HB 2008

Future Prospects for Laser Stripping Injection in High Intensity Machines

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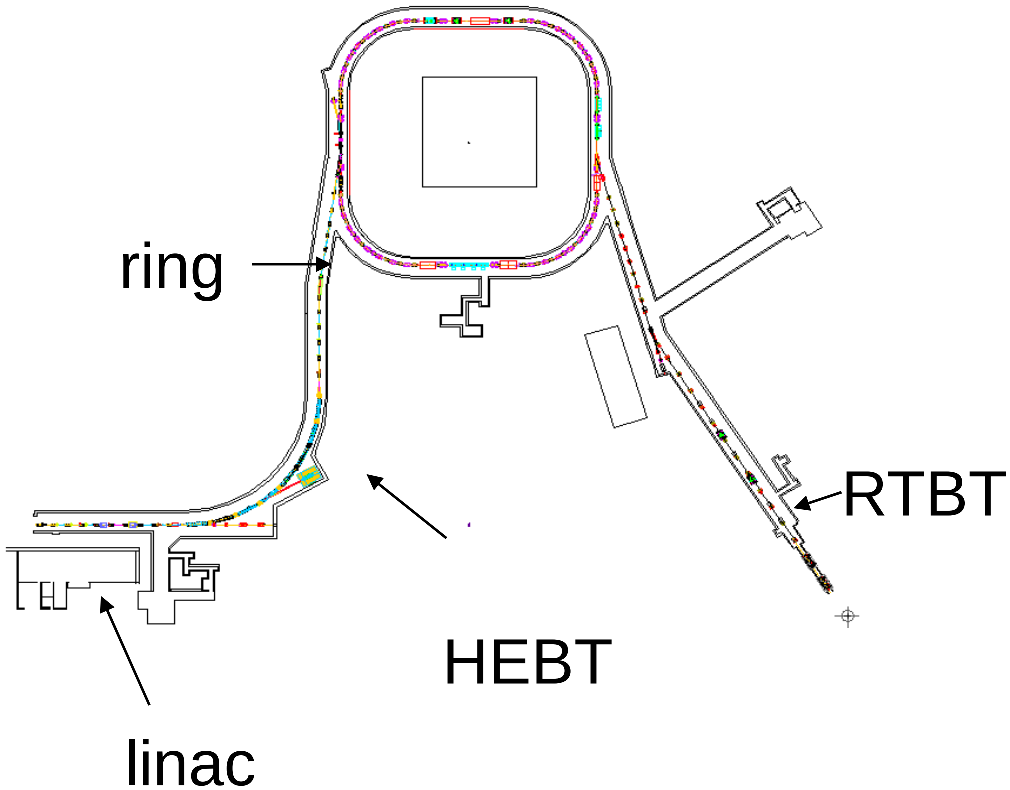
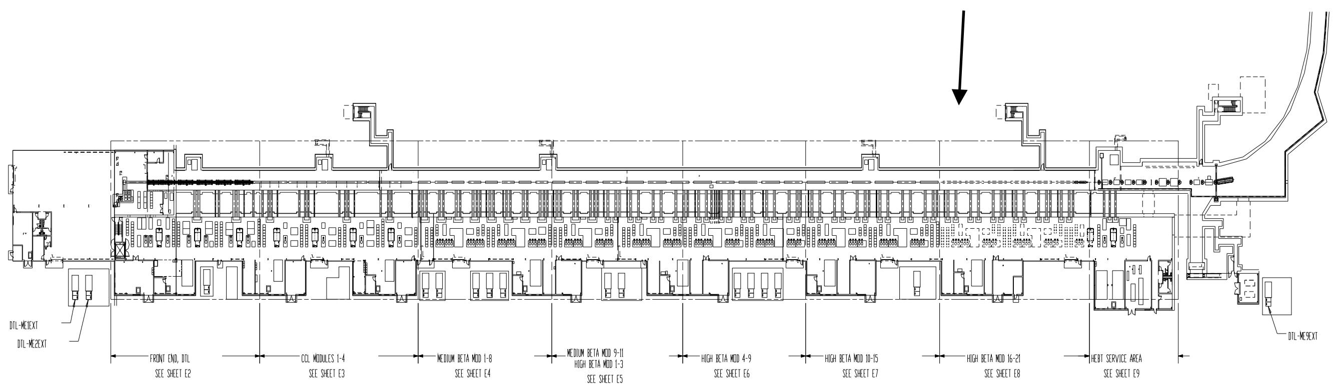
for the Department of Energy

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
- Foils used to get high density beams (non Liouvillian injection)

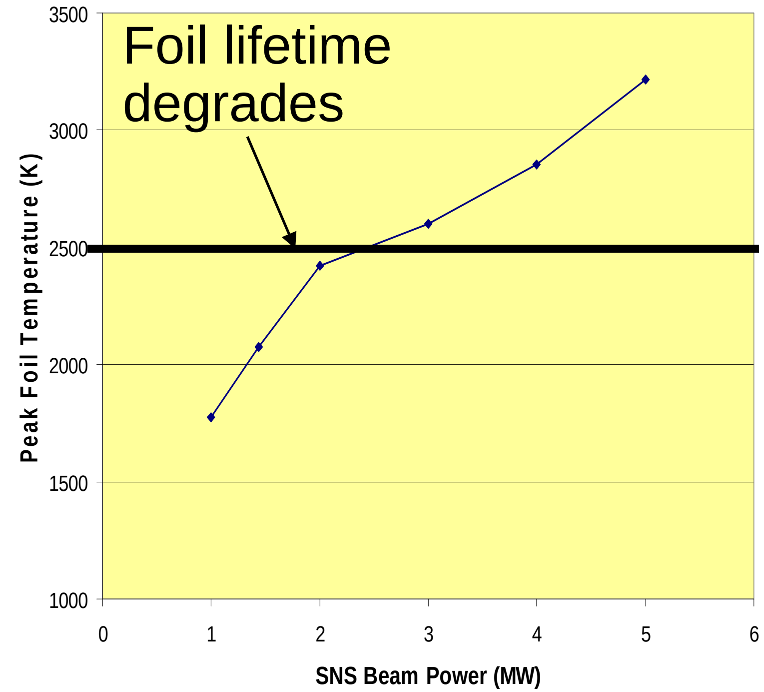




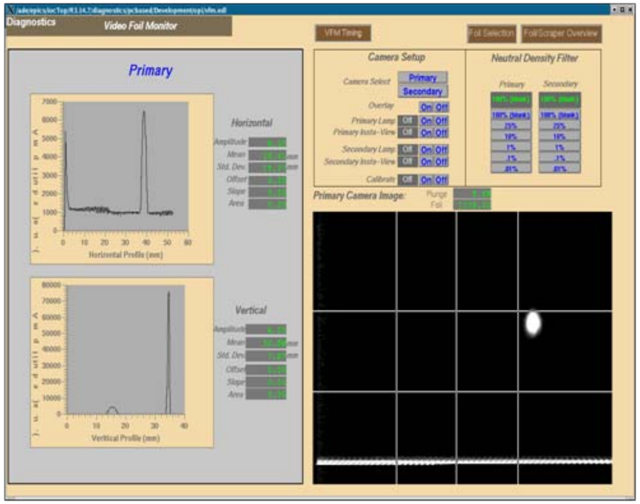
Stripping Foil Limitations

- The SNS will use 300-400 μg/cm² Carbon or Diamond foils
- Two 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

  Presently, injection area is the most activated at SNS



SNS Foil Glowing 160 kW

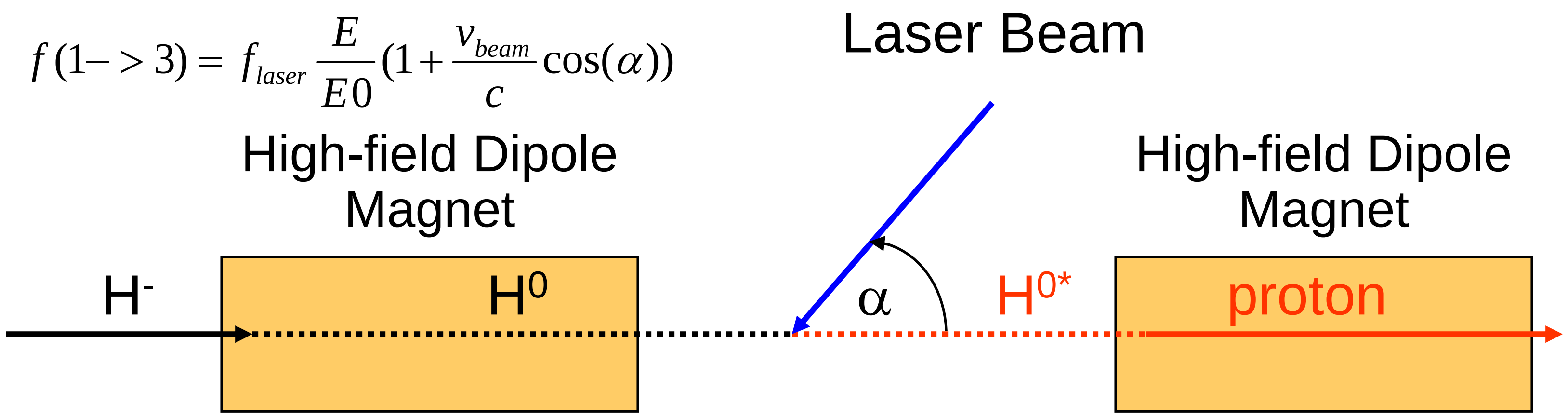


Damaged PSR Foil

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]**

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



Step 1: Lorentz Stripping

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

Step 2: Laser Excitation

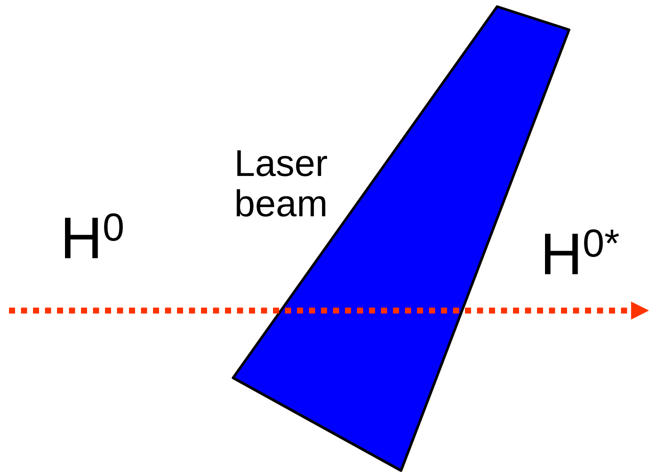
H^0 (n=1) + $\gamma \rightarrow H^{0*}$ (n=3)

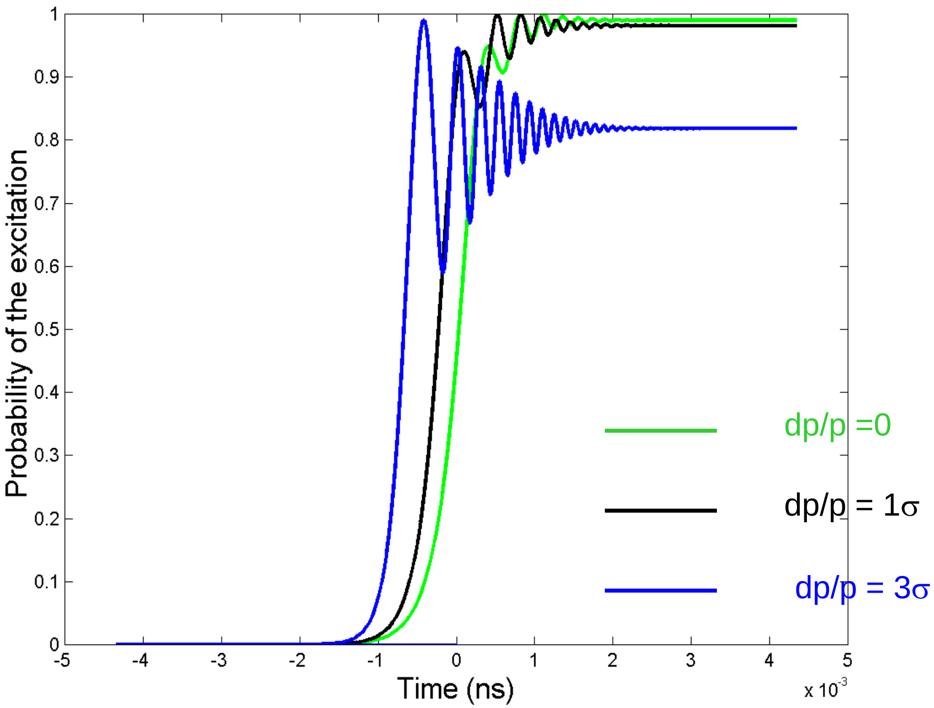
Step 3: Lorentz Stripping

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

Approach that Overcomes the Doppler Broadening

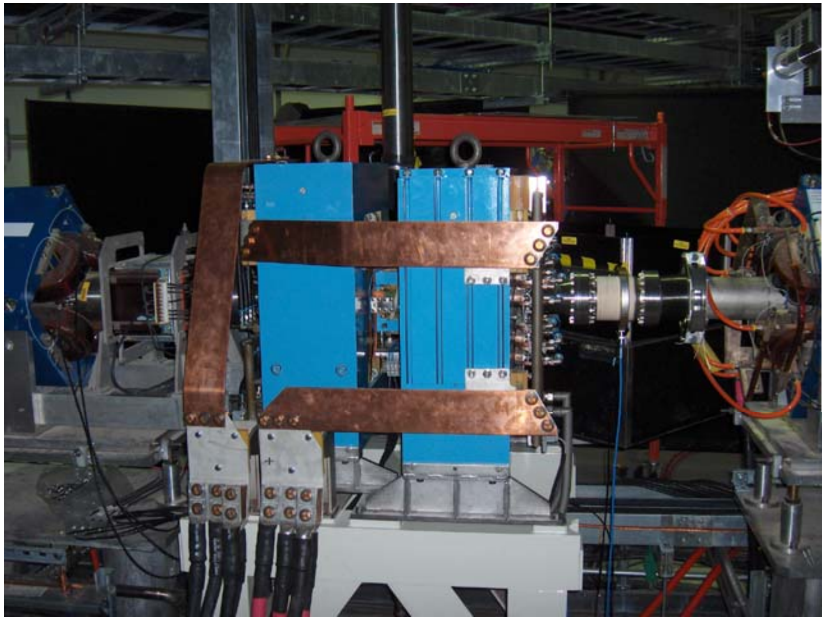
- **By intersecting the H^0 beam with a *diverging* laser beam, a frequency sweep is introduced:**

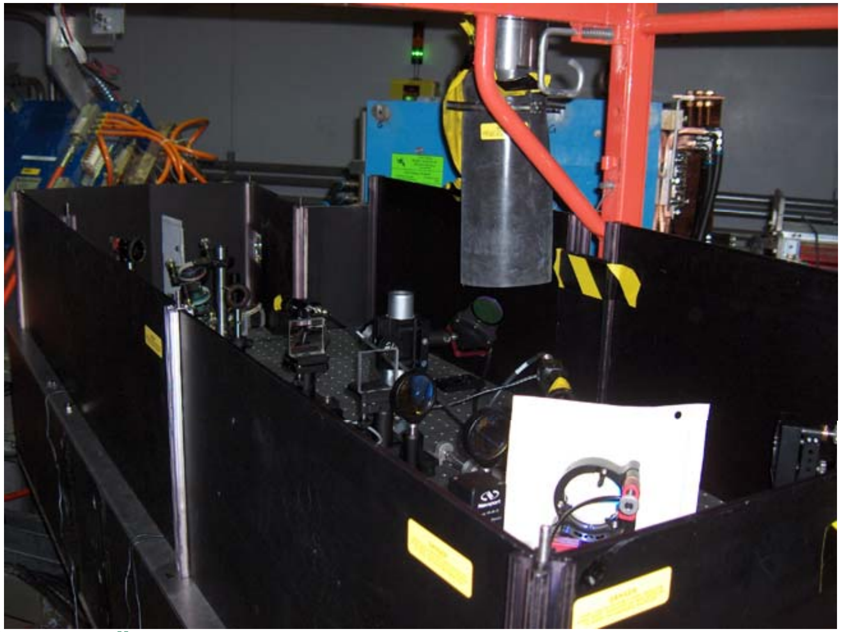




- The quantum-mechanical two-state problem with linearly ramped excitation frequency shows that the excited state is populated with high efficiency
- Estimations for existing SNS laser (10 MW 7 ns) gave 90% efficiency

Laser Stripping Assembly



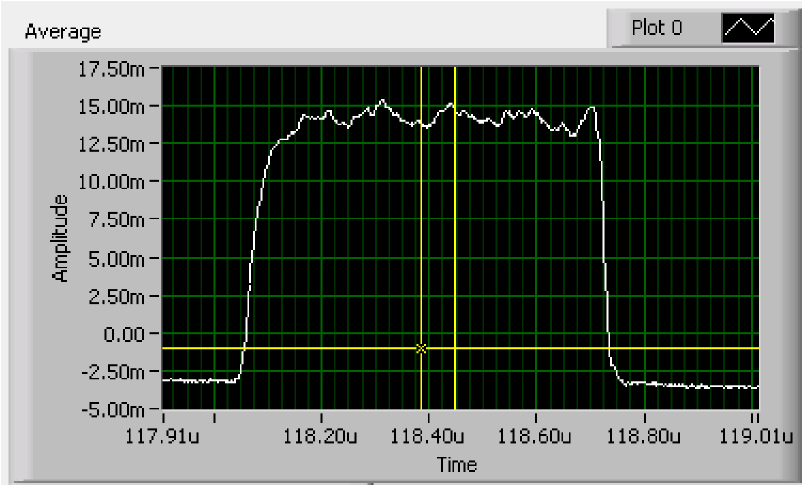


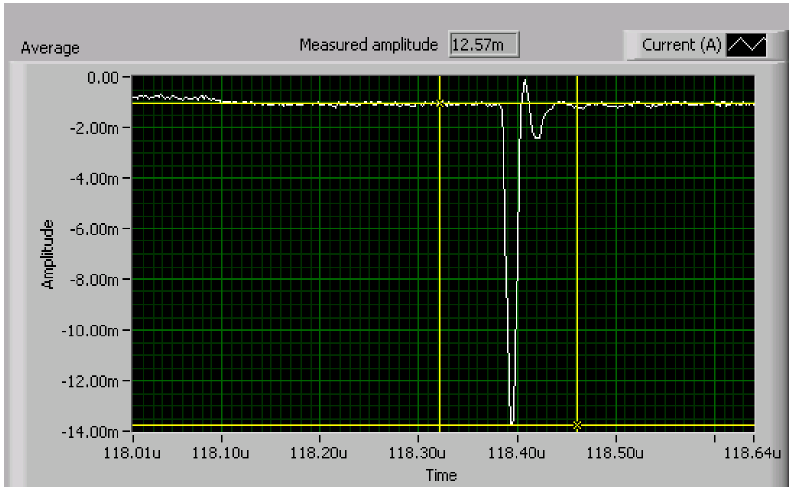
Magnets
(BINP production)

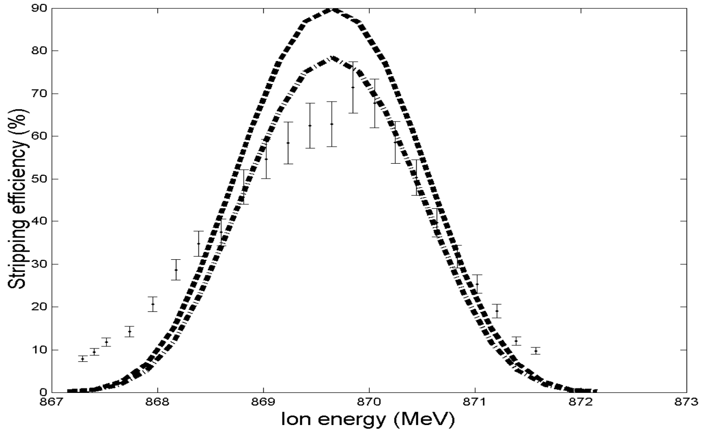
Optics table (1st experiment)
1st experiment – failed
2nd 50% efficiency achieved
(v. chamber failure afterwards)
3rd – 85% achieved
4th – 90 % achieved

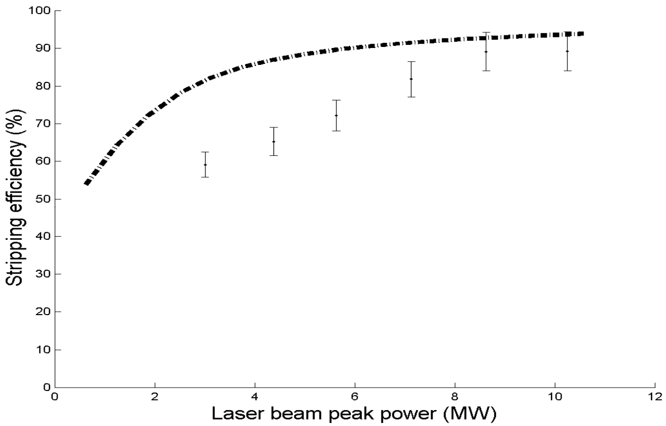
multiple problems were overcome
(e.g., windows broken by powerful laser)

Experimental results









The maximal achieved efficiency: 0.85±0.1 (3rd run) and 0.9 ±0.05 (4th run)
Straightforward use is costly – laser power needed is 10 MW*0.06=.6 MW

Laser power reduction – follow-up intermediate experiment

- **Matching laser pulse time pattern to ion beam one by using mode-locked laser instead of Q-switched**

  ~ x25 gain

- **Using dispersion derivative to eliminate the Doppler broadening due to the energy spread**

  ~ x10 gain

- **Recycling laser pulse**

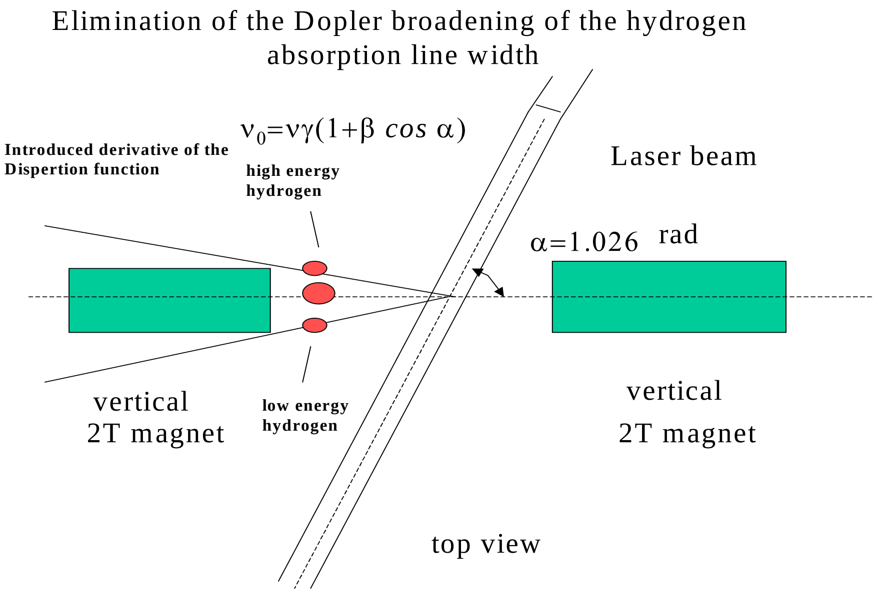
  ~ x10 gain

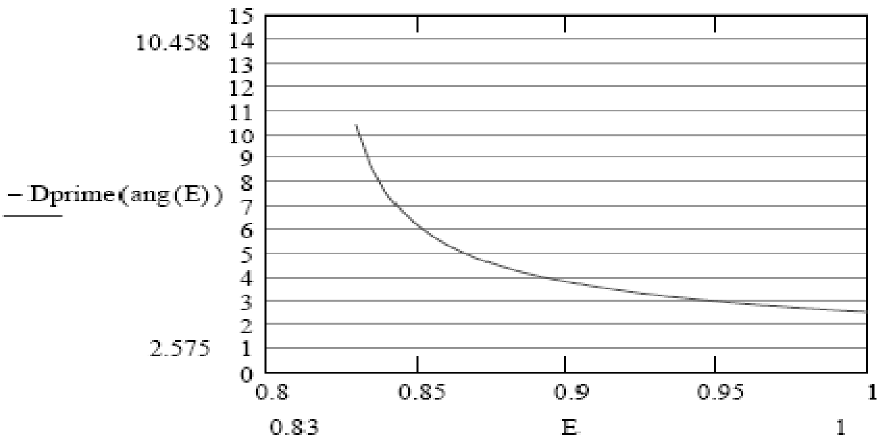
- **Vertical size and horizontal angular spread reduction**

  ~ x2-5 gain

By combining all factors the required average laser power can be reduced to 50 – 120W, which is within reach for modern commercial lasers.

Dispersion function tailoring





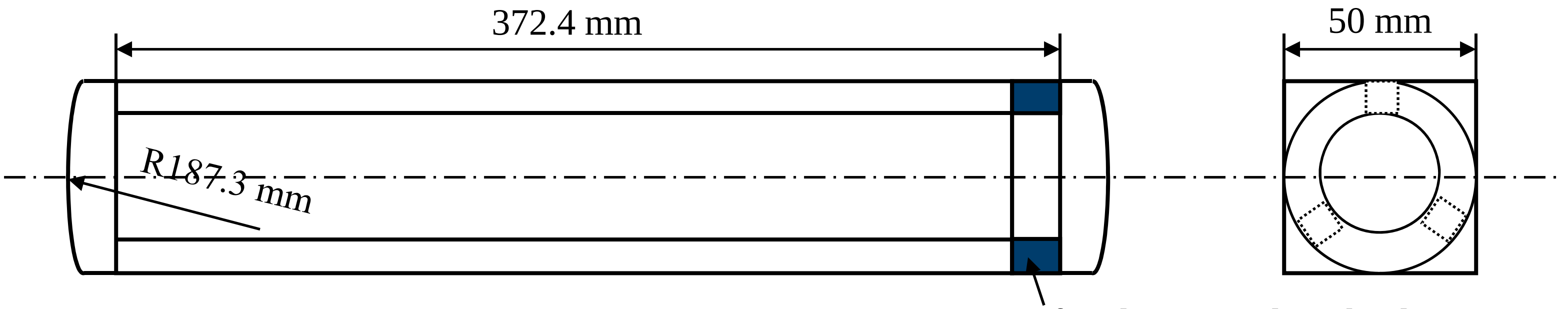
Introducing dispersion derivative at IP results in ion angle dependence on energy.

For 1 GeV SNS beam D'=2.58 is sufficient for full elimination of Doppler spread

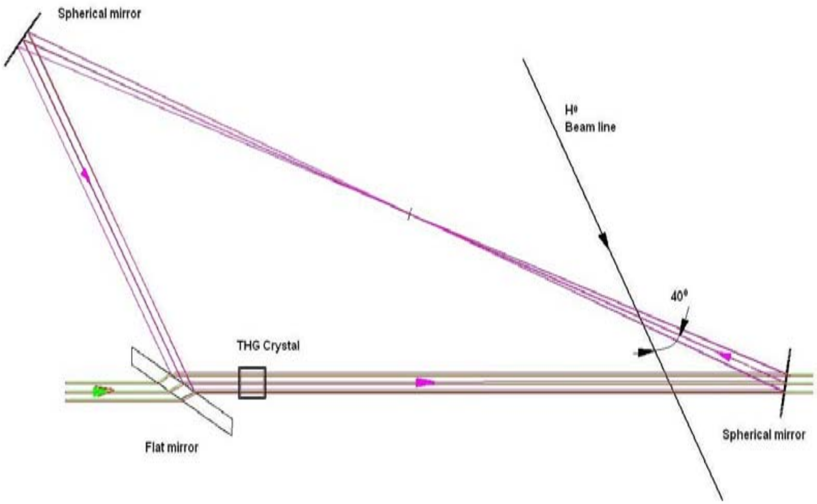
Required dispersion is a very nonlinear function of energy. Higher energy is much preferable.

OAK RIDGE National Laboratory

Fabri-Perot and Inside Crystal Conversion Schemes



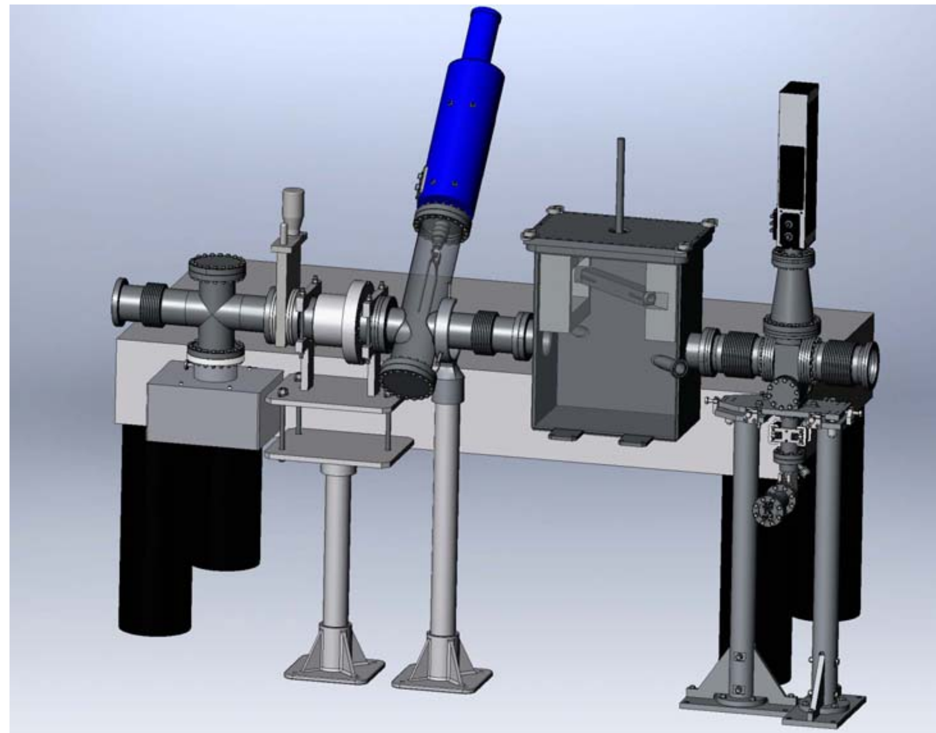
Design and production: Light Machinery
Finesse: ~ 37
Designed power amplification factor: ~ 10
R > 92% at 355 nm



Inside Crystal Conversion
Flat mirror is transparent to fundamental harmonics and reflects 355 nm light

New experiment place

Experimental assembly to replace HEBT straight section before the last bending magnet



New Choices for New Projects

Why H^- atom energy matters?

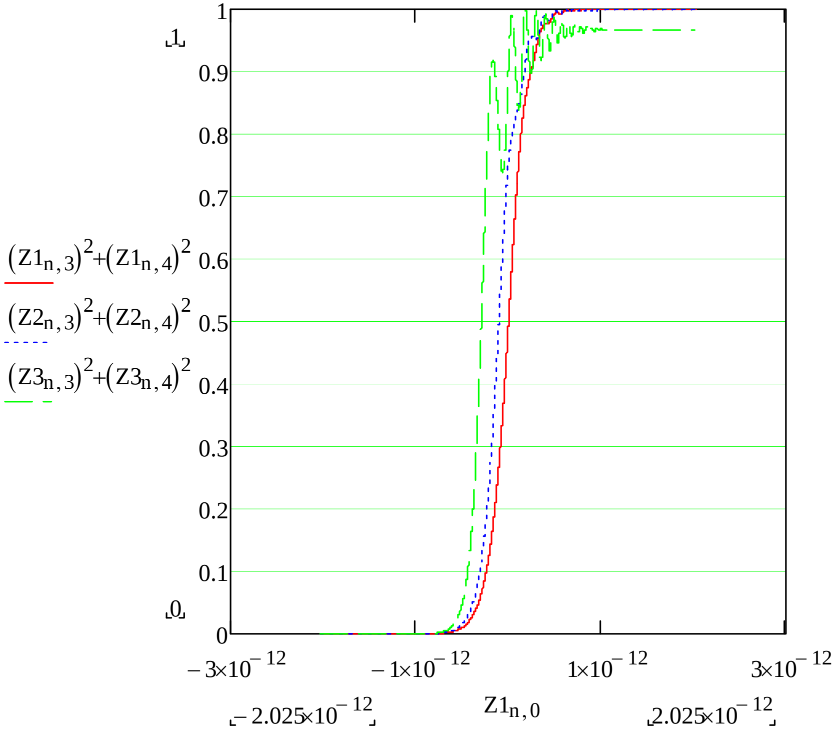
- **Doppler effect gives boost of photon energies – can use convenient IR instead of UV**
- **Magnetic field transforms into electric field in the rest frame of H^- beam as $\beta\gamma$- conventional warm magnets can be used for excited states stripping**
- **Lifetime of the excited states grows as γ - it reduces spread of angles in process of stripping**

SNS choice – n=3 for 1 GeV – only 3rd harmonic of 1064nm can reach the state, n=4 also a choice but needs more laser power

From 3.23 GeV the 1064 nm light reaches n=2 state in head-on laser-beam interaction – projects with E> 3.5 GeV can use infrared light – LHC upgrade linac (4 GeV) and Project X (8GeV)

LHC 4 GeV linac n=2 excitation

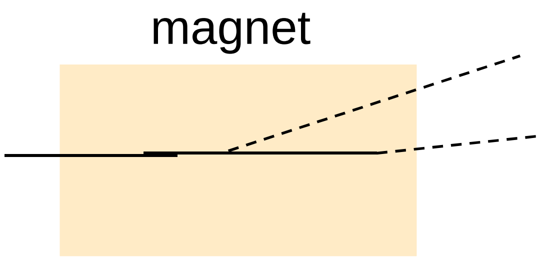
LHC case 4 GeV
SNS beam parameters
Ppeak=0.5 MW
Waist=0.6 mm
dE/E=0.6*10^{-3}
Rayleigh range=0.46 mm
Distance from waist=7cm
Excitation efficiency>98%



Q-switch laser 50 ps pulse 300 MHz repetition rate for LHC new booster
The average power = 2Hz*50ps*300MHz*0.6 ms*0.5 MW/Qcavity =.01 W
Qcavity=1000

Stripping of Excited States

Why angular spread?
Probabilistic process



two ions stripped at different time

The situation is involved
Spherical S(2,l,m) and Parabolic states P(n,n1,n2,m) are different

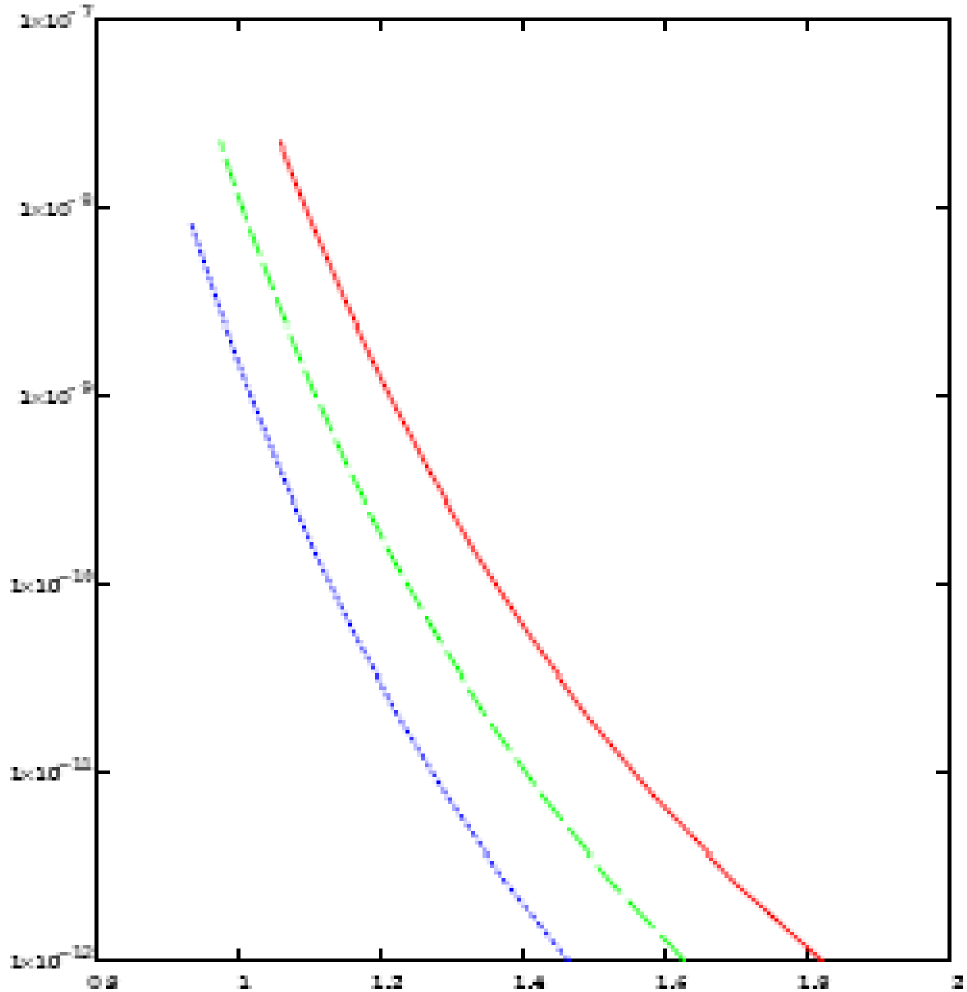
$$S(2,1,0) = \frac{1}{\sqrt{2}} P(2,1,0,0) - \frac{1}{\sqrt{2}} P(2,0,1,0)$$

Laser polarization ⊥ magnetic field

$$S(2,1,1) = P(2,0,0,1)$$

Laser polarization || magnetic field

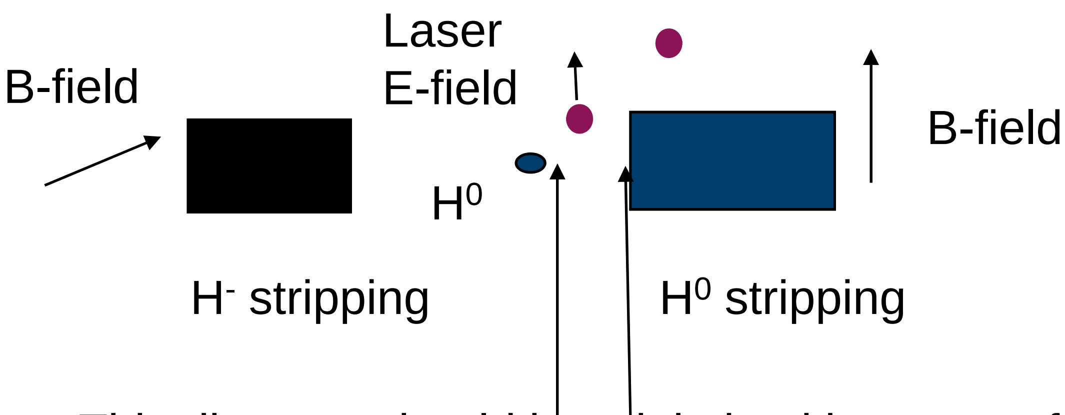
Angular spread dp/p (rms)=0.12 (0.07) mrad



Lifetime of n=2 states; m=1 is green (2 states total)

Laser Polarization and Magnets (usual injection)

Minimal emittance growth stripping

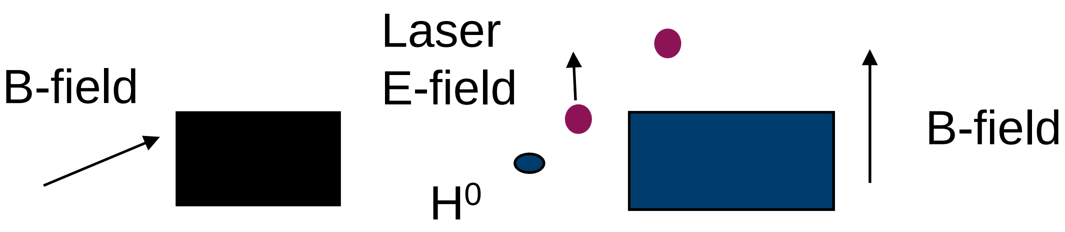


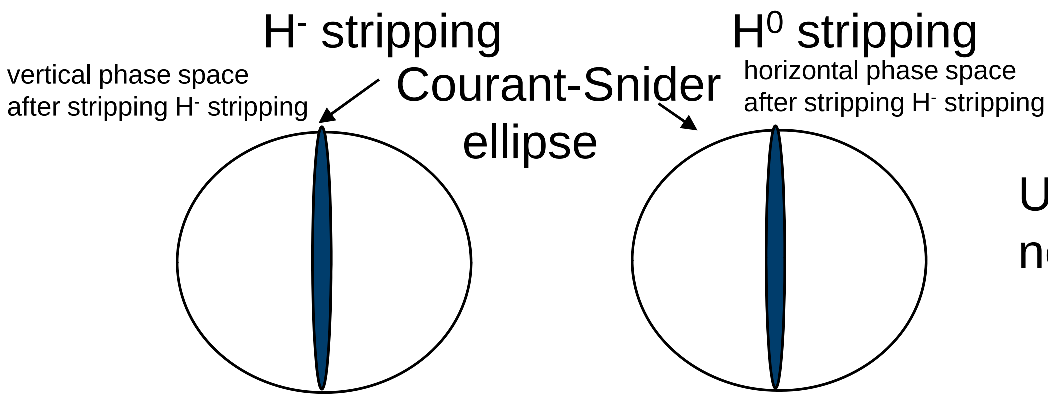
This distance should be minimized because of excited H^0 decay
Each 1 cm distance for LHC linac equivalent
to 1cm/1.6 $*10^{-9}$ (lifetime n=2)*5 (gamma)$3*10^{10}$ = 0.004 inefficiency
The IP shouldn't be in the strong field – Stark broadening suppresses the excitation
The ideal case – relative Stark broadening close to relative spread of energies
The method of stripping then converges to Yamane's proposed method of stripping

Booster beta-function limitations in this case
Emittance increase should be much less then the PS booster emittance
$3*10^{-6}/\gamma >> 0.07*10^{-3}/\beta$ - $\beta << 120$ m for injection region

Painting with Laser Stripping (new possibility)

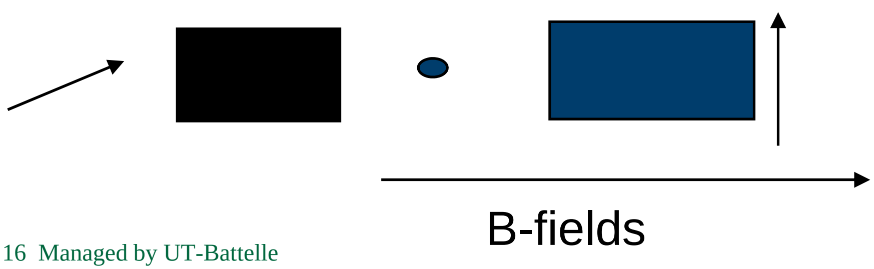
What if β=120 m? Then we don't need injection painting, at least in horizontal plane.

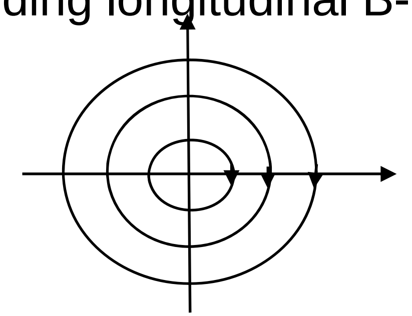




Unfortunately,
not matched distributions

It is possible to make it matched
self-consistent space charge by adding longitudinal B-field





X-y distribution
Uniform rotating
ellipse

Summary

- **Laser stripping POP project was a successful demonstration of stripping physics**
- **It opened the road to full-scale laser stripping device, follow-up development is underway – one SNS drawback is need for UV light**
- **The new projects with energies above 4 GeV may realize the stripping device with present technology**