Non-interceptive Beam Diagnostics in a H^- Linac During Operations Using Laser Comb and Virtual Slit

Yun Liu

Spallation Neutron Source

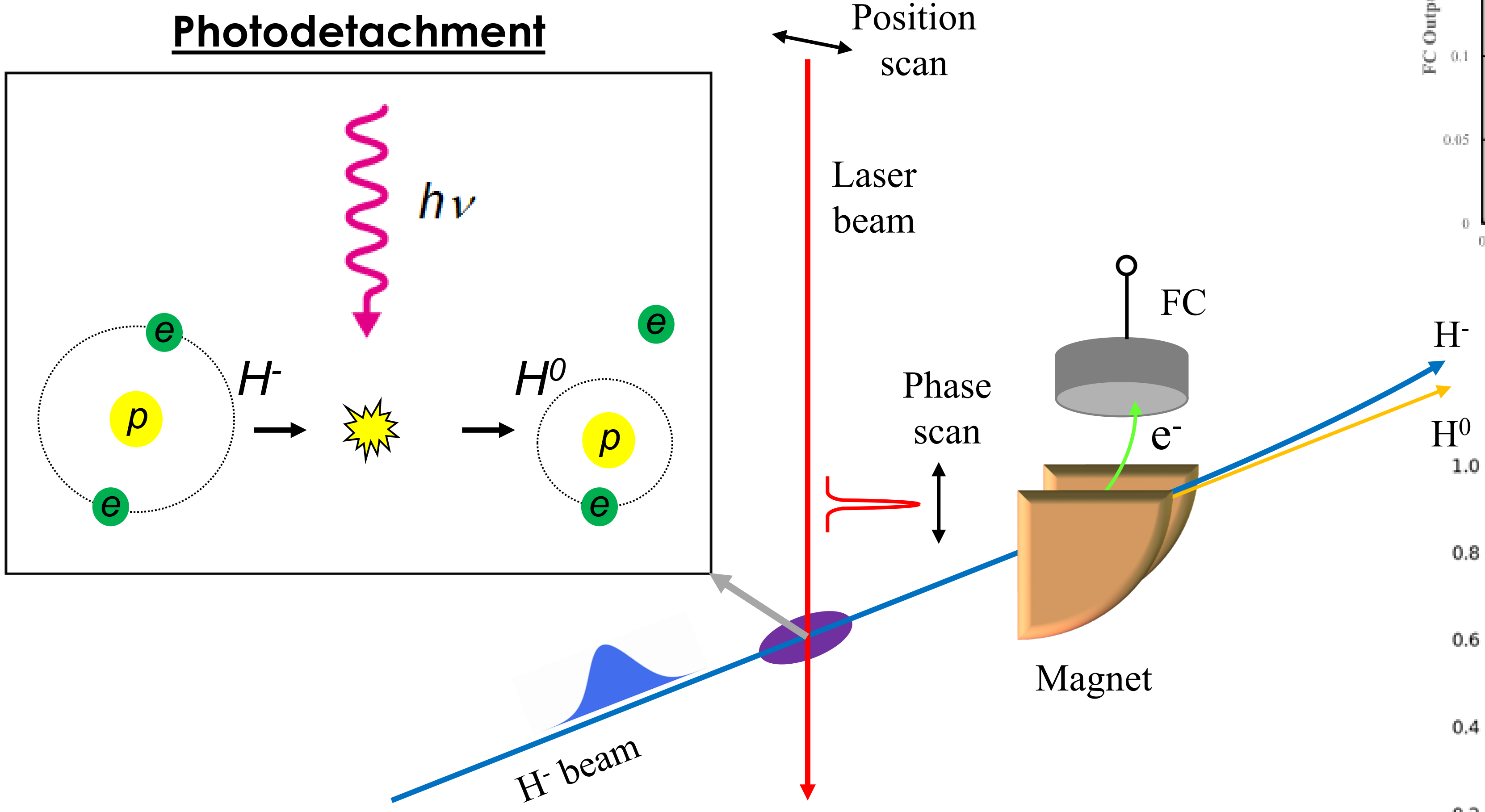
Oak Ridge National Laboratory

Outline

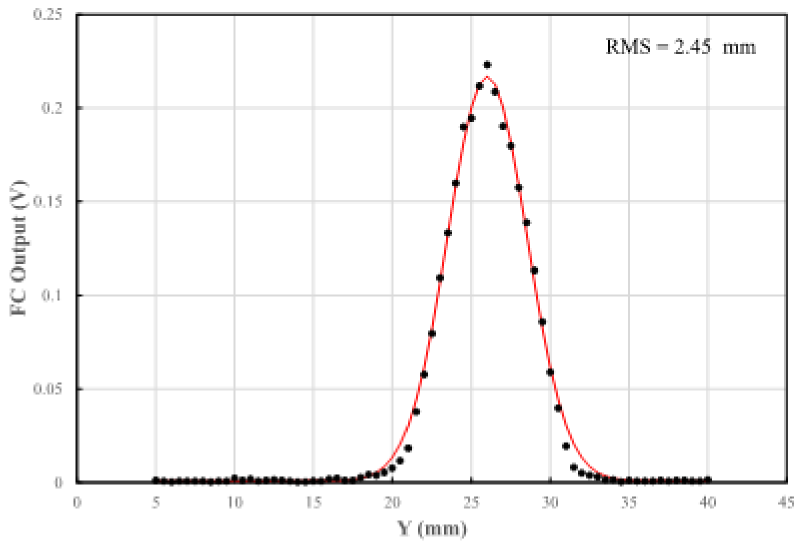
- General Overview
- Recent Progress
  - Virtual slit for short bunch measurement
  - Laser comb for time-resolved measurement
  - Recent measurement examples
- Outlook
- Challenges
- Summary

What is laser wire?

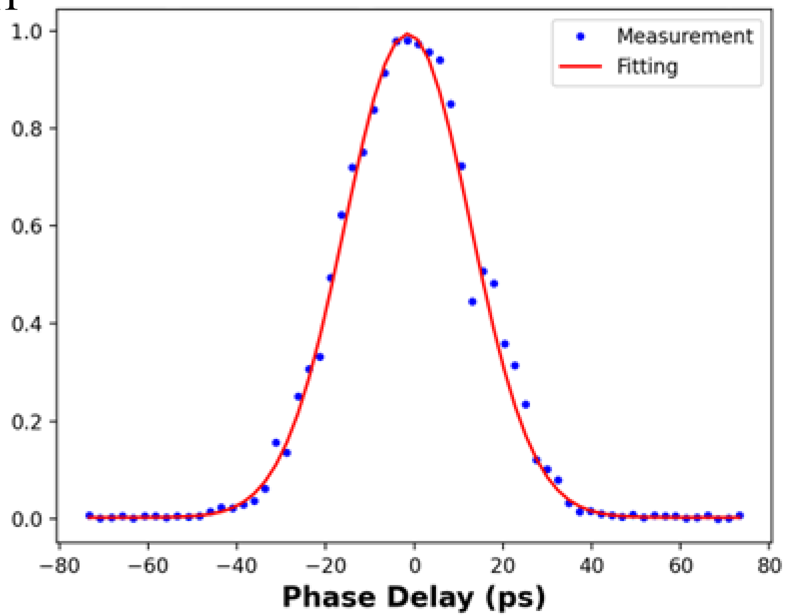
Laser wire is a nonintrusive wire scanner in which a focused laser beam replaces the carbon or metal wires.



Transverse Profile



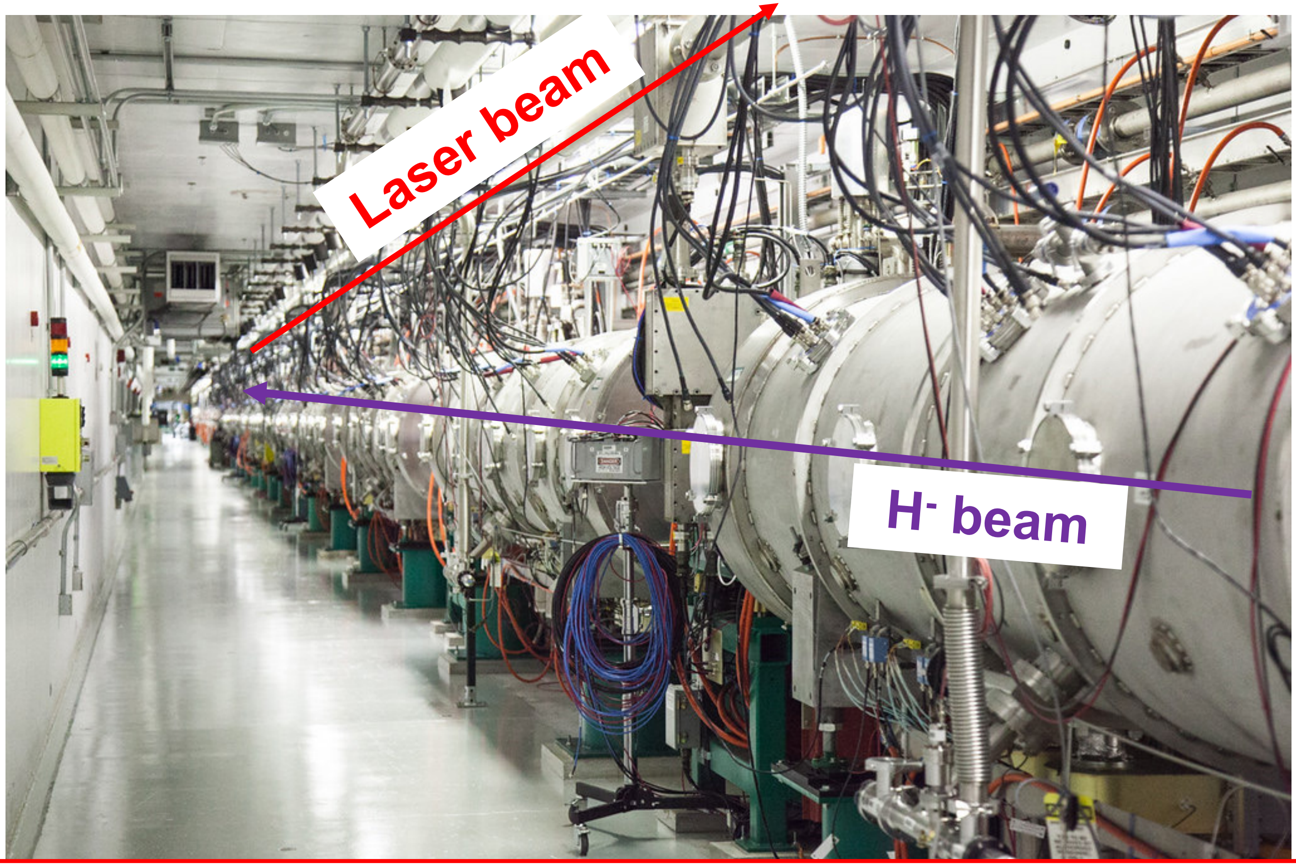
Longitudinal Profile

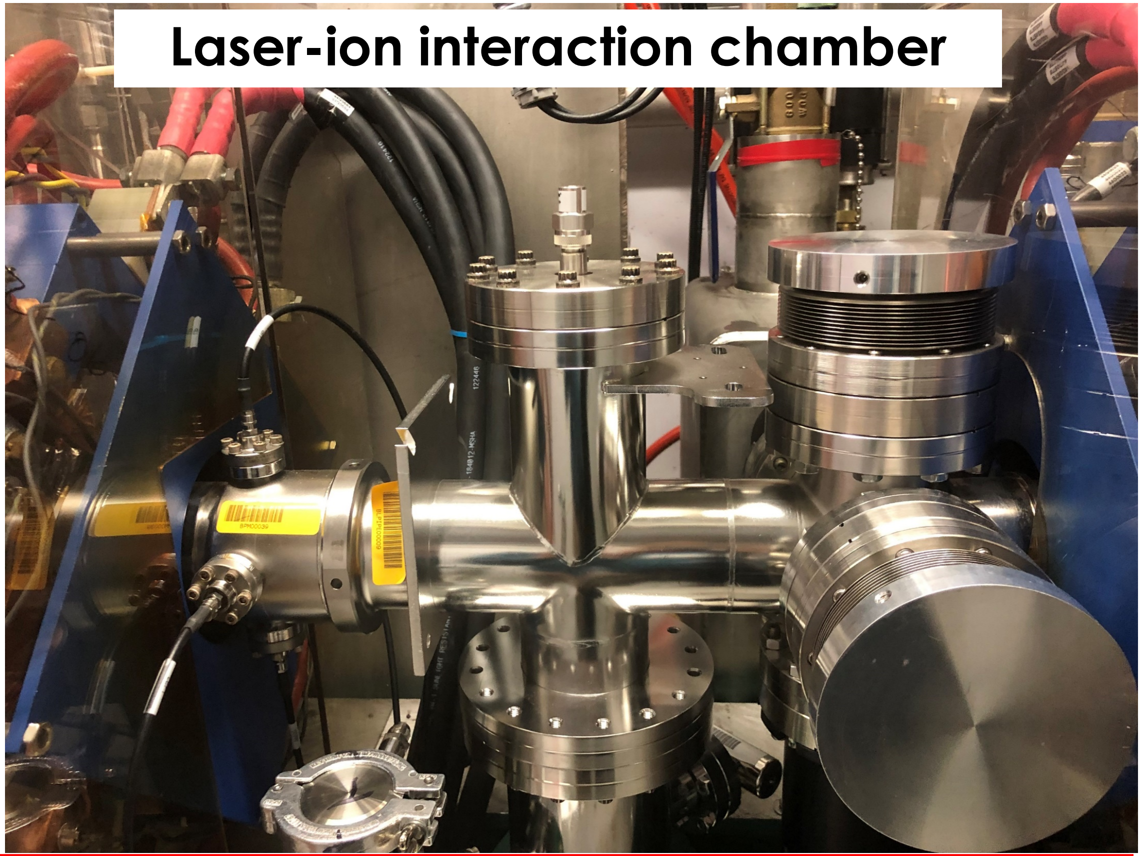


Laser wire based beam instrumentation in accelerator facilities

- Los Alamos Accelerator Test Stand
  - First demonstration of laser wire - *IEEE Trans. Nucl. Sci. (1985).*
- KEK-ATF
  - Developed laser-based beam profile/emittance monitors for electron beam.
- BNL – Laser wire beam energy/profile monitor
- RAL front end test stand
- CERN – Transverse emittance measurement at LINAC4 injector for LHC
- Fermilab
  - Laser chopper at the PIP LEBT line
  - Laser wire system in Fermilab PIP-II Injector Test beam line

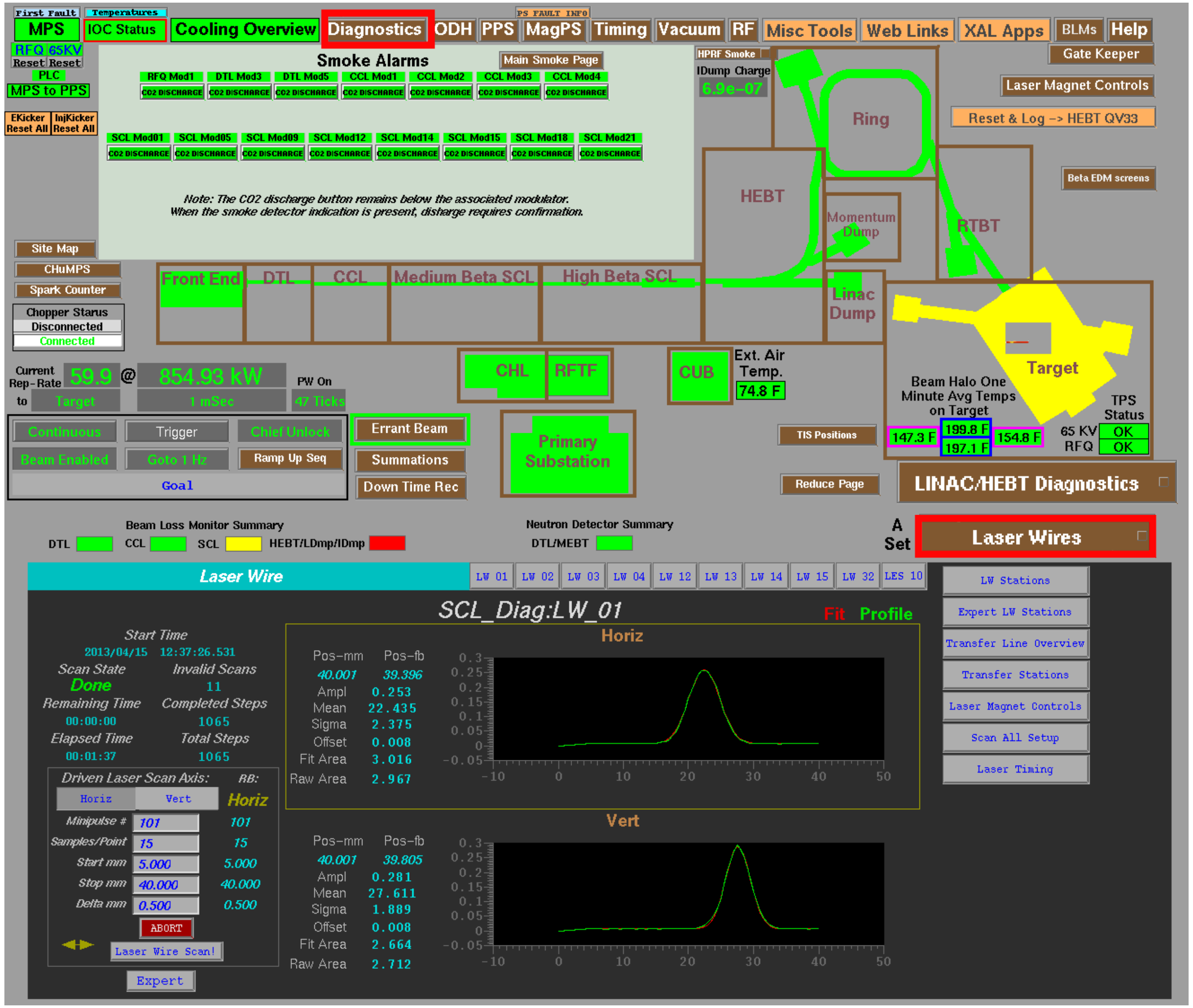
Laser wire measurement stations in the SNS superconducting linac





- Non-intrusive, applicable to operational beam
- No moving parts in vacuum, less concern on cavity damage
- Longitudinal profile scan using the same setup

Laser wire measurement stations in the SNS superconducting linac



Y. Liu et al., Phys. Rev. Accel Beams **16**, 012801 (2013).

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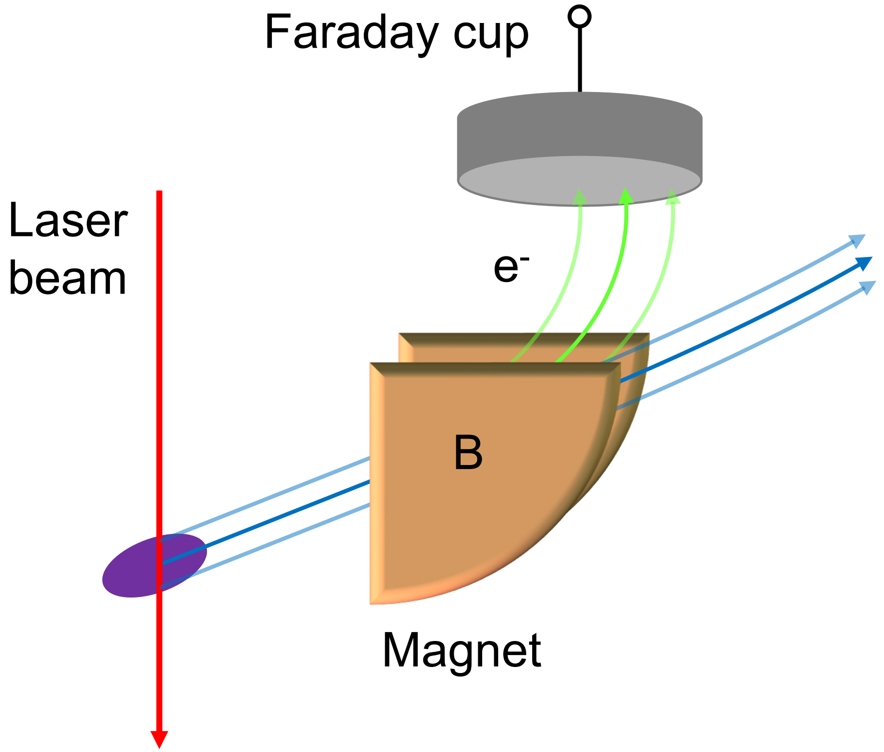
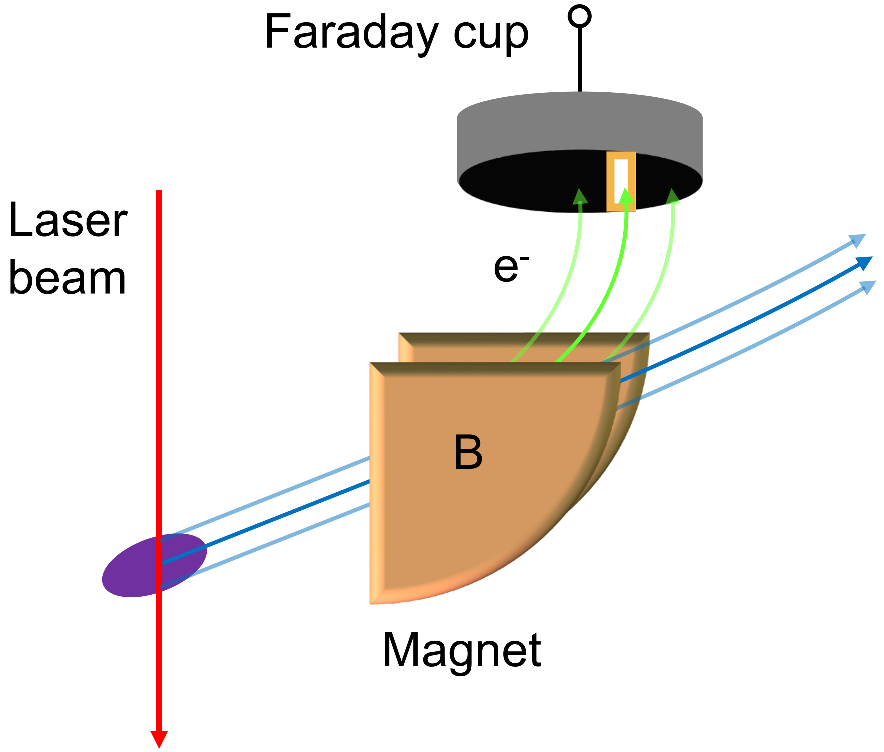
Longitudinal profile scan using a laser wire



In laser wire based longitudinal parameter measurements, the beam transverse size affects the measurement.

The position of the electrons in FC can be controlled by the magnetic field.

Longitudinal profile scan using a laser wire



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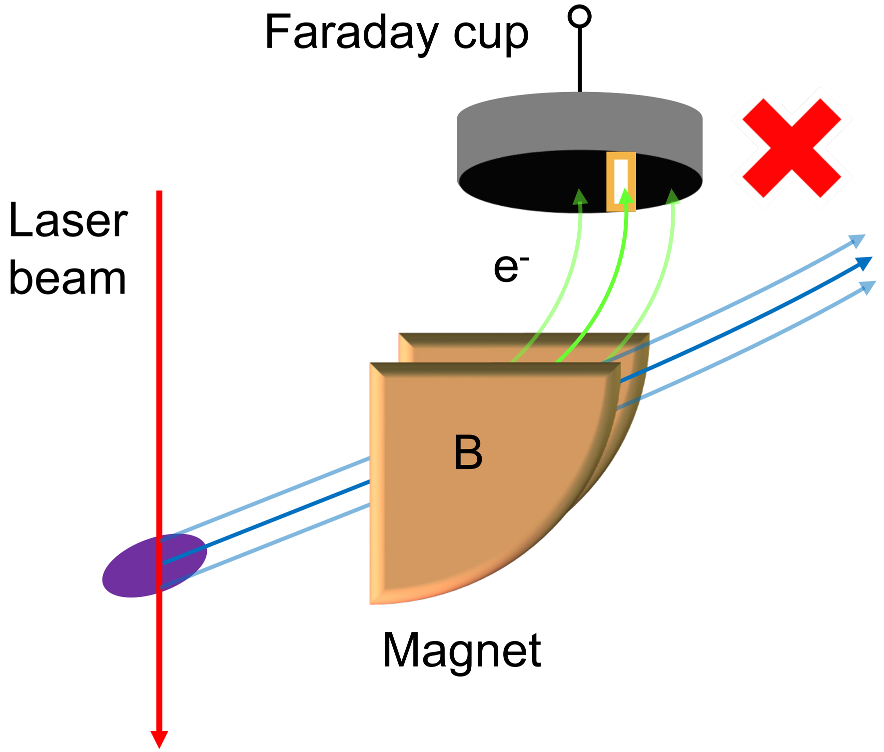

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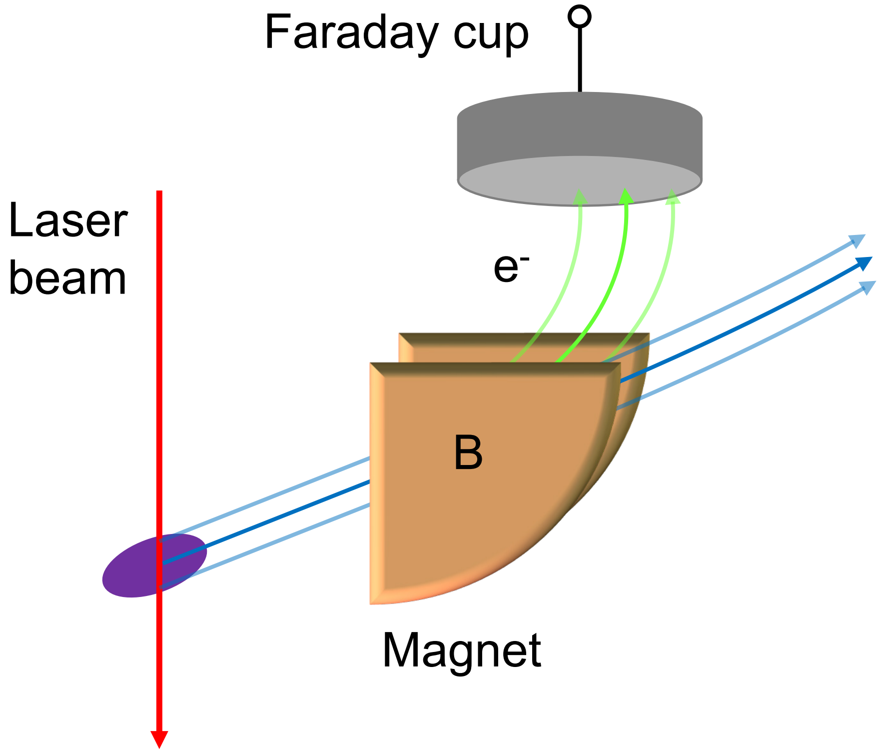

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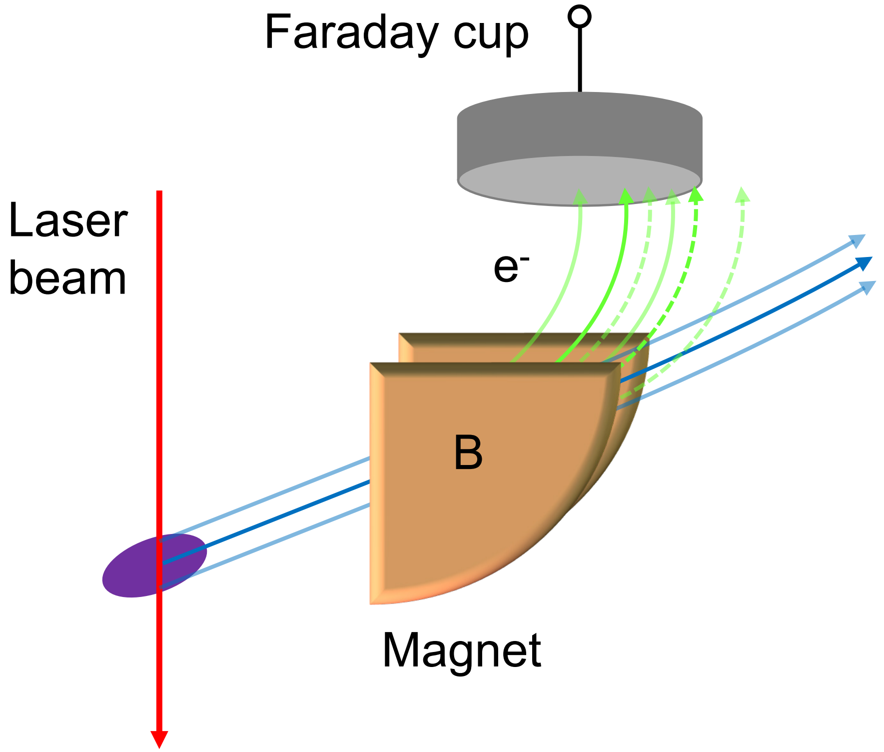

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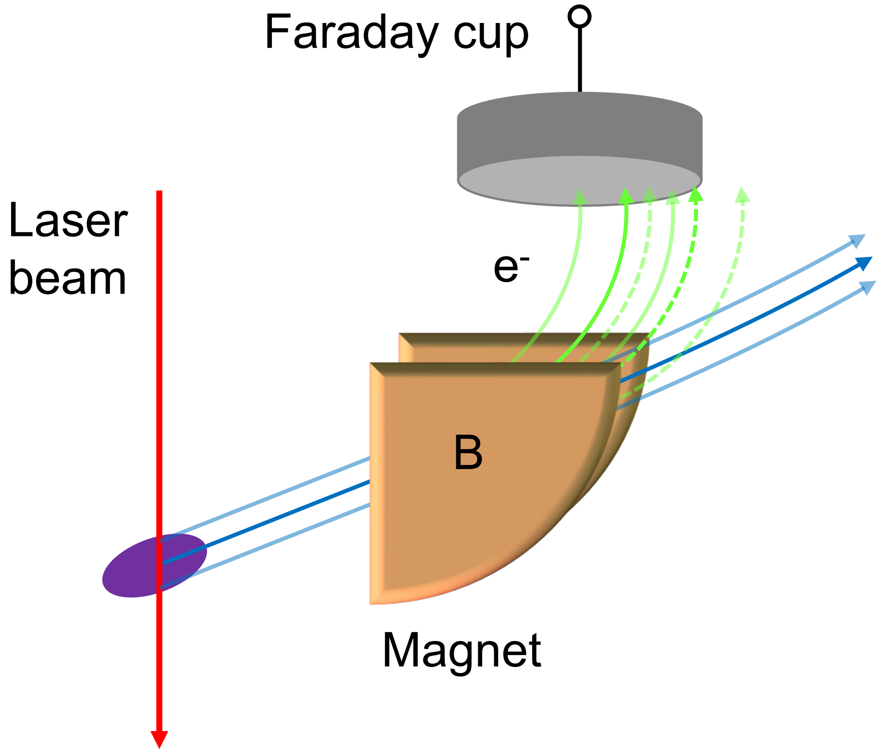

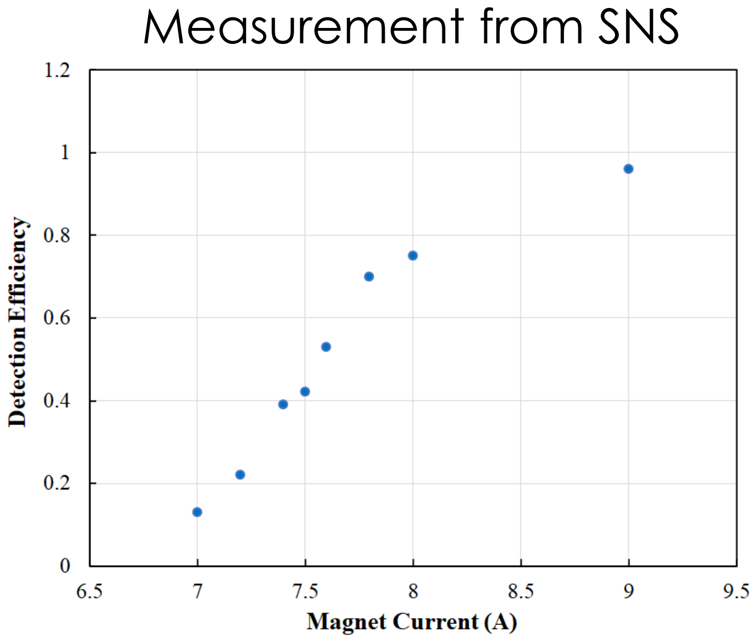

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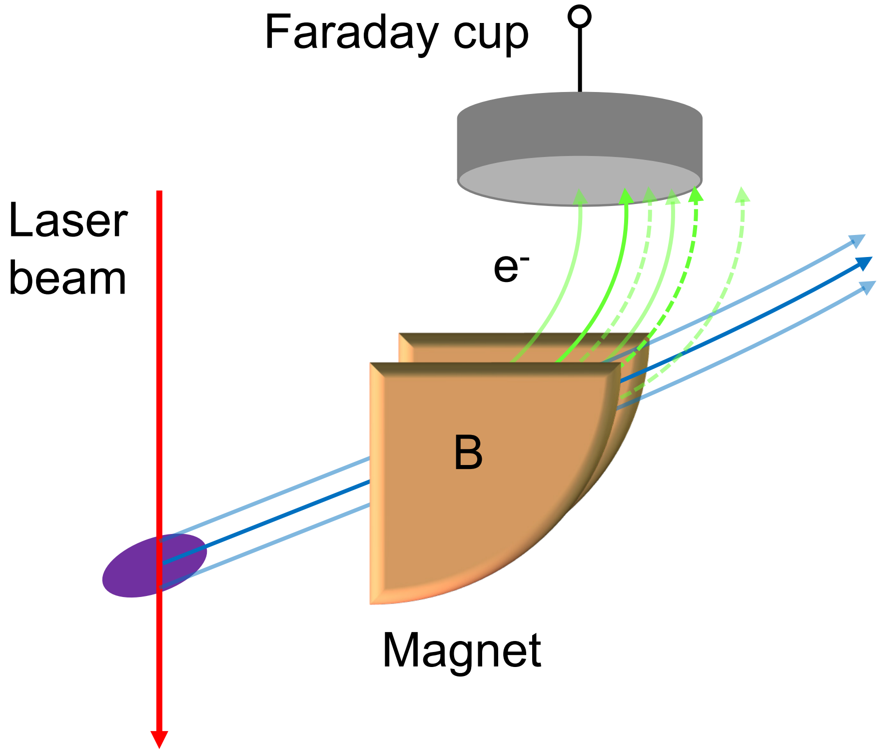
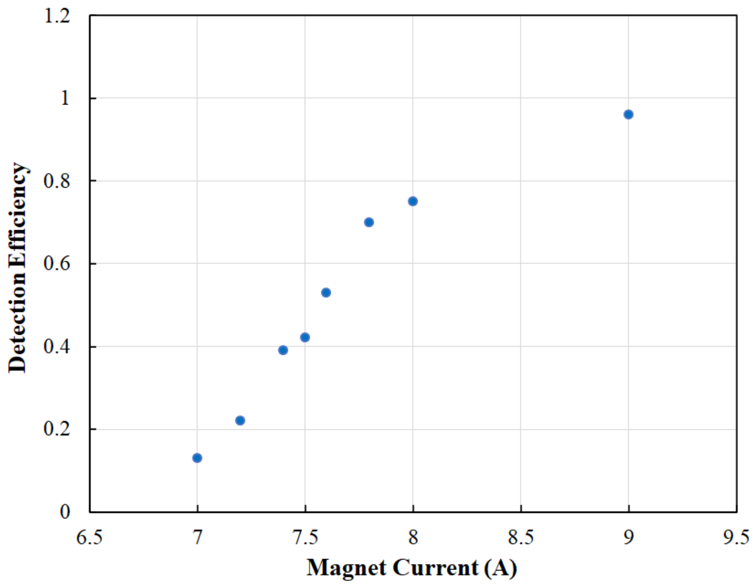
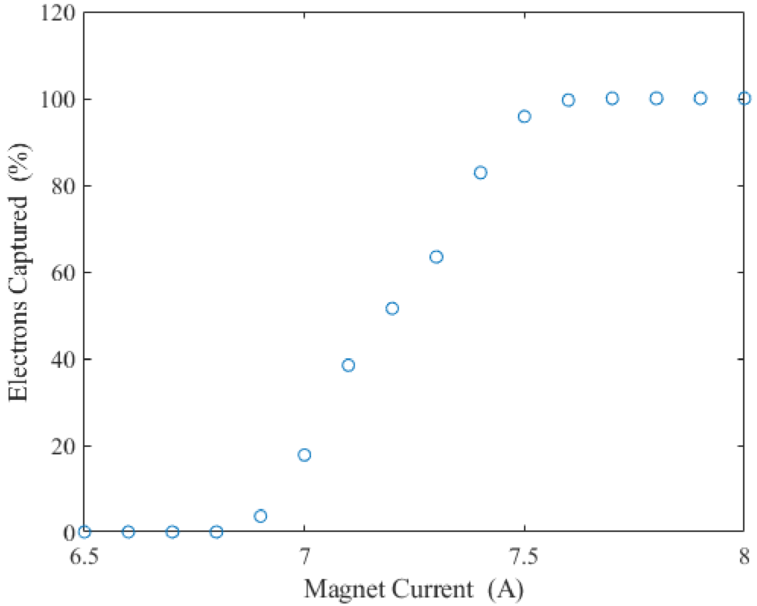


Measurement from SNS



Simulation from Fermilab



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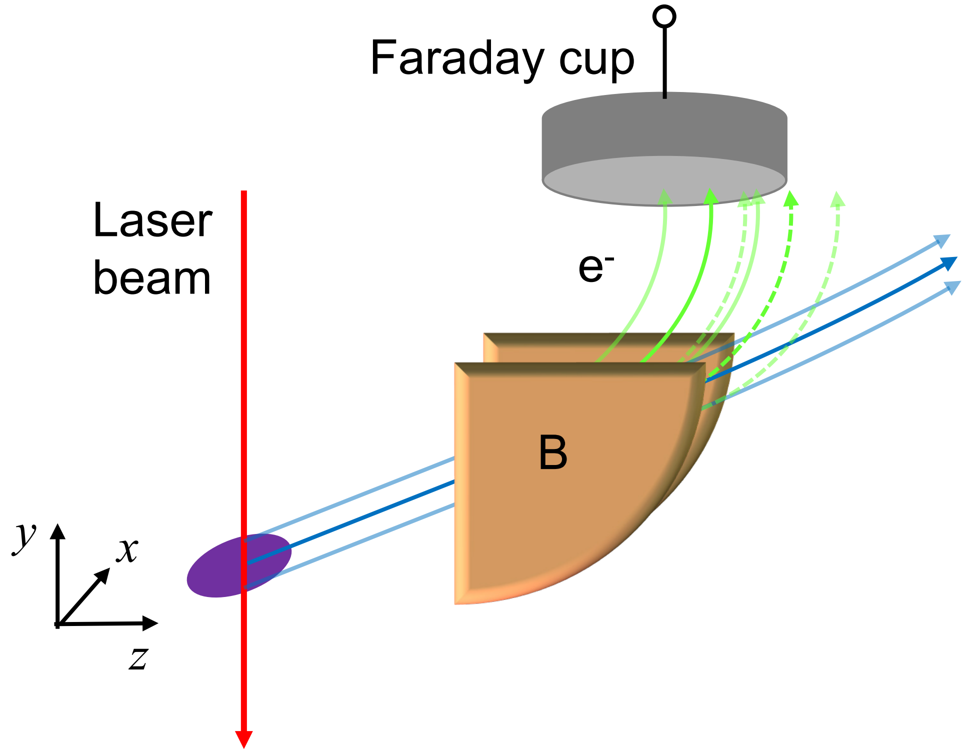
Creation of a virtual slit

Y. Liu et al., *Phys. Rev. Accel Beams* **26**, 042801 (2023).



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$$P(s;y) = \exp\left[-\frac{(y-as)^2}{2\sigma_2^2}\right]$$

N_{pd}: detection efficiency

s: phase to be measured

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$u(B)$: cut-off position that is a linear function of *B*

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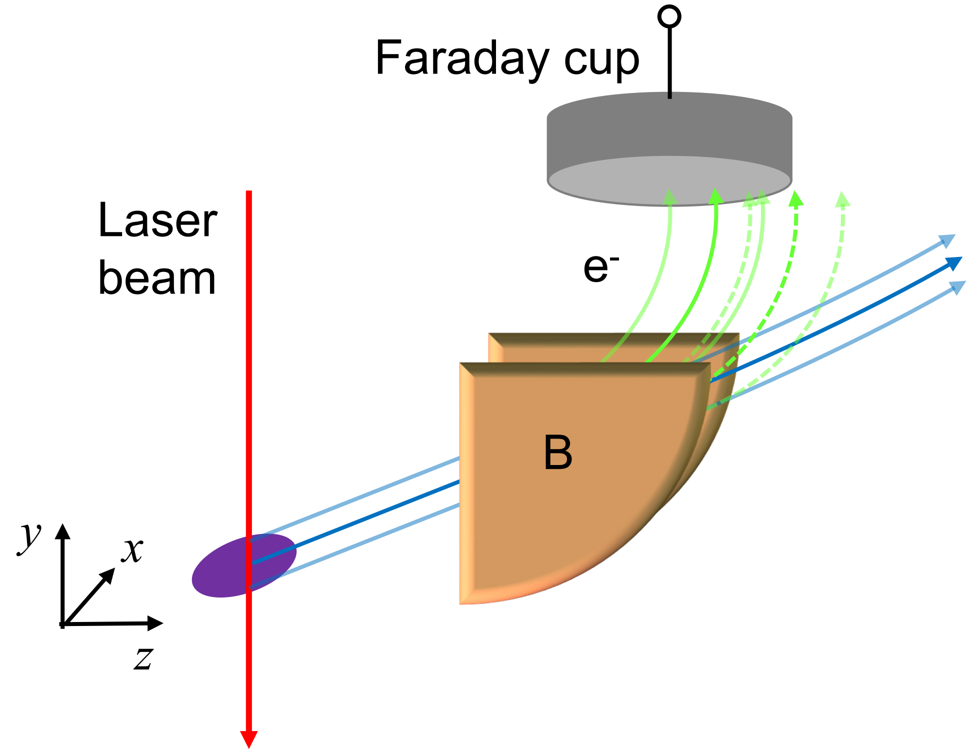

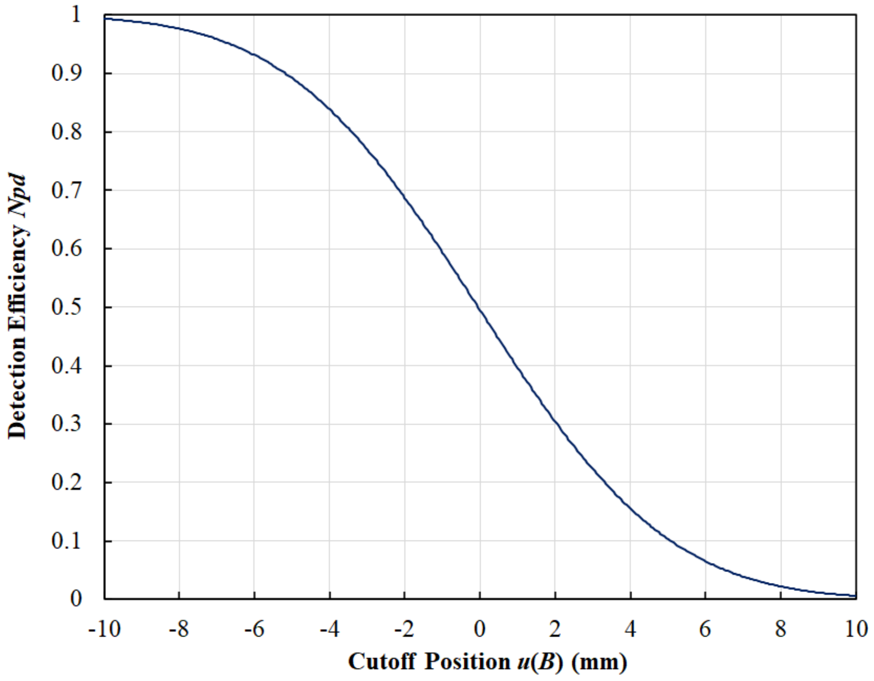

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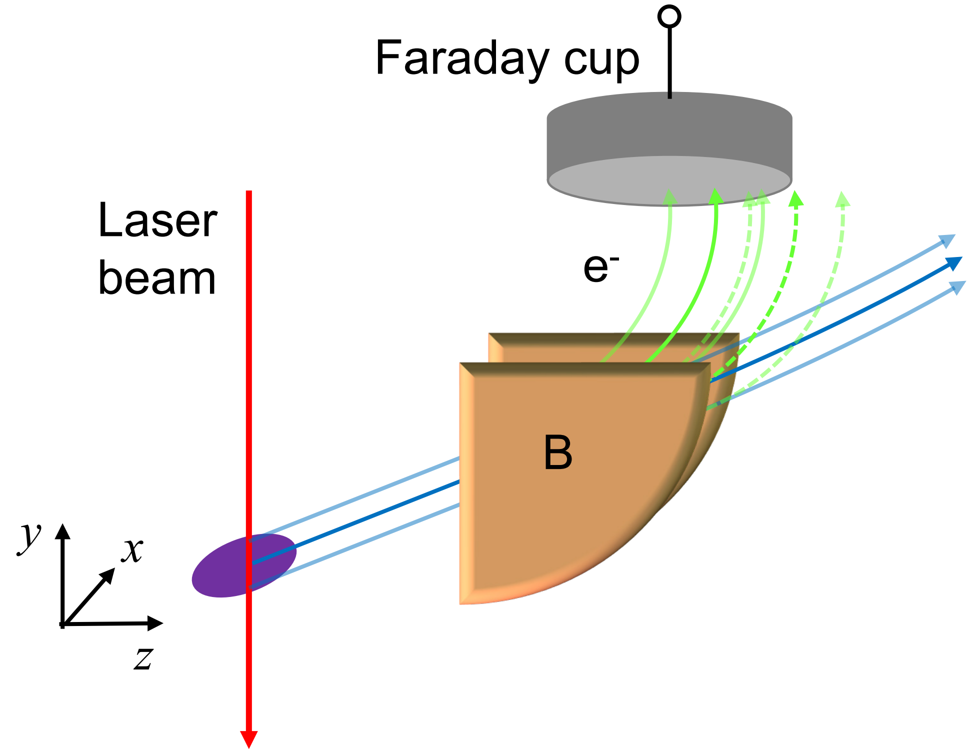

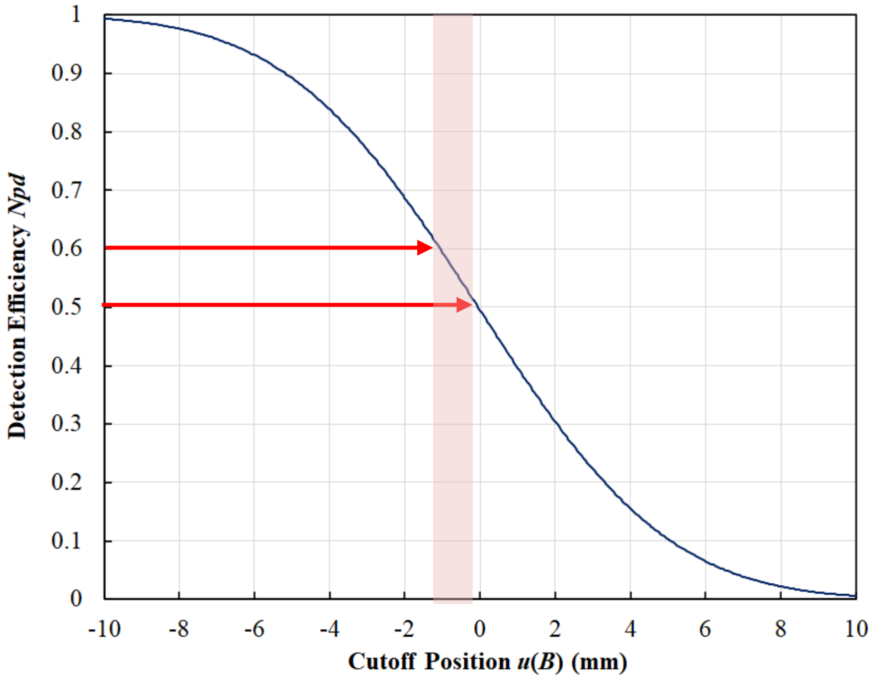

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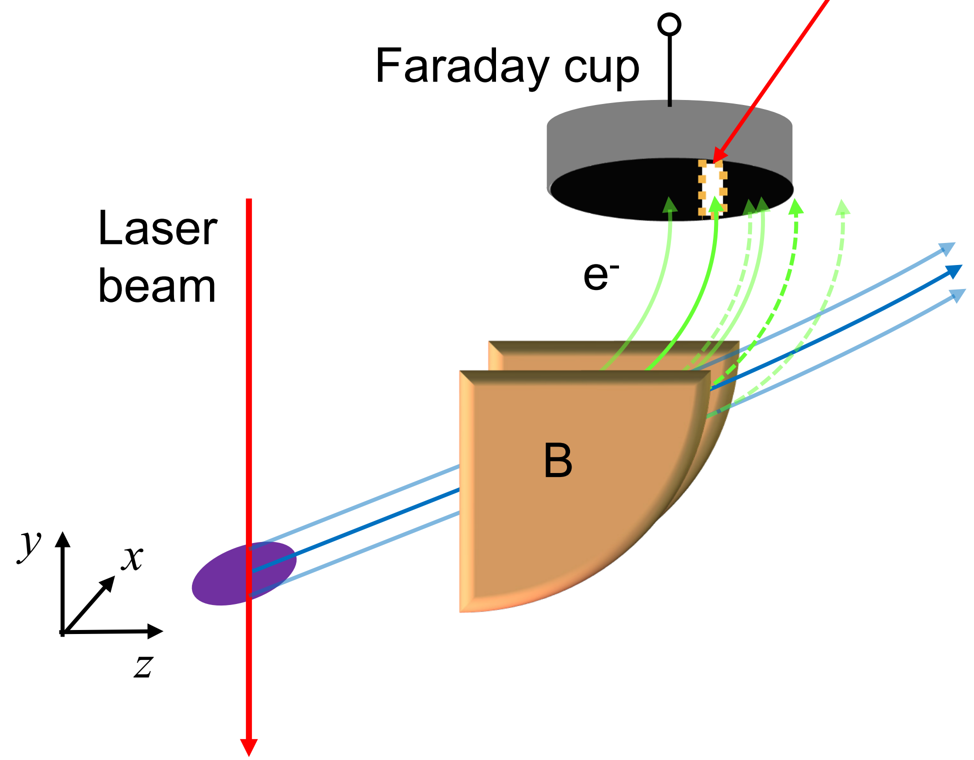

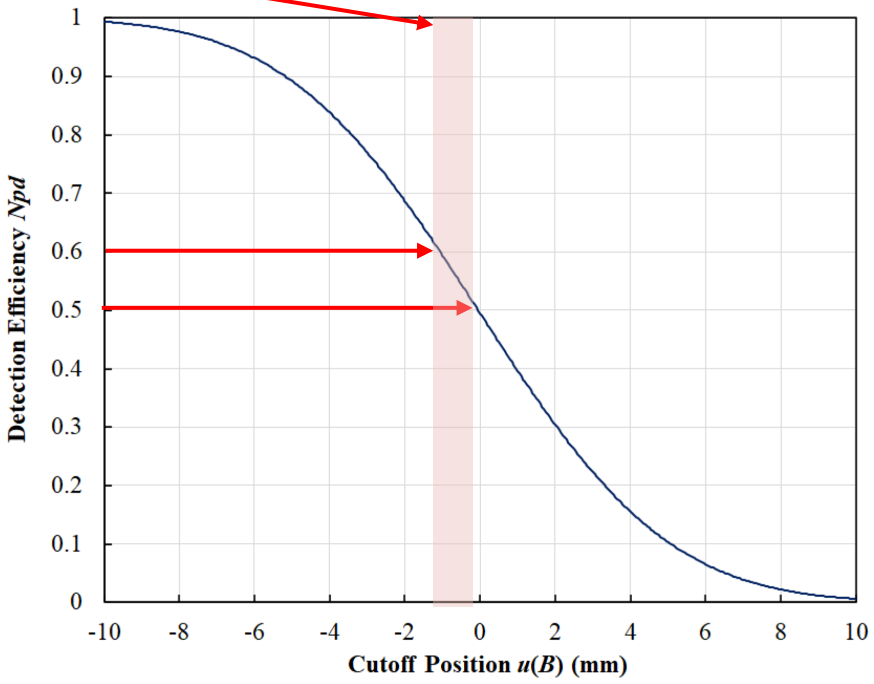

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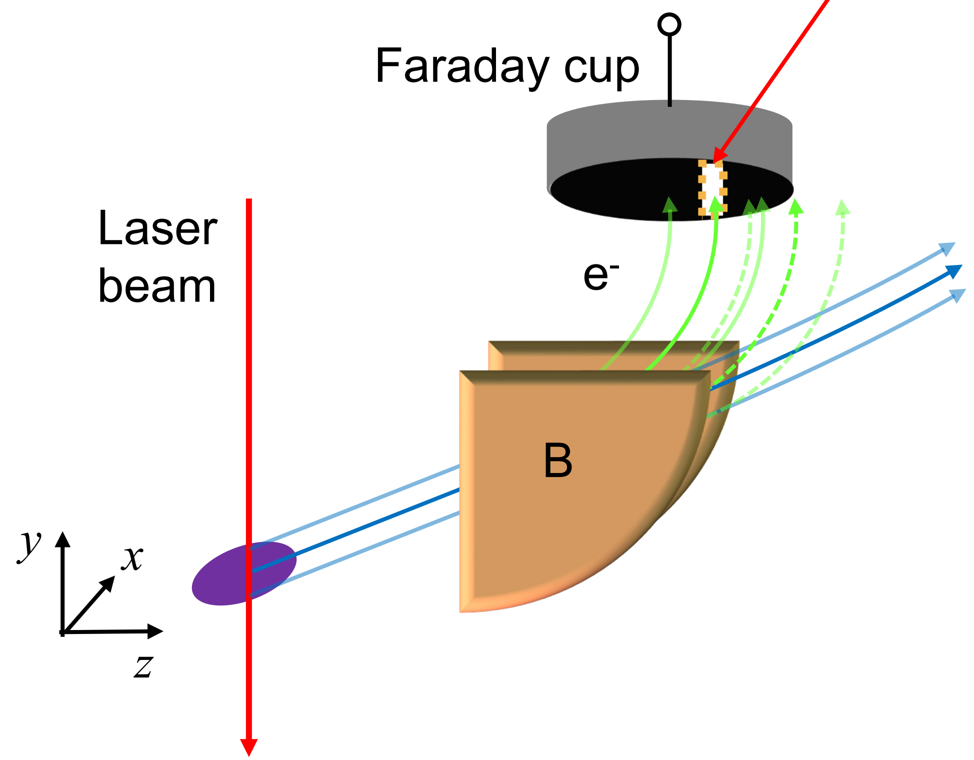

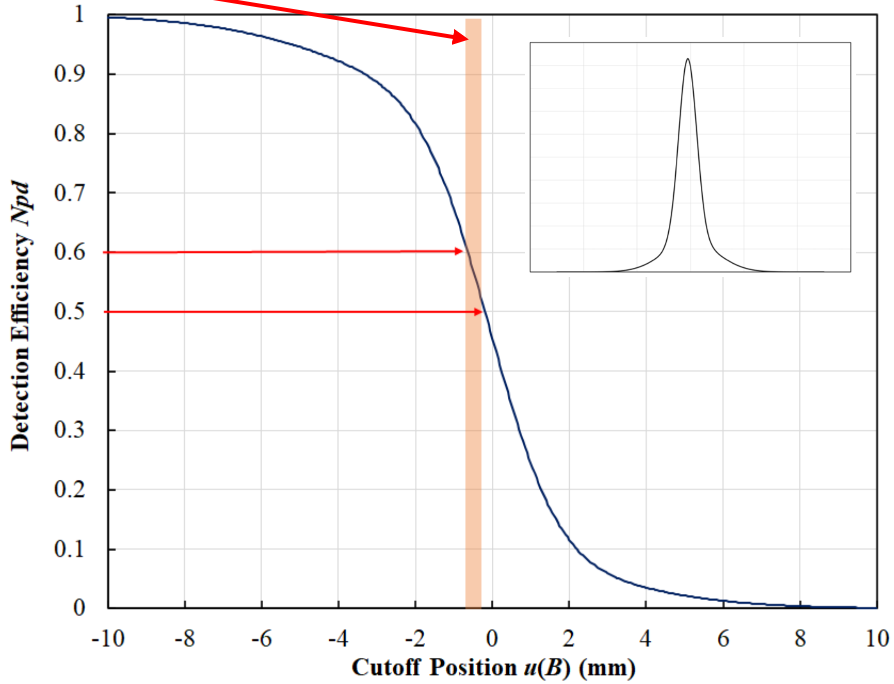

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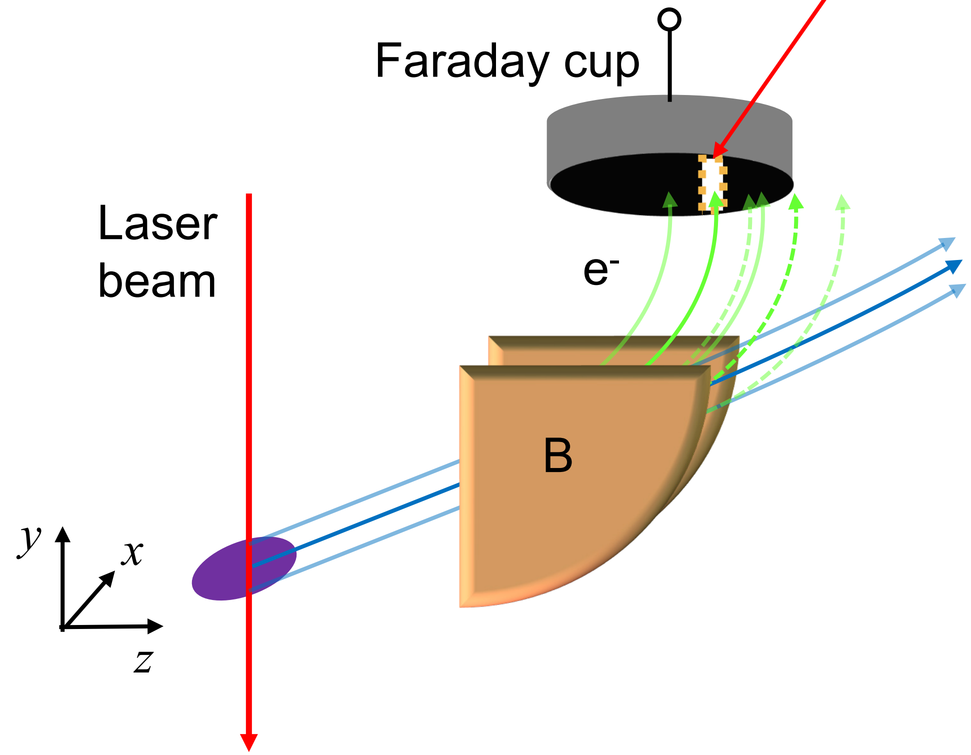

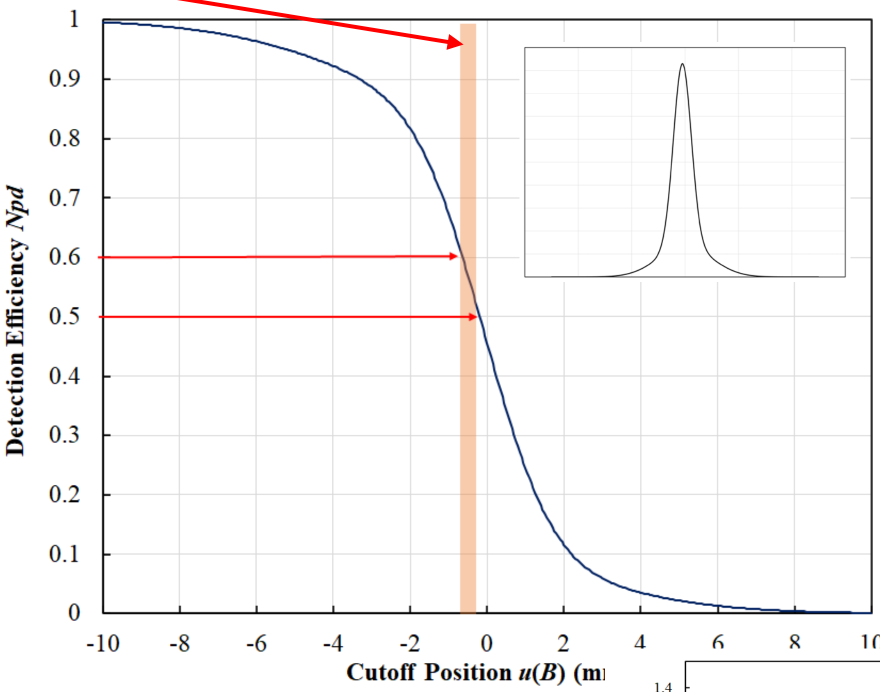

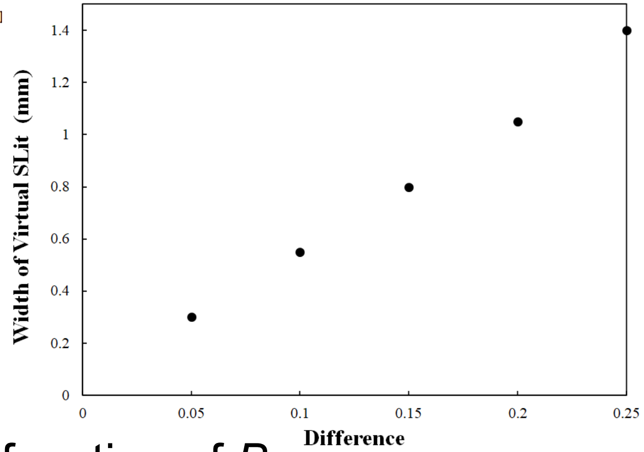

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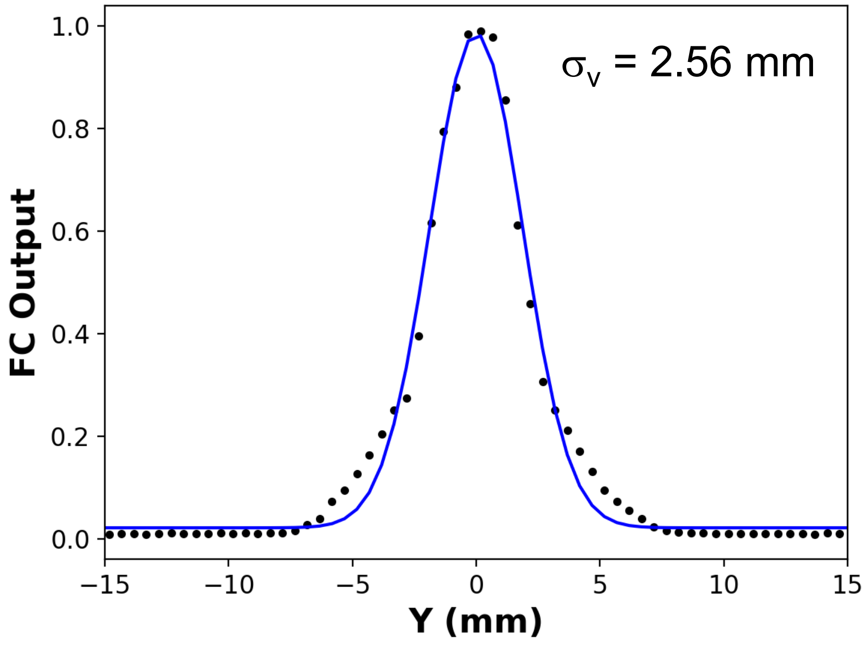
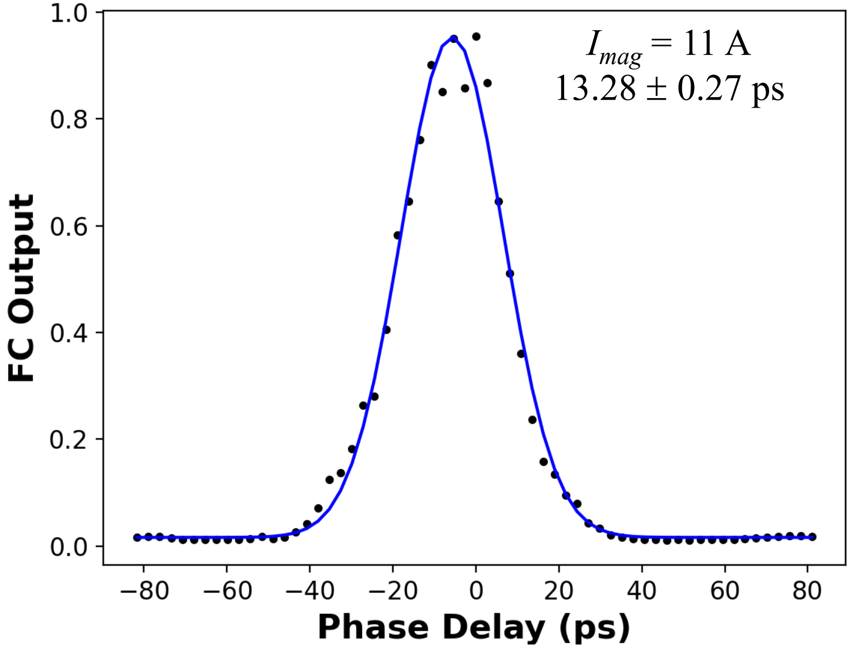
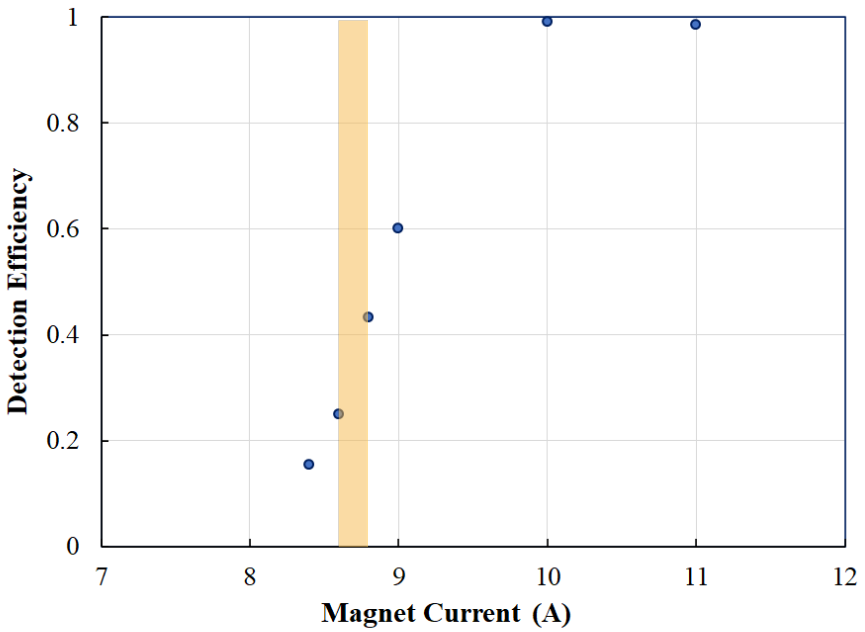
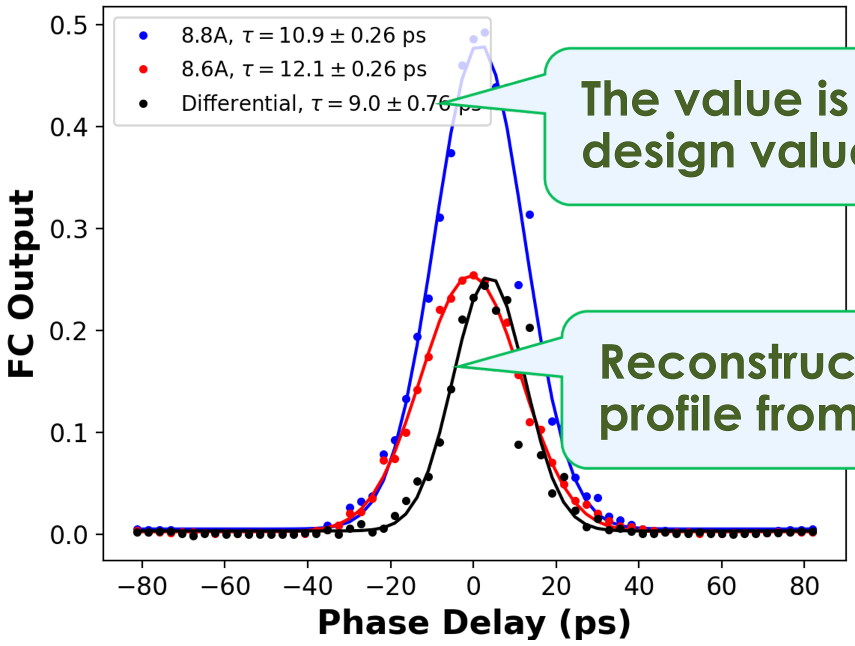
Measured transverse profile



Measured longitudinal profile



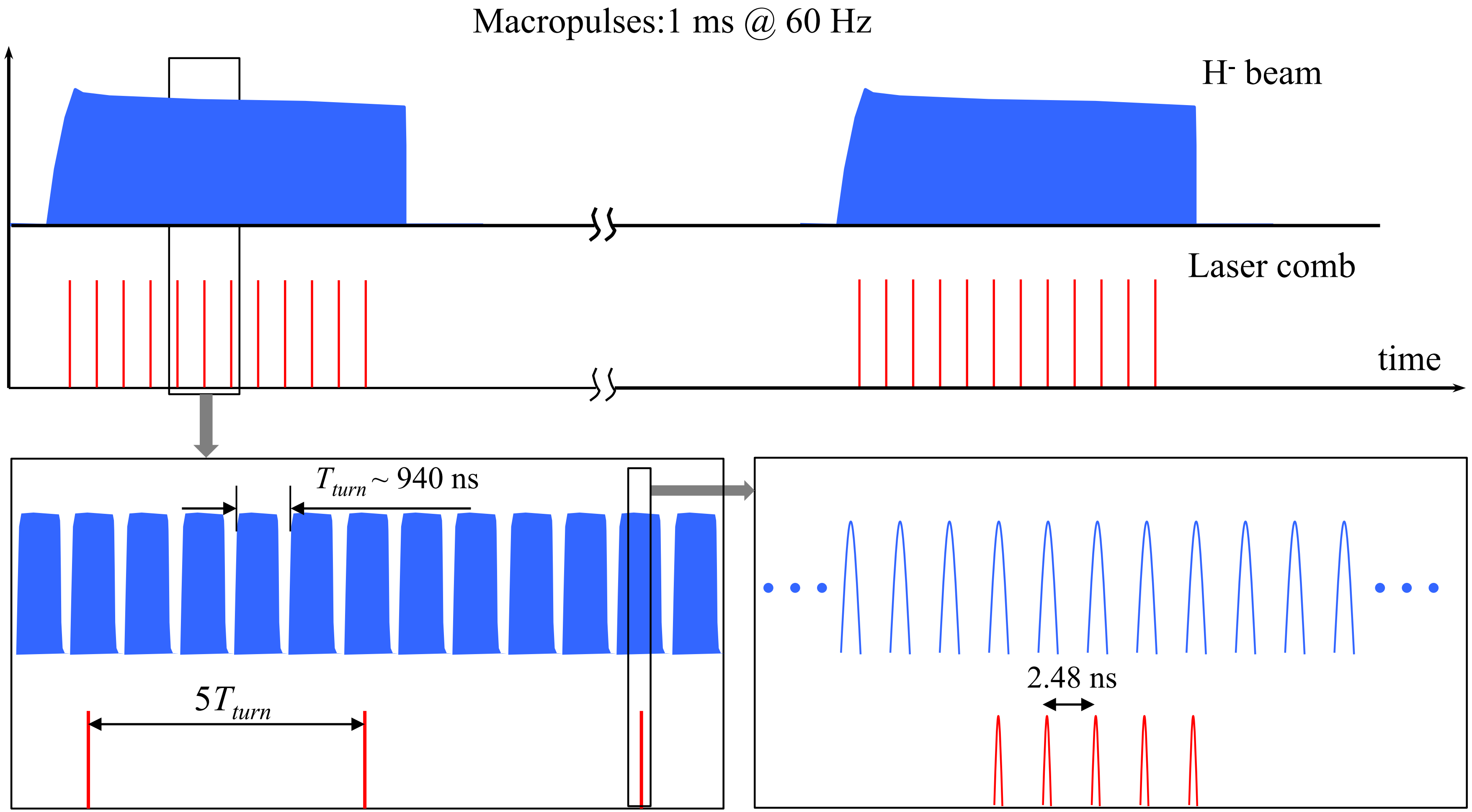




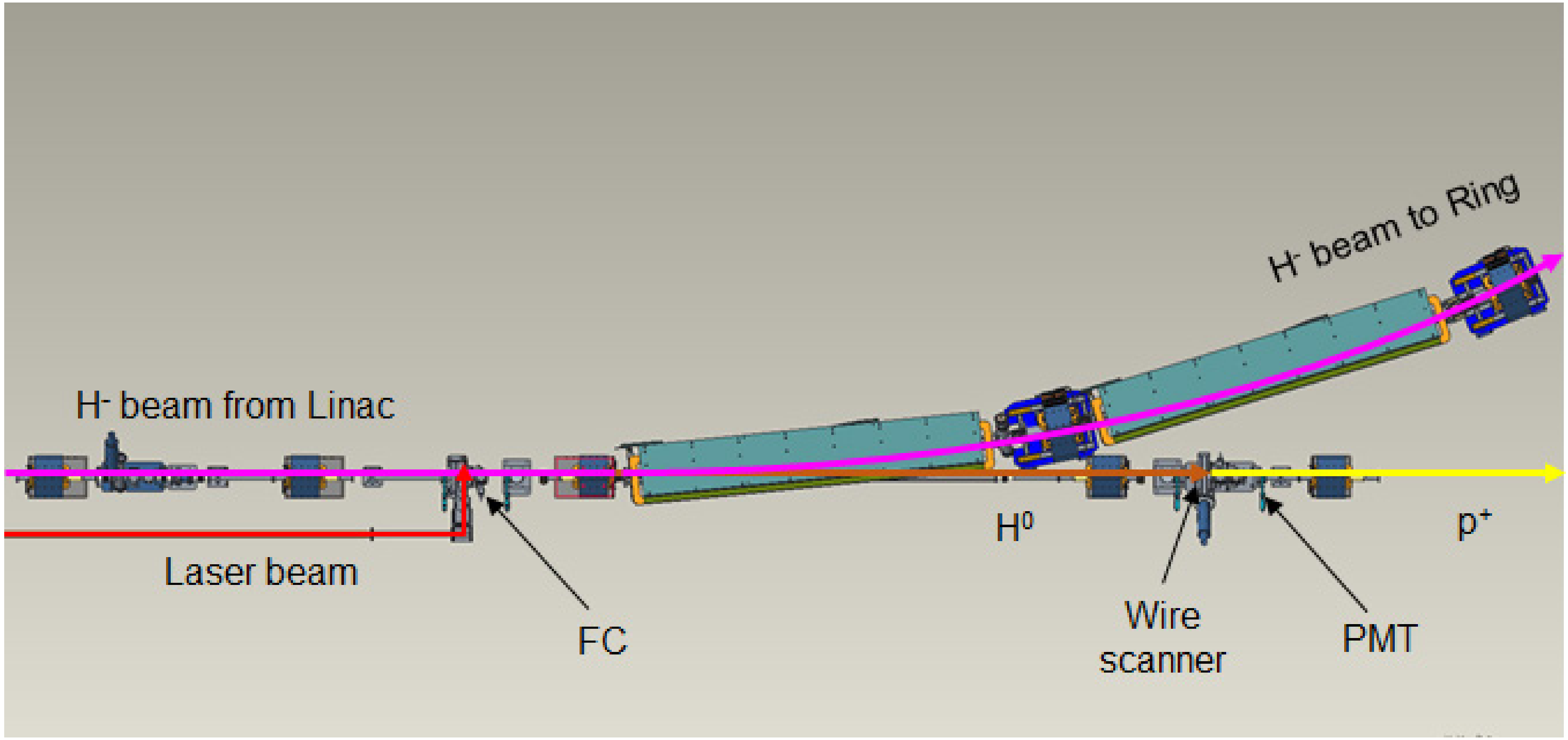
The value is close to the design value

Reconstructed longitudinal profile from virtual slit

Time-resolved measurement using a laser comb



H^- beam emittance measurement using laser wire



- Essentially a slit-detector emittance scanner
- Laser wire creates H^0 beam slit that preserves the angular distribution of the H^- beam
- Measurement of divergence of H^0 beam leads to the determination of H^- beam divergence
- Emittance measurement is time consuming, normally taking 20-30 minutes on a 60-Hz beam

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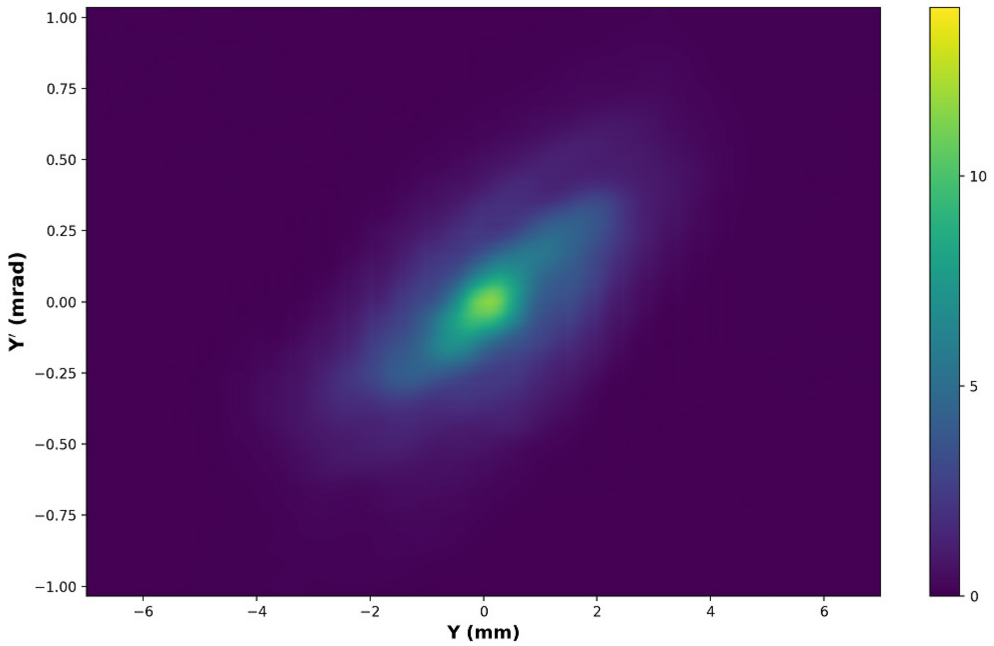

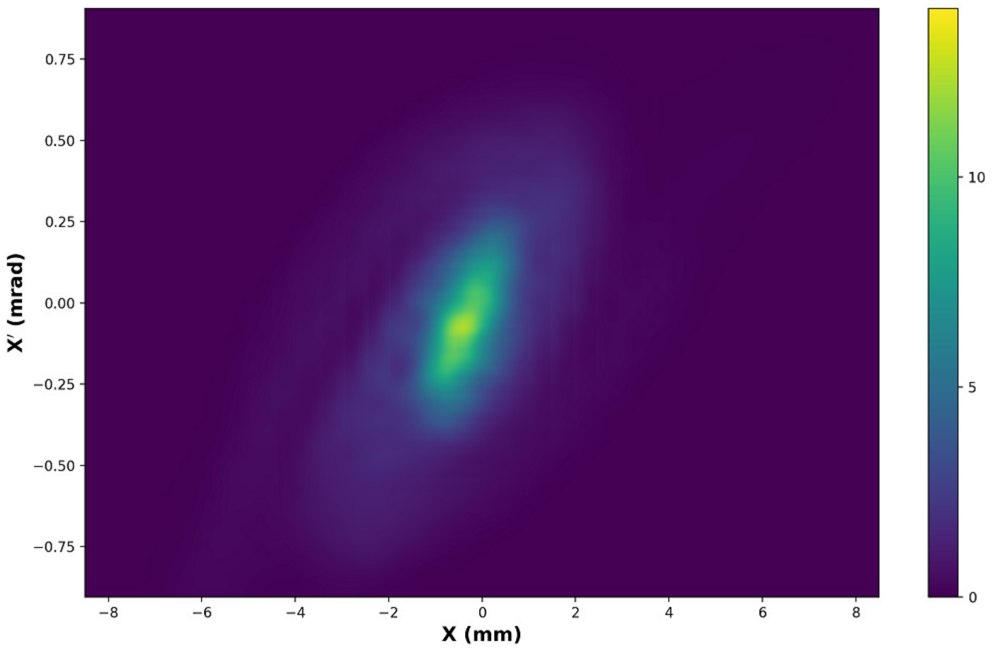

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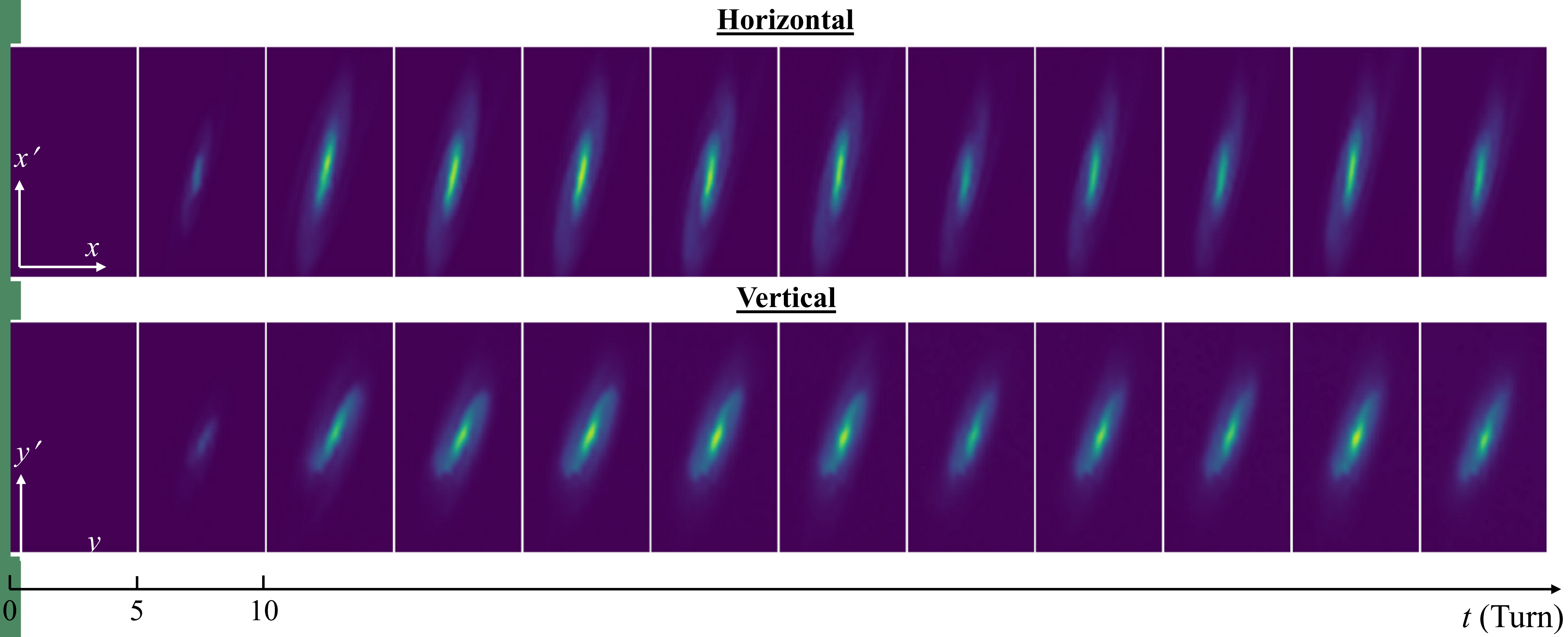
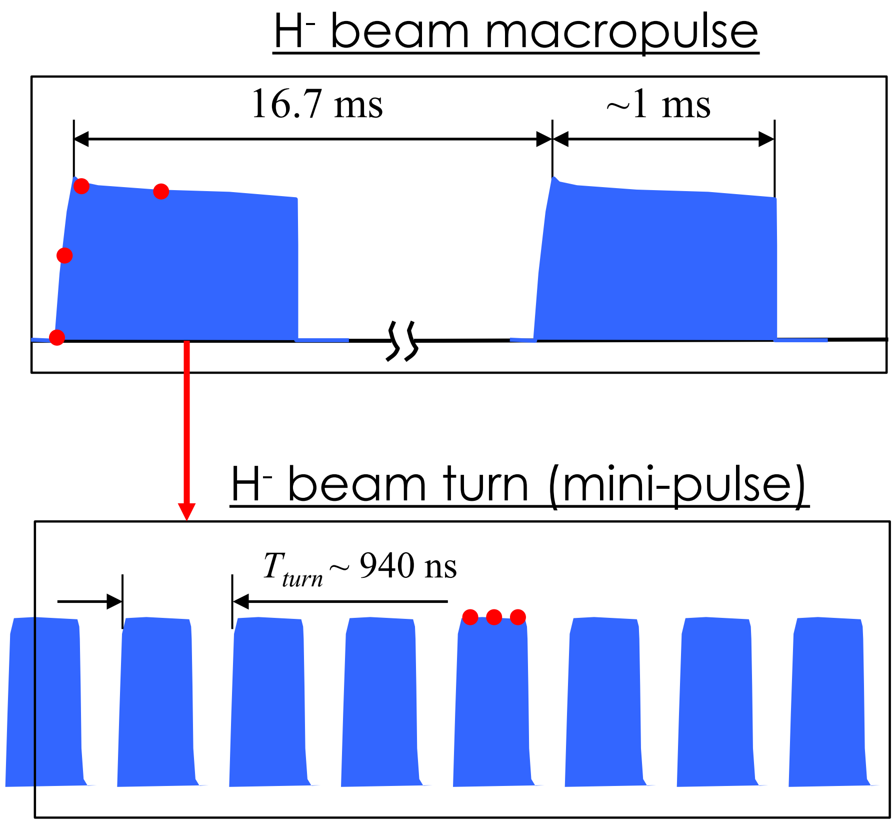
Multiple emittance slices over the ramp-up of the H^- beam macropulse measured from a single scan

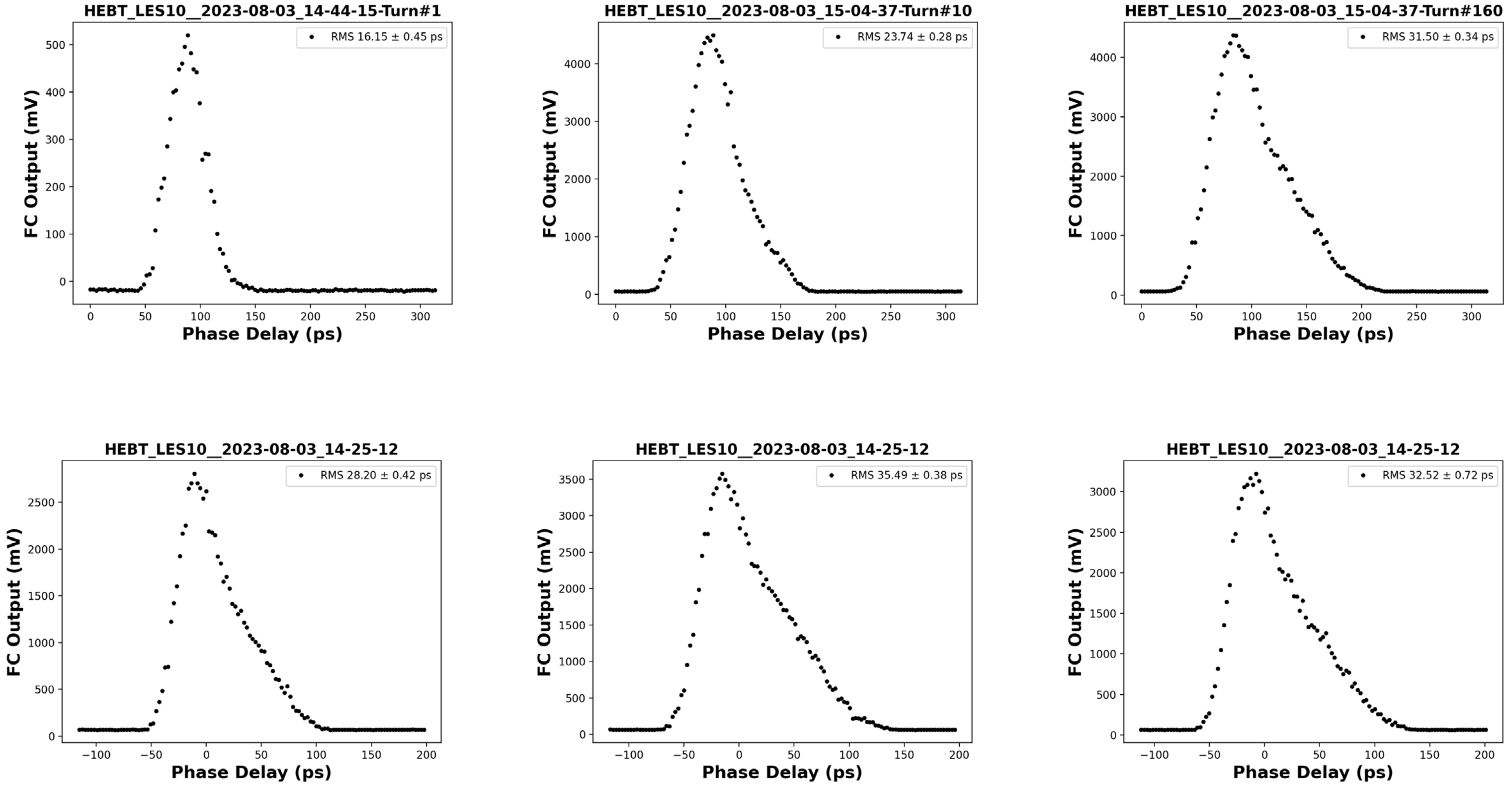


We measured up to 30 emittance slices (would take 12 hours) from one scan (< 30 minutes)

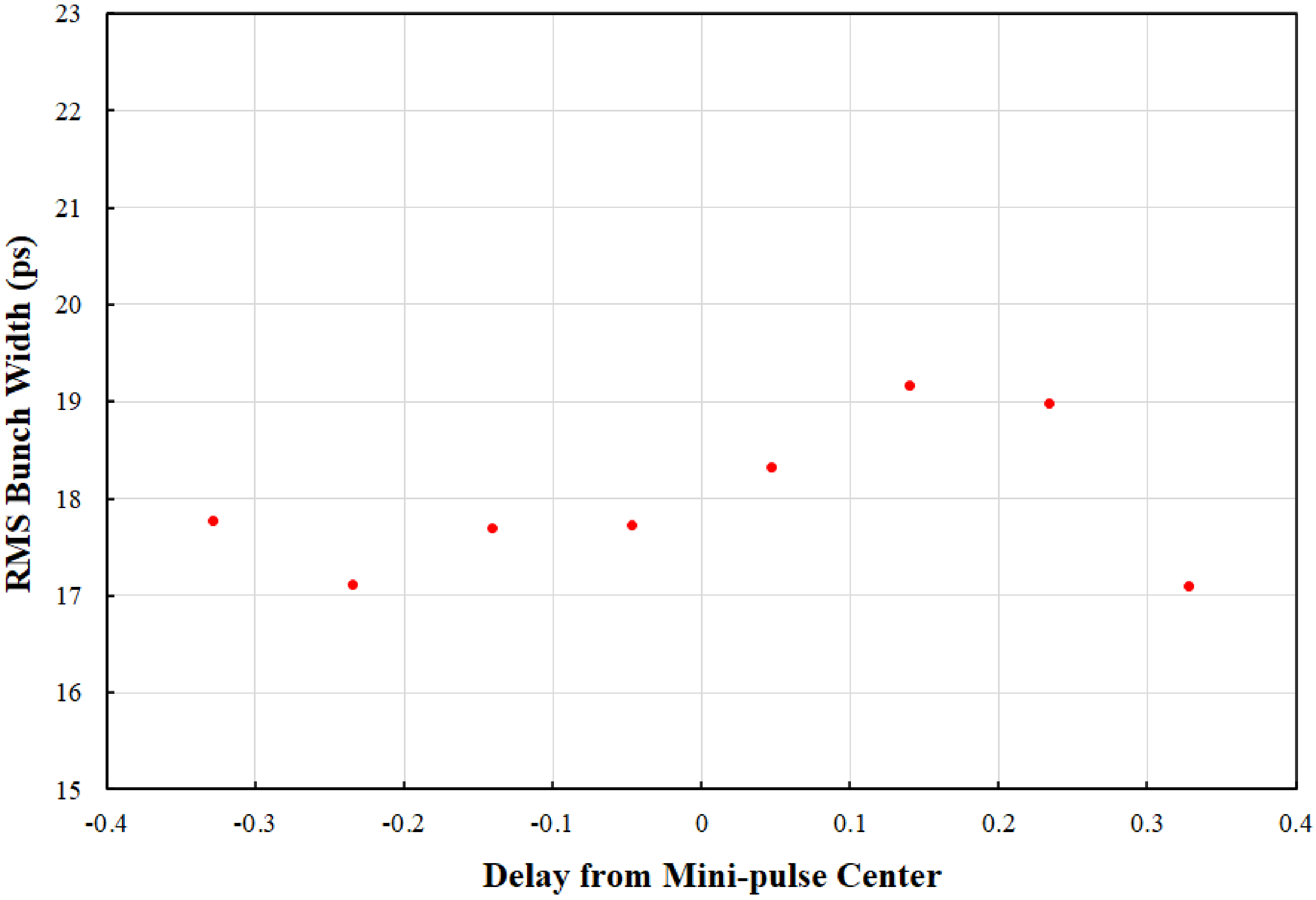
*Y. Liu et al., Phys. Rev. Accel Beams **23**, 102806 (2020)).*

Time-resolved measurements of longitudinal profiles





Measured bunch width variations within a H- beam mini-pulse and over different mini-pulses



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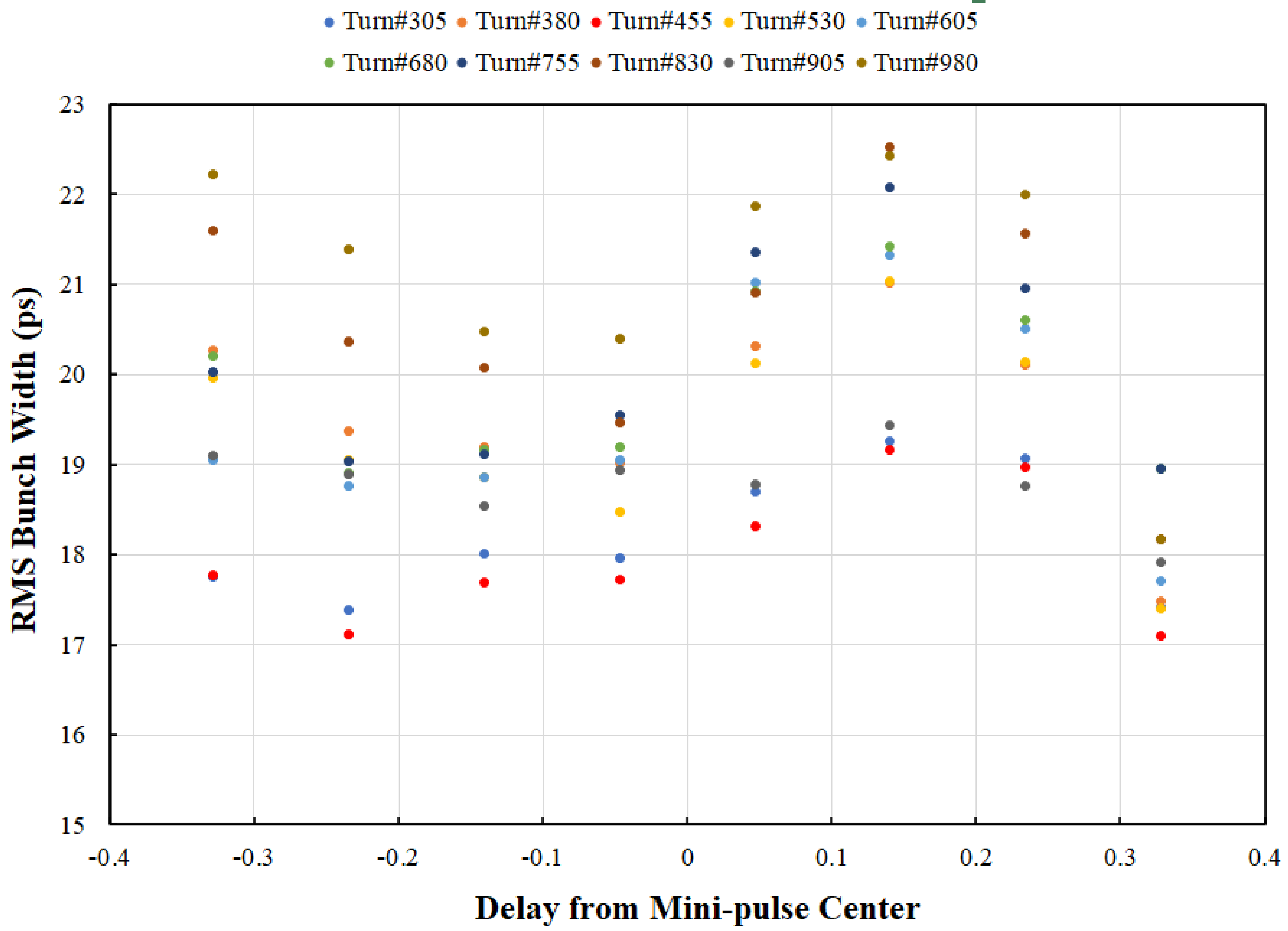
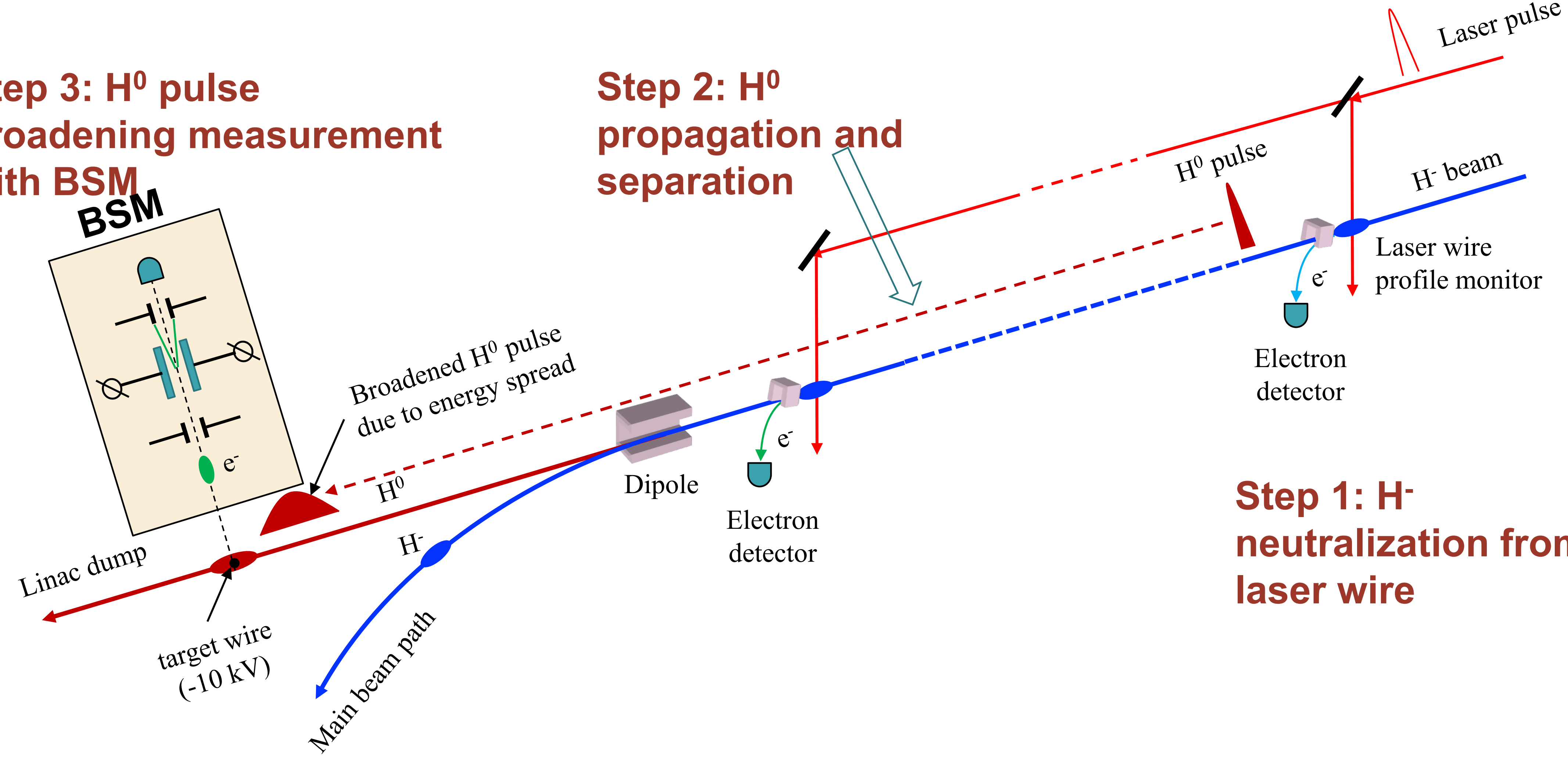


Outlook - Laser wire-based longitudinal phase space monitor

Step 3: H^0 pulse broadening measurement with BSM

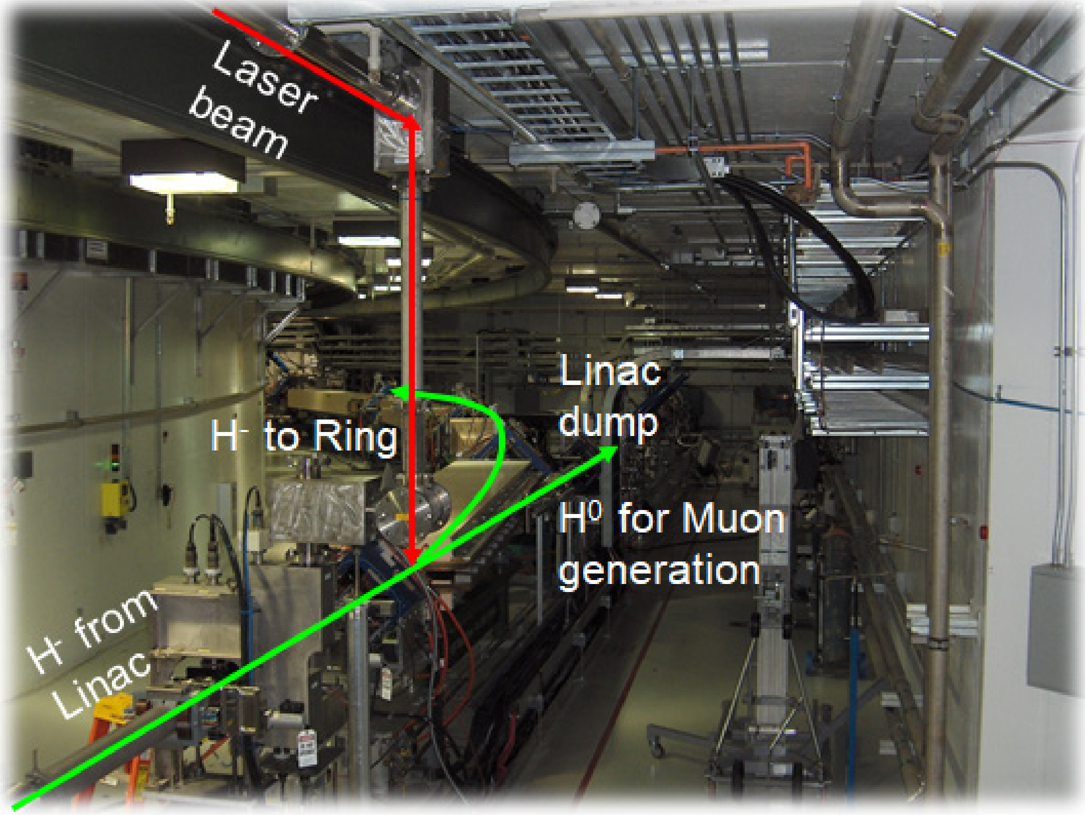
Step 2: H^0 propagation and separation

Step 1: H^- neutralization from laser wire



Outlook: laser-based proton beam extraction

- At SNS, a study is being carried out to leverage the existing accelerator serving new missions: Muon Spectroscopy (μSR) and Single Event Effects (SEE).
- μSR - material characterization, especially sensitive measurement of local magnetic field
- SEE – using n/p+ to test equipment against radiations for aerospace industry
- Using a laser beam with sufficient pulse energy, one can neutralize large portion of H^- bunches and extract them from the accelerator. The laser-based beam extraction is non-interceptive and has negligible impact on the primary neutron scattering mission.

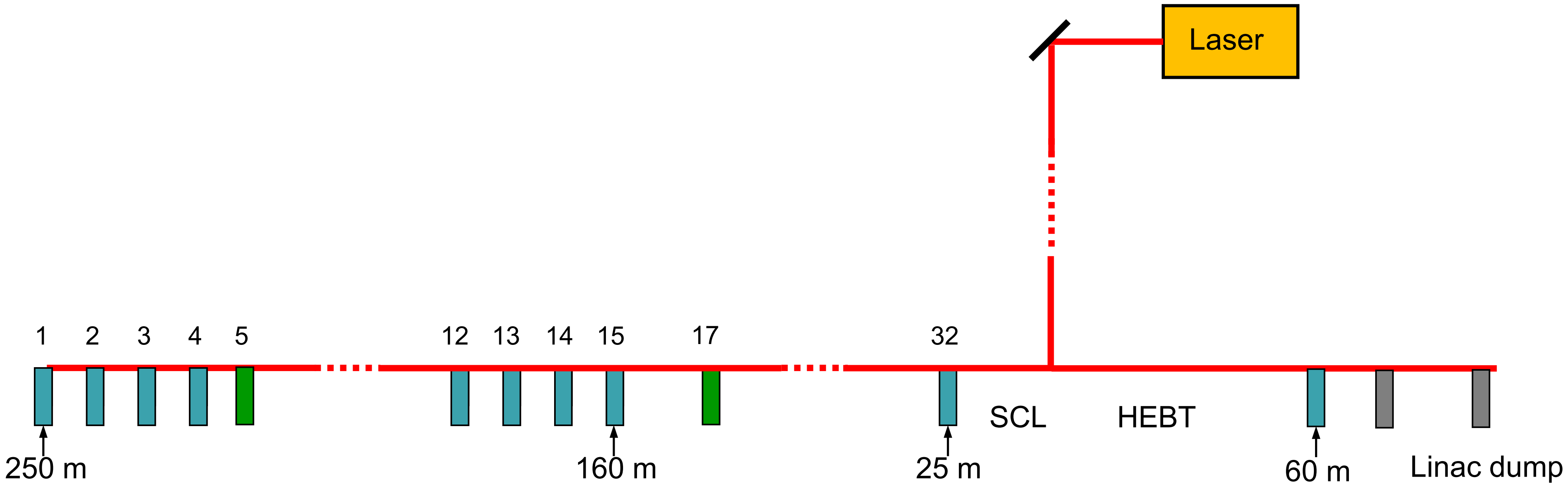


The optimal proton pulses for muon spectroscopy would be *30 ns* pulses spaced 20 μs apart (*50 kHz*), which can be produced using photo-neutralization. The fraction of the extracted beam is negligible (~ 0.2%).

Y. Liu et al., Nucl. Instrum. Methods Phys. Res., A **962**, *163706 (2020).*

Challenges and limitations

- Laser source
- Optical transport line
- Position stabilization



R. Hardin, Y. Liu, C. Long, A. Aleksandrov, W. Blokland, *Opt. Express* **19** (2011) 2874-2885.
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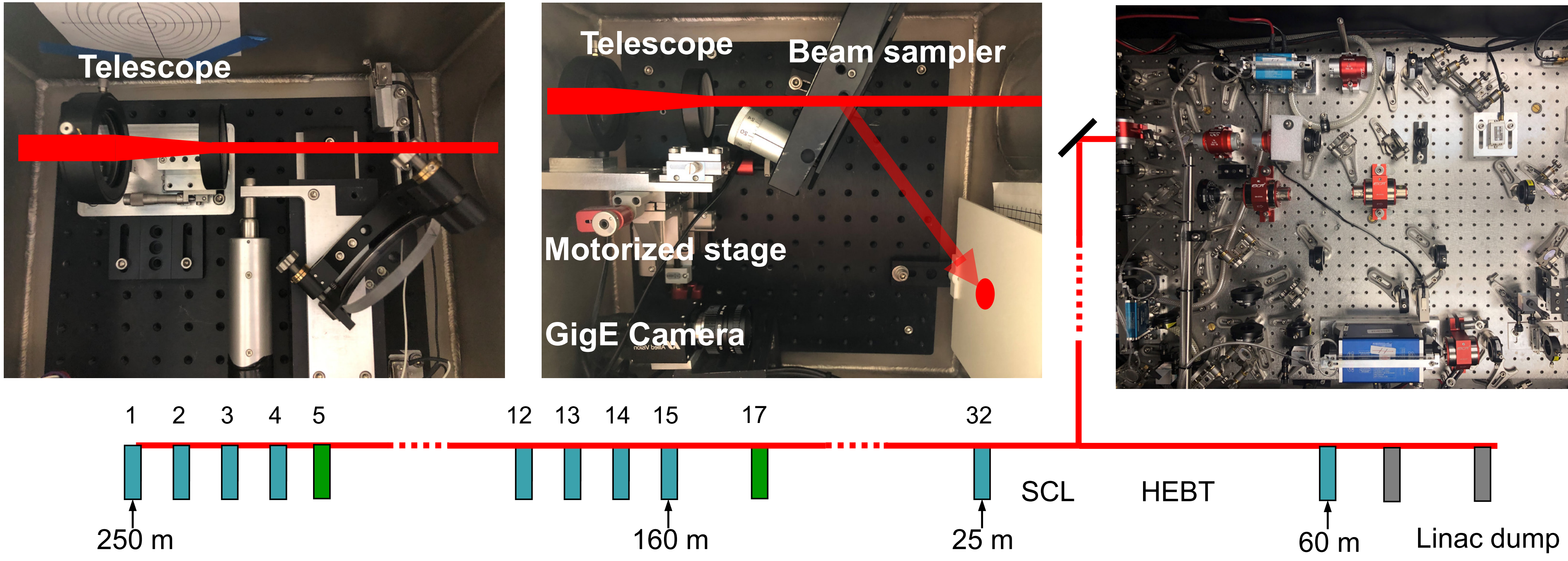

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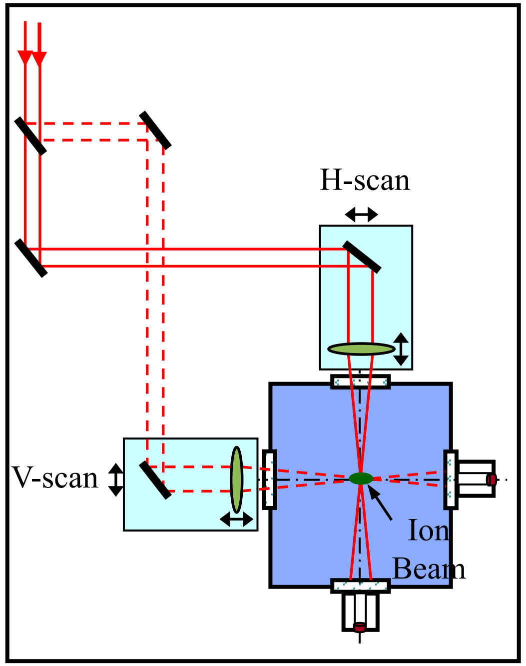
Challenges and limitations

Mitigation of reflected/scattered light in the measurement chamber is critical to achieve high dynamic range measurements.



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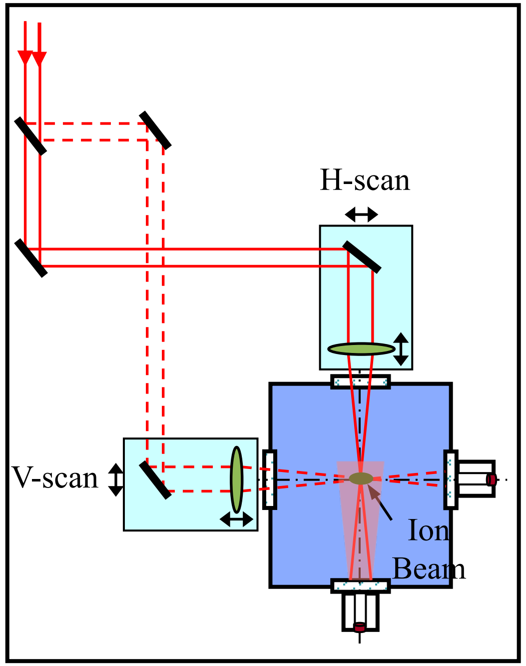

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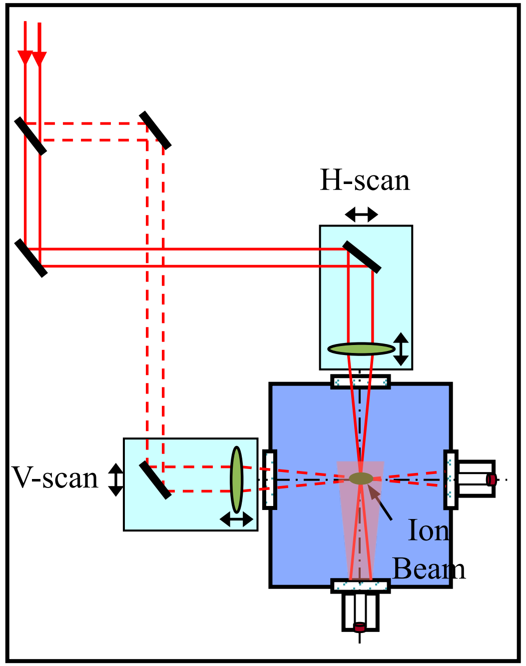
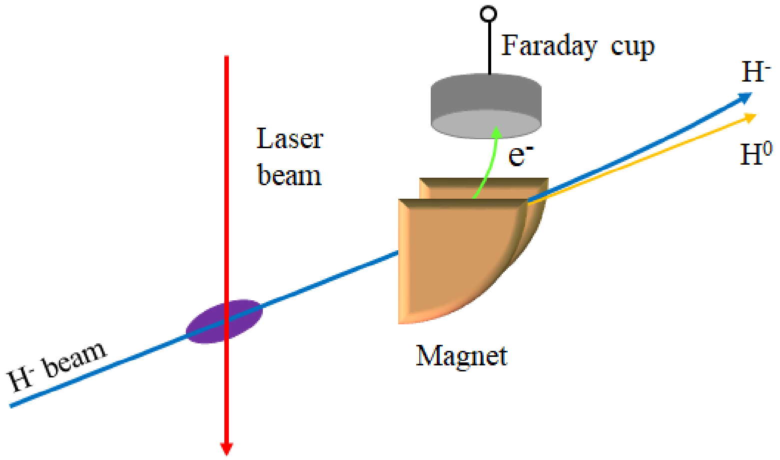


Orbit compensation and control of beam loss from the neutralized hydrogens are important to reassure non-interceptive operation.



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Summary

- We have described a laser wire system for the diagnostics of high-power H^- beam at the SNS linac during neutron production.
- The virtual slit technique enables longitudinal profile measurement of H^- beam bunches with a few picoseconds bunch width.
- Laser combs provide time-resolved measurements at a much higher speed, makes it possible to study beam parameter variations within a very short time interval.
- We have demonstrated that the laser-wire-based beam instrumentation can be made operational in a high-power accelerator facility and it provided novel functions which are not possible with conventional wire scanners or bunch shape monitors.

Acknowledgements

Technical contributions to the development of virtual slit and laser comb

- Cary Long
- Alexander Aleksandrov
- Andy Webster
- Syd Murray III
- Andrei Shishlo
- David Brown
- Randy Thurman-keup (Fermilab)
- Vic Scarpine (Fermilab)

Support from

- BI Group members at RAD/ORNL
- Sarah Cousineau
- Fulvia Pilat