PIP-II Laserwire Introduction

Vic Scarpine

PIP-II Beam Instrumentation Laser Wire Final Design Review

May 2, 2024

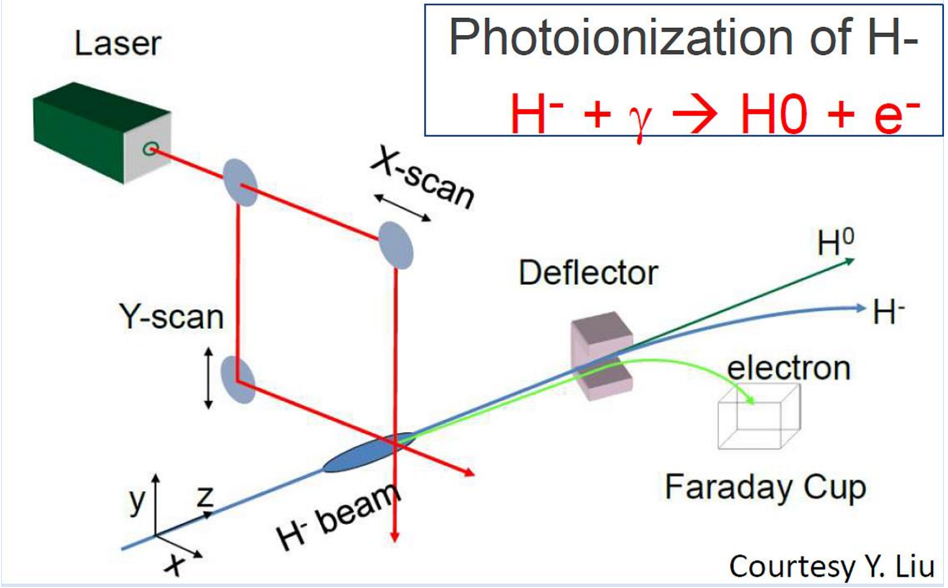
A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

Outline

- Laserwire Basics
- PIP-II Laserwire Requirements
- PIP-II Laserwire Interfaces
- PIP2IT Results
- PIP-II Laserwire Overview
- PIP-II Laser Hut
- PIP-II Laserwire Team
- PIP-II Laserwire Locations
- PIP-II Laserwire Emittance Monitor

Unique Issues with Profiling in a SC Linac

- Beam profile measurements in high-intensity, superconducting H- accelerators are a challenging task.
- Damage and contamination of superconducting RF cavity must be prevented at all costs.
  - Invasive measurements can lead to particle contamination, degraded vacuum, beam loss leading to heating then quenching
- This drives the need for non-invasive measurement of both transverse and longitudinal profiles.
- Ultra-high vacuum in SC linacs make ionization profile monitors difficult.

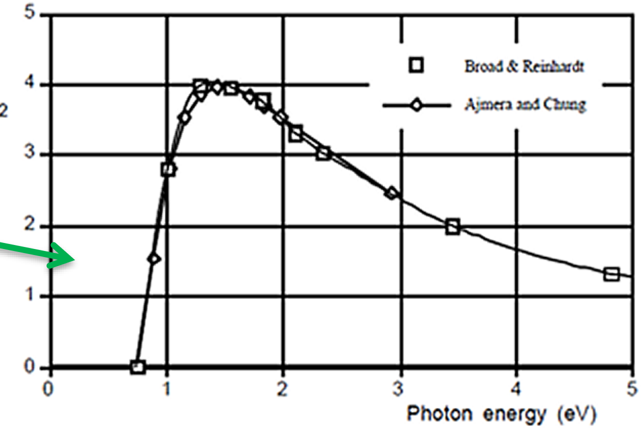


- The technique of photoionization ($H- + \gamma \rightarrow H0 + e-$) is preferred method for beam profiling.
- *PIP-II will utilize laser-based profile monitor (laserwires) for transverse and longitudinal profiling where possible.*

PIP-II Laserwire Choices and Challenges

Main issues for PIP-II

- Small cross section → small signal
  - 3.5 E–17 cm^2 at 1.17 eV (λ = 1064 nm)
- PIP-II low beam current → small signal
- Laser power limited by damage limit on optical vacuum viewports



High Peak Power Laser (free-space)

- More photons per bunch – **Pro**
  - More electrons → larger signal
  - Simple Faraday cup collector
- Need free-space transport – Con
- *Potentially larger power density on vacuum windows* – Con
  - Risk to damage windows → damage SRF cavities

Low Peak Power Laser (fiber)

- Less photons per bunch - Con
  - Less electrons → smaller signal
- Laser transport through fibers – **Pro/Con**
  - Easier transport but limited power through fibers
- Lower peak power density on vacuum windows – **Pro**
  - Less risk to SCF

Fiber-based, low-power option was tested at PIP2IT

Requirements

- Physics Requirements: ED0010230
  - Re-released and approved. No changes to laserwire.
- Laserwire Functional Requirements: ED0008303
  - Re-released and approved. No changes to laserwire.
- Laserwire Technical Requirements: ED0013714
  - Changing requirement T-ED0013714-E004 from:

“The free-space optics at each laserwire station shall keep the maximum average optical power density on the vacuum viewports to less than 3 W/cm^2 “

To

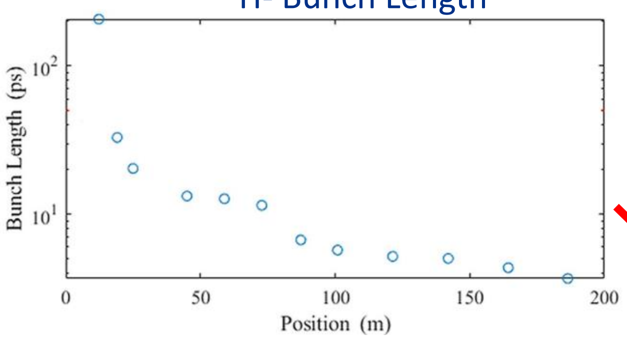
“The free-space optics at each laserwire station shall keep the maximum average optical energy density on the vacuum viewports to less than 150 mJ/cm^2 in 10µs and less than 3 J/cm^2 in 1s“

Note: industry standard is < 10 J/cm^2 for a single laser pulse. We are requiring a 3x less energy limit. Presently we are designing to keep this limit to 50 mJ/cm^2 in 10µs and less than 1 J/cm^2 in 1s.

Some Key PIP-II Numbers for Laserwire Design Guidance

Need to make profile measurements with commissioning beam

H- Bunch Length



H- Parameter	Nominal	Commissioning
Beam energy	2.1 to 800 MeV	2.1 to 833 MeV
Beam pulse length	550 µs	10 µs
Bunch Intensity	30 pC	1.2 to 60 pC
Bunch Intensity (particles)	1.5e8	6e7 to 3e8
Beam transverse size (rms)	2 mm	1 to 4 mm
Size of measurable region	±15 mm	±15 mm
Desirable typical scan time	<3 min	<5 min
Longitudinal bunch length (rms)	200 to 4 ps	200 to 4 ps

With small H- beam current, we are optimizing laser pulse overlap with H- beam pulse for each beam energy (see Signal Performance talk) with following guidance:

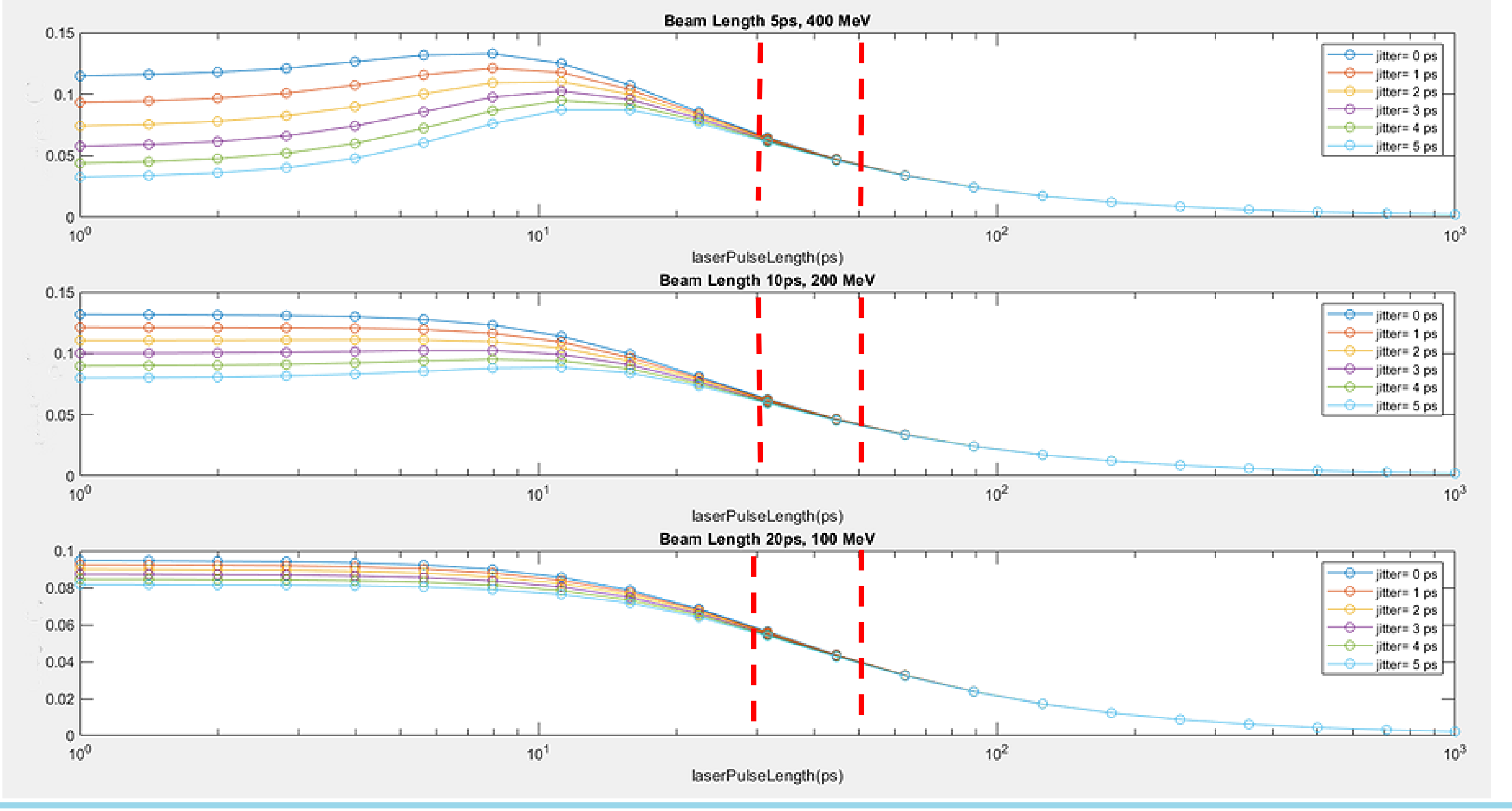
- Laser power on vacuum windows < 150mJ/cm2 per 10µs up to 20Hz
- Keep laser power per pulse in linear response region *(up to ~100µJ per pulse)*
- Select laser pulse width to maximize signal *(minimize wasted photons)*
- Select laser pulse pattern to match chopped H- beam pattern *(minimize laser power on windows)*
- Laser pulse rep rate ~10MHz over 10µs up to 20Hz for initial design *(minimize difficult laser amplifier design)*

Laser Pulse Length Studies

What is optimal laser pulse length for laserwire system?

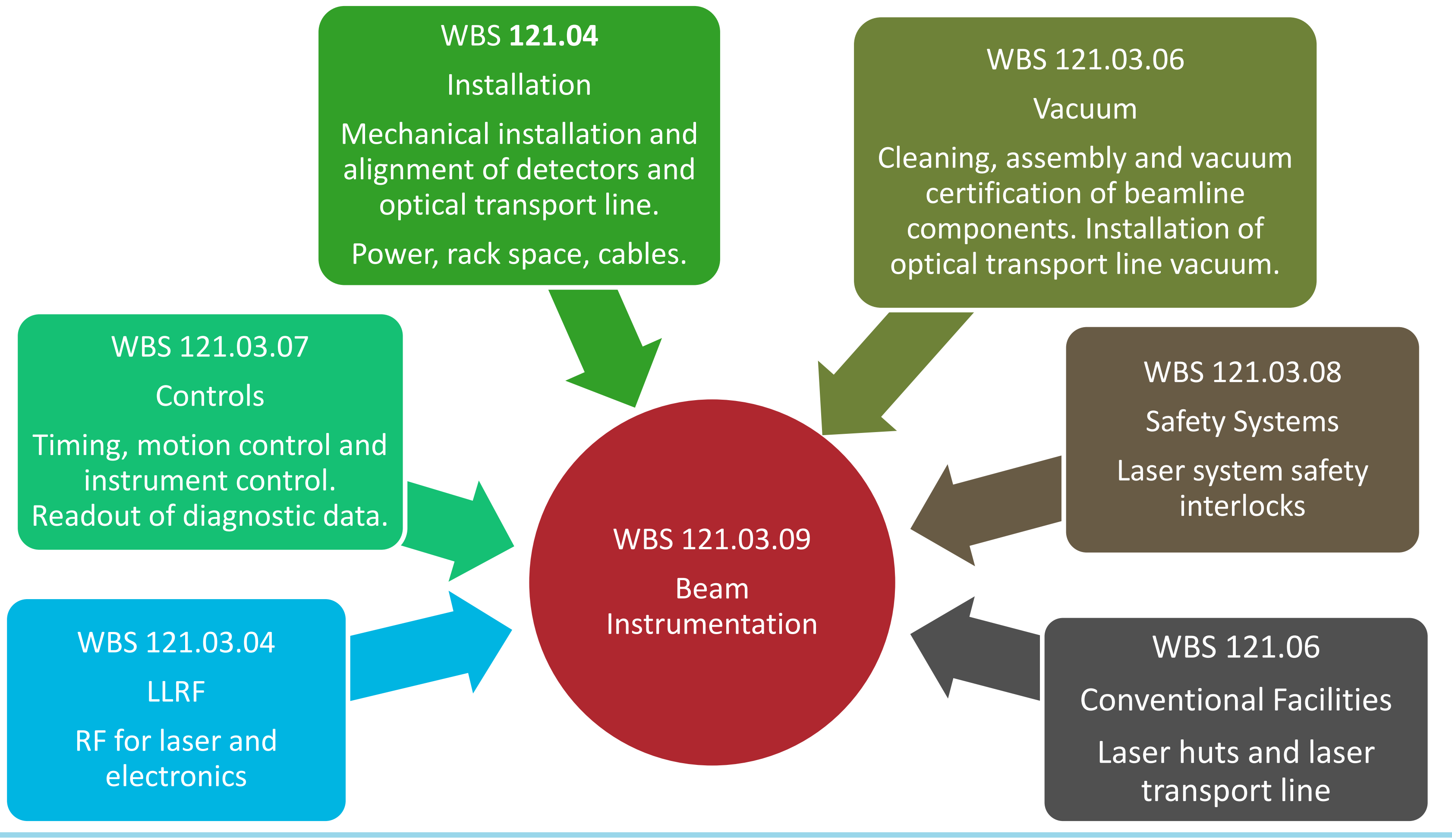
- *May optimize laser pulse length for different H- beam energies*
- *Laser design may allow for this. **Under study***

Amplitude of the charge profile for different jitter amplitudes, beam lengths and for laser pulse lengths from 1 ps to 1 ns



Laserwire Interfaces

- Interfaces identified and being managed though master interface controls document located in Teamcenter ED00010433 and Beam Instrumentation Noninvasive Beam Profile Monitor Interface Specification ED0016036.

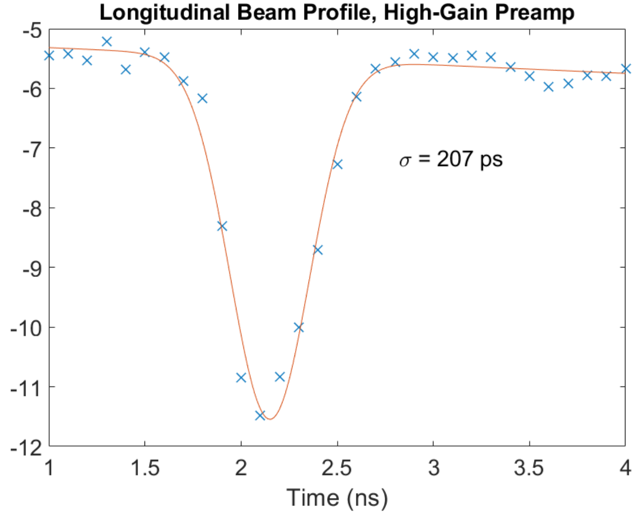


PIP2IT Prototype Laser Profile Monitor Measurements

Low peak power fiber-based laser with optical fiber transport

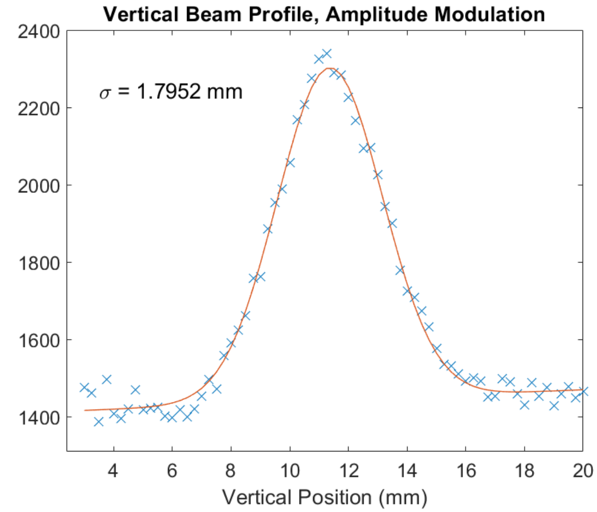
PIP2IT Laser

- Fiber Laser:
  - 162.5 MHz pulses *locked* to RF
  - 12 psec pulses at 1054 nm
  - Up to 1 W at beamline
  - ~6 nJ per pulse
- Faraday cup for electron collection
- Laser transport via LMA optical fiber



Longitudinal beam profile with high-gain preamp

- Preamp noise requires averaging
- Background electrons limit dynamic range of measurement



Vertical beam profile with laser amplitude modulation detection

- Potentially very sensitive technique
- Sensitivity is proportional to time
- Limited by cross-talk effects

Conclusion: Low peak power fiber laser limited by amplifier noise and background → Move to higher peak power laser with free space laser transport.

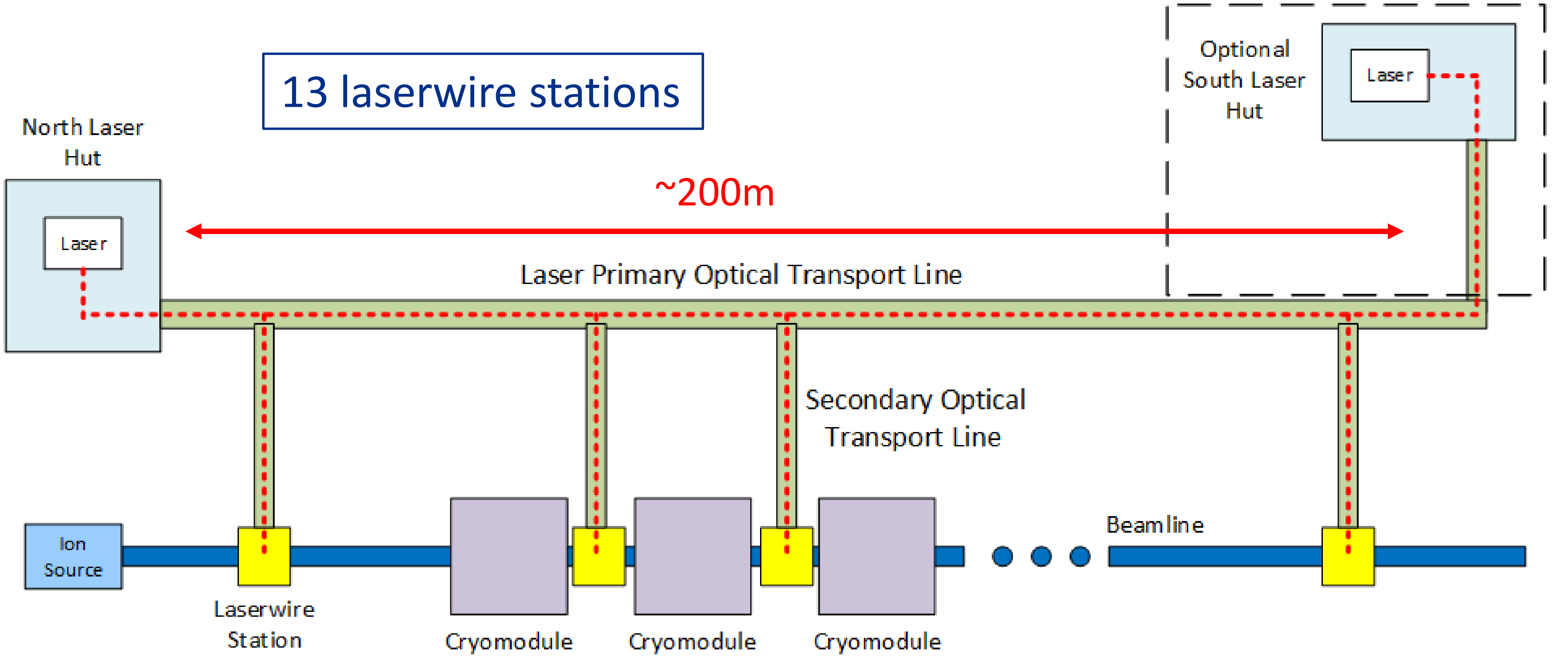
PIP-II Free-Space Transport Laserwire Design

PIP-II Laserwire

Charge #2

Free-space optical transport line above entire PIP-II WFE and Linac

- Laser located outside of PIP-II tunnel in laser hut
- Transport of laser light through vacuum pipe in PIP-II tunnel
- Mirror boxes select which laserwire stations receive laser
  - Can only select one profile measure location at a time

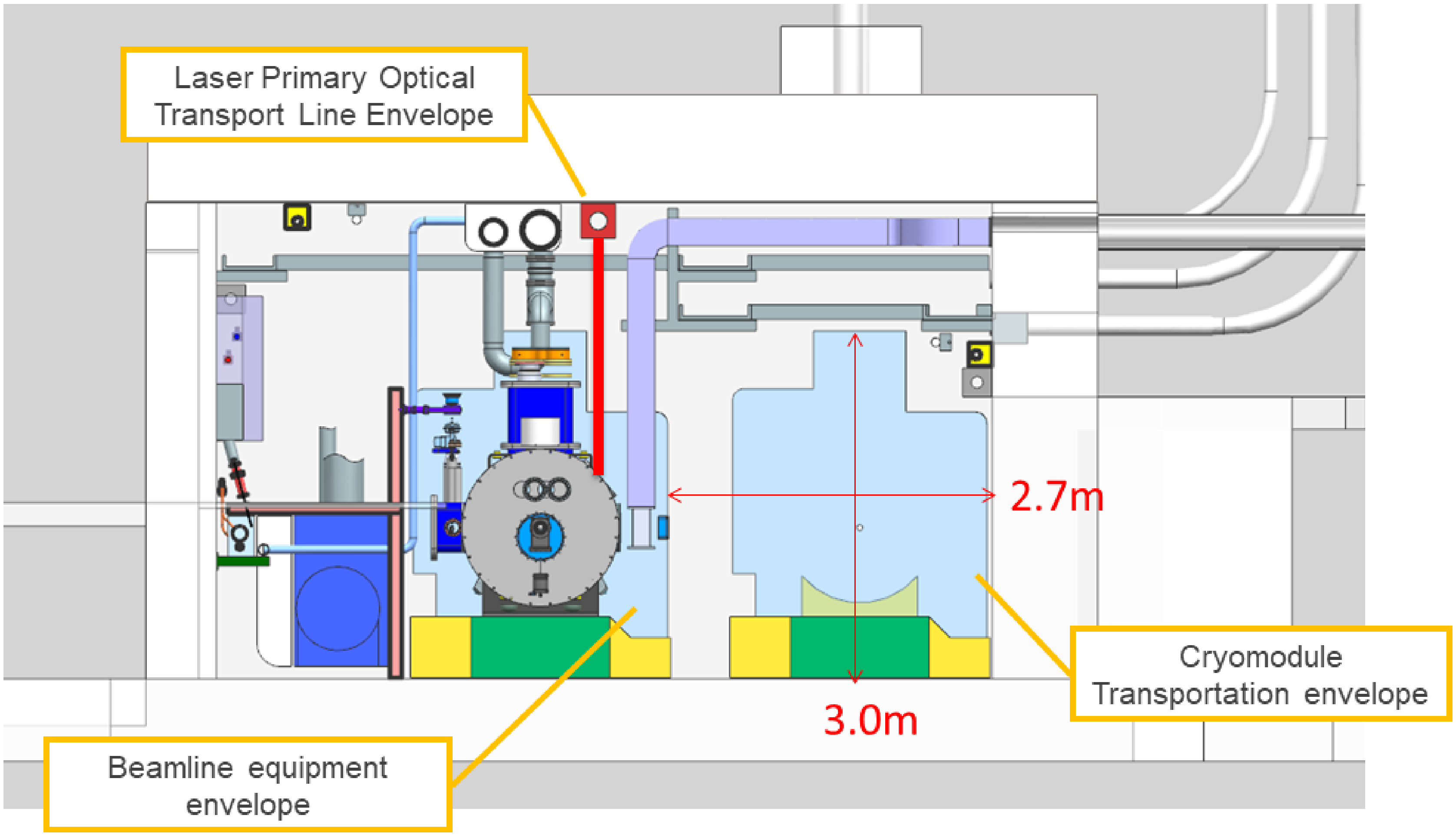


Laserwire for PIP-II

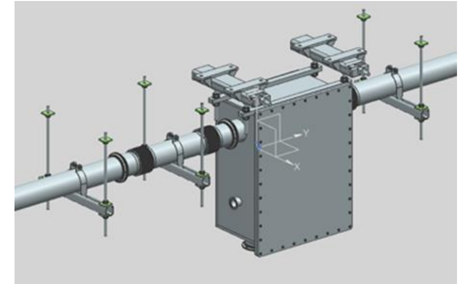
Charge #2

Cross sectional view of linac tunnel enclosure showing laser primary optical transport line envelope.

- Transport line capable of free-space transport → low-vacuum for safety

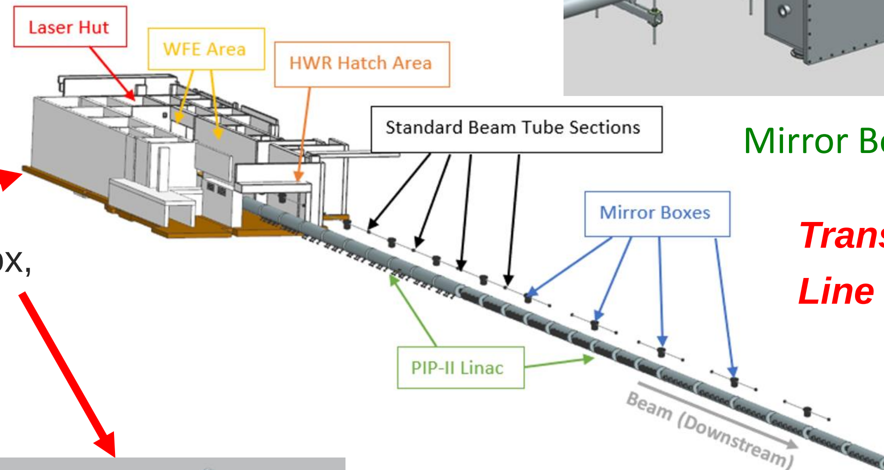


Laserwire Technical Progress

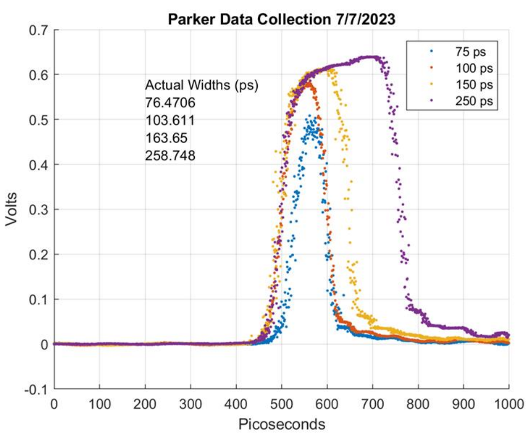


Progress:

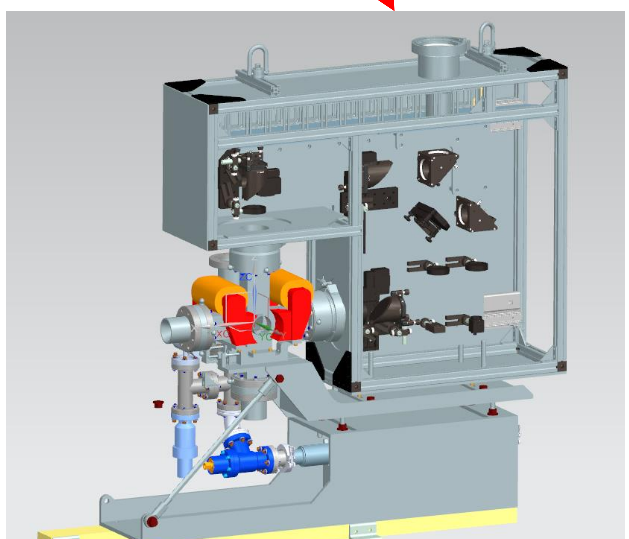
- Completed much of the design changes recommended from Nov 2022 mini-review of laserwire system.
- Laserwire FDR May 2, 2024
    - Will submit BCR to cover changes
- Optical transport line design stable
- Beamline design (vacuum chamber, optics box, stand, etc) moving toward final design
- Short pulse laser design under development
    - Lab measurements successful



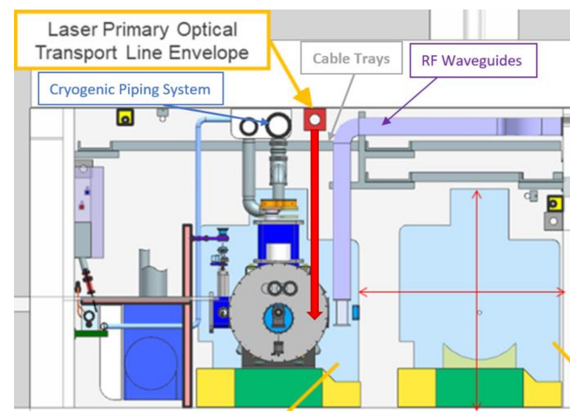
Transport Line Talk



Laser System Talk

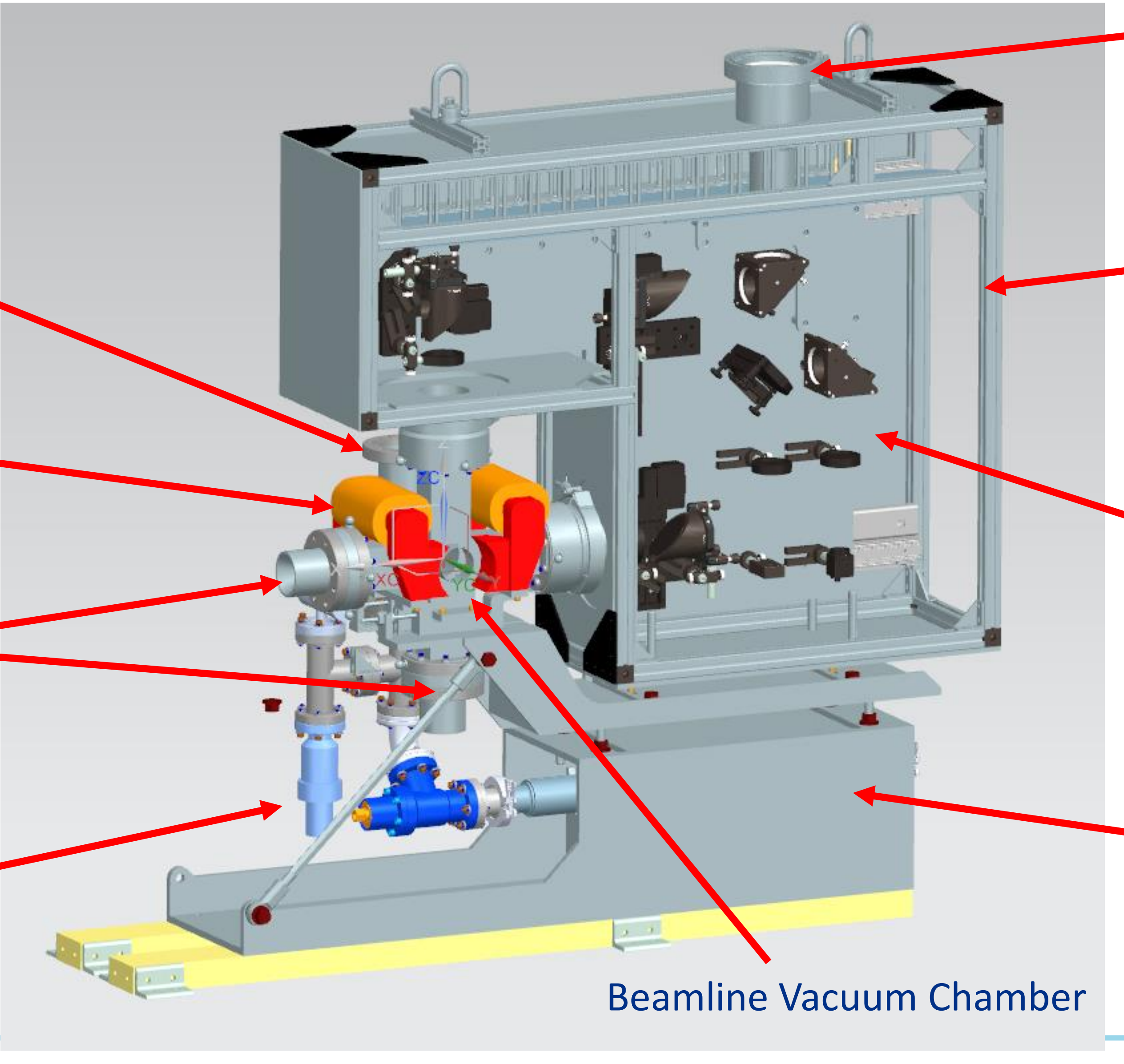


Mechanical Design Talk



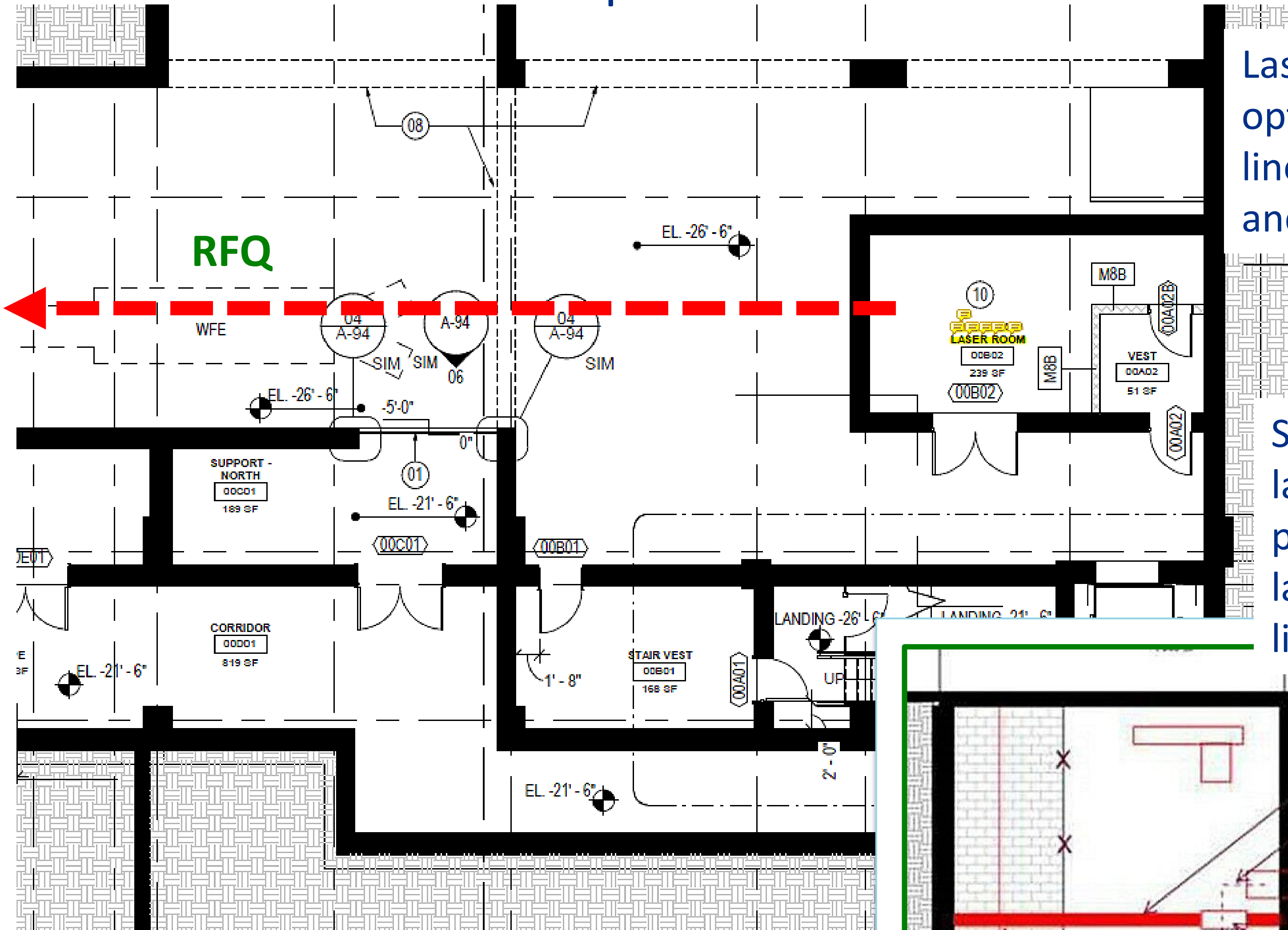
Laser Transport Optics and Alignment

Beamline Mechanical Design Labels



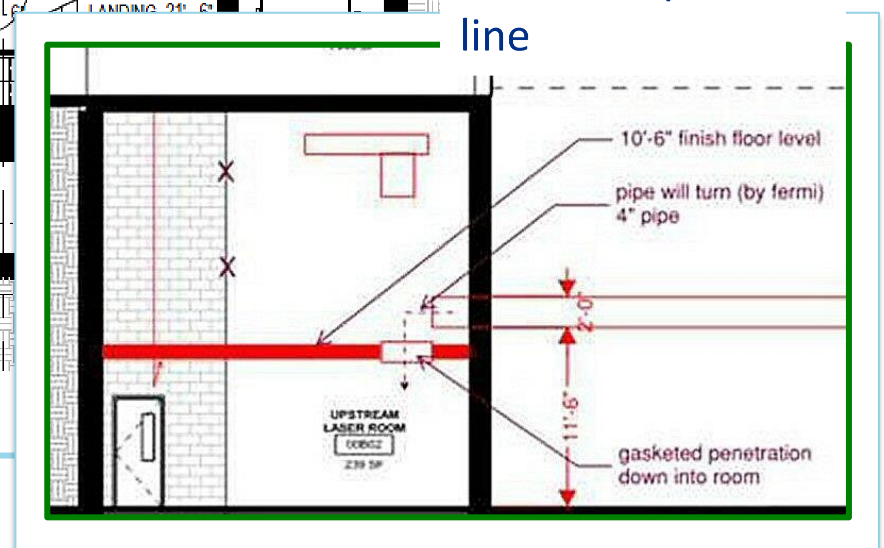
Laser Hut in Conventional Facility Drawings

Top View



Laser hut and optical transport line light-tight and interlocked

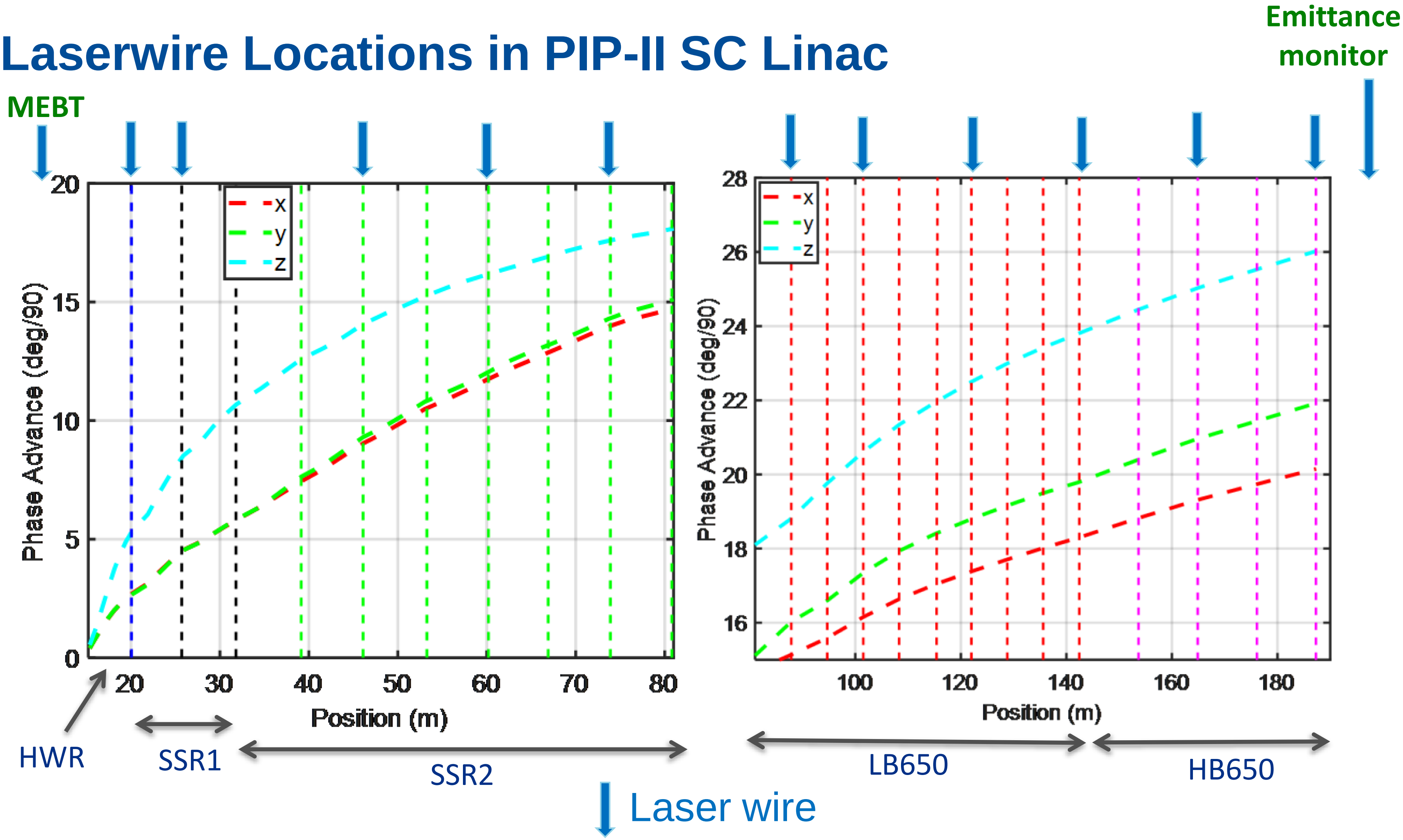
Side View showing laser hut ceiling penetration and laser transport line



Laserwire Design Team

- Project manager and instrument designer
  - Vic Scarpine, Scientist
- Modeling and simulations, magnet design, optics design
  - Randy Thurman-Keup, Scientist
  - Sanjini Wijethunga, Postdoc
- Laser design and development
  - Jinhao Ruan, Scientist, Laser Physicist
  - Parker Landon, Boston University graduate student
- Beamline mechanical design (vacuum chamber, stand, optics boxes)
  - Raul Campos, Mechanical engineer (Dakota Krokosz, ME)
  - Tiffany Price, Mechanical engineer
- Optical transport mechanical design
  - Bob Steinberg, Mechanical engineer
- Project CAM
  - Sherese Humphrey

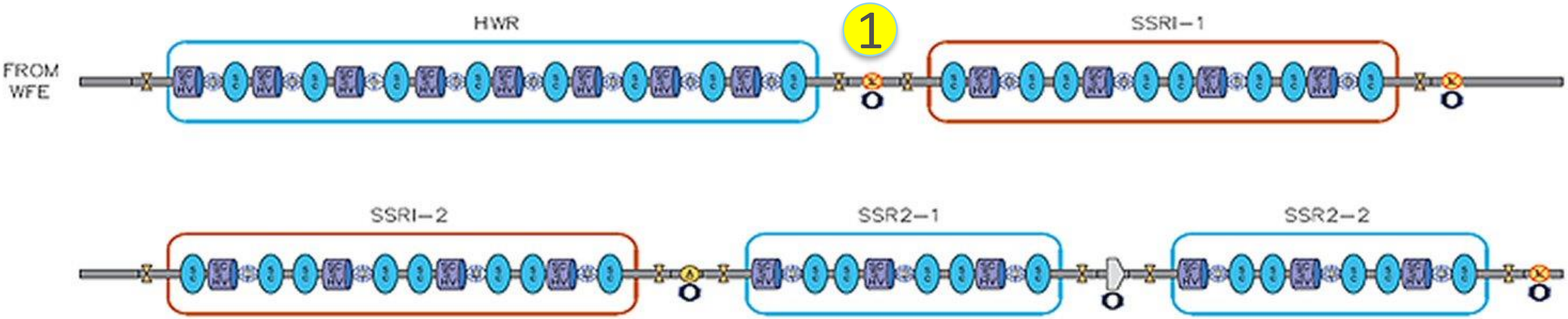
Laserwire Locations in PIP-II SC Linac



Most locations finalized in PIP-II accelerator physics lattice file.

- Emittance scanner laserwire location being finalized.

Laserwire Locations in Accelerator Physics Lattice File

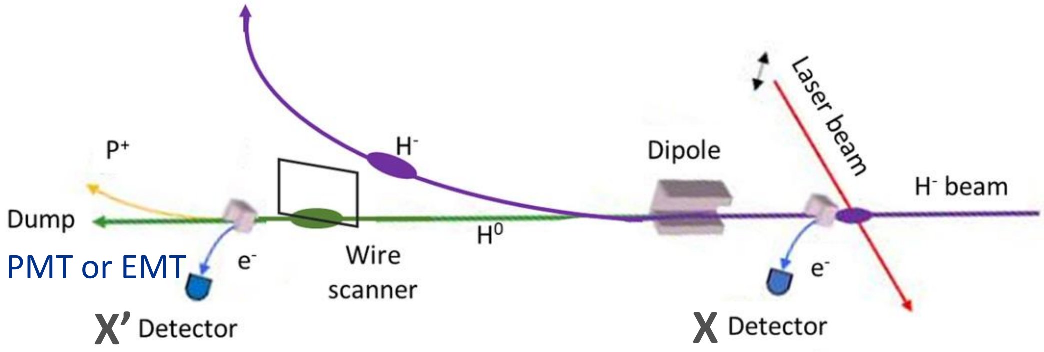


Accelerator Physics lattice file

1 →

15	FSCS coordinate system				
16	Line	Location	Typ_Code	Y	Z
17	N/A	N/A	N/A	Meter	Me
240	222	SCL-HWR-CAV-0108_UP	Marker	30493.080160	2
241	223	SCL-HWR-CAV-0108_CT	SCL-HWR-CAV	30492.955160	2
242	224	SCL-HWR-CAV-0108_DN	Marker	30492.830160	2
243	225	SCL-HWR-CM-0100_DN	Marker	30492.524880	2
244	226	SCL-HWR-LPM-0108_CT	SCL-XXXX-LPM	30492.431880	2
245	227	SCL-SSR1-CM-0100_UP	Marker	30492.074880	2
246	228	SCL-SSR1-CAV-0101_UP	Marker	30491.760880	2
247	229	SCL-SSR1-CAV-0101_CT	SCL-SSR1-CAV	30491.610880	2
248	230	SCL-SSR1-CAV-0101_DN	Marker	30491.460880	2

SNS Laserwire Emittance Monitor



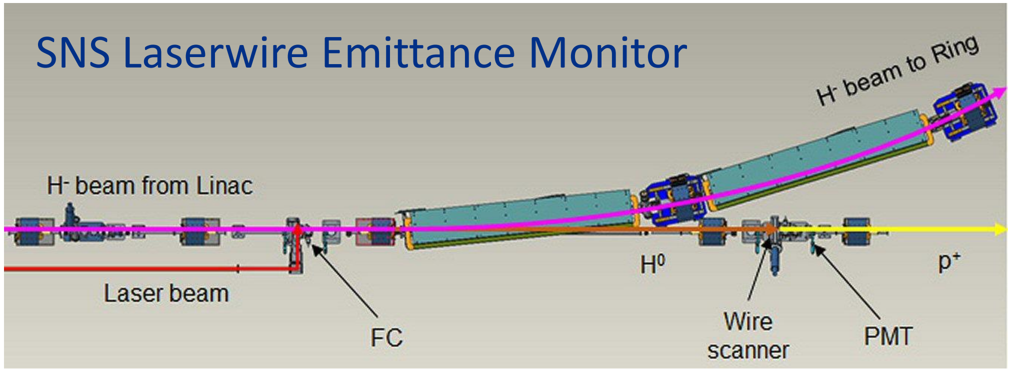
Laserwire Emittance Monitor Principle

- Use upstream laserwire to measure X profile
    - Downstream dipole steers H- but H0 goes straight
- Use straight ahead detector to measure H0 which is X' profile

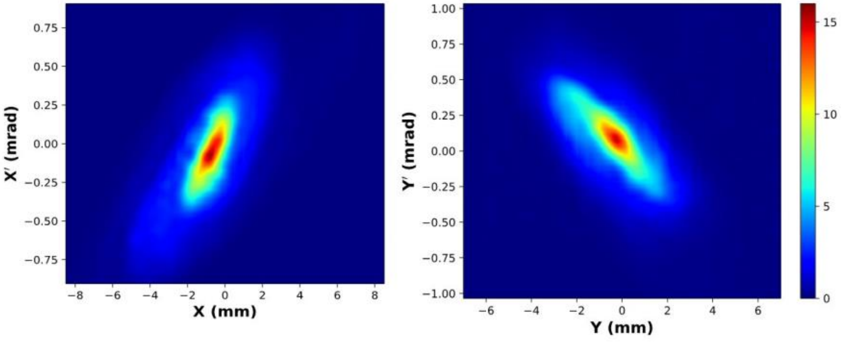
How to measure H0?

- *H0 very small signal → PMT/EMT*
- *H0 background from beam-beam stripping*

How far apart is laserwire from H0 detector?

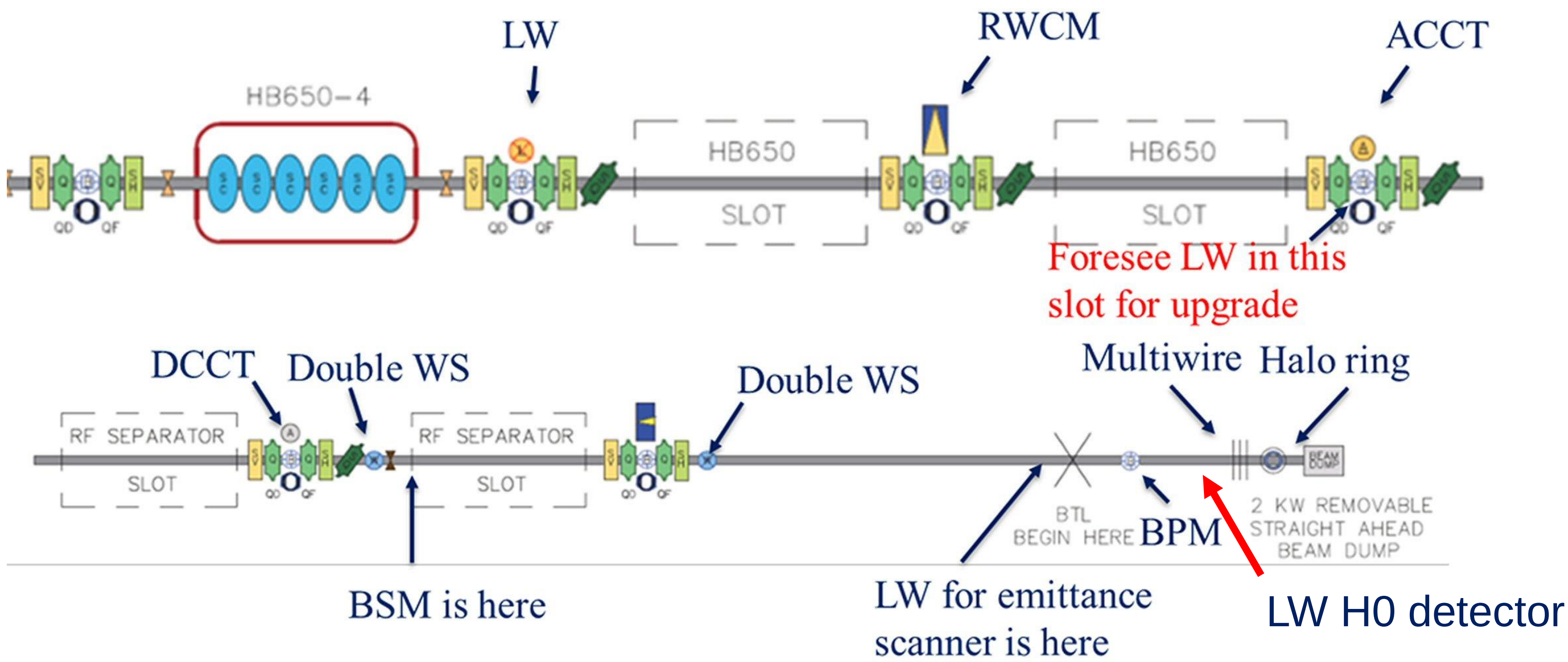


SNS Emittance Measurements

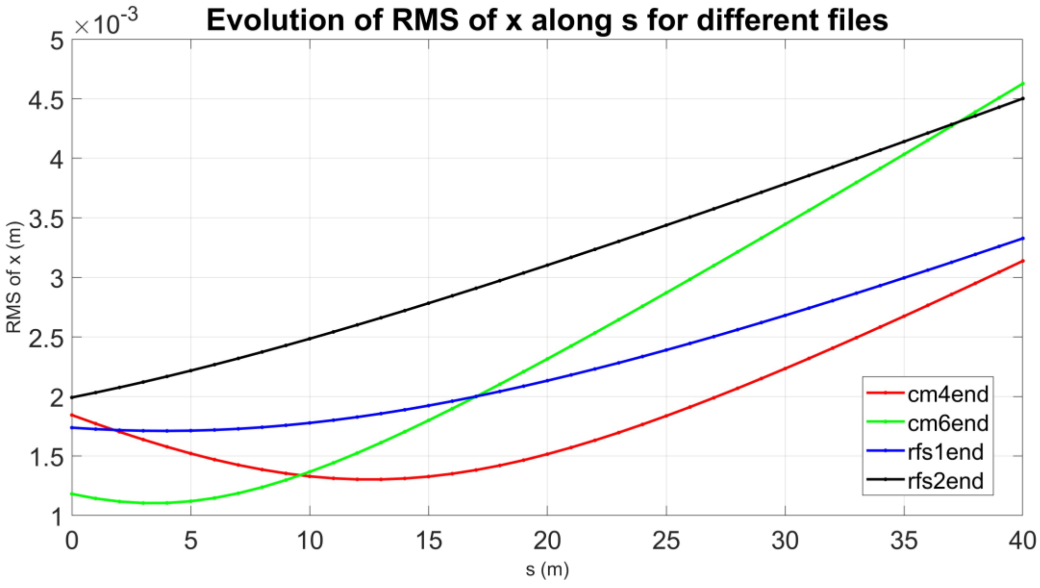


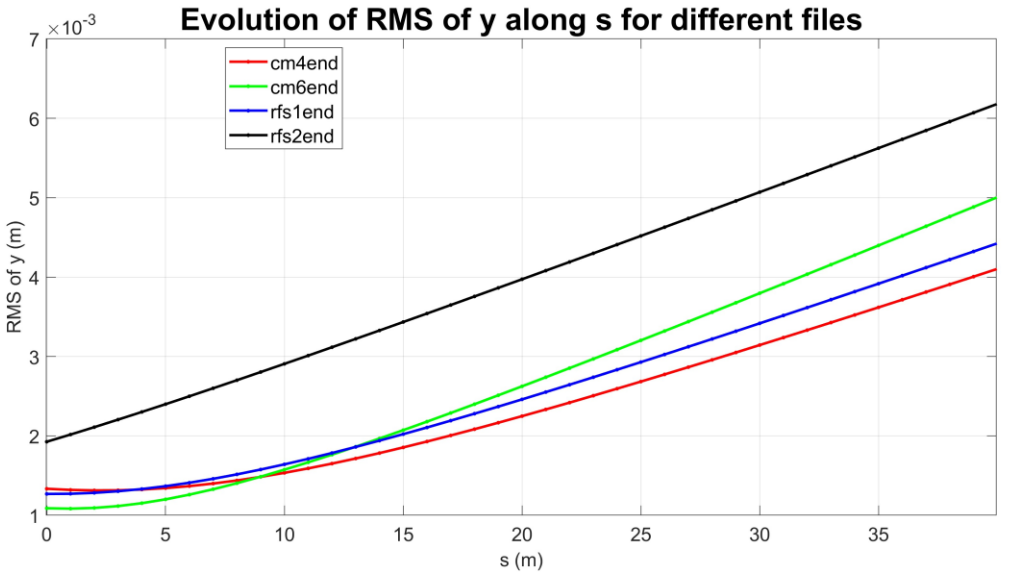
End of Linac Diagnostics – PIP-II Laser Emittance Monitor

- End of linac beam diagnostics being finalized in accelerator physics lattice file
- In the process of finalize LW for emittance location and H0 detector location
  - H0 detector early in design
    - Wire scanner + collection magnets + EMT
- Foresee LW is possible future LW location is additional cryomodules are added
  - This laserwire is not in PIP-II project scope.



Evolution of H0 after Laserwire (from Abhishek)





Use these plot to determine location of downstream H0 detector

- **If laserwire downstream after 2nd RF separator region then H0 detector can be 10 to 15 meters downstream**
- **A lot of flexibility in placement**

Summary

- PIP-II Laserwire is a challenging design
- PIP2IT experience was invaluable to PIP-II design
- Moving to free-space laser transport gives more flexibility to laser profile monitor operation
  - Allows for optimization of measurement performance
- Design of beamline laserwire units, laser optical transport line and laser design meet the PIP-II requirements
- Remaining talks will go into details of these designs