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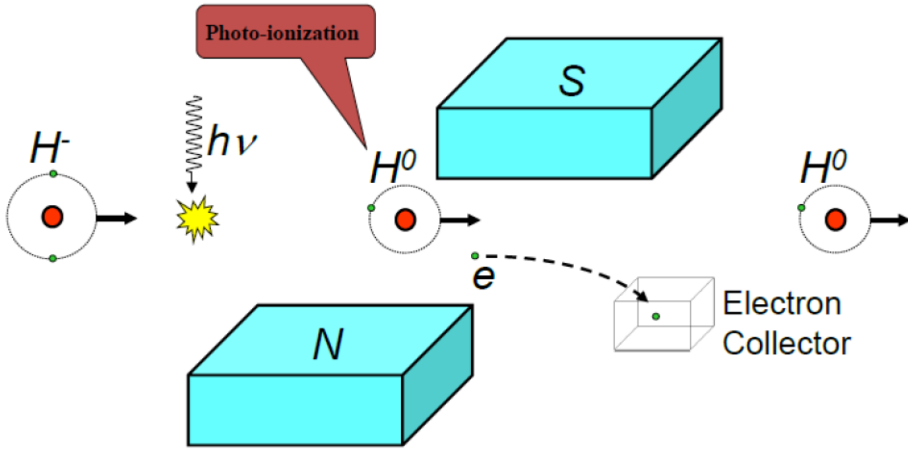
Update on Laser Profile Diagnostics for P2IT (with an eye toward PIP-II)

Vic Scarpine

PIP-II Meeting

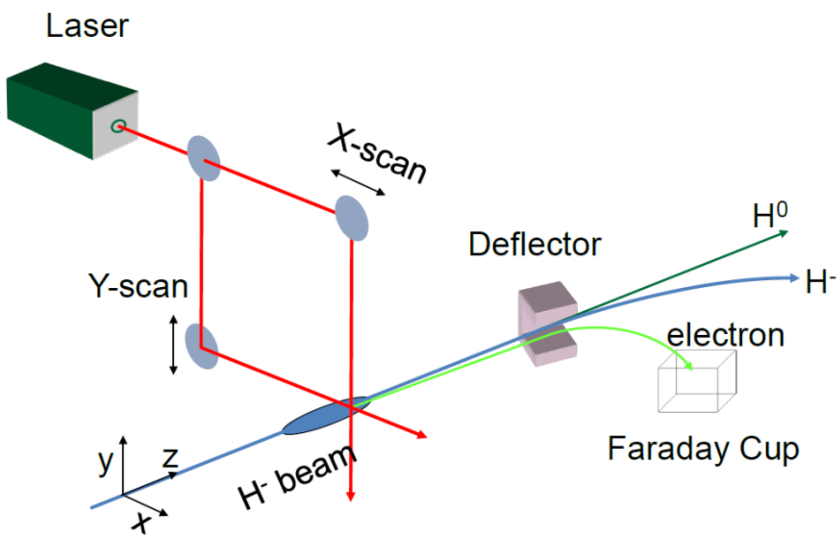
27 Sept 2016

Principle of Laser Profiles for H- Beams



Photoionization of H-

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

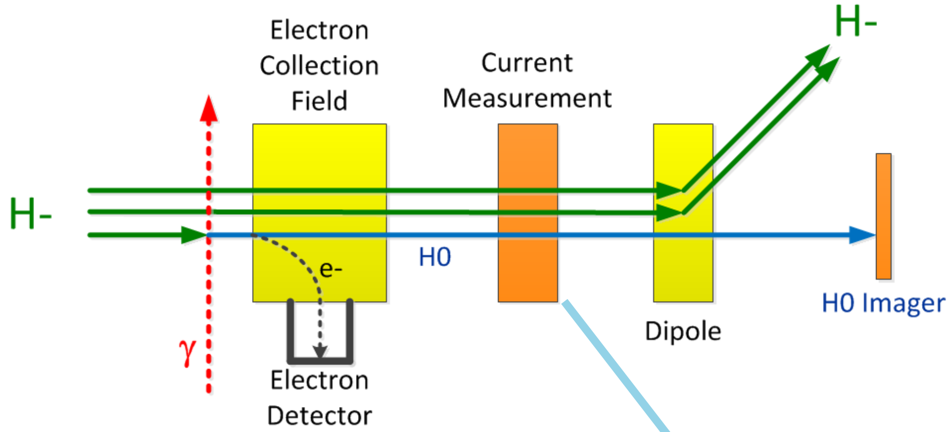


Concept of a generic laser profile station

Laser Diagnostics Discussion

Possible measurements:

1. Transverse profiles
2. Longitudinal Profiles
3. Transverse Emittance (measure H0)



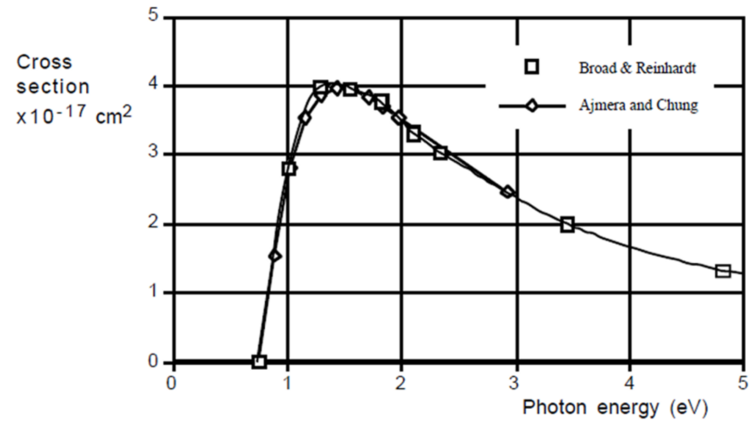
Laser Options:

- High-power free space laser
- Low-power fiber laser

Measurement Options:

- Direct electron detection
- Reduced H- current

Photodetachment Cross Section



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

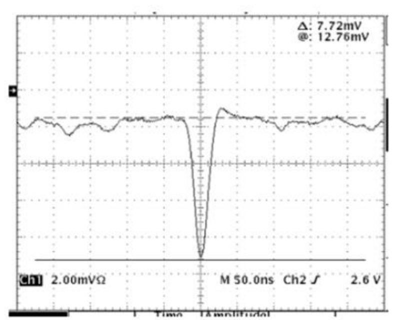


Figure 4: Scope trace of the current transformer signal showing notch created by the laser pulse.

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- High-power Nd:YAG
- 750 keV H-

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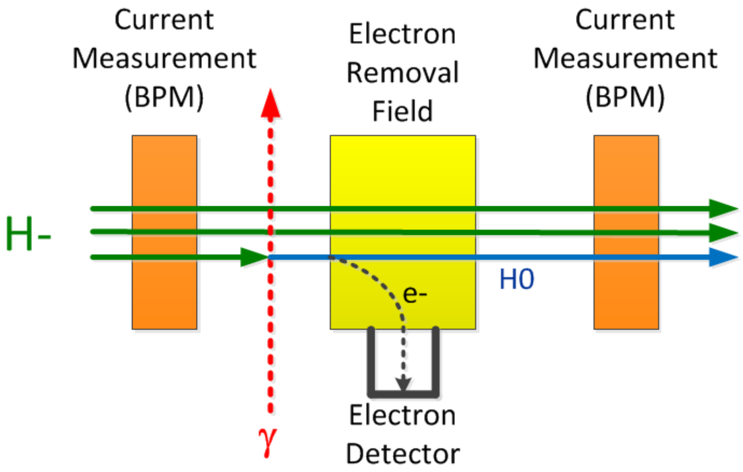
P2IT Goals

To demonstrate transverse (and longitudinal) profiling of 2.1 MeV P2IT MEBT H- beam using:

1. reduced beam current technique using either modulated low-power fiber laser (primary) – part of LDRD
2. electron collection of modulated low-power fiber laser (secondary)
3. High-power free-space laser (tertiary) – transverse profiles only

History:

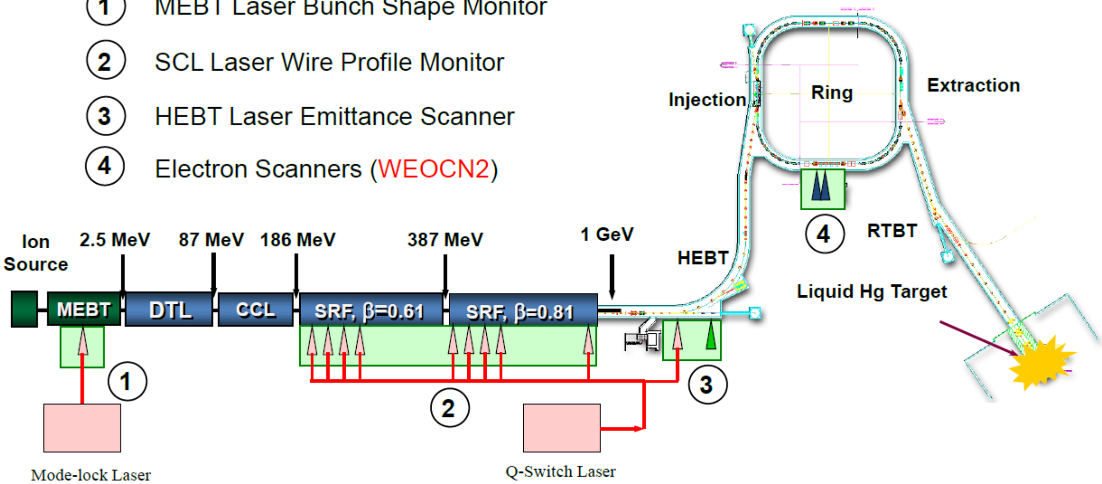
- Transverse profiling with high-power free-space laser and electron collection
  - *operational* at SNS
- Longitudinal profiling using lower-power fiber delivery system and electron collection
  - *demonstrated* at SNS
- Transverse profiling using high-power free-space laser and measurement of reduced beam current
  - *demonstrated* at BNL
- No one has demonstrated transverse or longitudinal profiling using lower-power fiber lasers and reduced beam current technique
  - *Because it's very difficult (LDRD)*

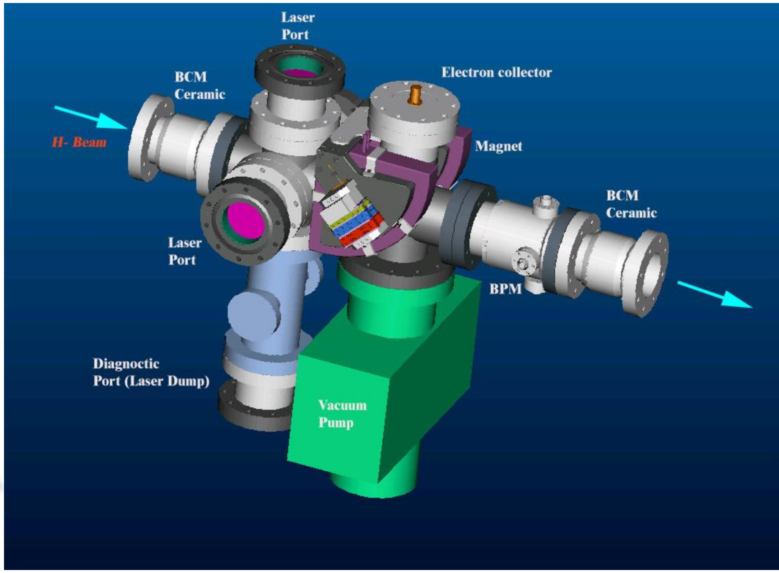


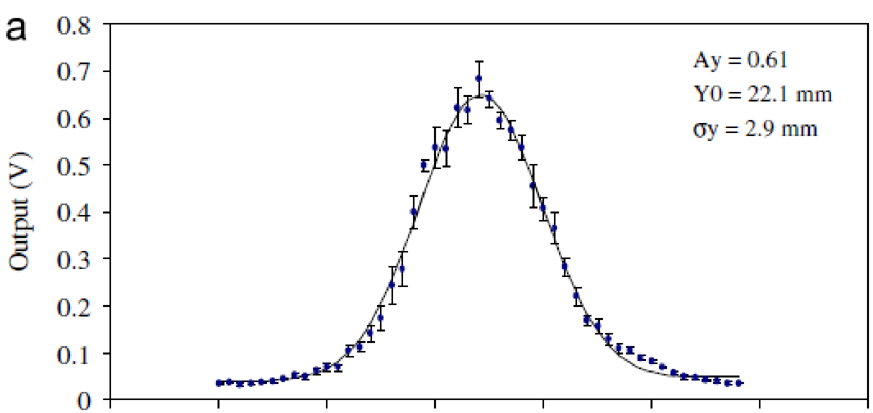
SNS Transverse Laser Profiling - Operational

Non-invasive Beam Profile Diagnostics at SNS

1. MEBT Laser Bunch Shape Monitor
2. SCL Laser Wire Profile Monitor
3. HEBT Laser Emittance Scanner
4. Electron Scanners (WEOCN2)







Q-switched Nd:YAG laser

- 1 J
  - Danger to optical windows
- 10 ns pulses, 30 Hz

Laser Transport Issues

- Laser drift over long transport
- Developed active feed-back mirror system
  - 5 μrad stability

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SNS MEBT Longitudinal Profiles - Demonstrated

- 2.5 MeV H-
- Scan psec laser through bunch in time
- Ti-Sapphire mode-locked laser
  - 2.5 ps
  - 80.5 MHz
  - Locked at 1/5 RF
  - Problems with free-space laser
    - Moved to fiber laser based system

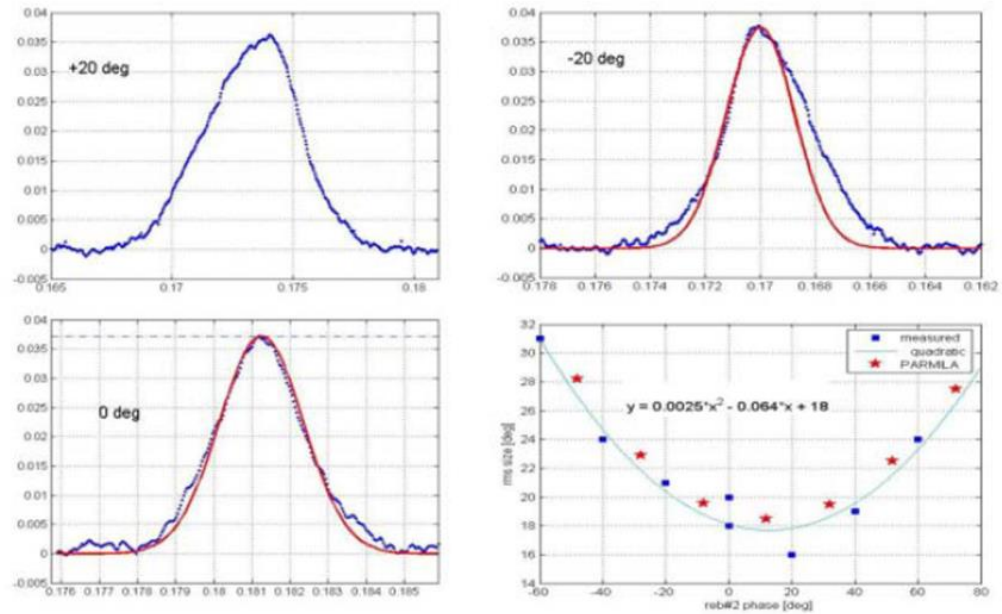


Figure 5. Longitudinal bunch profile measured with mode-locked laser in the MEBT (blue dots) and Gaussian fit (red line). RMS bunch-length vs. the rebuncher phase (measurements – squares, simulation – stars, solid line quadratic fit) are shown on bottom right figure.

Laser Profiling Options and Issues

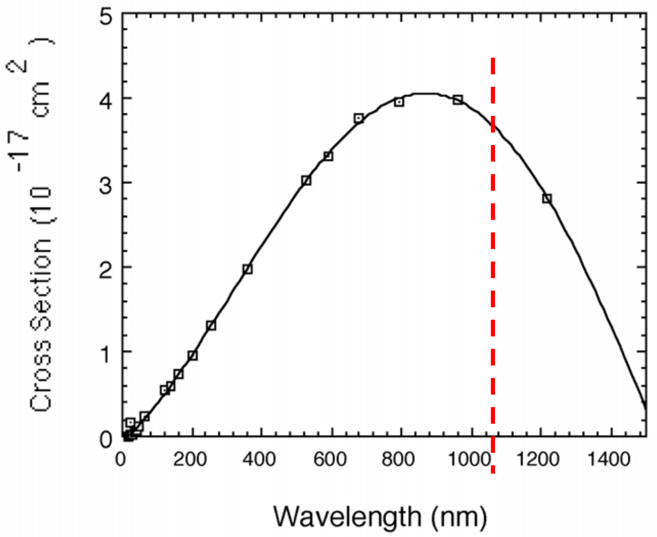
1. **High-power + electron collection**
   – Proven by SNS
   – Laser transport difficult and expensive or
   – Laser at each station expensive and radiation risk
   – Risk of optical vacuum window damage
2. **High-power + current reduction**
   – BNL has done this
   – Eliminates electron collection hardware
     • Requires excellent current measurements
   – Laser transport difficult and expensive or
   – Laser at each station expensive and radiation risk
   – Risk of optical vacuum window damage
3. **Low-power + electron collection**
   – SNS working on this → promising
   – CERN (LINAC4) also working on this
   – Eliminates laser transport problem
   – Transverse + longitudinal
   – Signal to noise? → fiber laser power
4. **Low-power + current reduction**
   – No one has done this
   – Eliminates laser transport problem
   – Eliminates electron collection hardware
     • Save space and money
     • Requires excellent current measurements
   – Transverse + longitudinal
   – **Signal-to-noise may be too small**

Proposed Prototype Laser Profile Station for P2IT

- Laser profiling still quasi-R&D
- Best (signal and cost) option for PIP-II not clear
  - Fiber laser plus current-reduction most desirable but also probably most difficult
- Develop “generic” laser profile station to test in/end of P2IT MEBT
  - Transverse and longitudinal
  - Free-space and fiber lasers
  - Electron collection and current reduction

Options	High-Power laser	Fiber Laser
Electron Collection	****	***
Current Reduction	***	*

Some Numbers for low-power option



- 1056 nm photon energy = 1.88e-19 J = 1.17 eV
- E_{laser} = 6.15 nJ per pulse (1 W @ 162.5 MHz)
- N_{phot} = 3.3e10 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) ~ 4000 e^- → 8e-5 reduction

N(H- at 1σ) ~ 2500 e^- → 5e-5 reduction

N(H- at 2σ) ~ 400 e^- → 8e-6 reduction

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

So for 1 W laser we need ~8e-6 beam current modulation sensitivity for reduced current detection

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

Low-Power Transverse and Longitudinal Laser Wire

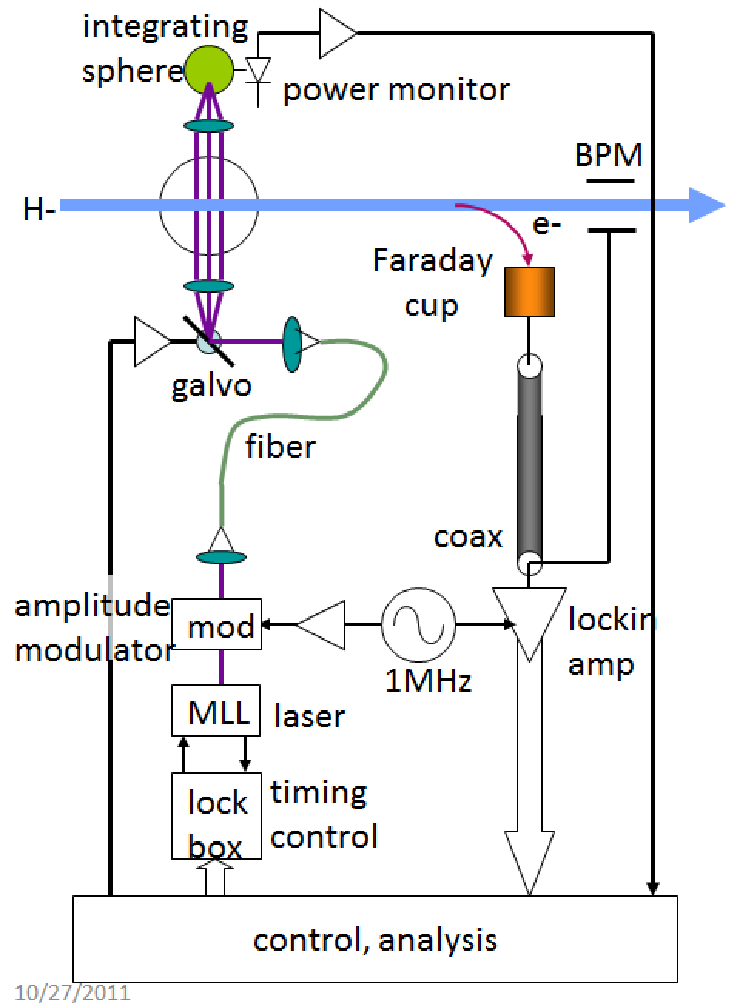
Mode-locked psec laser used to measure both transverse and longitudinal profiles

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

Questions:

- What is photo-dissociation at low laser power?
- What are the noise issues?
- What are the limits to power in the fiber?
- What signal-to-noise ratios and averaging times are practical?
  - Accelerator and laser stability, RF noise, etc
- How short of a longitudinal pulse needs to be measured?

Fall-back laser wire option is to use high-power laser technique similar to SNS

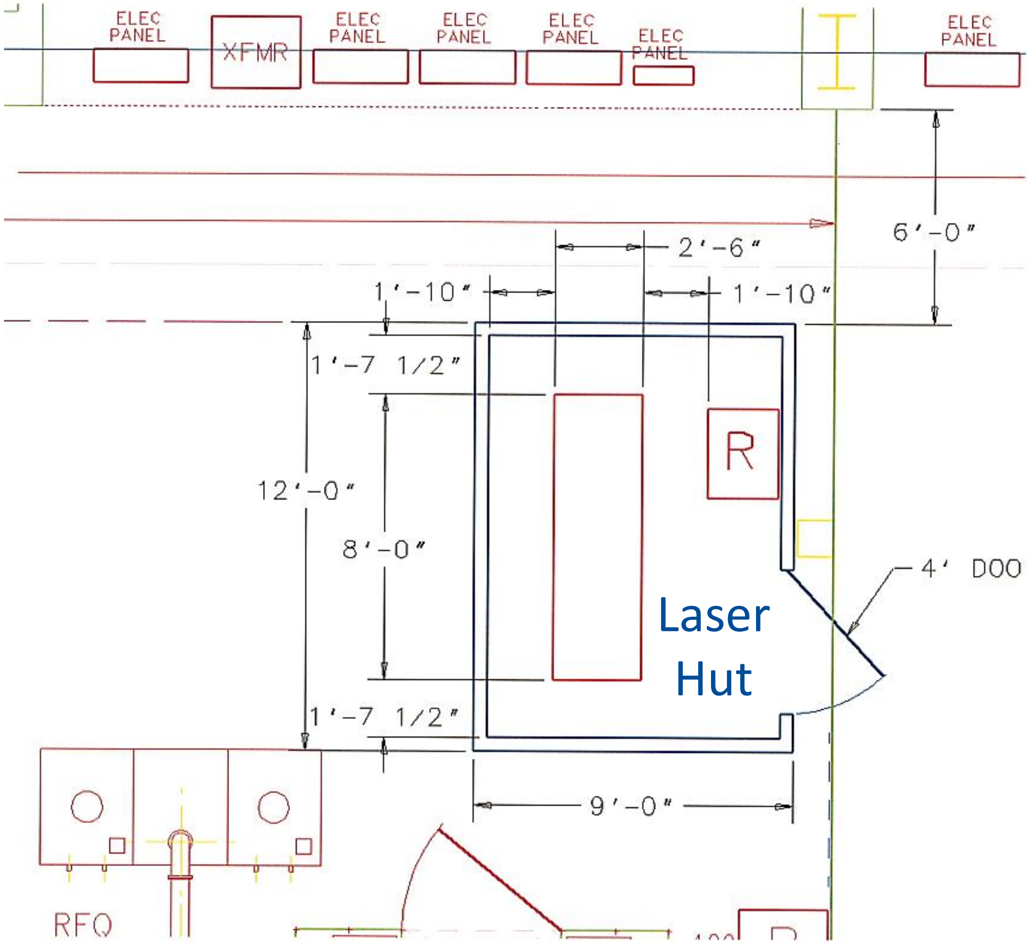


R. Wilcox, LBNL

P2IT Research and Development Plan

- The design and development of a high rep-rate, picosecond, mode-locked fiber laser system and the understanding of laser amplification issues
- Understand and optimize the coupling and transport of laser light through optical fibers
- Design and construct the associated accelerator vacuum hardware for a system test at P2IT
- Design and develop the associated optics and synchronous detection electronics
- Installation of instrument at P2IT
- Experimental studies with beam at P2IT with the aim to meet the primary and secondary research goals

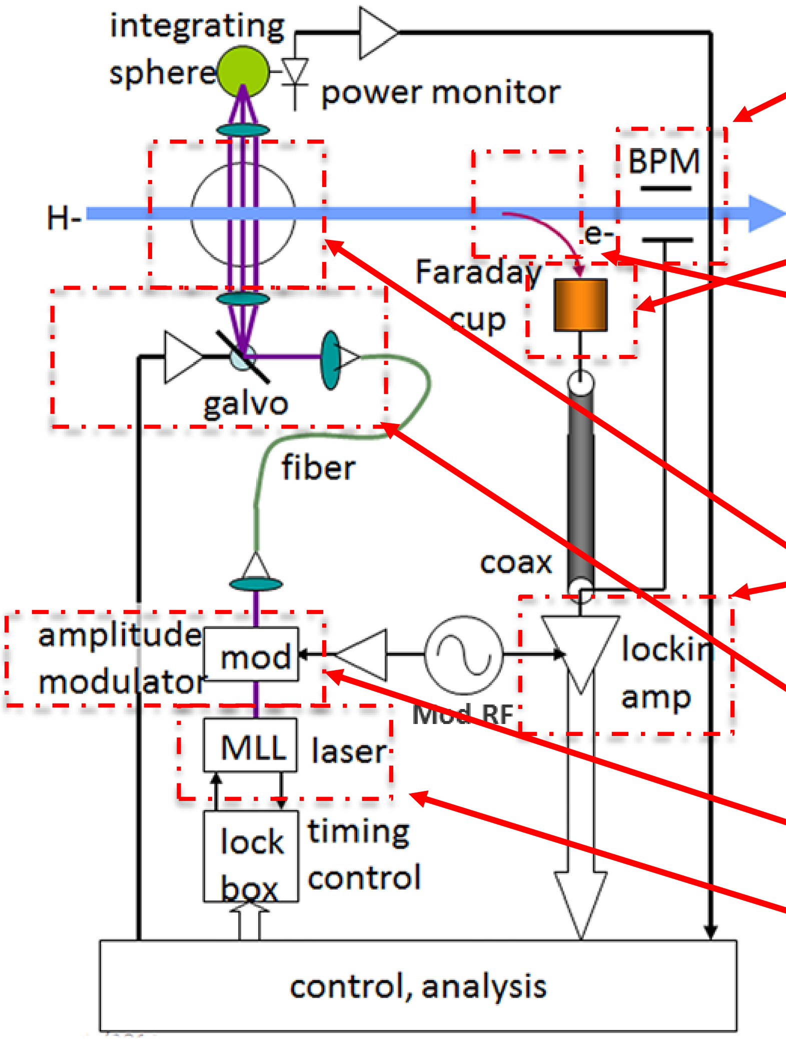
CMTF Infrastructure – Laser Hut



PXIE Cave

- Operation of Class IV laser requires safety measures
- Construction of an interlocked laser hut at PXIE
  - Funds in T&M
- Design almost complete
- Sign-off by laser safety and FESS required

Laser Profiler Component Status



- BPMs installed in P2IT MEBT
  - Front-end FPGA operation
  - Starting on FPGA lock-in detection
- Electron collector identified and ready to purchase
- Magnetic field design mostly complete
  - Magnets in-hand
- Stand-alone lock-in amplifier in-hand
- Vacuum chamber design progressing
- Optical design starting
- Optical modulator in hand
- Laser specified and vendor quote received

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Laser

- Laser design completed and quote received
  - $91,300
  - *Purchase on hold due to LDRD funding restrictions*
- Laser purchase key to profiler development

Customer:

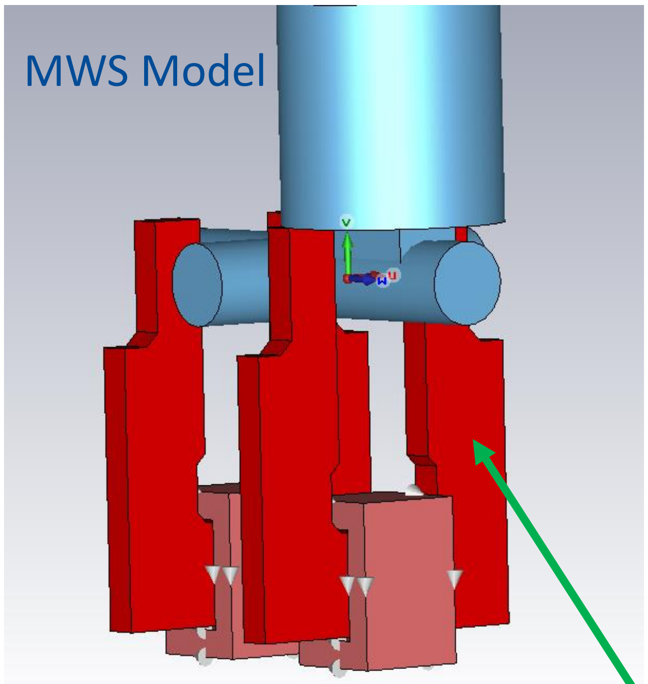
Fermi National Accelerator Laboratory AD/APC/IOTA P.O. Box 500, M.S. 306 Batavia, IL 60510-0500	Attn: Dr. Jinhao Ruan Ph: +1-630-840-5699 Fx: +1-630-840-5231 Email: ruanjh@fnal.gov

Inquiry Reference		F.O.B.	Shipment Date
Phone call		Destination	60 days ARO

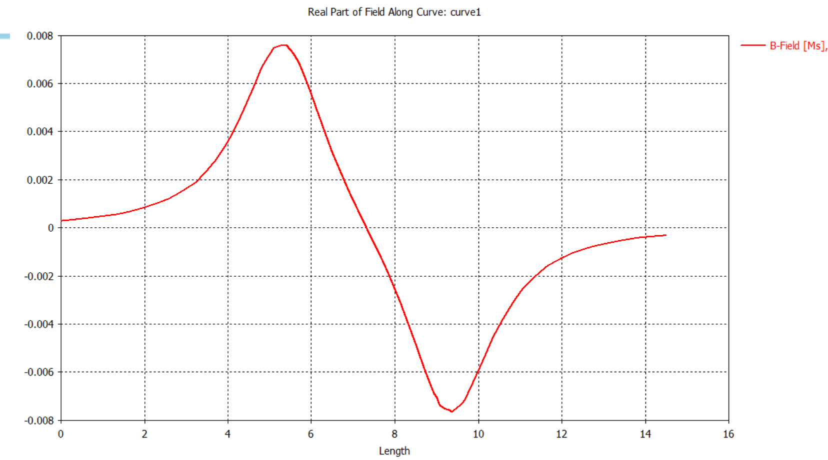
Ln	Description	Unit	Qty	Price/Unit	Ext. Price
1	UOC Ultrafast Optical Clock (1.3 GHz) Model: UOC-Yb-MM • Locks to and Requires External RF Clock at 1.300000 GHz • Tunable Pulse repetition rate in steps of 15 MHz • PM single mode fiber laser • Continuously tunable PRR range: ± 600 KHz ○ +/- 40 KHz with piezo; rest with mechanical stage • Wavelength tuning Range: 1040-1060 nm • QuickChange Filter Cartridge Design • Pulsewidth ≤ 5 ps at specific wavelengths • Average output power: ≥ 10 mW @ 1.3 GHz • Capability to adjust cavity length by 25 mm with manual micrometers • Supermode extinction ratio ≥60 dB • PM primary output via FC/APC connector • Multiple optical outputs (One Primary and 2 Secondary) • Simultaneous front panel display of pump current, modulator DC bias, RF power monitor, error signal. • Optically switch laser into internal dump when interlock engaged	Ea	1	US$54,500	US$54,500 (Fifty four thousand five hundred US Dollars)
2	Option – Optical Pulse Picker • Insertion loss for picked pulse: < 4 dB • Picks every eight pulse from a train of pulses at 1.30 GHz ○ Need external phase lock for correct bunch selection • Electrical bandwidth: 1.3 GHz • Automatic DC bias adjustment for stability	Ea	1	US$15,500	US$15,500 (Fifteen thousand five hundred US Dollars)
3	Low Noise, High Power, Polarization Maintaining Yb Optical Fiber Amplifier with Output Isolator, Model LNHP-PM-YbFA-33-NMA • Two stage Yb doped Optical Fiber Amplifier with core pumped preamp and cladding pumped power amp • PM single mode fiber amplifier • Preamp output spliced internally to power amp input • Saturated Output power = 33 dBm at Pulse Repetition Rate of 162.5 MHz • Wavelength range = 1040 – 1070 nm • Signal gain ≥ 30 dB • Isolators at both input and output • Output: PM FC/APC connector • Fixed wavelength ASE noise rejection filter between preamp and power amp • Diagnostic monitor optical port • Low input optical power interlock – turn off pump when low or no input	Ea	1	US$21,300	US$21,300 (Twenty one thousand three hundred US Dollars)
	PriTel certifies that the above product has not been sold to any other customer at lower than the quoted price.				

Magnet Field Modeling

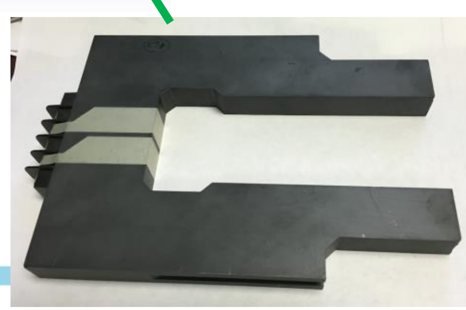
- *Magnet design critical to overall design*
- Work done on magnet design and particle tracking

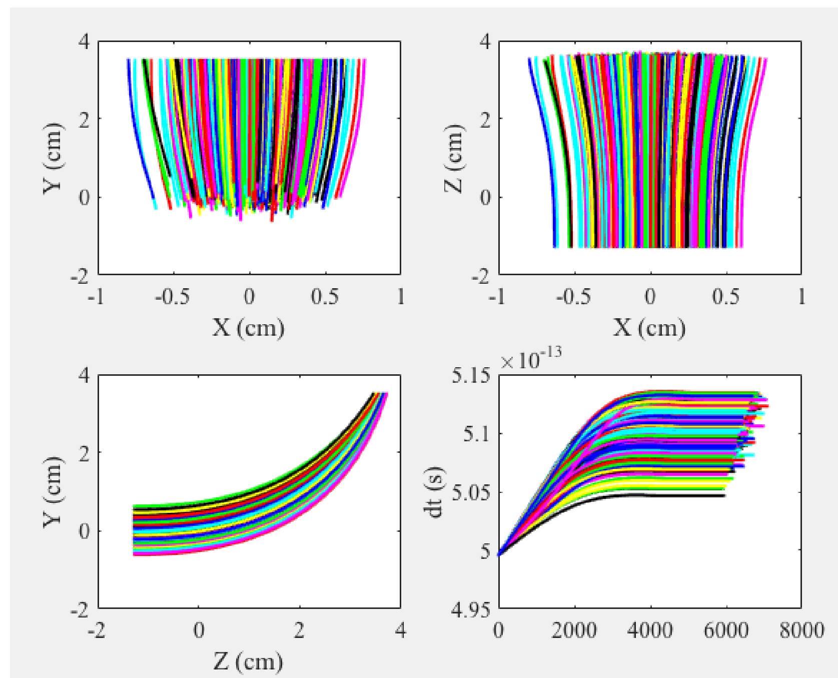


B-field
on axis



5 mA H-
2 mm rms



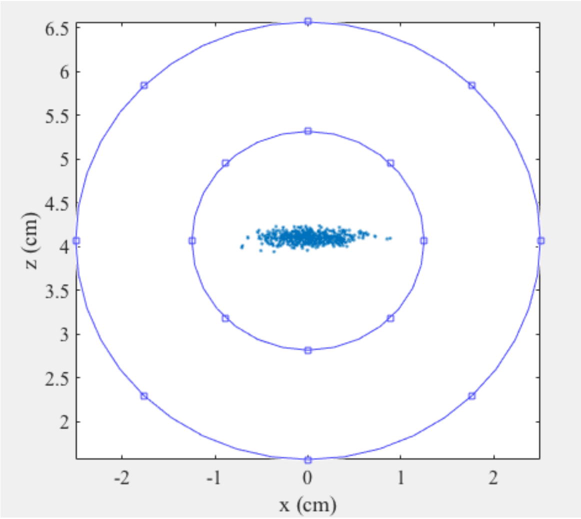


Electron Collection Particle Tracking

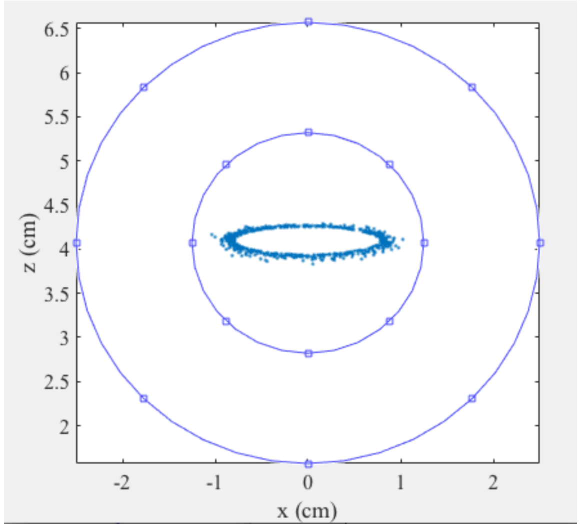
Electron tracking to collector

- What is collection efficiency?
- Can we see tails?

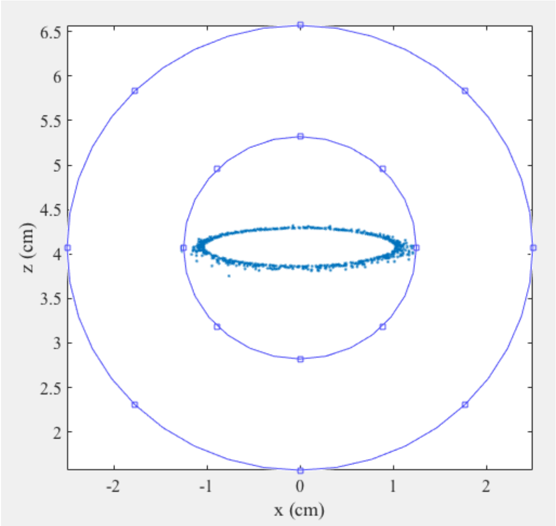
All Particles



3-sigma cut



4-sigma cut



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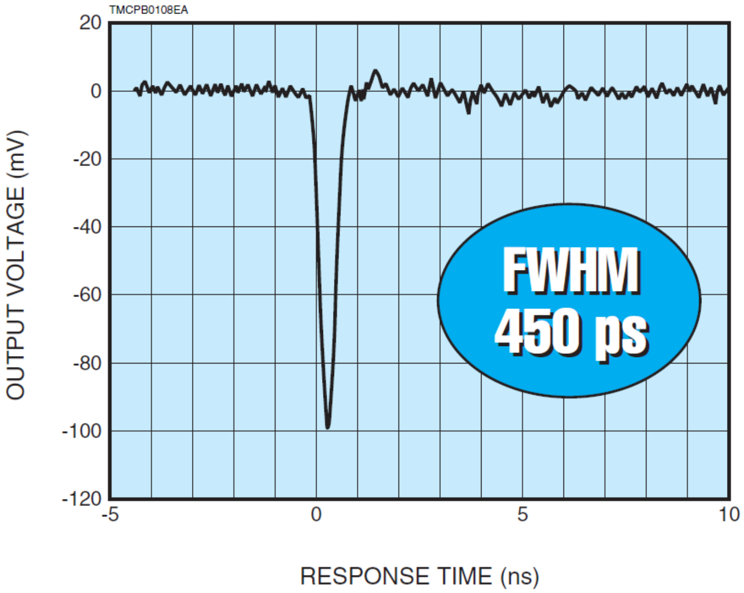
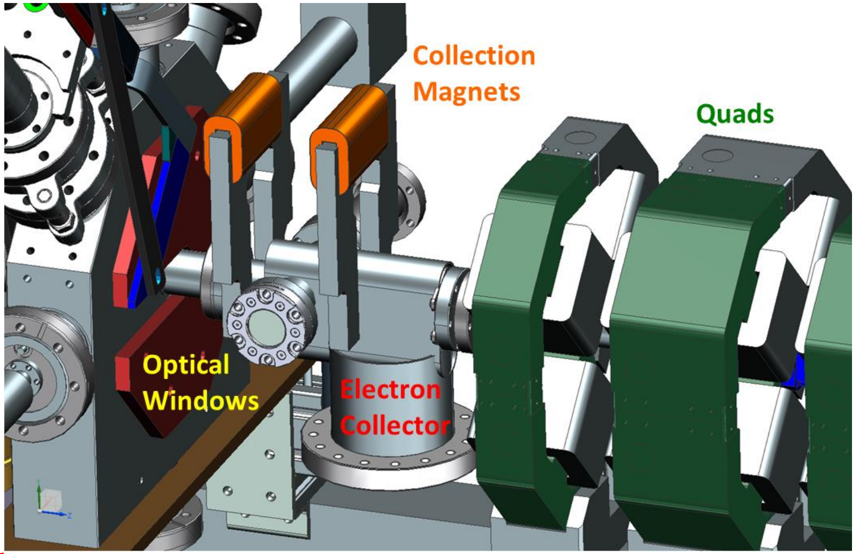
Electron Collection

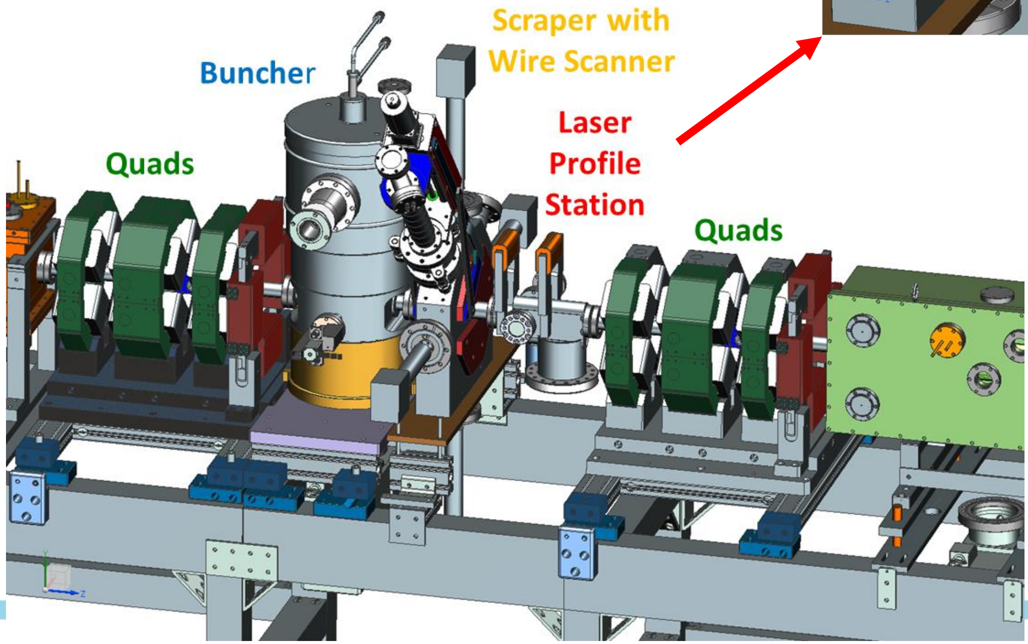
- Hamamatsu MCP-based electron collector
- Large collection area
  - 27 mm diameter
- Gain up to 1e6
- High bandwidth
- Floating HV operation
  - Allows for suppression of low energy background electrons
  - Allows for potential beam energy spread measurement (BNL)



Vacuum Chamber Design

- Design underway
- Tight fit in MEBT
- Single plane measurement only – vertical profiles
  - Looking to fit 2nd plane
- Looking for vacuum chamber construction in Q1 FY17





Summary

- P2IT prototype laser profile station
  - Transverse and longitudinal profiling
  - Both reduced current detection and electron collection
  - Many components of station are coming together
  - Laser purchase remains an issue
- PIP-II VS LDRD
  - LDRD attempts difficult technique for laser profiling
  - PIP-II needs a operational solution
  - P2IT prototype laser profile station allows development on both fronts