LASER STRIPPING OF H^- BEAMS: THEORY AND EXPERIMENTS

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UT-BATTELLE

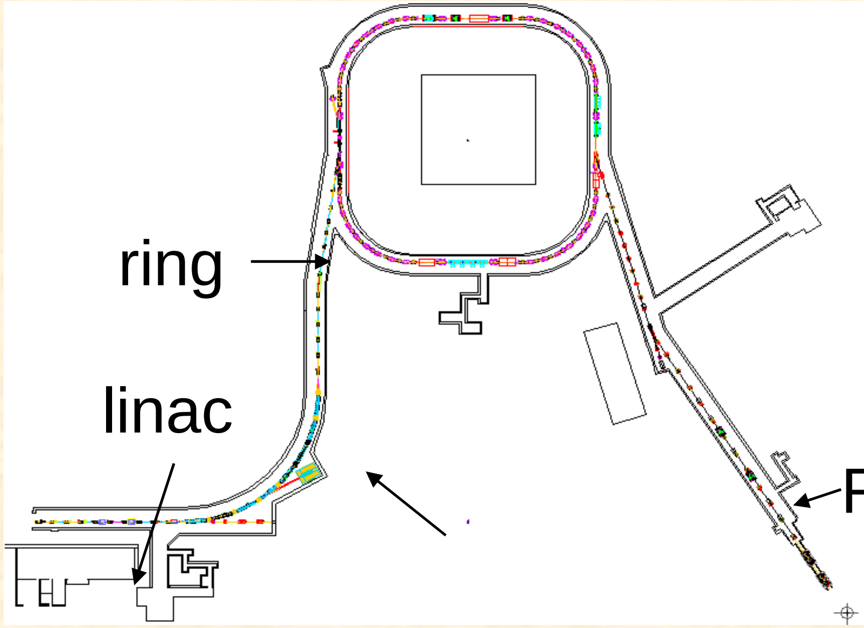
SNS SPALLATION NEUTRON SOURCE

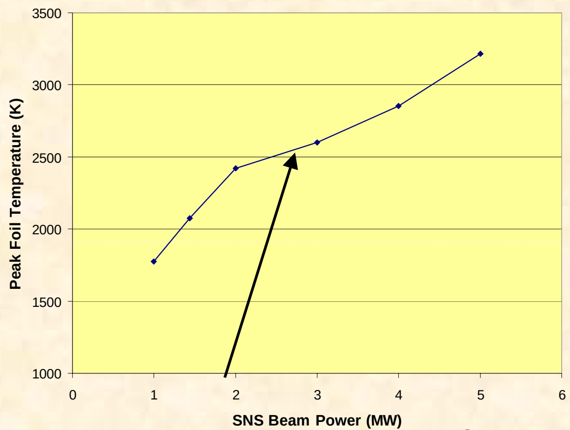
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Powerful Facilities Motivation (SNS Example)

Ring parameters:

- ~ 1GeV (860-931 MeV in our studies)
- Design intensity – 1.4×10^{14} protons
- Power on target – 1.4 MW at first stage
- The ring design was low-loss high intensity oriented
- Foils used to get high density beams (nonLiouvillian injection)
- Drawbacks – short lifetime, activation, high loss





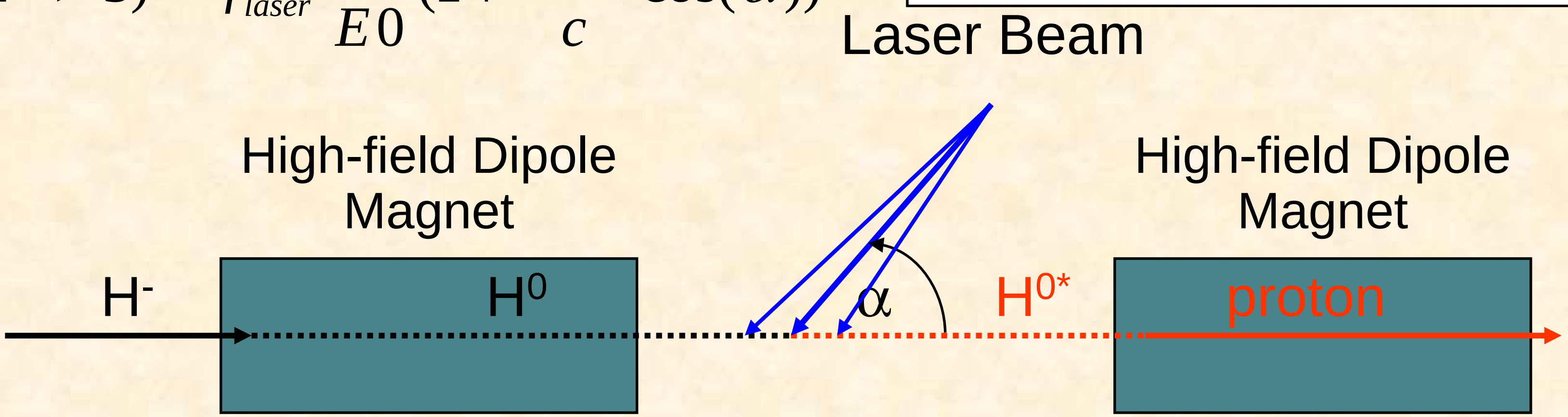
Foil degrades

Three-Step Stripping Scheme

Main problem –beam energy spread

$$f(1->3) = f_{laser}\frac{E}{E0}(1+\frac{v_{beam}}{c}\cos(\alpha))$$

- **Our team developed a novel approach for laser-stripping which uses a three-step method employing a narrowband laser**



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

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

Froissart – Stora Solution

- **Linear in Time Frequency Change – Two State Quantum Resonant System. Ideal case from t=- ∝ to t=+ ∝**

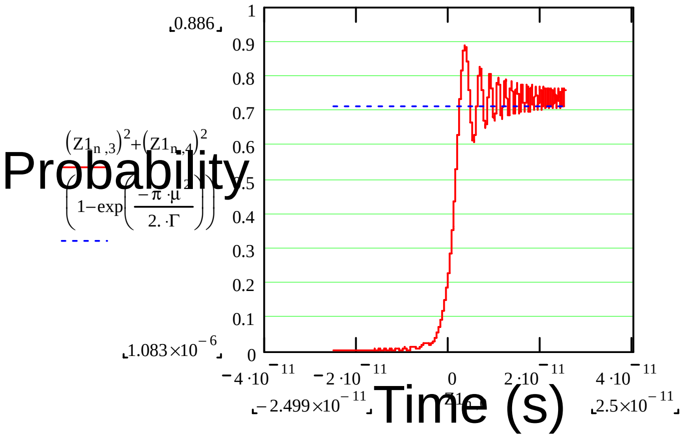
- **Asymptotic probability of excitation C_n^2 is expressed via Rabi frequency Ω and light frequency derivative with respect to time $\Gamma = d\omega/dt$**

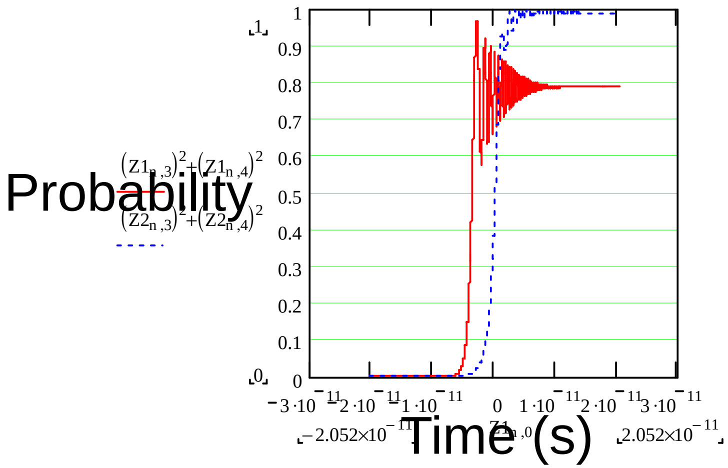
$$C_n^2 = 1 - \exp\left(-\frac{\pi\Omega^2}{2\Gamma}\right),$$

$$\Omega^2 \propto P_{laser}$$

Principles Behind Simulations

- Two level approximation (n=1 -> n=3,l=1,m=0).
- Benchmark – constant electric field density is in very good agreement with Froissart-Stora formula
- Two examples – constant laser power density with sharp edges (left) and Gaussian round beam:

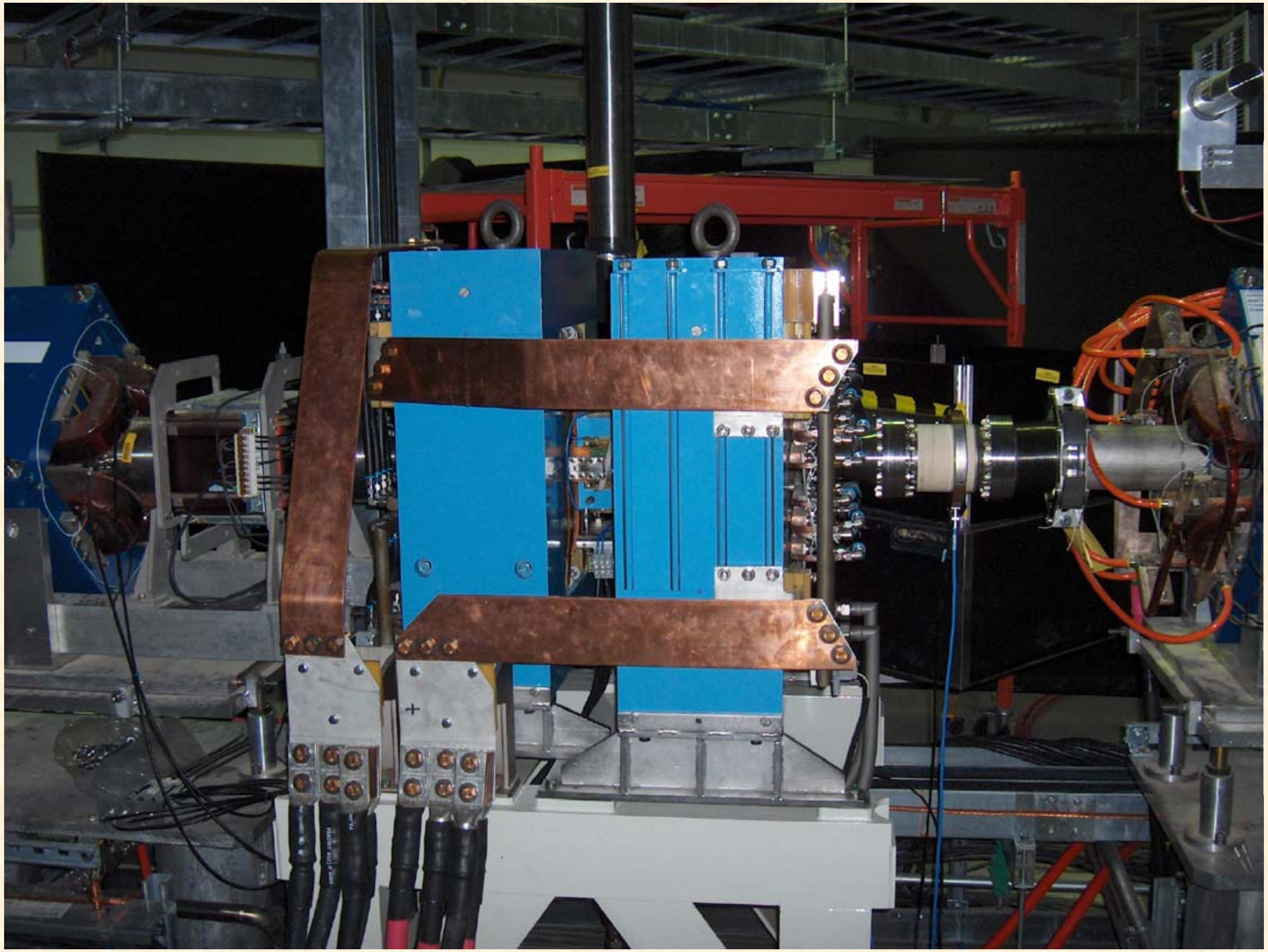




Our case (10 MW laser power) – around 90 %, without divergence (Rabi oscillations) – 0.1%. It was worth to check the new approach – led to POP experiment

Experiment Animation

Laser Stripping Assembly

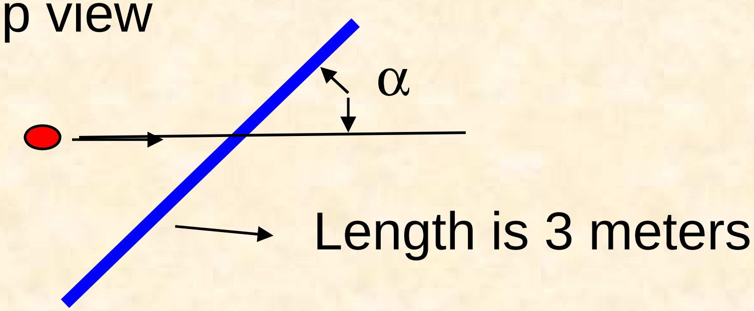


Important Beam Parameters

1) **Energy – through Doppler effect;**
2) **Angle – same effect. Need good accuracy – 1 degree error gives 10 MeV energy error;**
3) **Small vertical size. No large tails**

$$f(1->3) = f_{laser}\frac{E}{E0}(1+\frac{v_{beam}}{c}\cos(\alpha))$$

Top view



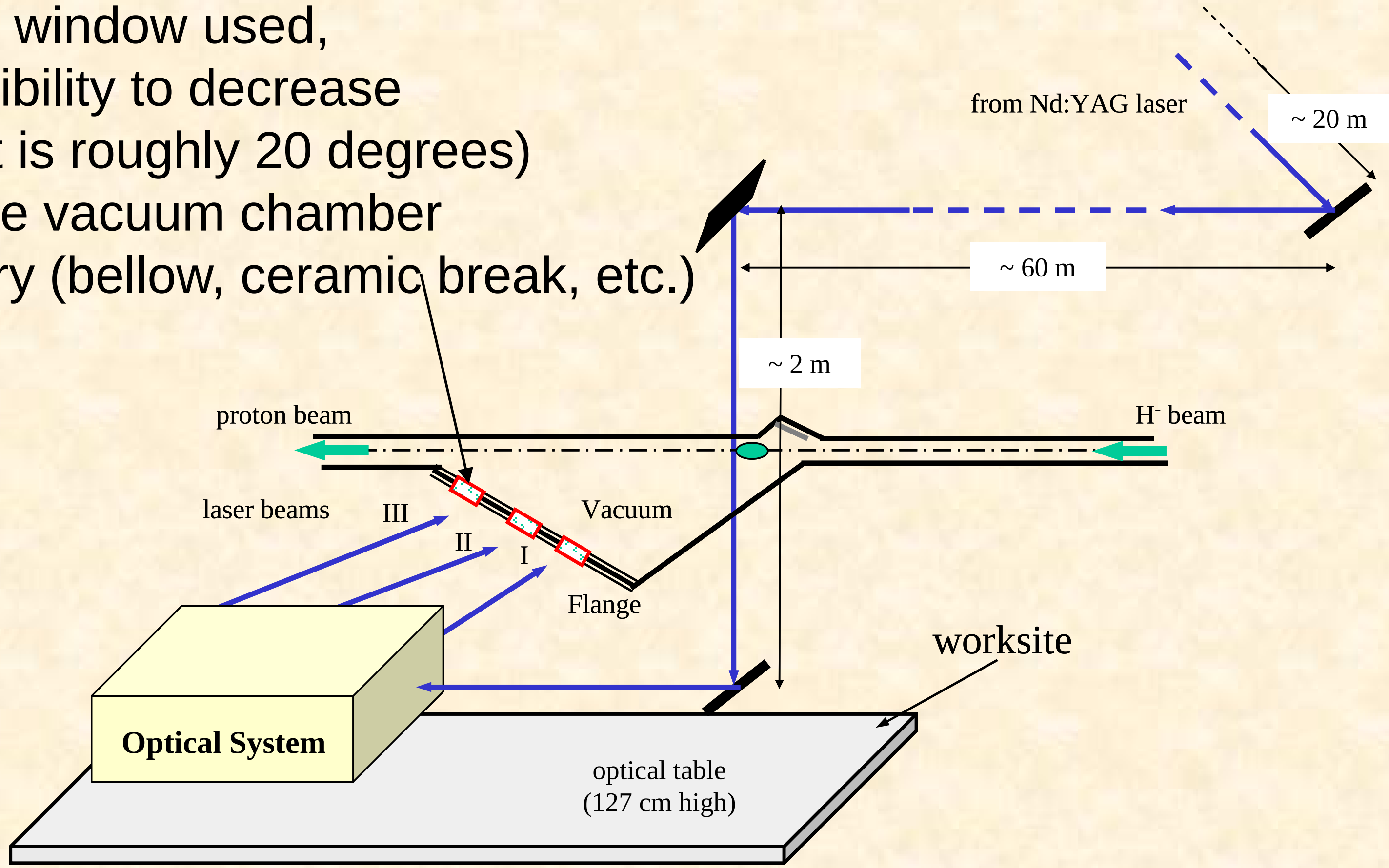
Side view

Vertical overlap is absolutely important

Laser Beam Transport System

Minimal ion beam energy – 870 MeV. Laser system:
3rd harmonic Nd:Yag laser 7ns pulse

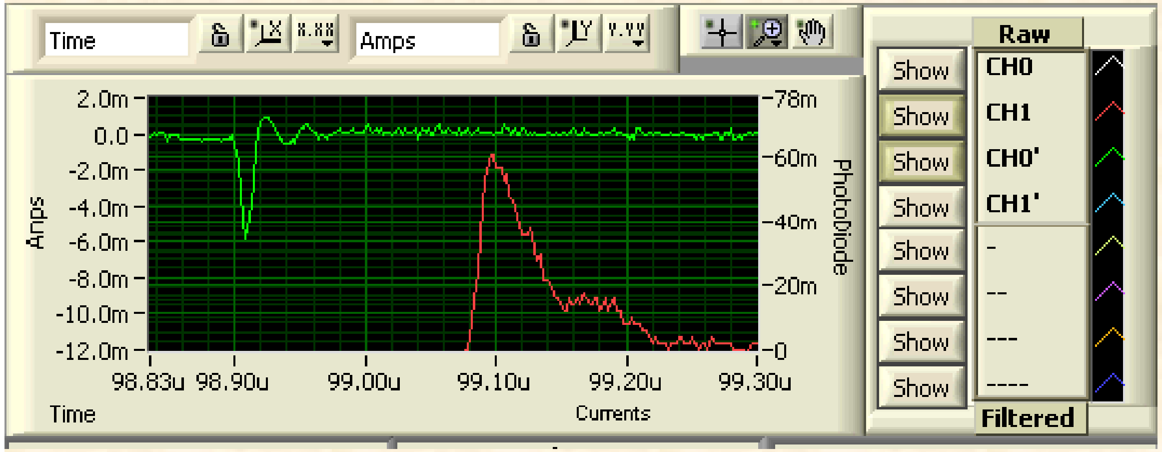
leftmost window used,
no possibility to decrease
angle (it is roughly 20 degrees)
because vacuum chamber
geometry (bellow, ceramic break, etc.)



Four Sets of Experiments Description

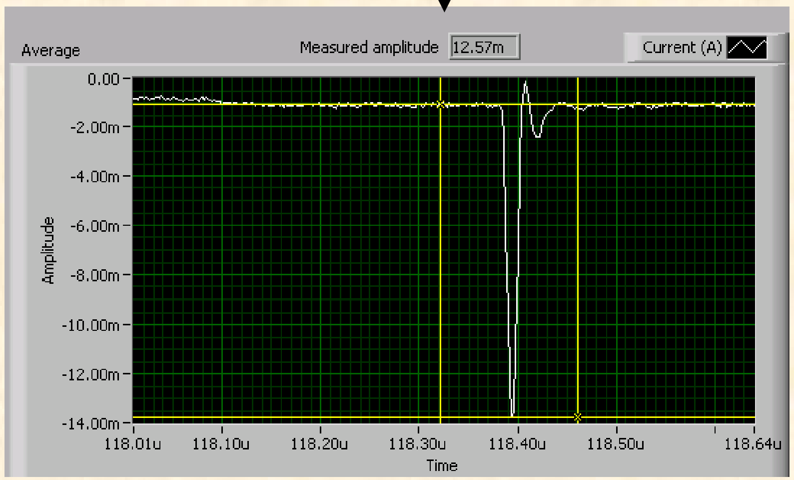
- 1st experimental run (December 2005)-no stripping seen. We wish we could get the answer to this puzzle
- 2nd experimental run preparation – laser moved to the table. It tripled the laser beam power
- Laser beam incident angle and beam parameters (energy of the ions) were more carefully measured
- Second run (March 2006) led to a first success (about 50% of stripping)
- Third run (August 2006) –successful (around 85% of stripping achieved)
- Forth (final) run (October 2006) – 90% stripping achieved, additional effects studied

Stripping Signals

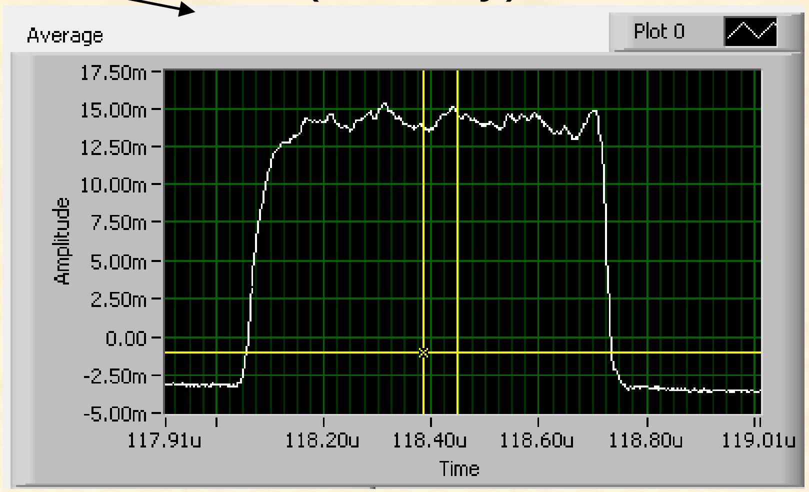


First observed signal (March2006) duration is around 10 ns –little longer than the laser one (7 ns) This was taken into account to estimate the actual stripping percentage. One hour experiment produced one (the only) set of data.

August 2006. Maximal signal seen - 12.6 ma out of 18.9 ma

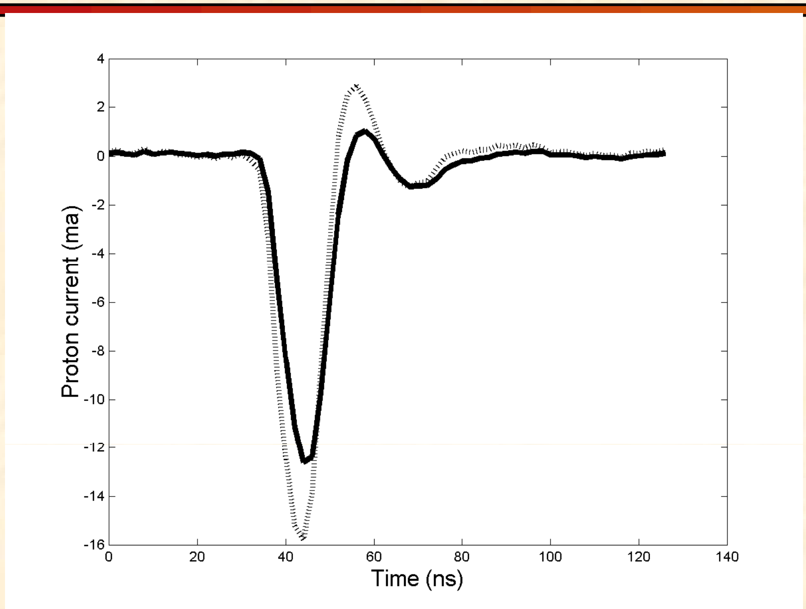


magnets and laser on



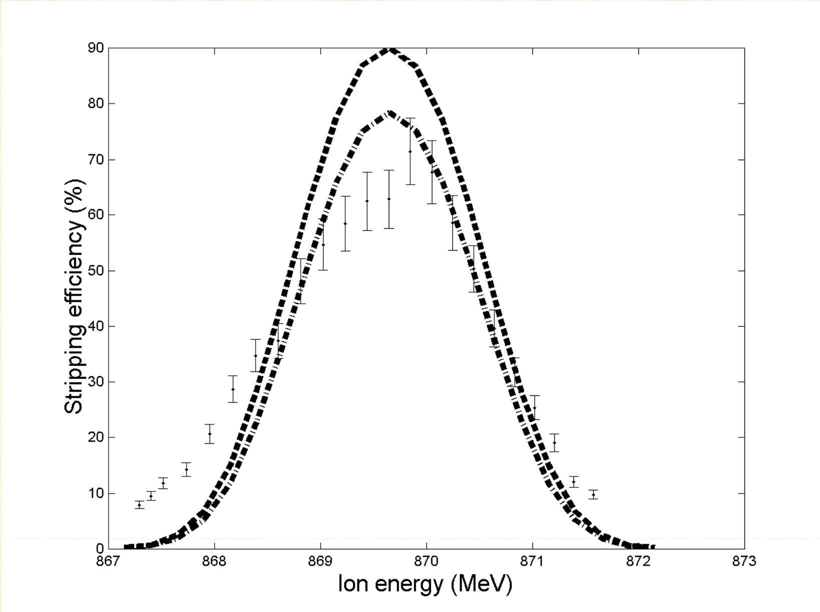
original current

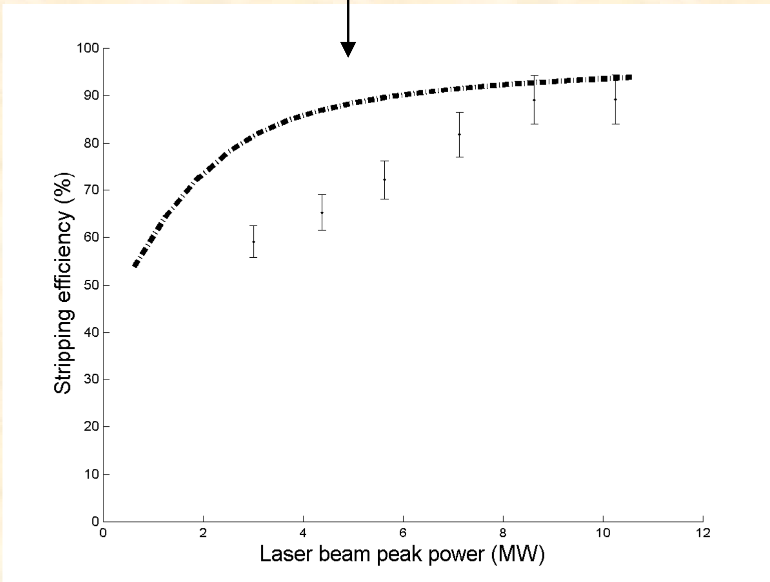
Main experimental results



More careful data processing results: red line shows experimental signal, green line – restored BCM signal
It shows maximal signal of 16 ma.
The maximal efficiency was 16/19~0.85±0.1 (August 2006) and 0.9 ±0.05 (October 2006)

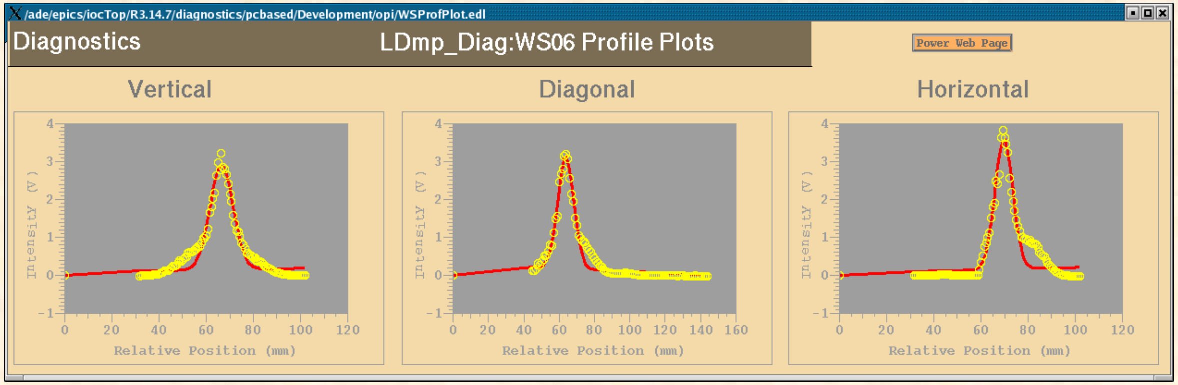
Energy and power dependence





Problems

Powerful laser breaks the windows – in our experiment the laser density was reduced by factor 2 to prevent window damage. The maximal efficiency achieved when laser power increased to maximum and laser spot area increased two times



Controlling beam tails and size. There is some room for improvement. The vertical beam size uncertainty gives largest error in calculations. Our estimation for vertical size 0.6 mm. theoretically can be 0.3 mm

Exp. Summary and New Development

1) Our theoretical expectations (around 90% efficiency) were met.
2) We have good theoretical understanding of the process and can go to the next intermediate step – long pulse stripping at the end of HEBT.

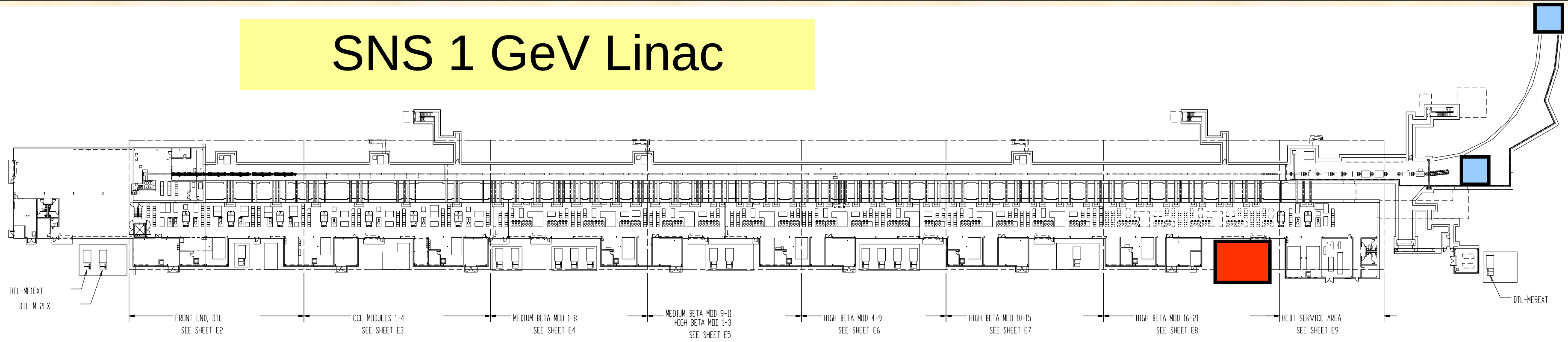
We stripped few nanosecond beam. 10MW*0.06=0.6 MW if same laser the final goal is to strip 60 Hz 1 ms beam with low cost laser

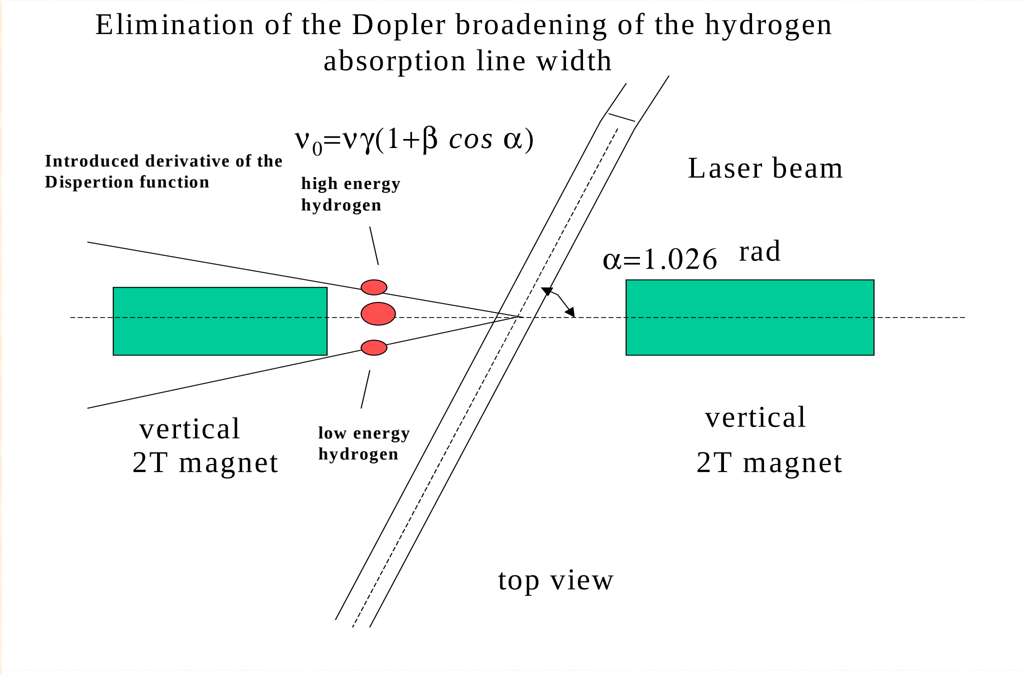
- Laser beam power reduction:
- 1) Matching laser pulse time pattern to ion beam one
- 2) Dispersion derivative to eliminate the Doppler broadening of the absorption line width (factor 10 of reduction)
- 3) Bunch length reduction
- 4) Recycling (factor 10 of reduction anticipated)
- 5)Vertical size reduction (factor 3 available)
- 6) Horizontal angular spread reduction (factor 1.5-2 possible)

Intermediate experiment – strip 1-100 μs ion beam with high efficiency

New place for experiments, new possibilities

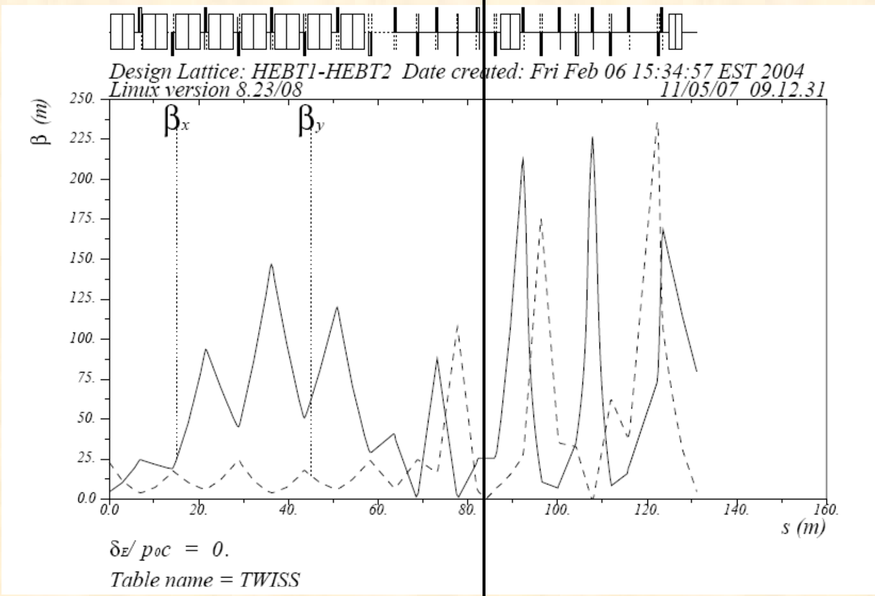
SNS 1 GeV Linac





Dispersion function tailoring (dispersion derivative at IP) results in ion angle dependence on energy.
1 GeV SNS beam
D'=2.58 for full elimination of Doppler spread of absorption line width due to energy spread

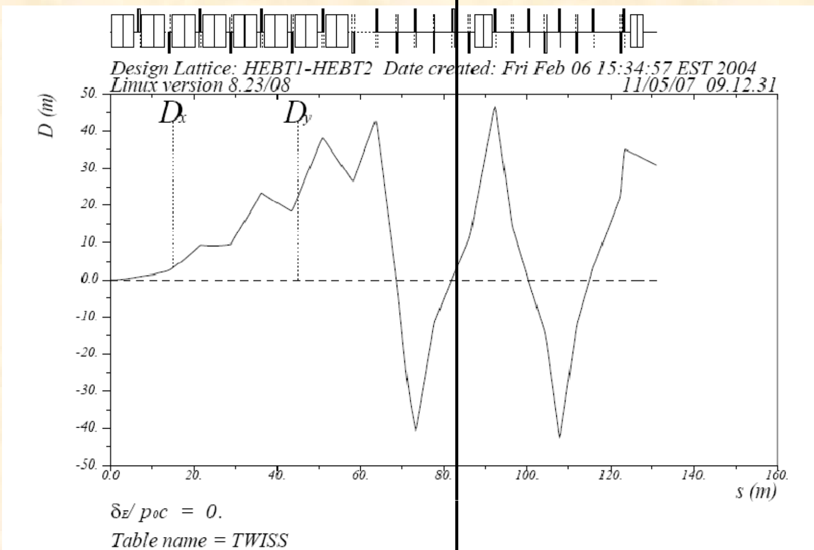
Transverse Ion Beam Optics



Betax (solid), betay (dashed)

Main requirements:

1) Low vertical size;
2) Large horizontal size, zero betax derivative;
3) D'=2.58

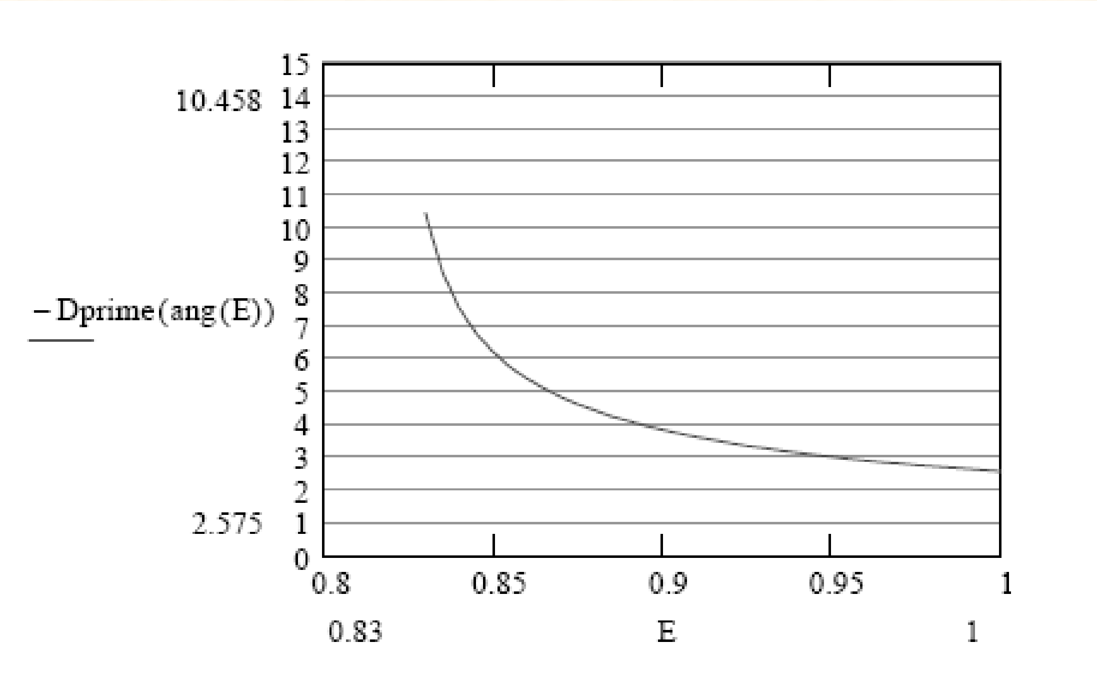


Dx

IP

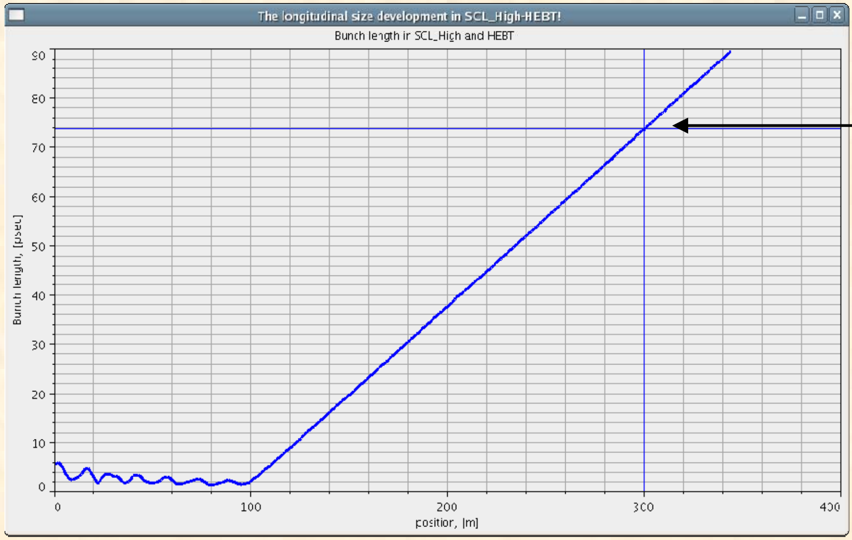
Need for Higher Energy

$$D' = -\frac{\beta + \cos\alpha}{\sin\alpha}$$

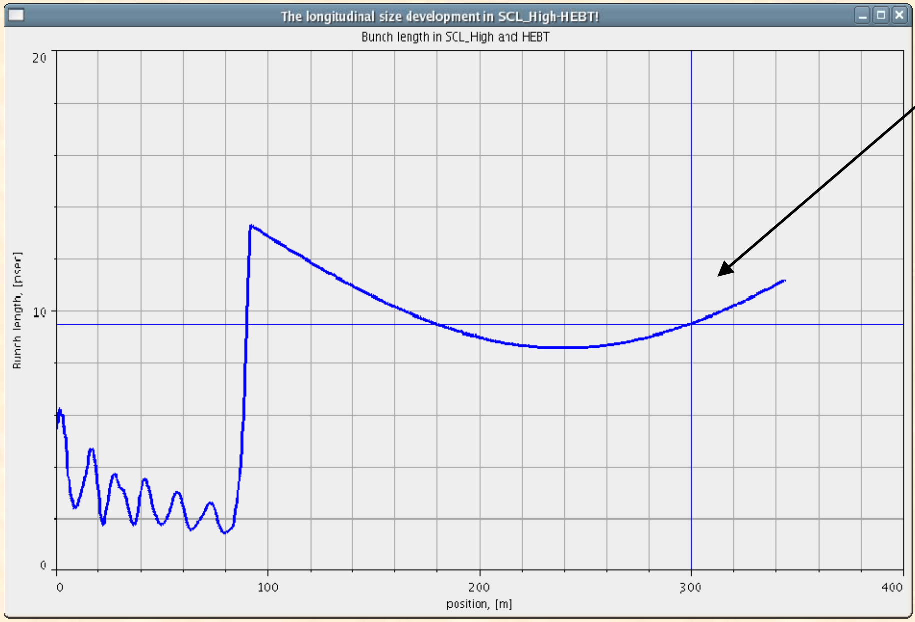


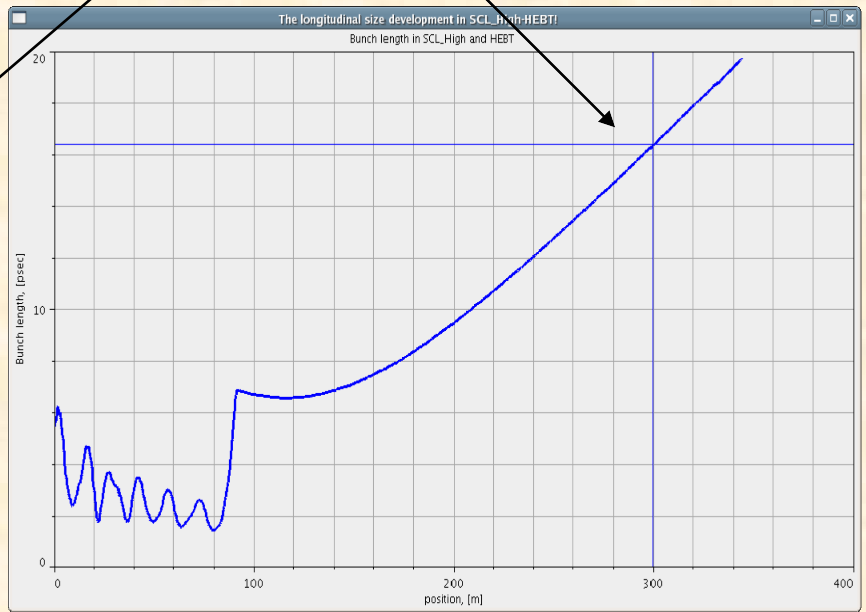
Needed dispersion derivative is a very nonlinear function of energy.
840 MeV – absolute minimum for 355 nm.
In reality 950 MeV is already a problem for optics.
Contrary to first experiment,
We need 1 GeV to get
Needed dispersion.

Linac Retuning



Linac bunch length too large (100 ps FWHM)
Phases of last 6 cavities were optimized to squeeze the beam longitudinally. The length came out to be 10 ps (52 MeV energy drop) and 16 ps (4 MeV drop) (focusing is exchanged for energy)



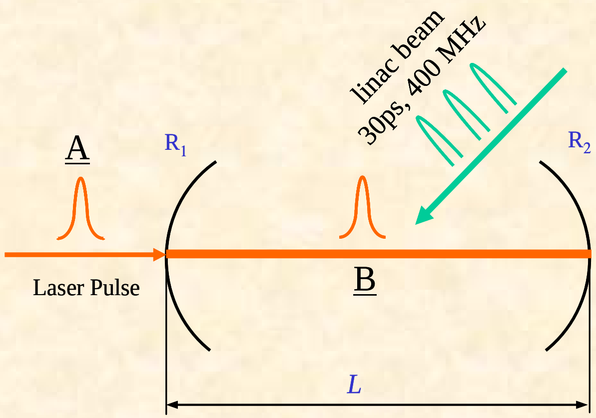


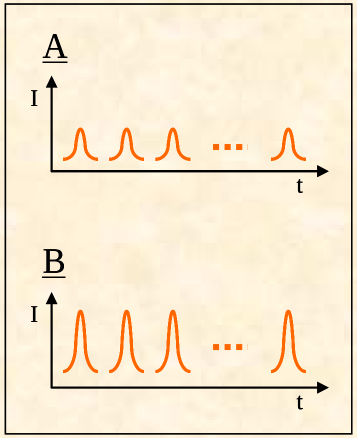
Interaction Region Requirements

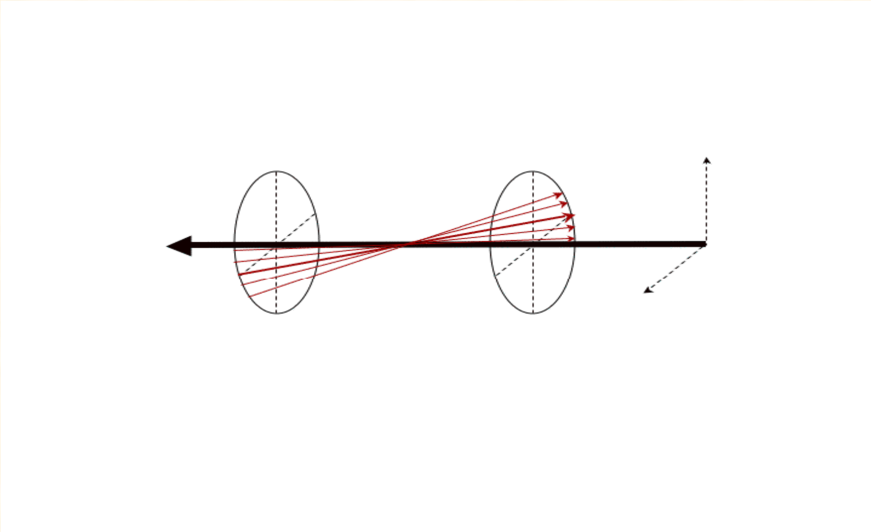
1) Transverse ion beam optics (dispersion, vertical beam size, small horizontal) suitable;
2) Enough space for optics, magnets, diagnostics;
3) Low radiation;
4) Short ion beam.

All (but 4th) requirements are met for this place. The linac bunch is (unfortunately) long. It is 5 ps FWHM after SCL, here it is 120 ps min.
To reduce the ion bunch from linac we have to retune last few cavities of SCL. Preliminary results are very positive. Linac bunch length can be as low as 10ps after retuning

Laser Beam Recycling







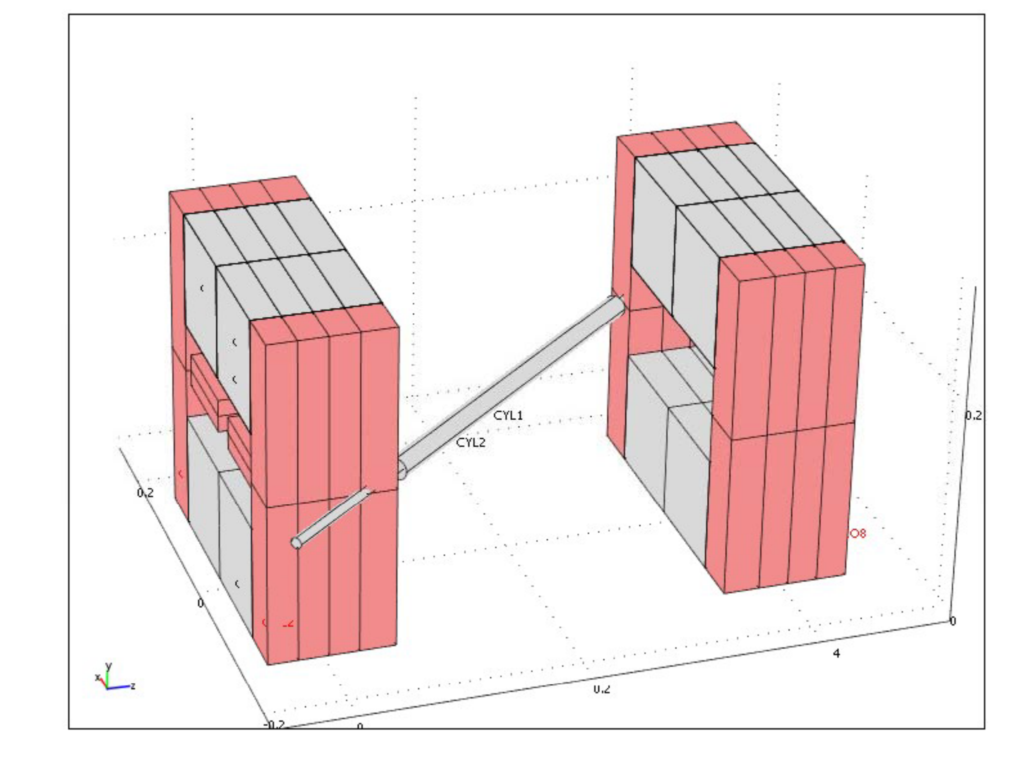
We use only 10^{-7} photons in one collision

Two options –
Fabry-Perot cavity (upper plot)
and mirror-bouncing (lower plot)
In addition – laser pulses match ion bunches in length (50 ps)

final average laser power becomes reasonable if all factors included

$$P_{ave} = 10^6 W \cdot 50 \cdot 10^{-12} s \cdot 40.25 \cdot 10^6 Hz \cdot 10^{-3} s \cdot 60 Hz = 120 W$$

New Magnets for Stripping



Main reason for new magnet design – there is no possibility to shrink the vacuum chamber aperture because of risk to interfere with neutron production

The idea is to use permanent magnets (NdFeB), combine them with laser optics, make it movable, and put whole system in vacuum chamber

Summary and Status

1) POP experiment was successful;
2) Intermediate experiment (high efficiency up to 100 μs pulse stripping) on planning stage;
3) Necessary lasers can be built (we have quotes from some laser companies);
4) Preliminary ion optics investigation is done – the results are encouraging;
5) Beam recycling demonstration is now first priority.

After two options of beam recycling are explored, we start designing the stripping device for the long pulse stripping.

Acknowledgements

Collaborators:

ORNL: S. Aleksandrov[2],S. Assadi[2], J. Barhen[1], W. Blokland[2], Y. Braiman[1], D. Brown[2], S. Cousineau[2],V. Danilov[2],C. Deibele[2], W. Grice[1], M. Hechler[2], J. Holmes[2], Y. Liu[1], B.Lang[2], C. Long[2], G. Murdoch[2], M. Plum[2], K. Potter[2], A. Shishlo[2]

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