SNS Laser Profile Monitors Project– Performance and Future Plans

Saeed Assadi

for the SNS Laser Diagnostics Team

July 3, 2006

Laser Wire mini Workshop

Keble College, Oxford England

The Spallation Neutron Source Partnership

Oak Ridge, Tennessee

35° 49' N , 83° 59' W

~500 People work on the construction of the SNS accelerator

Outline

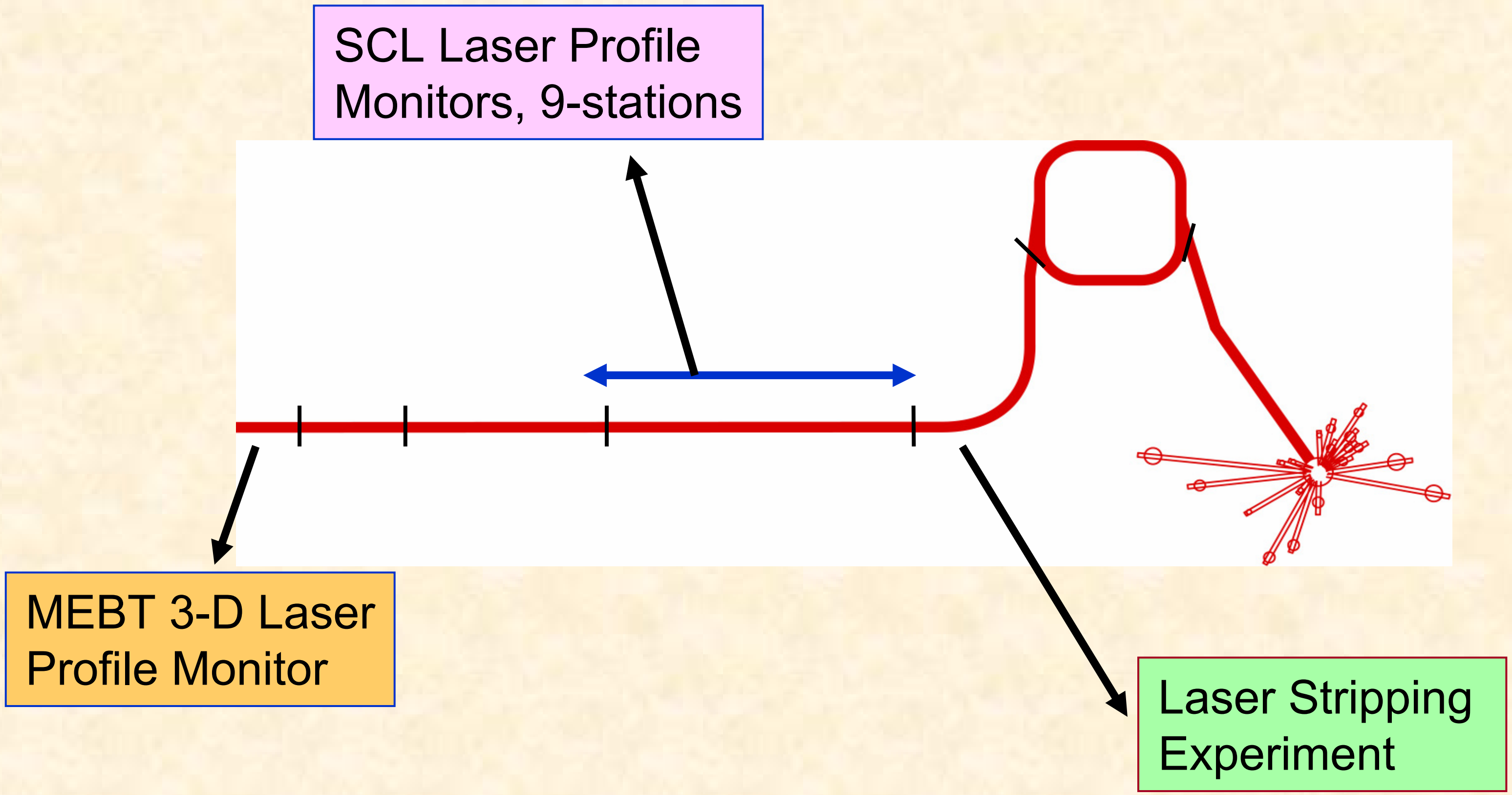
- Introduction to SNS laser profile monitor history
- Transverse profile monitor design for SCL
- Longitudinal profile monitor design for the SNS.
- Future R&D such as laser stripping
- Improvements

SNS Laser Team

Alignment: Joe Error
Data acquisition and Software: G. Armstrong, W. Blokland, C. Long [TL]
Electron Collector & Electronics: Craig Deibele [TL], J. Pogge, V. Gaidash, I. Nesterenko
Installation & manufacturing: J. Diamond, D. Newby, S. Murray, D. Purcell, A. Webster [TL],
Mechanical Design Team: G. Murdoch, D. Stout, A. De-Carlo , J. Kelly, B. Lane, K. Potter (TL), T. Roseberry (Design Engineer)
Mechanical Design Advisory Team: P. Ladd, M. Hechler; P. Gibson.
Magnet design: T. Hunter
Optics: W. Grice, Y. Liu
Physics: S. Aleksandrov,
Project Lead: S. Assadi
Timing: C. Sibley, D. Thompson

ORNL-SNS Laser Diagnostic Activities

1) MEBT Mode-lock laser initially in 1-D – 9/2004
2) SCL Nd:YAG 1064 nm Laser, 9-station – 3/2005
3) Laser Stripping test Nd:YAG, 3ed harmonic, 3/2005



History of Laser Profile Monitor Development for the SNS

December 2000: BNL (Roger Connolly), LANL (Bob Shafer) and others

"We know it works we just don't know how to do it."

March 2002: 750 KeV at BNL, 200 MeV, 2.5 MeV MEBT at LBNL tests

“We know how to do it, but not very well.” – Roger Connolly

January 2003: 2.5 MeV MEBT test at ORNL

“We know how to do it, and we know how to do it well” – Anonymous

August 2005: 2.5 MeV to 1000 MeV at ORNL

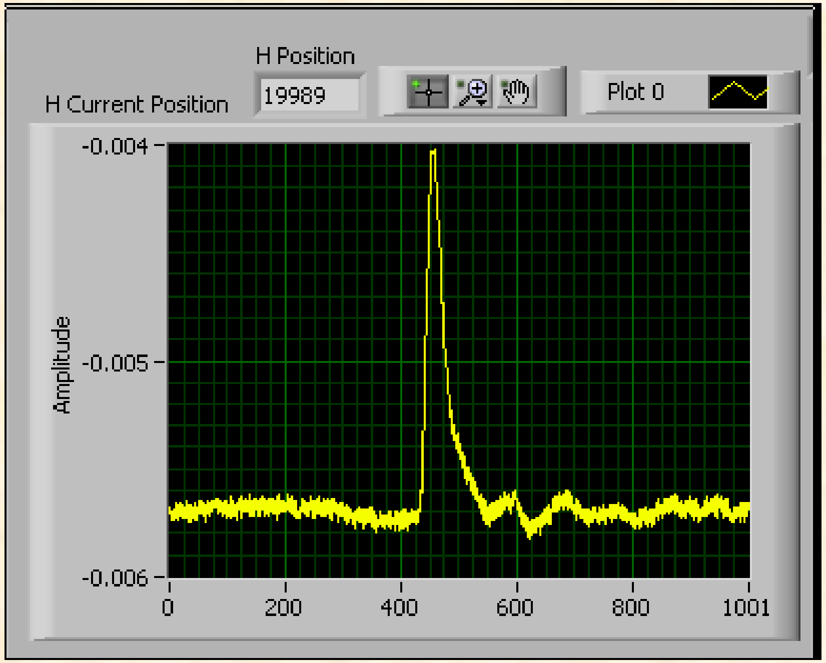
“It Works well, we need to automate the system” – SNS Laser Team

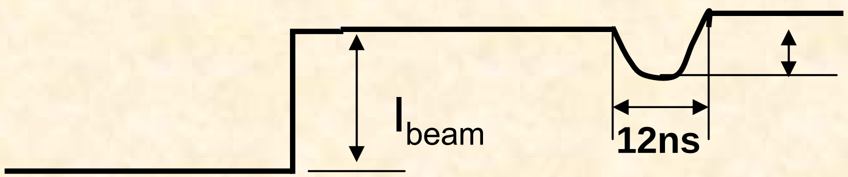
What does the Laser do? Photo-neutralization

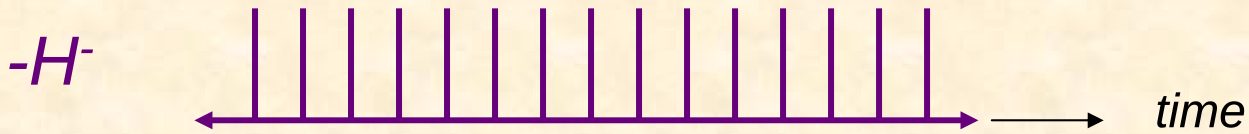
$h\nu$ → H^- ⇒ $H^0 + e$

Requirements

- *High peak power*
- *Small spot size*
- *Transverse scan*
- *Temporal stability*
- *Detection*







Cross-section is well known therefore stripping efficiency calculation is a matter of algebraic manipulation (tech. notes)

Why Choose Laser-wire over Conventional Wire?

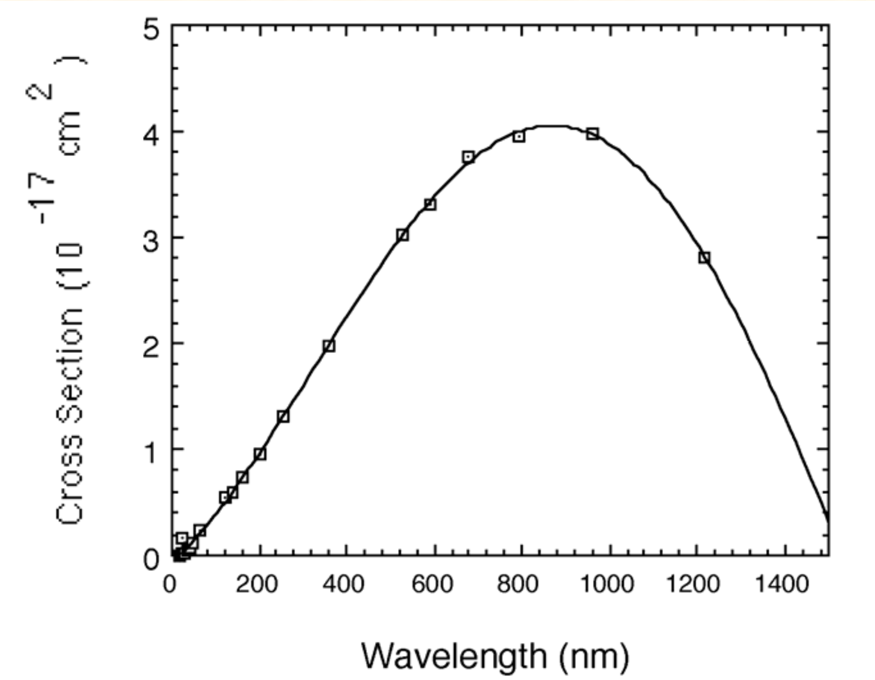
Conventional Wire

- Requires off-operation with 100 μs macro-pulses at low rep rate
- Ablation from the wire may contaminate the SRF cavity
- Signal to noise not a problem
- Maintenance requires vacuum access
- Very radiation hard

Laser Wire

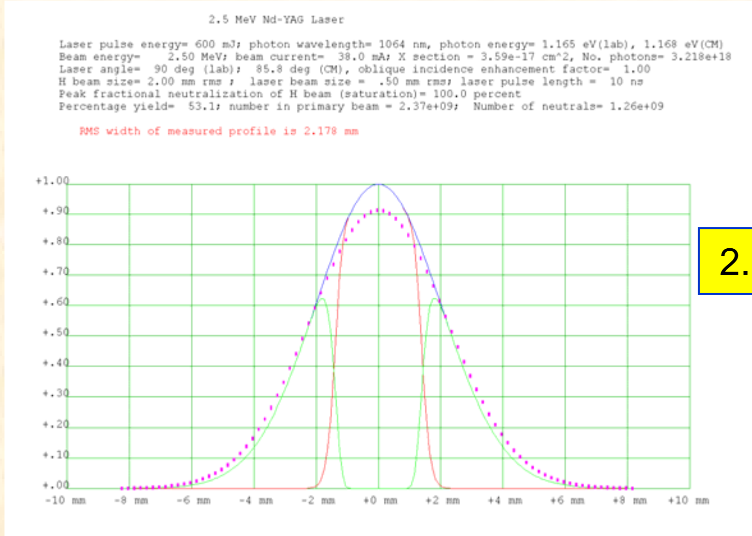
- Minimal impact on normal operation
- Virtually no impact on SRF cavities or vacuum
- Low signal to noise ratio on differential current measurements but excellent s/n using electron collector.
- No parts inside the vacuum
- Radiation hard @ λ<1500nm

Laser Photo neutralization cross section

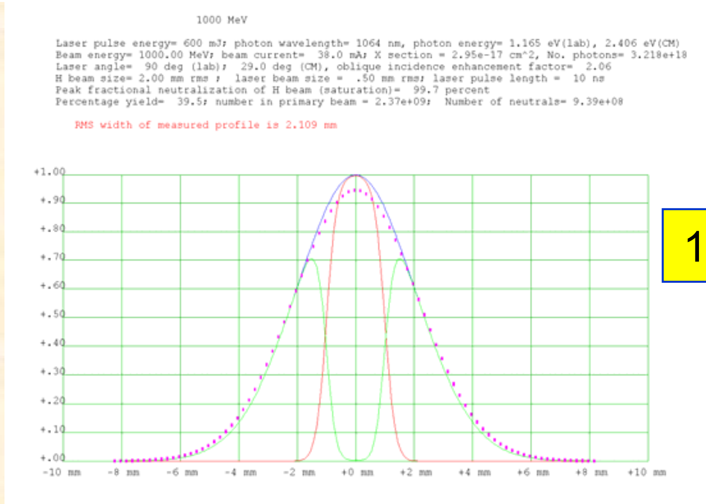


Calculated cross section for H- Photo-neutralization as a function of photon wavelength.*

Nd:YAG laser has λ=1064nm where the cross section is about 90% of the maximum.



2.5 MeV

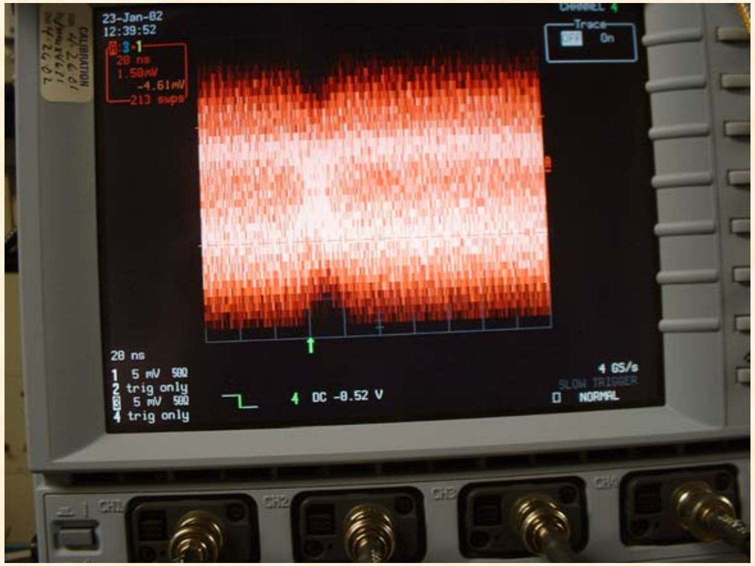


1 GeV

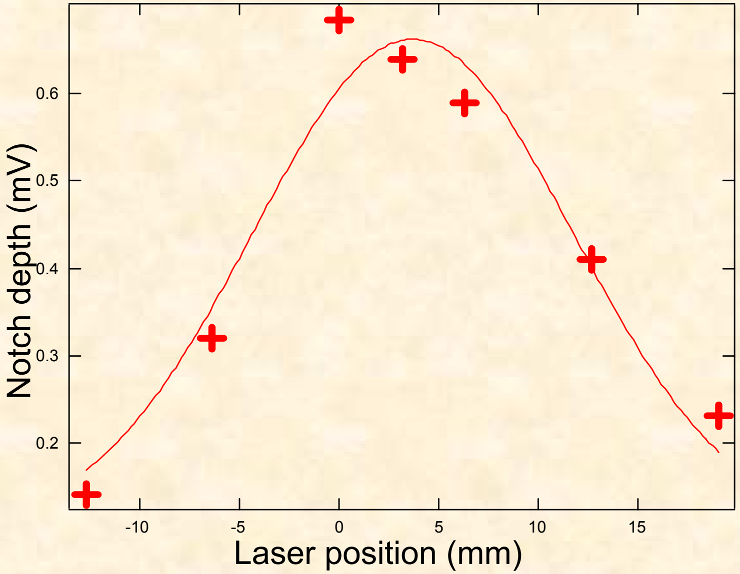
*J.T. Broad and W.P. Reinhardt, Phys. Rev. A14 (6) (1976) 2159.

Initial Laser Monitor Development at BNL: Laser "notch" in strip-line signal

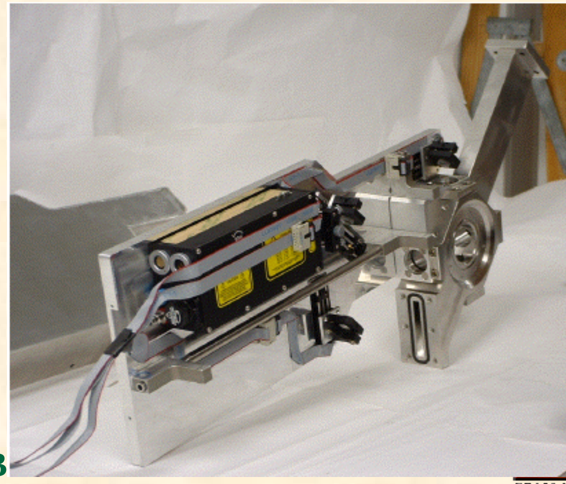
Scope was set on infinite persistance for several hundred beam pulses. This is difference signal at 400 MHz from upstream and downstream BPMs.



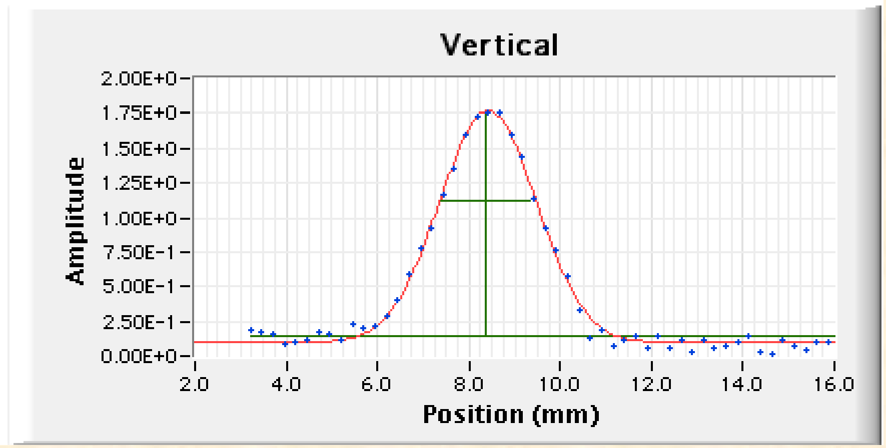
Laser Wire Profile with 100uA 200MeV Polarized Beam



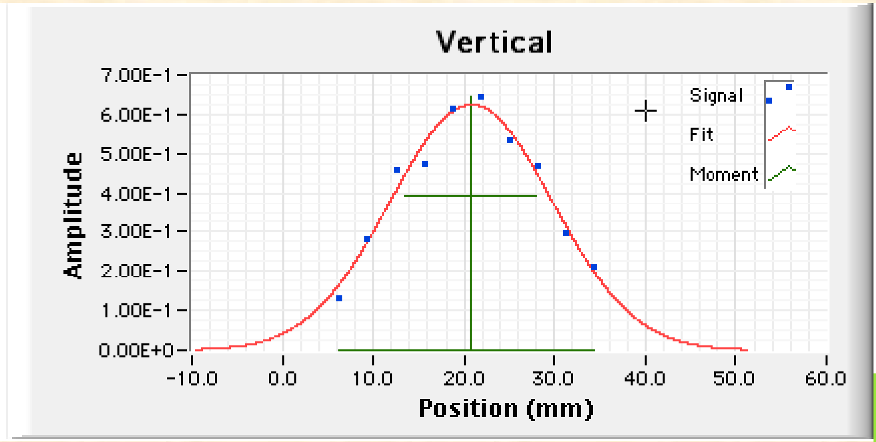
200 mJ Q-switch Nd:YAG Laser



Proof of Principle – Only one sigma profiles could be measured



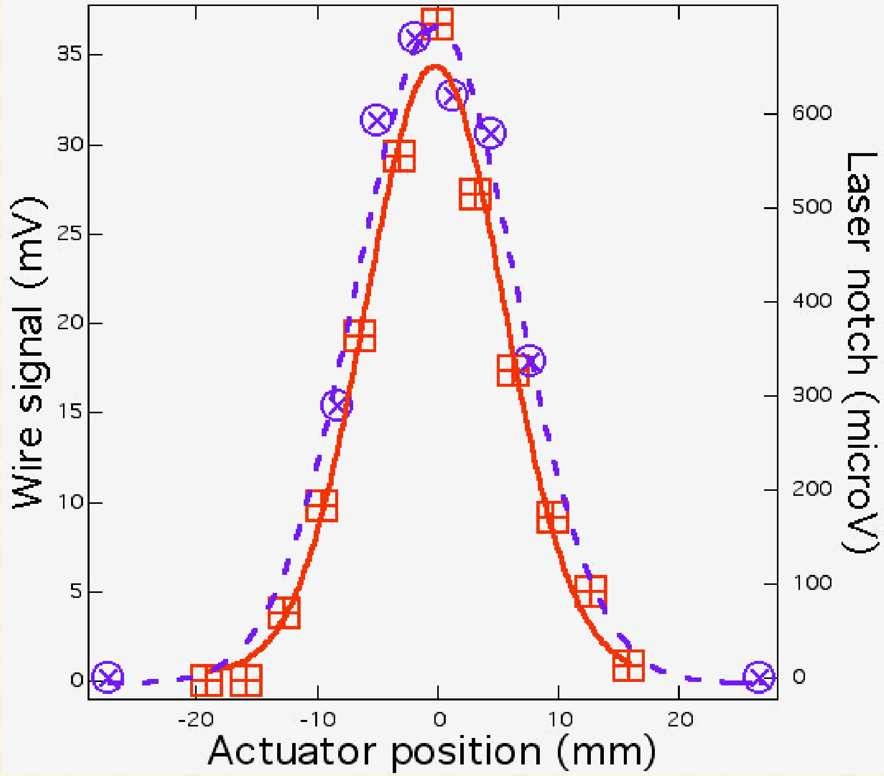
Profile from the 2.5 MeV MEBT at Berkeley



Profile from the BNL 200MeV LINAC

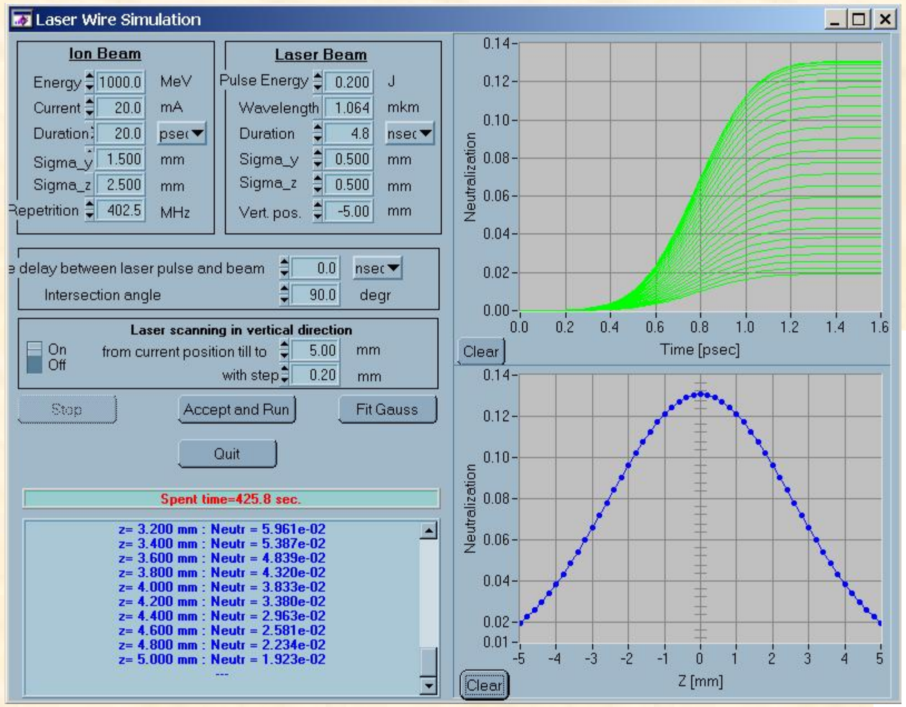
Software: Wim Blokland

Courtesy of Roger Connolly



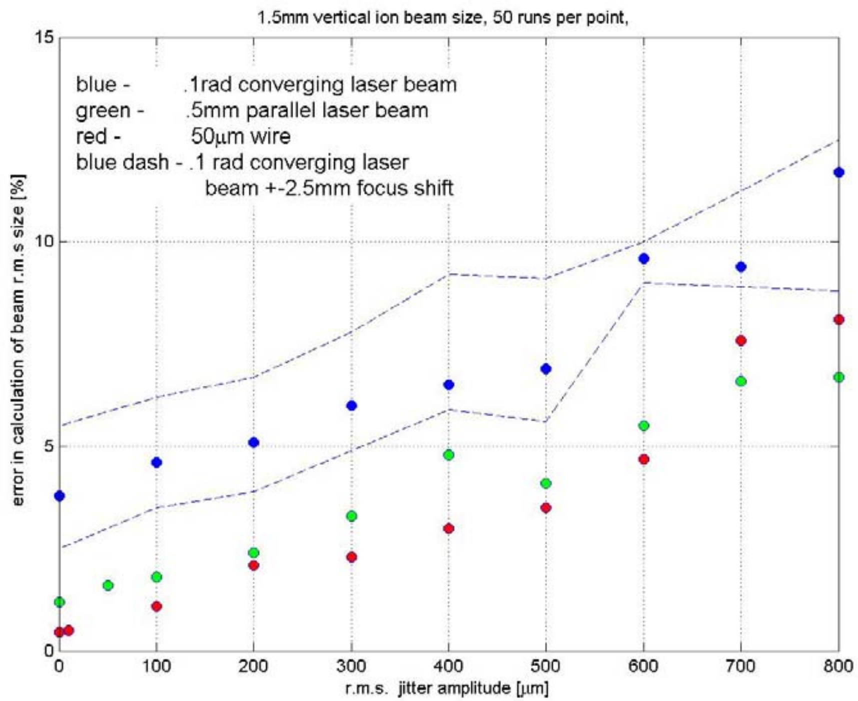
Comparison of Laser-wire and Carbon-wire data at BNL 200 MeV line

Modeling and jitter analysis guides our design



Models being developed by Sasha Aleksandrov and Victor Alexandrov from BINP

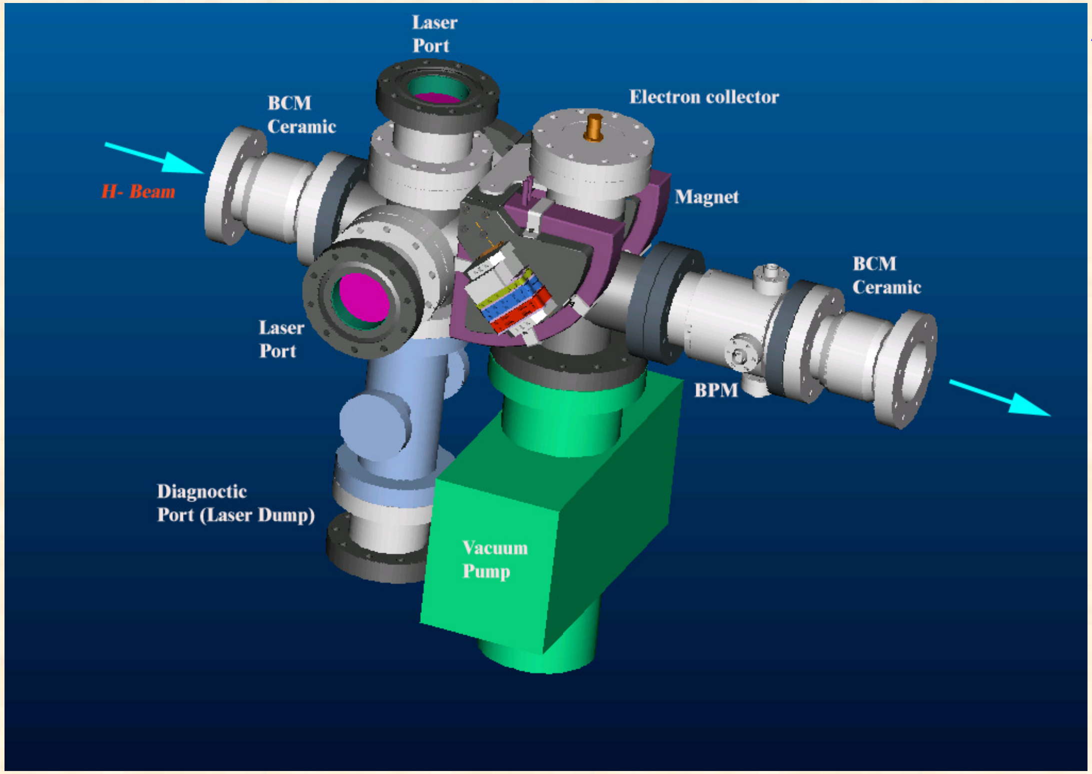
branch at Protvino



Dependence of error upon jitter amplitude for:

1. ***Converging laser beam***
2. ***Parallel laser beam***
3. ***Thin wire***

Direct measurement of the liberated electrons via the electron detector

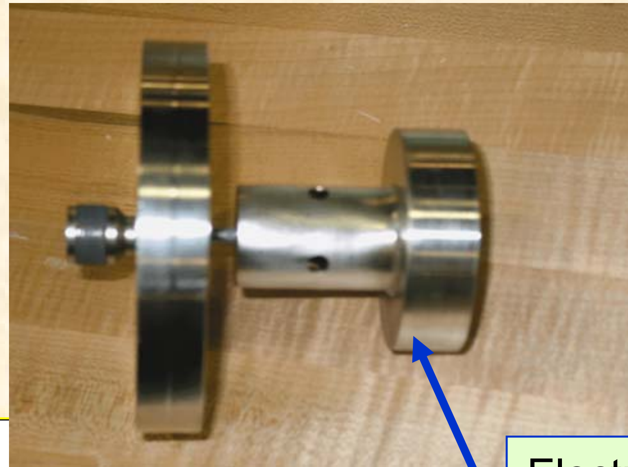


Advantages:

- large number of electrons
- charge integrating amplifier similar to BLM
- Energy of electrons is well defined
- Electron beam is well collimated

Drawbacks

- External magnets are required
- In vacuum collectors are required
- Might suffer from beam loss background



Electron Collector
C. Deibele

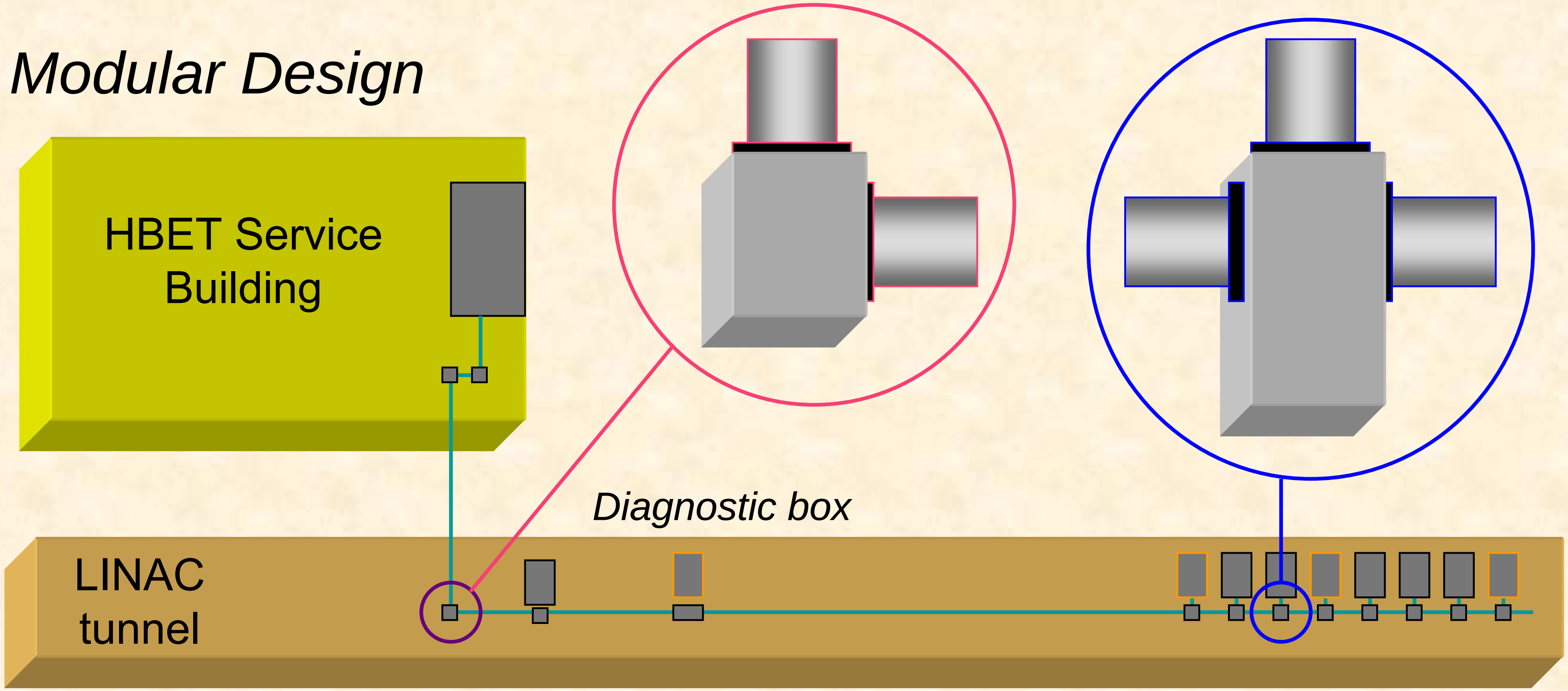
Required Magnetic Field

Table1.

E[MeV]	186	204	223	241	259	277	296	314	332	351	369	387
B[Gs]	70	74	77	80	84	87	90	94	97	100	103	105
E[MeV]	438	489	540	591	642	694	745	796	847	898	949	1000
B[Gs]	113	121	128	136	143	150	157	163	170	177	183	190

Transport Line

Modular Design



- *Boxes secured to building walls, ceilings, etc.*
- *Designed to accept a variety of optical components*
- *Cable feedthroughs*
- *Pipes mounted between boxes*

4 LW from 186 MeV,

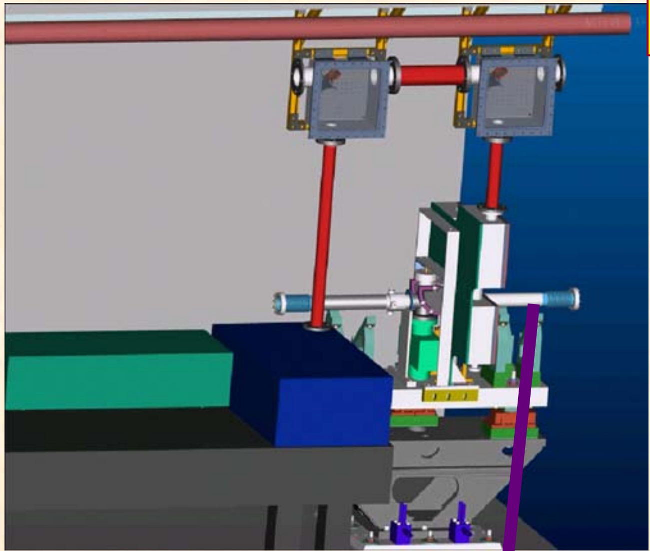
4 LW from 386 MeV

1 LW at 1 GeV

Laser Wires Locations

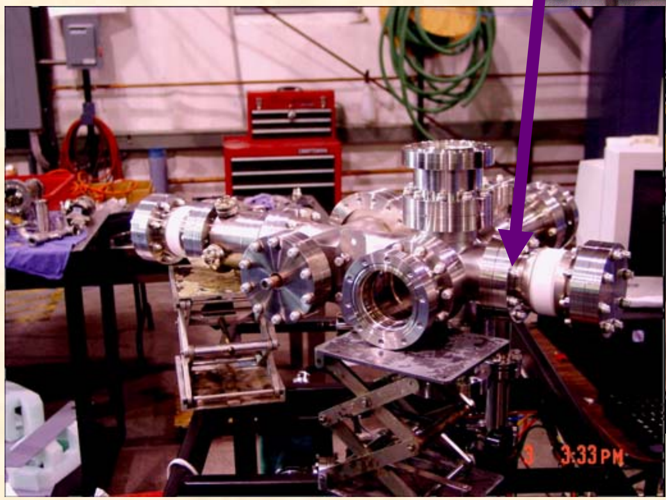
SCL Laser Profile Monitor – Test on MEBT at ORNL

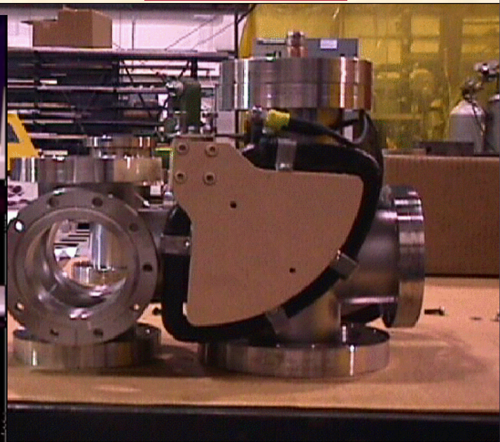
Courtesy of the ORNL Mechanical Group.



Prototype Station on MEBT

Magnet



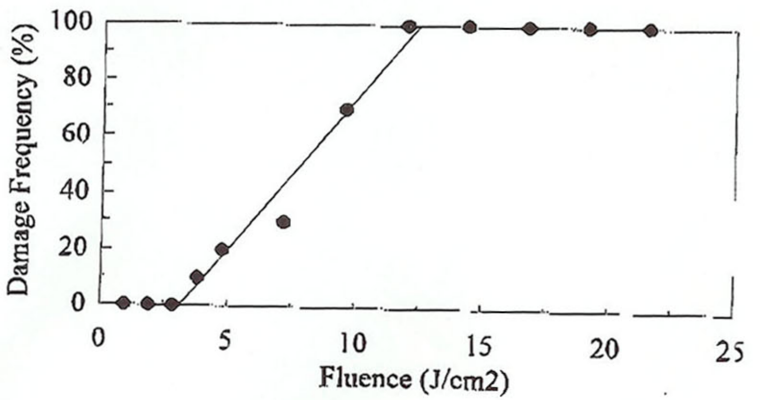


Courtesy of Ted Hunter (Magnet GL)

Laser Profile Monitor Safety Concerns:

One concern was raised: What is the probability of laser beam burning through the vacuum window?

1.5 million pulses at 44 times the required power did not show any damage to the coating or the window at our laser lab.

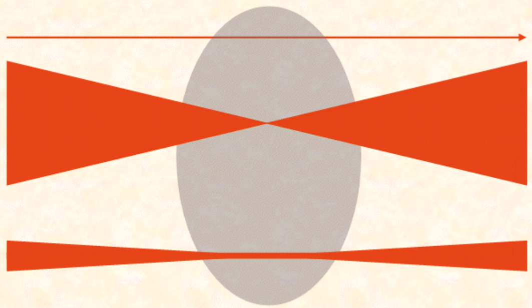


J/cm2	MW/cm2	%Fail
21.5	979	100
19.1	870	100
16.7	761	100
14.4	652	100
12	544	100
9.57	435	70
7.18	326	30
4.78	217	20
3.83	174	10
2.87	130	0
1.91	87	0
0.96	43.5	0

Independent lab [Big Sky Laser] tested the SNS vacuum windows
And confirmed that we need 150 MW/Cm^2 to start damaging the window.
That is about 80 times the power we expect to need.

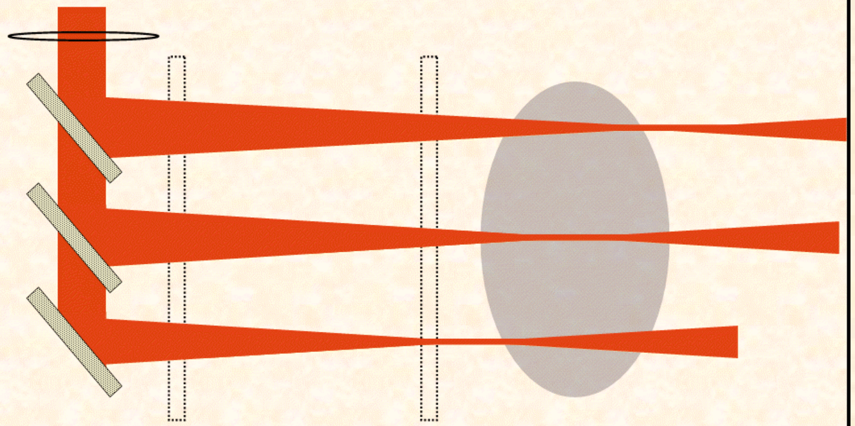
Evolution of the Beam-line Optics Design

Design Considerations



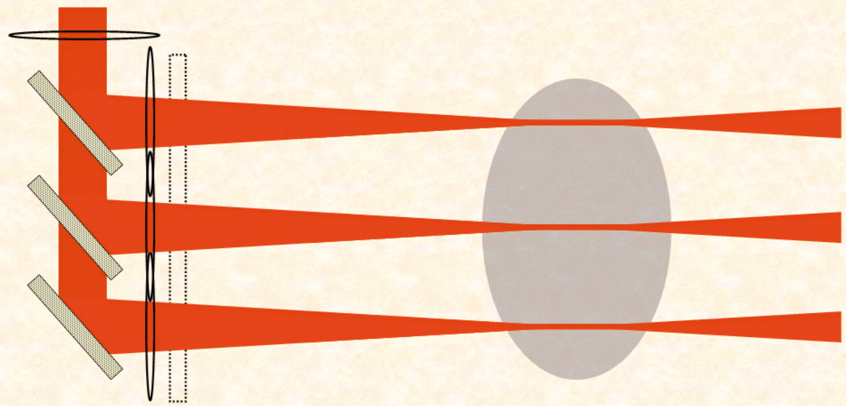
- *Collimated laser beams do not exist*
- *Small spot size attainable over a limited region*
- *Choose Rayleigh range to match H^- beam size*

Design Considerations



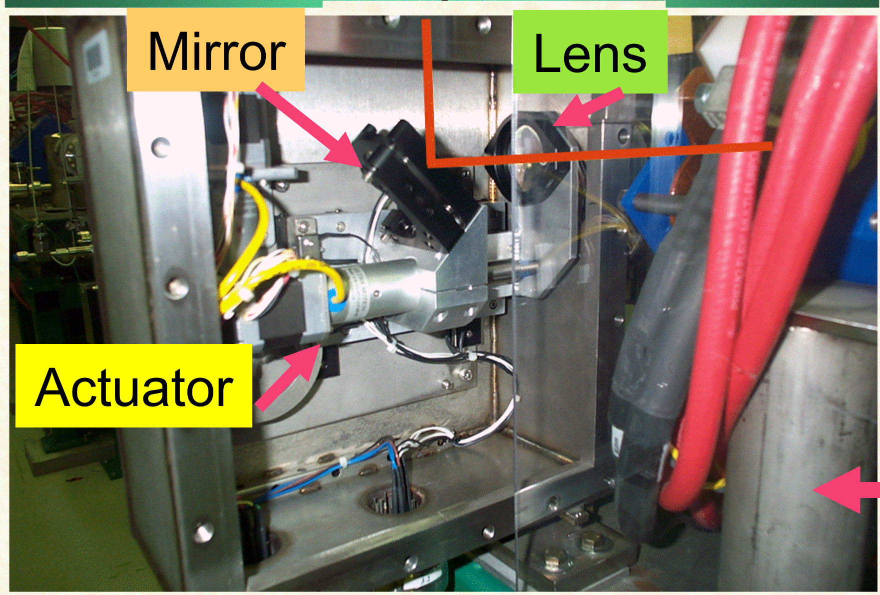
- *Window must be placed far from focus*

Design Considerations



- *Large beam needed at window*
- *Lens should move with scanning mirror*

The System

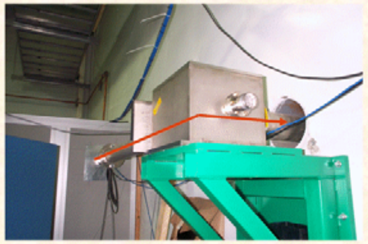


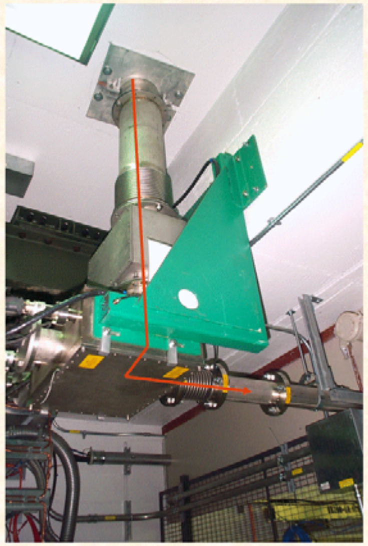
SCL Laser Transport Line

The System

- *Q-switched Nd:YAG*
- *1064 nm*
- *8 ns*
- *30 Hz*
- *650 mJ*
- *Injection seeded*

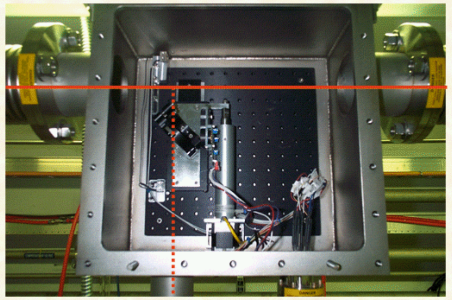
The System



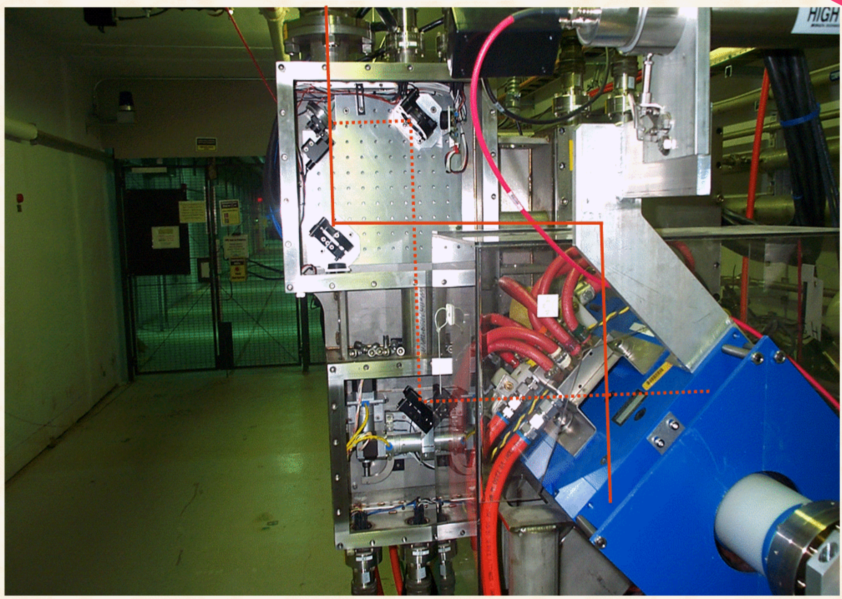


- *Note Safety Features*

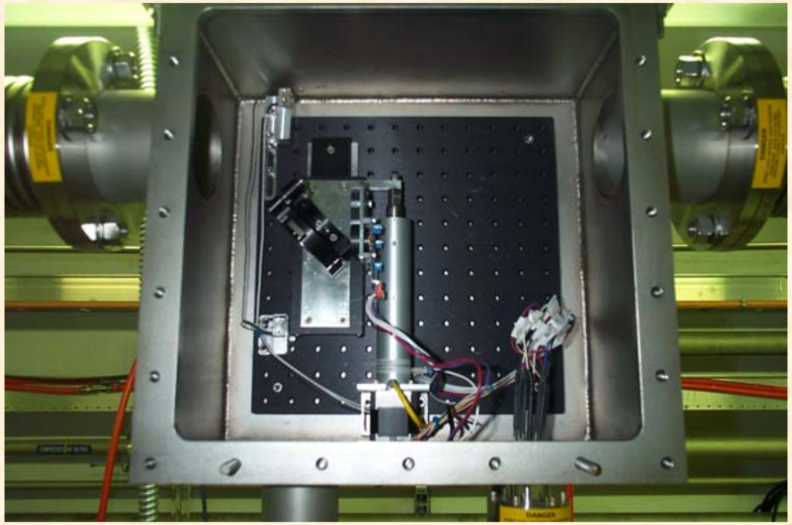
The System



The System

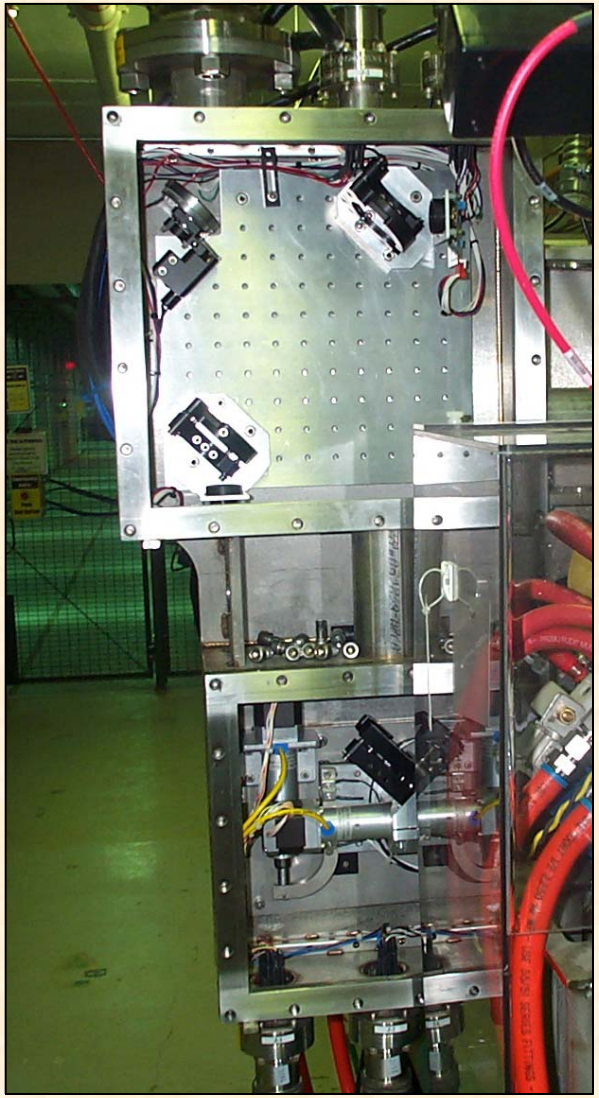


All Movable Mirrors, Lenses and Actuators are Controlled Remotely.

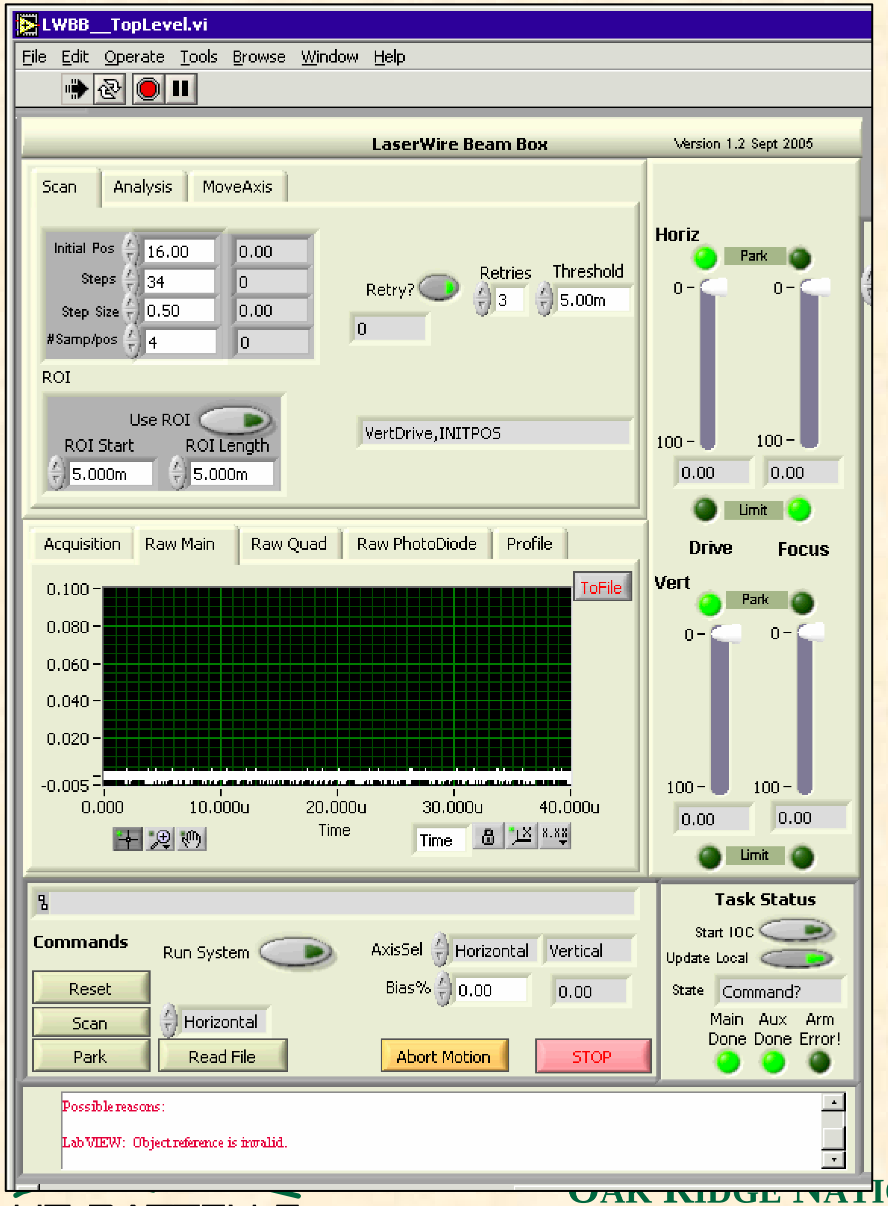


Transfer Line

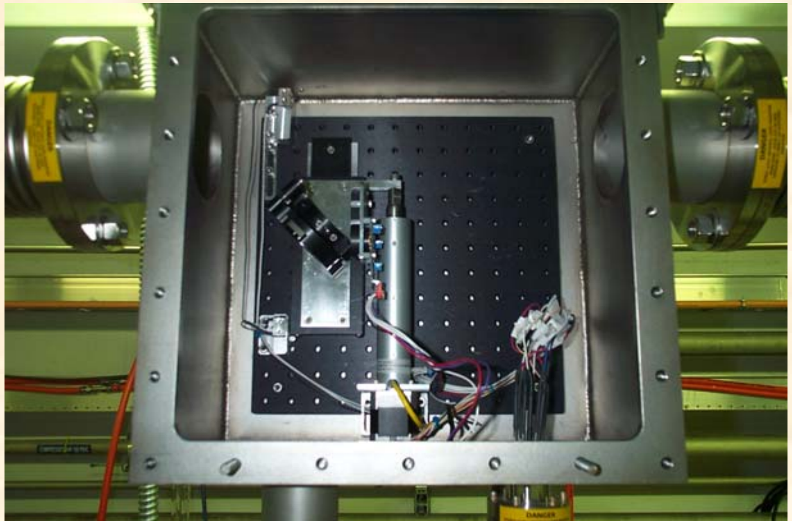
Station-32



Data Acquisition and Laser Control



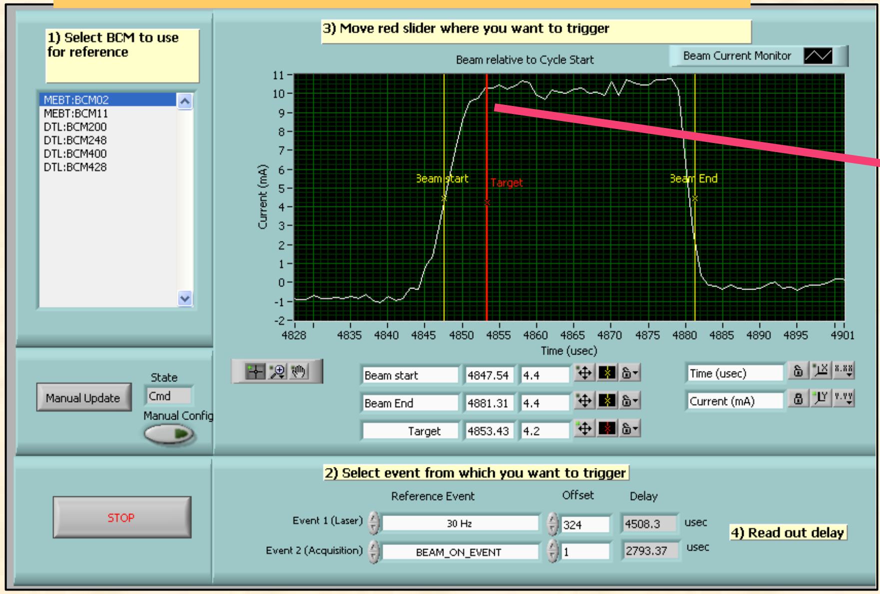
- *Make sure laser is aligned*
- *Set laser timing*
- *Insert pick-off mirror*
- *Power magnet*
- *Search for signal*
- *Set acquisition parameters*
- *Set scan parameters*
- *Acquire data*

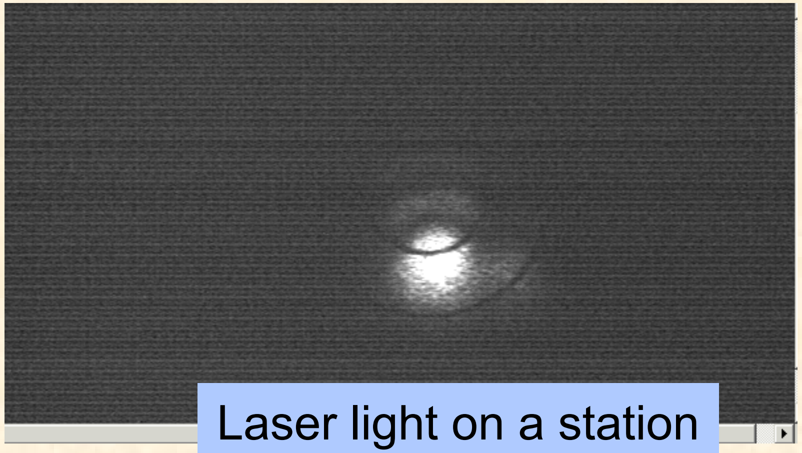


Data Acquisition and Laser Control

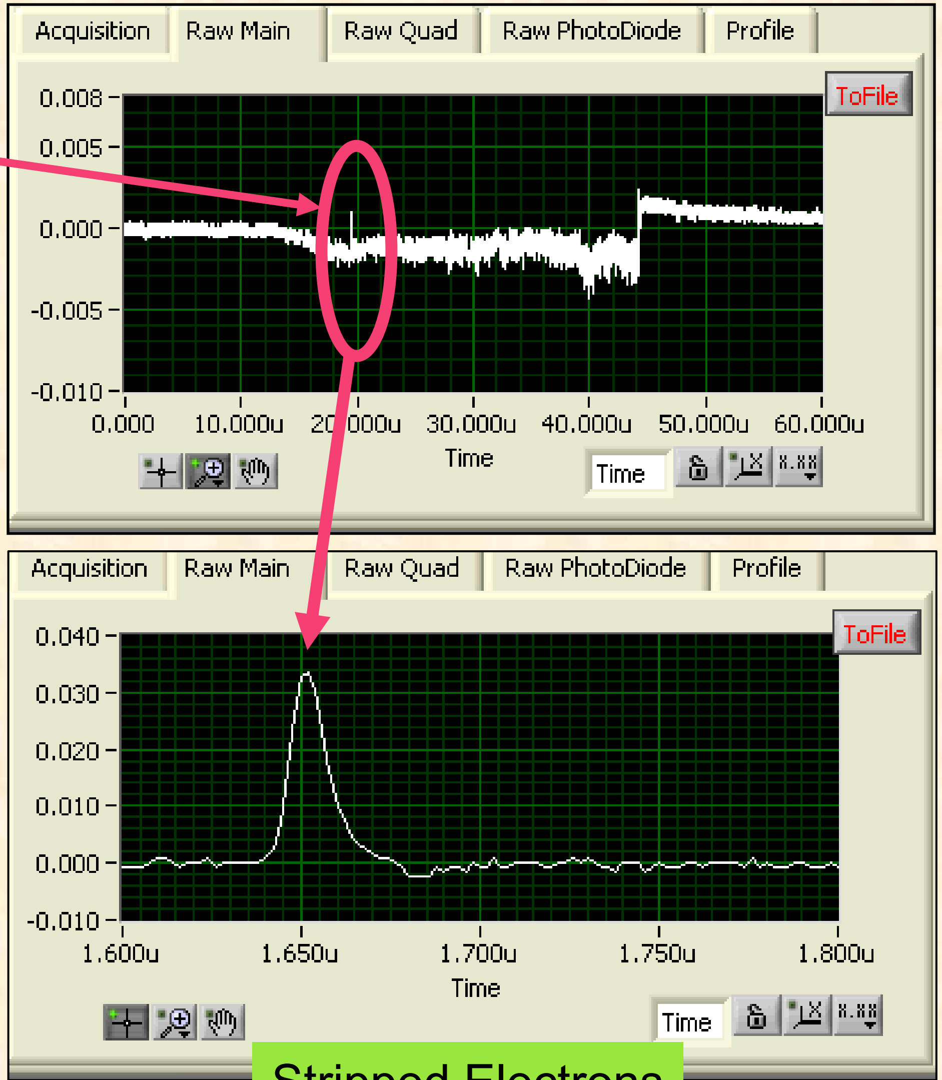
Laser light timed in to H- Beam

Laser Notch





Laser light on a station



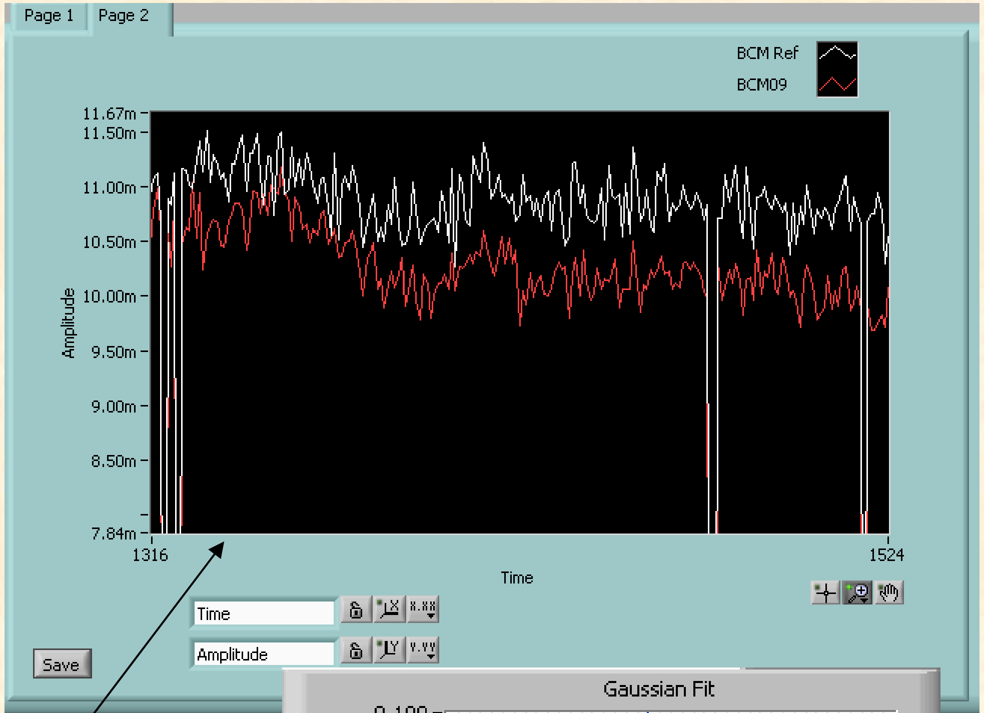
Stripped Electrons

UT-BATTELLE

Oak Ridge National Laboratory
U. S. Department of Energy
Laser Mini Workshop at Oxford, July-3, 2006

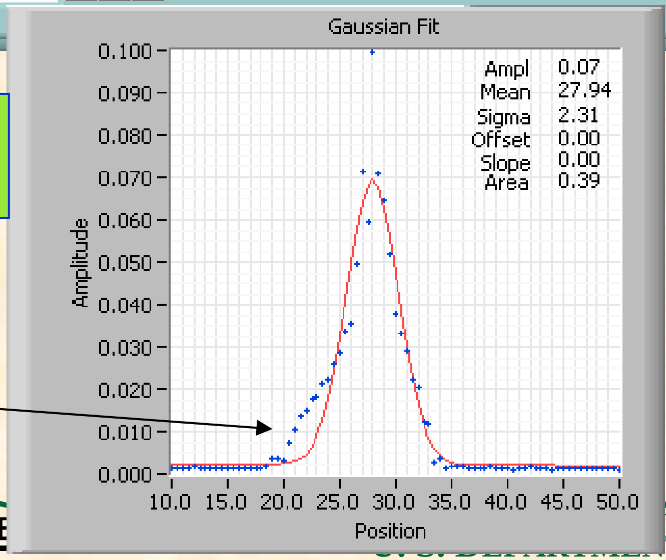
SNS Spallation Neutron Source

The SCL Laser Profile monitor is good to 2.5 sigma. – Can we go to 4 sigma? -YES, we need to understand the laser and beam jitter to do proper averaging

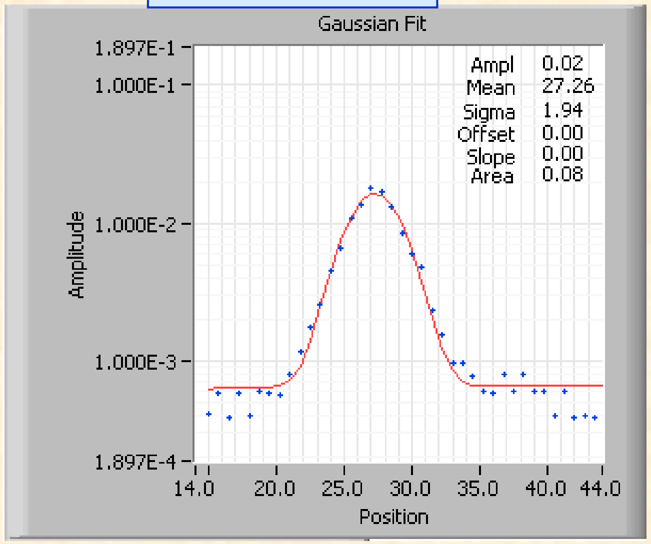


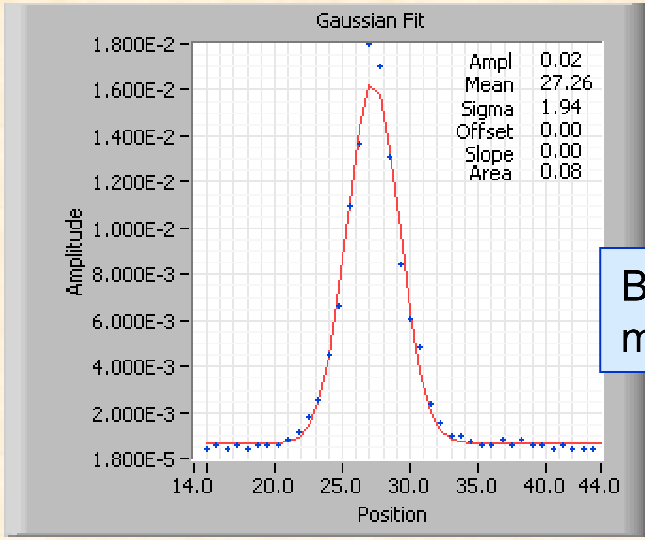
Beam jitter from two BCMs

CCL to SCL is Not matched



Semi-log plot

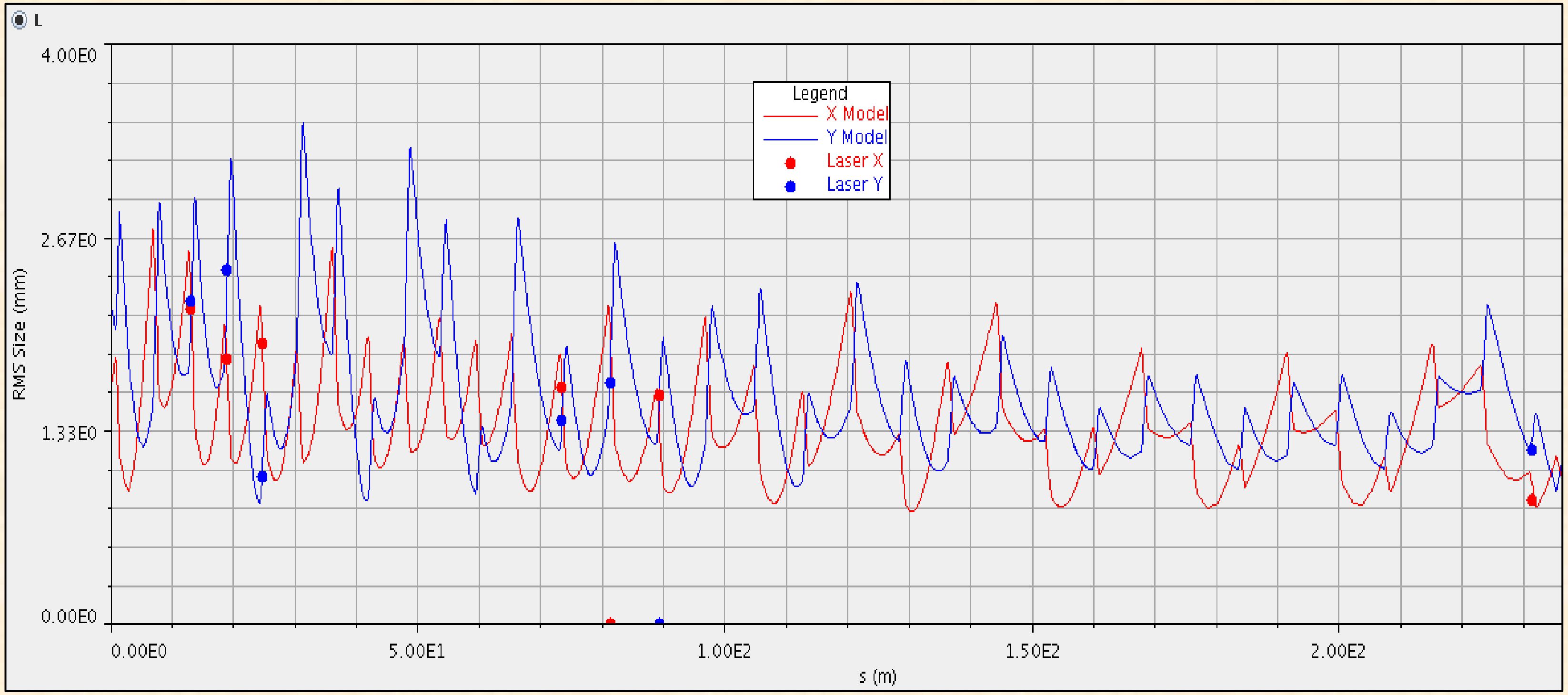




Better matched

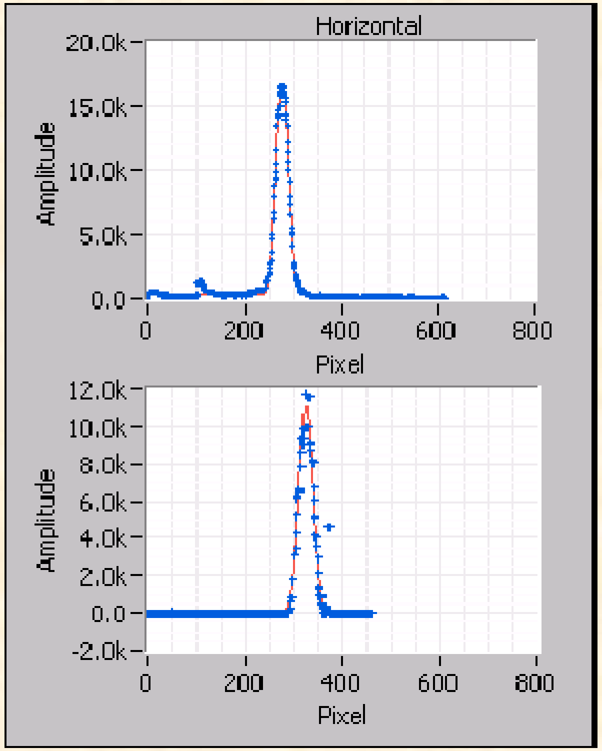
It only matters if SCL model agrees! -- Success

- ***Comparison to Model***



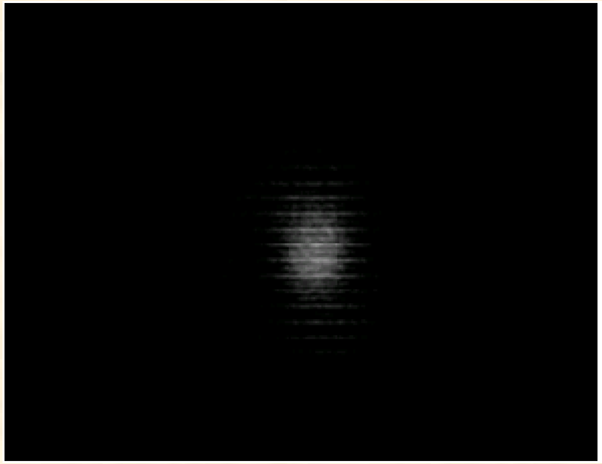
XAL and online model: J. Galambos, et. Al.

Synchronized video capture and vibration tests are accomplished using pulsed Nd-YAG Laser. Measurements at Cryo-station 17.



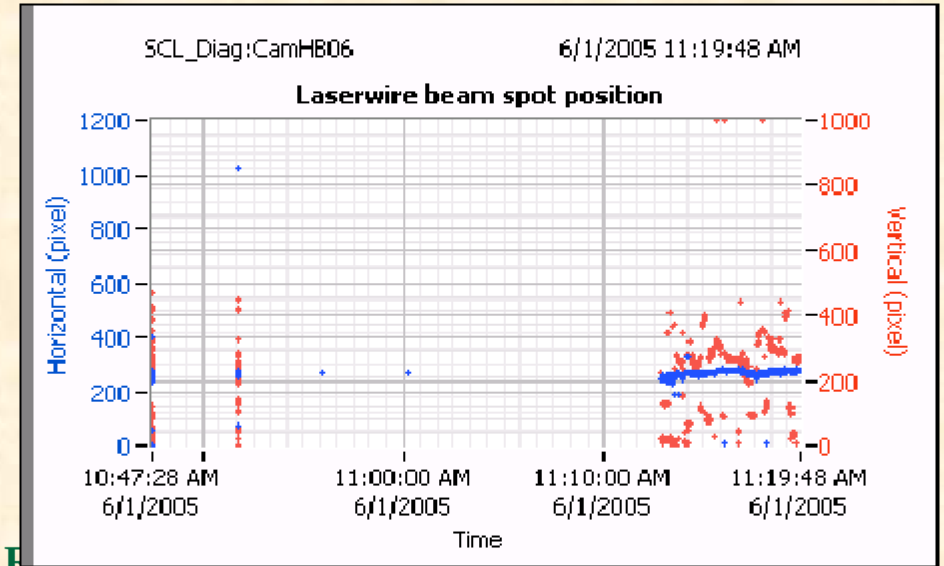
Horizontal (top) and Vertical laser light profiles (bottom)

10 nano-sec laser pulses are captured by the video system.

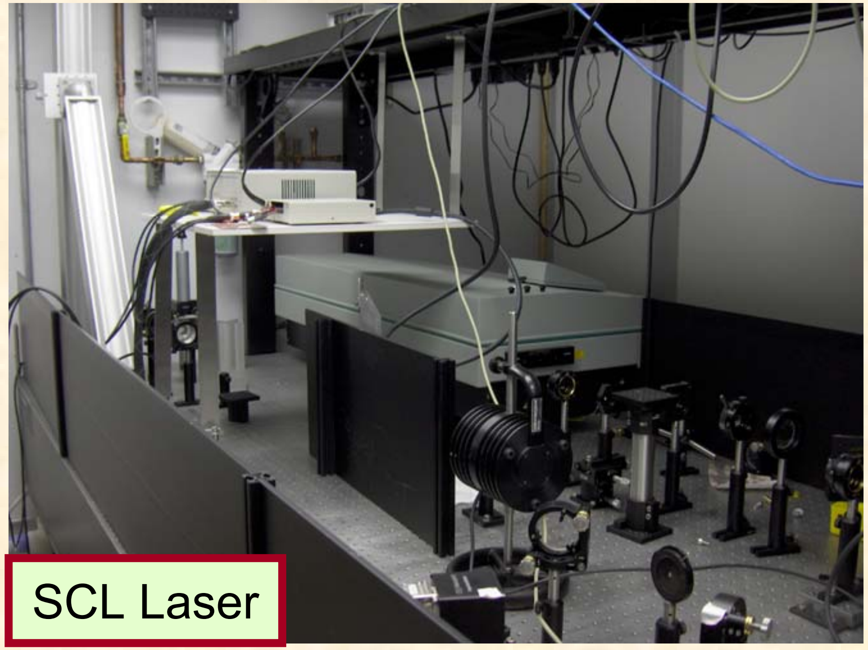


Igor Nesterenko

SCL Laser

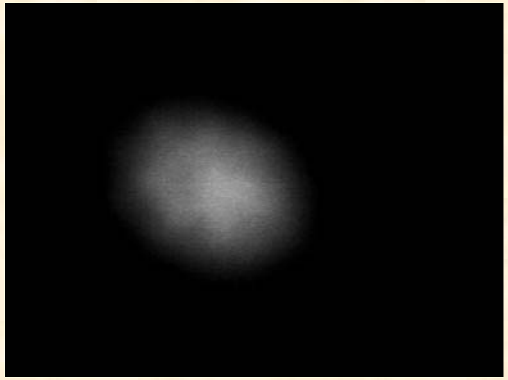


Synchronized Video capture for drift compensation is ready, vibration feedback system is under development and testing

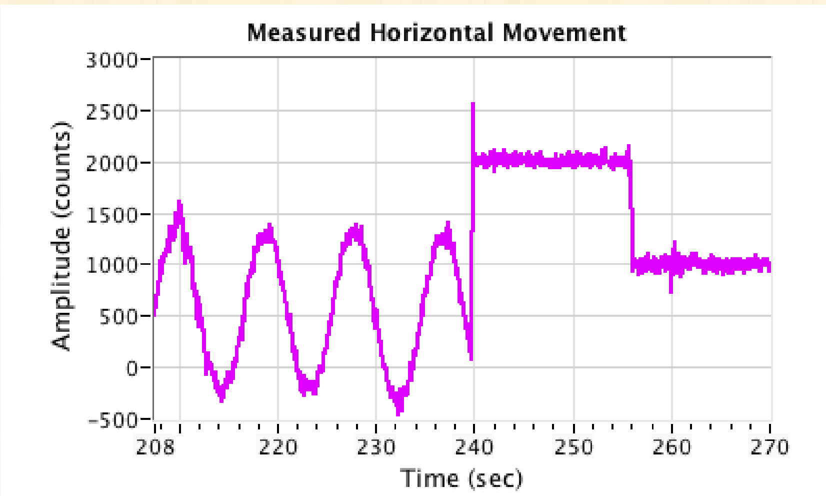


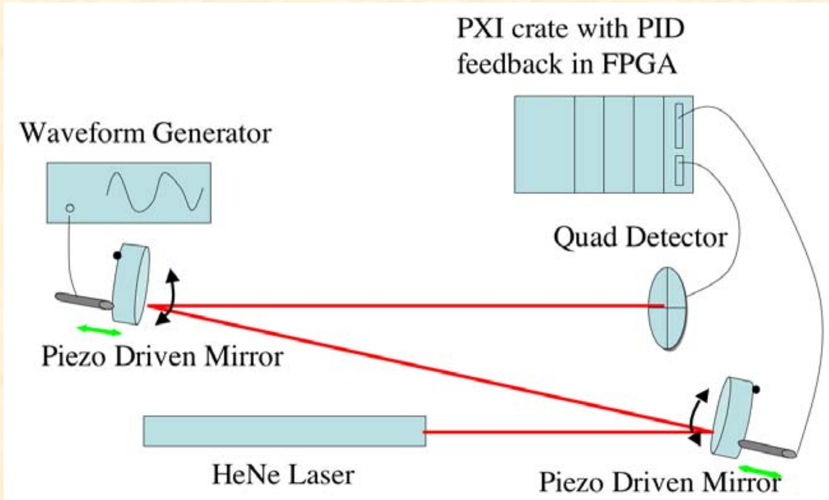
SCL Laser

CW HeNe laser light is captured by the video system.



W. Blokland





Summary of SCL Laser Profile Monitor

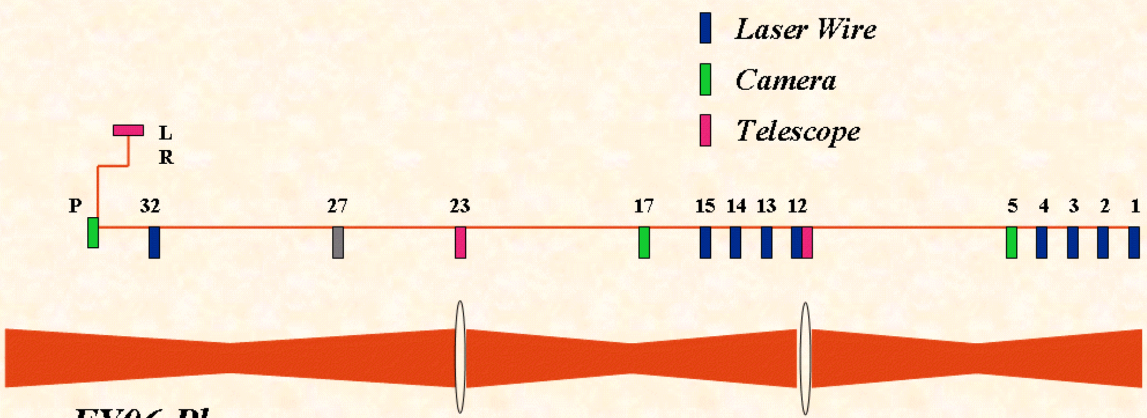
- System Works.

- Profiles are as good as the carbon wire scanners – it is good to 2.5-3.0 Sigma fit.
- We need to remove the signal amplifiers from the tunnel.
- We need to have a better laser/beam synchronization timing implemented to be able to use averaging.
- Automation and feedback, trend and drift corrections are being designed.
- Laser is being manually turned on and off by the experts only. We have plans to upgrade the laser system to automate that as funding becomes available.

**************************** OVER ALL SUCCESS ***

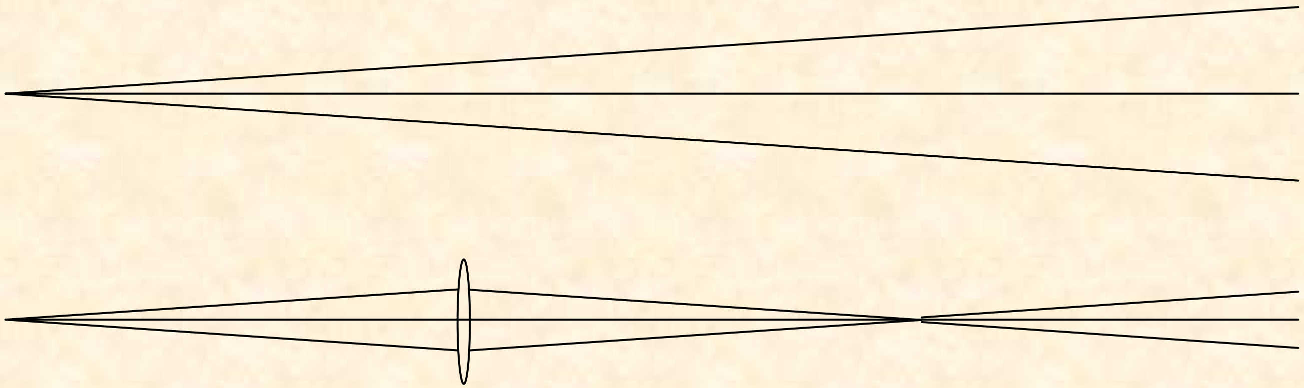
Stability Via additional telescopes

Laser Alignment



FY06 Plan

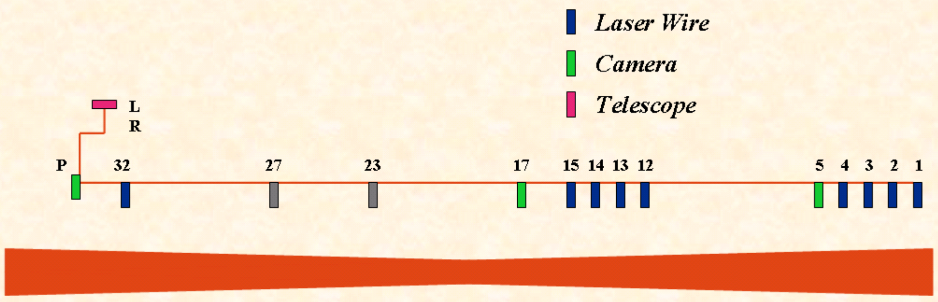
- *Improve telescope design to reduce vibration*
- *Determine optimum number and placement of telescopes*
- *Develop "point-to-point" stability algorithm*
- *Determine optimum placement of detectors, etc.*



Laser Alignment Challenges and Solutions

Now

Laser Alignment



Original Plan

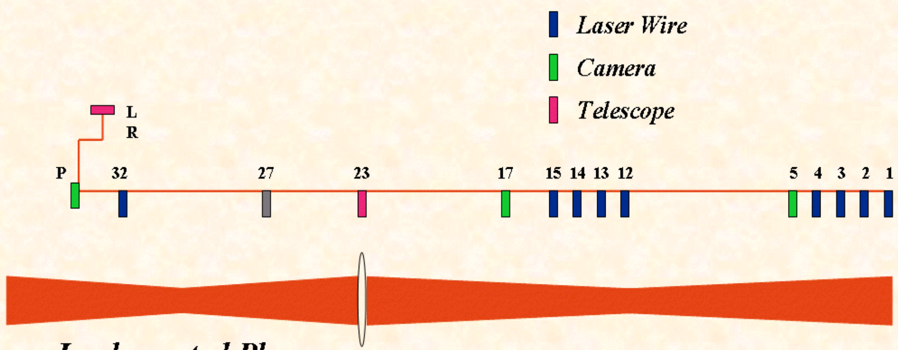
- *Large unfocused beam "protects" mirrors, windows, etc.*
- *Goal is to make the system "stable enough"*
- *Cameras characterize beam shape and provide feedback for active control in LR*
- *Quad detectors verify that the beam is where it should be*

Problems

- *Vibrations at the front end are problematic*
- *Misaligned optics reduce effective aperture*
- *Transfer line diagnostics don't work as well as needed*

Next

Laser Alignment



Implemented Plan

- *Optics still "protected"*
- *Beam can be steered by the telescope*
- *Effect of front-end vibrations is reduced*

Problems

- *Beam can be steered by the telescope (new source of jitter)*
- *Effects of tweaking are less clear*

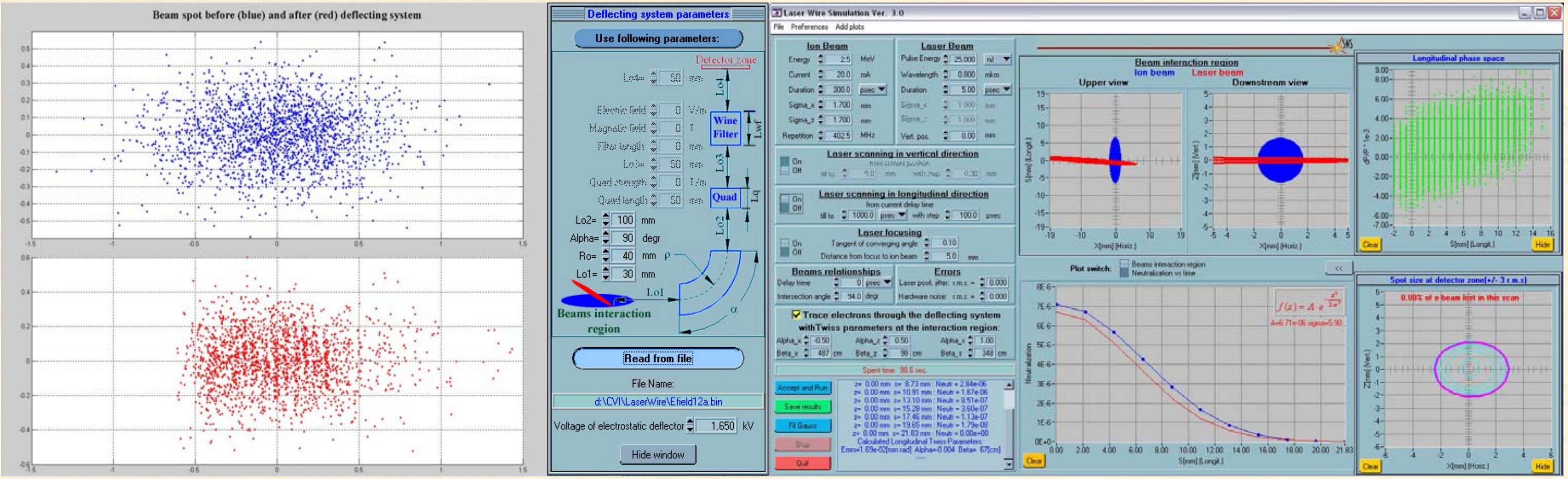
Status of SCL Laser Profile Monitors

- Revamp existing diagnostics
- Add new diagnostics (cameras)
- Install larger optics where needed
- Optical engineering to improve beam stability
- Automate beam alignment algorithm
- Restore focus-tuning functionality
- Put all aspects of laser operation under computer control
- Increase the laser stations from 9 to eventual 32
- LOTS of software

Longitudinal Profile Monitors R&D and Prospect

3-D Bunch Measurement

Mode-locked Ti-Sapphire laser on order.



Initial tests planned for MEBT commenced in Sept-04 longitudinal plane only.

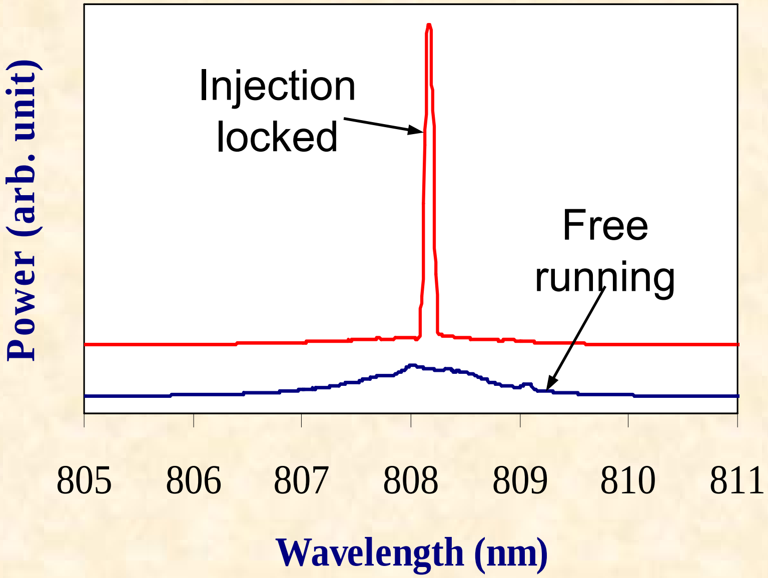
Complete system simulation – beam/laser interaction, electron transport

Demonstration of High Quality Laser Beam in ORNL Optics Laboratory

Optical Injection Locking

Improvement of laser linewidth and beam quality while maintaining the high output power

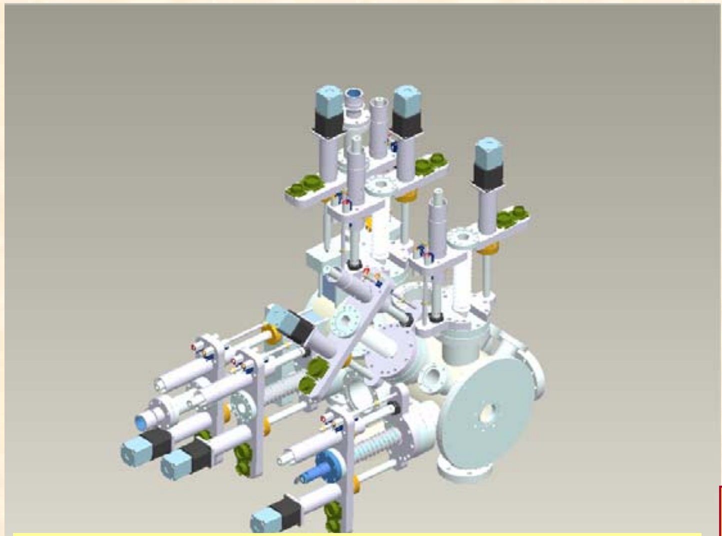
Appl. Phys. Lett. **81**, 978 (2002);
Appl. Opt. **41**, 5036 (2002);
J. Vac. Sci. Technol. B, **20**, 2602 (2002).



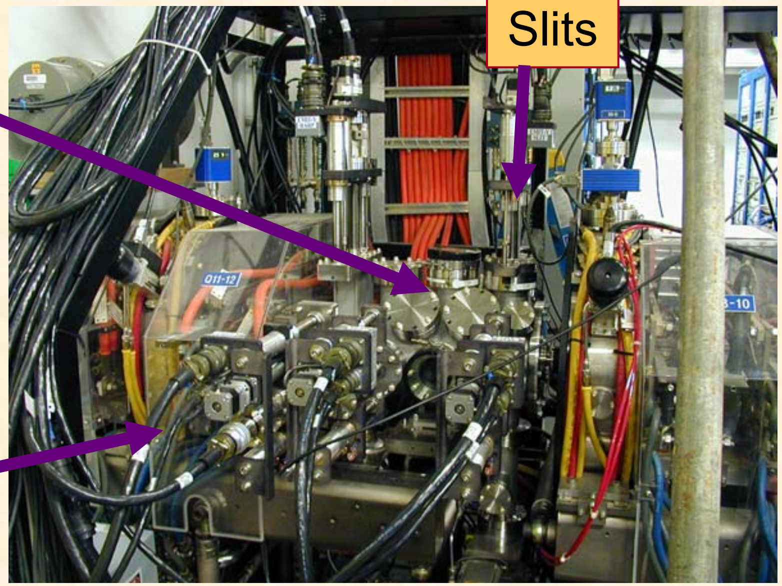
Collection of Diagnostics for the 2.5 MeV MEBT

- 6 months, concept to deployment
- Another multi-group effort: Diagnostics, mechanical, and physics,
  - Fast faraday cup
  - Scintillator, phosphor viewing screen
  - 3 different size beam apertures
  - X-Y Beam Slits
  - Camera Port
  - Beam Stop/ Slow Faraday Cup

Design Engineer is Tom Roseberry from ME group



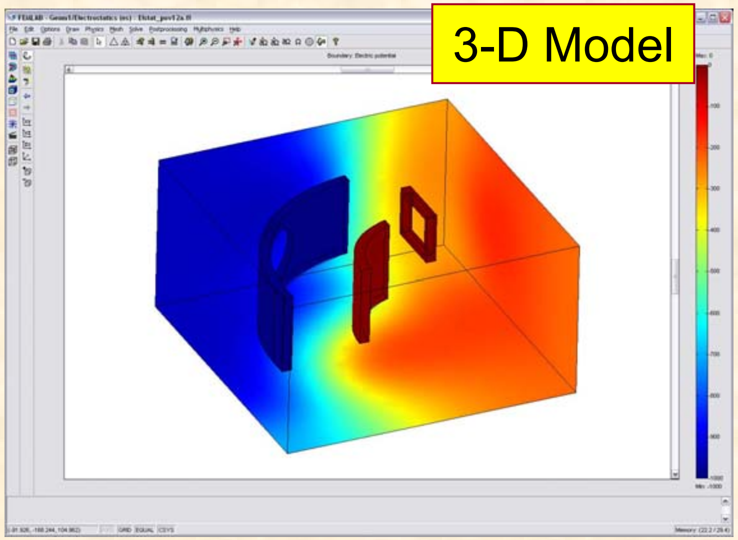
D-Box as proposed 6 months ago

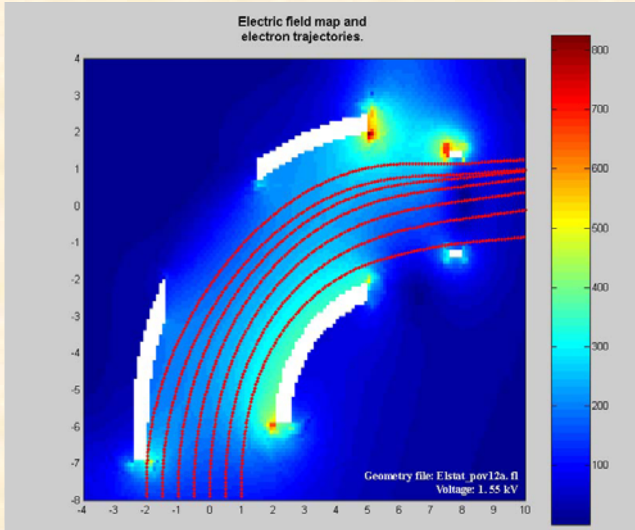


D-Box installed and operating in MEBT

Laser System-- 3-D Bunch Measurement

3-D Model

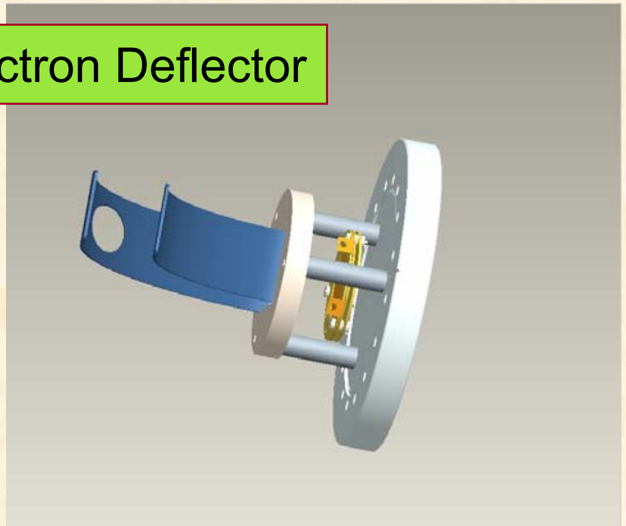




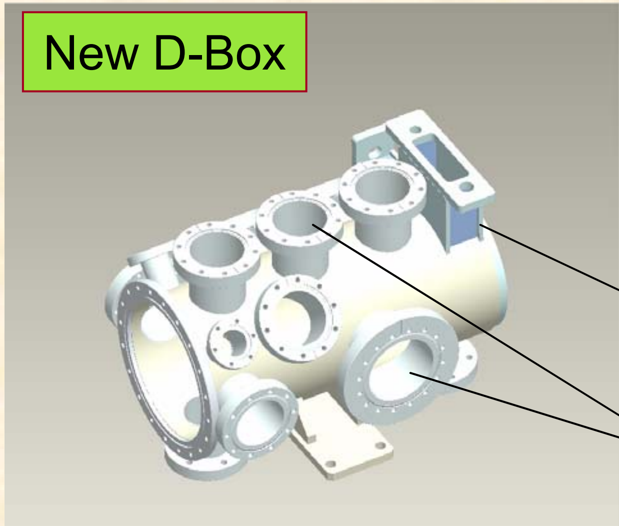
Electron trajectory

Modeling:
Victor Alexandrov

Electron Deflector



New D-Box

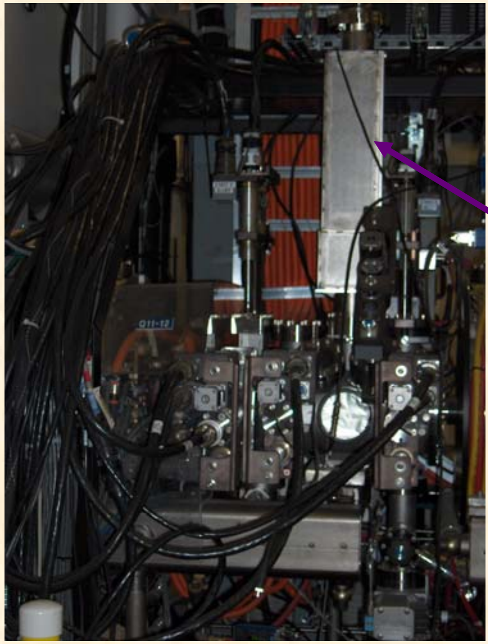


Design Engineer:
Tom Roseberry

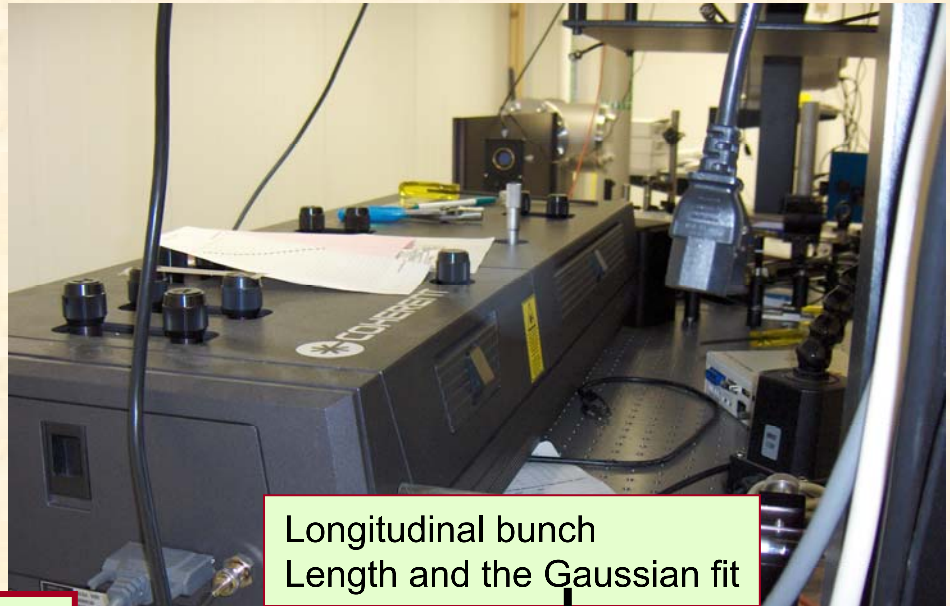
Harp Port

Laser Port

We Have successfully Measured longitudinal bunch-length using mode-lock Laser and directly collected electrons via MCP at 2.5MeV

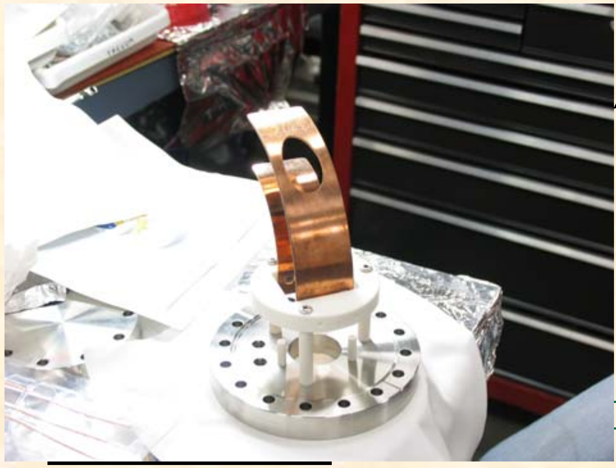


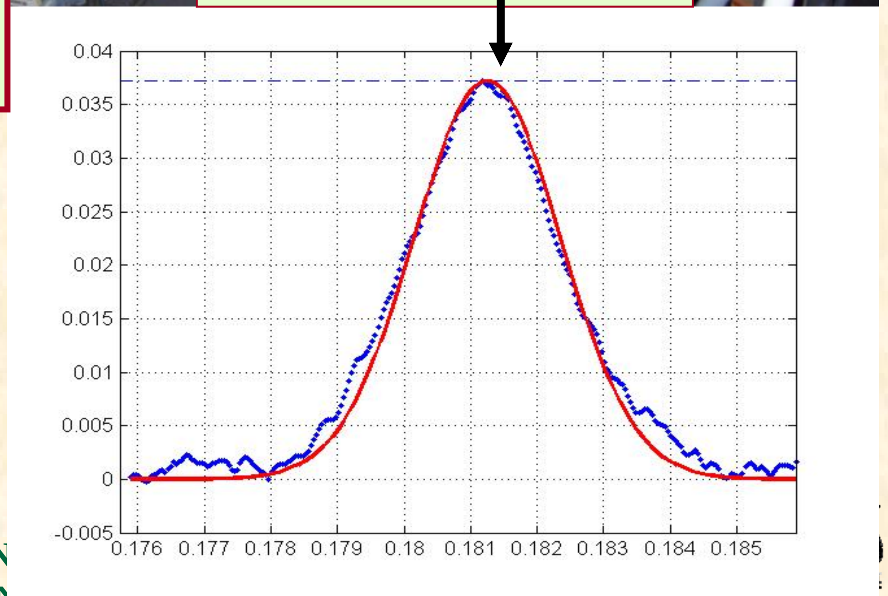
1-D mode
Lock Laser
Optics Box



Longitudinal bunch
Length and the Gaussian fit

Electron deflector
And MCP assembly





Status of the longitudinal Laser Profile Monitors

- We have proven that mode-lock lasers with MCP and electron detectors are well suited to measure 3-D Profiles.
- Model and experiment matched well [EPAC 2006]
- Automation and timing improvements are essential for the final product.

ORNL funded Experiment at 1 GeV SNS LINAC

- H- Laser Stripping Proof-of-Principle Experiment for the Spallation Neutron Source Power Upgrade

Y. Braiman,[1] S. Aleksandrov,[2] S. Assadi,[2] J. Barhen,[1] V. Danilov,[2] W. Grice,[1] S. Henderson (ASD:PI),[2] Y. Liu[1]

[1]Computer Science and Mathematics Division, ORNL

[2]Accelerator Systems Division, Spallation Neutron Source, ORNL

Please refer to V. Danilov EPAC-06 talk

Laser Stripping Experiment – ORNL LDRD funded

Successful ORNL – SNS Collaboration

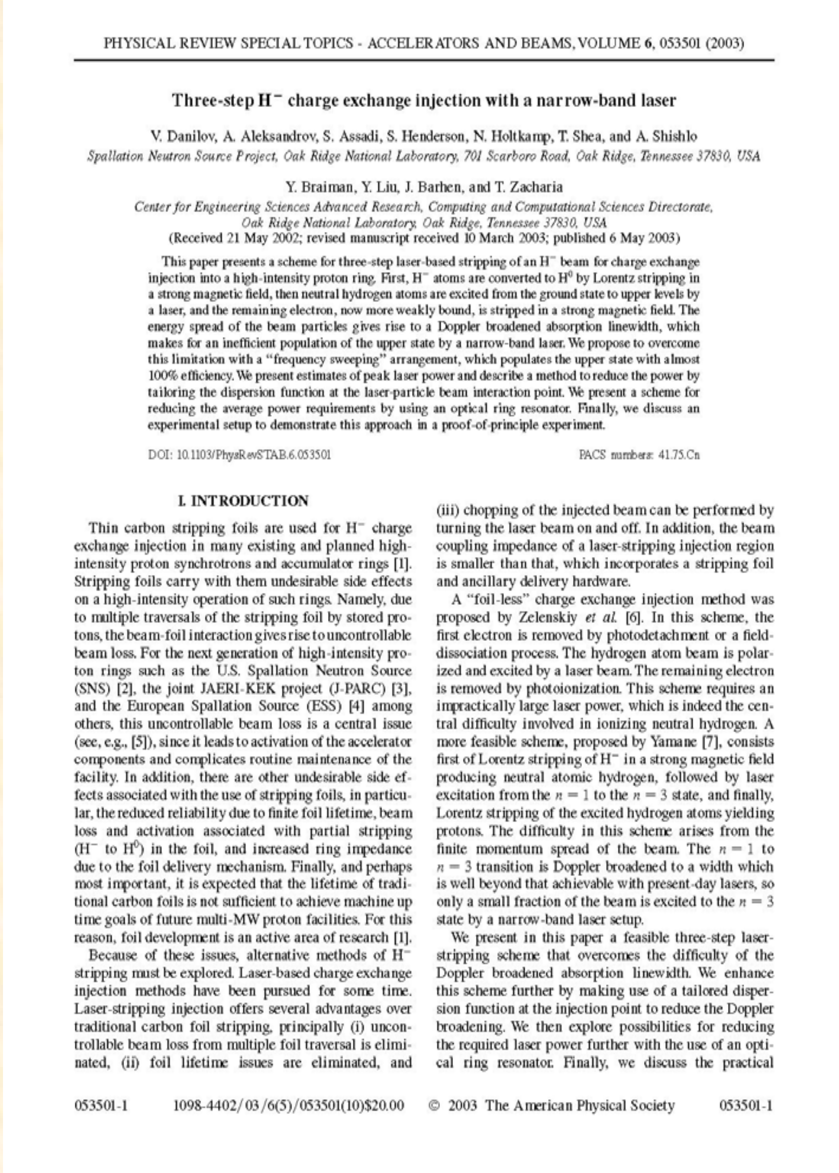
Accelerator Physics (SNS)

Laser Optics (ORNL)

Our team has developed a realistic method for high efficiency H^- laser stripping

S. Danilov, A. Aleksandrov, S. Assadi, S. Henderson, N. Holtkamp, T. Shea, and S. Shishlo (**SNS**), Y. Braiman, J. Barhen, Y. Liu, and T. Zacharia (**ORNL**) *A Novel Solution for H^- Laser Stripping*, ORNL Report No SNS – NOTE – AP – 48, (2002).

S. Danilov, A. Aleksandrov, S. Assadi, S. Henderson, N. Holtkamp, T. Shea, and S. Shishlo (**SNS**), Y. Braiman, J. Barhen, Y. Liu, and T. Zacharia (**ORNL**) *Three-step H- Charge Exchange Injection with a Narrow-band Laser*, Physical Review Special Topics – Accelerators and Beams **6**, 053501 (2003).



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **6**, 053501 (2003)

Three-step H^- charge exchange injection with a narrow-band laser

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(Received 21 May 2002; revised manuscript received 10 March 2003; published 6 May 2003)

This paper presents a scheme for three-step laser-based stripping of an H^- beam for charge exchange injection into a high-intensity proton ring. First, H^- atoms are converted to H^0 by Lorentz stripping in a strong magnetic field, then neutral hydrogen atoms are excited from the ground state to upper levels by a laser, and the remaining electron, now more weakly bound, is stripped in a strong magnetic field. The energy spread of the beam particles gives rise to a Doppler broadened absorption linewidth, which makes for an inefficient population of the upper state by a narrow-band laser. We propose to overcome this limitation with a "frequency sweeping" arrangement, which populates the upper state with almost 100% efficiency. We present estimates of peak laser power and describe a method to reduce the power by tailoring the dispersion function at the laser-particle beam interaction point. We present a scheme for reducing the average power requirements by using an optical ring resonator. Finally, we discuss an experimental setup to demonstrate this approach in a proof-of-principle experiment.

DOI: 10.1103/PhysRevSTAB.6.053501 PACS numbers: 41.75.Cn

I. INTRODUCTION

Thin carbon stripping foils are used for H^- charge exchange injection in many existing and planned high-intensity proton synchrotrons and accumulator rings [1]. Stripping foils carry with them undesirable side effects on a high-intensity operation of such rings. Namely, due to multiple traversals of the stripping foil by stored protons, the beam-foil interaction gives rise to uncontrollable beam loss. For the next generation of high-intensity proton rings such as the U.S. Spallation Neutron Source (SNS) [2], the joint JAERI-KEK project (J-PARC) [3], and the European Spallation Source (ESS) [4] among others, this uncontrollable beam loss is a central issue (see, e.g., [5]), since it leads to activation of the accelerator components and complicates routine maintenance of the facility. In addition, there are other undesirable side effects associated with the use of stripping foils, in particular, the reduced reliability due to finite foil lifetime, beam loss and activation associated with partial stripping (H^- to H^0) in the foil, and increased ring impedance due to the foil delivery mechanism. Finally, and perhaps most important, it is expected that the lifetime of traditional carbon foils is not sufficient to achieve machine up time goals of future multi-MW proton facilities. For this reason, foil development is an active area of research [1].

Because of these issues, alternative methods of H^- stripping must be explored. Laser-based charge exchange injection methods have been pursued for some time. Laser-stripping injection offers several advantages over traditional carbon foil stripping, principally (i) uncontrollable beam loss from multiple foil traversal is eliminated, (ii) foil lifetime issues are eliminated, and (iii) chopping of the injected beam can be performed by turning the laser beam on and off. In addition, the beam coupling impedance of a laser-stripping injection region is smaller than that, which incorporates a stripping foil and ancillary delivery hardware.

A "foil-less" charge exchange injection method was proposed by Zelenskiy *et al.* [6]. In this scheme, the first electron is removed by photodetachment or a field-dissociation process. The hydrogen atom beam is polarized and excited by a laser beam. The remaining electron is removed by photoionization. This scheme requires an impractically large laser power, which is indeed the central difficulty involved in ionizing neutral hydrogen. A more feasible scheme, proposed by Yamane [7], consists first of Lorentz stripping of H^- in a strong magnetic field producing neutral atomic hydrogen, followed by laser excitation from the $n = 1$ to the $n = 3$ state, and finally, Lorentz stripping of the excited hydrogen atoms yielding protons. The difficulty in this scheme arises from the finite momentum spread of the beam. The $n = 1$ to $n = 3$ transition is Doppler broadened to a width which is well beyond that achievable with present-day lasers, so only a small fraction of the beam is excited to the $n = 3$ state by a narrow-band laser setup.

We present in this paper a feasible three-step laser-stripping scheme that overcomes the difficulty of the Doppler broadened absorption linewidth. We enhance this scheme further by making use of a tailored dispersion function at the injection point to reduce the Doppler broadening. We then explore possibilities for reducing the required laser power further with the use of an optical ring resonator. Finally, we discuss the practical

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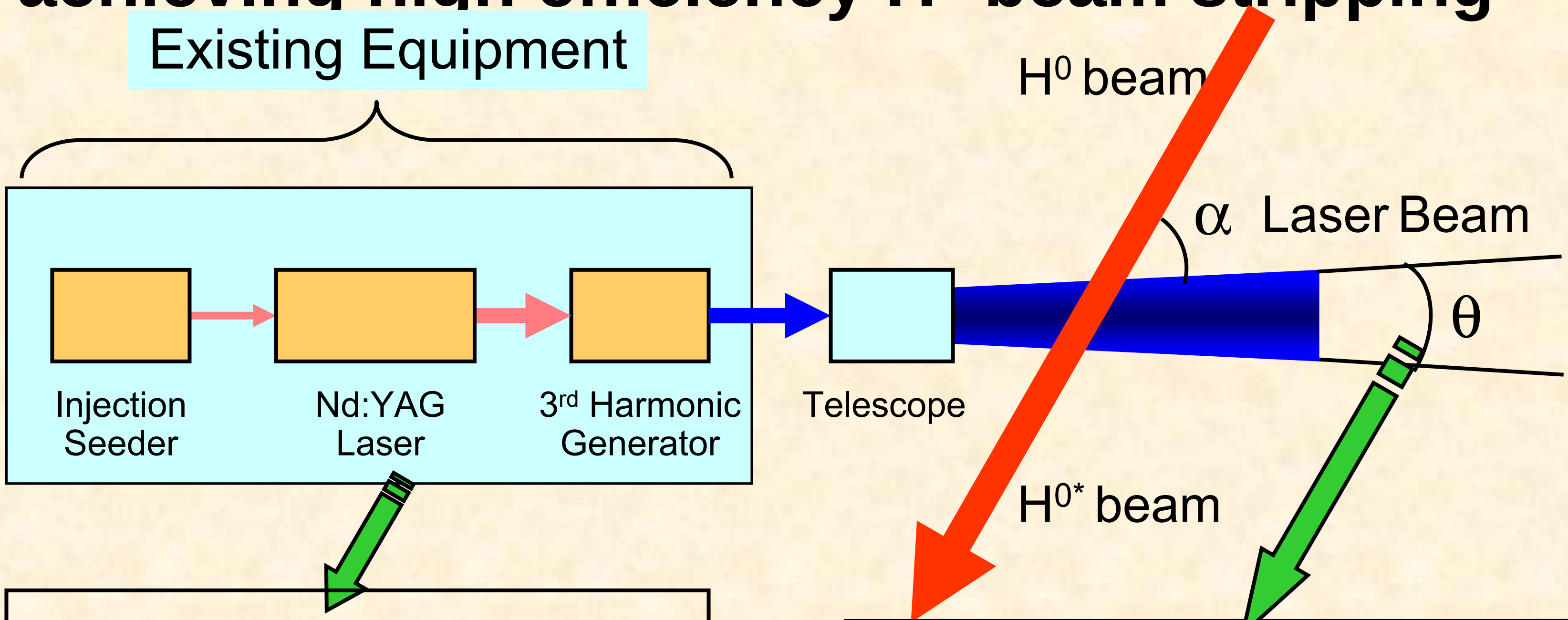
Proof-of-Principle Experiment: Laser Beam Design

- **Appropriate laser beam design is essential for achieving high efficiency H^0 beam stripping**



Optical Source:

Wavelength: 355 nm

Linewidth: < 100 MHz

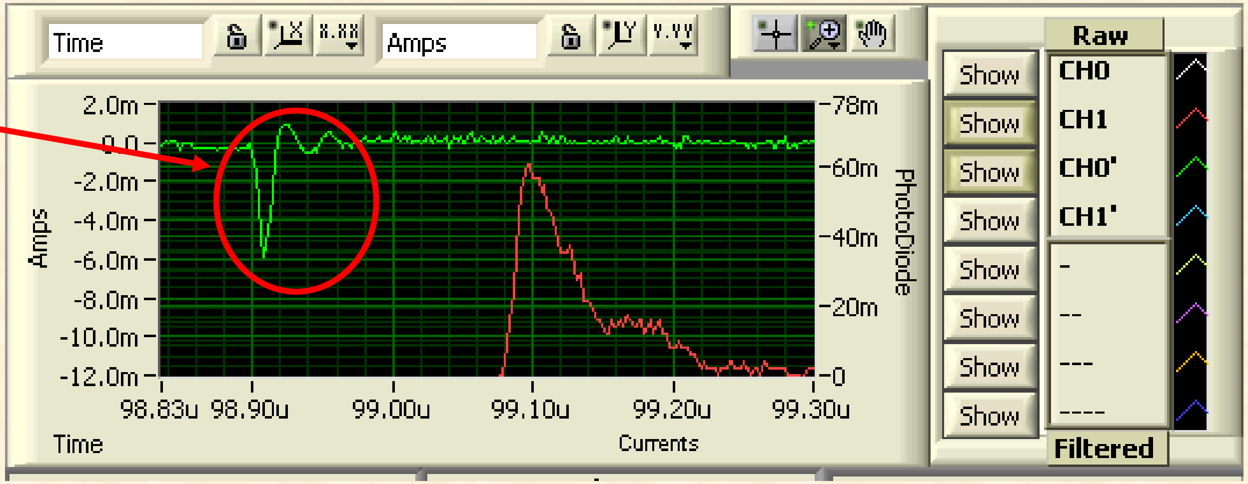
Pulse Energy at 355 nm: 150 mJ

A beam divergence angle of θ~2 mrad creates a frequency sweep range about 3 times the Doppler frequency spread

Laser Stripping Experiment:

- **Characterizing full stripping with Magnet on will continue in May after vacuum chamber is repaired.**
- **We observed about 50% of double stripping (H- to p+) on the first try. We will do further optimization to obtain higher efficiency but the concept is proven.**

Negative Notch:
$H^- \rightarrow H^+$



Conclusion:

1) Successful test of the SNS Laser Profile Monitor is demonstrated.

2) Direct collection of the electrons allows us to measure the profiles to 3 sigma and beyond.

3) Modeling has shown the laser beam jitter is not a problem.

4) Vibration (Mechanical or drifts) are non-issue.

5) Temporal Profile Measurement using mode-lock laser is possible but we need to make it automated and beyond R&D.

6) Third Harmonic of Nd:YAG laser for the laser stripping studies was implemented successfully.

7) Laser Stripping proof of principle R&D has been a success.