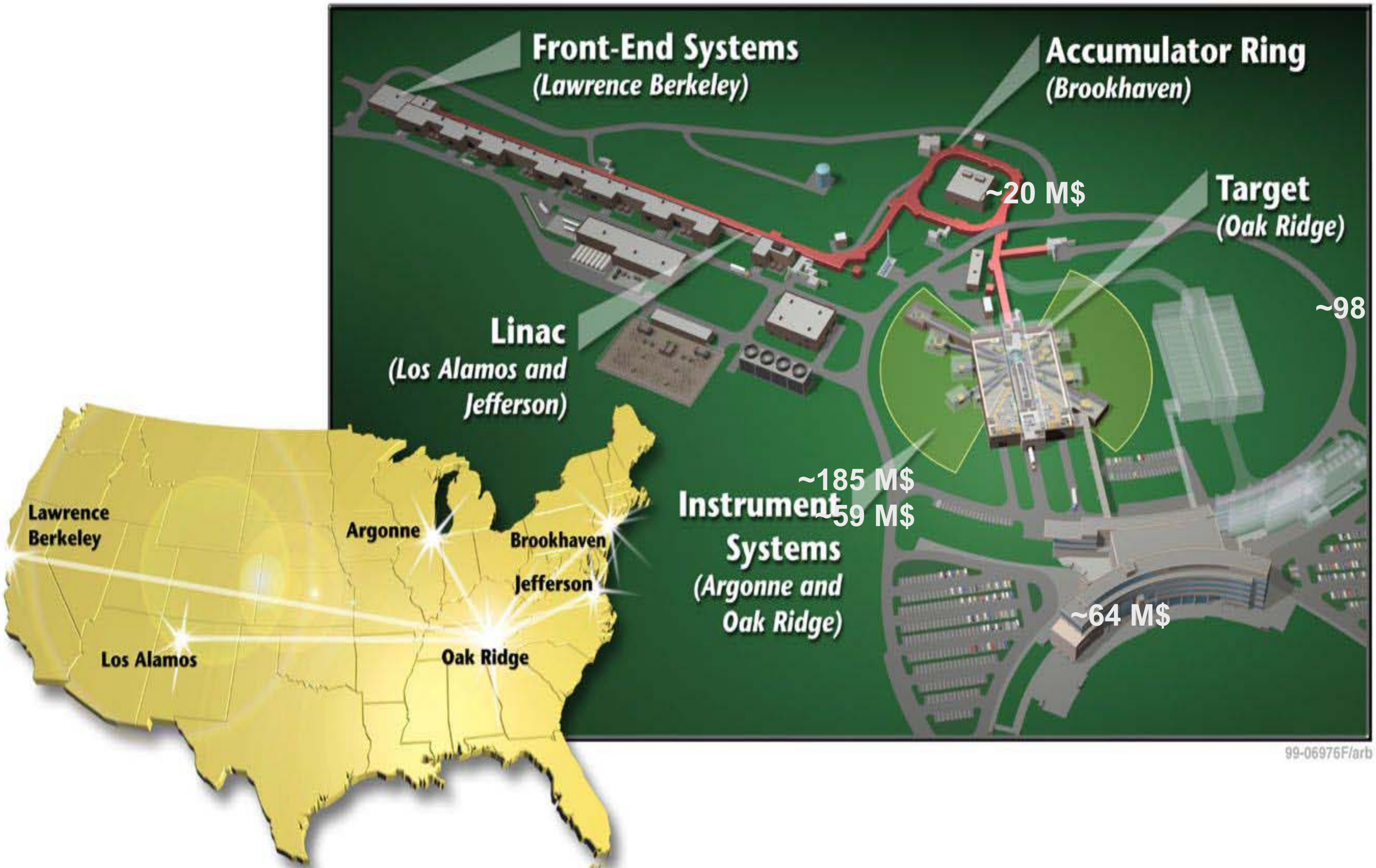
Laser profile monitors implementation at SNS and laser stripping R&D for the future high power upgrade

Saeed Assadi

ORNL-SNS Diagnostic Group

May 18, 2004

The Spallation Neutron Source Partnership



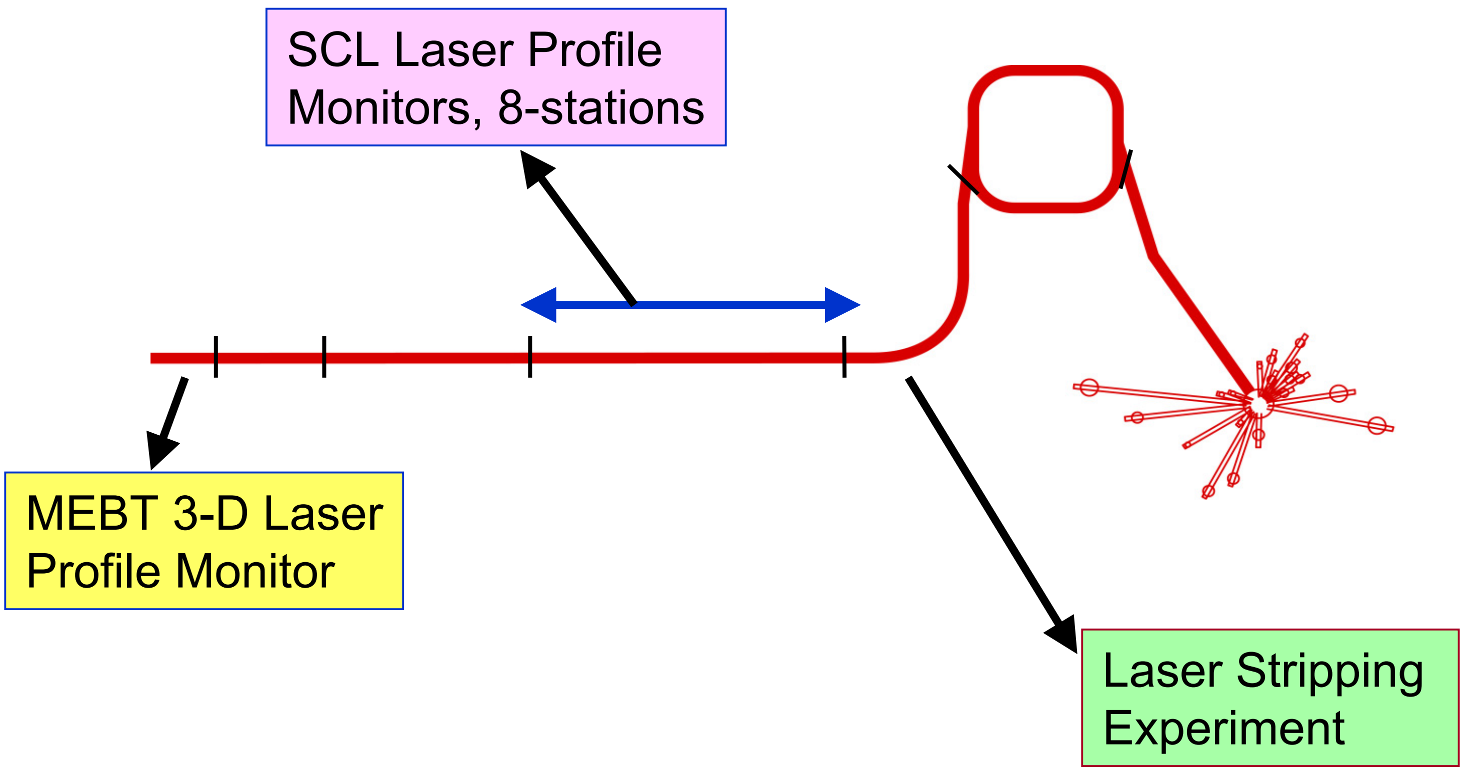
~500 People work on the construction of the SNS accelerator

Oak Ridge, Tennessee

35° 49' N , 83° 59' W

ORNL-SNS Laser Diagnostic Activities

1) MEBT Mode-lock laser initially in 1-D – 9/2004
2) SCL Nd:YAG 1064 nm Laser, 8-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

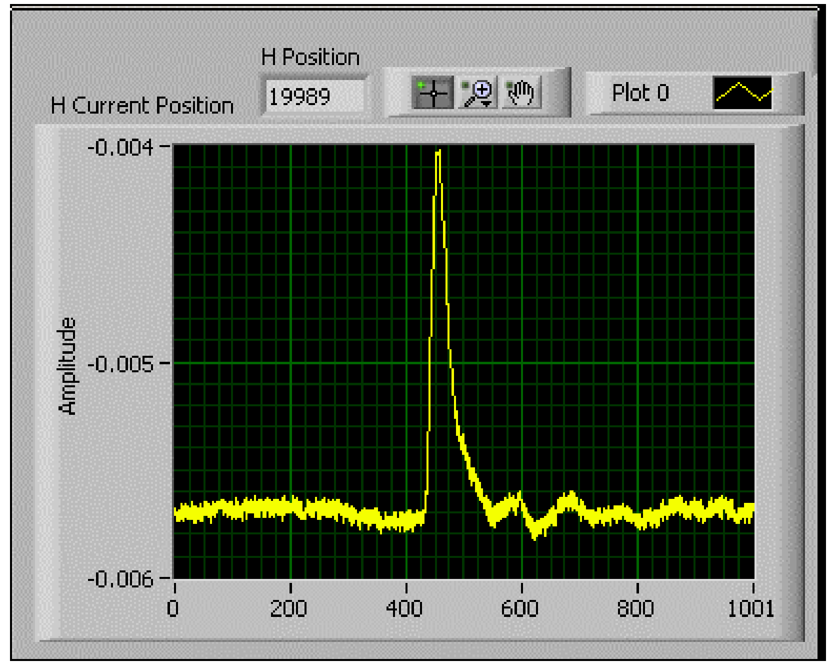
“We know how to do it, and we know how to do it well” – Anonymous

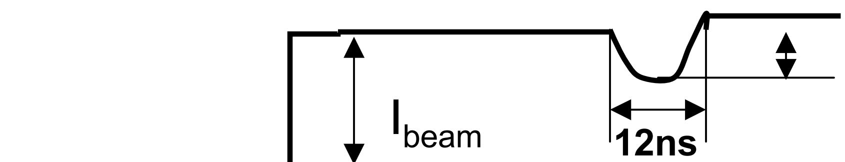
What does the Laser do? Photo-neutralization

$h\nu$ H^- → $H^0 + e$

Requirements

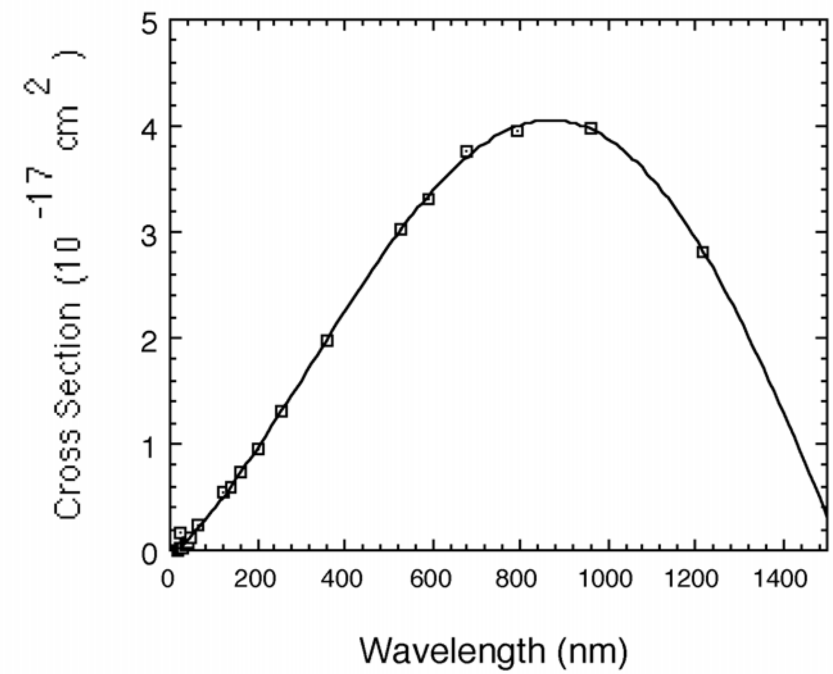
- *High peak power*
- *Small spot size*
- *Transverse scan*
- *Temporal stability*
- *Detection*

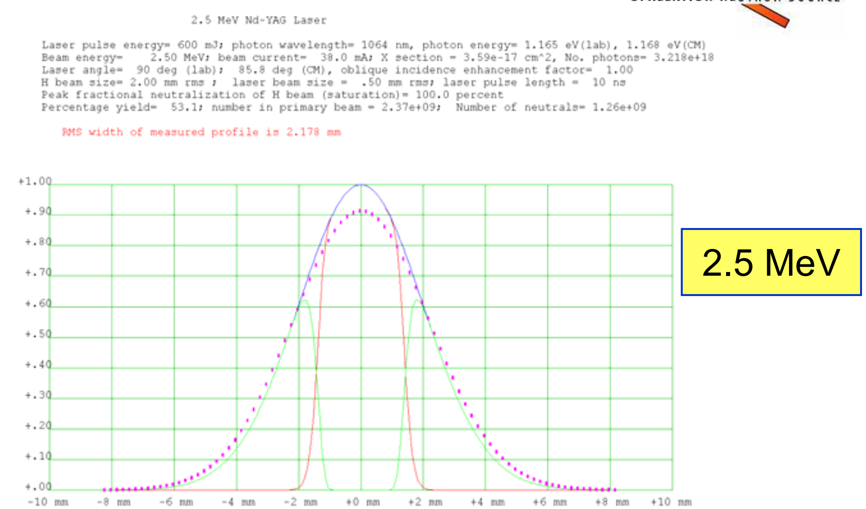


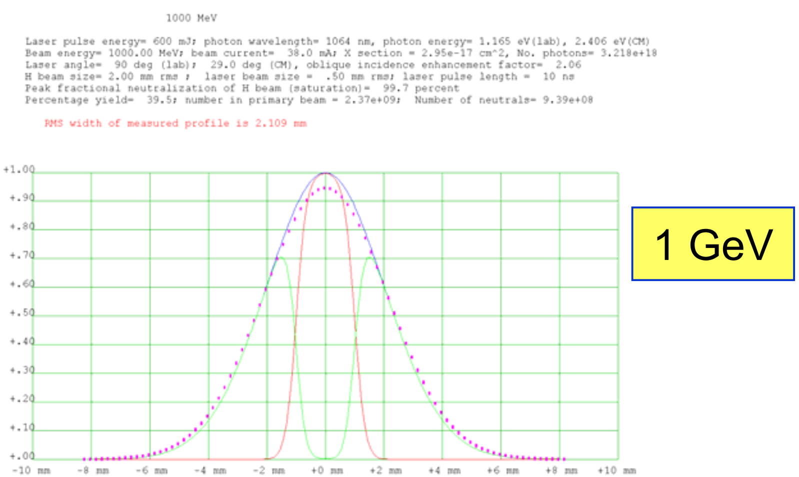


Cross-section is well known therefore stripping efficiency calculation is a matter of algebraic manipulation (tech. notes)

Laser Photo neutralization cross section







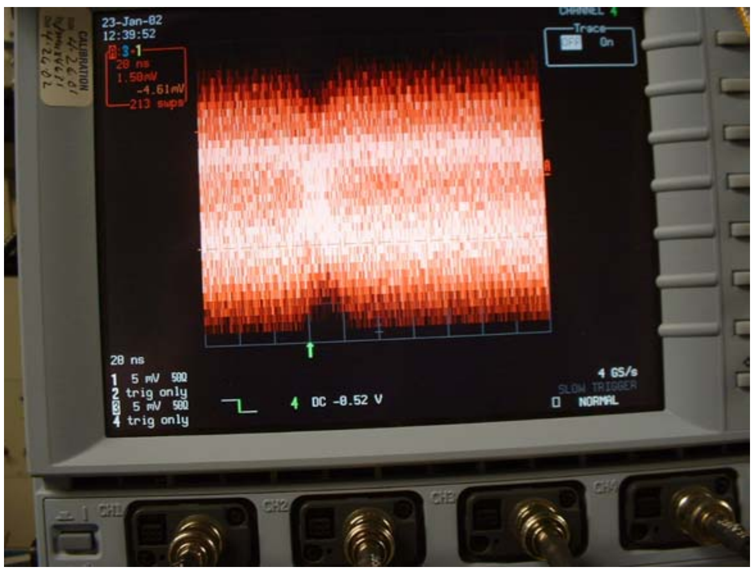
Calculated cross section for H- photoneutralization as a function of photon wavelength.*

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

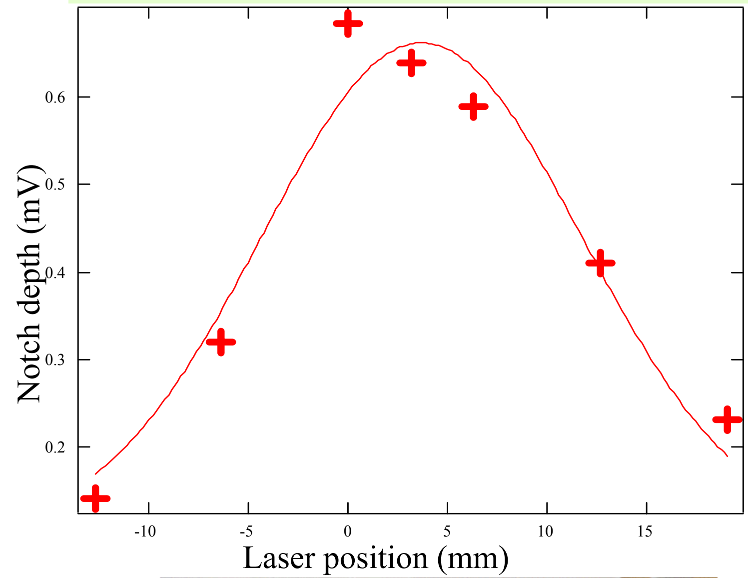
*J.T. Broad and W.P. Reinhardt, Phys. Rev. A14 (6) (1976) 2159.

Initial Laser Monitor Development at BNL: Laser "notch" in stripline signal

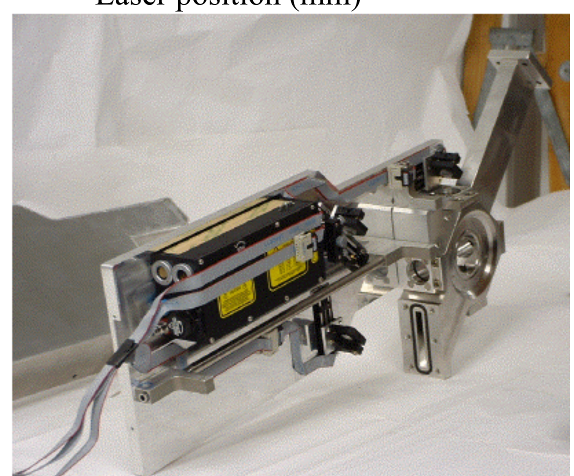
Scope was set on infinite persistance for several hundred beam pulses. This is difference signal at 400 MHz from upstream and downstream BPMs.



Laser Wire Profile with 100uA 200MeV Polarized Beam



200 mJ Q-switch Nd:YAG Laser



May 18, 2004

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

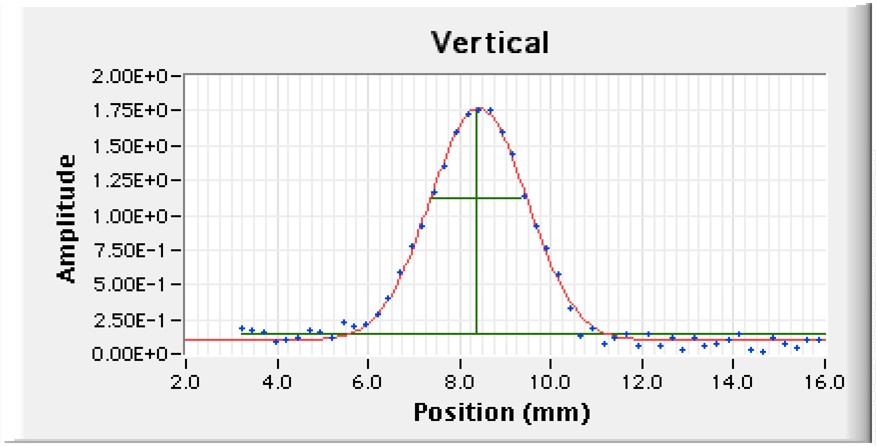
- Minimal impact on normal operation
- Virtually no impact on SRF cavities or vacuum
- Low signal to noise ratio on differential current measurements but excellent s/n using electron collector.
- No parts inside the vacuum
- Radiation hard @ λ<1500nm

Multi National-Lab Diagnostic Collaborators

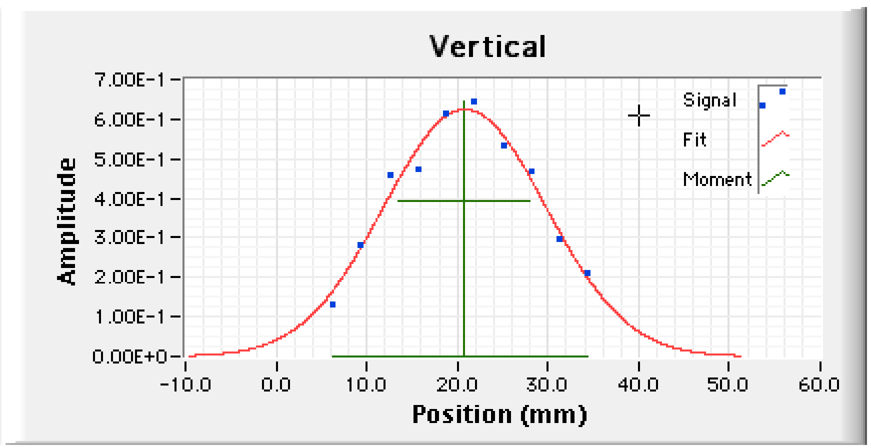
ORNL	**Tom Shea, Sasha Aleksandrov, Saeed Assadi, Willem Blokland, Craig Deibele, Warren Grice, Dave Purcell**
BNL	**Peter Cameron, Roger Connolly, Craig Dawson, Chris Degen, Sheng Peng, Marty Kesselman, Bob Sikora,**
LANL	**Mike Plum, John Power, Bob Shafer, Jim Stovall**
LBL	**Larry Doolittle, Darryl Oshatz, Alex Ratti**
SLAC	**Joe Frisch , Keith Jobe, Marc Ross,**
FNAL	**Jim Crisp, Bob Webber**

Proof of Principle – Requirement set by the SNS management

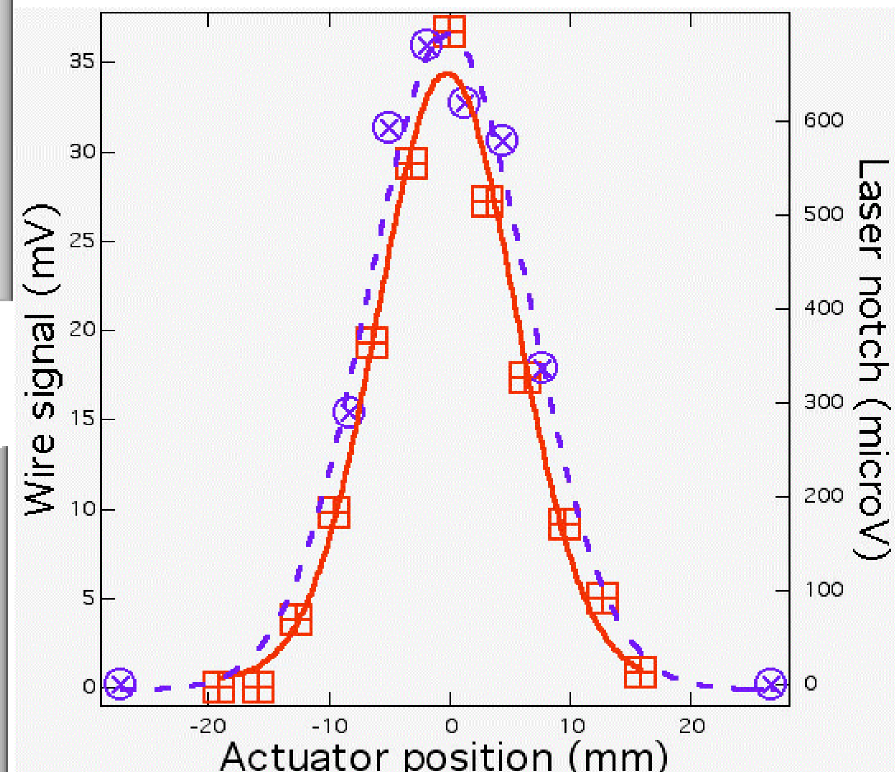
Software: Wim Blokland



Profile from the 2.5 MeV MEBT at Berkeley



Profile from the BNL 200MeV LINAC



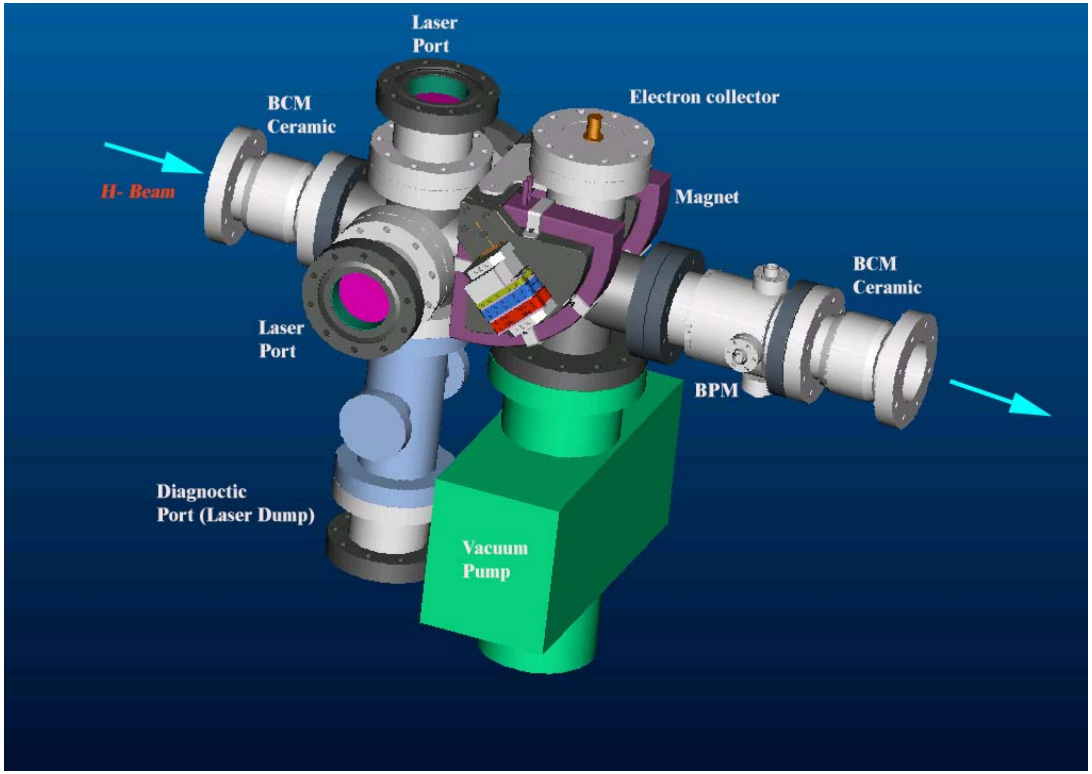
Comparison of Laser-wire and Carbon-wire data at BNL 200 MeV line

Courtesy of Roger Connolly

ORNL Laser Profile Monitor Design Team

Alignment: Joe Error
Data acquisition and analysis: Wim Blokland
Electron Collector: Craig Deibele
Electronics: James Pogge
Installation: Dave Purcell, Anthony Webster
Mechanical Design Team: Graeme Murdoch, Dan Stout, Arnold DeCarlo , James Kelly, Bonnie Lane, Kerry Potter (GL), Tom Roseberry (Design Engineer)
Mechanical Design Advisory Team: Peter Ladd, Mike Hechler, Paul Gibson.
Magnet design: Ted Hunter
Optics: Warren Grice
Physics: Sasha Aleksandrov
Project Lead: Saeed Assadi

Direct measurement of the liberated electrons via the electron detector

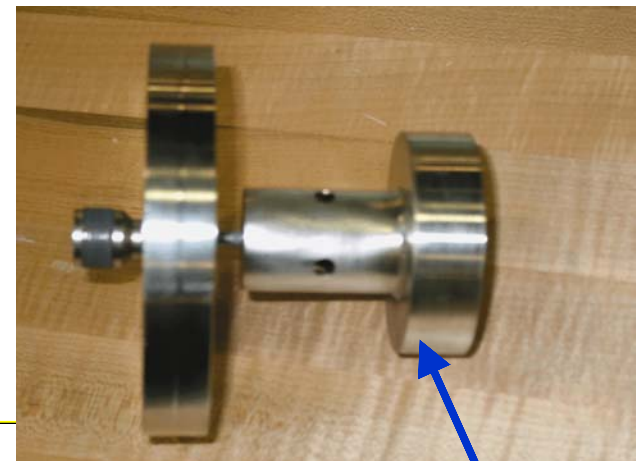


Advantages:

- large number of electrons
- charge integrating amplifier similar to BL
- 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 backgroun



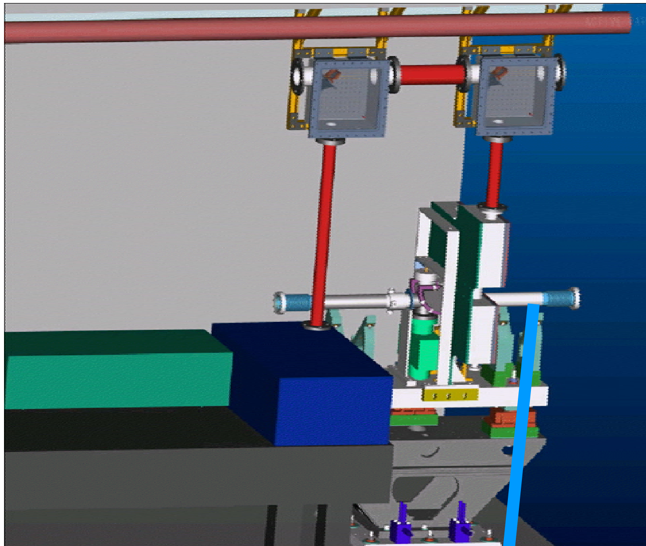
Electron Collector
C. Deibele

Required Magnetic Field

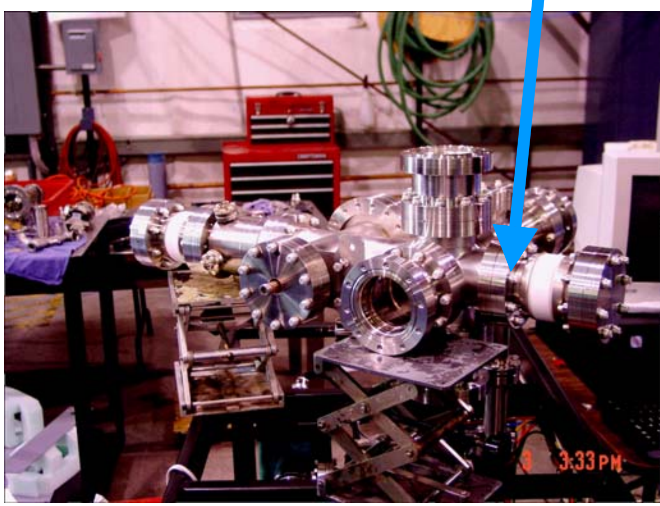
Table1.

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

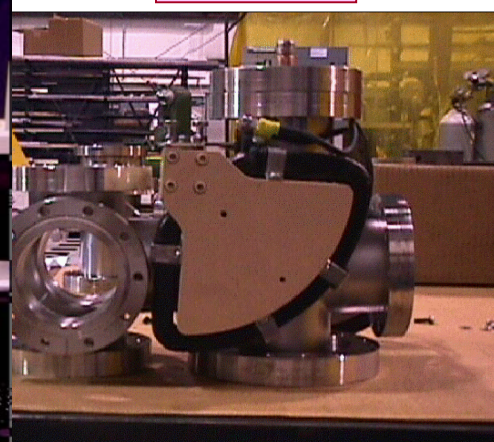
SCL Laser Profile Monitor – Tests on MEBT



Courtesy of the ORNL Mechanical Group.



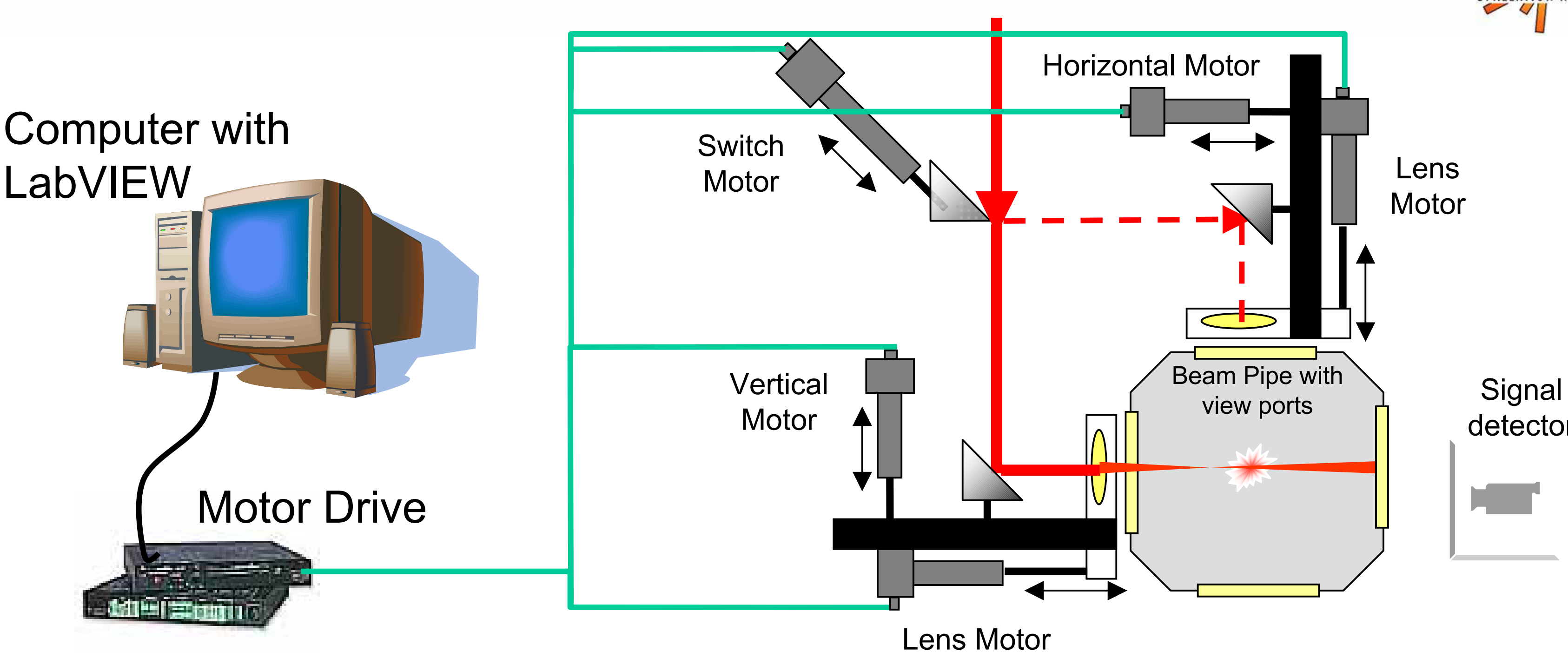
Magnet



Prototype Station on MEBT

Courtesy of Ted Hunter (Magnet GL)

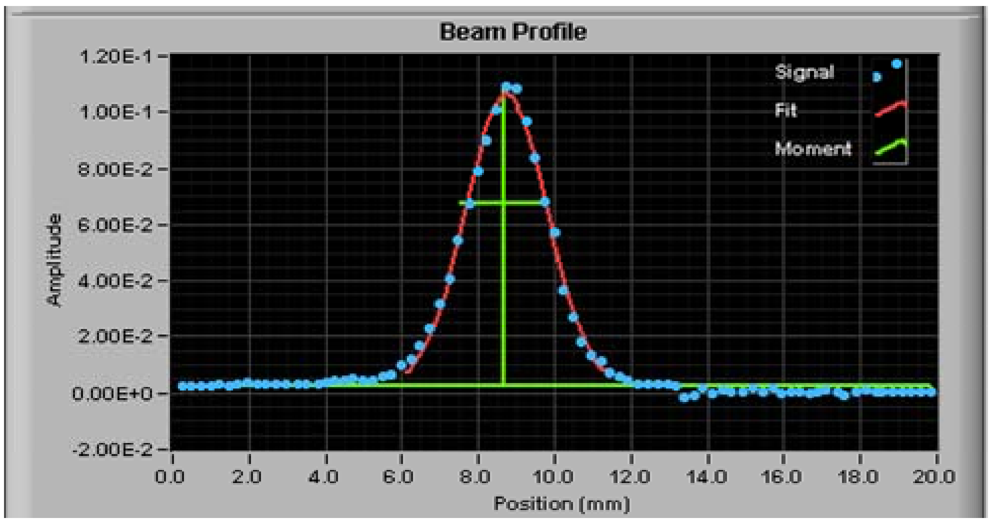
Laser-wire Actuator System



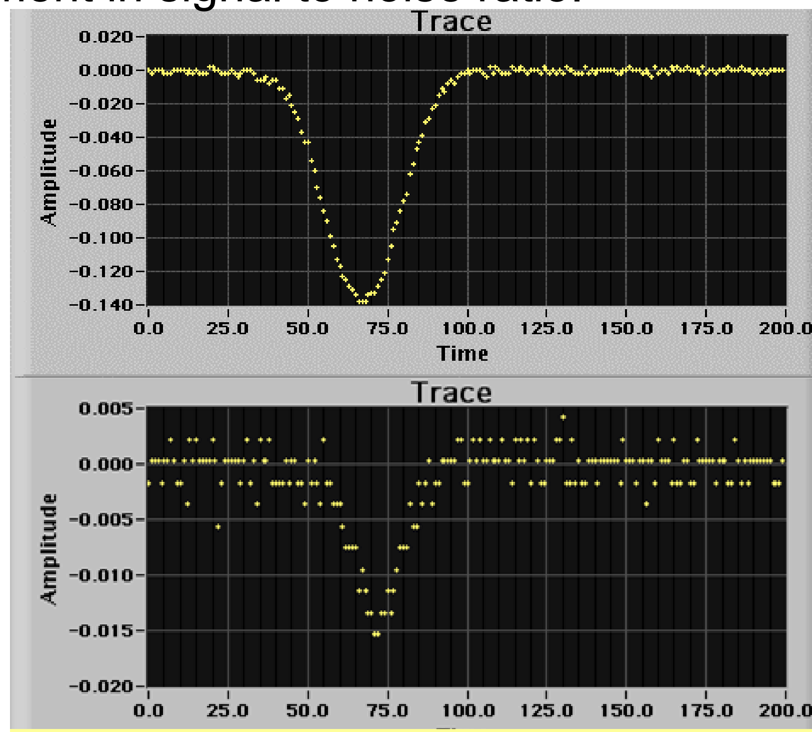
- A rack mounted 2U high PC (Desktop for test)
- NI PCI-7334 motion controller (inside PC) (x2 depending on switch mirror)
- PCI digitizer card (inside PC) (TDS 7404 for test)
- PCI Timing card (inside PC)
- NI MID-7604 4 axis stepper motor driver (1U drive) (x2)
- 4 Ultramotion HT17-075 radiation hard actuators with built-in potentiometer

Laser Profile Monitor Progress Report

- Verification of electron collector for SCL laser profile monitor
- Reliable measurements to about **3 sigma**
- Anti-reflection coating has been applied to the final windows.
- We expect an order of magnitude improvement in signal to noise ratio.



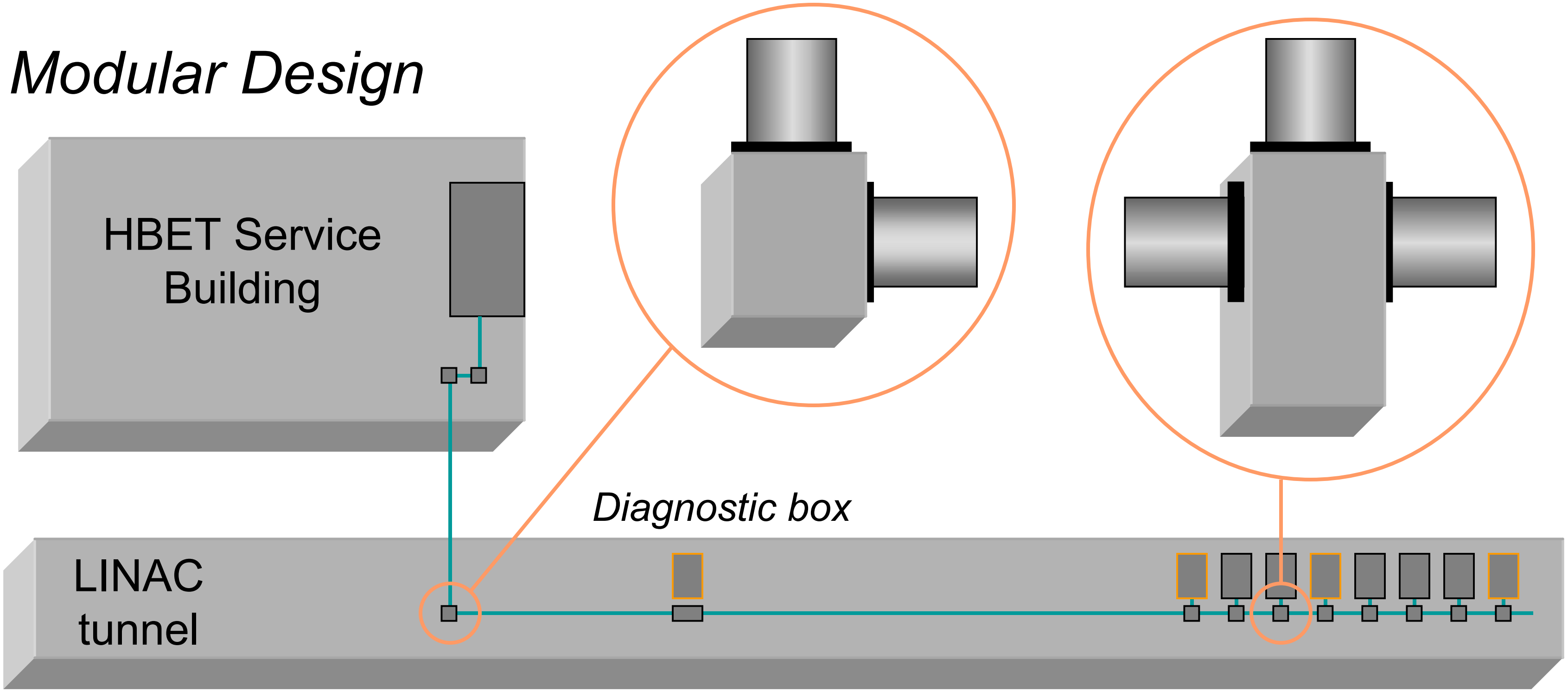
Horizontal Profile
1/25/2003 13:06
Gaussian fit plotted out to 2.5x Sigma
Sigma = 1.07 mm



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

Transport Line

Modular Design



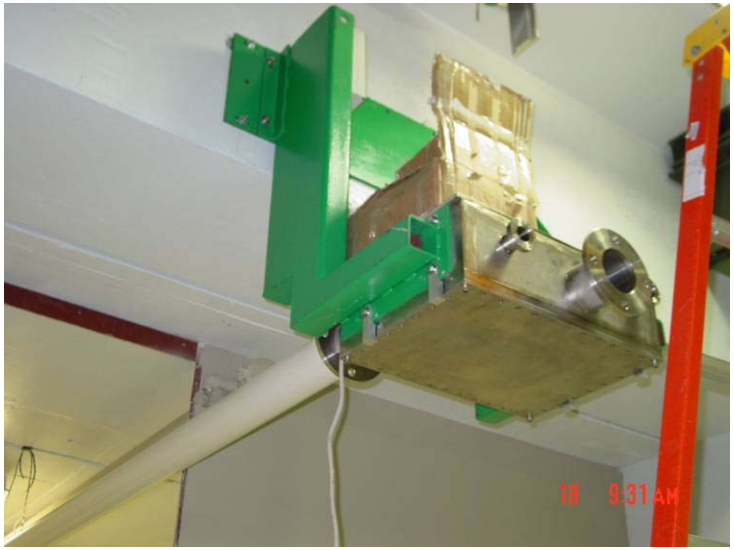
- *Boxes secured to building walls, ceilings, etc.*
- *Designed to accept a variety of optical components*
- *Cable feedthroughs*
- *Pipes mounted between boxes*

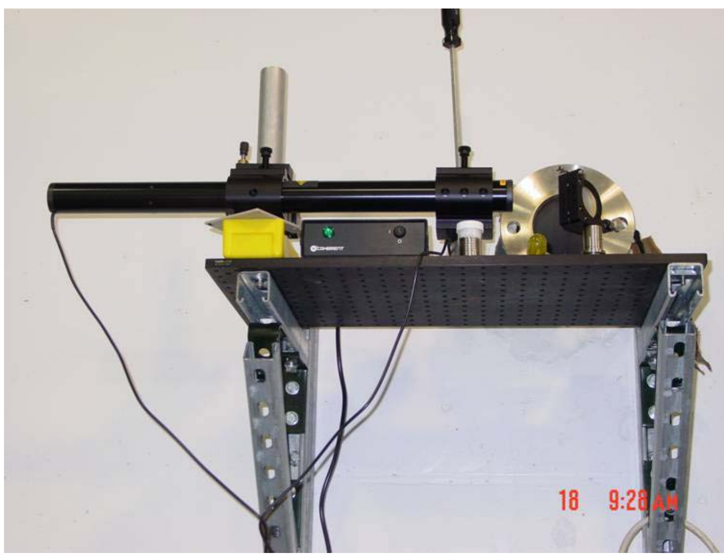
4 LW from 186 MeV,

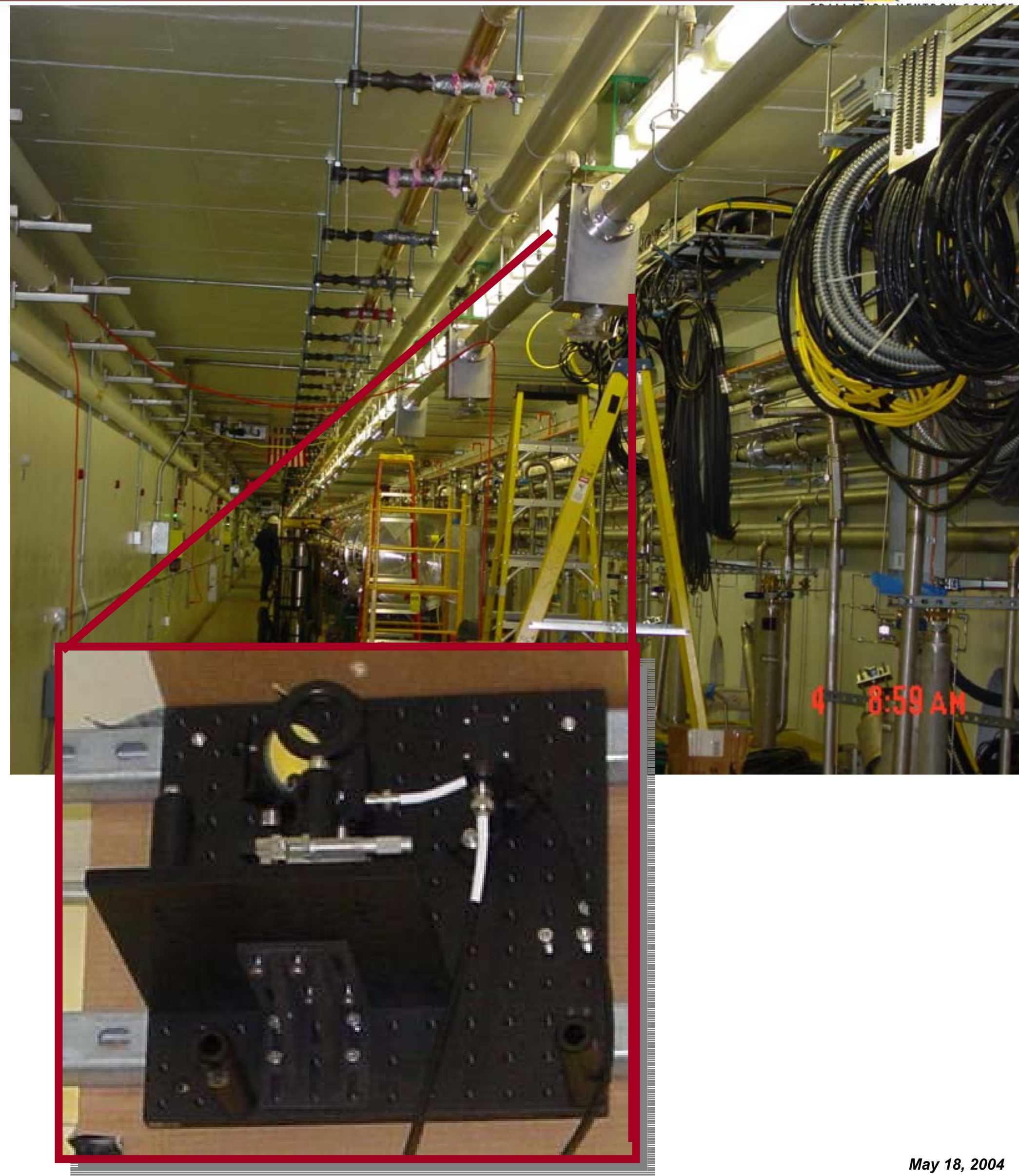
4 LW from 386 MeV

Laser Wires Locations

SCL Laser Transport-line Installation:

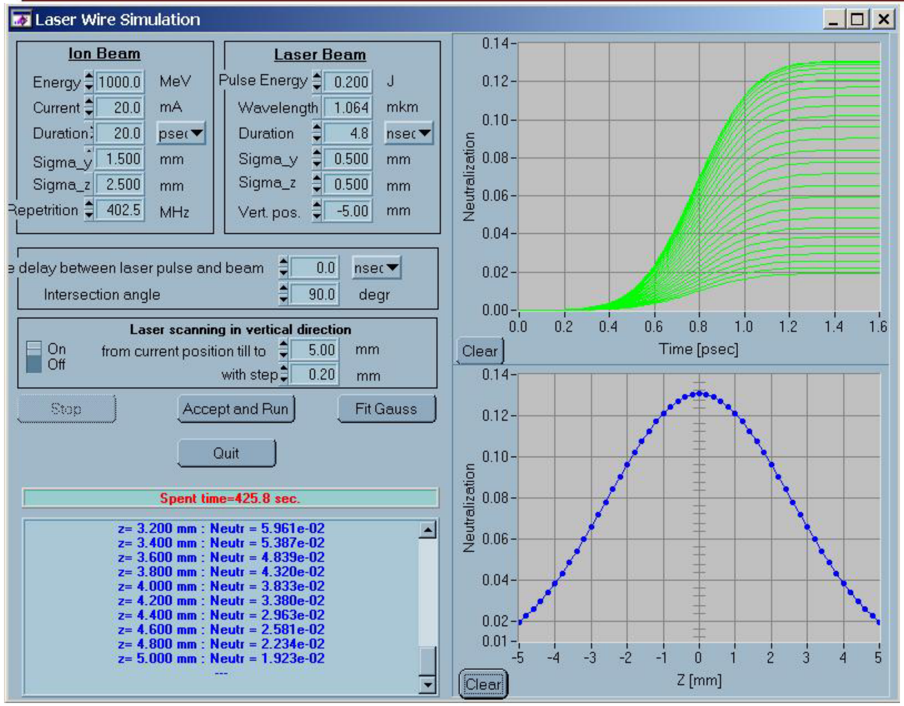






May 18, 2004

Modeling and jitter analysis guides our design

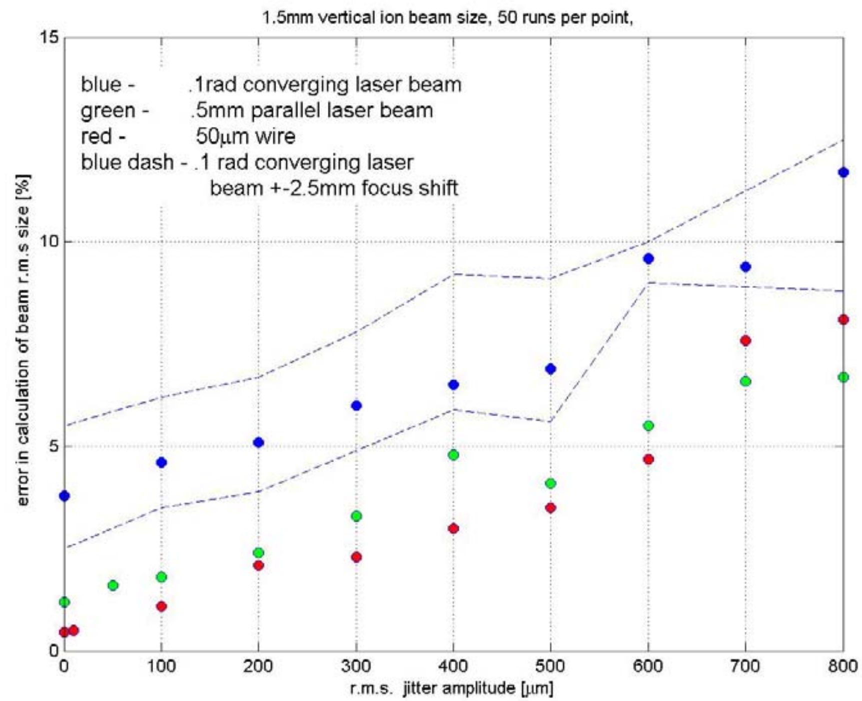


Models being developed by Sasha Aleksandrov and Victor Alexandrov from BINP

branch at Protvino

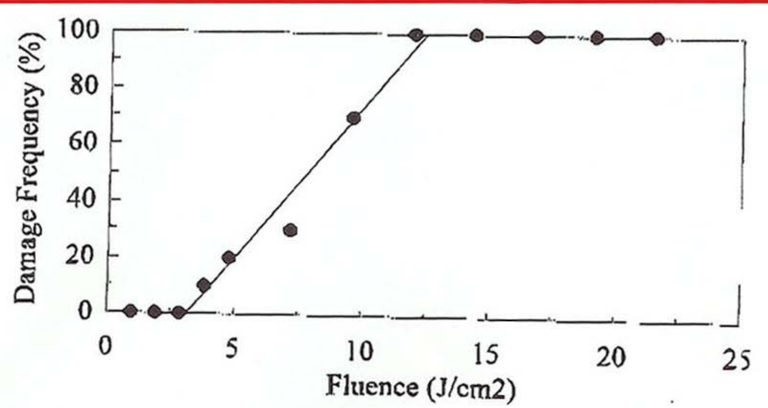
Dependence of error upon jitter amplitude for:

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



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

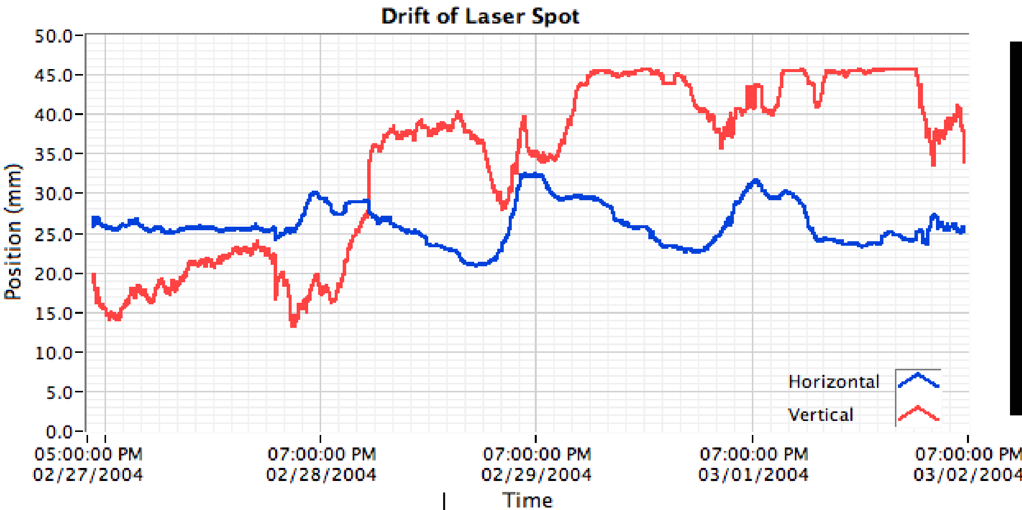
1.5 million pulses at 44 times the required power did not show any damage to the coating or the window at our laser lab.

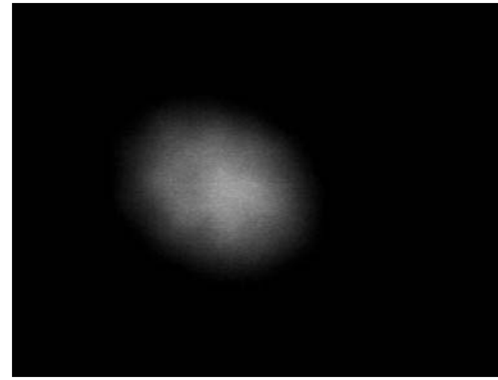


J/cm2	MW/cm2	%Fail
21.5	979	100
19.1	870	100
16.7	761	100
14.4	652	100
12	544	100
9.57	435	70
7.18	326	30
4.78	217	20
3.83	174	10
2.87	130	0
1.91	87	0
0.96	43.5	0

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.

Laser Beam Vibration Studies

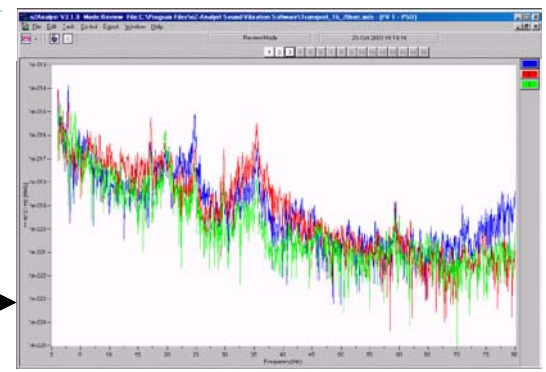




Green CW Laser spot at 500 ft in The tunnel

Slow Laser drift over 4 days

Mechanical Vibration of the optics box (Power Spectrum, 3Hz,25Hz)

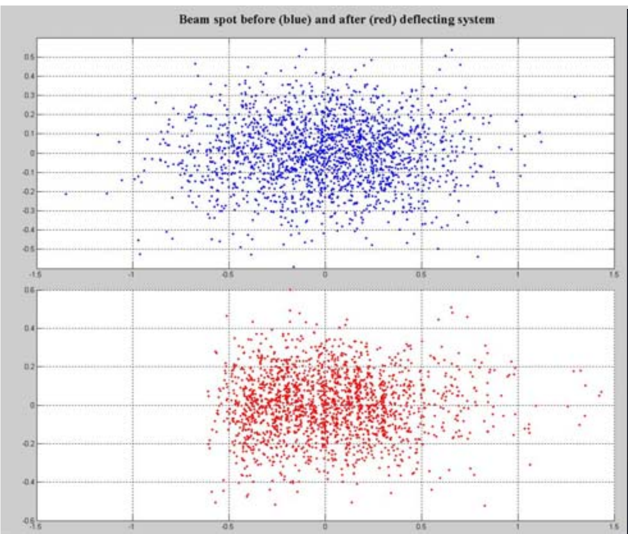


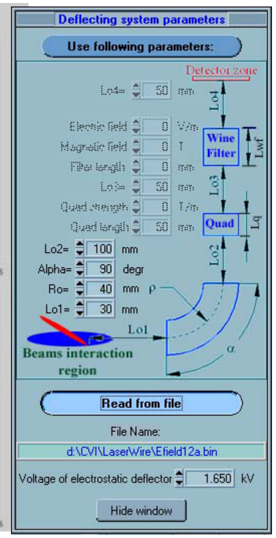
1) Vibration studies at 500 feet from the laser room entrance to the tunnel.
2) HeNe and CW Yag Lasers are used for 100 hours.
3) The worst case is 10 mm (50% beam diameter) drift over 24 hours.
4) Drift is very slow. High frequency vibration is not observable with the present setup. Accelerometer shows only 3 Hz and 25 Hz (.2 micron at source).

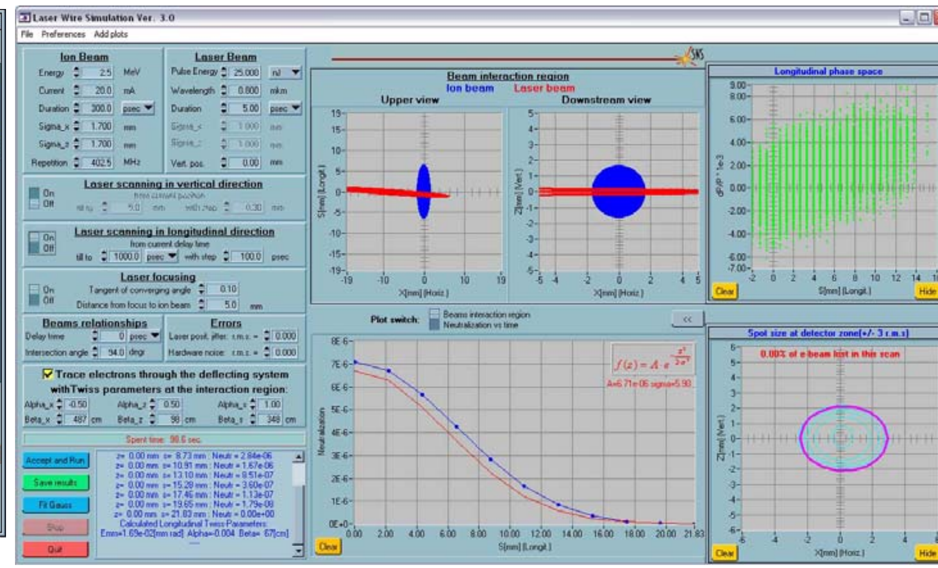
Laser System-- 3-D Bunch Measurement

Response to May 2003 DOE Review

- Mode-locked Ti-Sapphire laser on order. [purchased from cost savings of magnets, beam boxes, power supplies.]





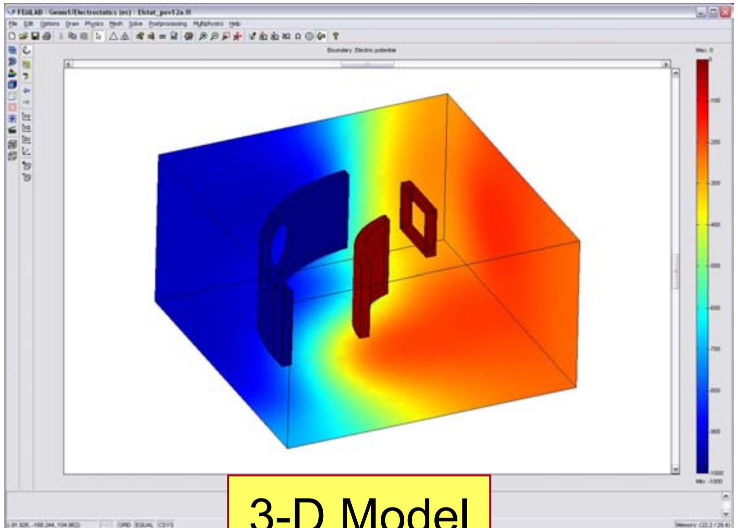


Initial tests planned for MEBT will commence in Sept-04, longitudinal plane only.

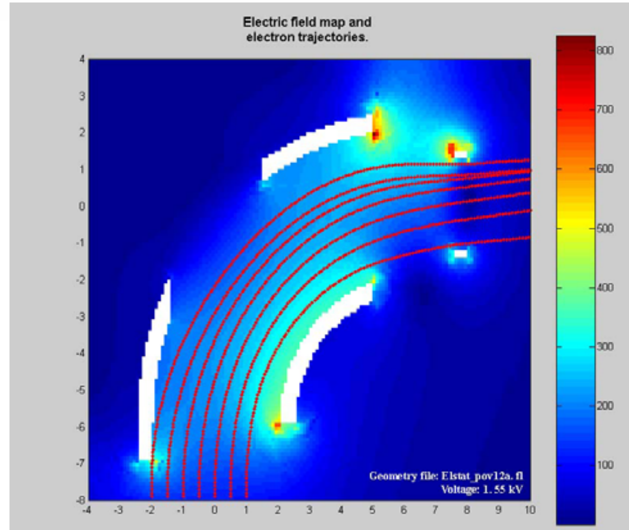
Complete system simulation – beam/laser interaction, electron transport

Laser System-- 3-D Bunch Measurement

SNS SPALLATION NEUTRON SOURCE

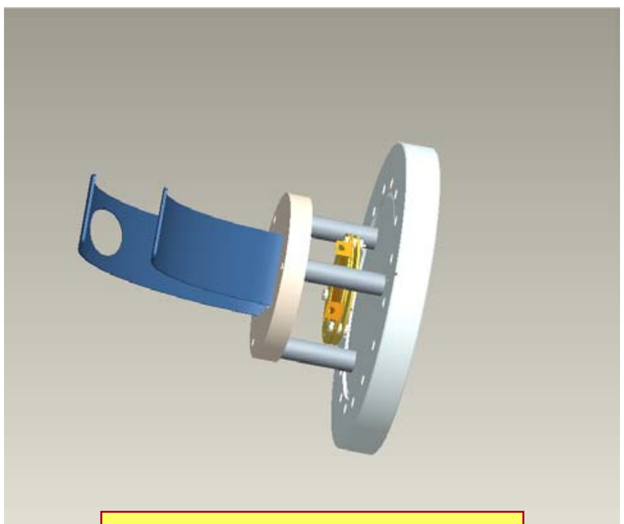


3-D Model

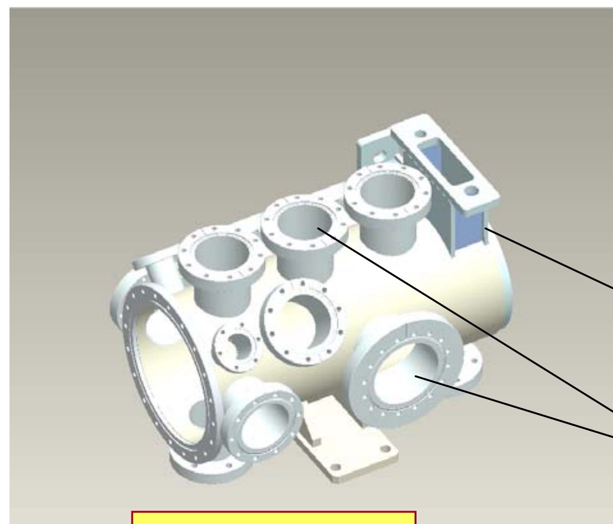


Electron trajectory

Modeling:
Victor Alexandrov



Electron Deflector



New D-Box

Design Engineer:
Tom Roseberry

Harp Port

Laser Port

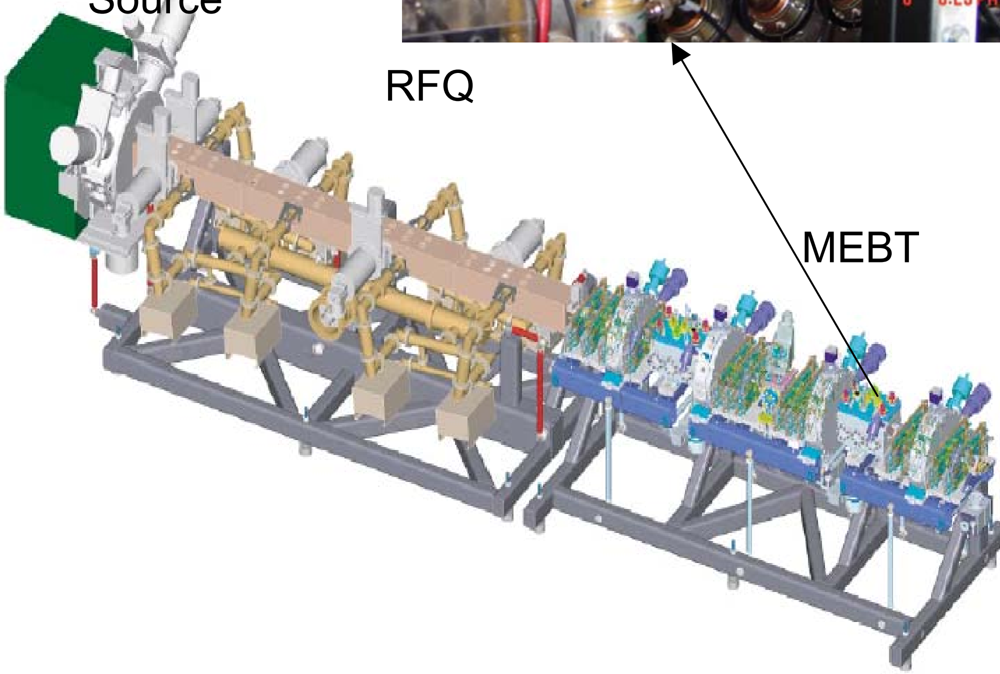
2.5 MeV Mode-lock Laser Setup

Present D-Box

Ion Source

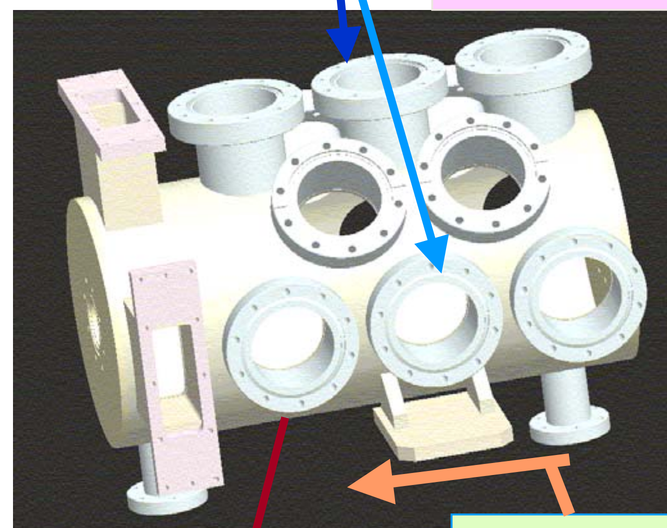
RFQ

MEBT



Laser Ports

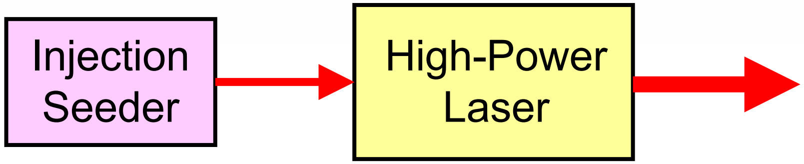
New D-Box



Collector Port

Beam Direction

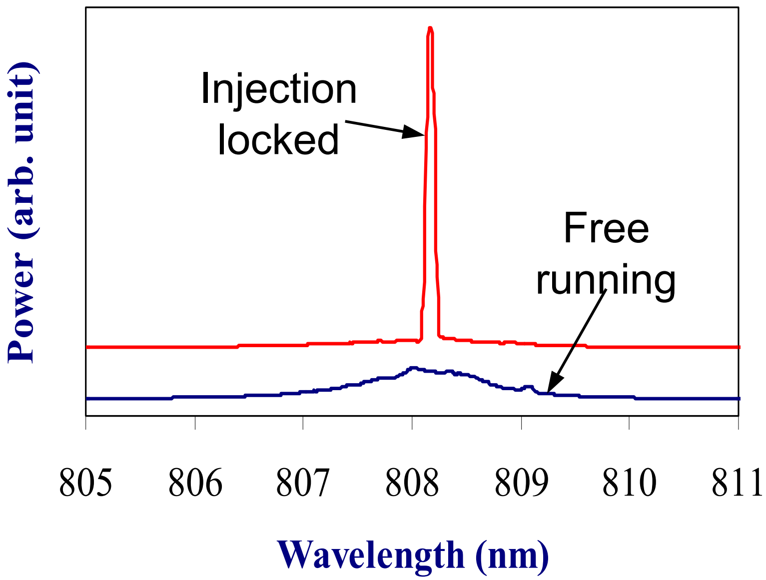
Demonstration of High Quality Laser Beam in CESAR/ORNL Optics Laboratory

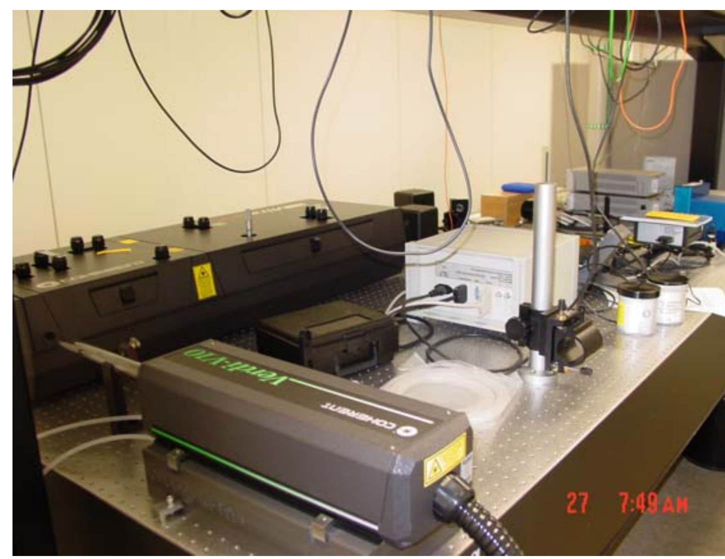


Optical Injection Locking

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).





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

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

V. Danilov, A. Aleksandrov, S. Assadi, S. Henderson, N. Holtkamp, T. Shea, and A. Shishlo
Spallation Neutron Source Project, Oak Ridge National Laboratory, 701 Scarboro Road, Oak Ridge, Tennessee 37830, USA

Y. Braiman, Y. Liu, J. Barhen, and T. Zacharia
Center for Engineering Sciences Advanced Research, Computing and Computational Sciences Directorate, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA
(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].

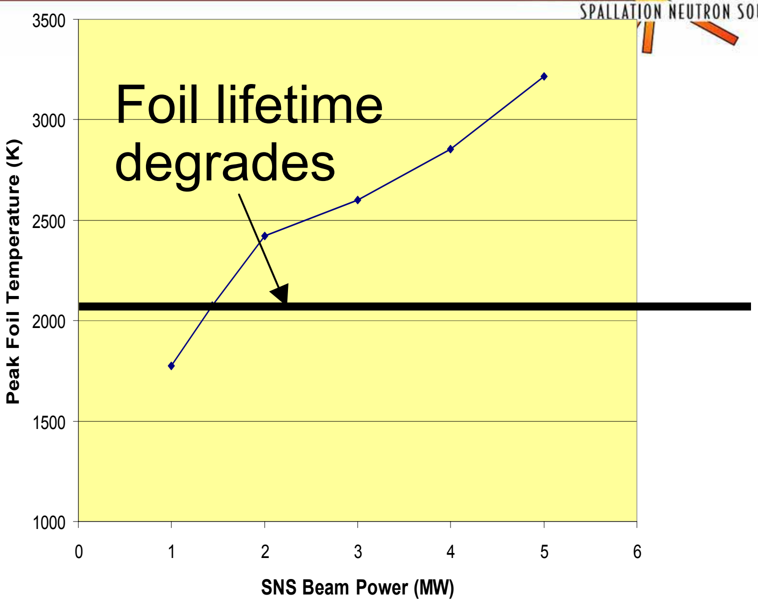
Because of these issues, alternative methods of H^- stripping must be explored. Laser-based charge exchange injection methods have been pursued for some time. Laser-stripping injection offers several advantages over traditional carbon foil stripping, principally (i) uncontrollable beam loss from multiple 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.

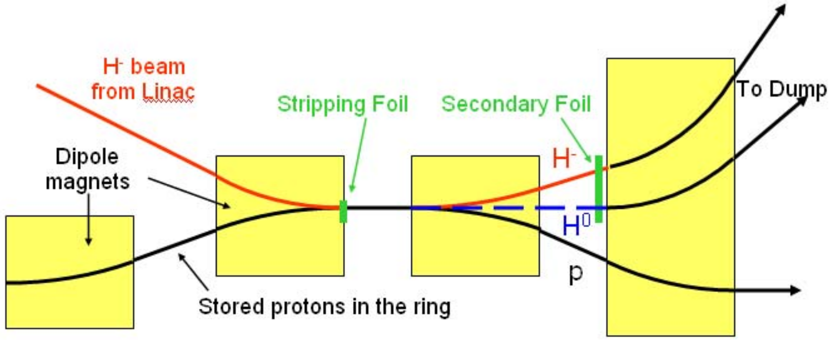
A "foil-less" charge exchange injection method was proposed by Zelenskiy *et al.* [6]. In this scheme, the first electron is removed by photodetachment or a field-dissociation process. The hydrogen atom beam is polarized and excited by a laser beam. The remaining electron is removed by photoionization. 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

Stripping Foil Limitations

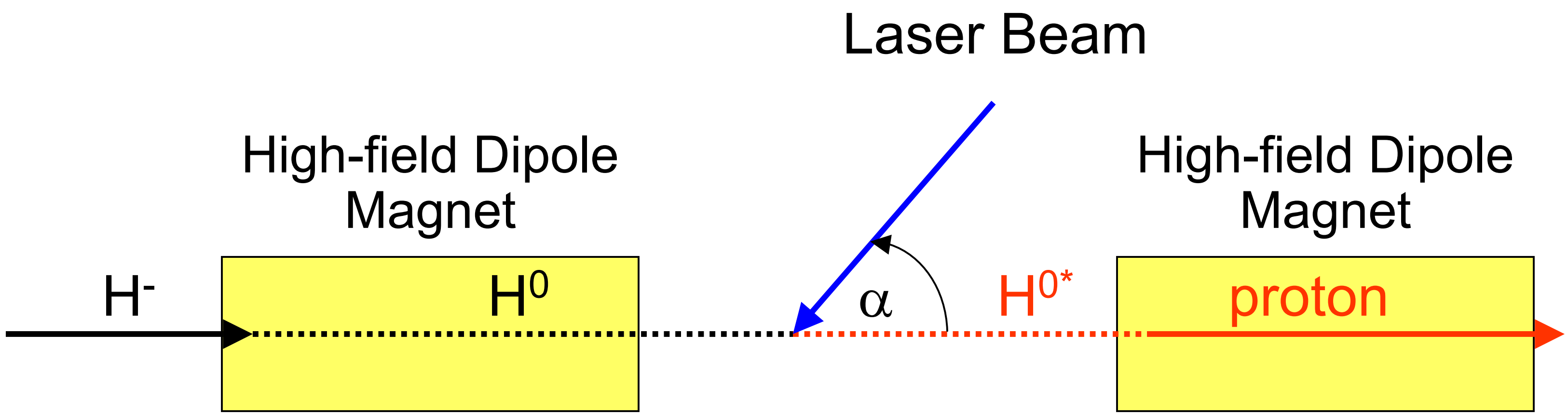
- The SNS will use 300-400 μg/cm² Carbon or Diamond foils
- Three important limitations:
  1. Foil Lifetime: tests show rapid degradation of carbon foil lifetime above 2500 K, yet we require lifetime > 100 hours
  2. Uncontrolled beam loss: Each proton captured in the ring passes through foil 6-10 times: leads to uncontrolled loss of protons
  3. Stripping inefficiency: leads to further beamloss, residual activation and wasted beam power





Three-Step Stripping Scheme

Our team developed a novel approach for laser-stripping which uses a three-step method employing a narrowband laser [V. Danilov et. al., Physical Review Special topics – Accelerators and Beams 6, 053501]



Step 1: Lorentz Stripping

$H^- \rightarrow H^0 + e^-$

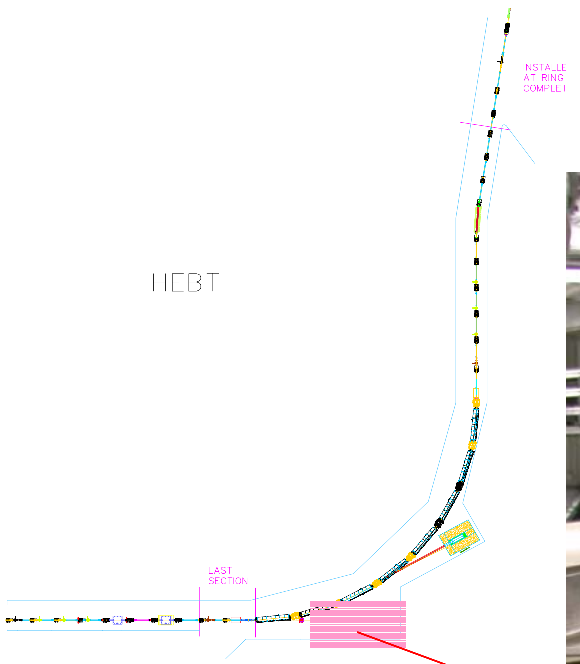
Step 2: Laser Excitation

$H^0 \ (n=1) + \gamma \rightarrow H^{0*} \ (n=3)$

Step 3: Lorentz Stripping

$H^{0*} \rightarrow p + e^-$

Laser Stripping Proof of Principle Experiment

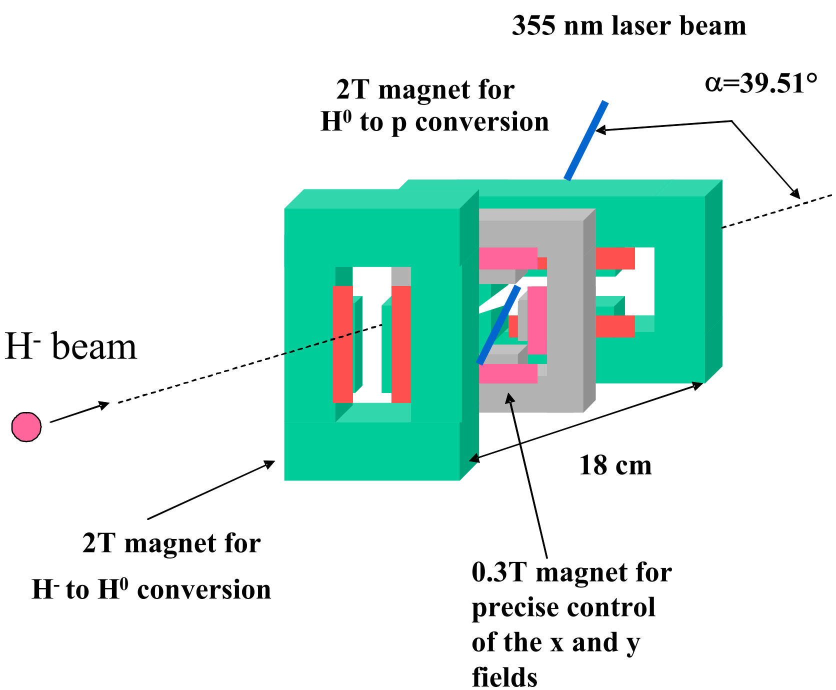


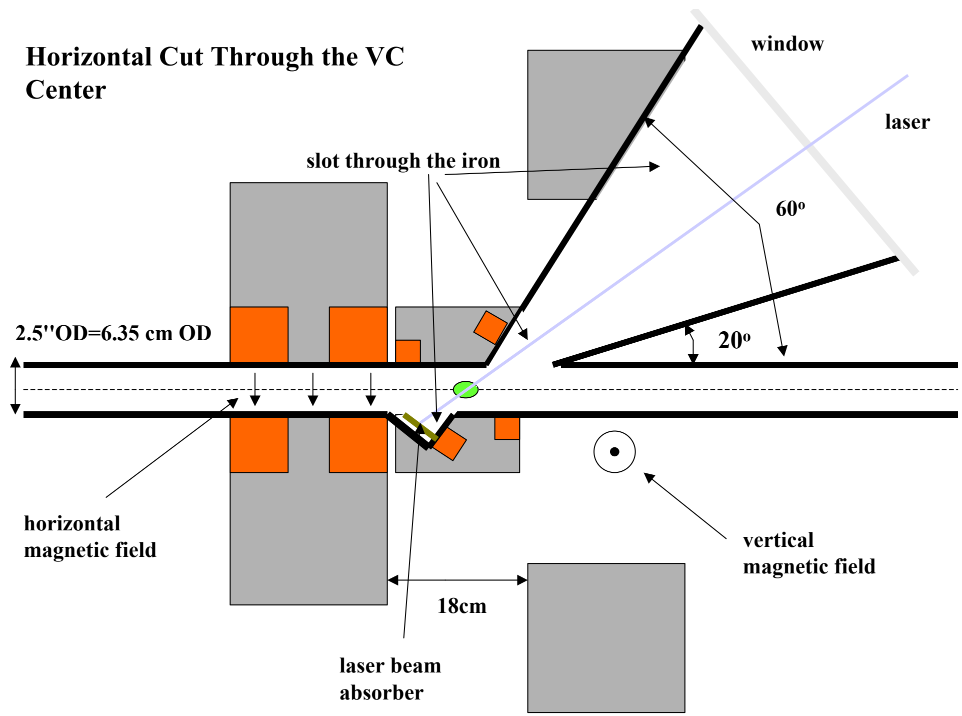
Laser Stripping Location

May 18, 2004

Proof-of-Principle Experiment: Beamline Layout

We plan to add beamline hardware between two quadrupoles in the transport line at the exit of the SNS Linac





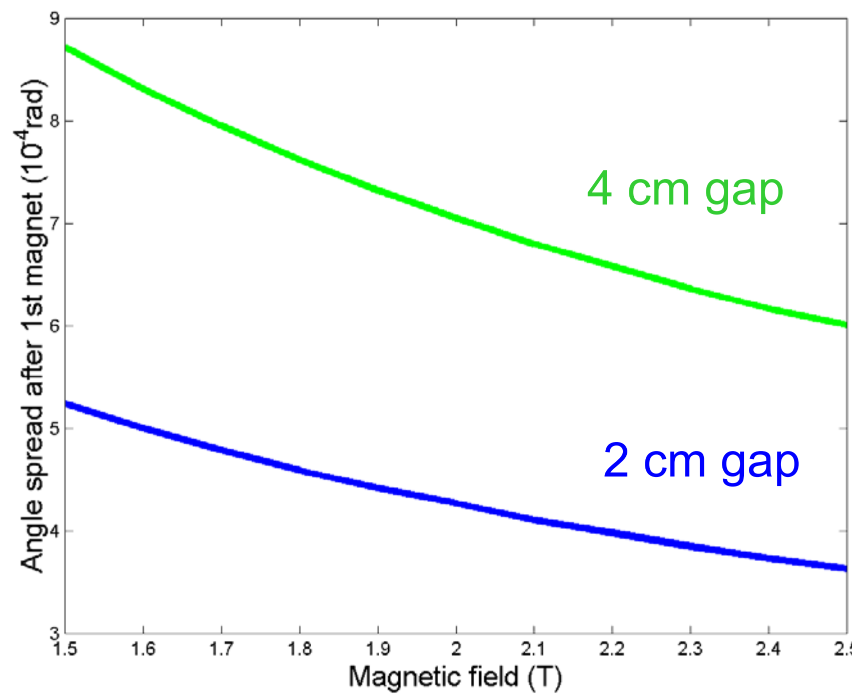
Electron Disassociation by Lorentz-Stripping

A magnetic field in the laboratory frame generates a strong electric field in the rest frame of the H^- ion from Lorentz transformation:

$$E = \gamma\beta c B$$

One electron is readily disassociated from the H- ion due to the small binding energy (0.755 eV)

- The H^0 (n=3) state is also easily stripped with a similar magnet
- Lorentz-stripping is governed by exponential decay: 1 GeV ion in 1 T field has mean decay length 1 cm.
- Due to the exponential decay, very steep fields are required to avoid adding angular spread



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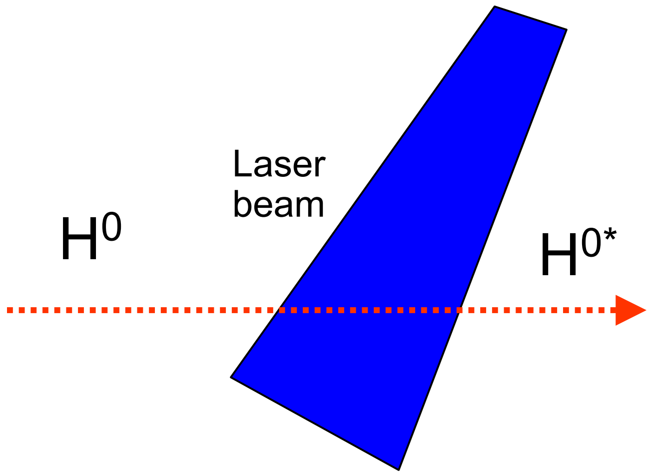
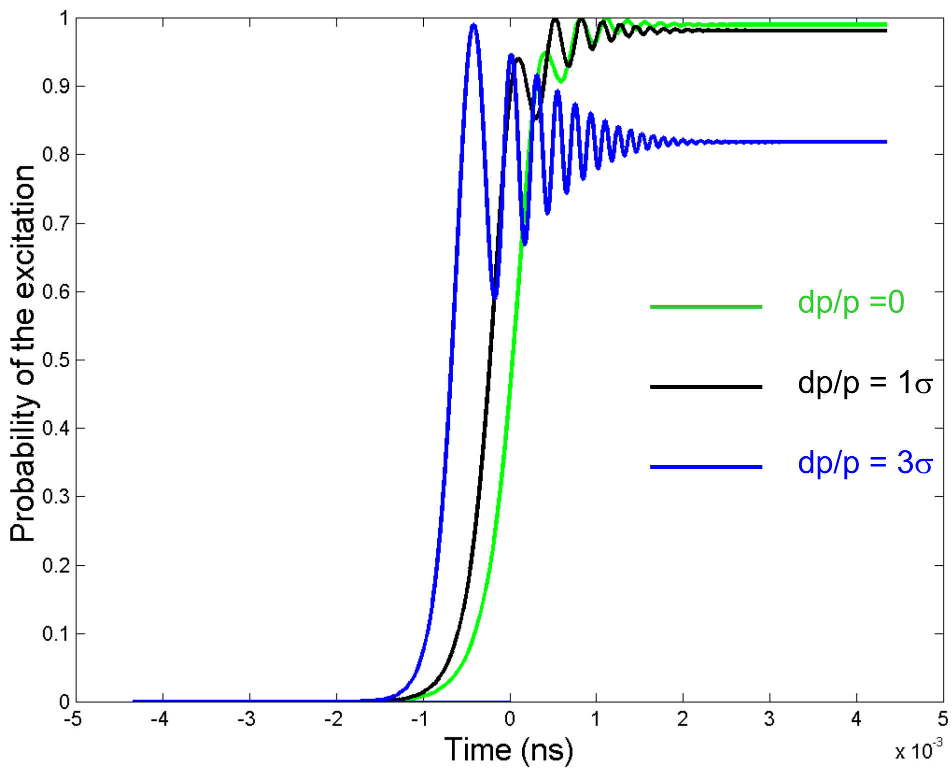
We Have Formulated an Approach that Overcomes the Doppler Broadening

SNS SPALLATION NEUTRON SOURCE

By intersecting the H^0 beam with a *diverging* laser beam, a frequency sweep is introduced:

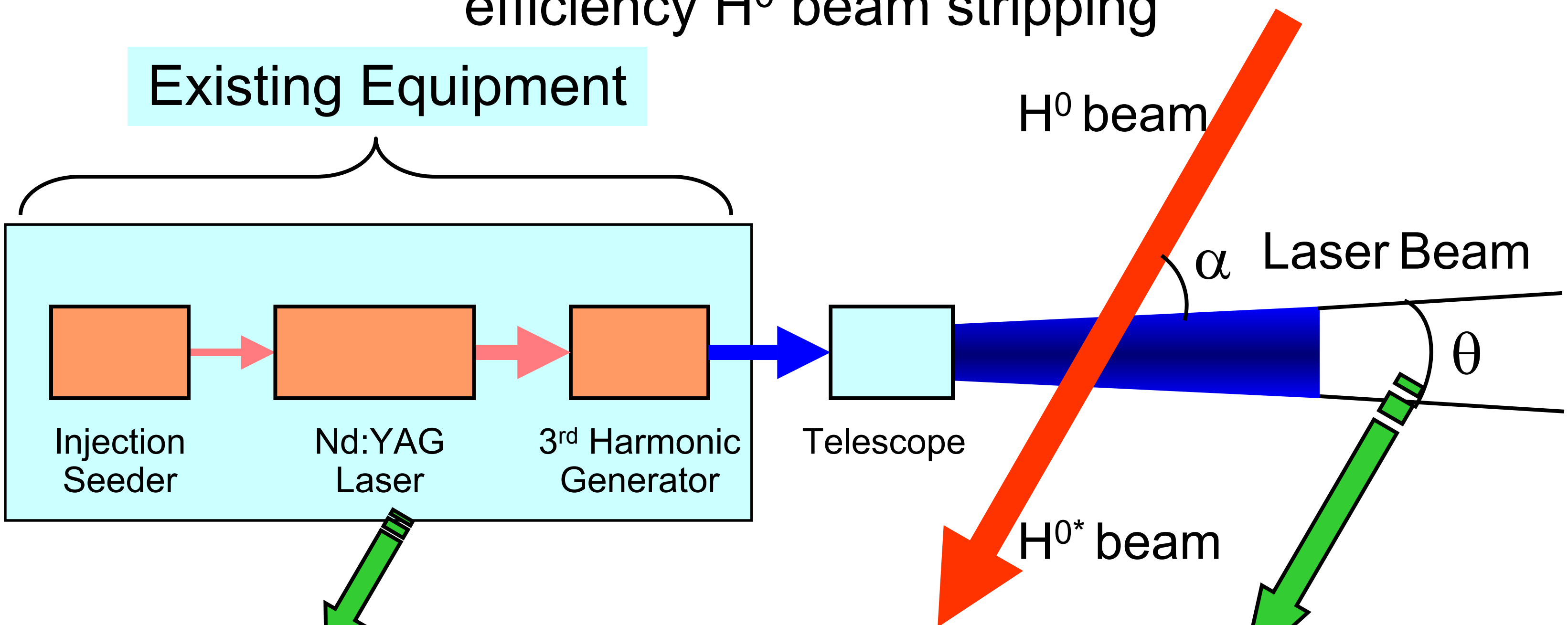




- The quantum-mechanical two-state problem with linearly ramped excitation frequency shows that the excited state is populated with very high efficiency with greatly reduced laser power

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

Proof-of-Principle Experiment: Key Parameters

Doppler frequency spread	3.6×10^{12} sec^{-1}
Laser beam angle	39.5°
Frequency sweep range	1.1×10^{13} sec^{-1}
Angular divergence	1.8 mrad
Rabi frequency	1.3×10^{12} sec^{-1}
Lab-frame peak laser power density	34 MW/cm^2
Lab-frame peak laser power	1.4 MW
Required laser pulse energy	11 mJ
Stripping efficiency over pulse	> 90%

Conclusion:

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

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

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 under construction.

6) Third Harmonic of Nd:YAG laser is ready for the laser stripping studies.

7) Laser Stripping proof of principle R&D is making good progress.

SNS Diagnostics Deployment

Operational

FY04

New to 2004

New to FY04

½ Laser in 04

FY2004/5

MEBT
6 Position
2 Current
5 Wires
[2 Thermal Neutron]—9/04
[3 PMT Neutron] —9/04
1 Emittance
[1 fast faraday cup]—9/04
1 faraday/beam stop
D-box video
D-box emittance –9/04
D-box beam stop
D-box aperture
Differential BCM
[laser prototype]—9/04

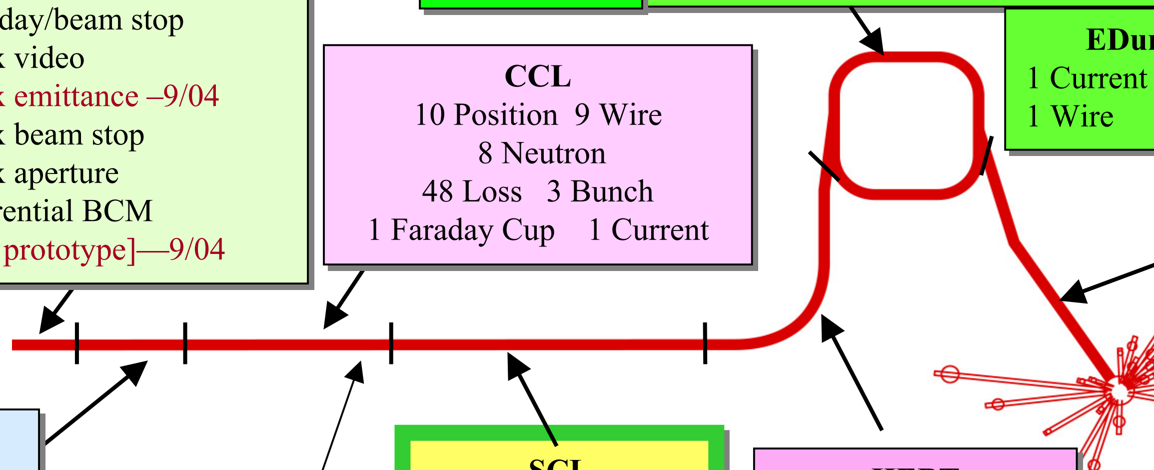
IDump
1 Position
1 Wire
1 Current
6 BLM

RING
44 Position 2 Ionization Profile
70 Loss 1 Current
5 Electron Det. 12 FBLM
2 Wire 1 Beam in Gap
2 Video 1 Tune

CCL
10 Position 9 Wire
8 Neutron
48 Loss 3 Bunch
1 Faraday Cup 1 Current

EDump
1 Current 4 Loss
1 Wire

RTBT
17 Position
36 Loss
4 Current
5 Wire
1 Harp
3 FBLM



DTL
10 Position 5 Wire 12 Loss
5 Faraday Cup 6 Current
6 Thermal and 12 PMT Neutron

SCL
32 Position 86 Loss
8 Laser Wire
7 PMT Neutron

HEBT
29 Position 11 Wire
46 BLM, 3 FBLM
4 Current

CCL/SCL Transition
2 Position 1 Wire
1 Loss 1 Current

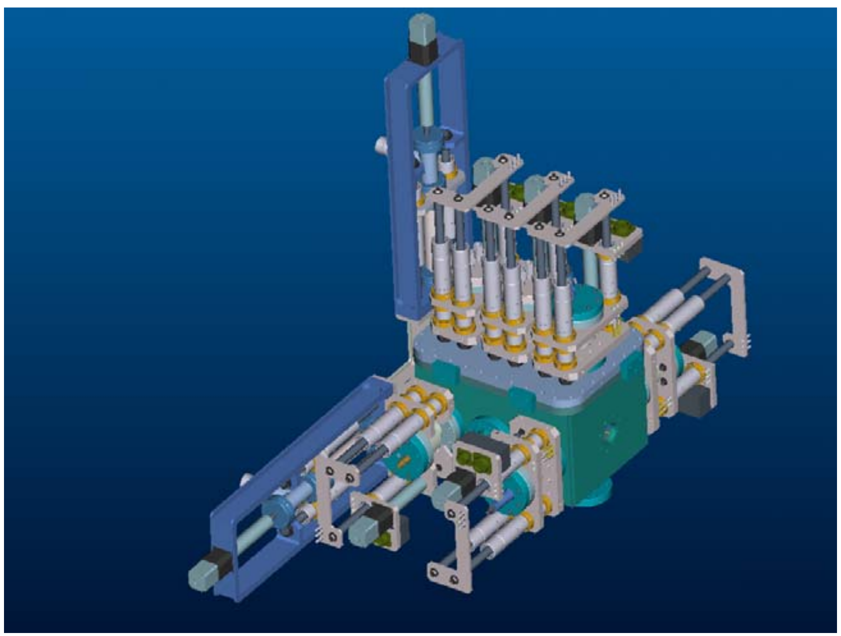
LDump
6 Loss
6 Position
1 Wire

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