OAK RIDGE National Laboratory

Charge Exchange Injection at SNS: Current and Future

MSU

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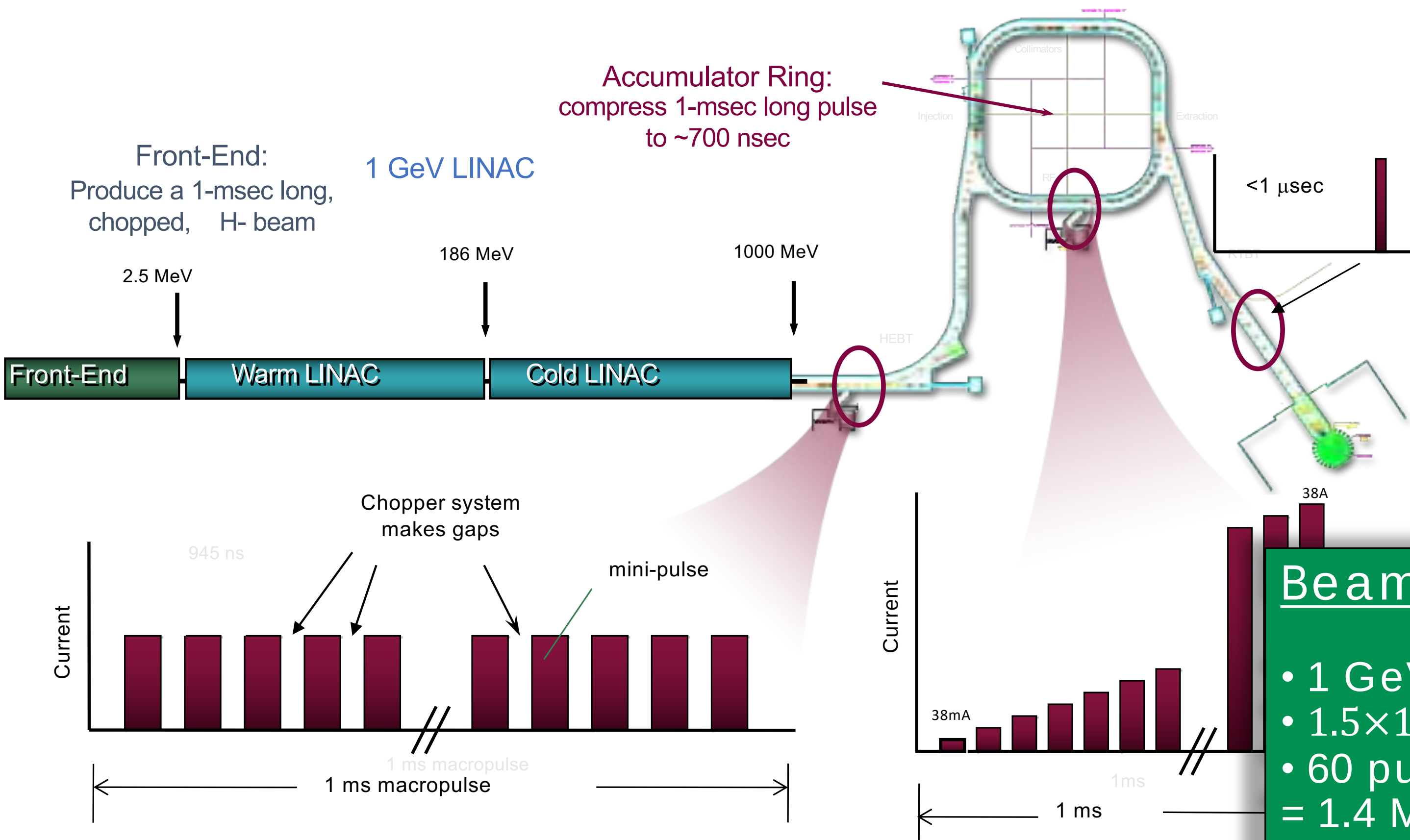
Sept 10, 2021

U.S. DEPARTMENT OF ENERGY

The Spallation Neutron Source Accelerator



Beam At Target:

- 1 GeV (0.9c)
- 1.5×10^{14} protons per pulse
- 60 pulses a second

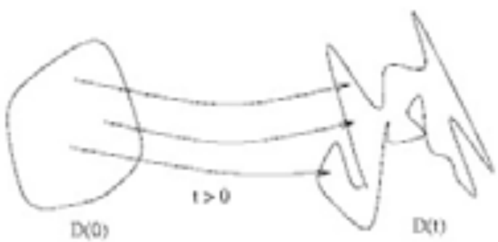
= 1.4 MW proton beam power

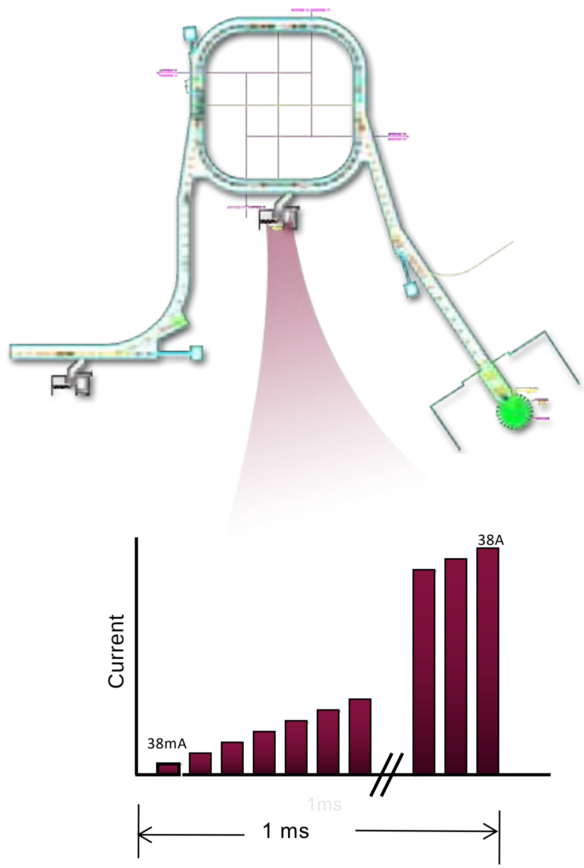
Part I: Foil history, development, success at SNS

High power accelerators get around Liousville's Theorem

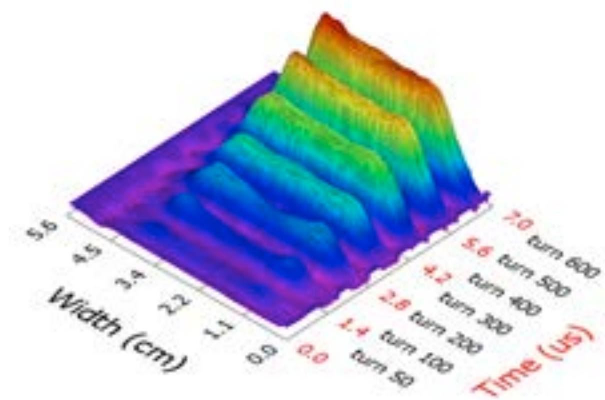
Liouville's Theorem:

The density of particles in a phase space is constant.
(for a Hamiltonian system).



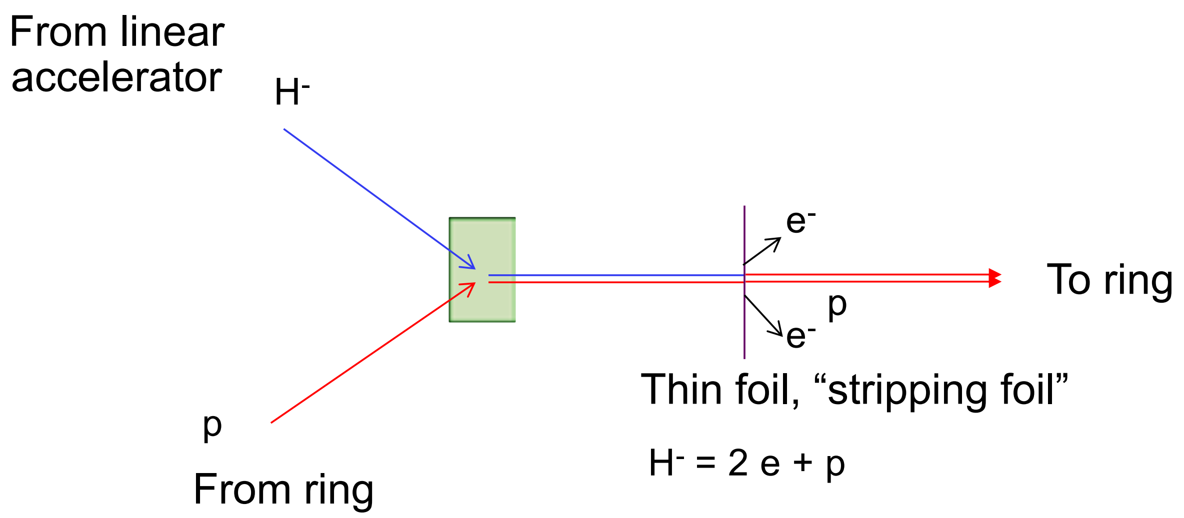


Measured bunches in the ring during accumulation



We are increasing the particle density. How?

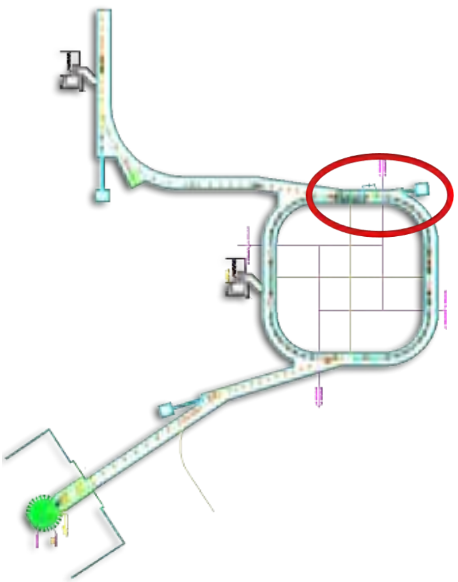
H^- Charge Exchange Injection Concept



In principle, we can accumulate extremely dense beams of particles in this way.

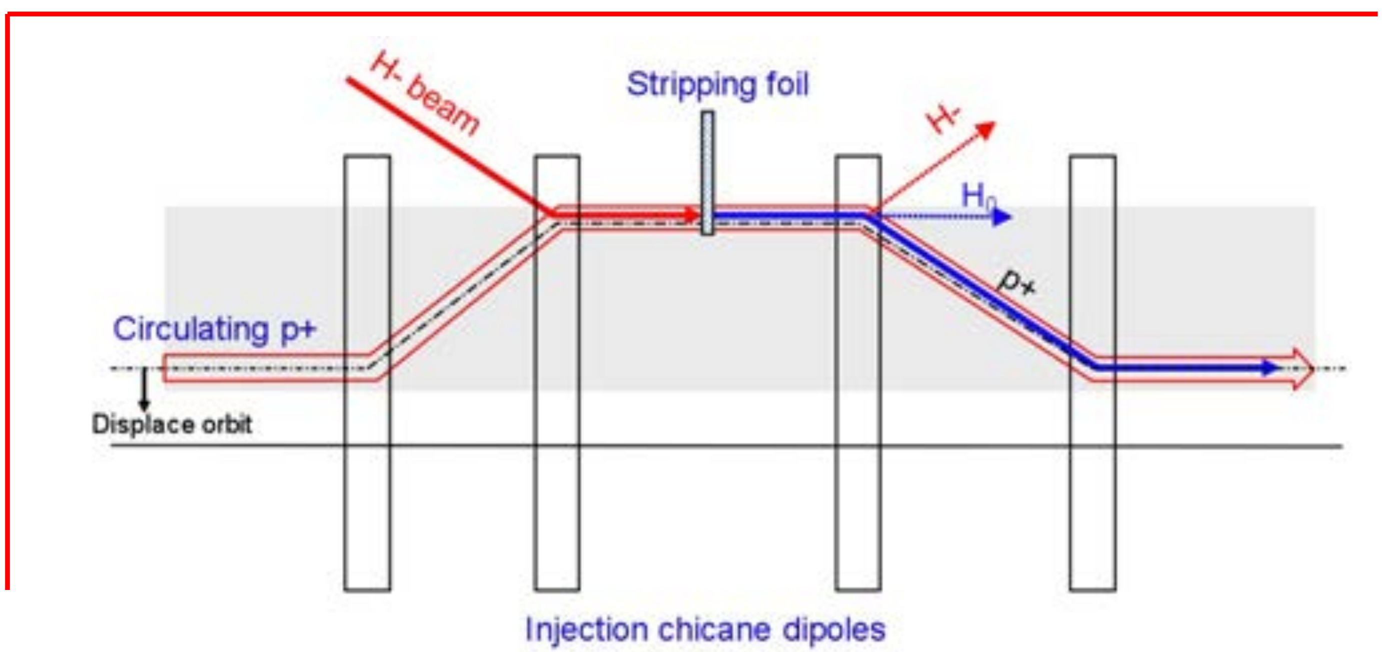
Unfortunately, the use of a foil to strip the electrons is limiting…

Charge exchange at SNS is utilizes dogleg bump and foils

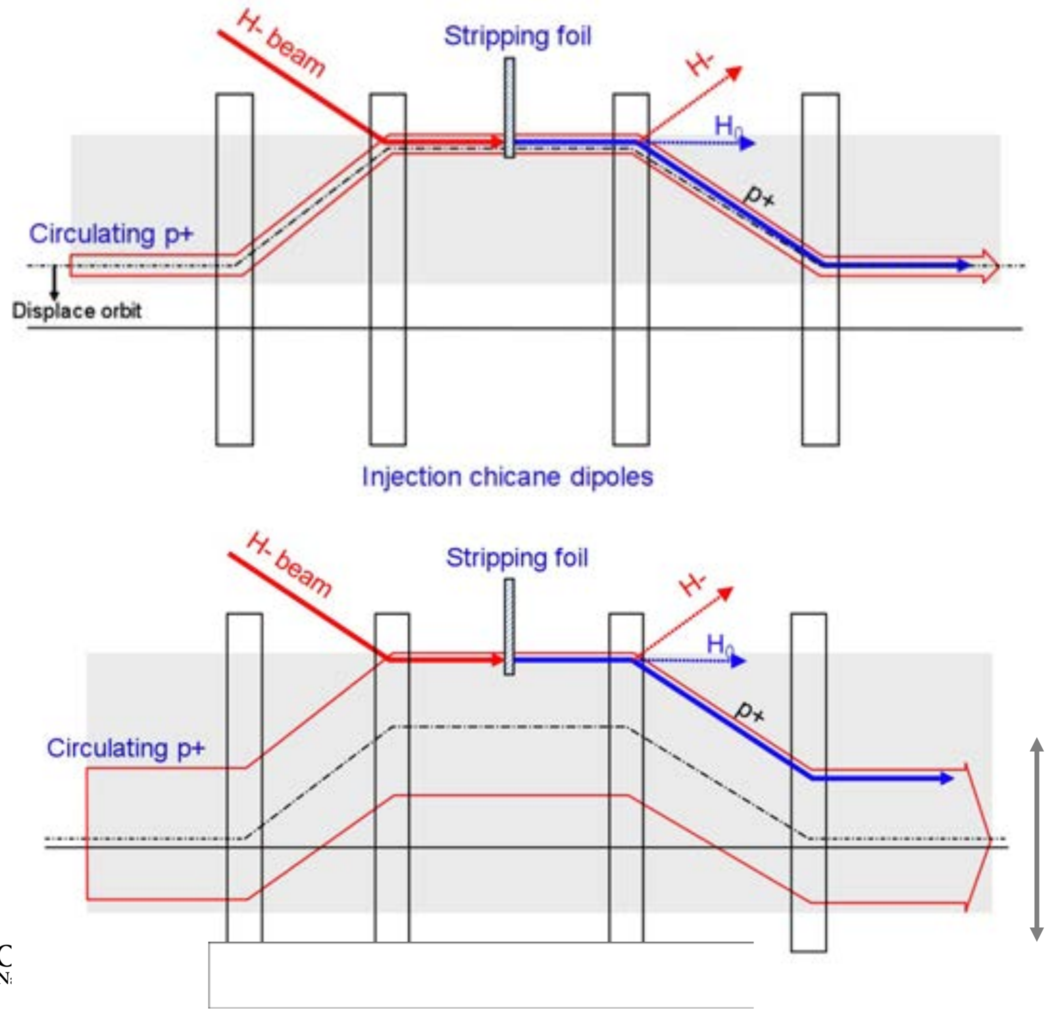


New Foil Used Foil

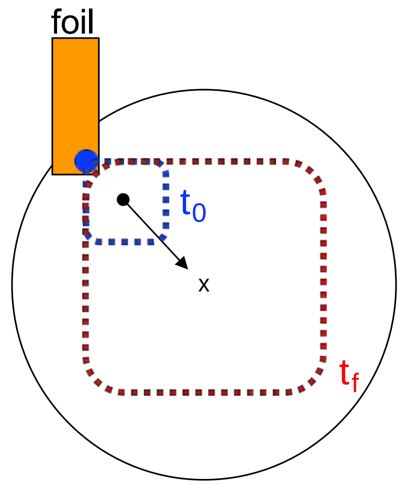
~400 $\mu g/cm^2$ nanocrystalline diamond foils



Injection painting is created with variable strength kickers



- Helps minimize circulating beam foil passes
- Helps build custom phase space distributions

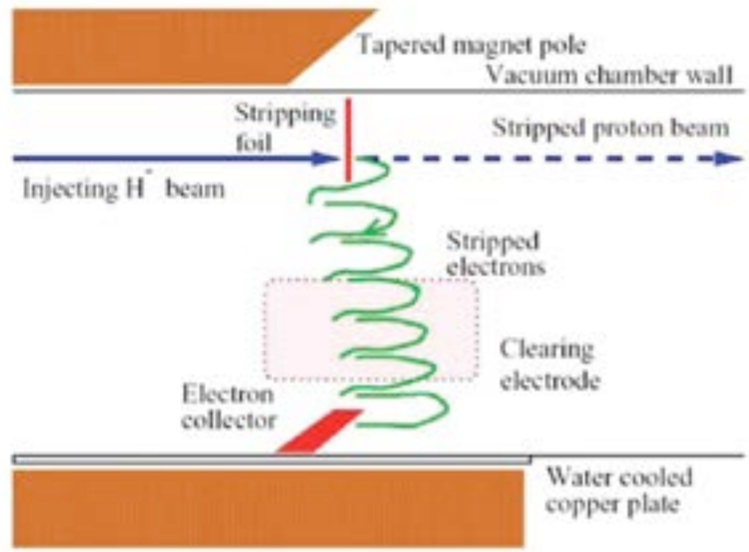


Painting regime

SNS had early foil and foil mounting issues that limited beam power

Early issues have been overcome:

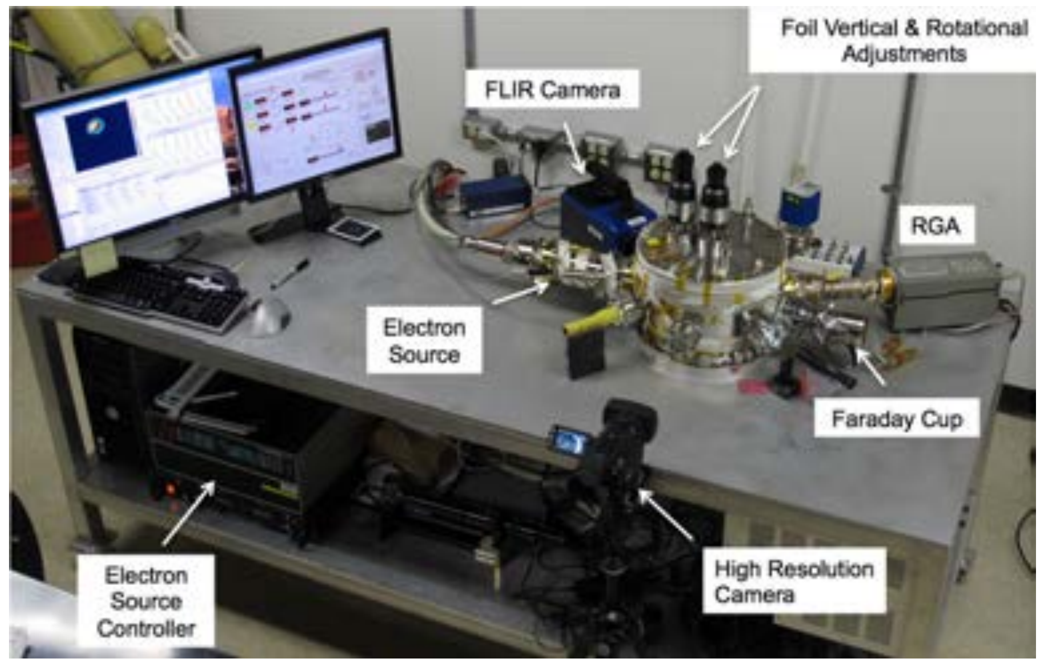
- Changed foil bracket from Al to TZM
- Aggressive foil R&D and production program



SNS Foils – Fabrication and Testing capabilities in house

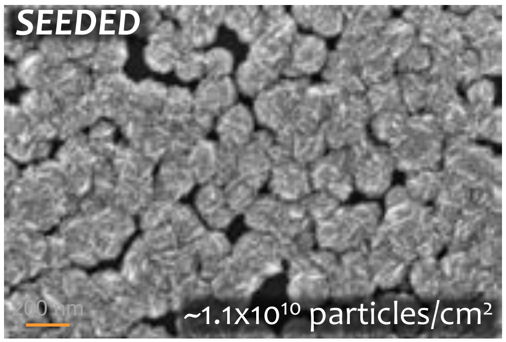
- CVD tool used to grow SNS foils at Center for Nanophase Material Science (co-located with SNS)

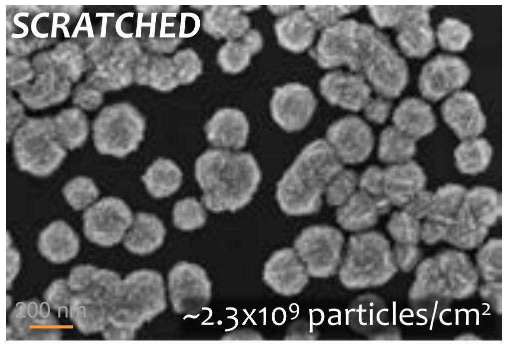
Pulsed, 30 keV electron beam, 5 mA, 0.3 mm^2 spot size can simulate 2.8 MW equivalent heat loads on small spot

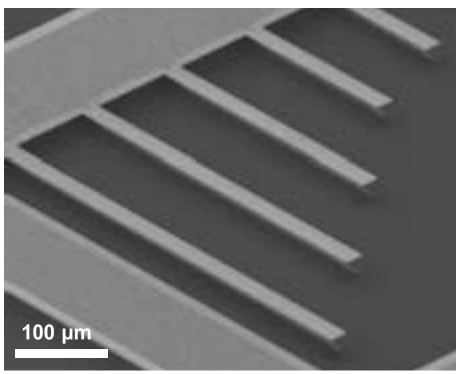


R&D partnership with center for nanophase material science focused on foil production and characterization

Analysis of Nanocrystaline Diamond Foil Nucleation Techniques







Photos Courtesy of S. Retterer

CNMS
Nano-scale Characterization

Grain Size Uniformity
Residual Stress
Changes during conditioning

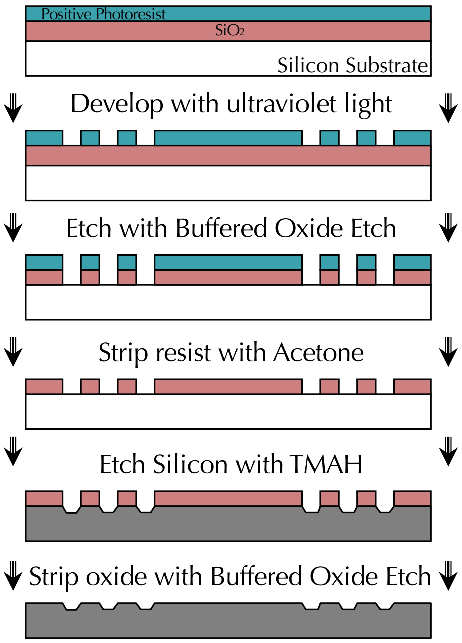
Test stand and SNS Operations

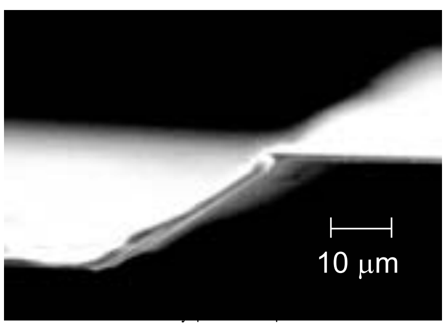
Foil Flutter
Holes
Curling
Buckling
Tearing

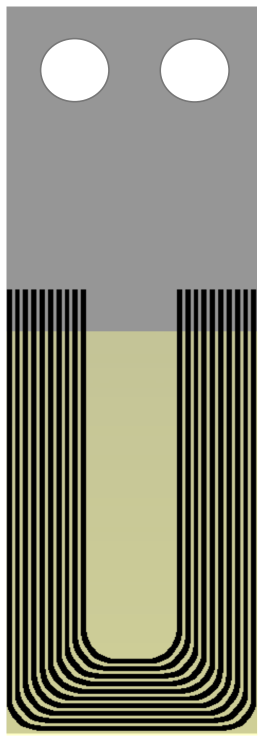
Connect observations to improve foil uniformity and reliability, and understand how performance is related to structure

Photo: C. Luck

Foil recipe development now produces foils that last months at 1.4 MW

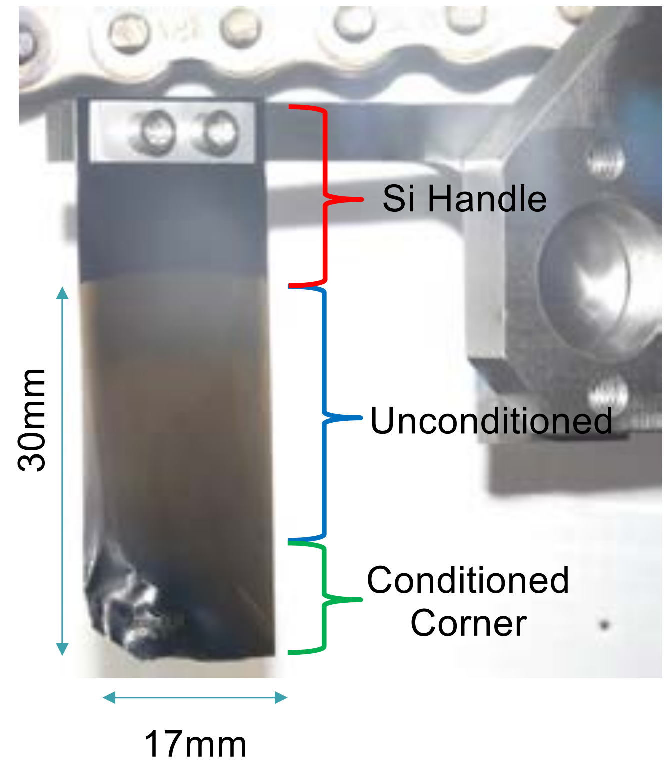






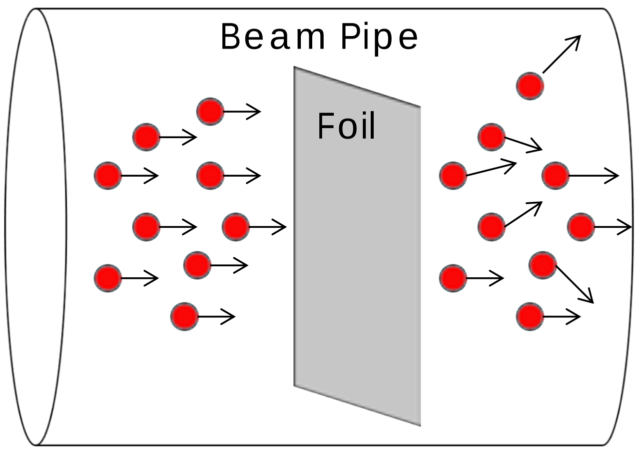
Engineered features

Used foil on bracket in SNS



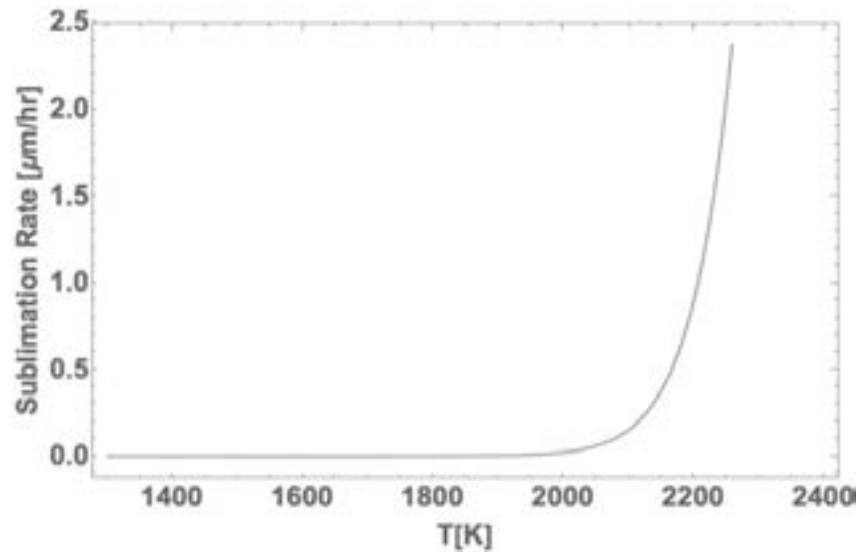
Foils have 2 major limitations

1. Radiation:



- Scattered particles hit beam pipe, cause radiation.
- Typical radiation: 1 rem per hour

2. Foil sublimation limit :

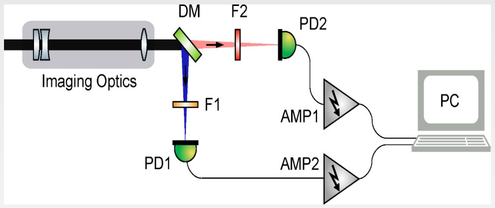


- There is a practical beam power density limit for foil use.
- Until recently, relationship between foil temp and beam power unknown

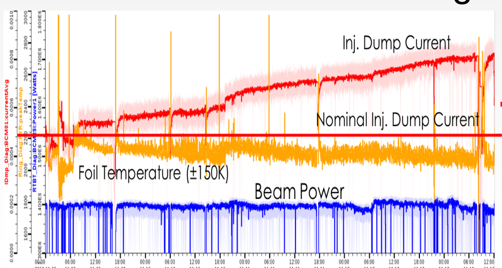
These problems limit achievable beam power

Foil temperature and sublimation measured for first time

Foil temp measurement



Beam-based foil thinning



1st prediction of failure limit

Foil test stand experiments

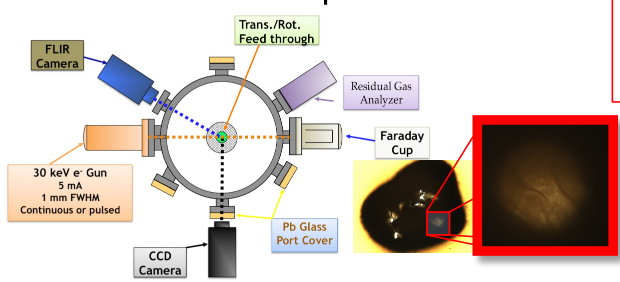
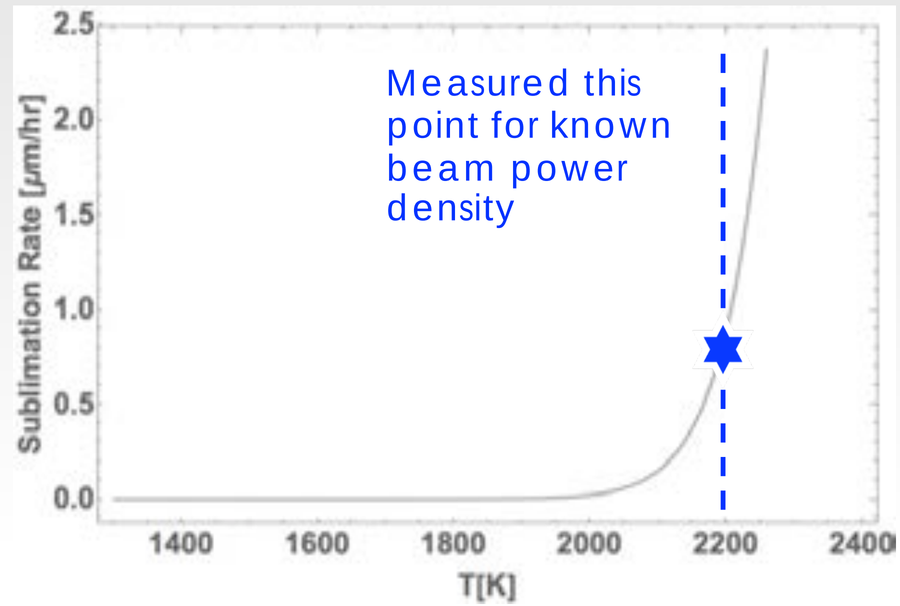


Figure 2.1 - Illustration of the Foil Test Stand

2nd prediction of failure limit

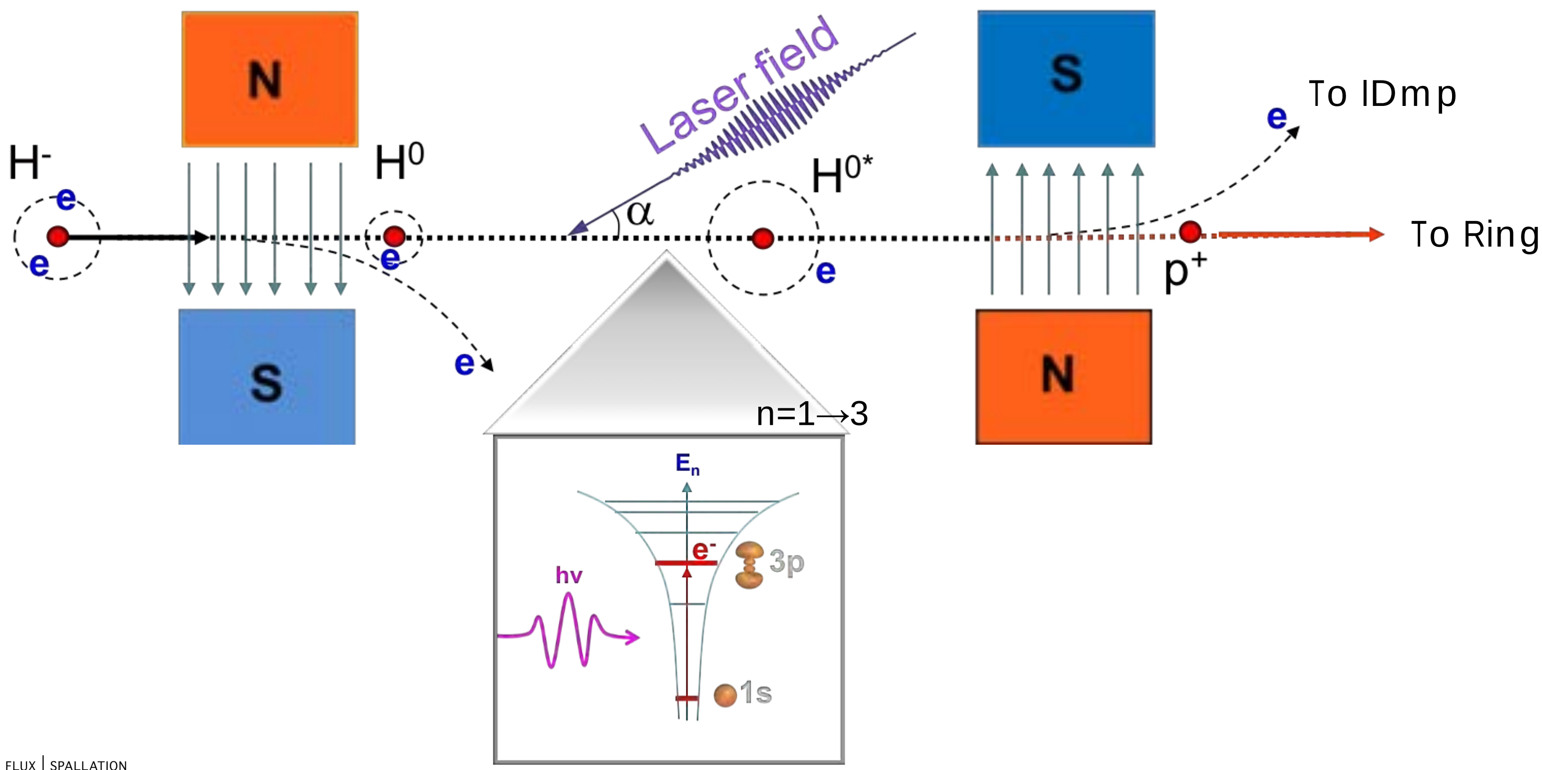


Practical beam power limit for foil use at SNS is 6-8 MW for 1 – 1.3 GeV

Part II: Replacing foils with non-interceptive technique

The Concept: Laser Assisted Charge Exchange (LACE)

"Doppler effect" formula $\lambda_0 = \frac{\lambda}{\gamma(1+\beta\cos\alpha)}$,



Primary Challenge has historically been laser power

1984
- Initial concept proposed
- Required unrealistic laser powers, due to energy spread in ion beam

2006
- Laser divergence proposed to accommodate energy spread
- 6ns stripping POP achieved with 10 MW peak UV laser

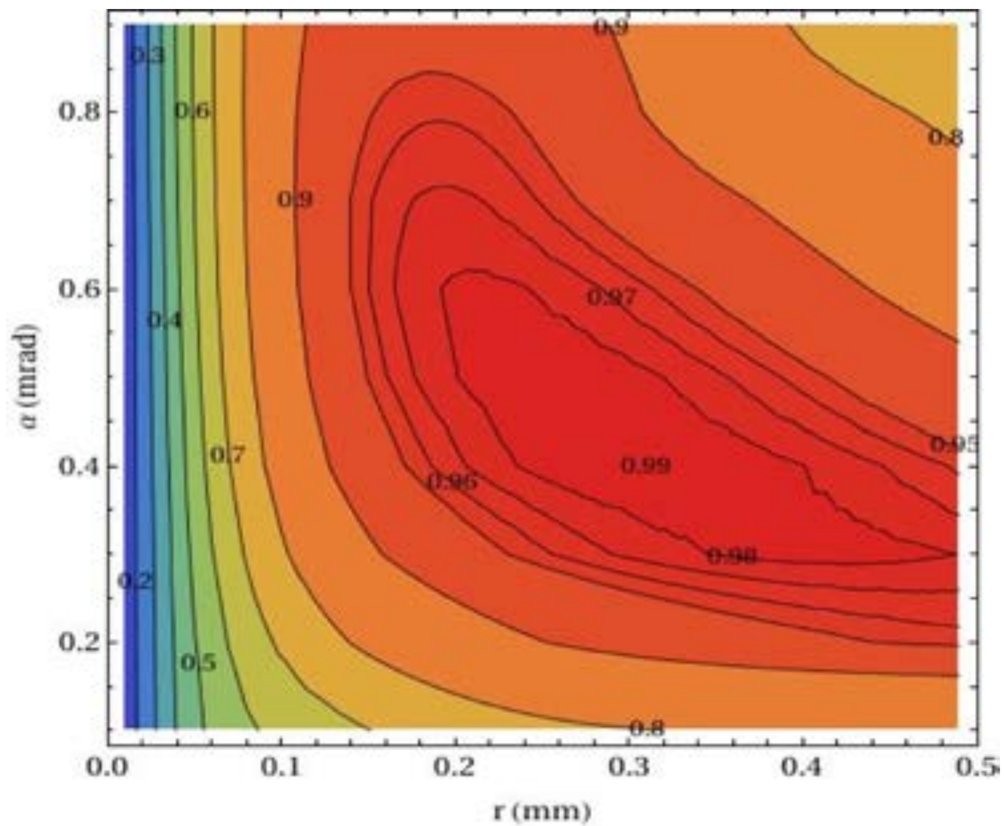
2015
- Ion beam laser power savings techniques, reduced required laser power by x10
- Temporal matching, reduced average power by x100
- 10 μs macropulse stripping with 1 MW UV peak laser power

Now
- Full duty factor capable method proposed
- Sequential resonance reduces required power by x3-4
- POP experiment underway
- Moving to green laser will give x2 increase in laser power

Challenges with precision of laser parameters

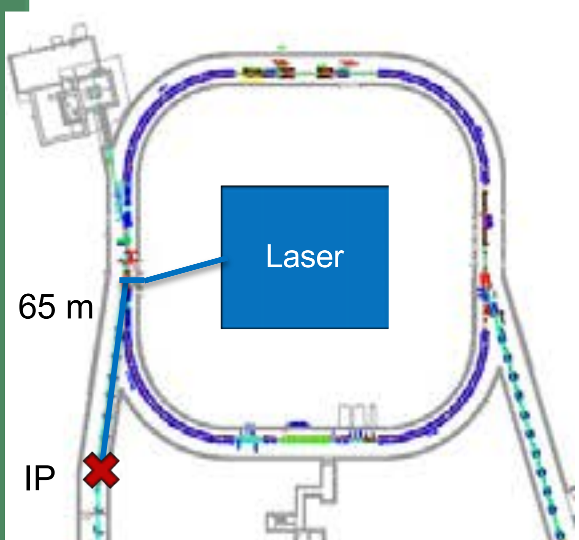
- Experiment requires very high precision in laser angle.
- This is an alignment and stability challenge

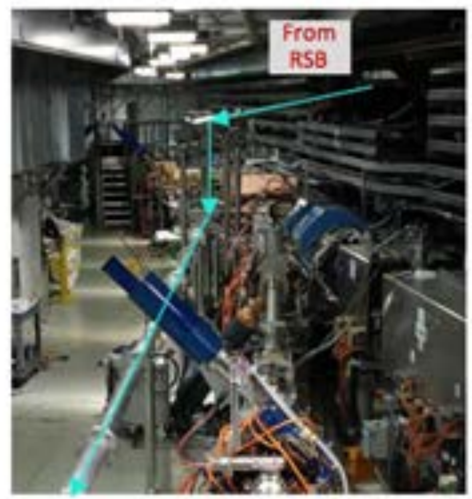
Stripping Efficiency vs Laser Radius and Angle

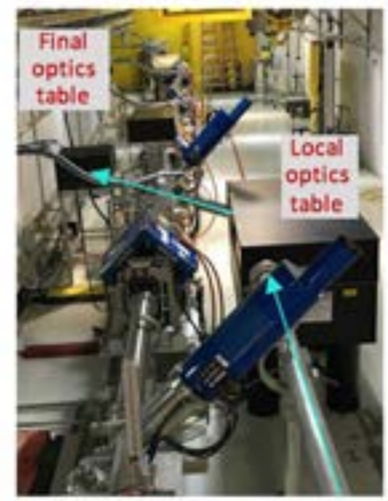


Challenges with laser Transport Line

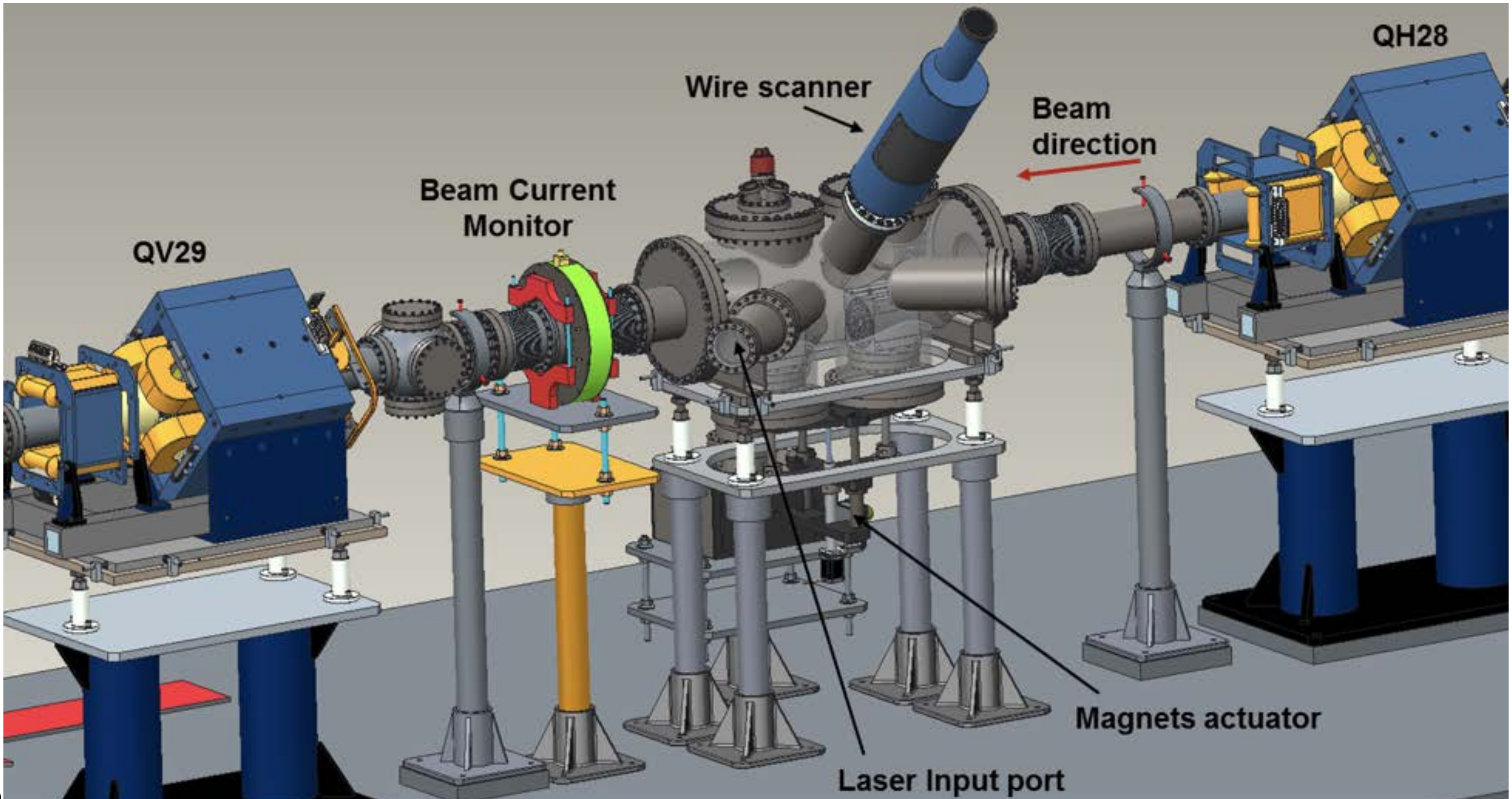
- Due to high radiation near the laser-H^0 IP, the laser source had to be placed in a remote location, 65-meters away
- A laser transport line (LTL) was retrofitted into the existing accelerator tunnel
- LTL is significant source of instability
  - Uncontrolled environment (i.e., non-evacuated, vibrations, temperature & humidity changes)





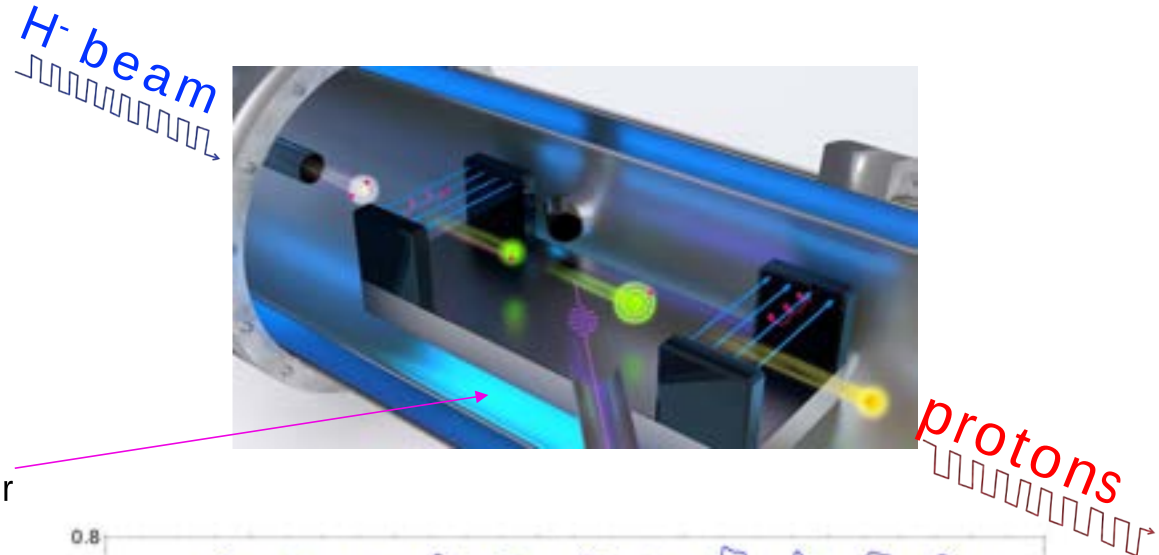


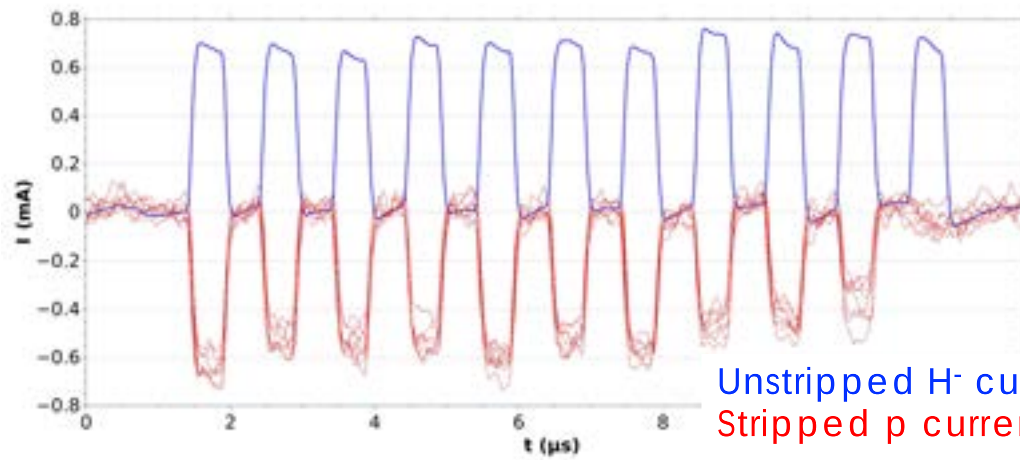
Experimental vessel and setup was installed



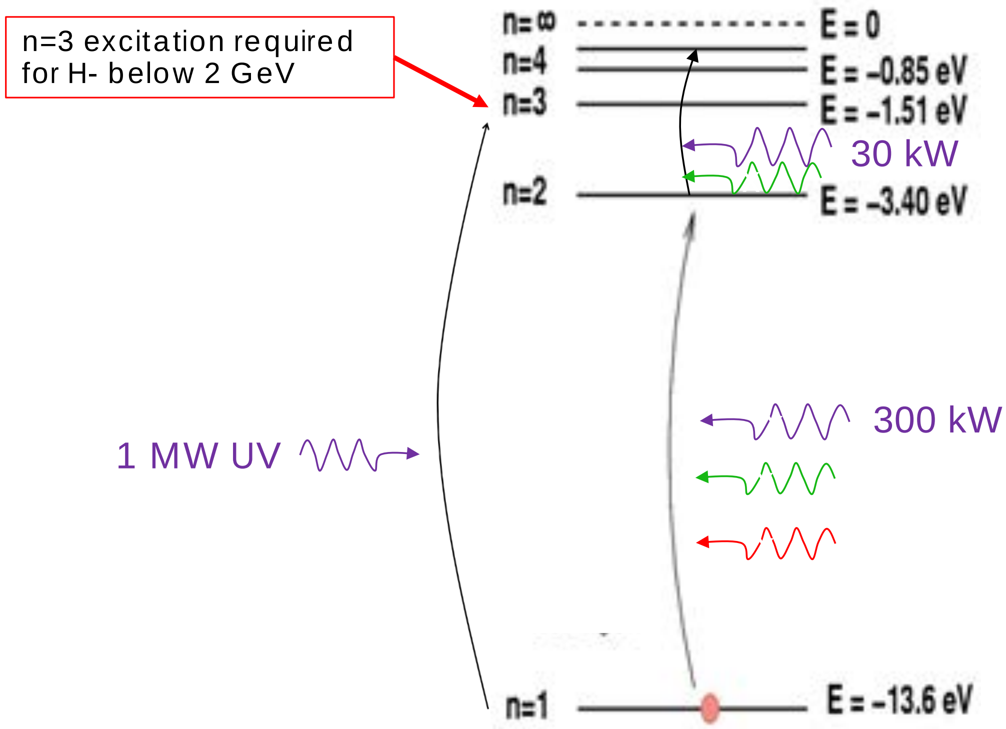
Status: Experiment demonstrated 95% stripping efficiency for 10μs

- 1000x better than first 6 ns experiment, but 100 time less than needed
- Requires 1 MW peak power
- Limitation to go to full 1 ms was laser power – can't hold on to 1 MW peak for 1 ms





Recent Breakthrough: Sequential resonance excitation is the solution to power challenge



Power savings in two ways:

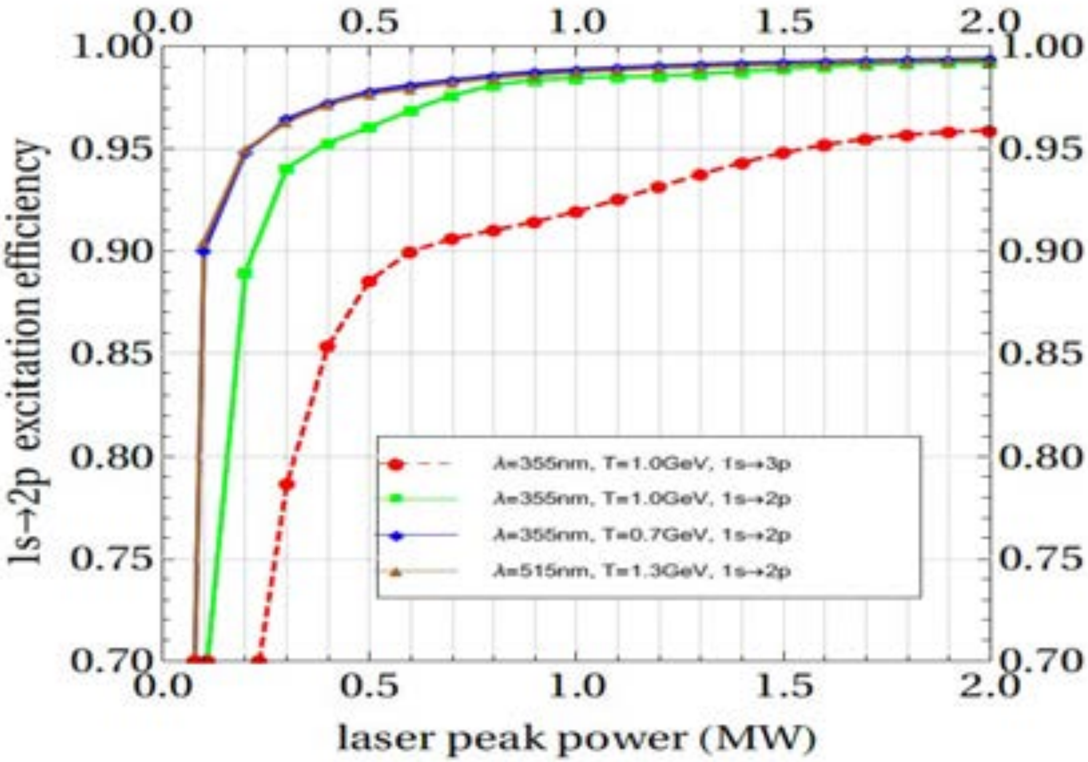
1. Less power required for each excitation
2. Possibility of using other laser wavelengths. Generating UV laser from an IR laser requires cutting original power twice in the harmonic conversion

This makes LACE operationally feasible

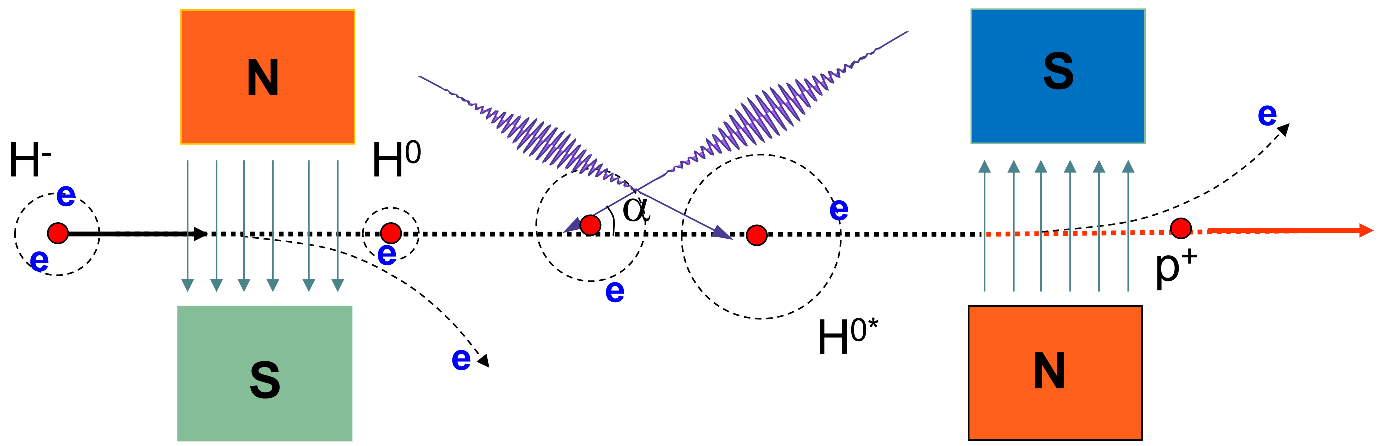
Sequential resonance excitation provides many benefits

First Step n=1→2 is extremely efficient for certain cases:

- UV at 700 MeV and Green at 1.3 GeV (blue and brown curves)
- Red curve was first experiments at SNS



Two laser-ion interactions in sequential resonance scheme

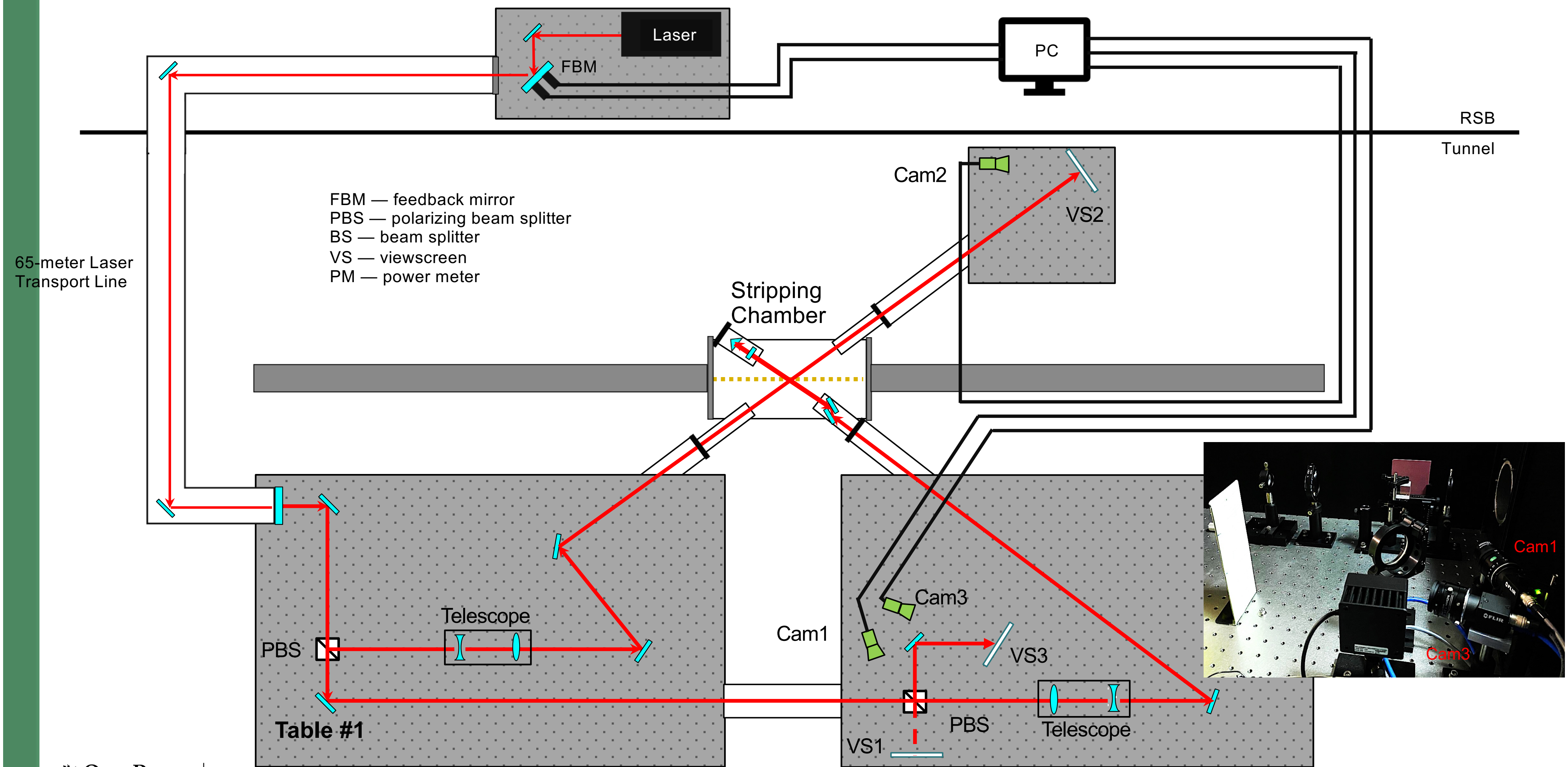


For proof of principle experiment, retrofit original vessel to save cost

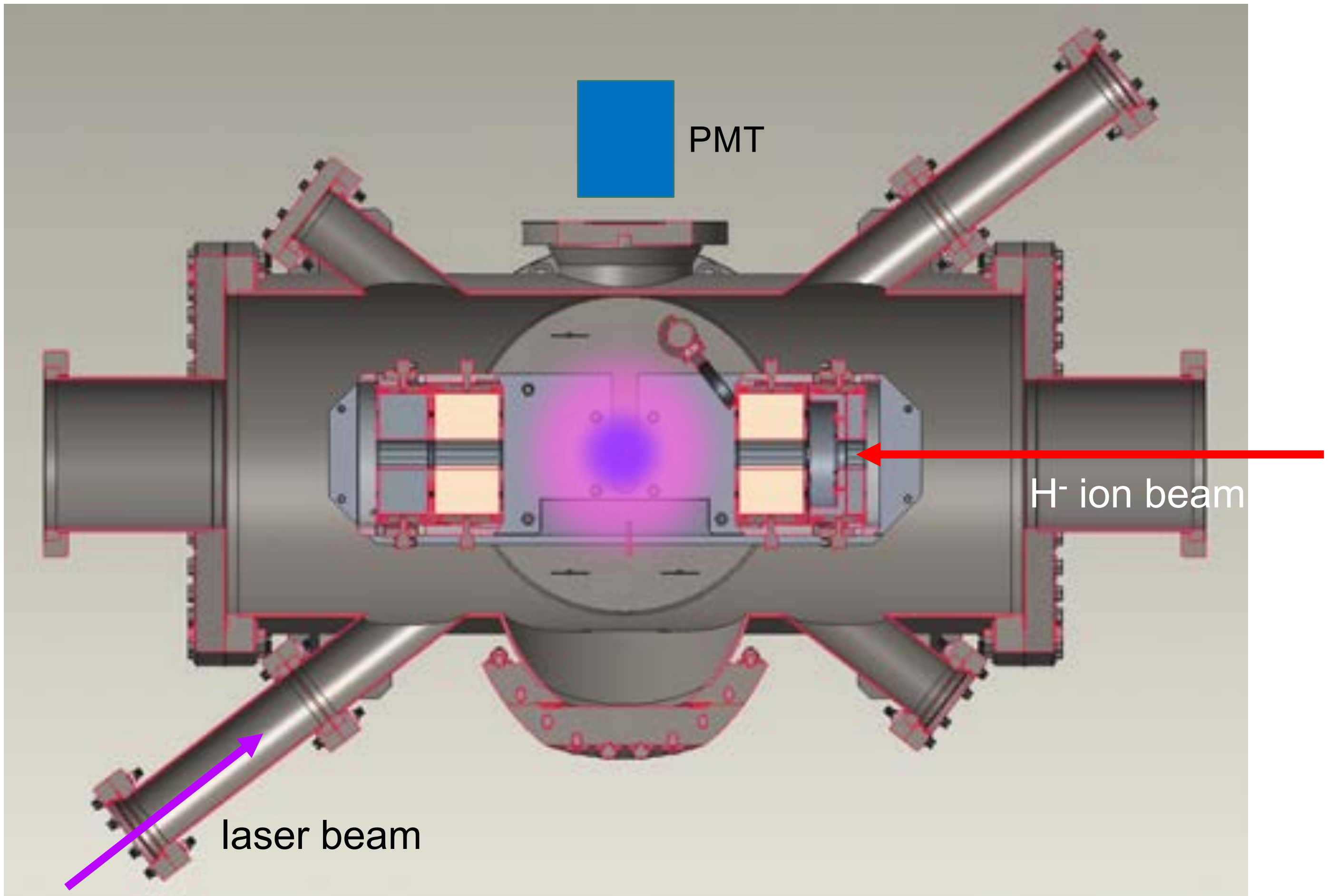
Chose setup: n = 1→2, and then n = 2→4

Current System Layout

Feedback stabilization



First step was to confirm n=1->2 excitation

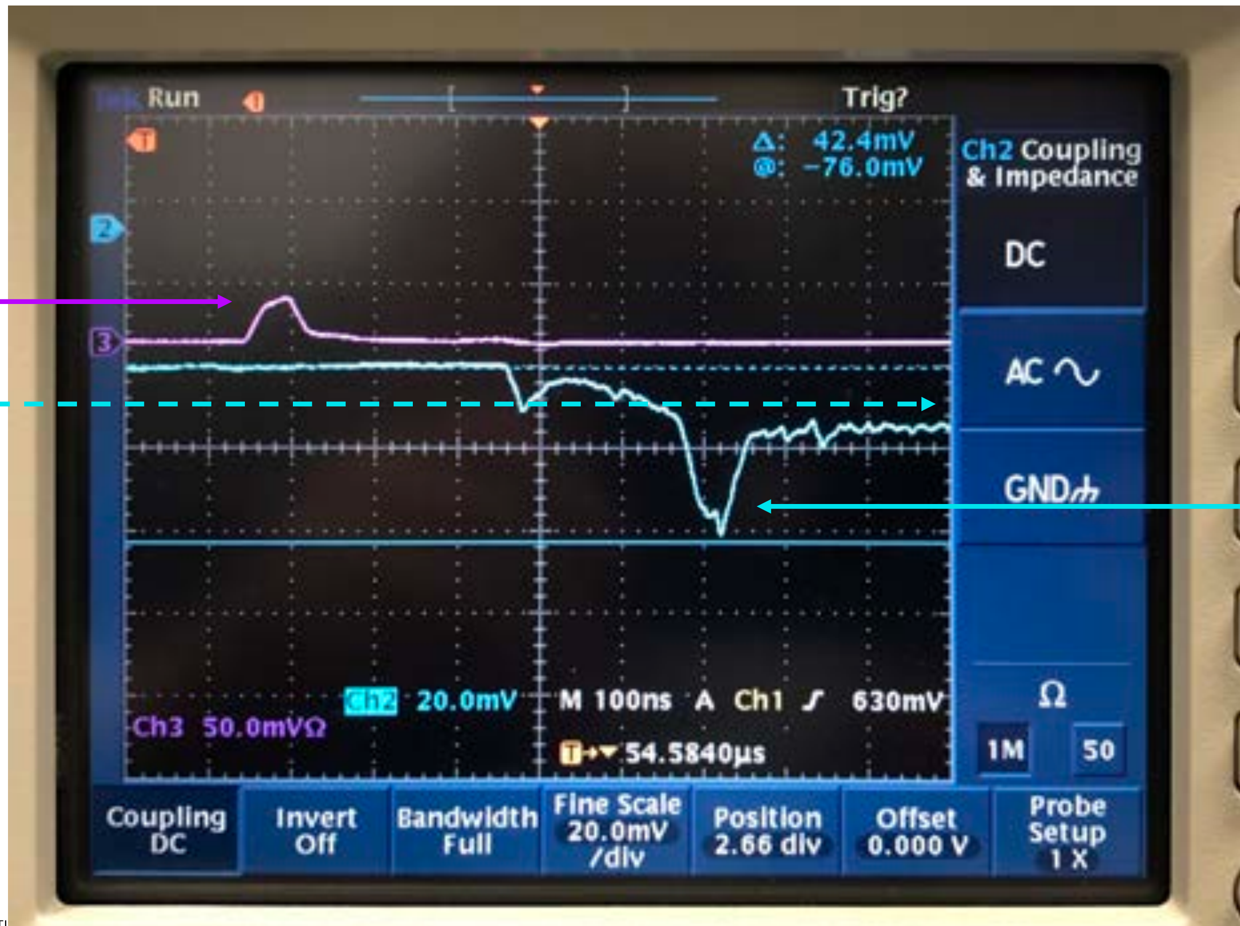


- Excite n=1->2
- Measure fluorescence from n=2->1 de-excitation
- Wavelength of detected light depends on angle of view

Experimental results confirms 1st excitation step

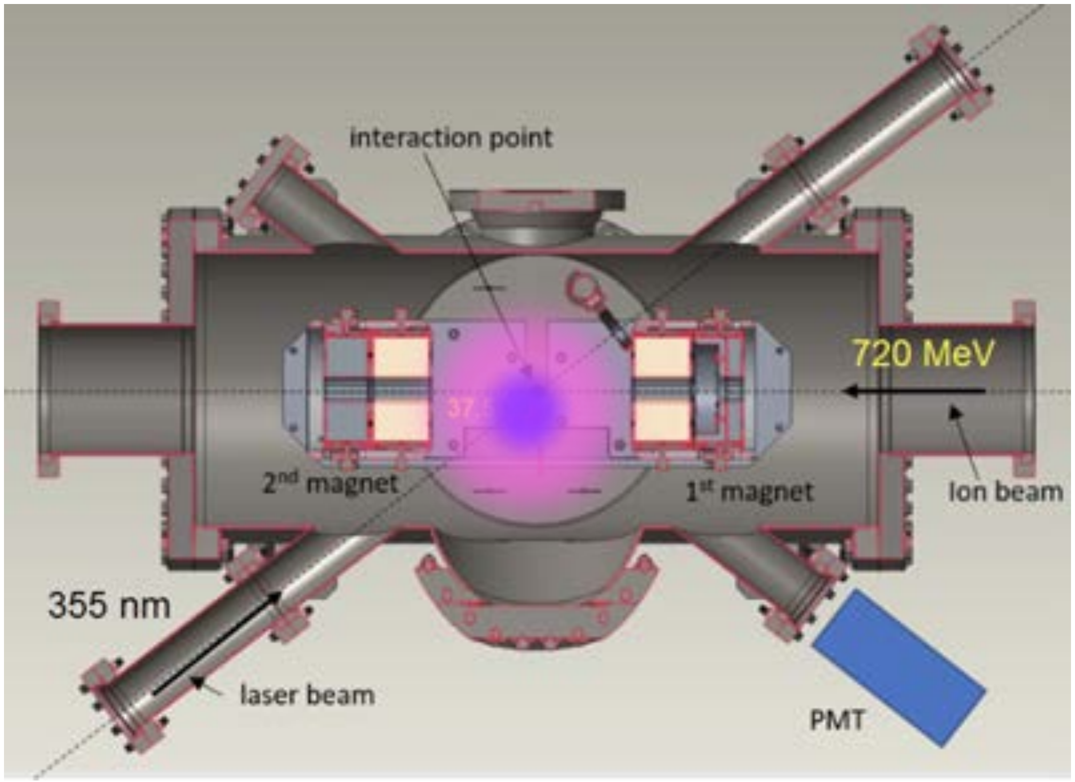
Laser signal

Beam loss



Flourescence (de-excitation) signal

First attempt to detect 1st step with fluorescence: We all do dumb things sometimes…

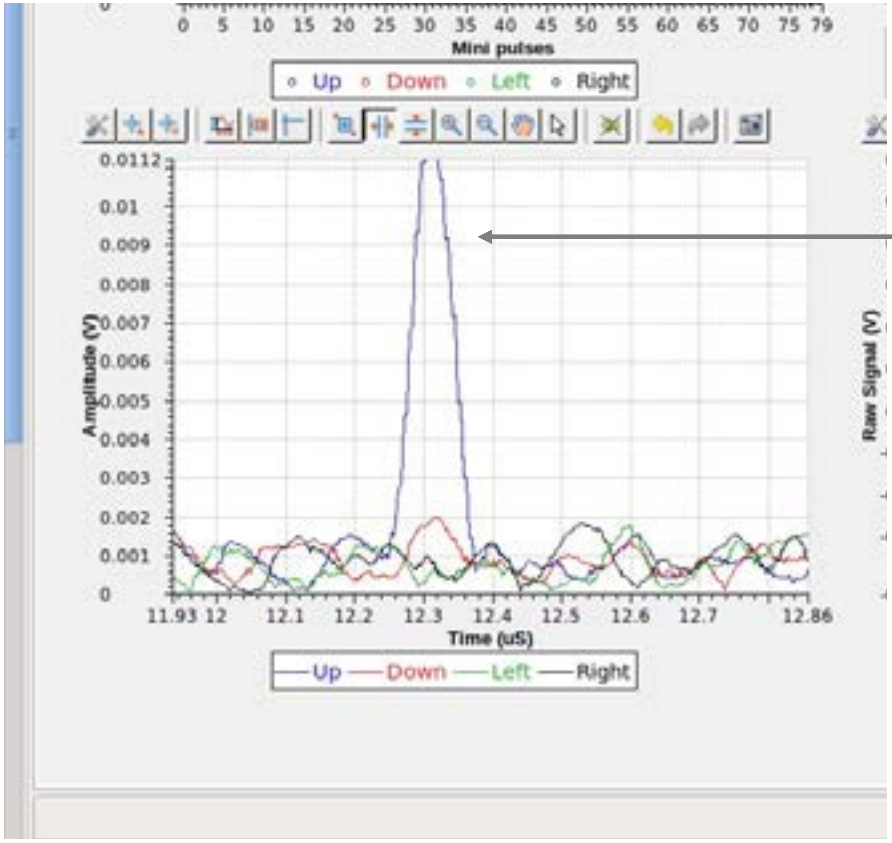


We put the light detector exactly at position where light would appear at laser wavelength in lab frame.

Couldn't untangle it from laser light reflections.

Duh 🙄….

First detection of 2-excitation stripping achieved

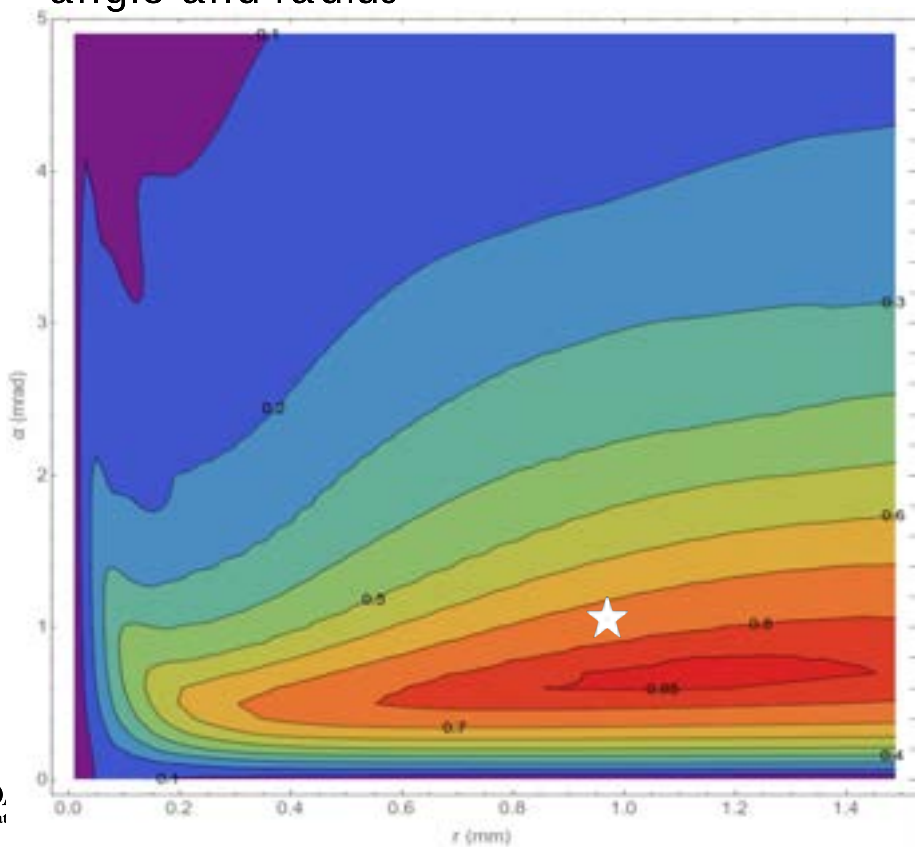


0.6 mA of protons detected

- Efficiency is very low. Why?

Retrofitting previous experimental vessel does not allow ideal laser parameters.

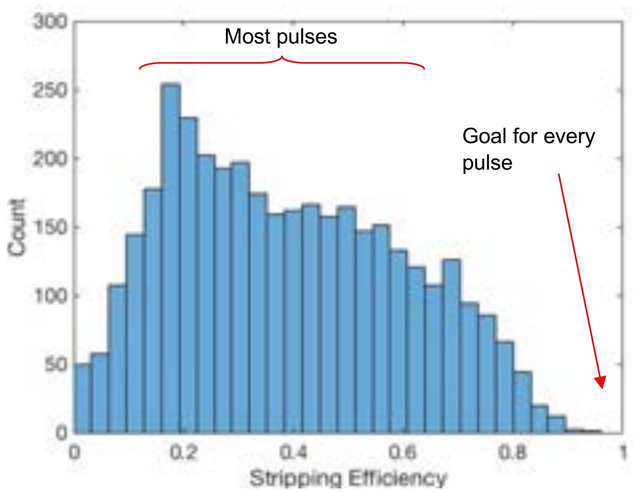
First step excitation efficiency vs laser angle and radius

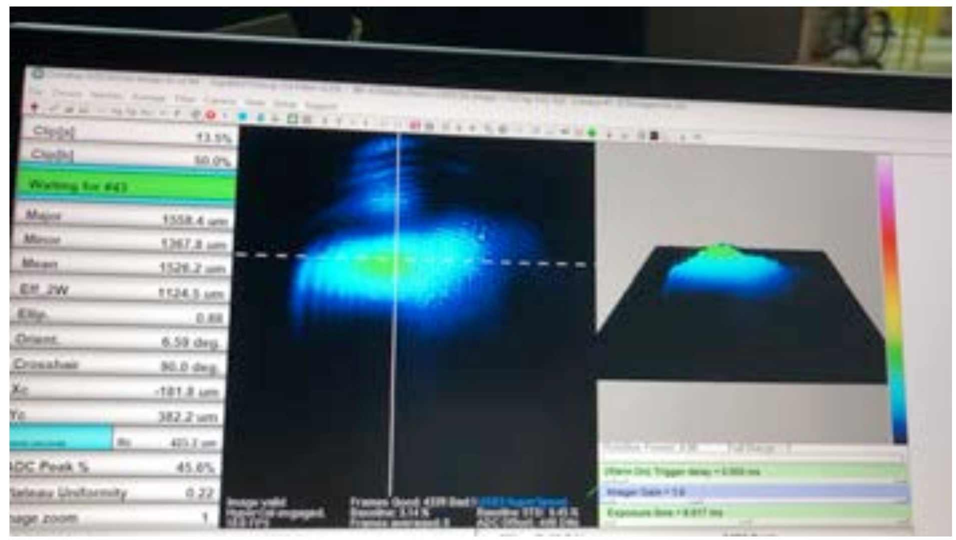


Due to non-ideal laser parameters:

- Can achieve no better than 70% excitation from n=1→2
- Can achieve no better than 30% excitation from n=2→4

Laser beam positional and spot stability is major issue, seems to be gettering worse





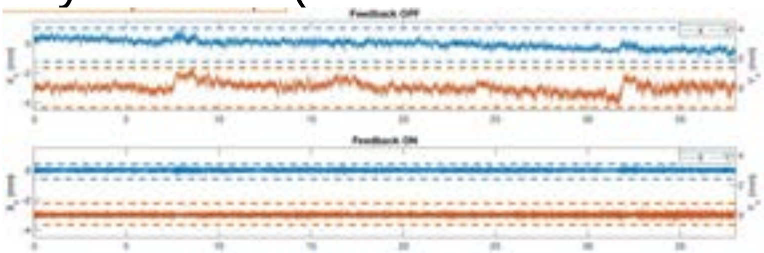
In 10 us experiment, pulse to pulse efficiency was low in original experiment due to laser positional jitter.

Now see significant instability in laser spot size – cause unknown

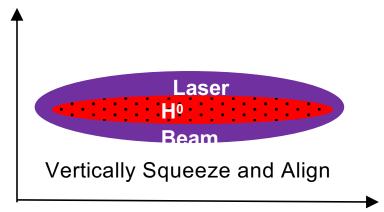
Efficiency improvements will be implemented

To increase stripping efficiency with this set up, we can:

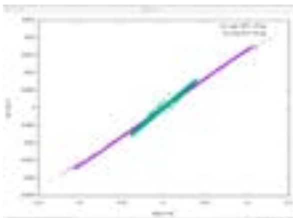
- Improve stability of laser (feedback and troubleshoot)



- Squeeze vertical beam size, so laser density can be high

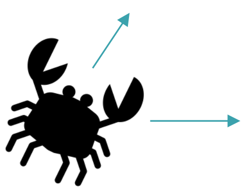


- Minimize ion beam energy spread

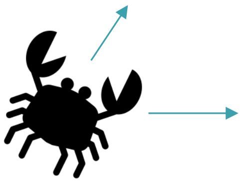


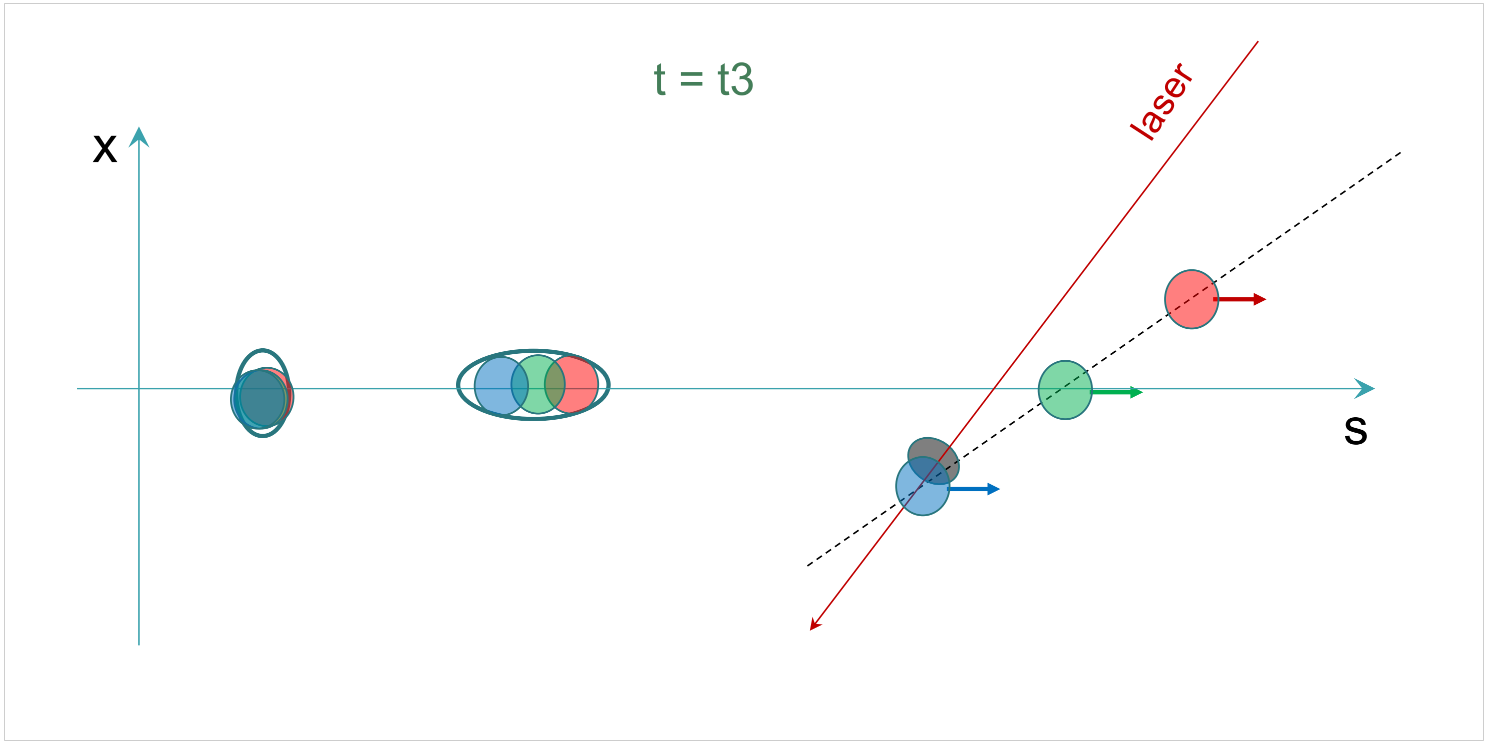
- Tailor the dispersion to provide energy spread compensation

- Squeeze the beam longitudinally



Longitudinal Crab-crossing squeeze





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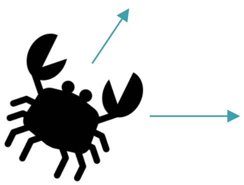

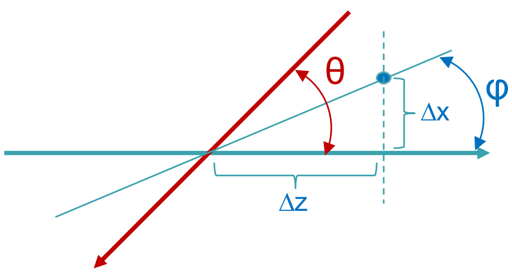

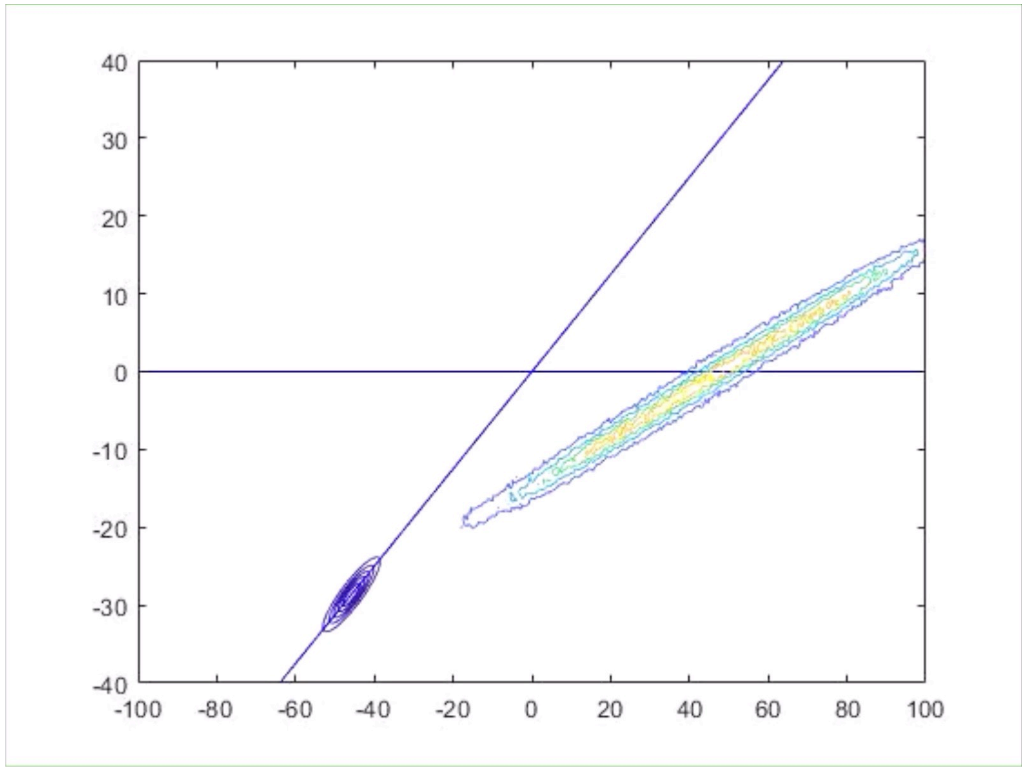

$$D = \frac{\Delta z}{\Delta w/_{w}} \frac{\sin\theta}{\beta+\cos\theta} \approx \frac{L}{\gamma(\gamma+1)} \frac{\sin\theta}{\beta+\cos\theta}$$

Timeline

2019-2020
- Demonstration of 1st step sequential resonance – Done!

2021-2022
- Low efficiency demonstration 2nd step sequential resonance laser-assisted stripping – Ongoing
- High efficiency demonstration 2nd step sequential resonance laser-assisted stripping – Soon
- Begin design of real injection concept – Ongoing

2023-2024
- PPU upgrade to 1.3 GeV @ 2.8 MW at SNS
- Switch to green laser technology and repeat stripping demonstration
- Complete design of real injection concept

2025-2026
- Install test concept in SNS injection region
- Test laser stripping for real injection into ring