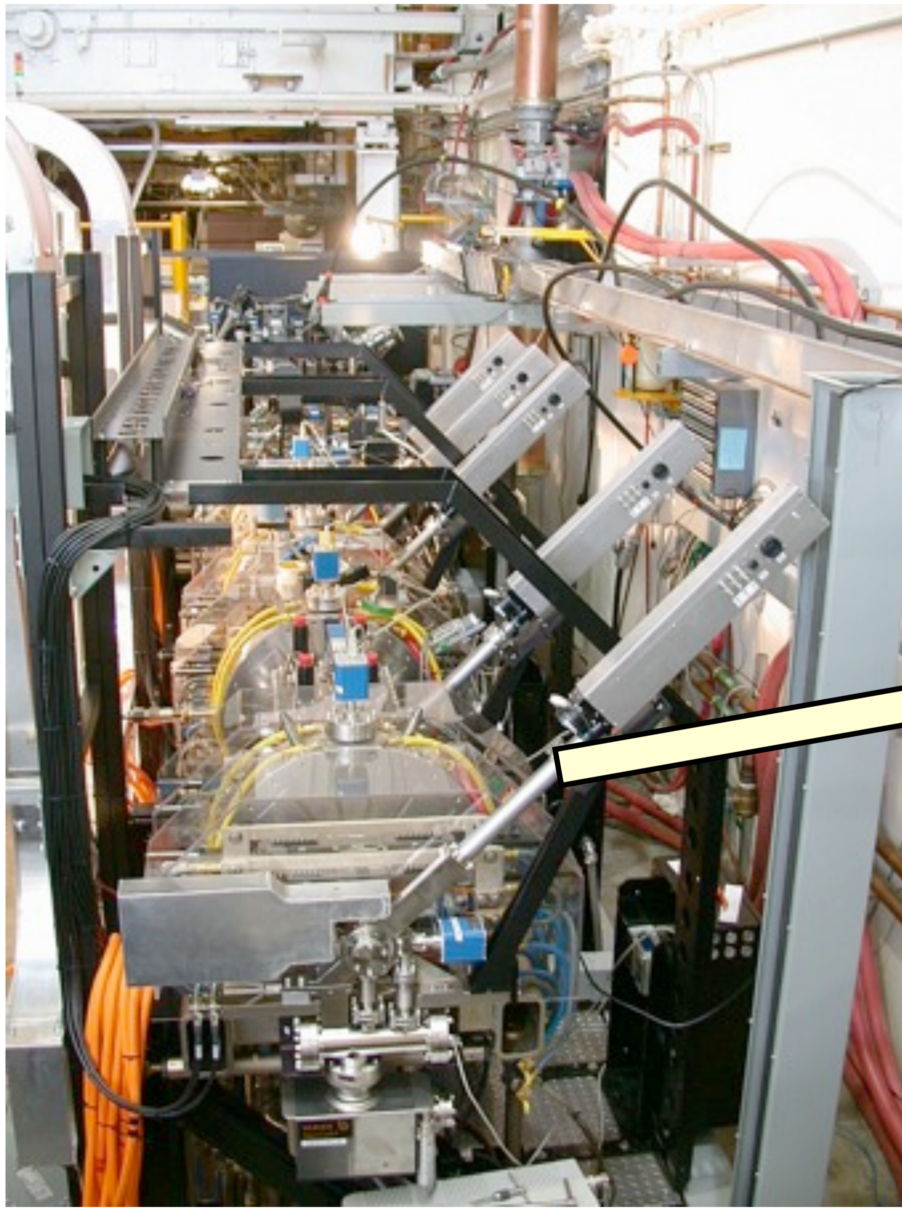
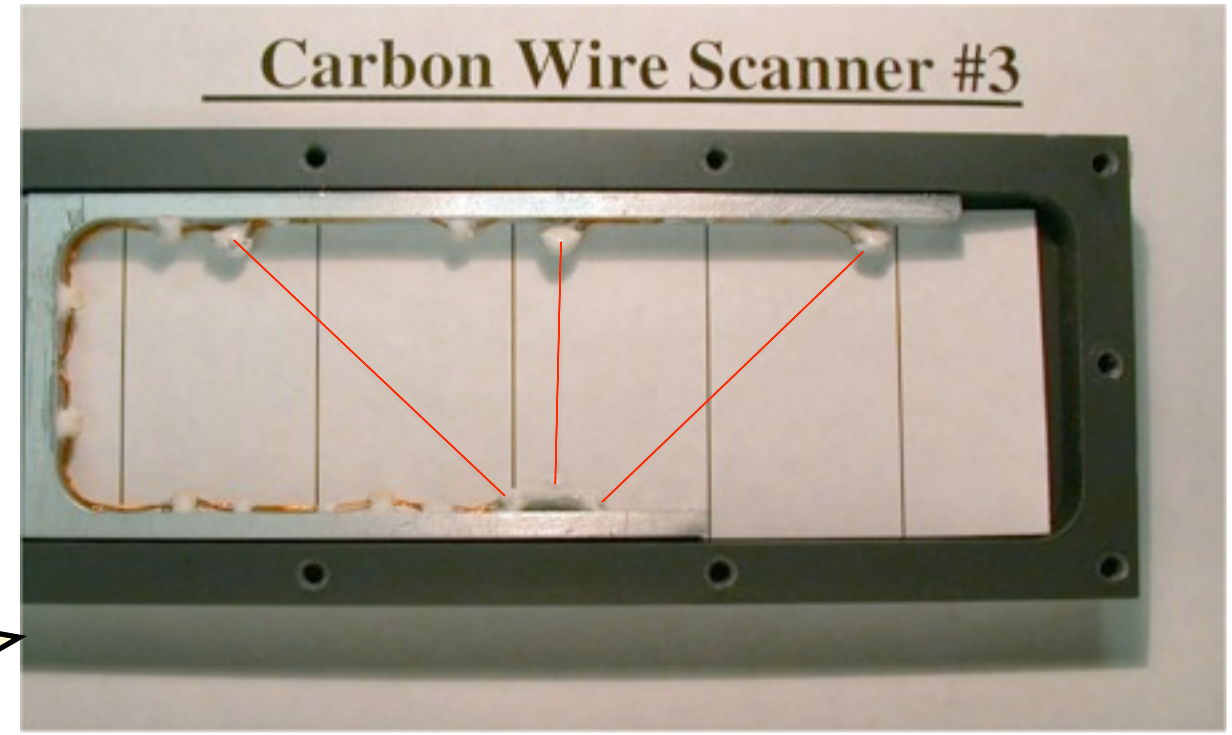
Laser Diagnostics for H- Beams

Tom Shea (ORNL)
USPAS and University of New Mexico
Albuquerque NM, June 23-26, 2009

Material adapted from presentations by many people in the accelerator community, particularly: R. Connolly and Y. Liu.

Conventional Carbon Wire Scanner





Disadvantages

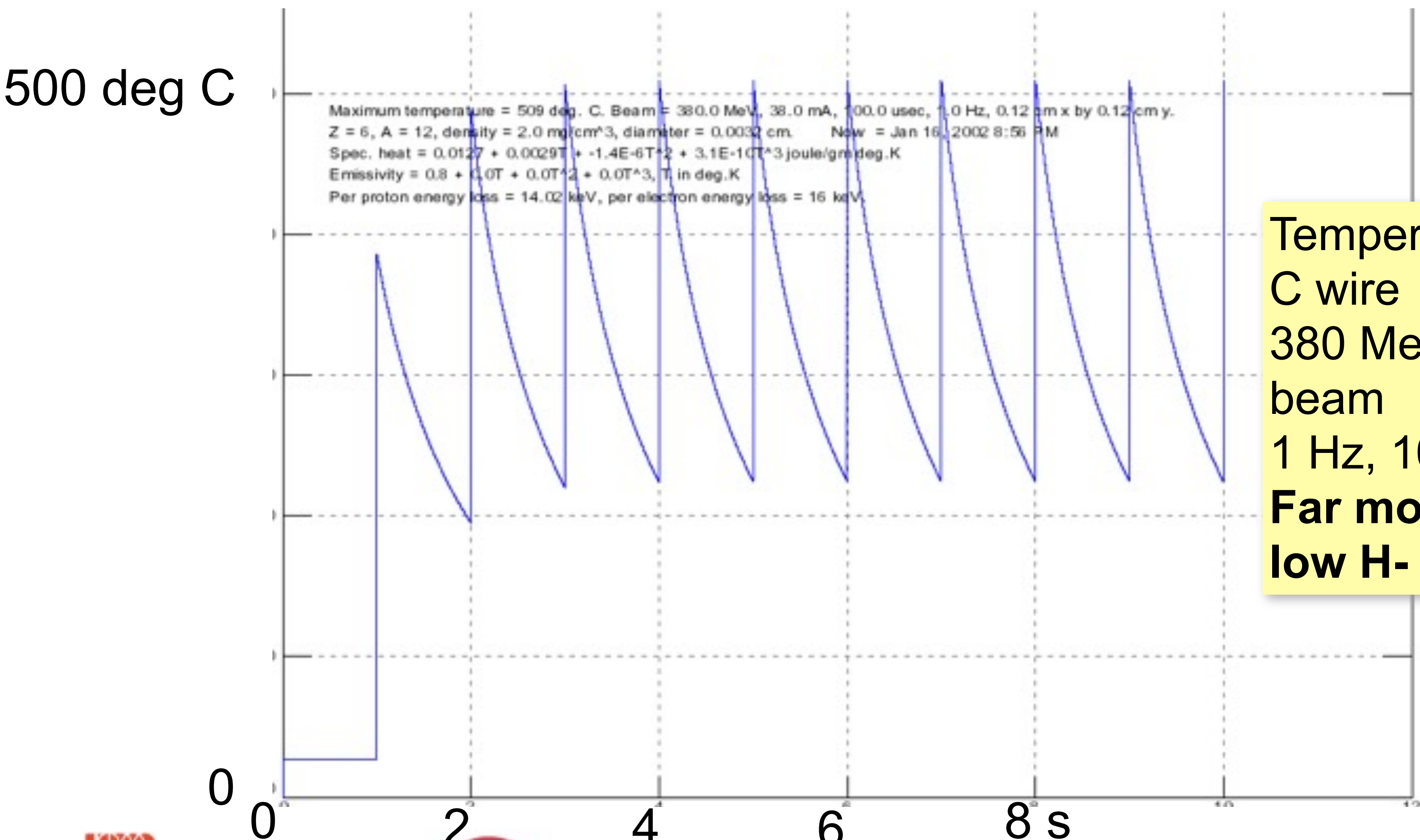
- Requires special low power operation mode
- Ablation from the wire may contaminate the superconducting cavity
- Maintenance requires vacuum access

Advantages

- Very radiation hard
- Excellent signal to noise ratio

Carbon Wire Heating

- Low power beam mode required for intercepting devices:
  - Short Macropulse: 50 microseconds (full power operations: 1 ms))
  - Low rep rate: < 6 Hz (full power operations: 60 Hz)
  - **Full power will destroy wire; measurement interrupts normal operations**

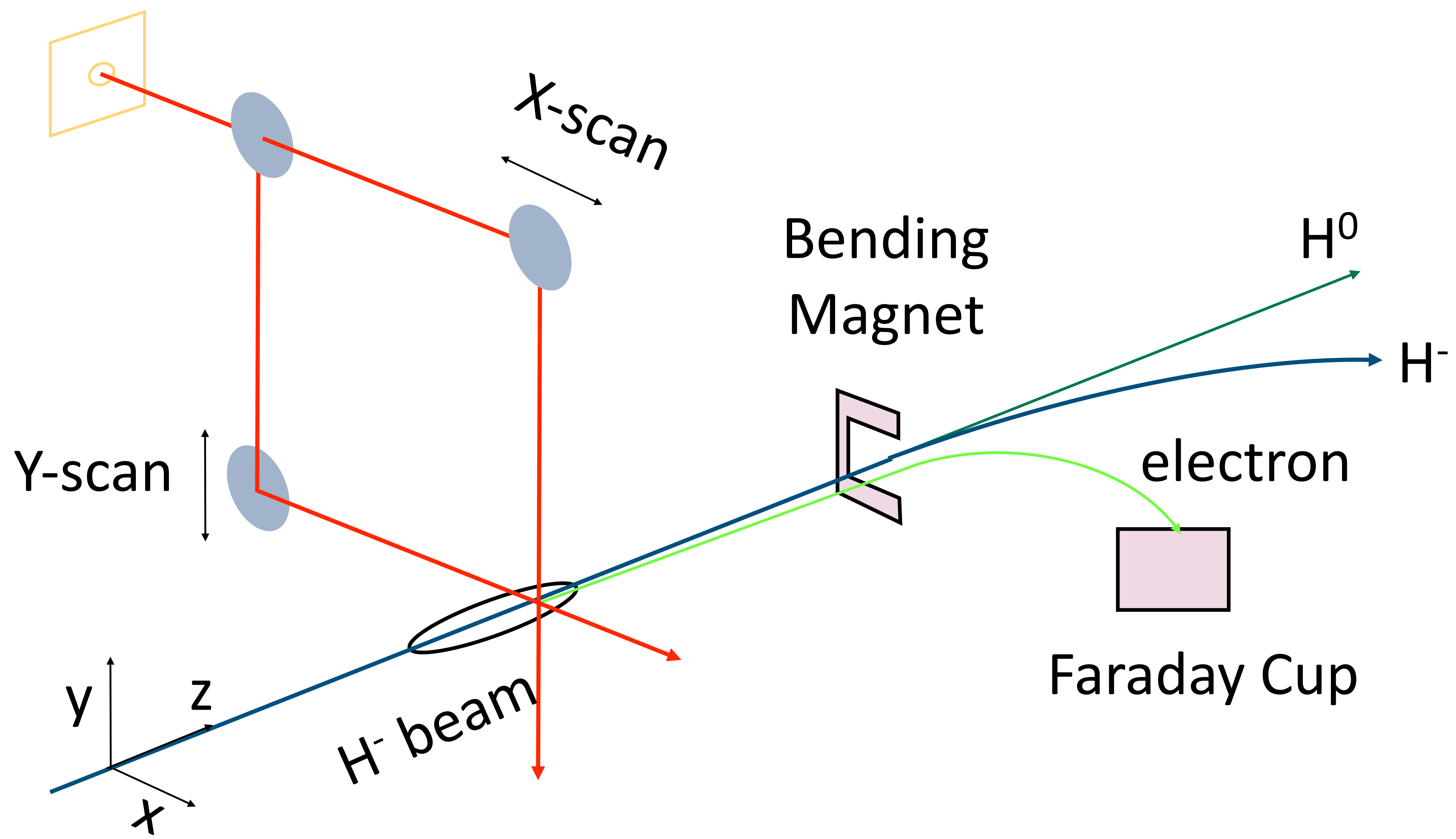


Temperature vs. time of 32 micron C wire
380 MeV, 1.2 mm x 1.2 mm rms H- beam
1 Hz, 100 microsecond
Far more energy deposition at low H- beam energy

Calculations: Mike Plum (LANL, now @ORNL); also C. J. Liaw (BNL)

Laser Wire

Replace carbon wire with a laser beam



Lasers and H- Beams

First ionization potential for H- ions is 0.75eV.

Photons with λ<1500nm can separate H- ion into free electron and neutral H.

The H- ion has no excited states so the electron is removed into the continuum.

Laser can be used to mark a portion of beam by neutralization.

Once a portion of the beam is marked, measurements can be made on the neutral beam, the removed electrons, or the reduced beam current with beam current transformer or BPM stripline.

This method has been used at Los Alamos for transverse and longitudinal emittance measurements.

History of H- photodetachment

In 1938 R. Wildt proposed that photodetachment of H- ions produced most of the continuous absorption in late-type stars.

ON THE NEGATIVE HYDROGEN ION AND ITS ABSORPTION COEFFICIENT

S. CHANDRASEKHAR AND MARGARET KIESS KROGDAHL
Yerkes Observatory
Received July 6, 1943

ABSTRACT

The continuous absorption coefficient of the negative hydrogen ion is discussed from the point of view of the sum rules, and it is shown that the absorption coefficient to the red of 5000 A is predominantly governed by the wave-function of the ground state of H^- at distances of the order of five times the Bohr radius from the center. It appears that the wave-functions for H^- now in use are not sufficiently accurate at these distances to provide reliable values for the absorption coefficient beyond 5000 A. Further, some objective criteria are stated which should enable the reliability of a given absorption curve to be tested.

1. It is now generally recognized that the negative hydrogen ion provides the principal source of opacity in stellar atmospheres. Consequently, some effort has been spent to evaluate its continuous absorption coefficient. The most recent of such attempts is that of R. E. Williamson,[1] who derived for this purpose a "sixth-order" wave-function to describe the ground state of H^- similar in form to Hylleraas' wave-function for the ground state of helium. However, when Williamson derived the theoretical color-effective tem-

"It is now generally recognized that the negative hydrogen ion provides the principal source of opacity in stellar atmospheres." Chandrasekhar and Krogdahl, 1943

ON THE CONTINUOUS ABSORPTION COEFFICIENT OF THE NEGATIVE HYDROGEN ION

S. CHANDRASEKHAR
Yerkes Observatory
Received June 25, 1945

ABSTRACT

In this paper it is shown that the continuous absorption coefficient of the negative hydrogen ion is most reliably determined by a formula for the absorption cross-section which involves the matrix element of the momentum operator. A new absorption curve for H^- has been determined which places the maximum at λ 8500 A; at this wave length the atomic absorption coefficient has the value 4.37×10^{-17} cm^2.

1. *Introduction.*—In earlier discussions[1] by the writer attention has been drawn to the fact that the continuous absorption coefficient of the negative hydrogen ion, evaluated in terms of the matrix element

$$\mu = \int \Psi_d^* (r_1 + r_2) \Psi_c d\tau \qquad (1)$$

(where Ψ_d denotes the wave function of the ground state of the ion and Ψ_c the wave

5. *Concluding remarks.*—A comparison of Figures 1, 2, and 3 clearly illustrates the superiority of formula (II) for the purposes of evaluating the continuous absorption coefficient of the negative hydrogen ion. The general reliability of the absorption cross-

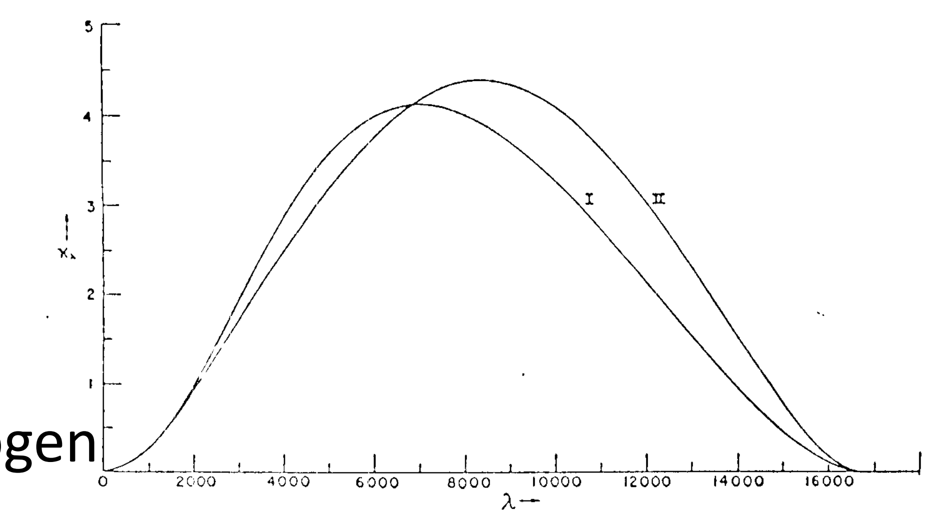
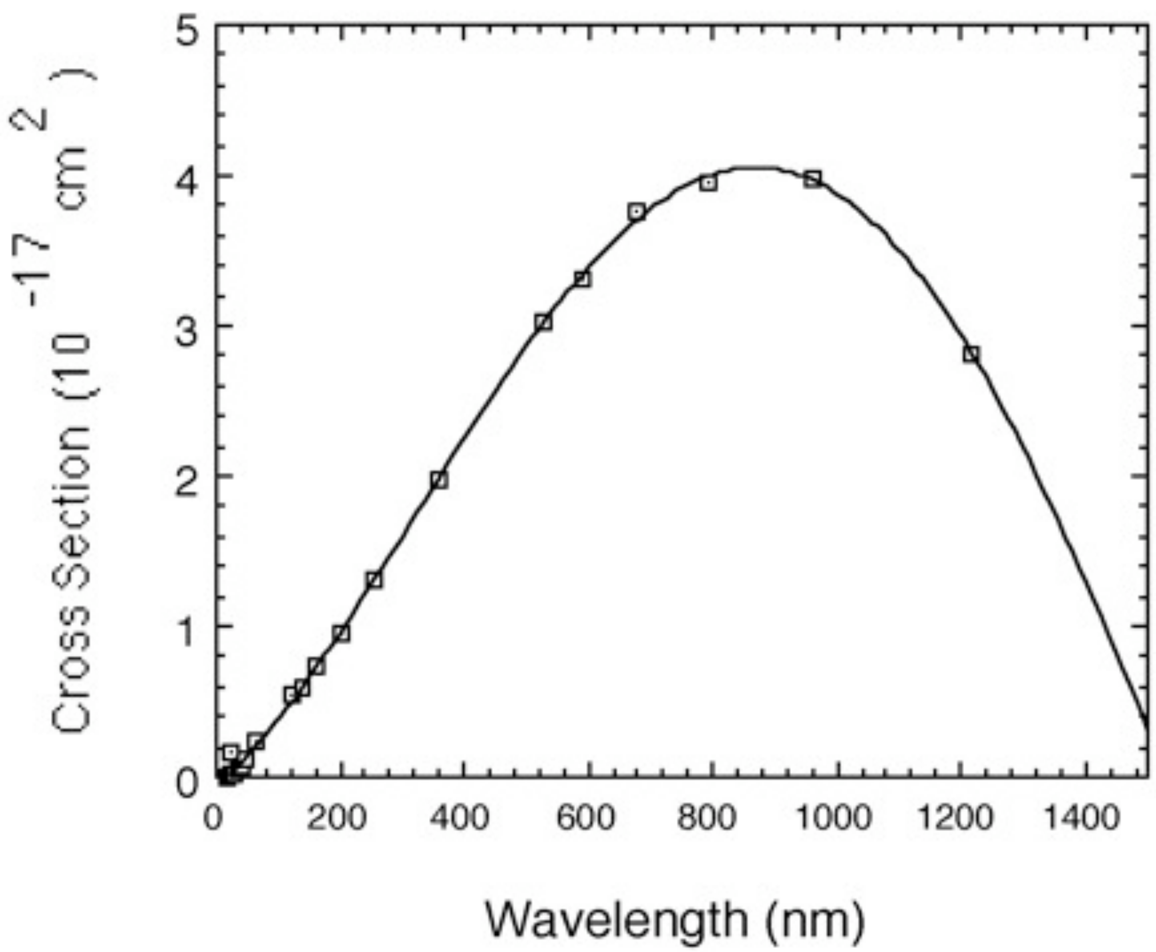


FIG. 3.—A comparison of the continuous absorption coefficient of H^- computed according to formula (II) and with wave functions of forms (2) (curve *I*) and (3) (curve *II*). The ordinates denote the absorption coefficients in units of 10^{-17} cm^2; the abscissae, the wave length in angstroms.

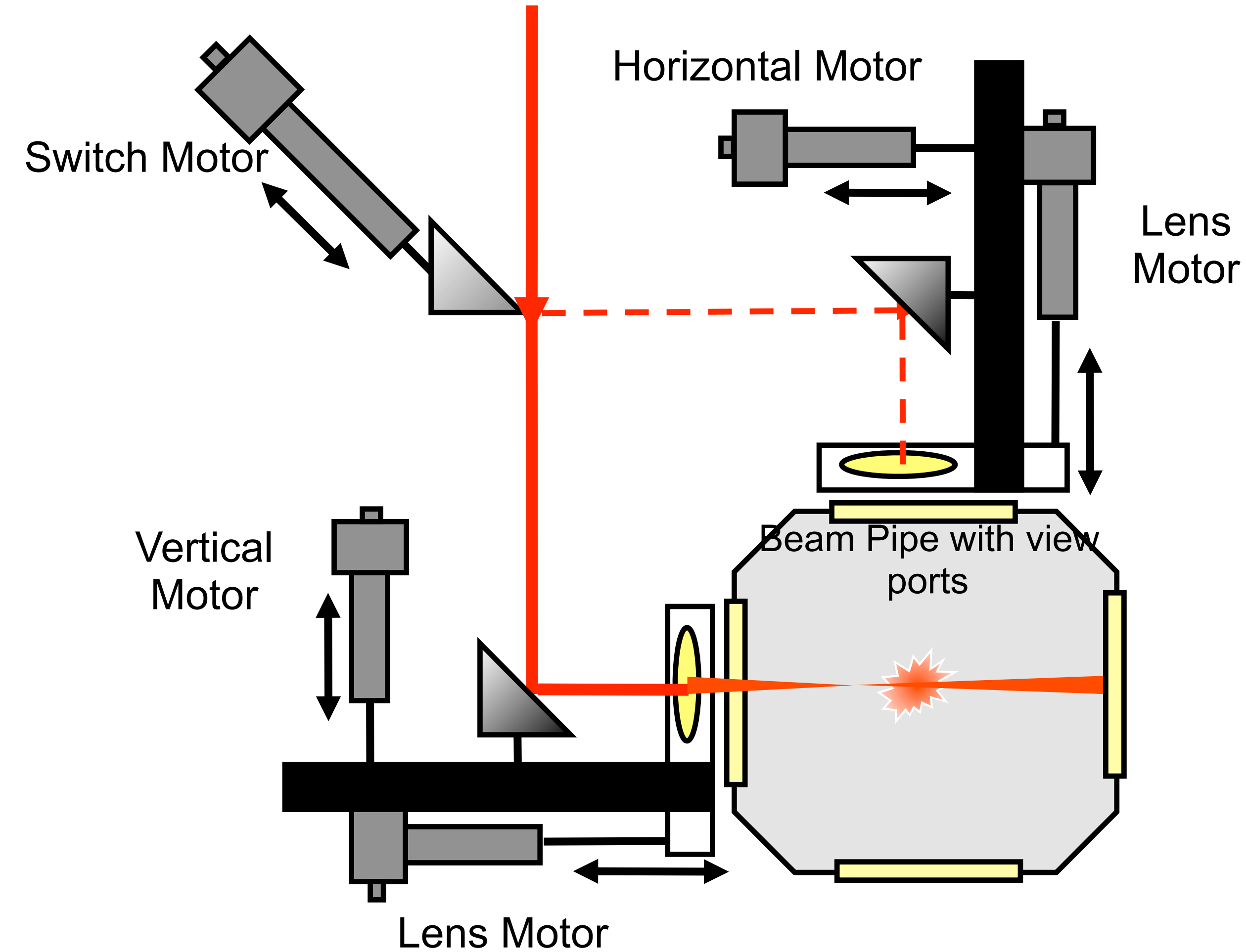
Toward a Laser Wire for SNS



Calculated cross section for H- photoneutralization as a function of photon wavelength.*

Nd:YAG laser has λ=1064nm where the cross section is about 90% of the maximum (at low beam energy).

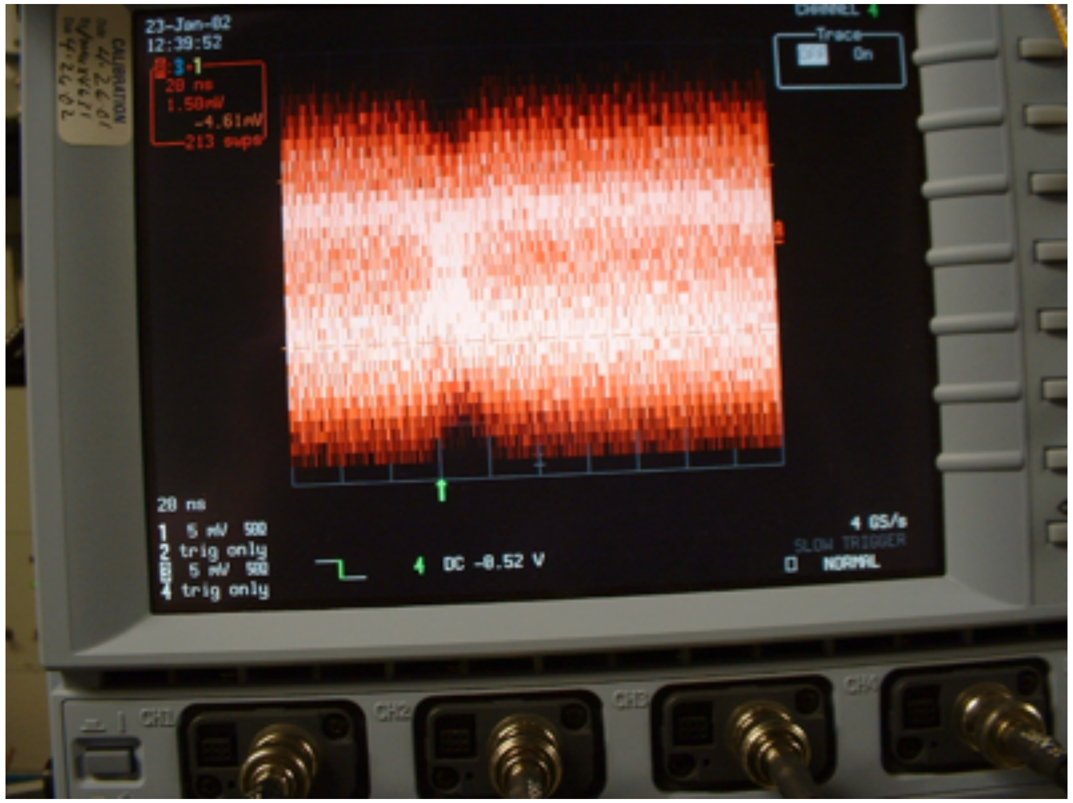
*J.T. Broad and W.P. Reinhardt, Phys. Rev. A14 (6) (1976) 2159.



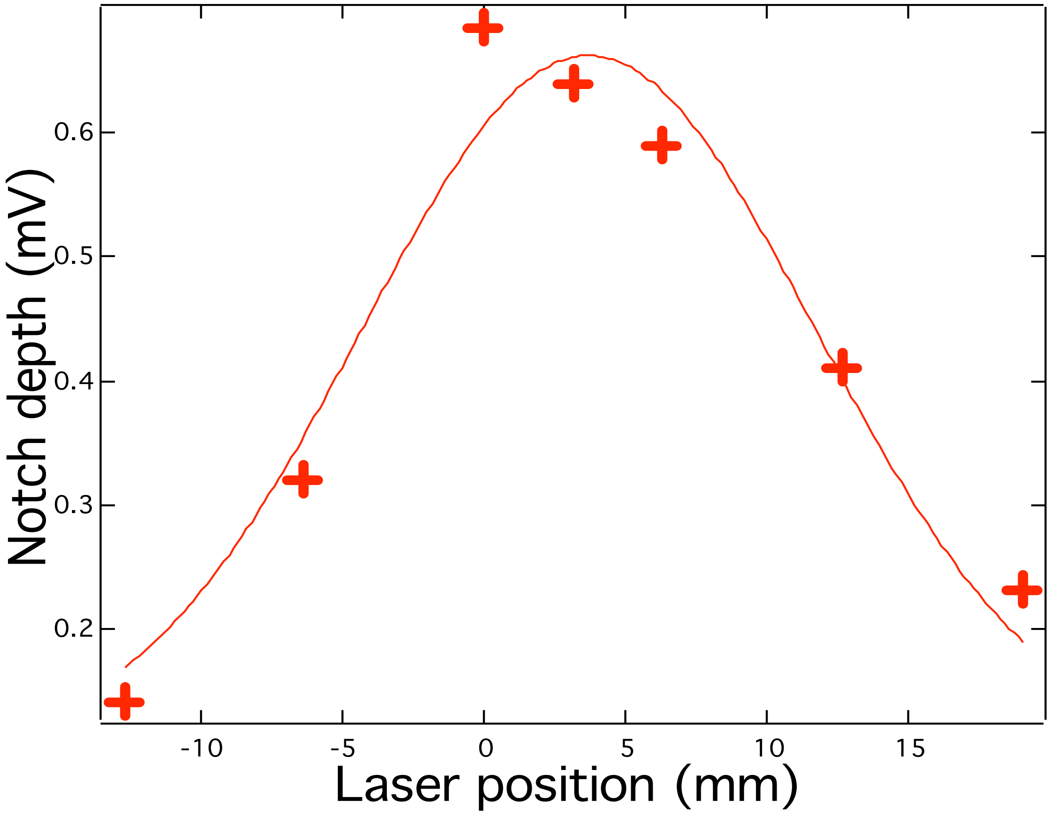
- Scan laser transversely across ion beam
- Plot one of the following vs. laser beam position:
  - Missing current in H- beam
  - Collected electrons liberated from H- beam

Laser Monitor Development at BNL: Meassure laser-induced "notch" in beam current signal

Scope was set on infinite persistence for several hundred beam pulses. This is difference signal at 200 MHz from upstream and downstream BPMs.

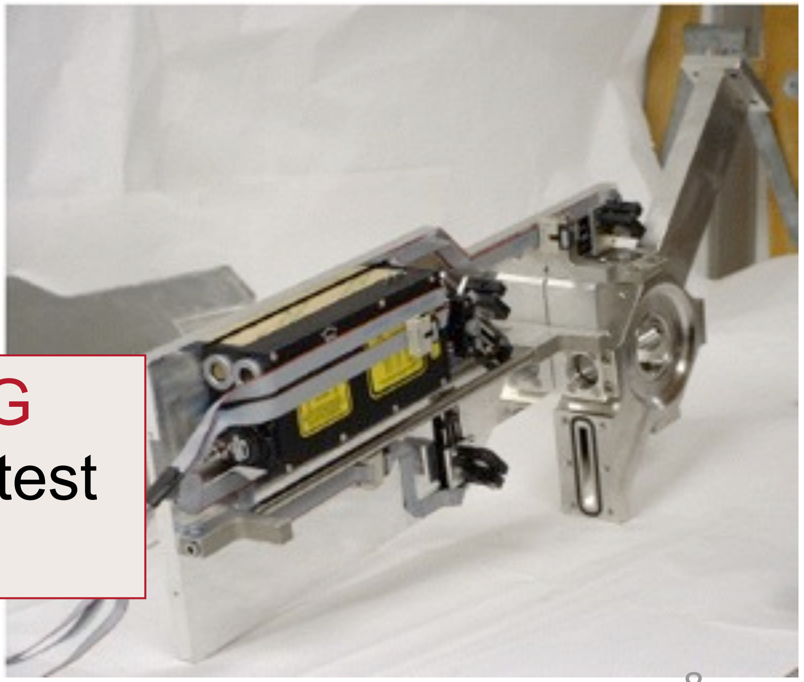


Laser Wire Profile with 100uA 200MeV Polarized Beam



"You've gotta be a believer" – Roger Connolly (BNL)

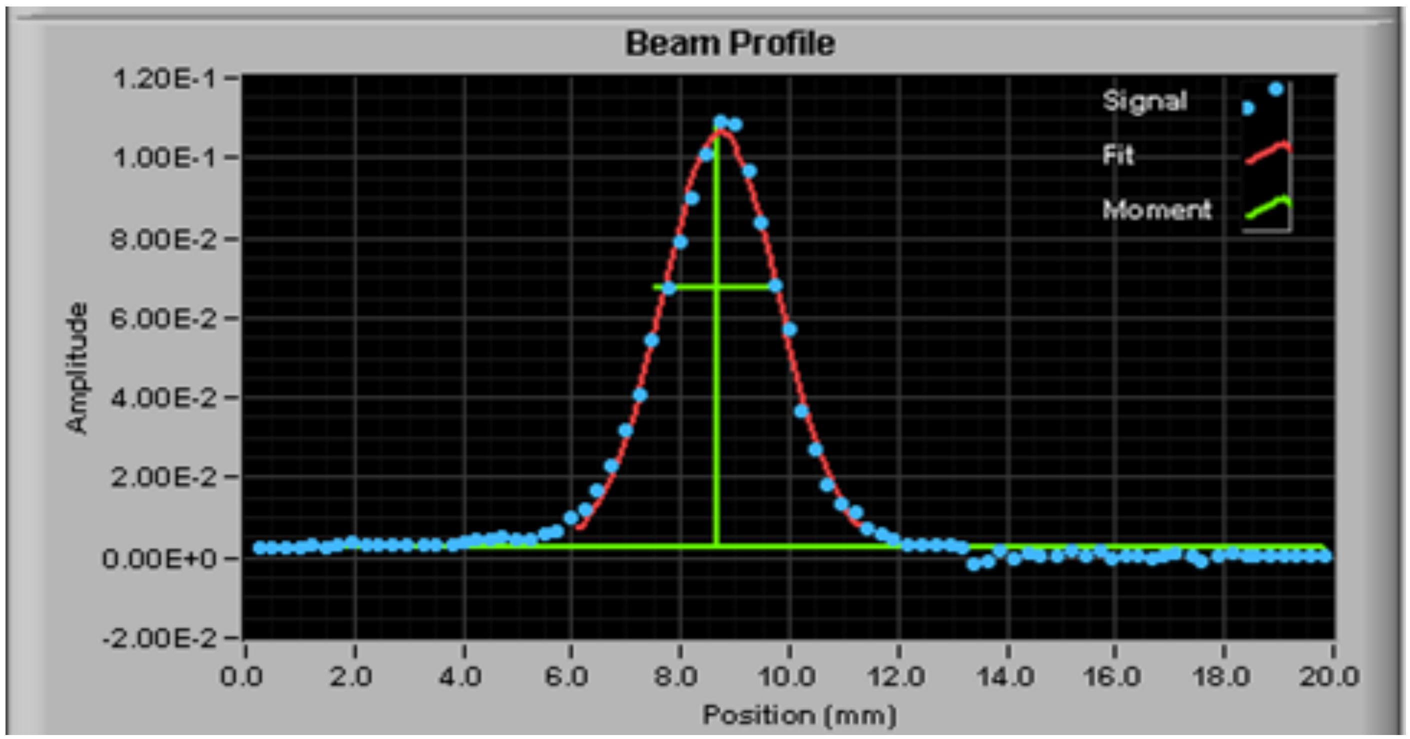
Small Q-switched Nd:YAG laser for similar 2.5 MeV test at LBNL



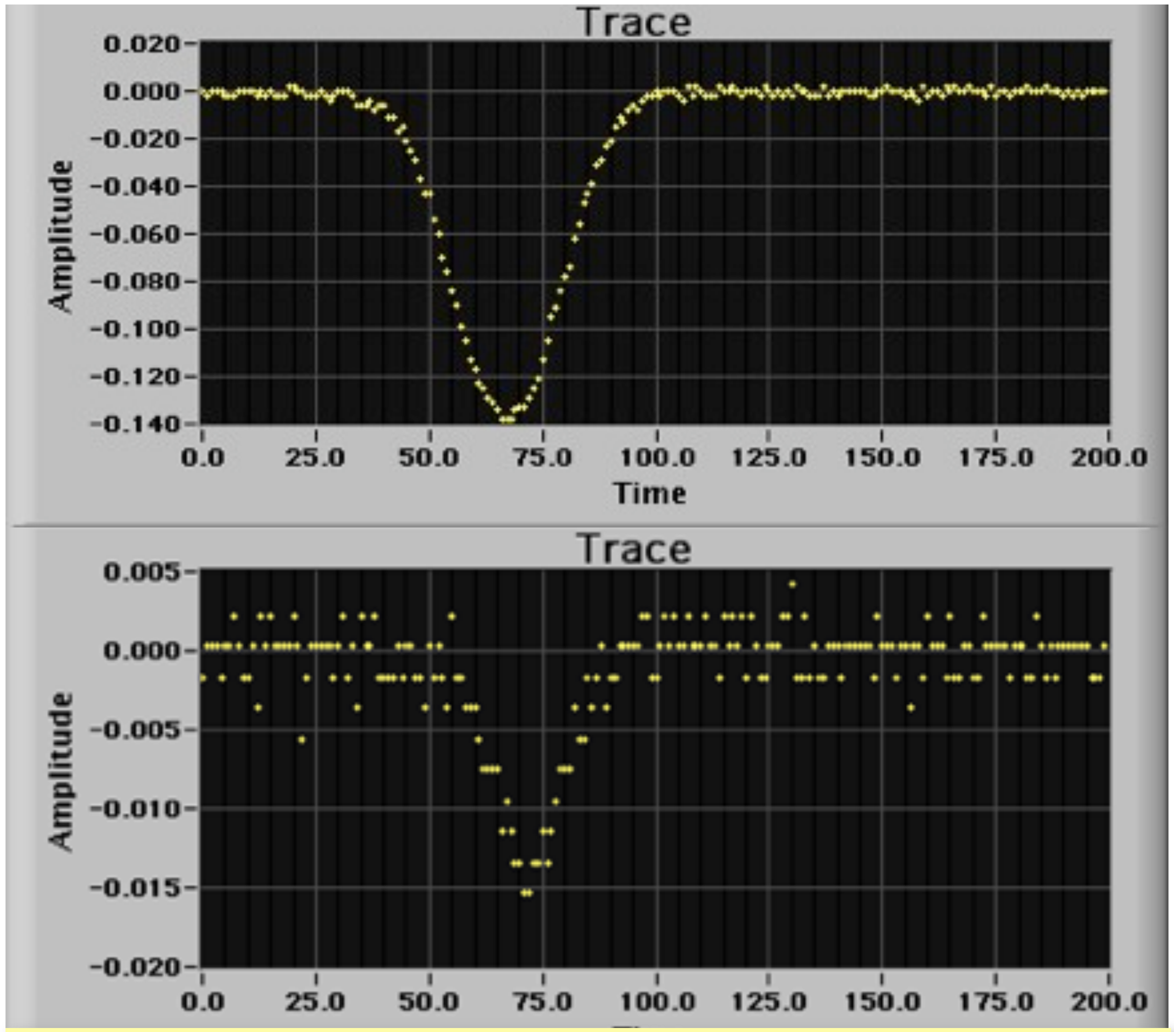
Front End at ORNL – Jan 2003
Laser Profile Monitor Results at 2.5 MeV

- Verification of **electron collection** technique
- Reliable measurements to about **3 sigma**

"Now I'm a believer" – N. Holtkamp (ORNL)

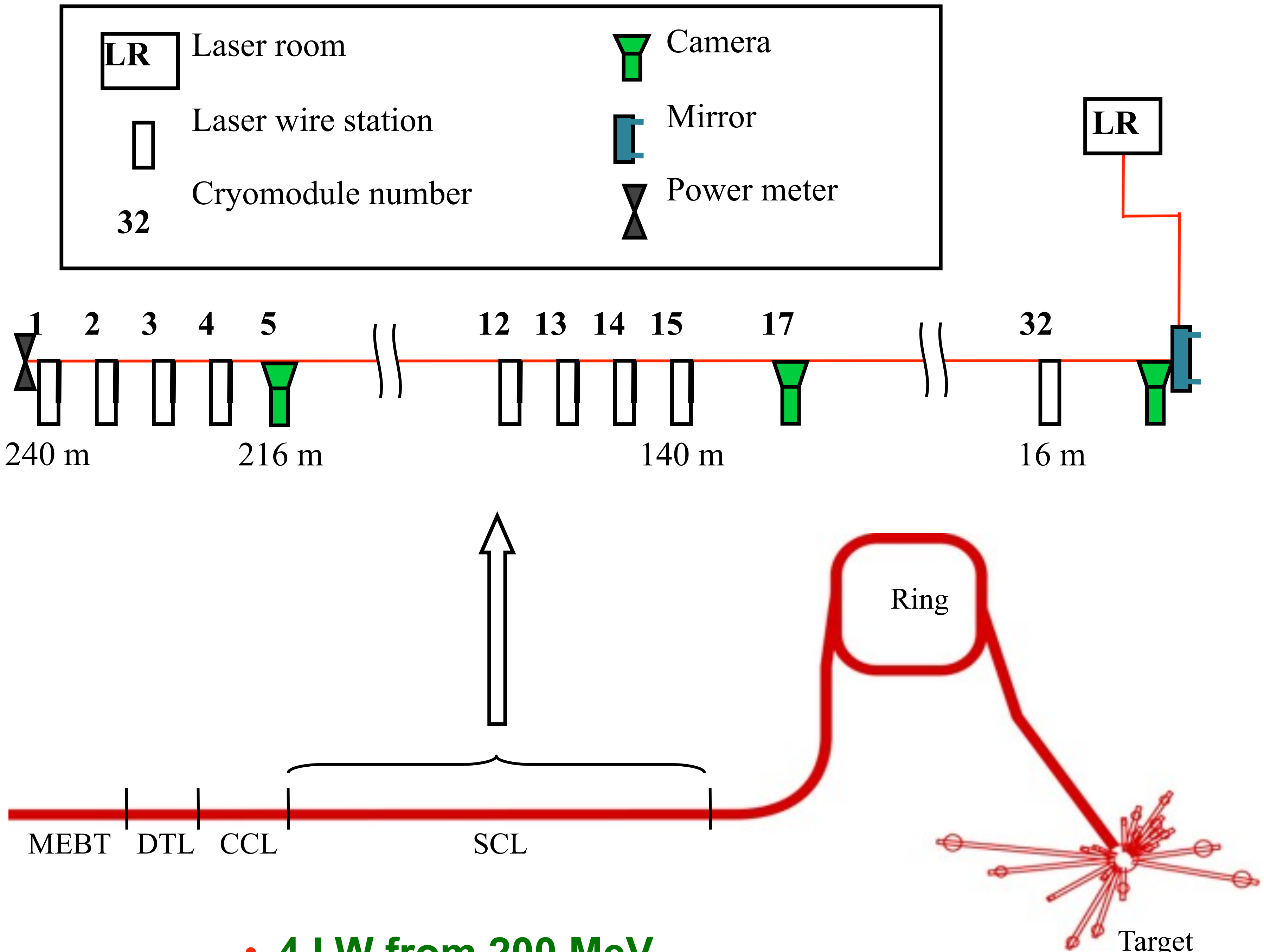


Horizontal Profile
1/25/2003 13:06
Gaussian fit plotted out to 2.5x Sigma
Sigma = 1.07 mm



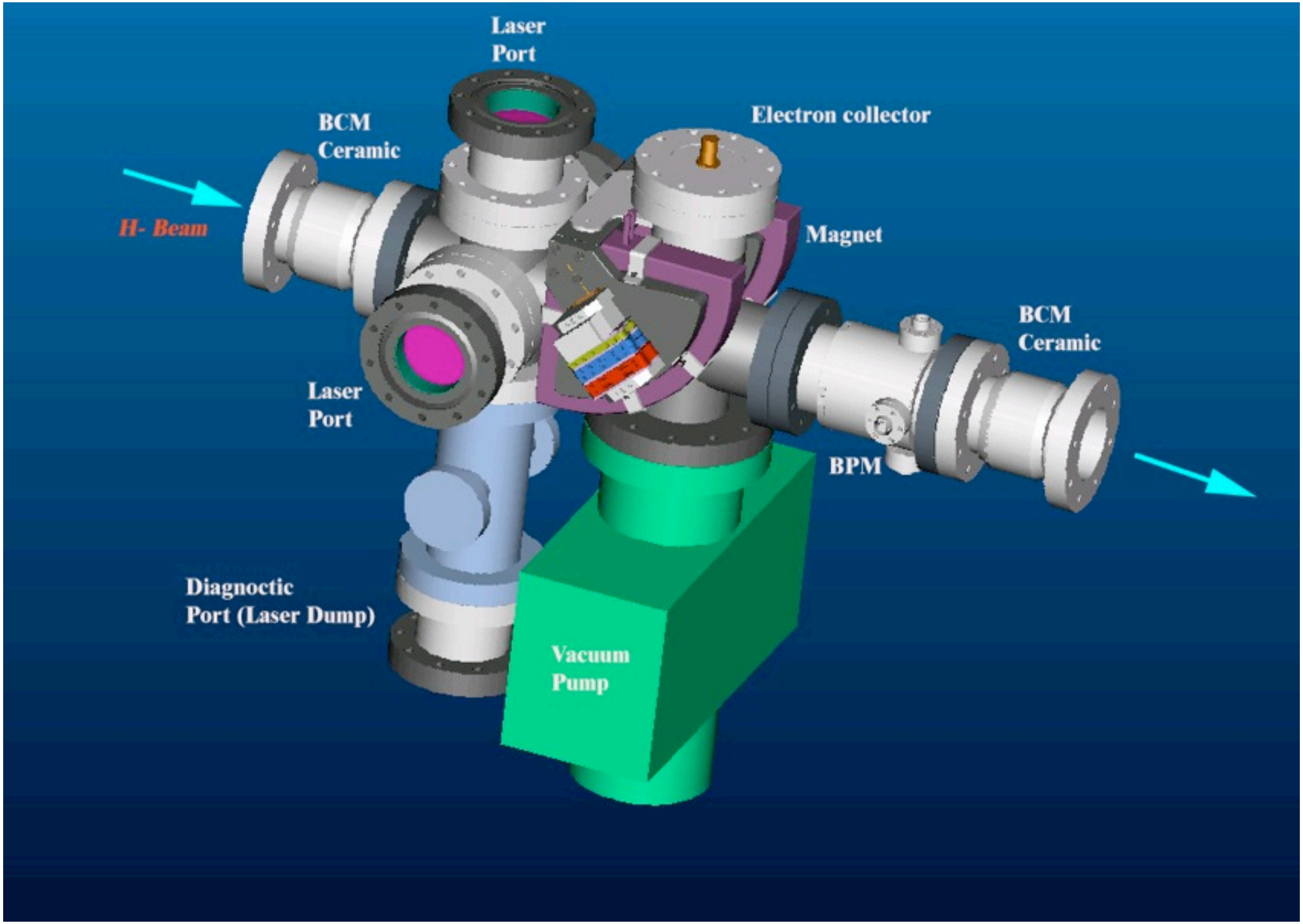
Signal from electron collector
Top: laser intercepting beam core
Bottom: laser intercepting beam tail

Layout of the SNS Laser Wire System

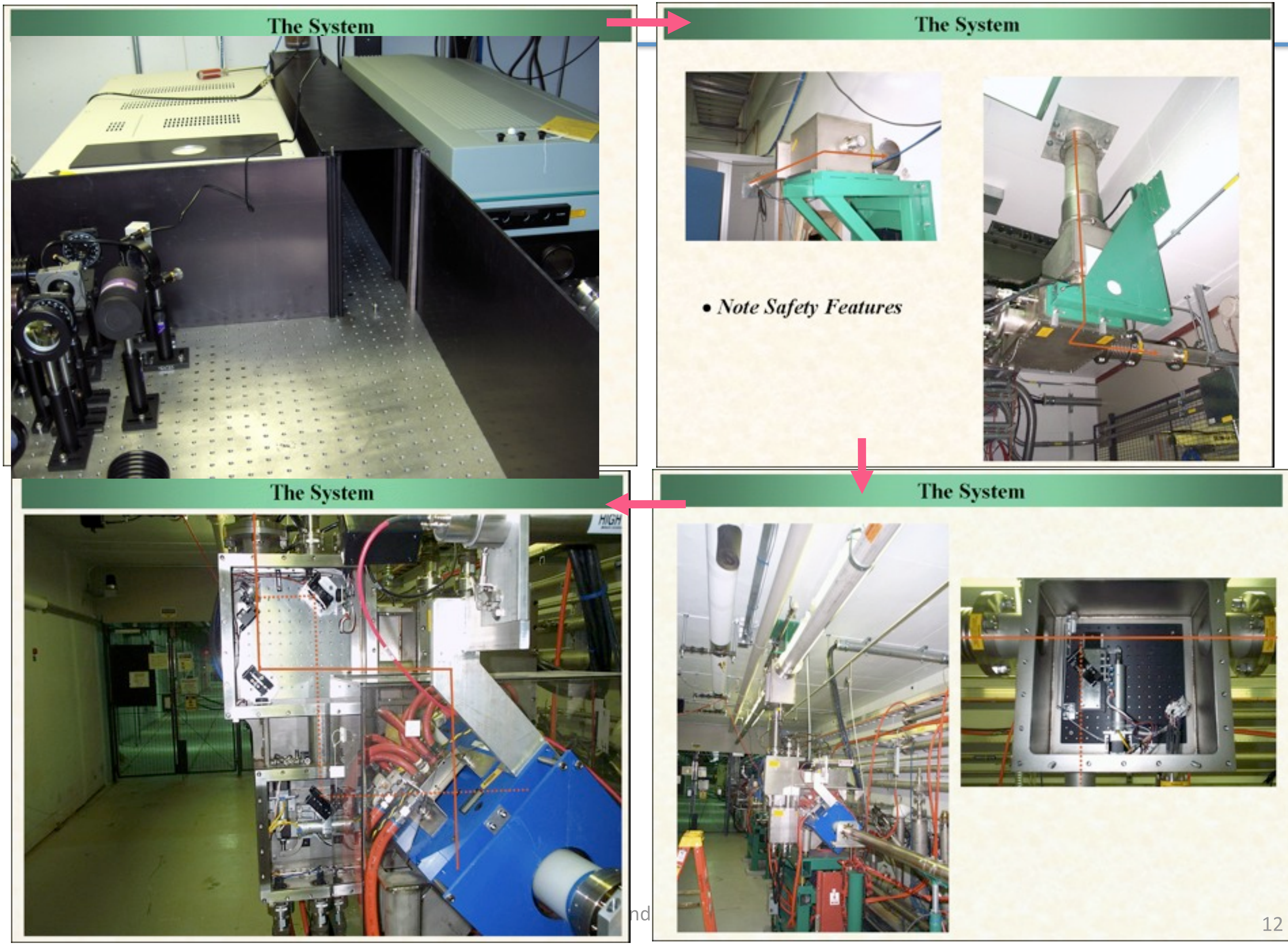


- 4 LW from 200 MeV
- 4 LW from 450 MeV
- 1 LW at 1 GeV

Laser Wire Station



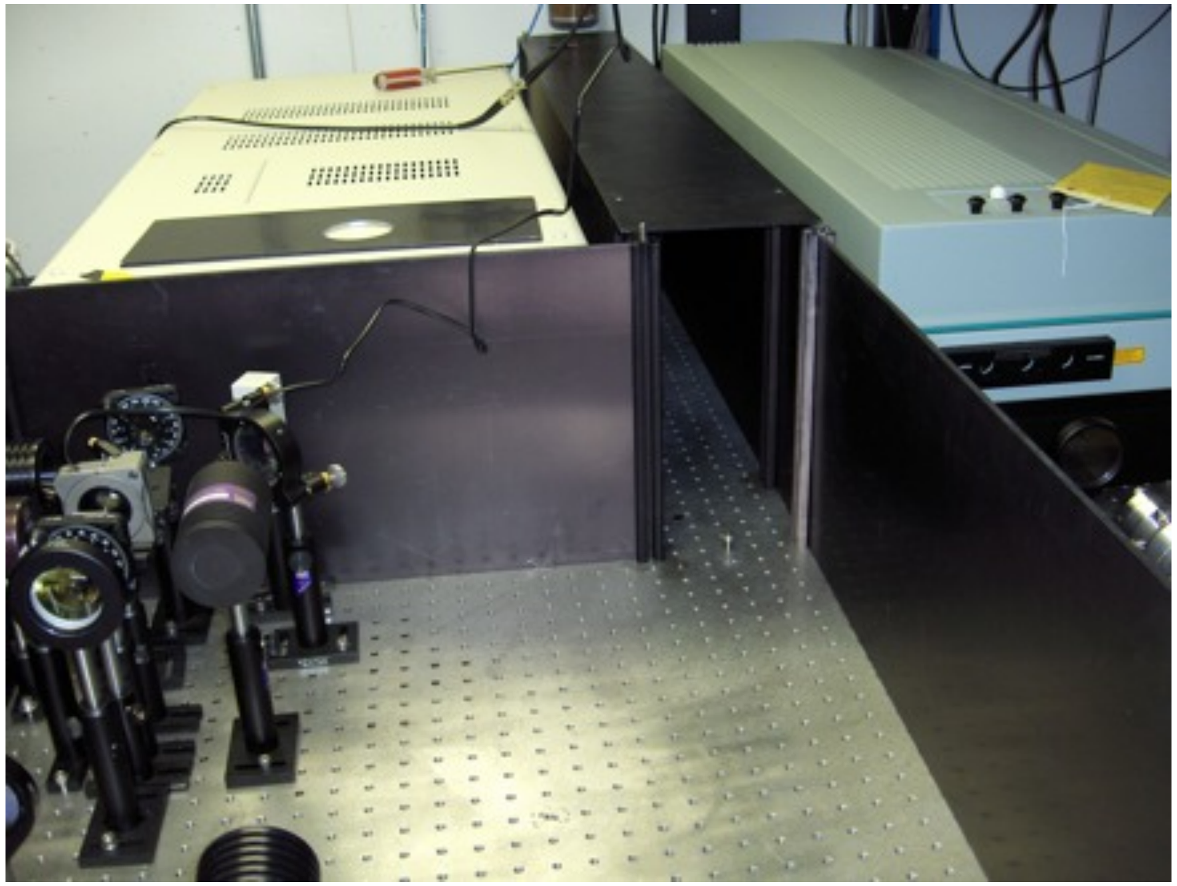
Laser Installation in Tunnel



Laser Requirements

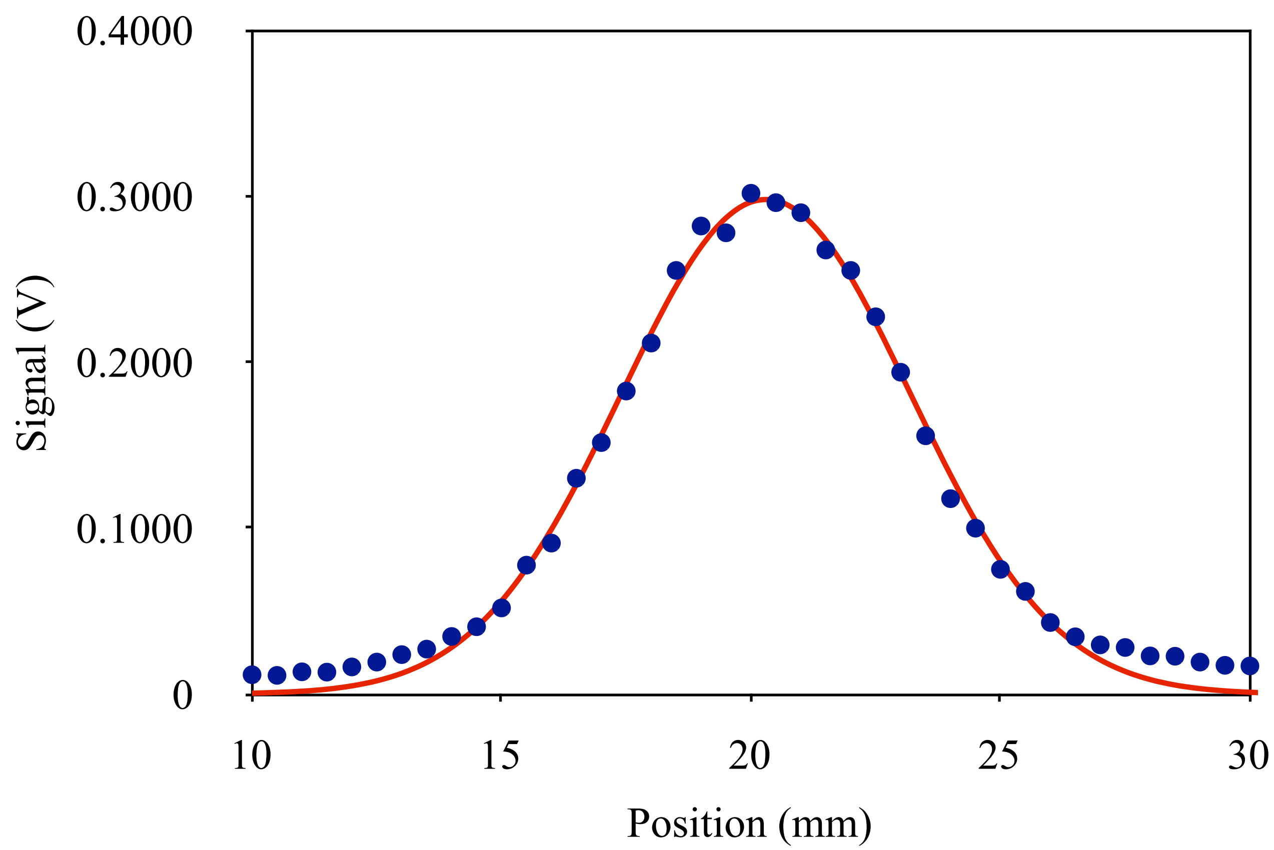
- High pulse energy
- Small spot size
- Single wavelength
- Pointing stability
- Temporal stability
- Outside of radiation area
- Enclosed laser room with interlocked door

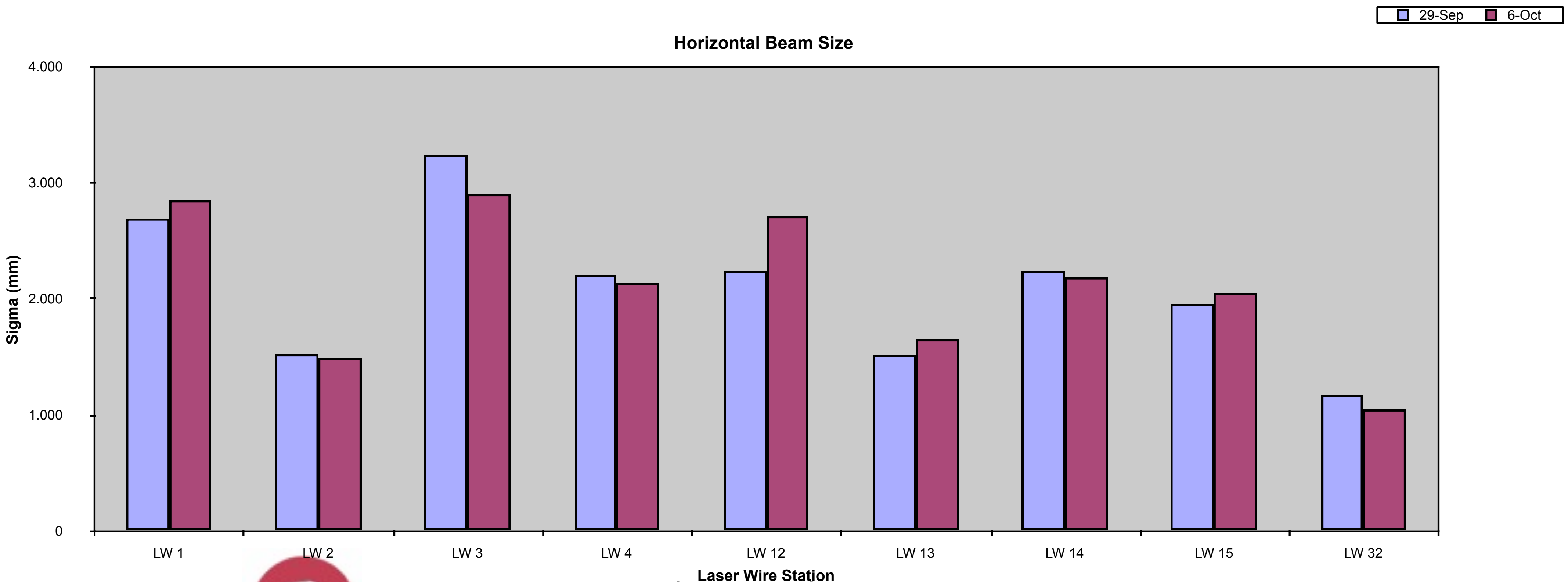
Laser Room



- Q-switched Nd:YAG laser
- λ = 1.06 μm
- f_{rep} = 30 Hz, T_w = 7 ns
- E_p = 50 – 200 mJ
- Injection seeded
- Timing synchronized to SCL

System Operating at SNS

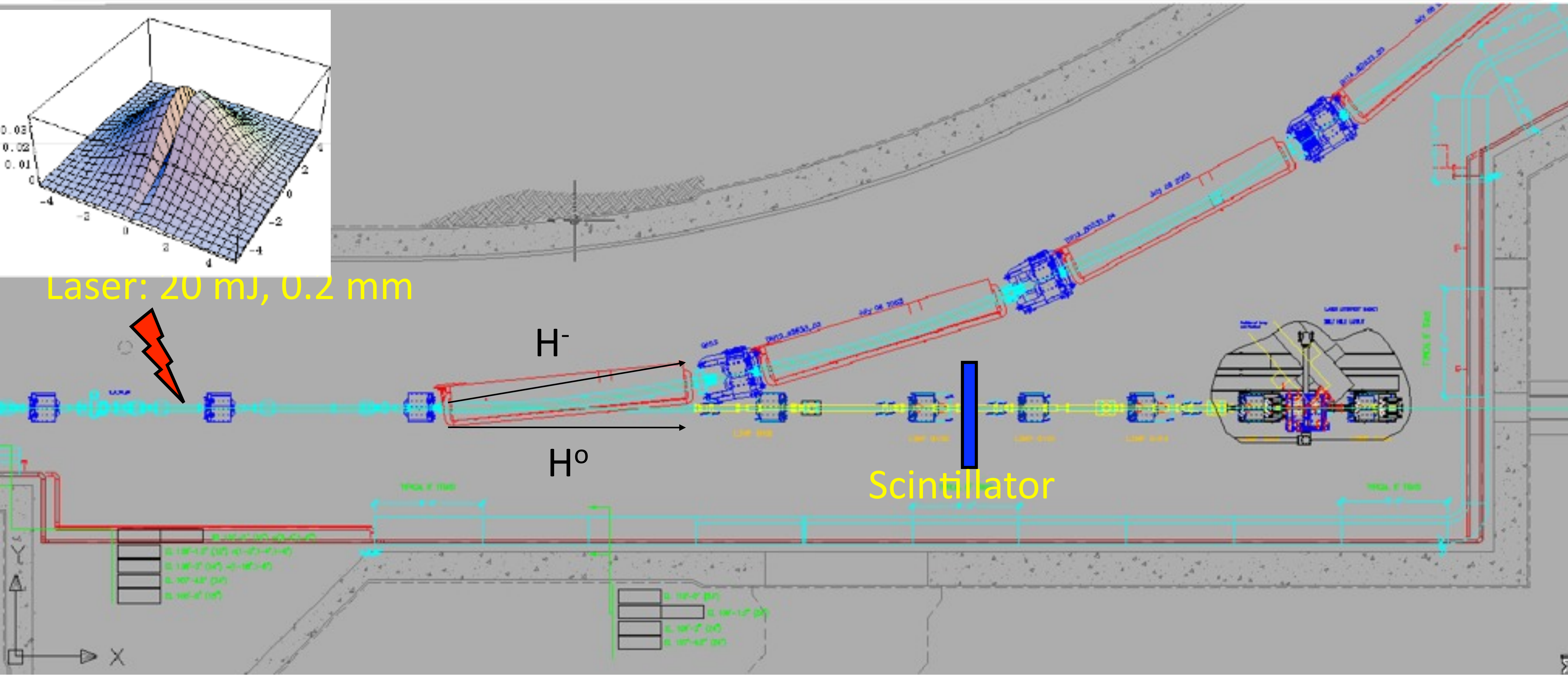




Liu, Assadi, Blockland, et al

S. Assadi HIB2008

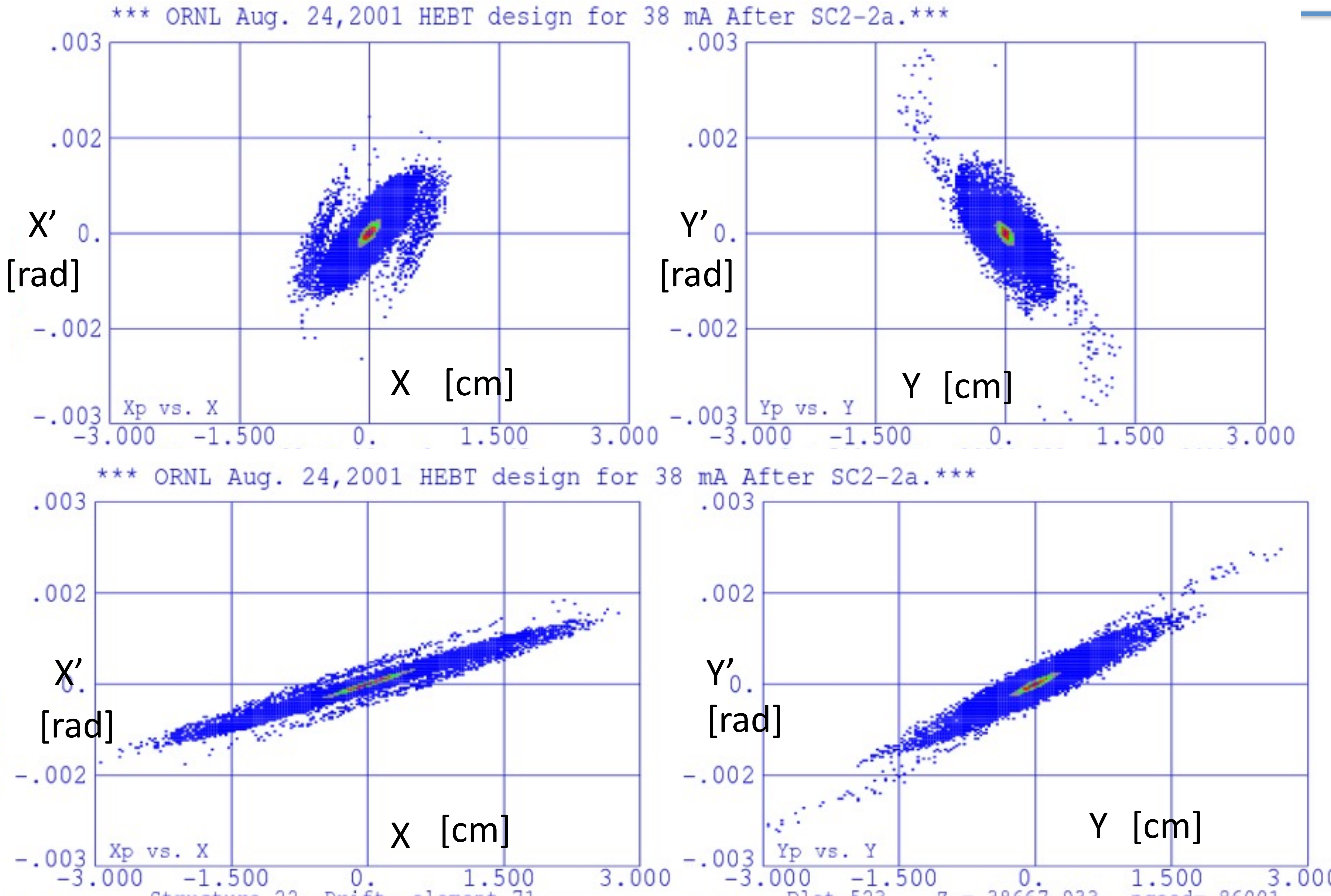
Laser-based Emittance Monitor



- Technique proposed by R. Shafer as part of beam-in-gap system
- System under construction is located upstream; HEBT Bending dipole deflects H^- beam and remaining electrons while H^o beam will travel free from the influence of dipoles, quads etc
- Gas stripping background measured, appears low enough

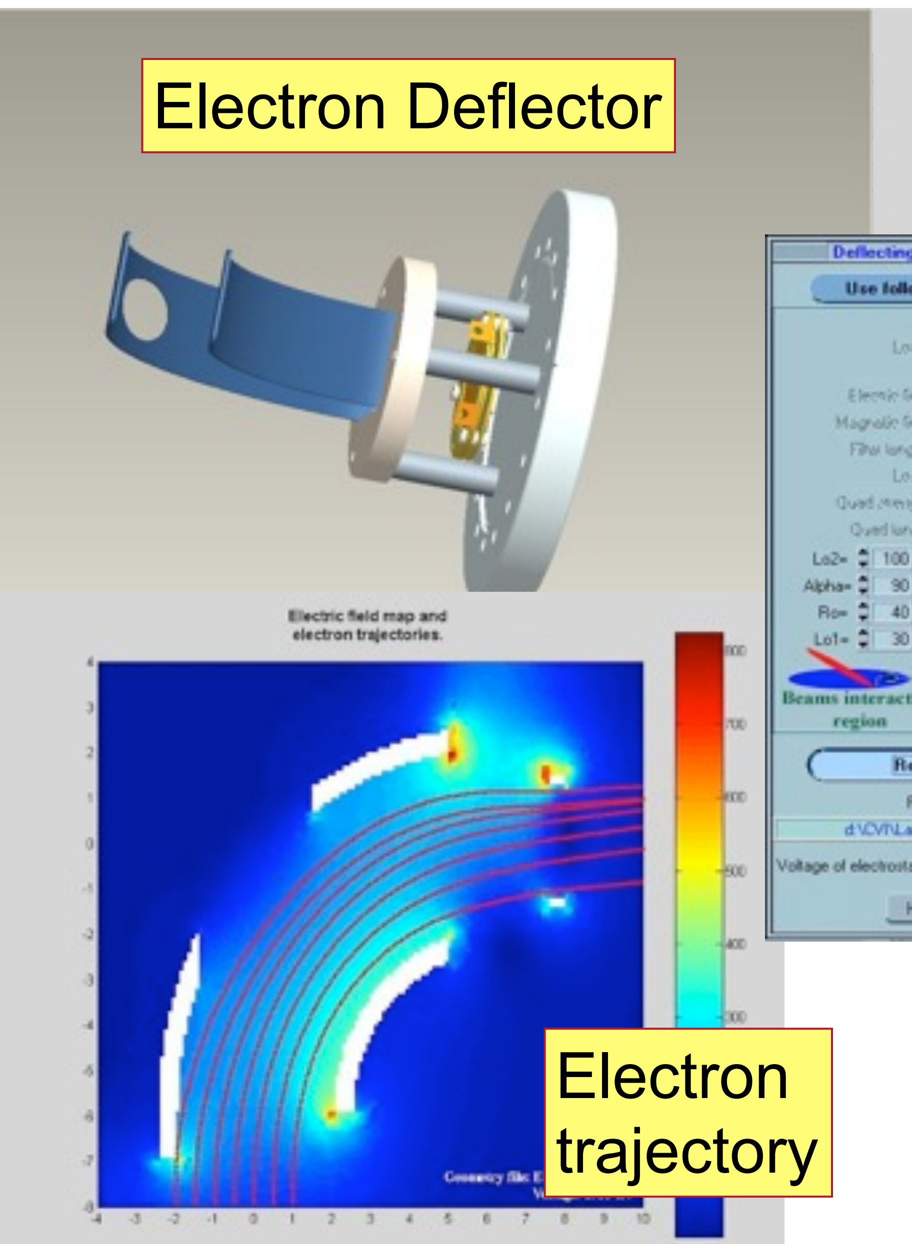
D. Jeon, J. Pogge, Y. Liu, A. Menshov, I. Nesterenko, W. Grice, A. Aleksandrov, S. Assadi

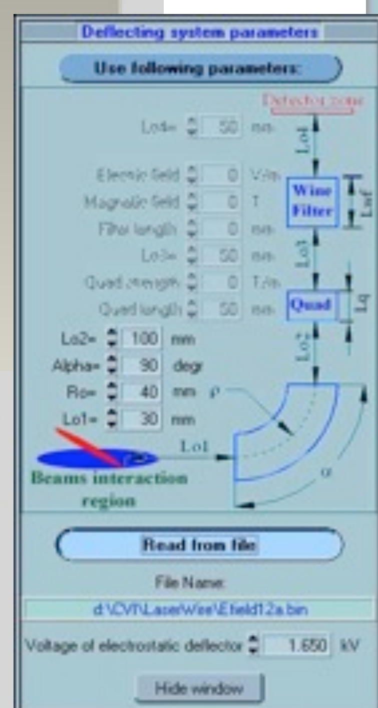
Expected beam distribution at laser and 17.7 m downstream at scintillator

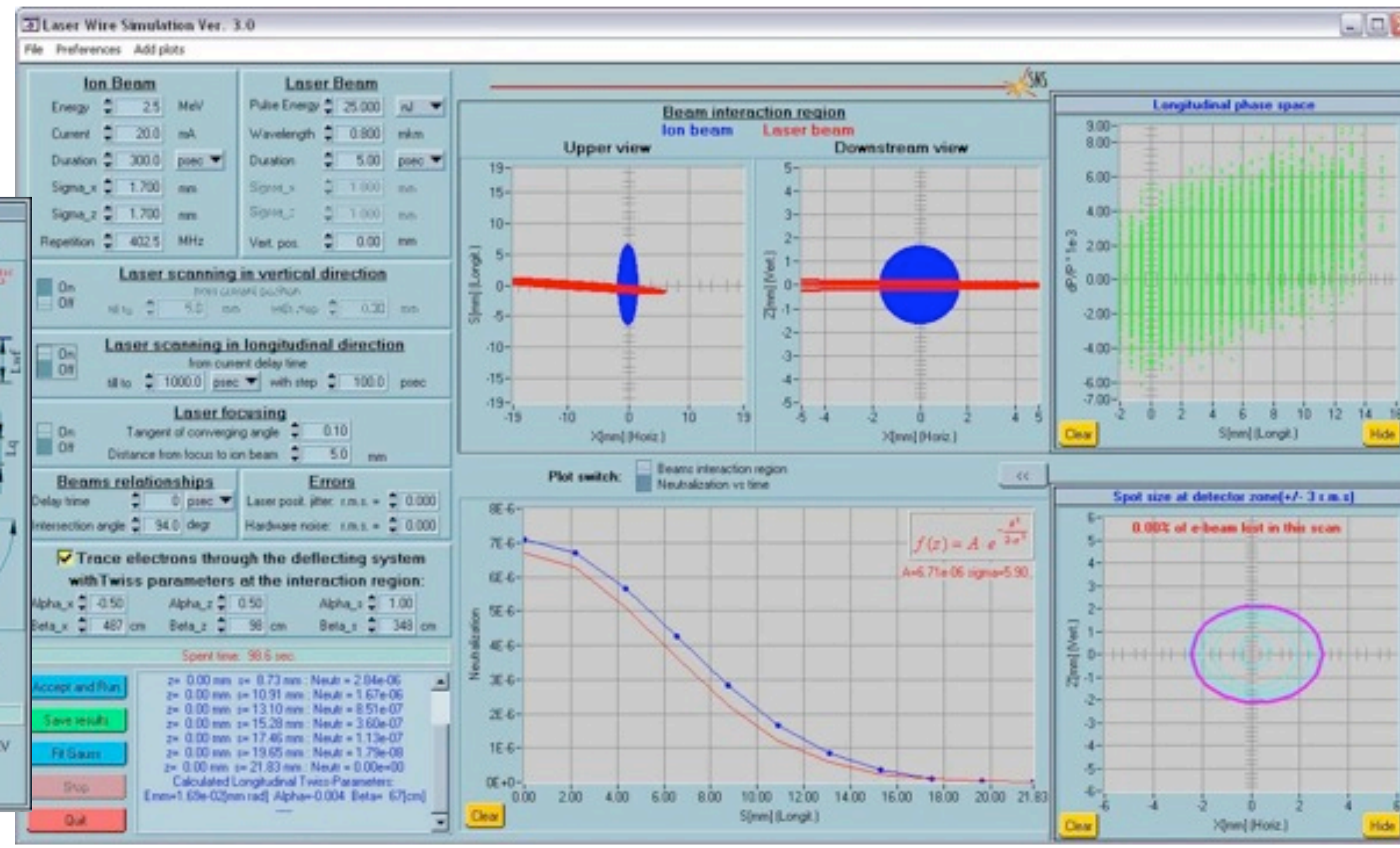


Longitudinal Measurement at 2.5 MeV

- Mode-locked Ti-Sapphire laser
- Tune laser to ~ps pulses, H- bunch: ~100ps
- Lock laser to sub-harmonic of RF, scan relative phase (timing).



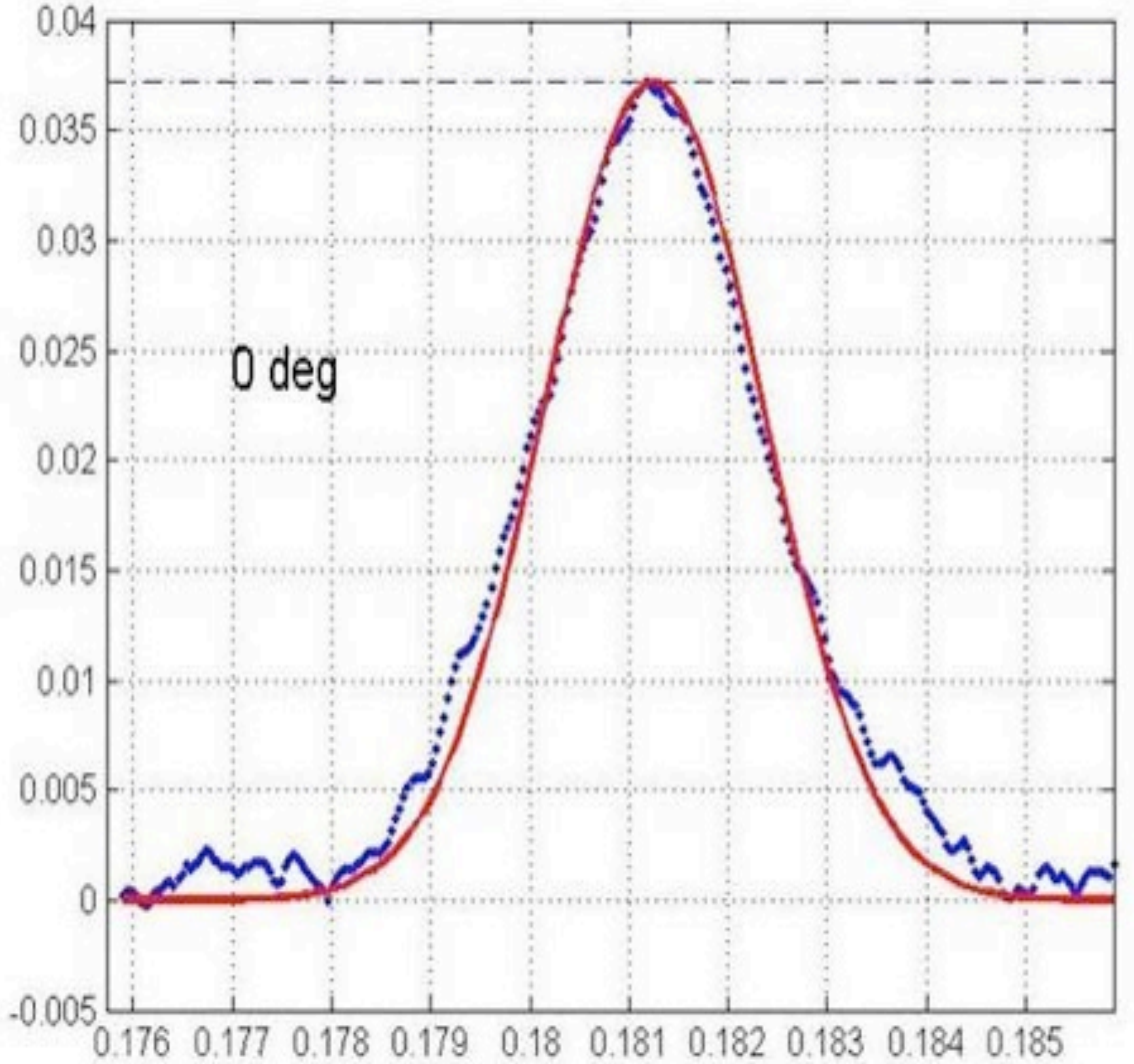




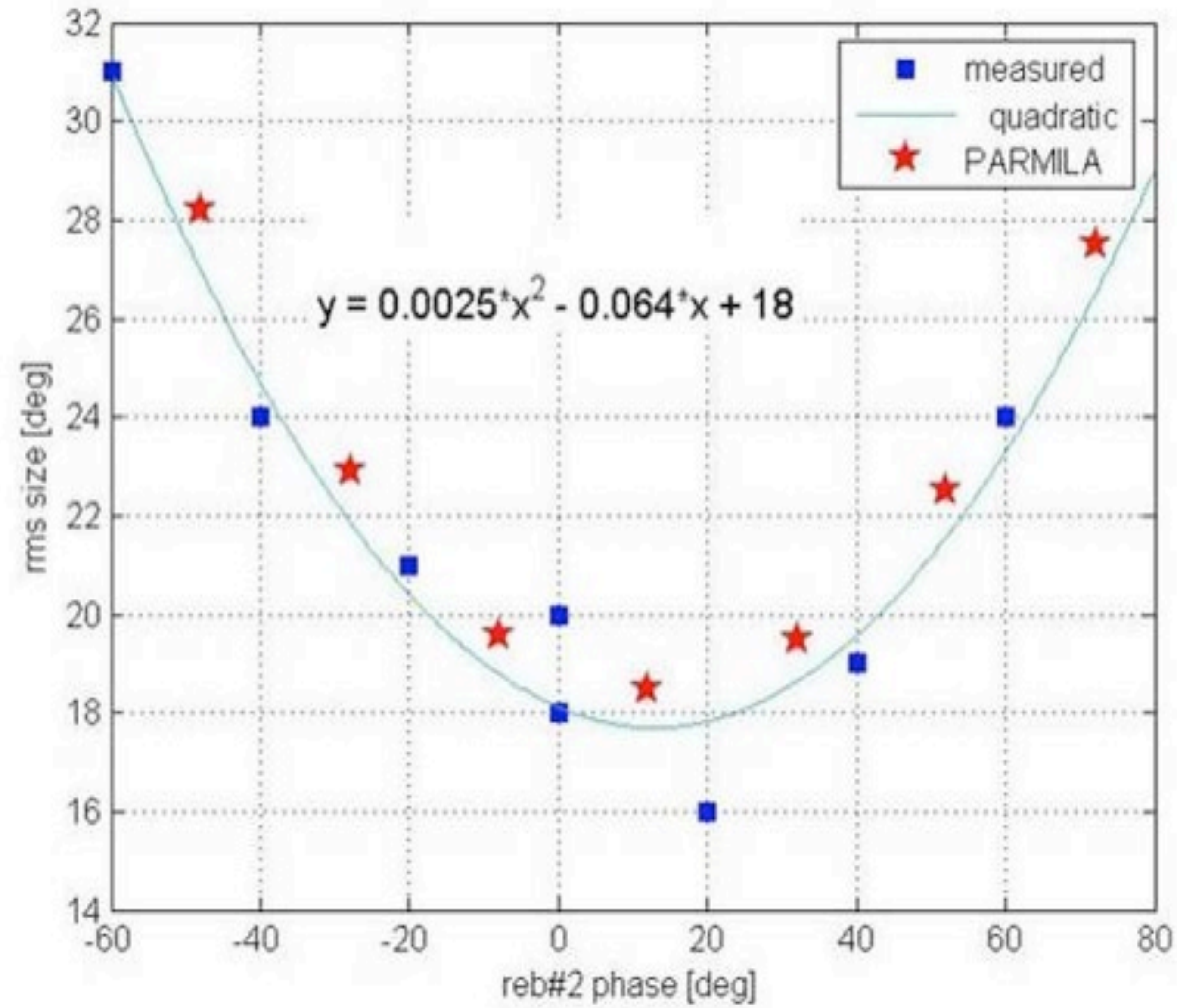
Complete system simulation – beam/laser interaction, electron transport – Victor Alexandrov

Longitudinal Measurements

2.5 MeV H-, 402.5 MHz bunching freq, mode locked Ti-Sapphire laser phase-locked @ 1/5th bunching frequency



collected electron signal plotted vs. phase



Measured and predicted bunch length vs. cavity phase setting

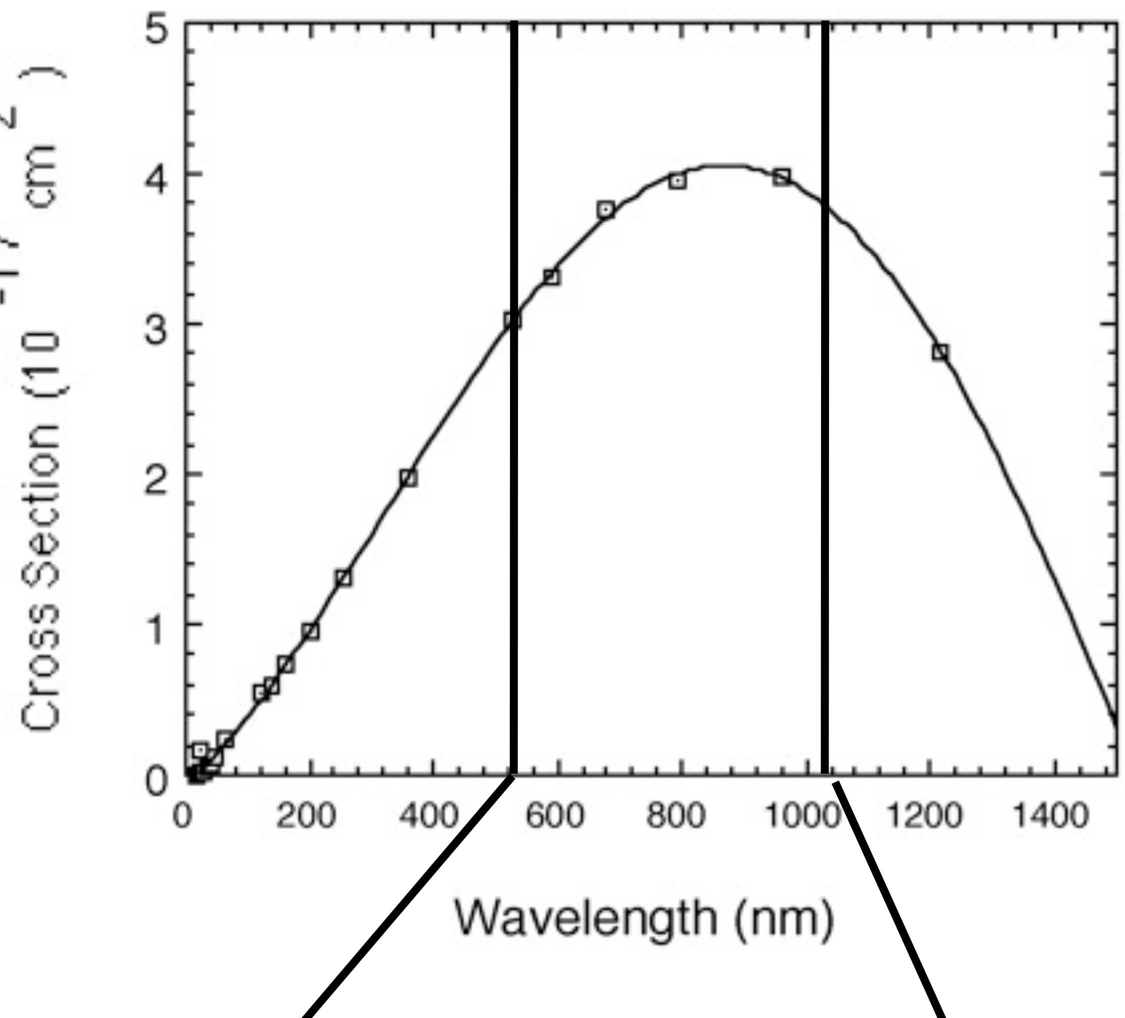
Grice, Assadi, et al

Summary

- Laser diagnostics have been a useful development for the particular case of high power H- beams
- Plenty of headroom for performance improvement and new applications

Additional Material

Laser neutralization cross section



Wavelength in 1GeV beam frame.

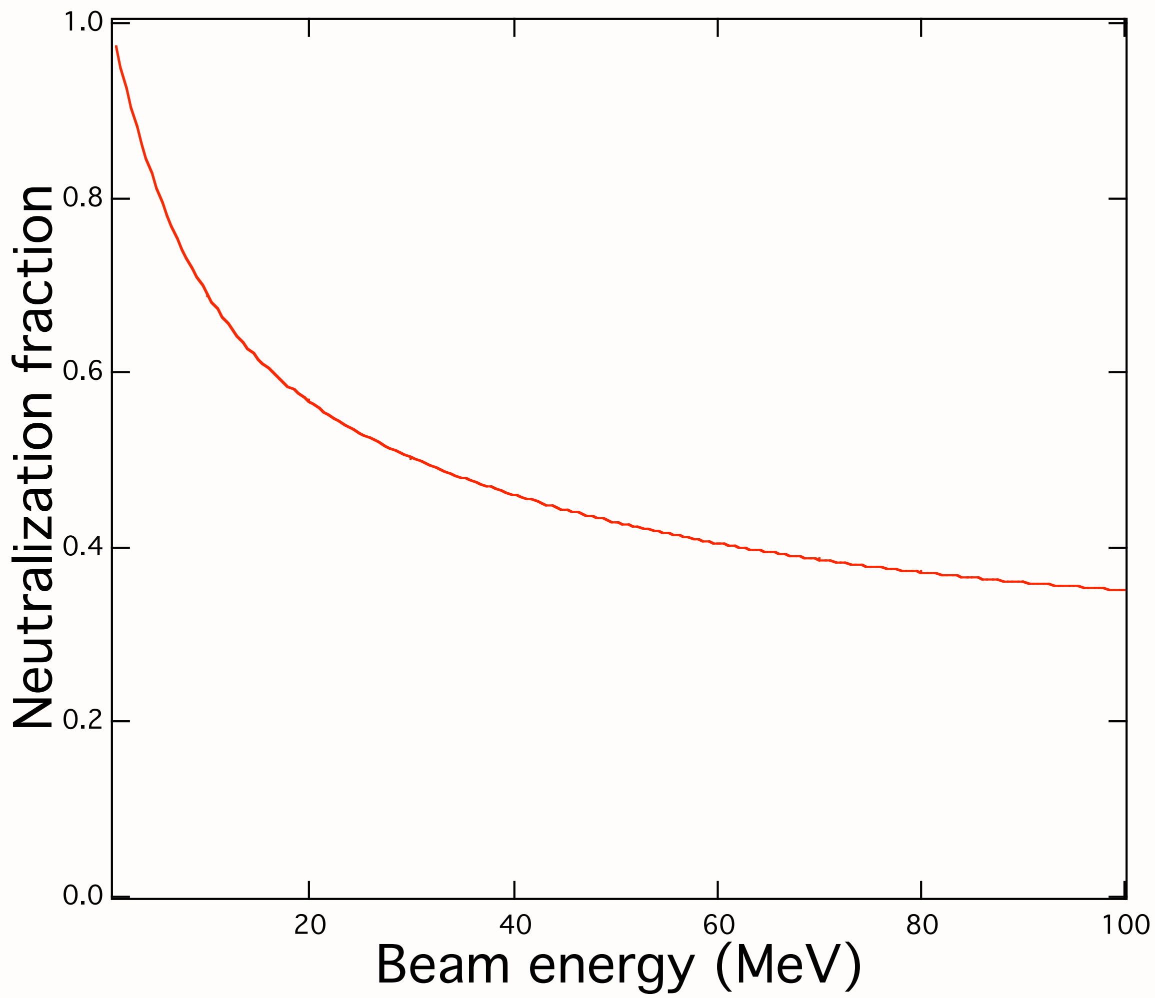
Lab frame laser wavelength

- Calculated cross section for H- photoneutralization as a function of photon wavelength.*
- Nd:YAG laser has λ=1064nm where the cross section is about 90% of the maximum.
- If laser beam crosses ion beam at angle θL, in lab the center of mass energy is given by:

  ECM=γEL[1-βcos(θL)]

- So Nd:YAG cross section at 1GeV is about 70% of low-energy cross section
- *J.T. Broad and W.P. Reinhardt, Phys. Rev. A14 (6) (1976) 2159.

Fraction of beam neutralized



Since we are measuring a notch in the beam current we are interested in the fraction of the beam neutralized by the laser which is given by,

$$f_{neut} = 1 - e^{-\sigma(E)Ft}$$

Here $\sigma(E)$, the cross section, is held constant, F is the photon flux ($\#/cm^2s$) and t is the travel time of the ions across the photon beam.

For instance the MEBT laser put out $50mJ/20ns/3mm^2 = 4.5 \times 10^{26}$ photons/cm^2s.

The beam at 2.5MeV had velocity of $\beta=0.073$ giving f_{neut}=90%

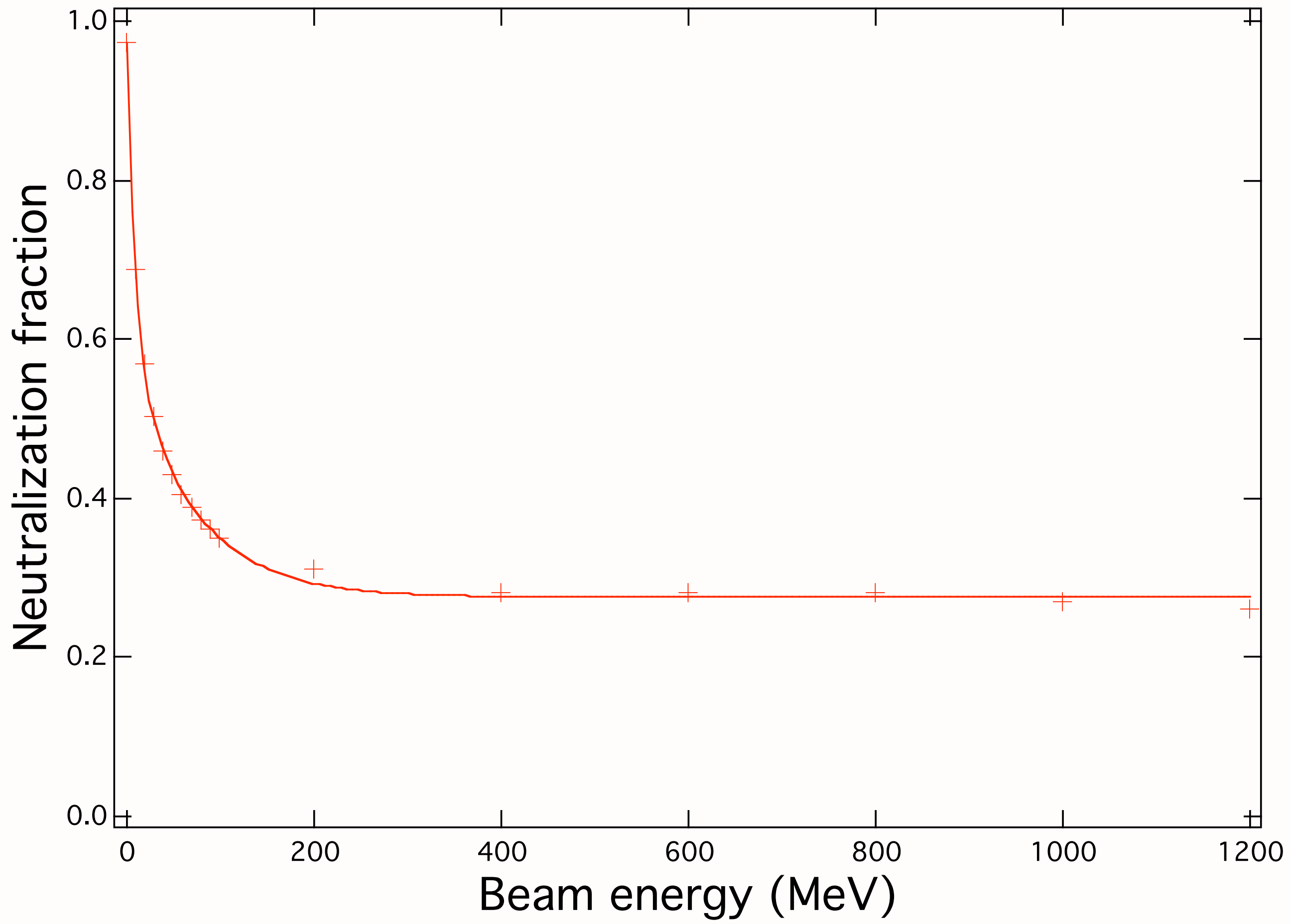
Higher photon flux is required as the beam energy increases for same signal. At 200MeV we used 200mJ laser to get 72% neutralization.

Neutralization fraction of 50mJ, to 1.2 GeV

At increasing beam energies the Lorentz boost in photon energy results in decreasing cross sections above about 500 MeV.

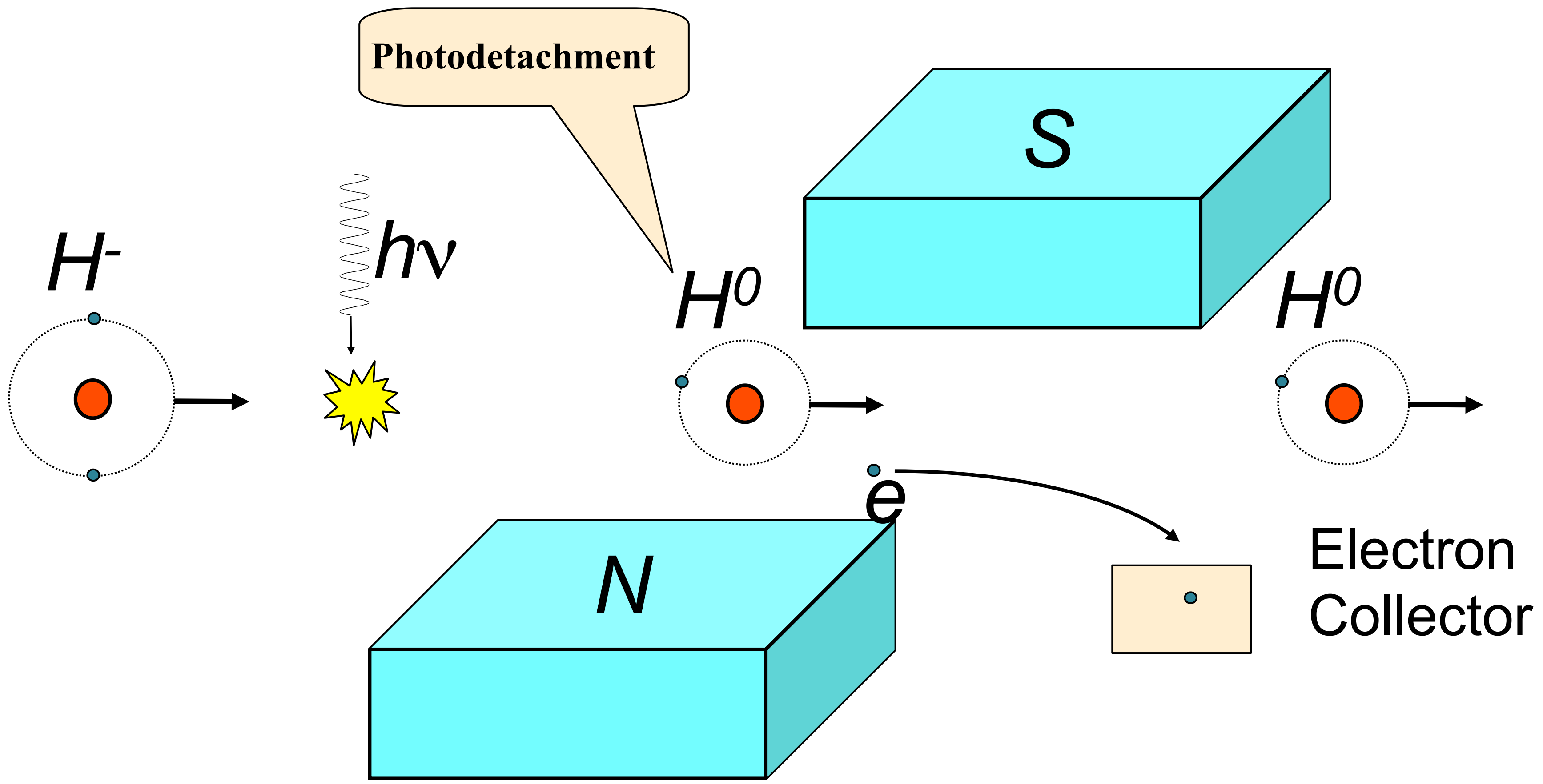
However the photon flux is also Lorentz boosted by the same factor as the photon energy,

$$F_{CM}=\gamma F_L[1-\beta\cos(\theta_L)]$$



The relativistic boost in the photon flux and the relativistic decrease in cross section approximately cancel resulting in a nearly constant neutralization fraction from 200MeV to 1.2GeV.

Non-Intrusive Profile Measurement - Laser Wire



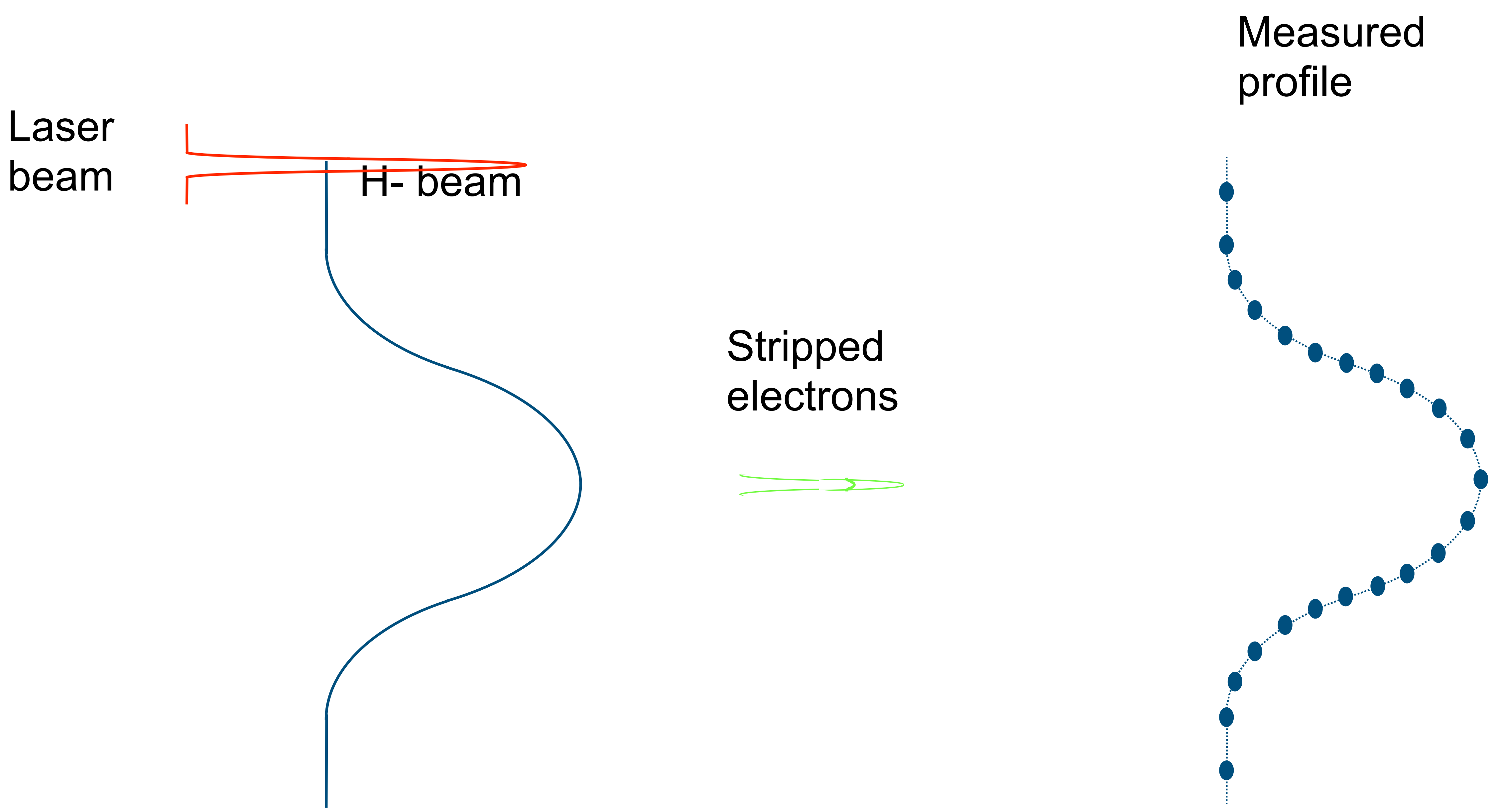
Advantages

- Minimal impact on normal operation
- Virtually no impact on SRF cavities or vacuum
- No parts inside the vacuum

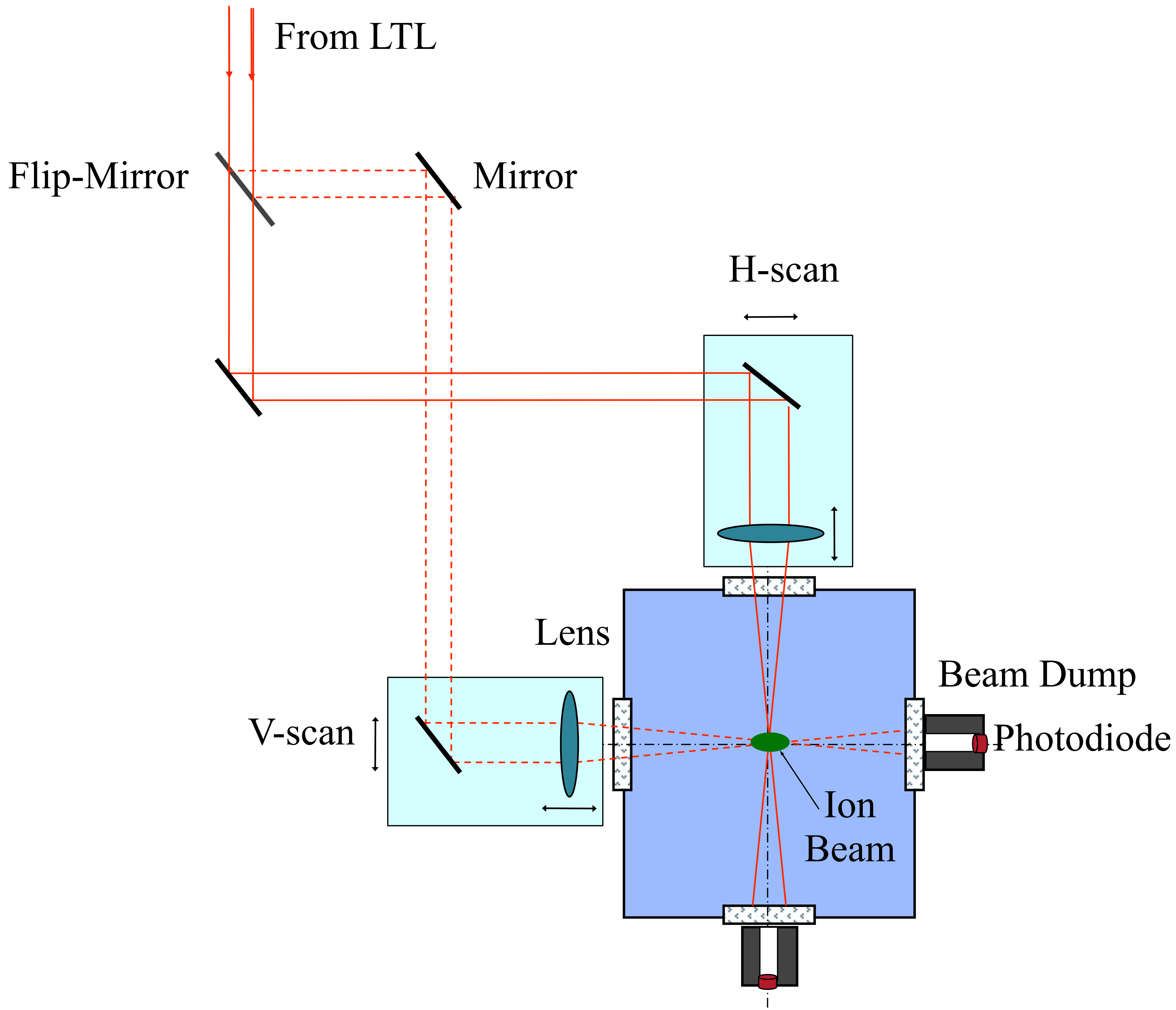
Challenges

- Low signal to noise ratio can be improved using electron collector
- Not radiation hard

Profile Measured with Laser Wire Scan

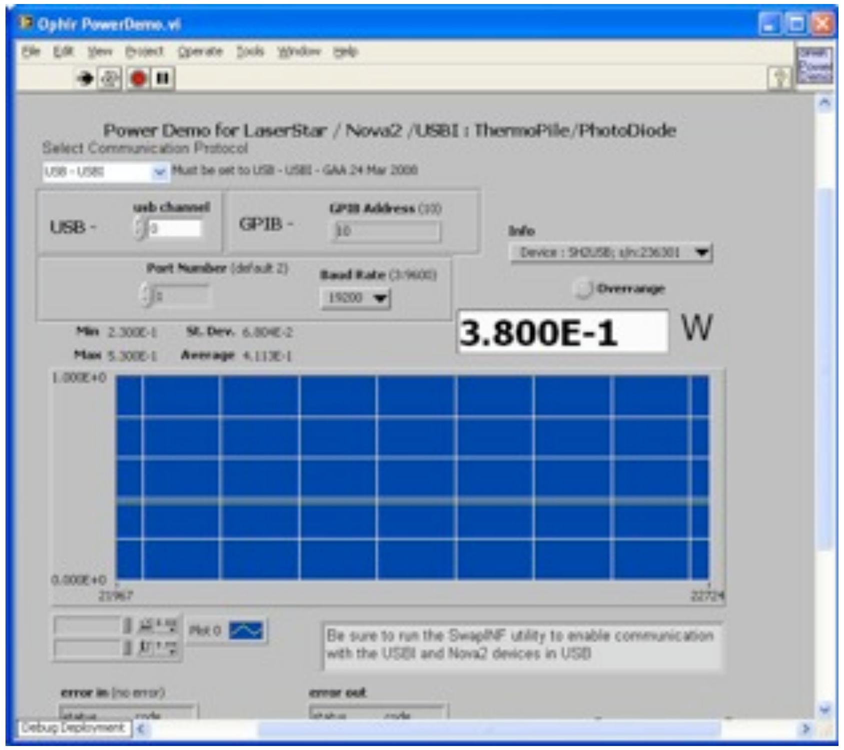


Schematic of Laser Wire Station Optics



Laser Transport Line Diagnostics

Laser room



End of SCL

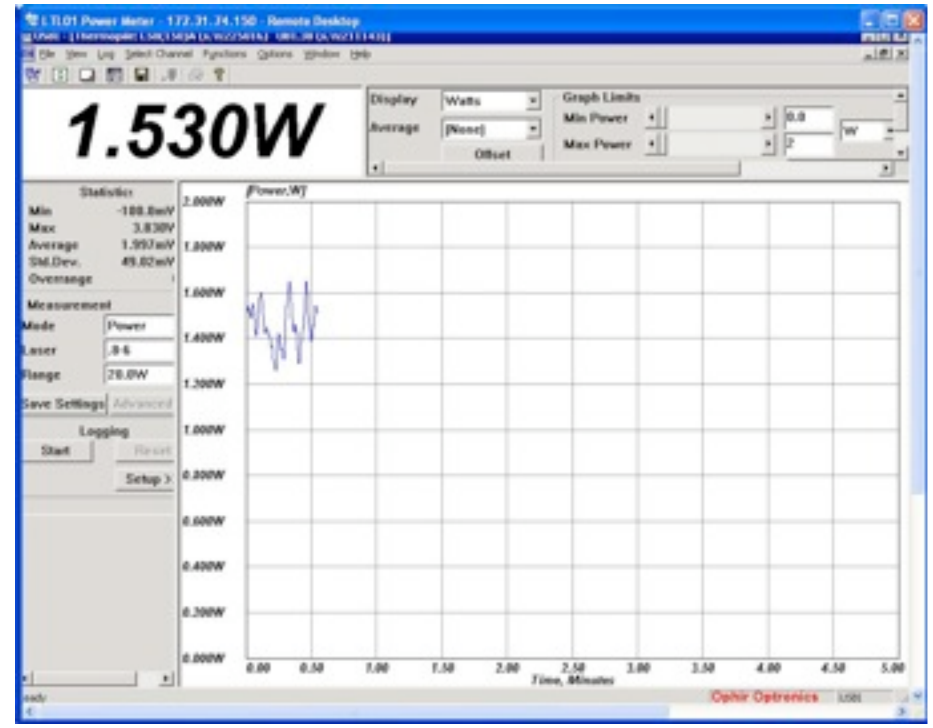


Image of Cam 17

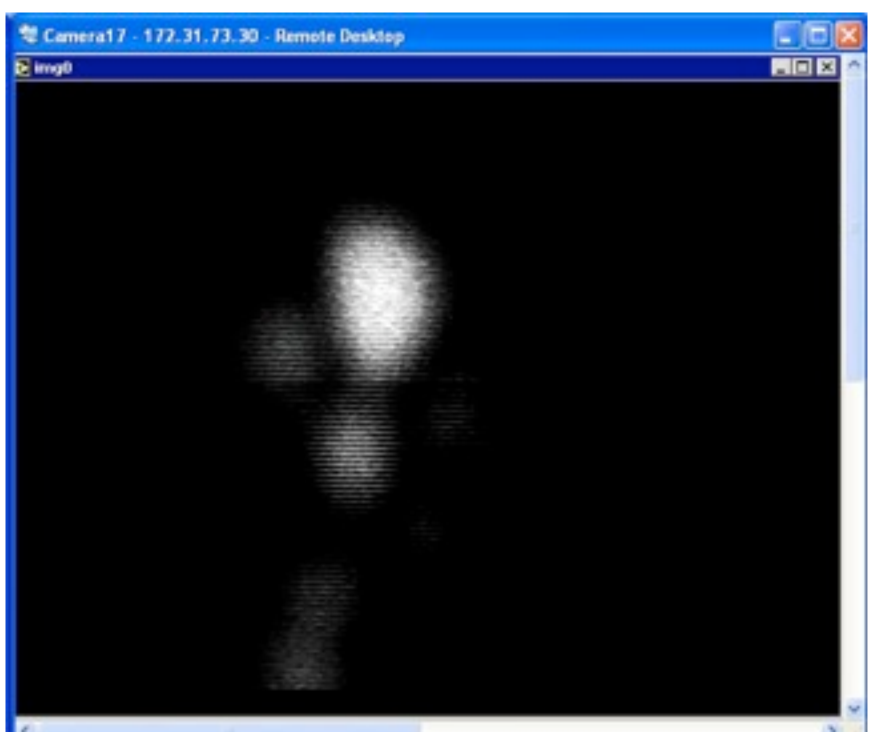
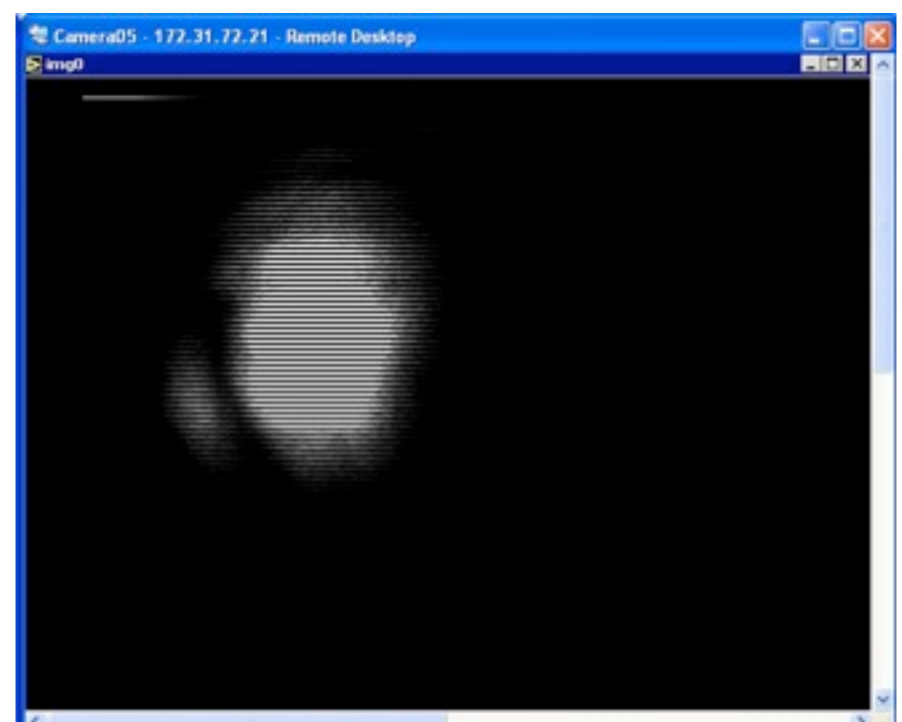
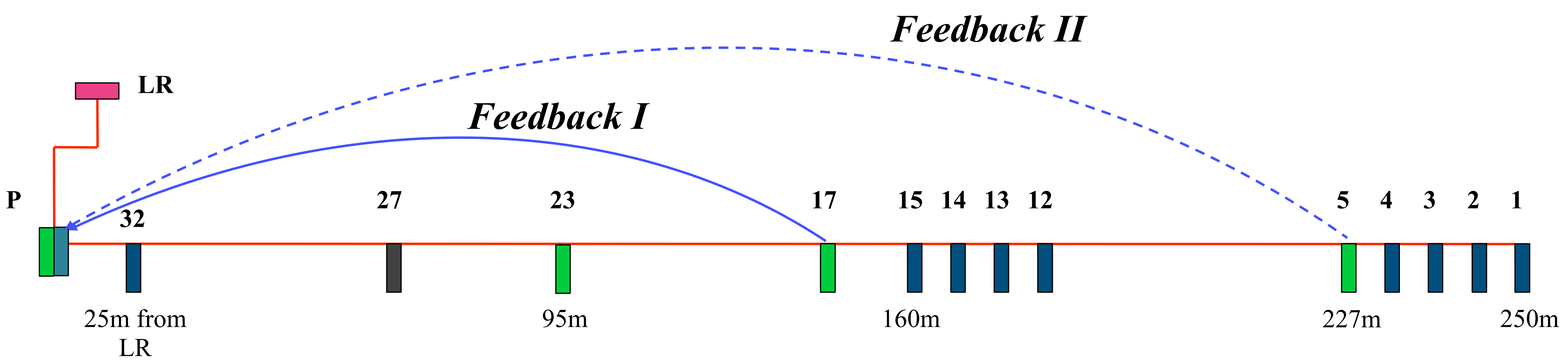


Image of Cam 5



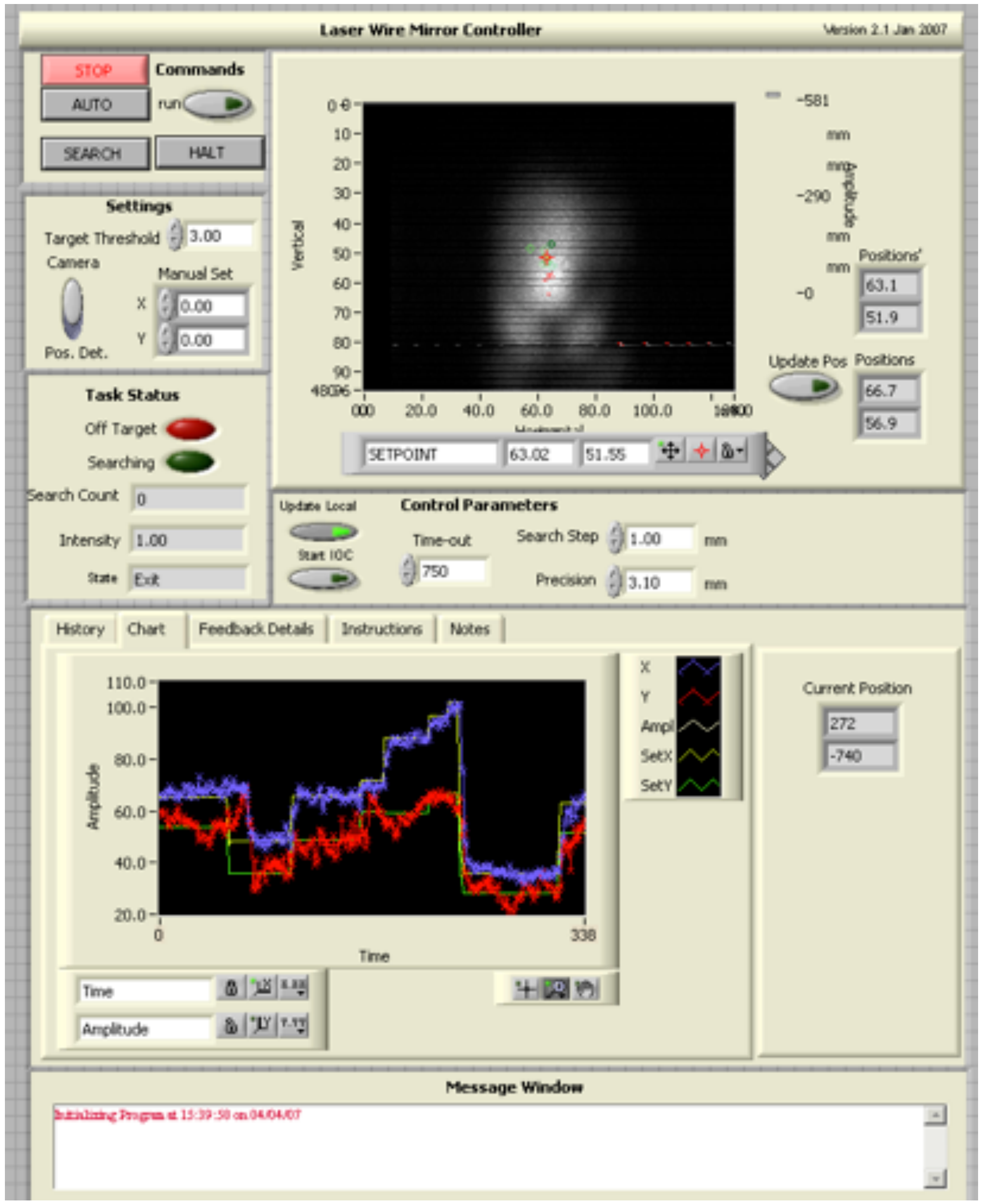
Feedback Control to Stabilize Laser Beam Position

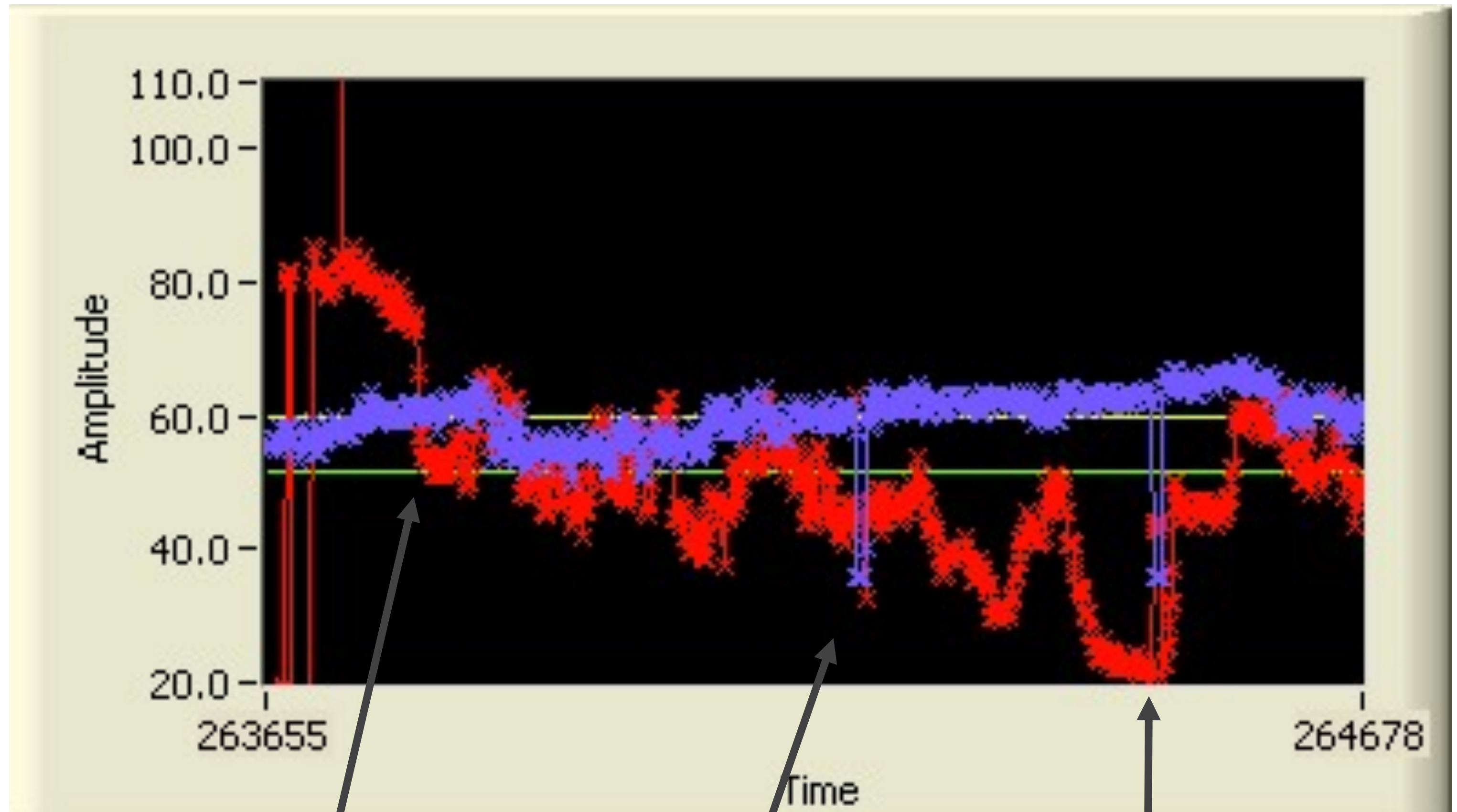
Station	LW1	LW2	LW3	LW4	LW12	LW13	LW14	LW15	LW32
Distance (m)	249.3	243.3	237.4	231.6	182.2	174.9	167	159.2	25.0



Feedback control is risked by the increasing level of radiation. The control unit has been moved to the laser room.

Feedback Program to Control Laser Beam Drift





Feedback on

Feedback off

Feedback on