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Fermilab Laser Profile Monitors

Vic Scarpine

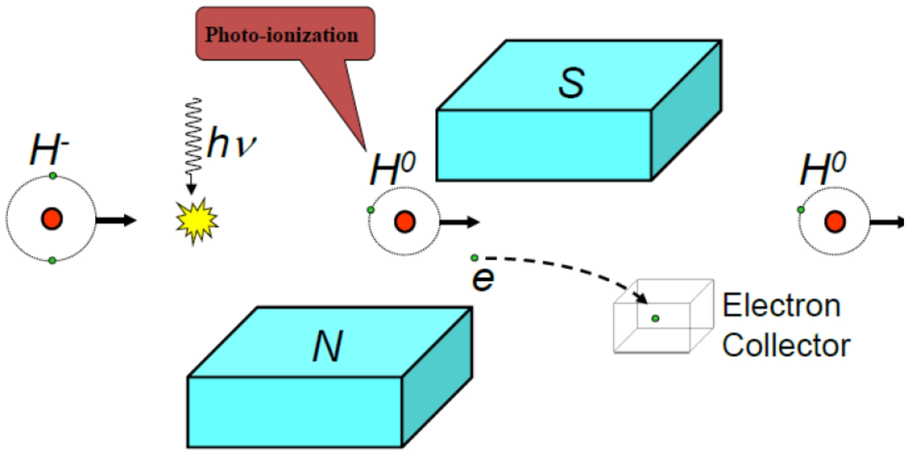
US – Japan Meeting on Laser Manipulation of H- Beams

March 28-29, 2018

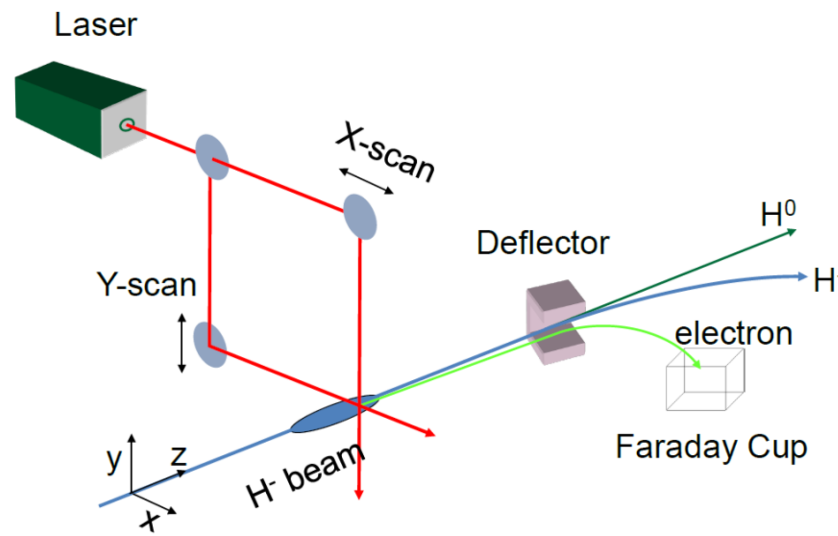
Principle of Laser Profiles for H- Beams

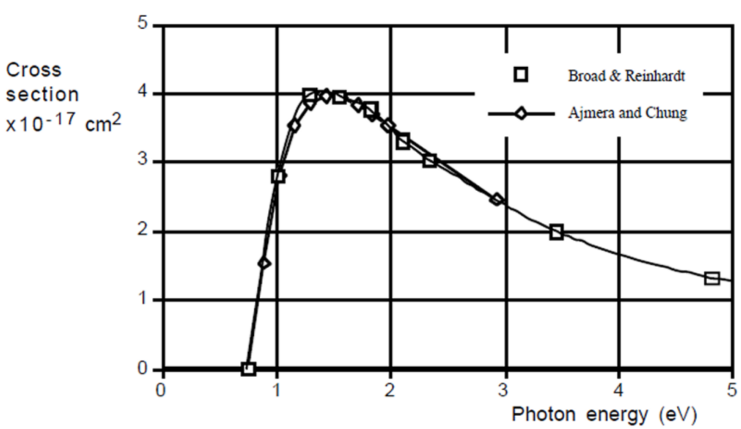
Photoionization of H-

$$H^- + \gamma \rightarrow H0 + e^-$$



Concept of a generic laser profile station





- 3.5 E–17 cm^2 at 1.17 eV
  - λ = 1064 nm
- Inversely proportional to β
  - Yield larger for low-energy beam

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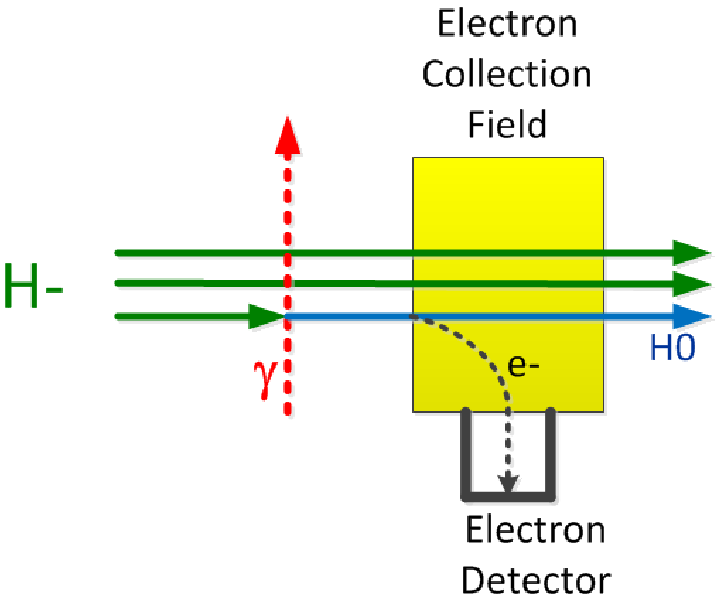
Laser Projects for H- Beams

- Laser Transverse Profiling
  - End of Fermilab linac
    - 400 MeV H- (Dave Johnson et al)
  - PIP-II Injector Test
    - Low Energy (up to ~20 MeV) portion of PIP-II linac
  - PIP-II linac
    - Between SC cryomodules
- Laser Longitudinal Profiling
  - PIP-II Injector Test
    - MEBT, 2.1 MeV
- Laser Notcher – Dave Johnson talk

Typical Laser Profilers

1. Require high-power, low rep-rate lasers (Hz)
   a. Slow → stability issues
   b. Safety issues → high power lasers are dangerous
      i. Complicated laser light transport
      ii. Possible damage to optical vacuum windows
   c. Separate transverse and longitudinal systems
2. Signal detection through electron collection
   1. Measure profile by scanning laser across (space or time) bunch



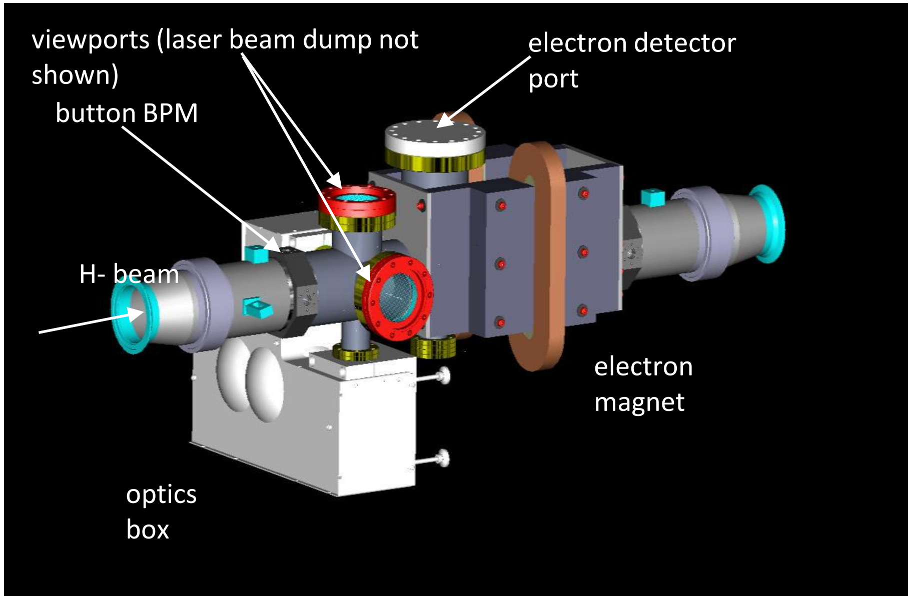
Transverse Laser Parameters
> 10's mJ per pulse
~ 10's Hz
~ 5-10 ns/pulse

SNS, Fermilab, BNL

Fermilab 400 MeV Configuration

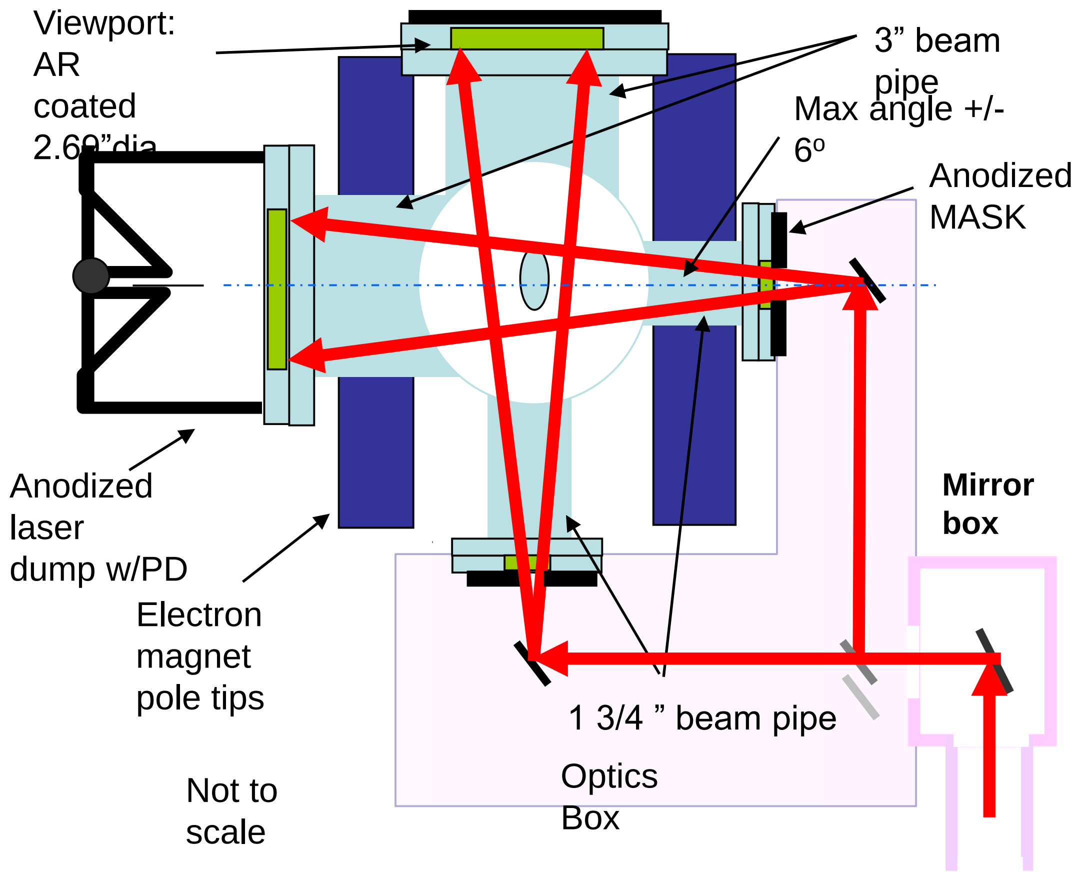
Use pulsed Nd:YAG Q-switched laser, λ = 1064 nm

- 50 mJ, 10 ns pulses → up to 92% neutralization
- Collect electrons → make transverse profile



Linac installation

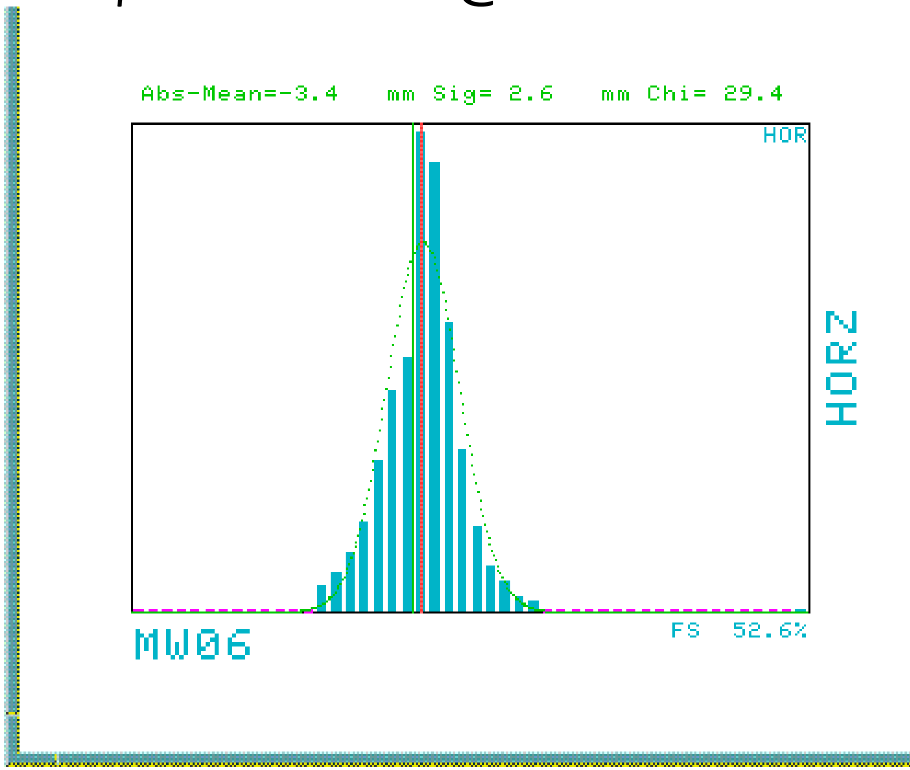
Cross section of the LPM

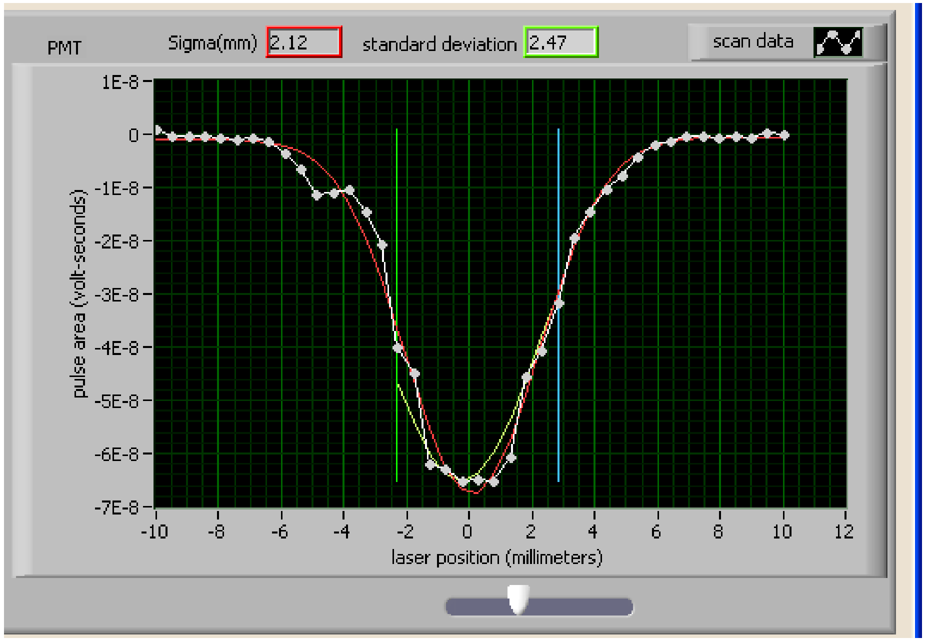


- Scan limits determined by size of laser dump viewport
  - +/- 33mm/264mm-> 125mr
  - +/- 7.16° optical (+/3.58° mechanical)
- Beam center -> +/-20 mm scan limits
- Mask at input viewport limits laser excursion to prevent launching laser up or downstream in vacuum chamber
- Cambridge Technology scanner
  - +/- 1 degree/volt -> input voltage of 3.58V
  - Repeatability 8 microradians
  - Galvonometers suffer from radiation damage – looking at alternatives

Comparison of Multiwire and LPM

Multiwire Data taken
$1D 11 turns @ 4E12

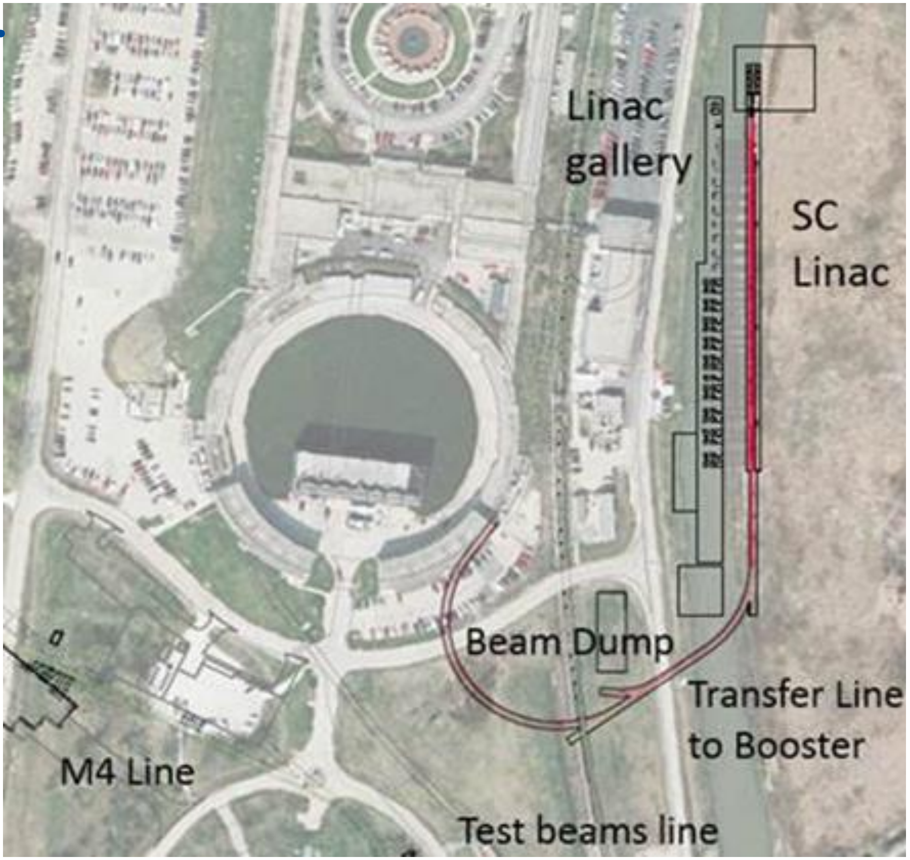




LPM profile
On $14 cycle (single bunch)

The PIP-II (Proton Improvement Plan II)

PIP-II is a proposed roadmap to upgrade existing proton accelerator complex at Fermilab. It is primarily based on construction of a 800 MeV superconducting linear accelerator that would be capable of operating in continuous wave (CW) mode.

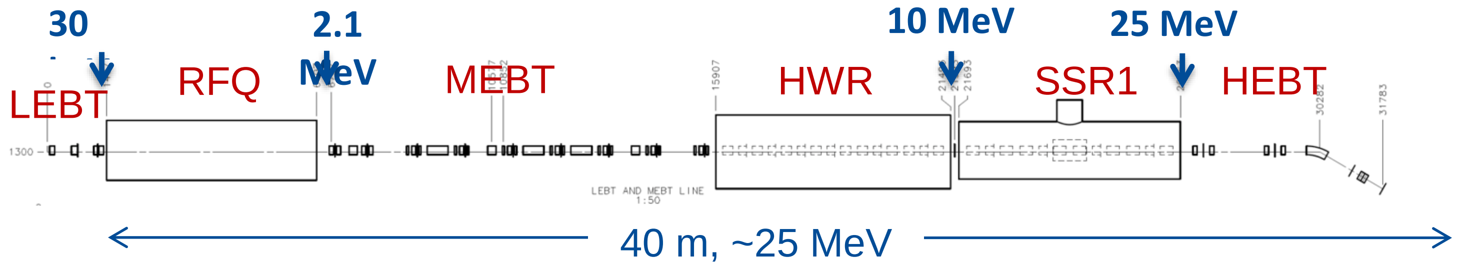


PIP-II Linac High Level Performance Goals

Beam Energy	800 MeV
Beam Current (chopped)	2 mA
Pulse Length	0.54 ms
Pulse Repetition Rate	20 Hz
Upgrade Potential	CW

PIP-II Injector Test (PIP2IT) Accelerator

PIP2IT will perform an integrated system test of the room temperature front-end and the first two cryomodules of the proposed PIP-II accelerator



PIP2IT will address:

- LEBT pre-chopping
- CW 162.5 MHz, 2.1 MeV RFQ
- Validation of chopper performance
  - Bunch extinction, effective emittance growth
- MEBT beam absorber
  - Reliability and lifetime
- CW Operation
- Operation of HWR and SSR1 with beam
- Emittance preservation

Parameter	Value	Unit
Beam kinetic energy, Min/Max	15/30	MeV
Average beam power	≤ 30	kW
Nominal ion source and RFQ current	5	mA
Average beam current (averaged over > 1μs)	1	mA
Maximum bunch intensity	1.9×10^{8}	
Minimum bunch spacing	6.2	ns
Relative residual charge of removed bunches	$< 10^{-4}$	
Beam loss of pass-through bunches	< 5%	
Nominal transverse emittance*	< 0.25	μm
Nominal longitudinal emittance*	< 1	eV-μs

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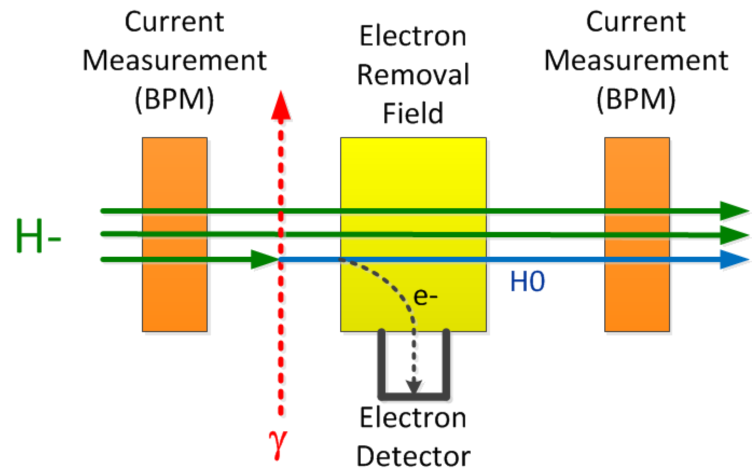
PIP2IT Approach

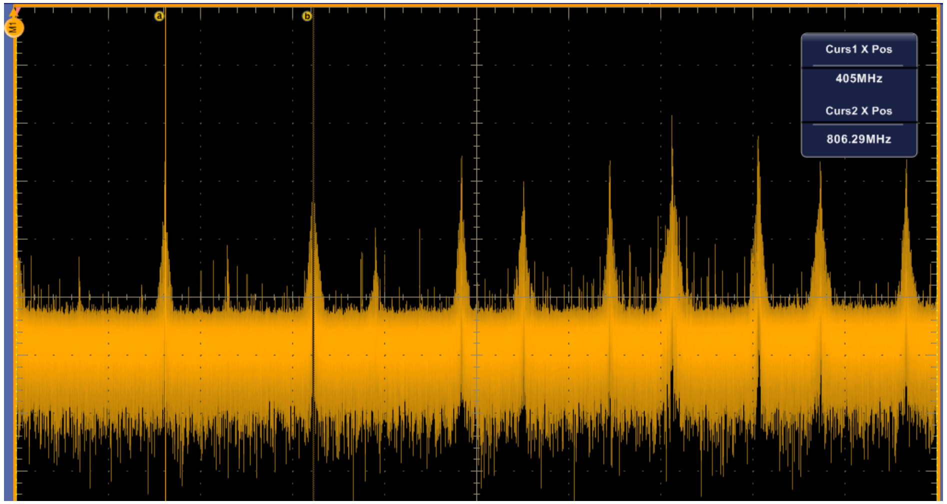
1. Use low-power, high rep-rate fiber mode-locked laser (MHz)
   a. Safe
   b. Combined transverse and longitudinal measurements
   c. High degree of synchronization to beam
   d. Amplitude modulated laser pulse for every beam bunch
2. Take advantage of signal detection via narrow-band synchronize detection
   a. Lock-in amplifier technique to decrease bandwidth and increase sensitivity by orders of magnitude
      a. Need long accelerator and laser pulses
   b. Detection of signals through BPMs → accelerators already have these
      a. Electron detection only for verification



Transverse and Longitudinal Laser Parameters
> 10's nJ per pulse (~ 2W CW pulses)
~ 162.5 MHz rep rate – phase locked to RF
~ 5-10 ps/pulse
Electro-optical modulation of pulse amplitudes ~ MHz's

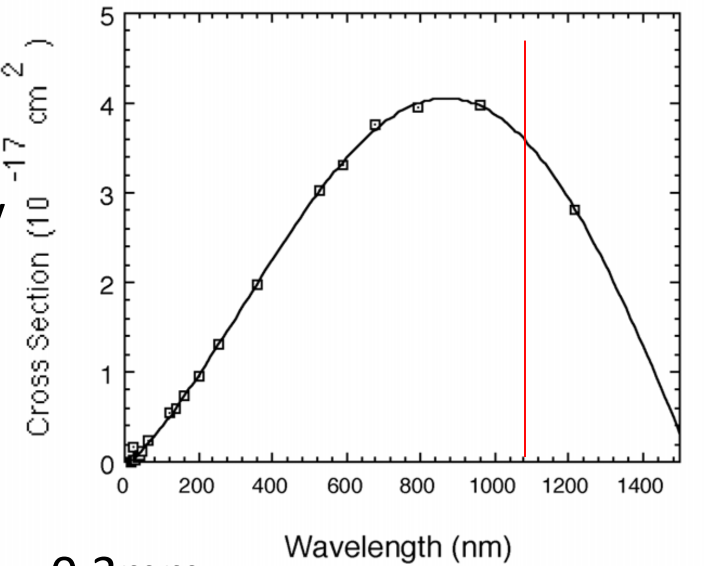
It's all about signal to noise

- Can increase signal by more beam or more laser power
  - Laser power gets expensive → We'll sample every bunch
- We'll reduce coherent noise by selecting correct modulation freq
- We'll reduce incoherent noise by narrow-band synchronize phase detection
- ***Calculation show we can reach 1e-6 detection sensitivity***



SNS laserwire electron detection signal spectrum

Some Numbers



- 1056 nm photon energy = 1.88e-19 J = 1.17 eV
- E_{laser}(1W at 81 MHz) = 12.3 nJ per pulse
- N_{phot} = 6.5e10 photons/pulse
- σ_{cs}(1056 nm) ~ 3.6e-17 cm^2
- Npart(5 mA @ 162.5 MHz) = 2e8 H- per bunch

Let σ(bunch) = 3 mm and σ(laser) = 0.1*σ(bunch) = 0.3mm

Then:

N(H- ion) = σ_{cs}/(2*π*σlaser^2)*Nphot*Npartoverlap

N(H- ionization at center) ~ 8000 → 4e-5 reduction

N(H- at 1σ) ~ 5000 → 2.5e-5 reduction

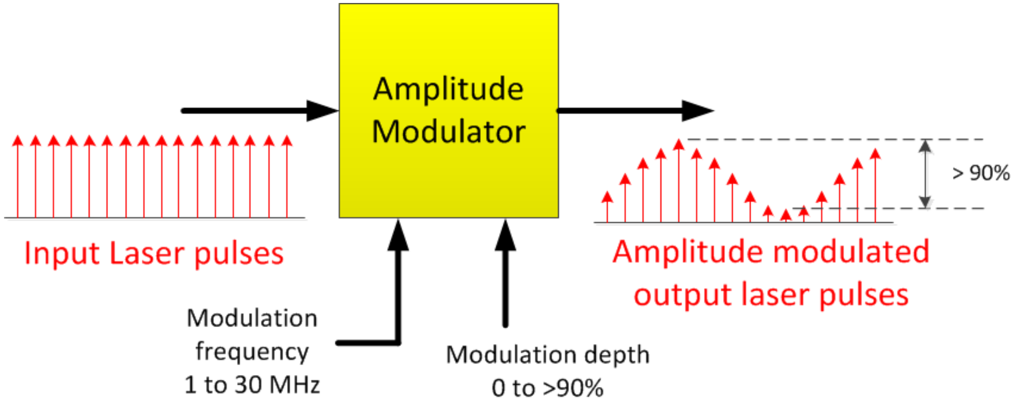
N(H- at 2σ) ~ 800 → 4e-6 reduction

Note: Laser to bunch shape matching may reduce these by ~50%

So for 1 W laser we need ~1e-6 beam current modulation sensitivity

Options: Can increase laser power and/or lower laser pulse rate

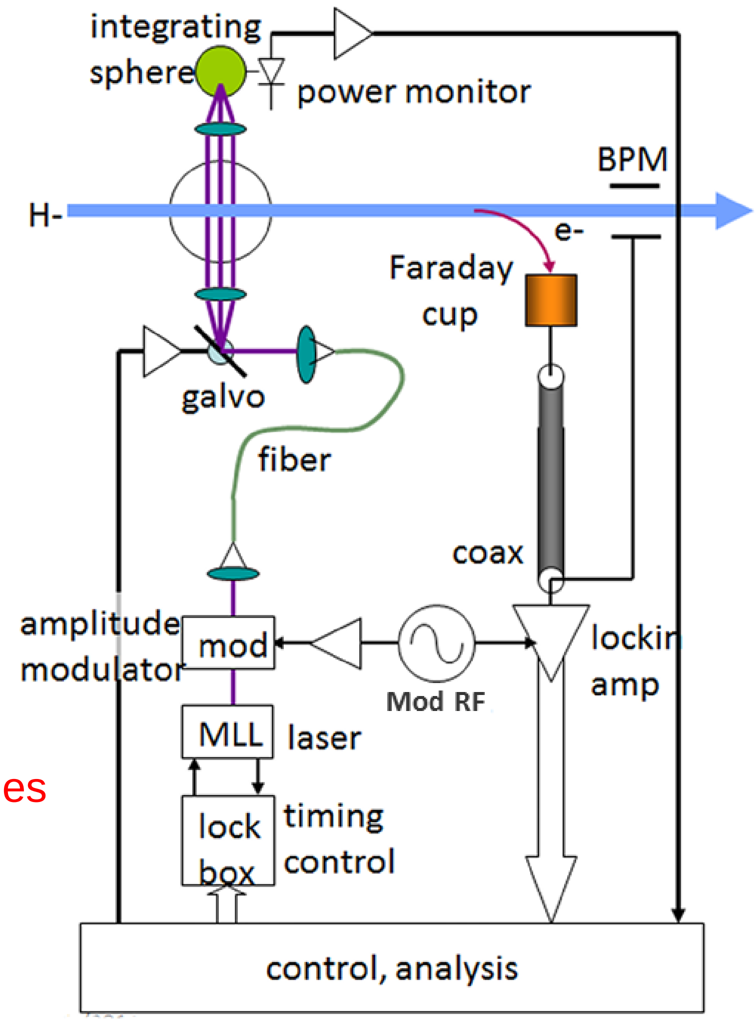
R&D – Laser Diagnostics Development – Low-power transverse (and longitudinal) laser wire for PIP-II



- Laser rep-rate is locked to accelerator RF
- Amplitude modulate laser pulses
- Distribute modulated laser pulses via fibers
- Measure profiles by either:
  - Collection of electrons
  - Use BPM as reduced-beam pickup
    - Allows laser monitor to fit between cryomodules
- Narrow-band lock-in amp detects modulated signal

Prototype laser wire

- Single plane measurement – vertical profiles
- Goal to test laser profiling at PIP2IT



R. Wilcox, LBNL

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PIP2IT Goals

Primary Goal:

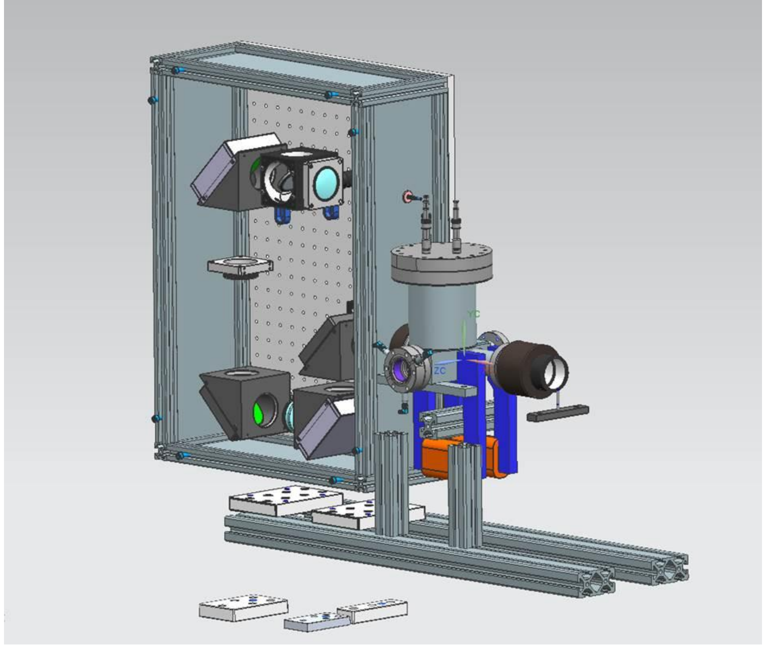
- Demonstrate both transverse and longitudinal profile measurements to a sensitivity of 1e-6 using low-power laser through fiber distribution and synchronized detection

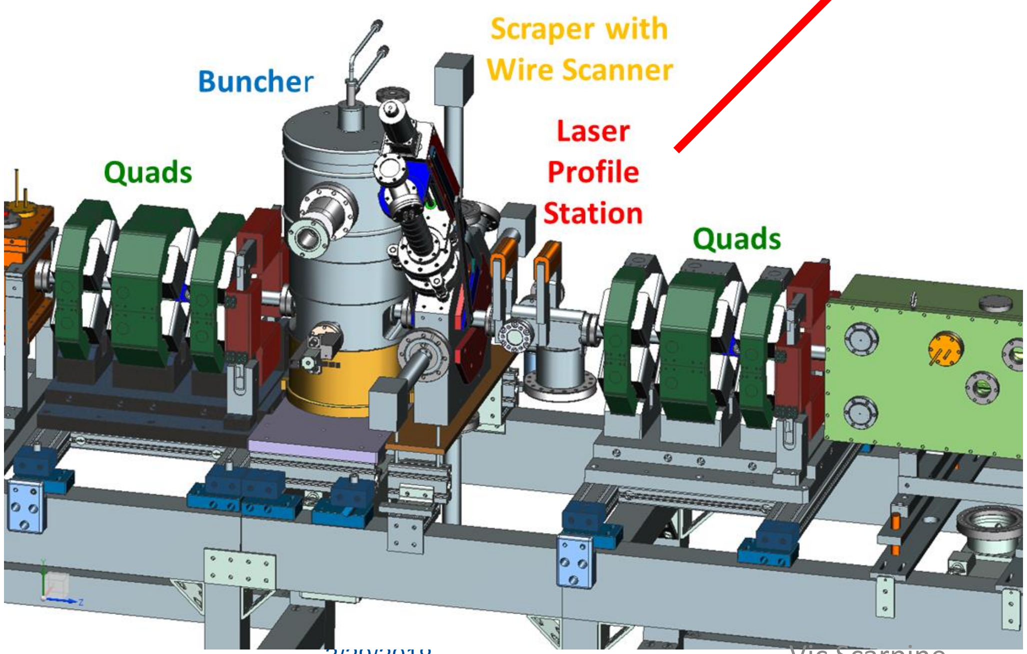
Secondary Goal:

- To understand any technology and systematic effects that would limit achieving primary goal

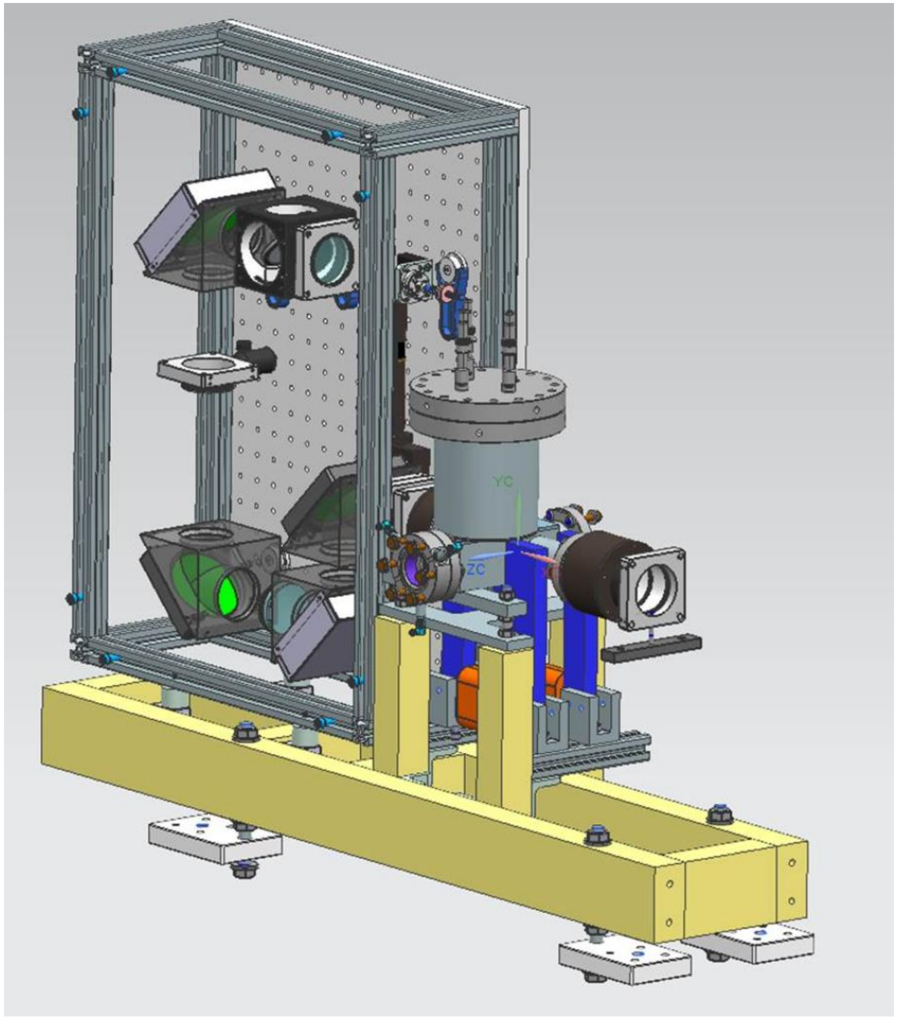
Vacuum Chamber Design

- Vacuum chamber welded
  - Installation in March?
  - Need vacuum windows
  - Ring pickup installed
- Single plane measurement only – vertical profiles

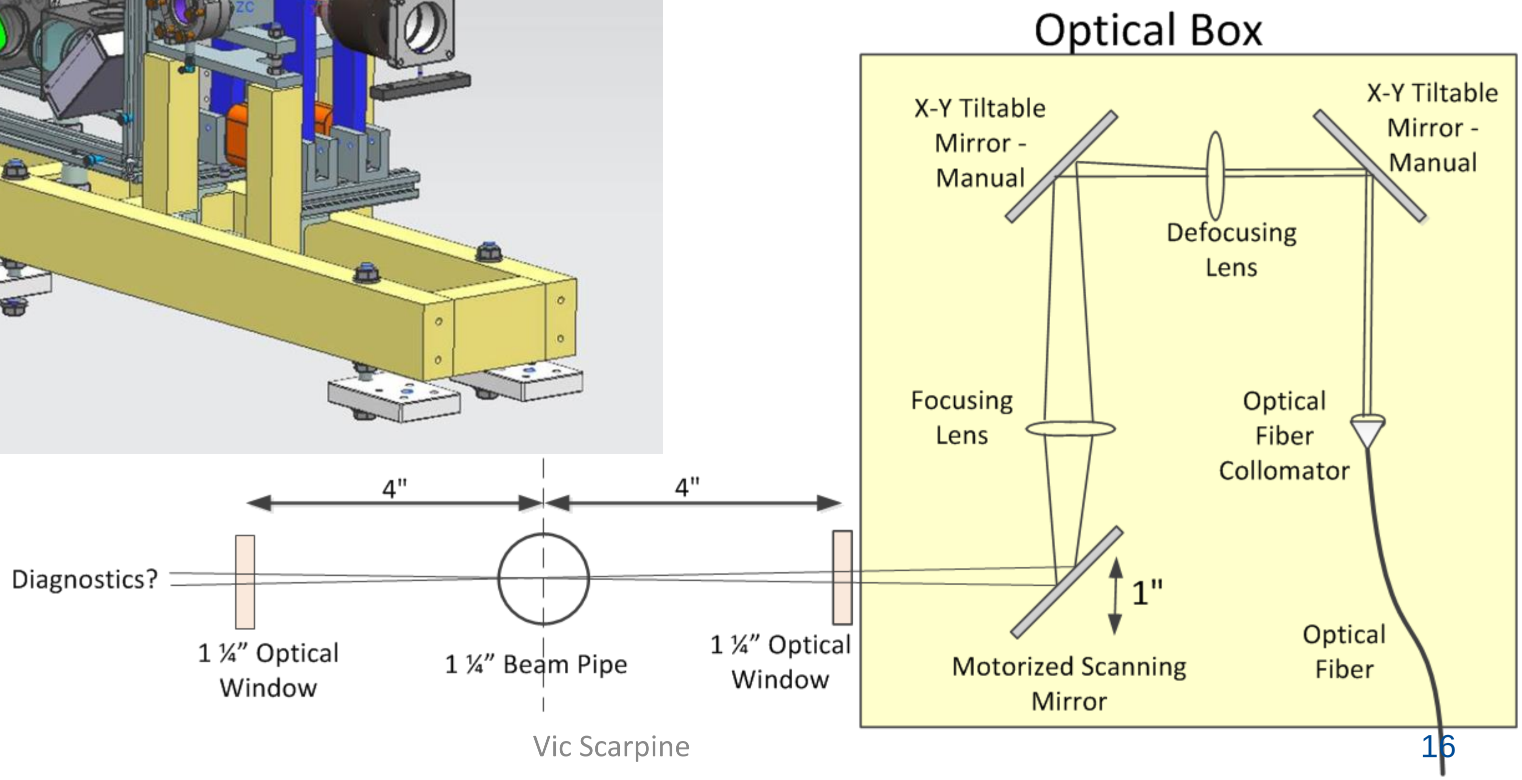




Optics



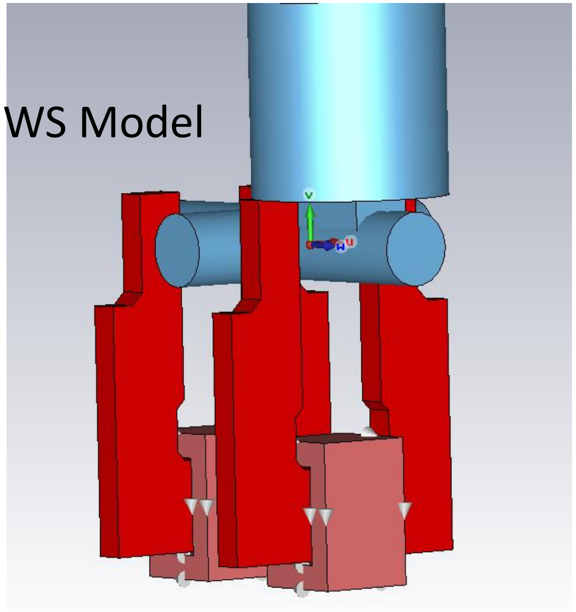
Optical design in progress



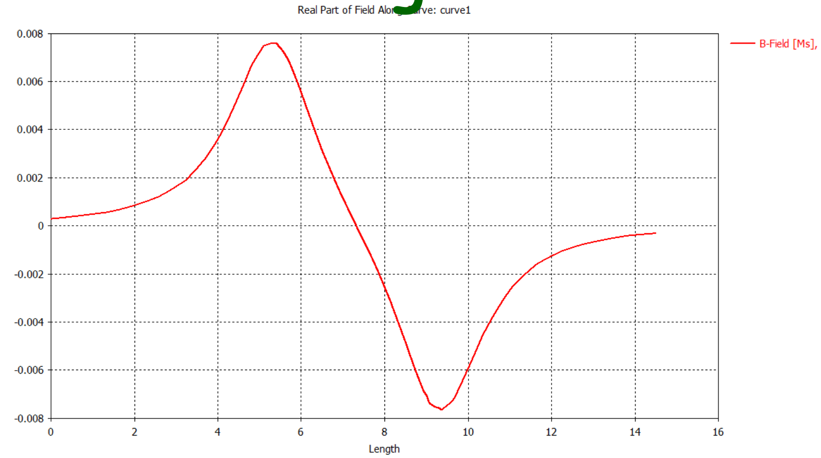
Laserwire Magnet Field Modeling

- *Magnet design and simulation critical*

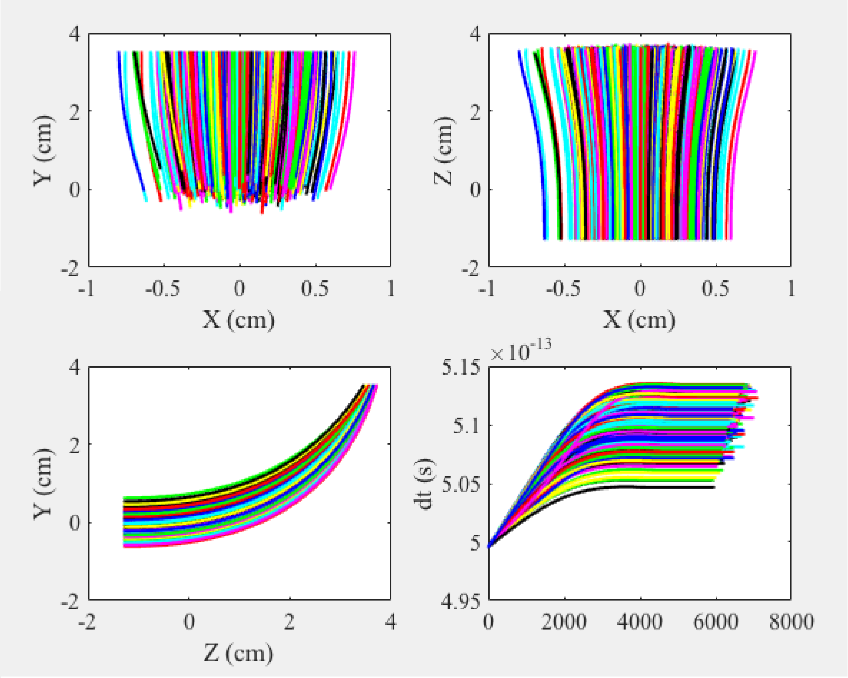
MWS Model



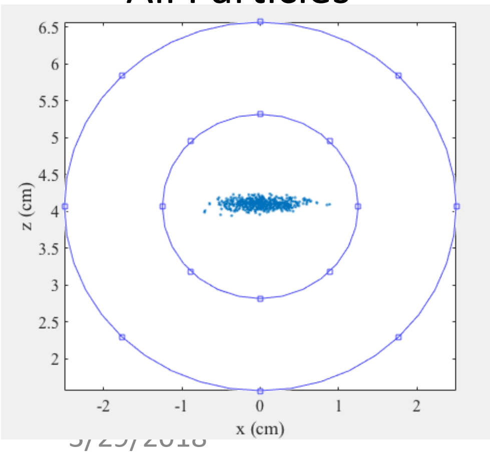
B-field on axis



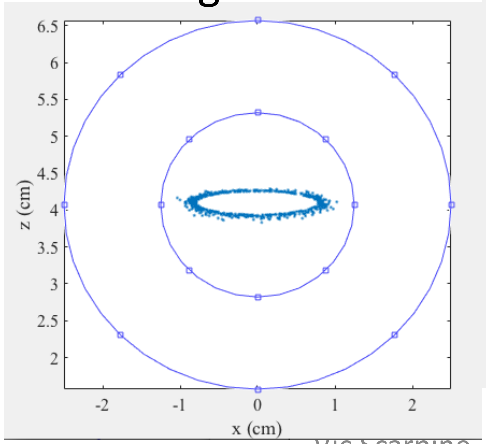
5 mA H-
2 mm rms



All Particles



3-sigma cut



Fiber Laser System

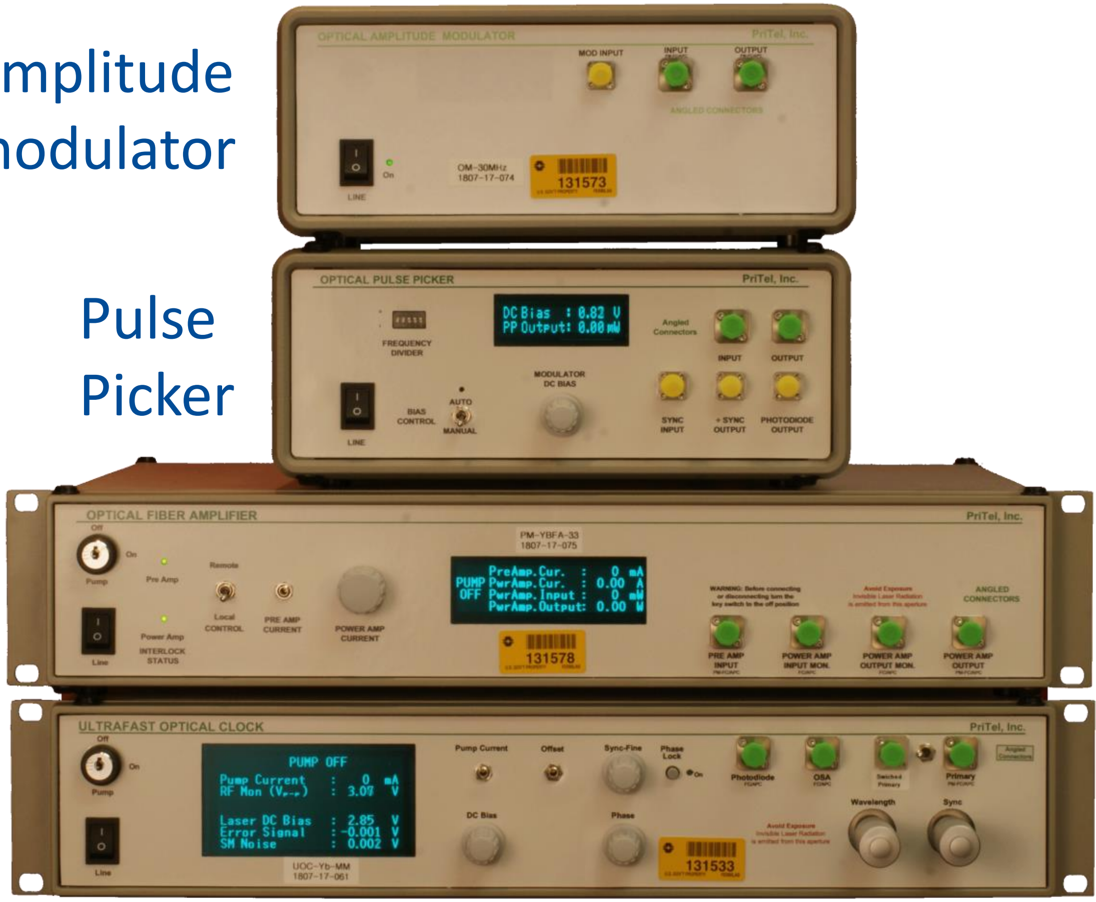
- Delivered from Pritel in December
- 2 W fiber laser
- < 12 psec rms
- Amplitude modulation

Amplitude modulator

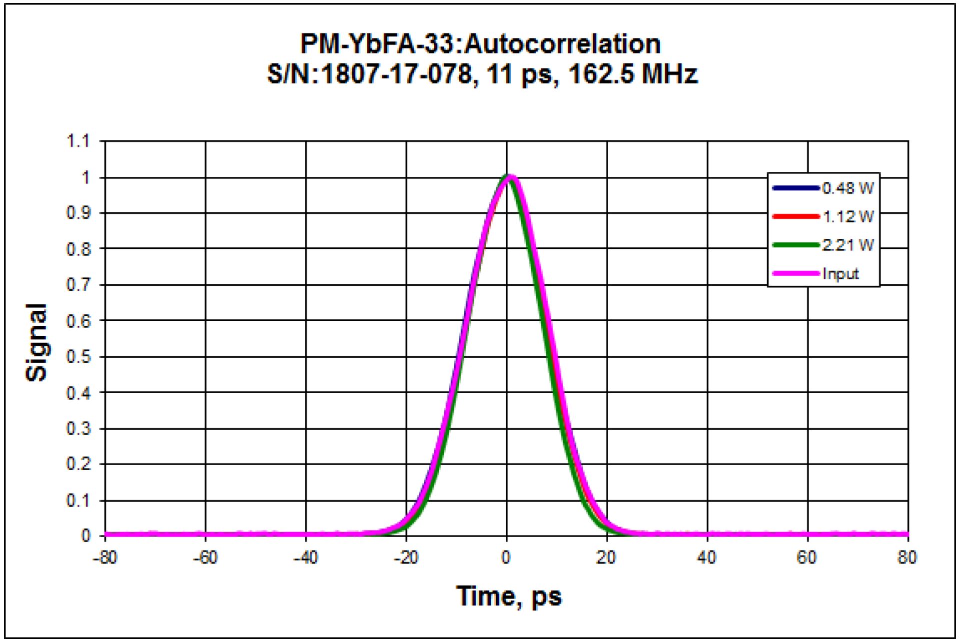
Pulse Picker

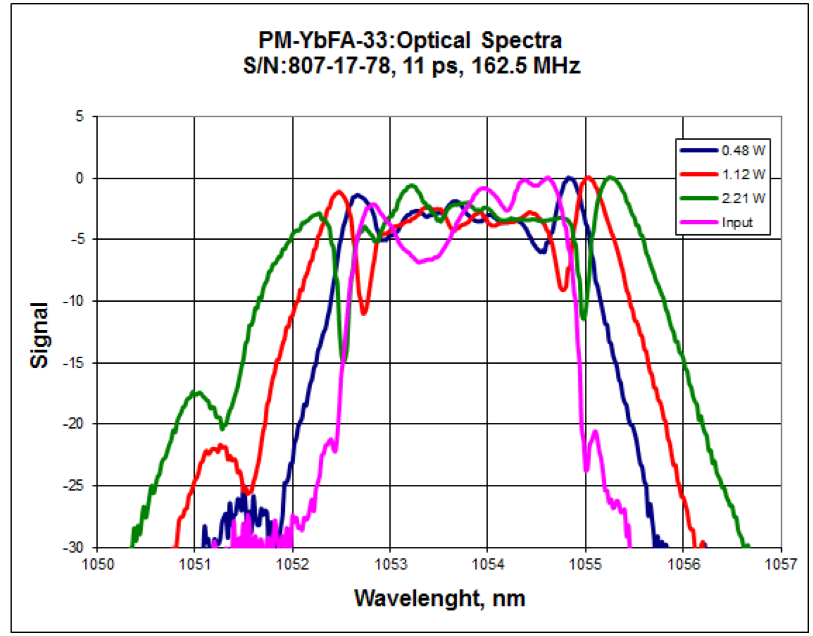
Fiber Amplifier

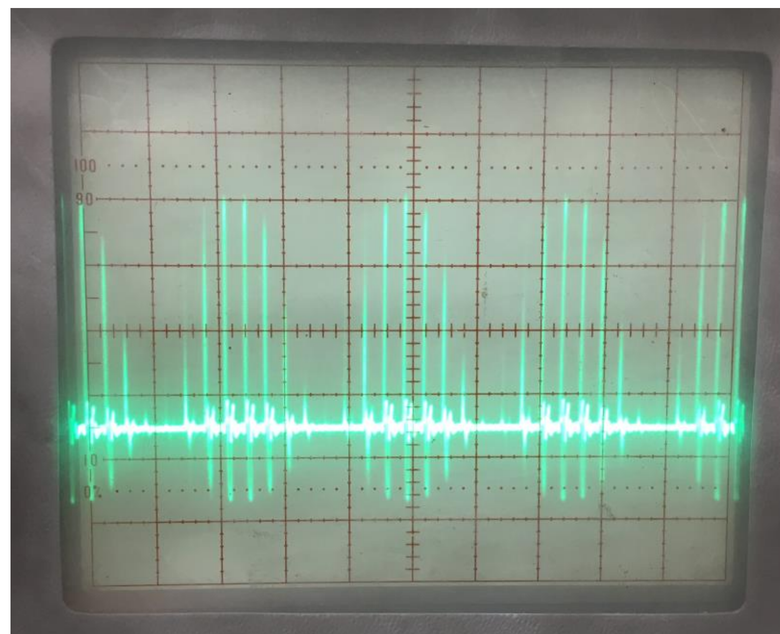
Fiber Seed Laser



Laser Performance







- > 2 W power
- 11 ps rms
- Amplitude modulated pulses

Summary

- Fermilab utilizing lasers to study and manipulate H- beams
- LPM in 400 MeV linac demonstrated transverse profile measurements with high-power laser
  - Galvonometer scanning systems needs replacement
- LPM at PIP2IT will investigate transverse and longitudinal profiling with low-power laser
  - Working to take initial measurements later this summer
- In the era of superconducting linacs, lasers are becoming the primary profiling tool for high-intensity H- beams