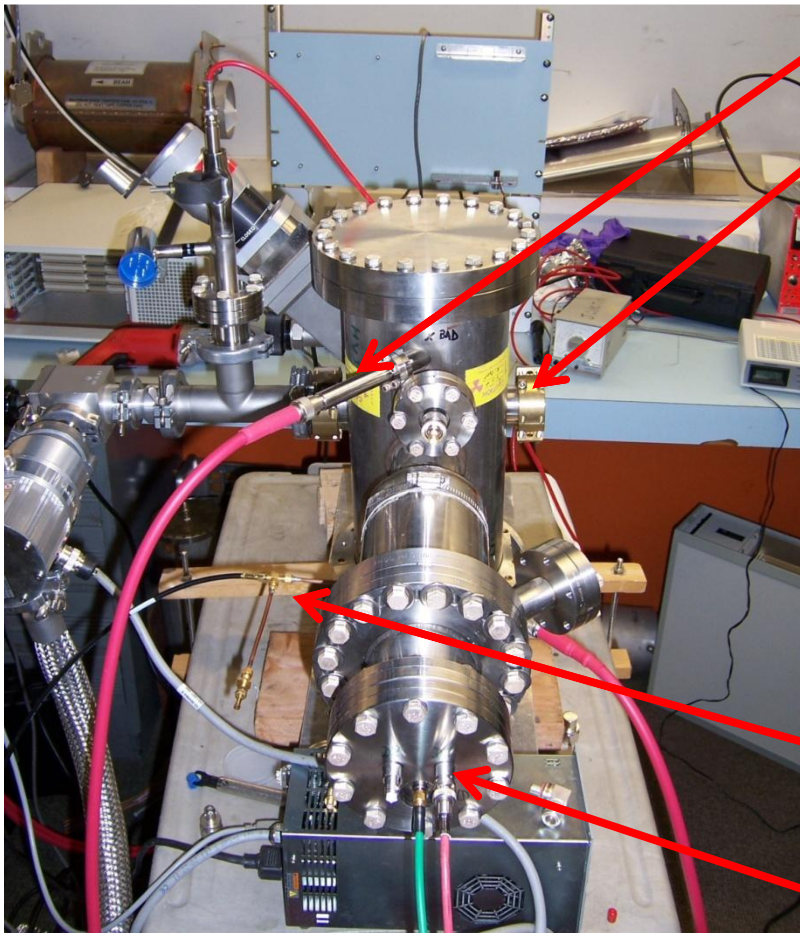
Beam Diagnostics R&D: Beam Position Monitors





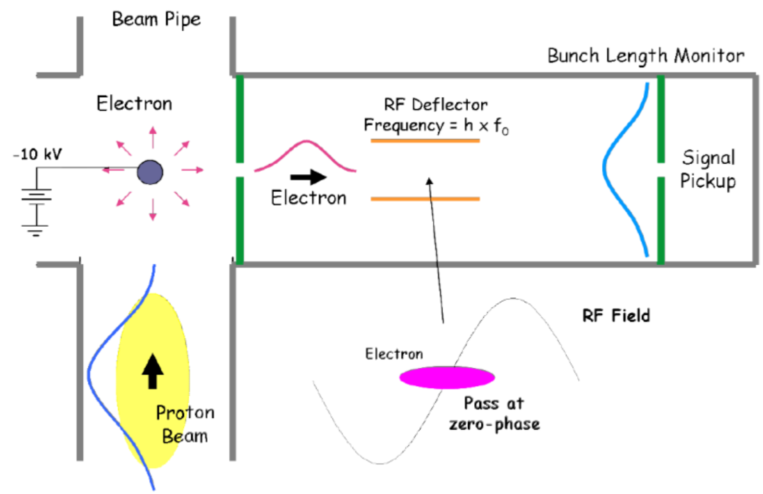


Beam Diagnostics R&D: Bunch Shape Monitor



Focus/Steering HV

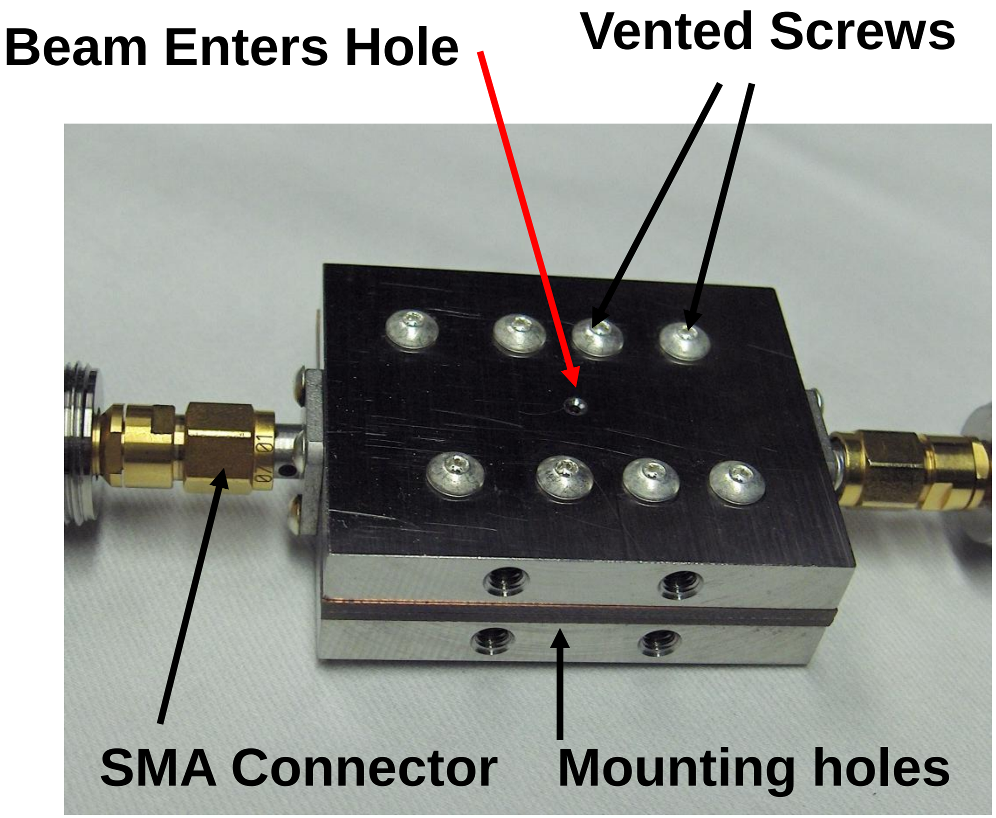
Beam Port



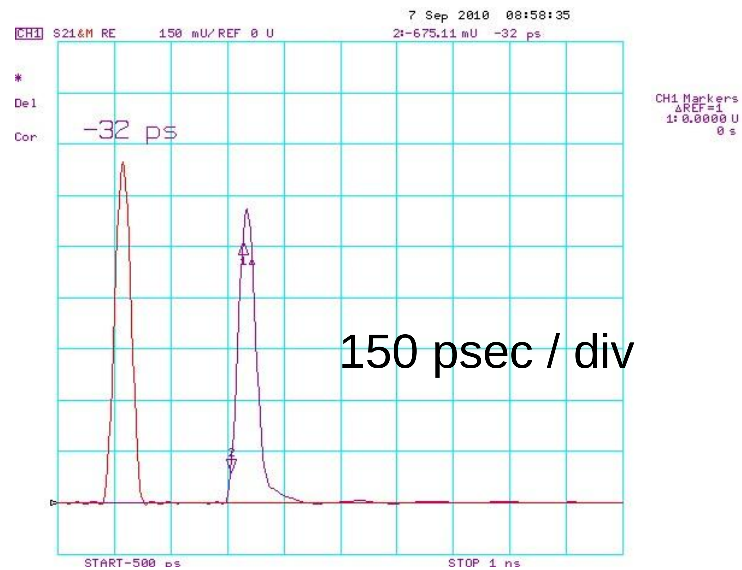
Deflector RF and Single-Stub Matching

EMT

Beam Diagnostics R&D: Fast Faraday Cup (SNS)

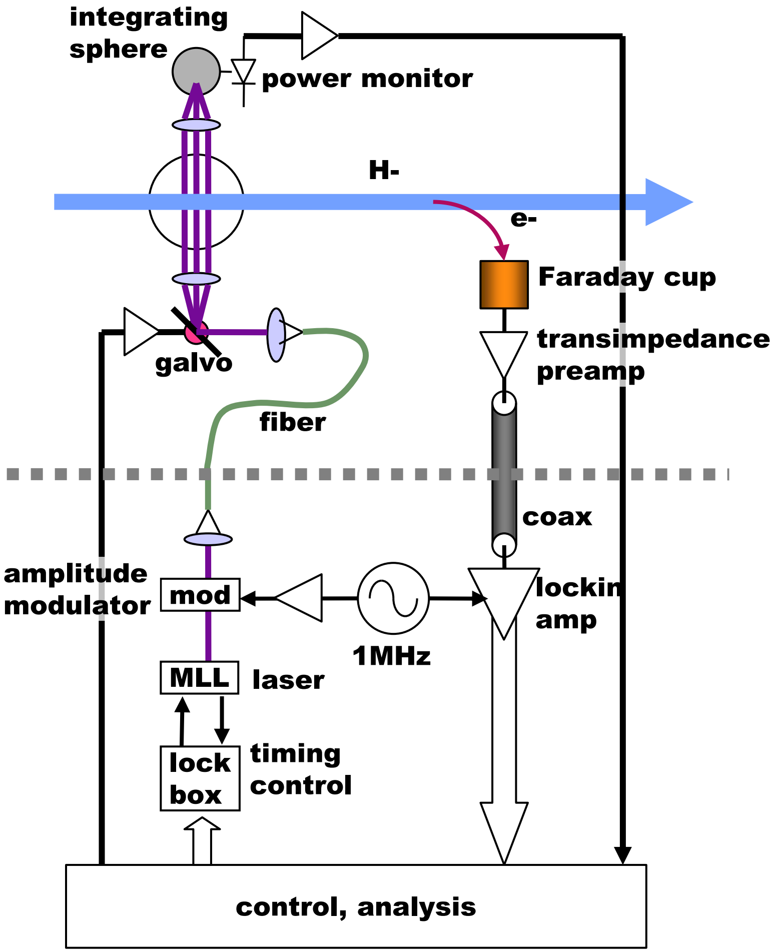


- TD S21 transmission measurement
  - 4 psec risetime increase
  - 12 % amplitude decrease



Courtesy C. Deibele / SNS

Beam Diagnostics R&D: Laser Diagnostics (LBNL)

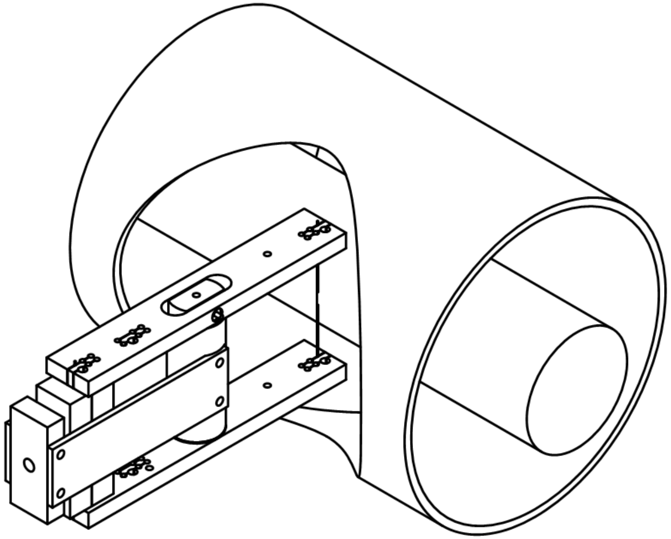


- Narrow band lockin amp detects 1MHz modulated signal
- Laser reprate is locked to 325MHz from machine
- Galvo scan is triggered by macropulse event signal
- Upper components are in tunnel, lower are in a laser hutch

Courtesy R. Wilcox / LBNL

Beam Diagnostics R&D: Beam Halo Diagnostics

- Vibrating wire
  beam halo diagnostics



Courtesy S.G. Arutunian / J. Bergoz

Summary

- High power SRF linacs put additional constraints to beam diagnostics
- Test accelerators are important for hands-on experiments and beam studies
- Fermilab will test a large variety of proton / H- beam diagnostics, many in collaboration with other laboratories.