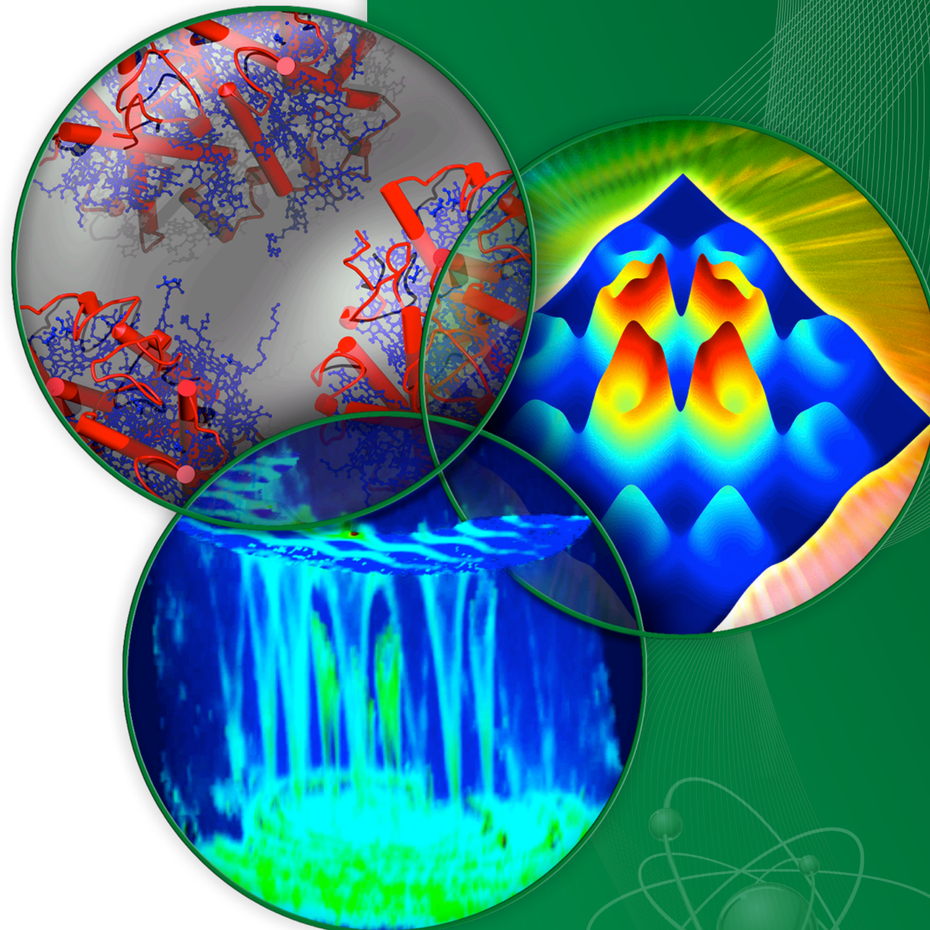
The SNS Laser Stripping Experiment and its Implications on Beam Accumulation



Sarah M. Cousineau
(on behalf of the UT/ORNL/Fermilab laser stripping team)

COOL Workshop
Jefferson National Laboratory
October 1, 2015

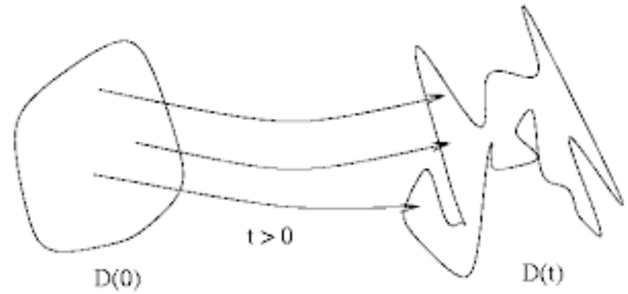
ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

Achieving High Beam Densities

Liousville's Theorem:

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



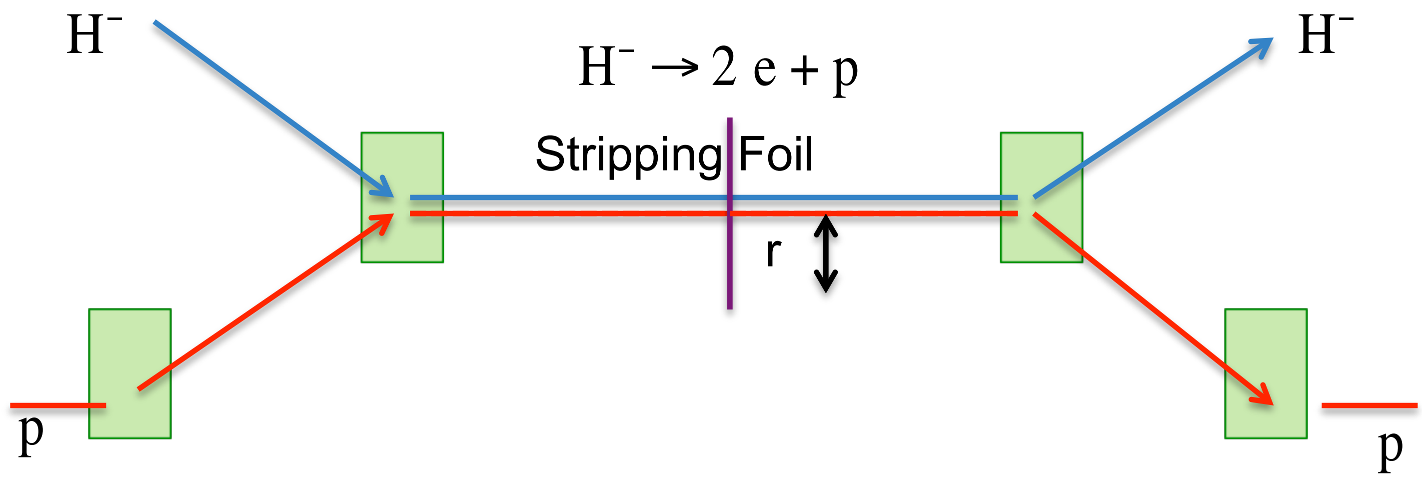
Increasing beam density requires non-Liousvillian techniques:

- **Increase beam density after injection:** Cooling
  - Electron cooling
  - Stochastic cooling
  - Laser cooling
  - …

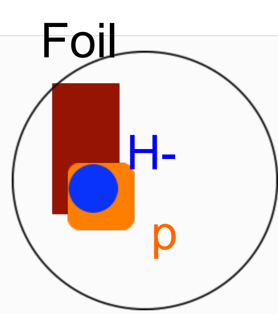
→ **COOL15**

- **Increase beam density during injection:** H^- charge exchange injection.

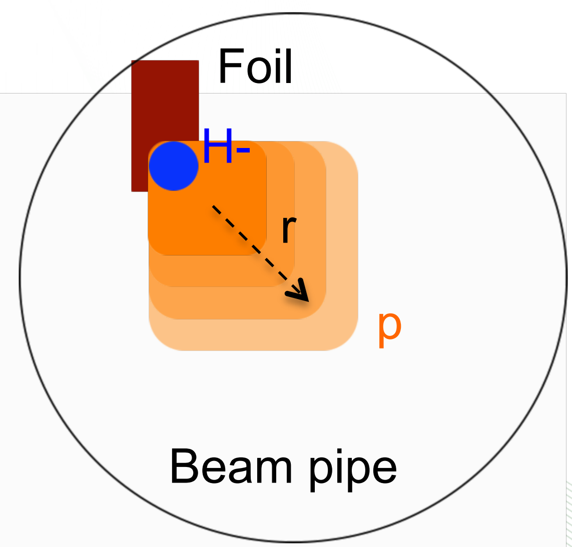
H^- Charge Exchange Injection Concept



<u>In principal:</u>
Can increase beam power density indefinitely.

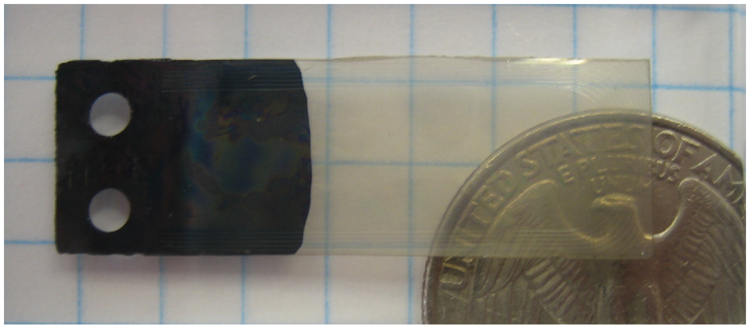


<u>In reality</u>: Need to minimize circulating beam passage through foil. Limits achievable beam power density.

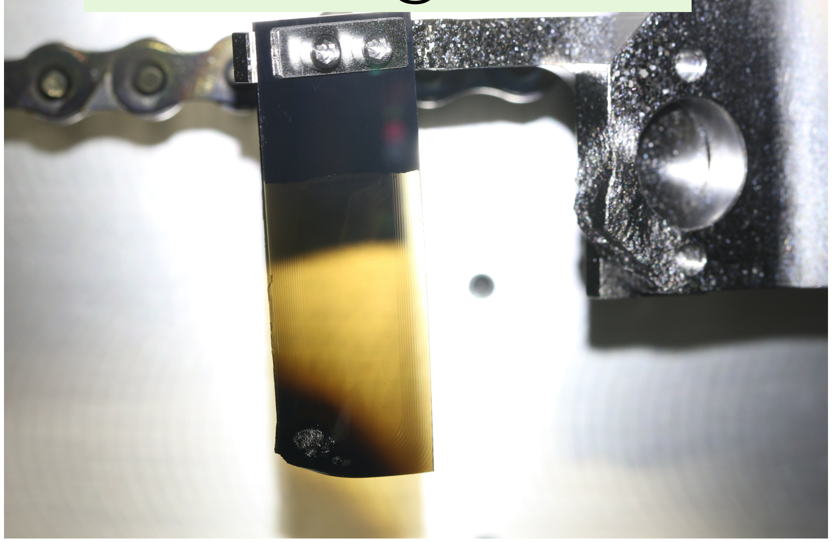


SNS Foils @ 1.3 MW

Nanocrystalline Diamond ~400 ug/cm^2 (1 μm thick)



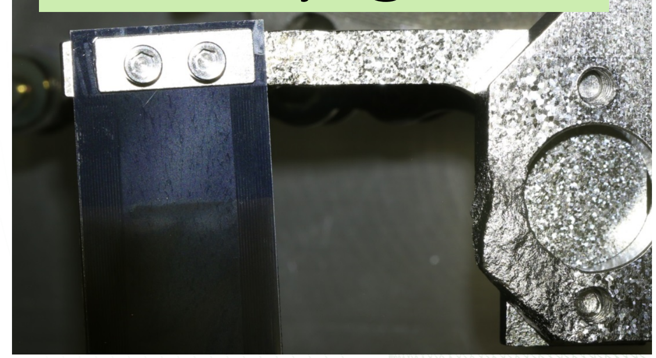
~1 month @1.3 MW



Bracket melting due to convoy electrons

Before

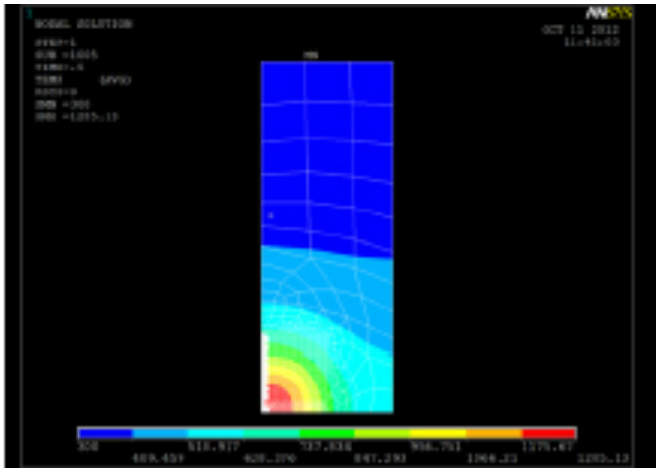
After 22 days @ 1.3 MW

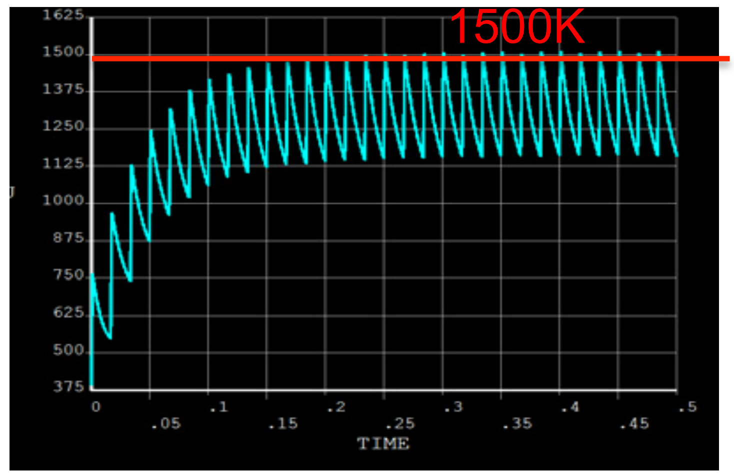


Courtesy C. Luck

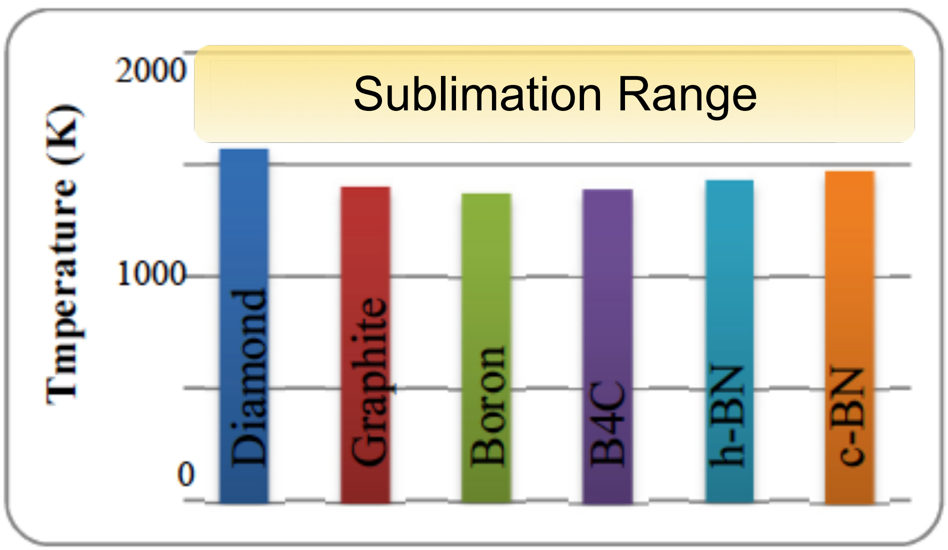
Limitation: Injection Foil Heating (SNS)

Foil heating simulations for SNS, 1.4 MW, 60 Hz





Sublimation is a limitation on achievable beam power density



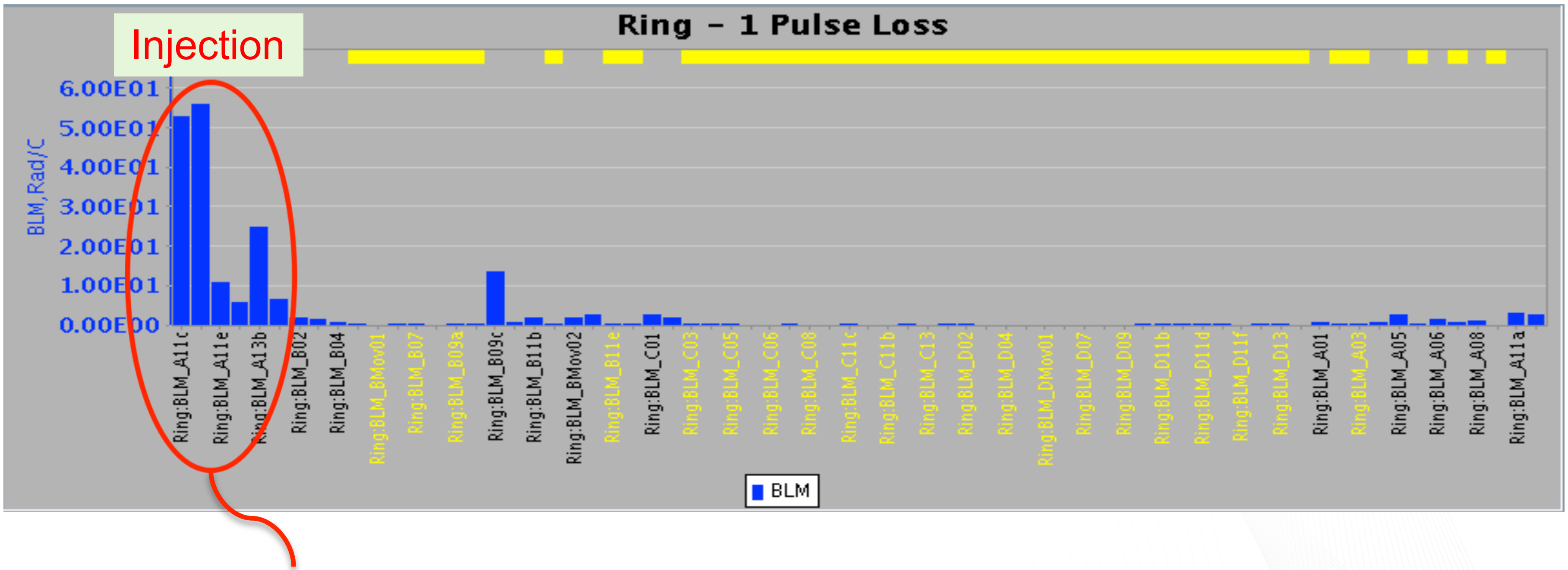
Courtesy Y. Takeda

Limitation: Foil-Induced Radiation

Typical injection losses 1 order of magnitude higher than rest of ring:

- SNS: 800 mrem/hr @ injection
- PSR: 1000 mrem/hr @ injection

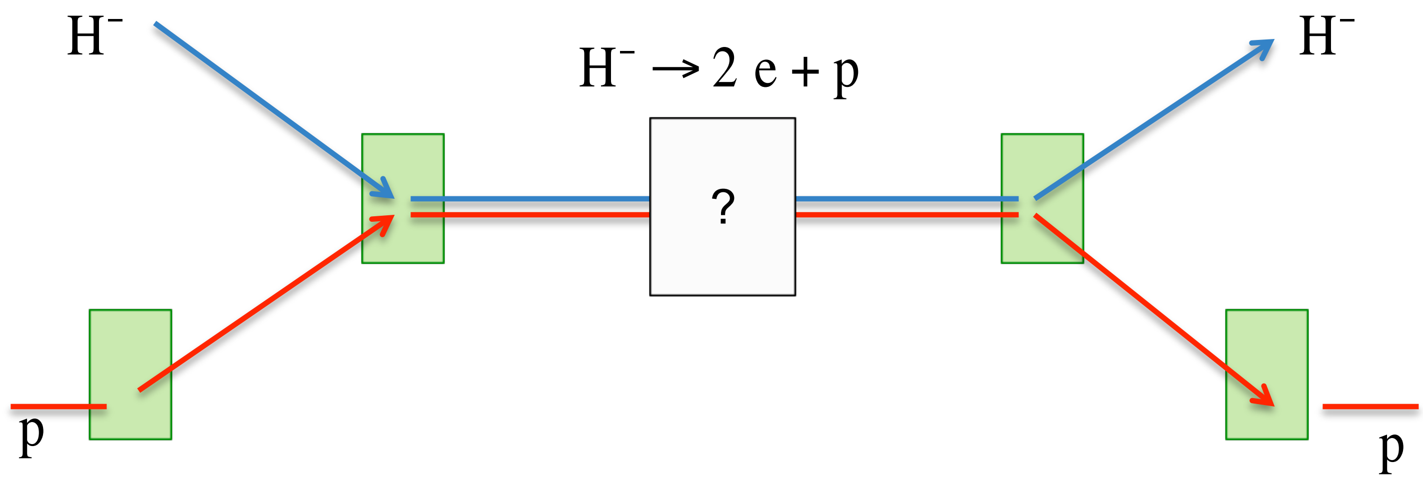
Typical Beam Loss Pattern SNS Ring, 1.3 MW



Dual plane injection painting utilized to minimize these losses.

Simulating "Foil-free" Injection

What if the foil didn't exist? Let's do the experiment.

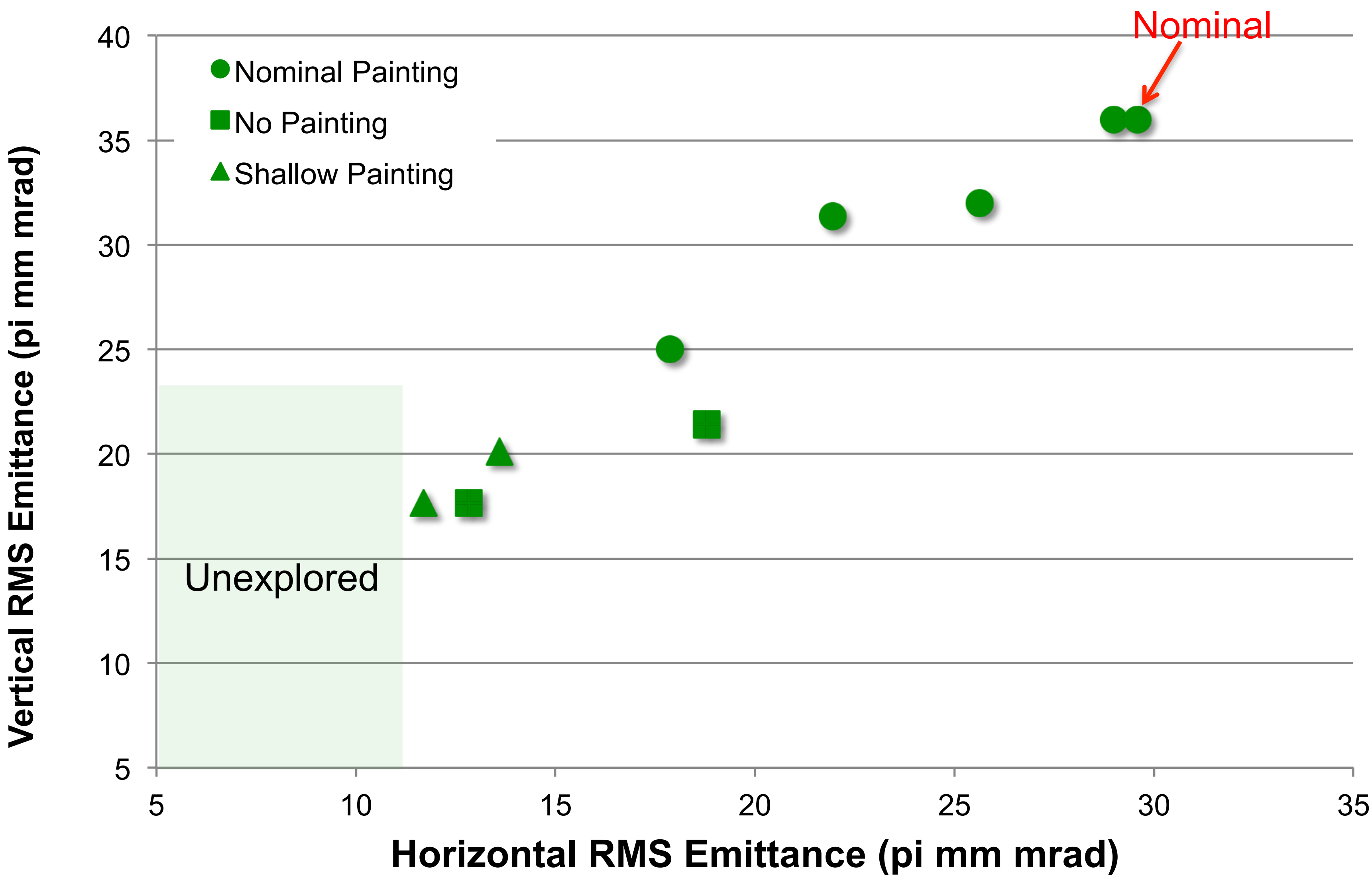


Parameters:

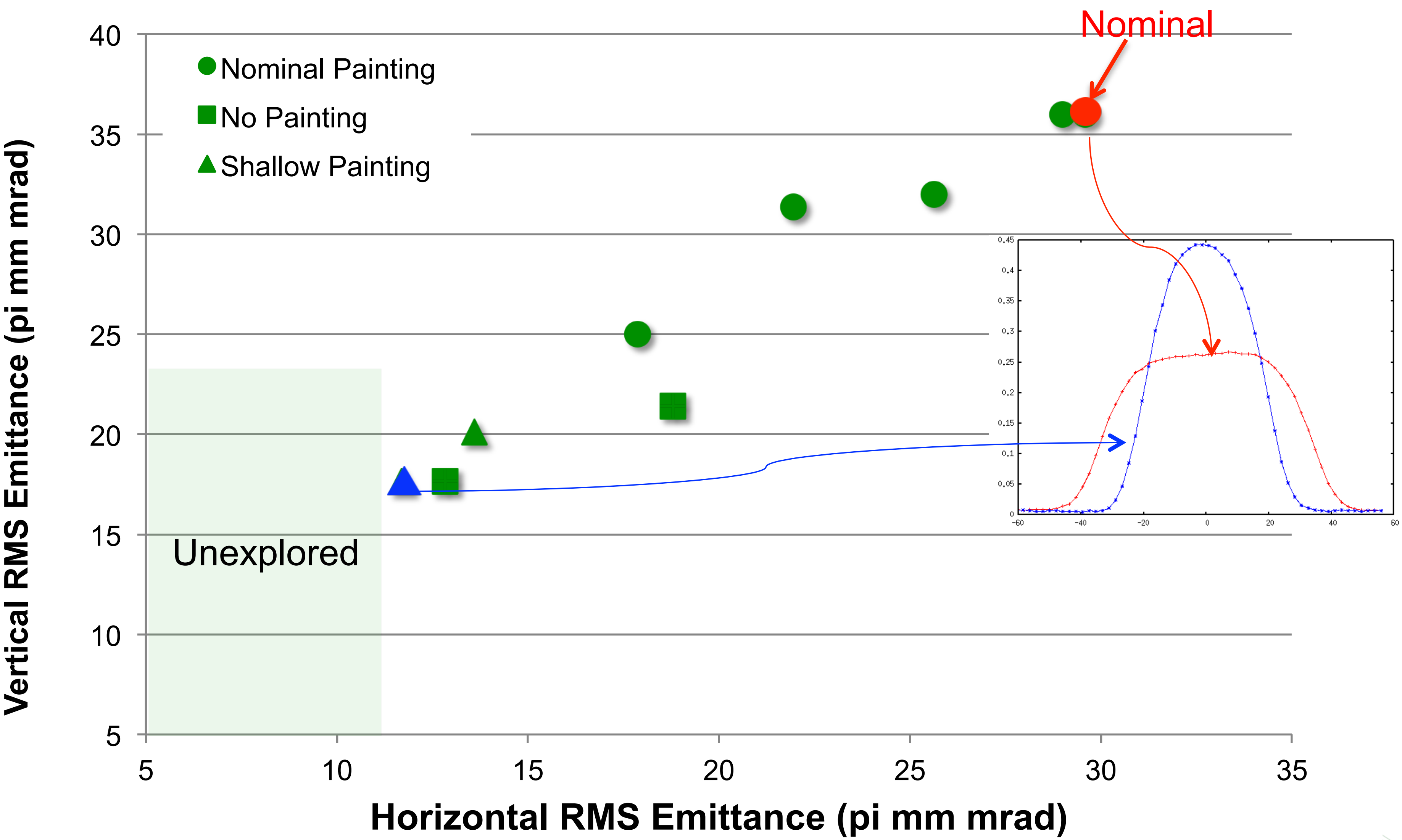
- 940 MeV
- 1 Hz (Nominal is 60 Hz)
- 1.3 x 10^{14} ppp (1.3 MW equivalent @ 60 Hz)
- 1 ms accumulation (1000 turns)

Quick, non-comprehensive scan through different accumulation configurations.

Measured RMS Emittances



Measured RMS Emittances



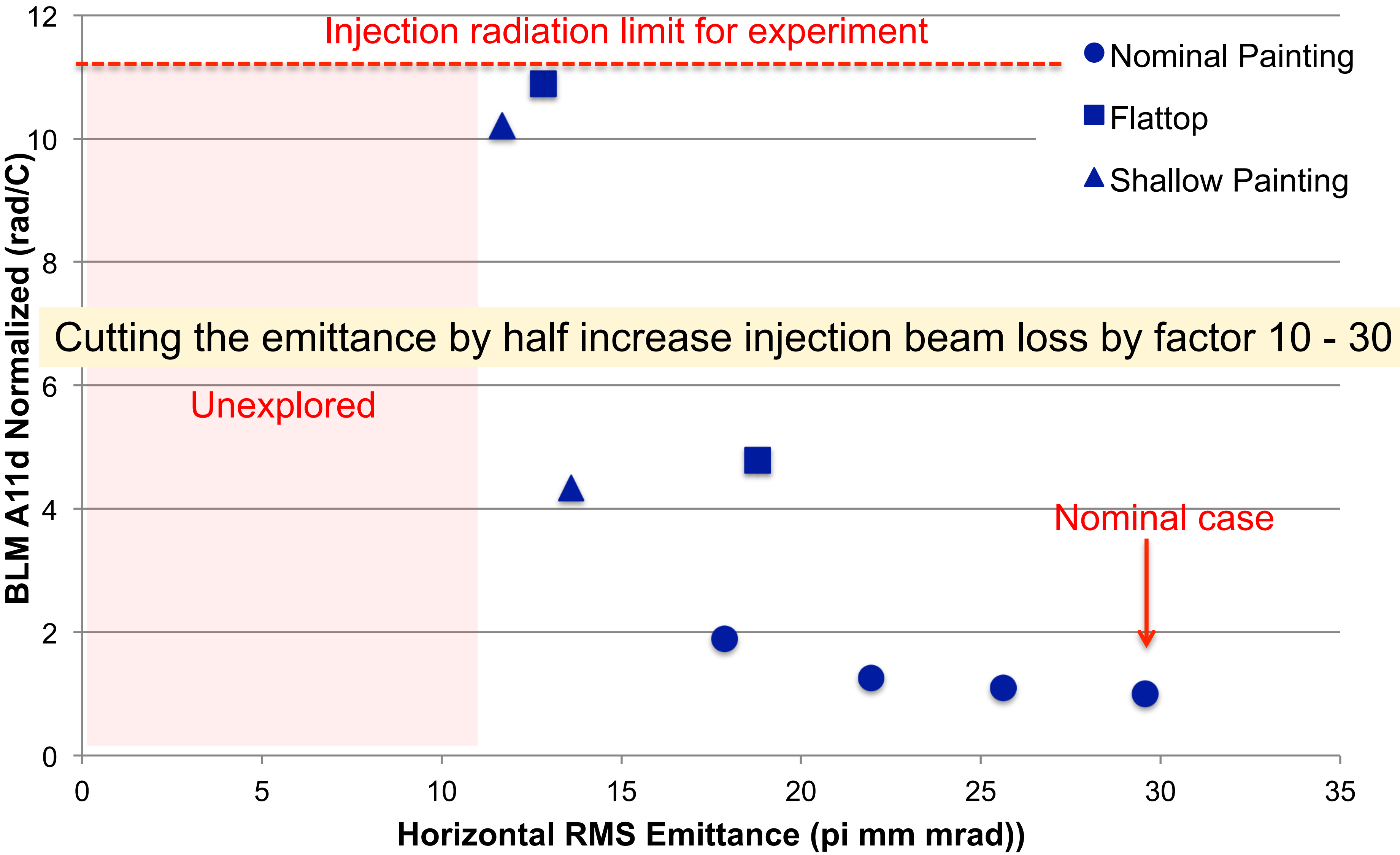
Implications of Foil Free Higher Beam Density (“In Principle”)

Scenario: Factor 2 smaller emittance beam, no foil.

Simply scaling implies (SNS example)….

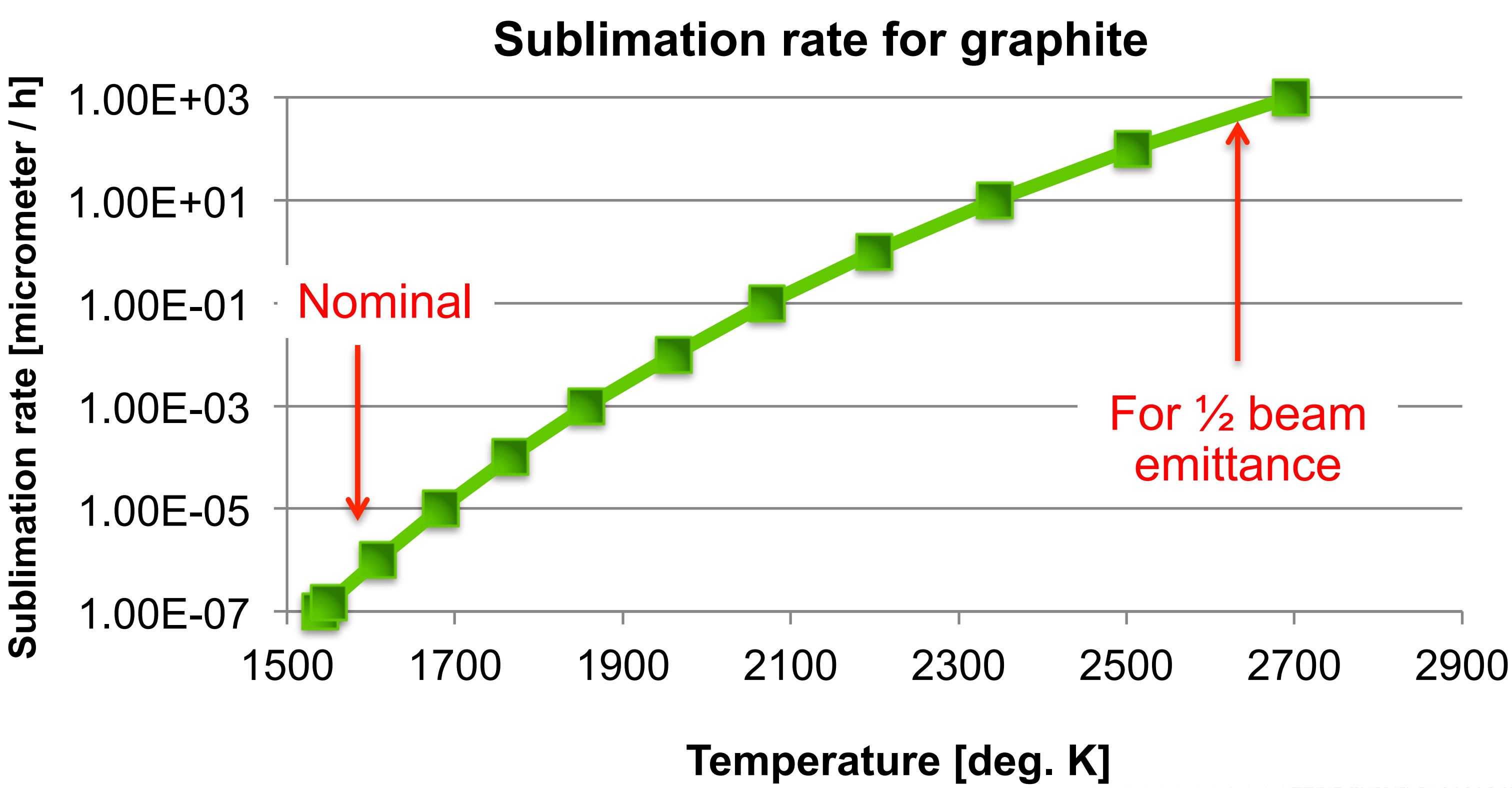
Parameter	Currently	Fictitious No Foil Case
Injection Radiation	1 rem/hr	< 5 mrem/hr
Machine aperture	100 cm	70 cm
Injection Painting	Optimized to reduce foil passages	Optimized for space charge, distribution

Implications of High Power Density ("In Reality")

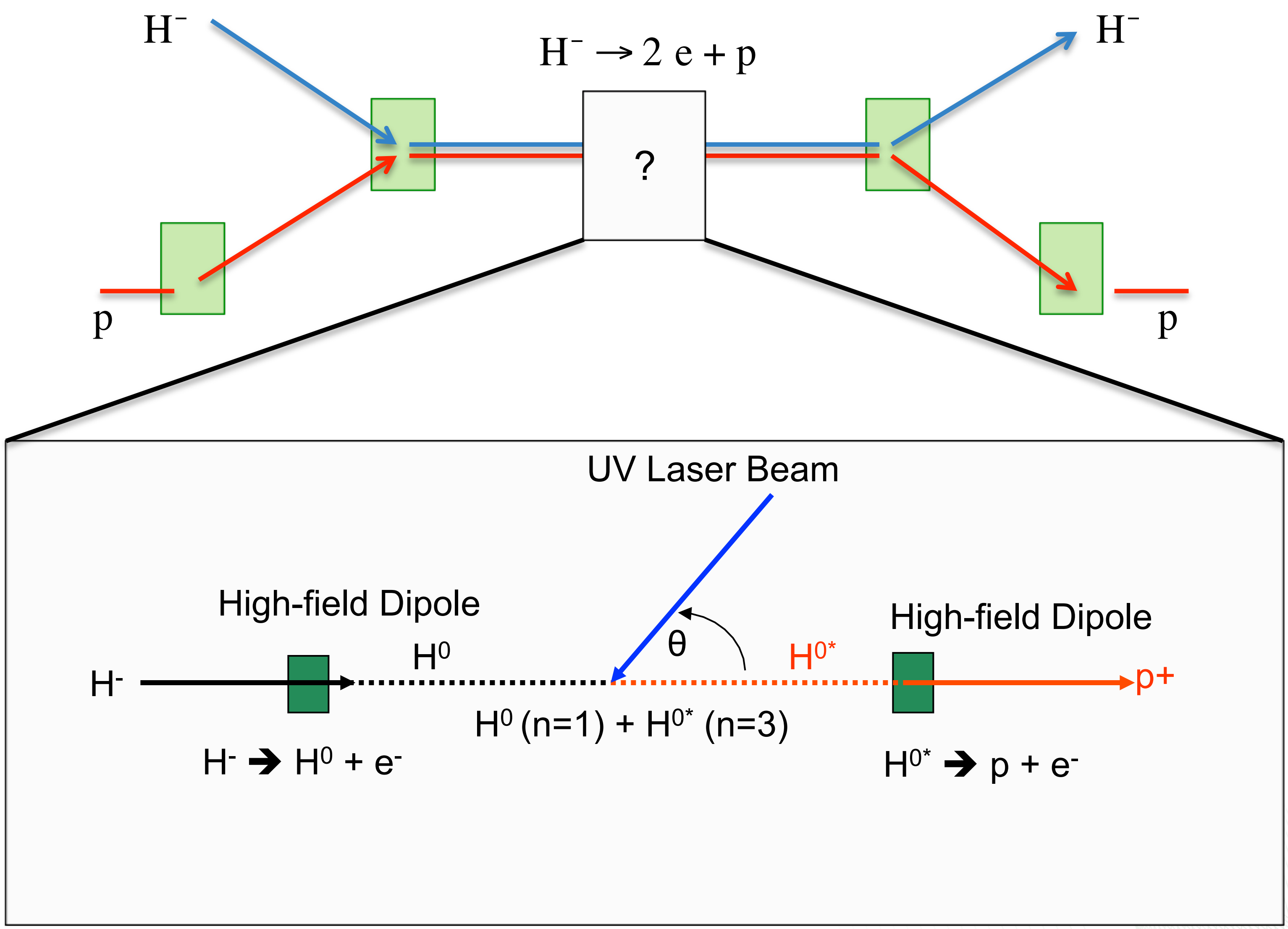


Implications of Higher Density Beam (Reality)

Parameter	Currently	Highest Density Case
Injection Radiation	1 rem/hr (@ 30cm)	> 10 rem/hr (@ 30cm)
SNS Foil Max Temp	1550 K $\left(P \propto \sigma T^4\right)$	> 2500K

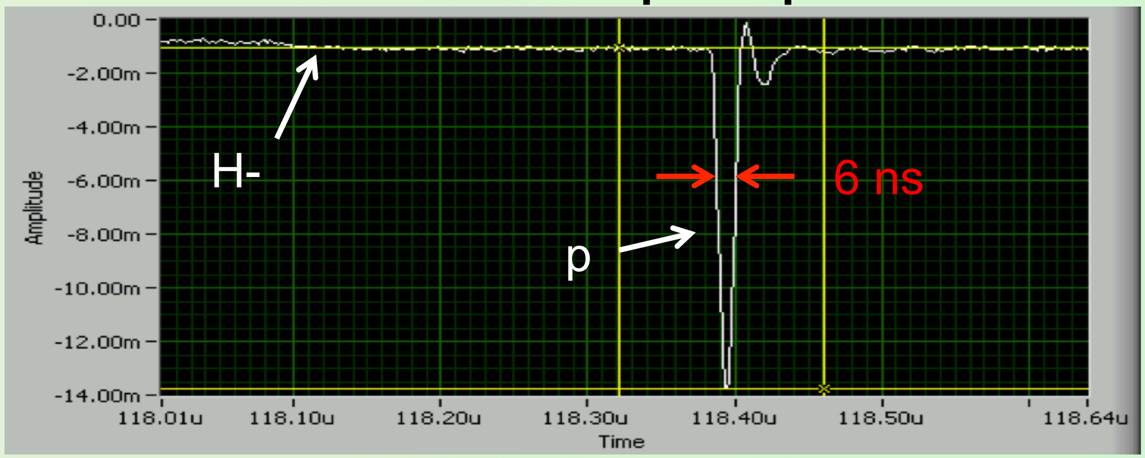


Laser Stripping Concept



The Laser Stripping Project

2006 Proof of Principal Experiment



- Required 10 MW, diverging laser to accommodate excitation frequency spread
- Straightforward scaling to 1 ms requires **~600 kW avg UV laser power (too much!)**

SNS Laser Stripping Project:

UT Oak Ridge National Laboratory Fermilab

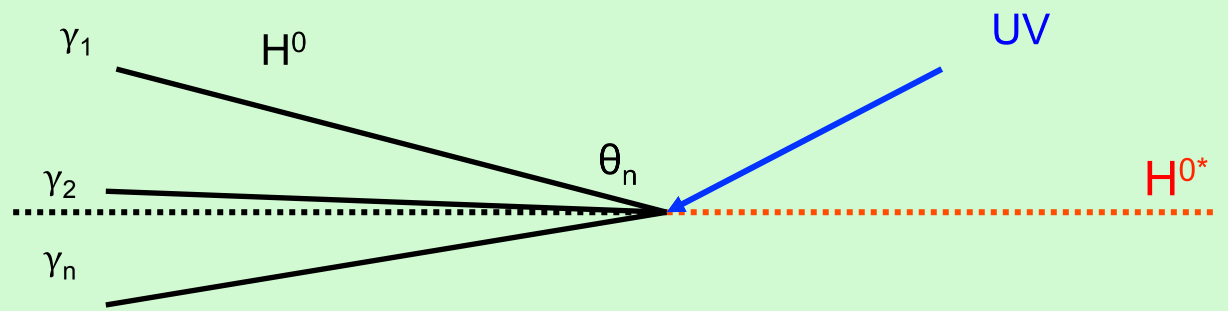
- Demonstrate laser stripping for longer pulse lengths:
  - 10 us (2016)
  - 1 ms (2019?)
- Technology aimed at HEP applications.
- Funded by DOE HEP grant (DE-FG0213ER41967) UT, ORNL, Fermilab

Reducing Peak Laser Power Requirement

Eliminate transition frequency spread fundamentally:

1. Dispersion Tailoring (Danilov *et al*)

$$f_{\text{rest frame}}(1 \rightarrow 3) = \gamma_n (1 + \beta \cos(\alpha_n)) f_{\text{beam frame}}$$



2. Minimize transverse angular spread, Twiss α=0

Maximize laser-ion beam interaction with vertical squeeze:

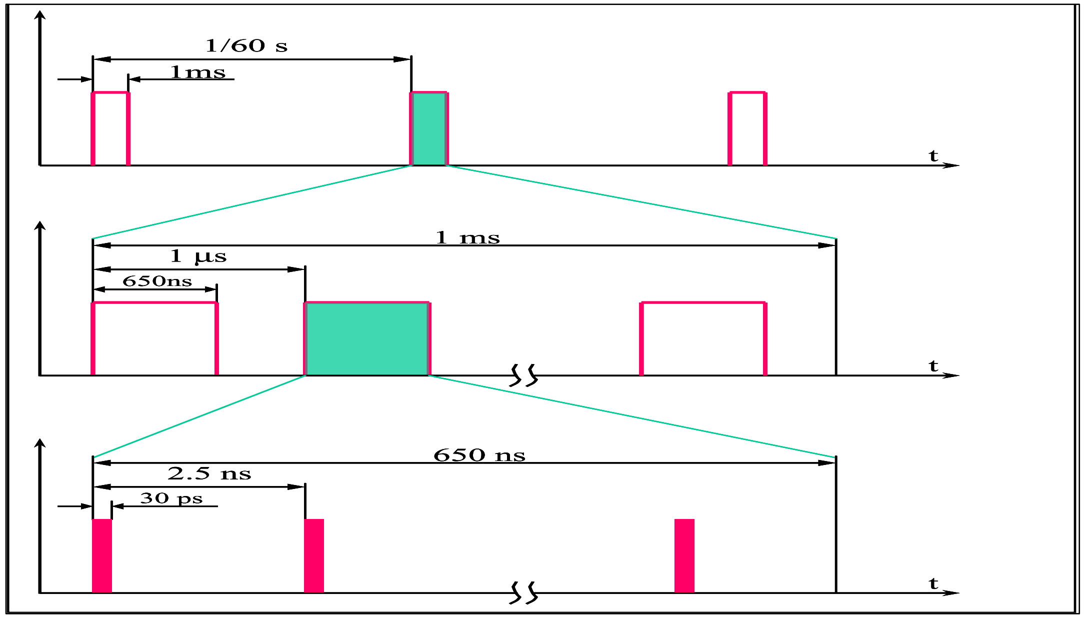
1. Transverse (vertical) squeeze: $\sigma_y < 0.2$ mm

Required peak UV laser power: 10 MW ➡ 1 MW

Reducing Average Laser Power Requirement

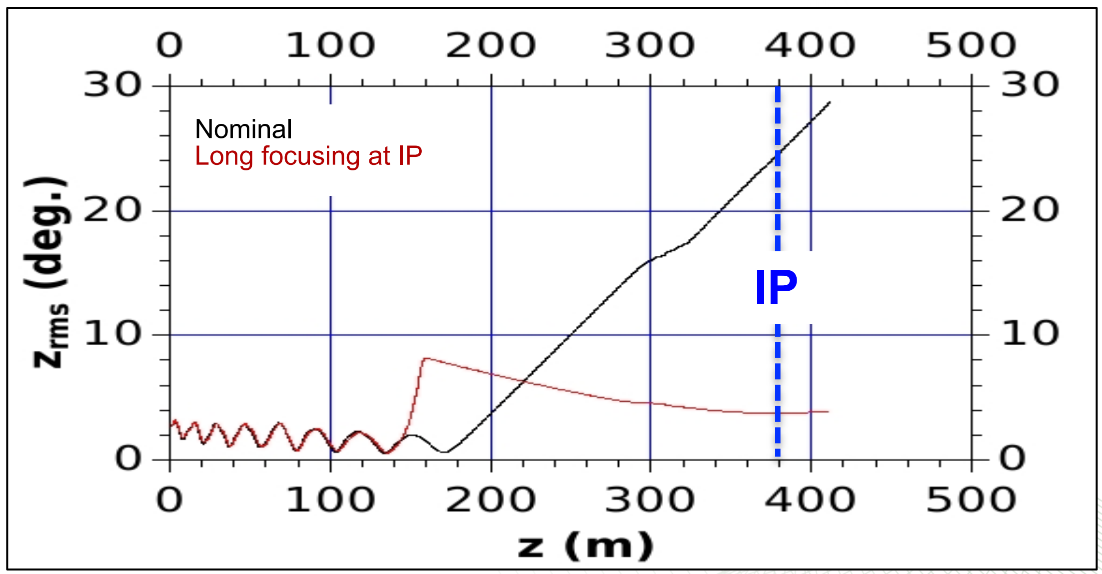
Temporal matching

Only have the laser on when beam is present, i.e., match 402.5 MHz structure.



Bunch squeeze to maximize interaction

Configure last ~10 SCL cavities to provide long focusing at interaction point.



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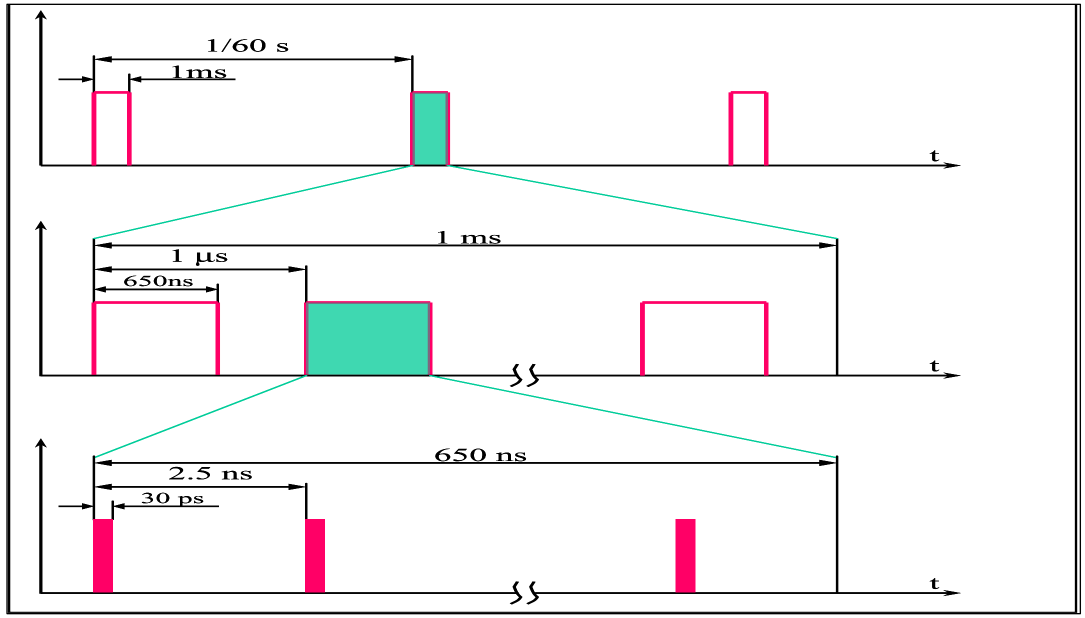

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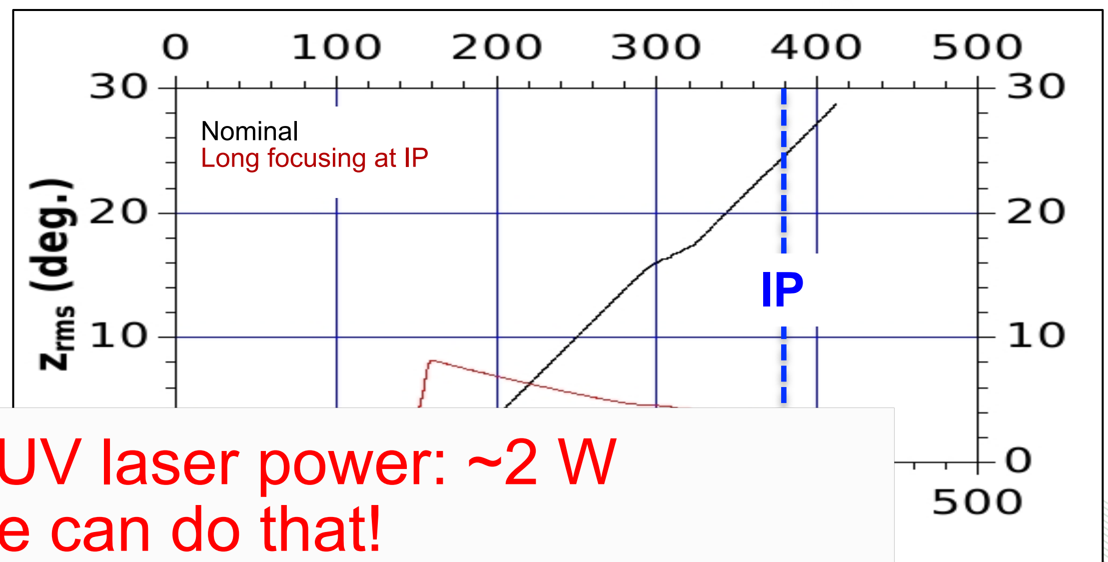
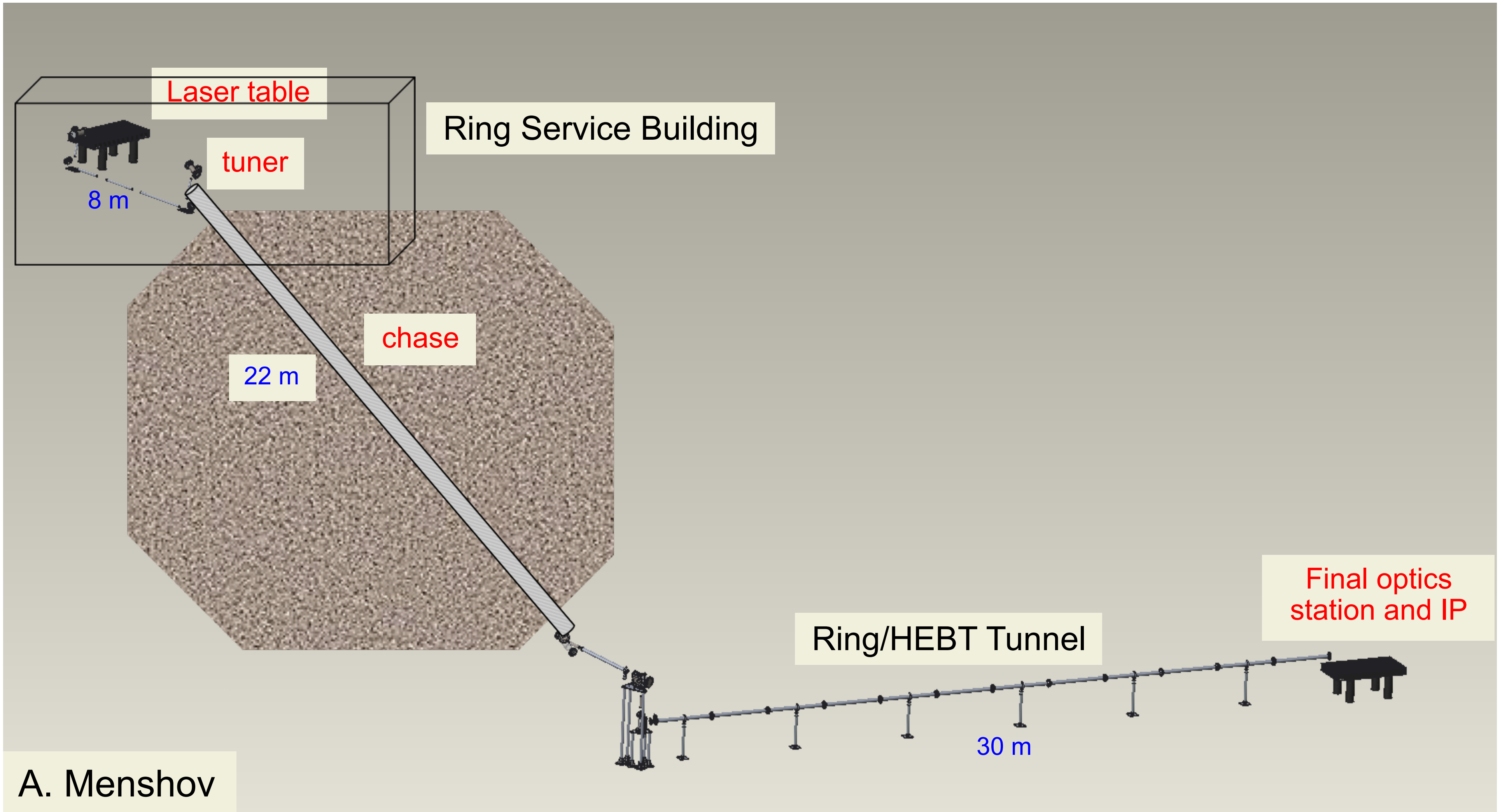


Final average UV laser power: ~2 W
OK, we can do that!

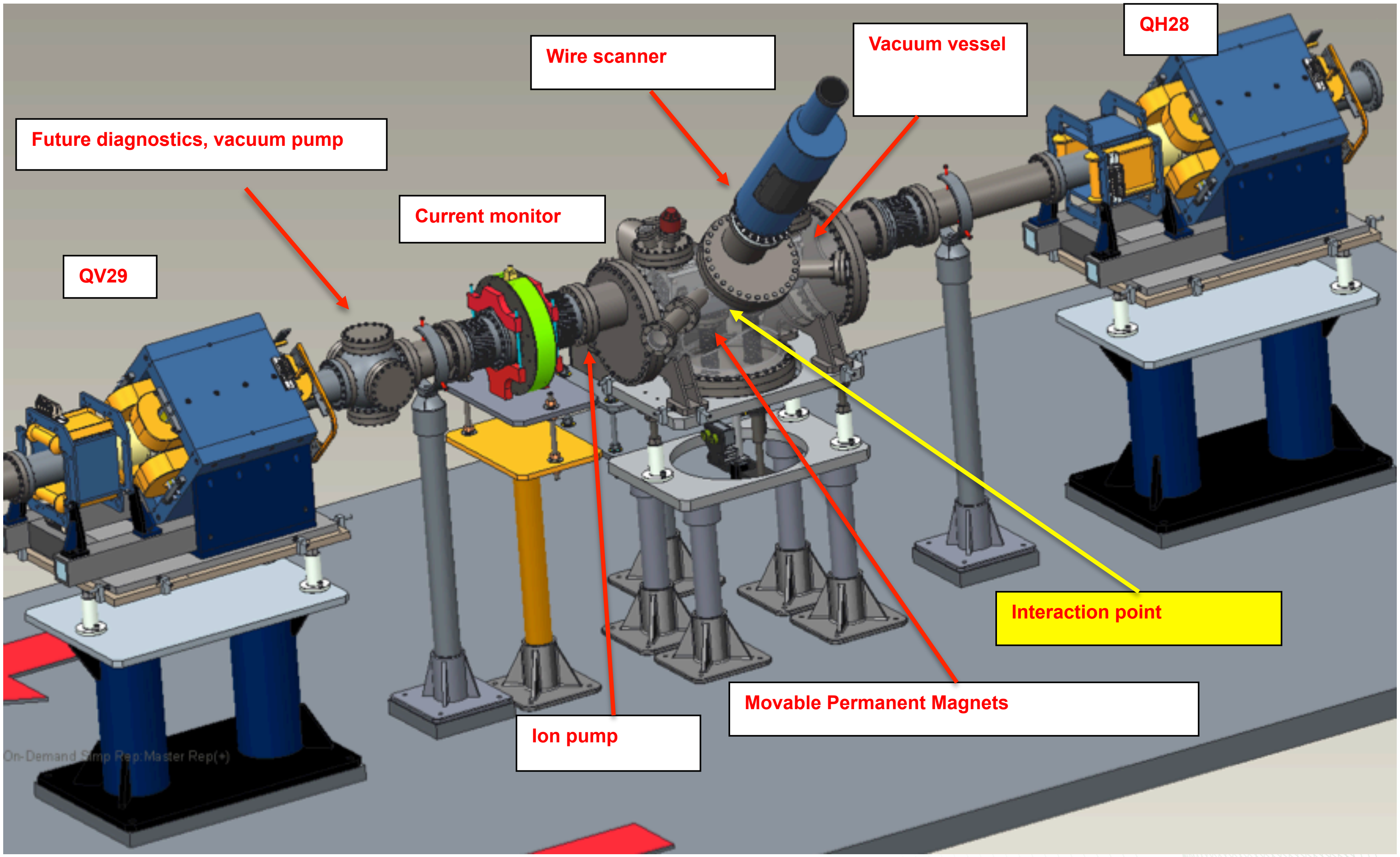
Experimental Configuration

Interaction point in the HEBT, laser in the Ring Service Building.

Laser transport introduces complications (power loss, pointing stability)

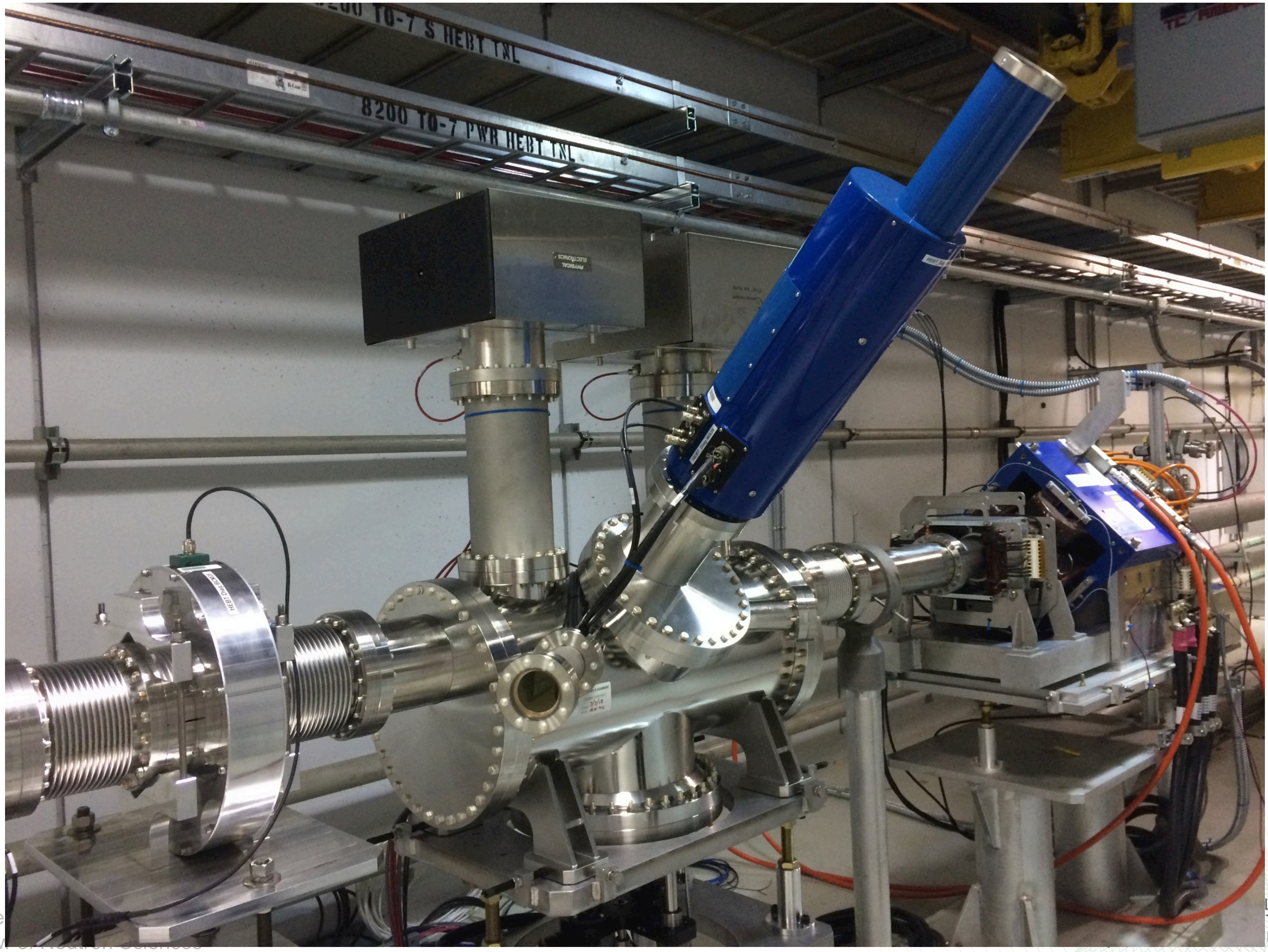


Experimental Station Final Design



A. Menshov

Installed Experimental Station

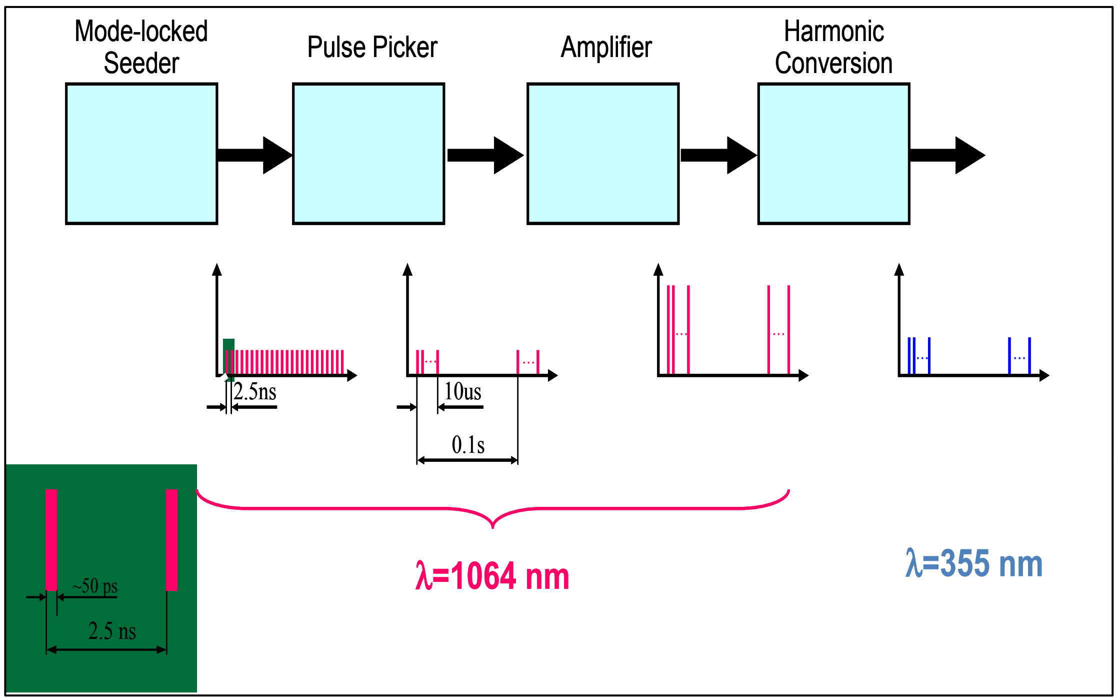


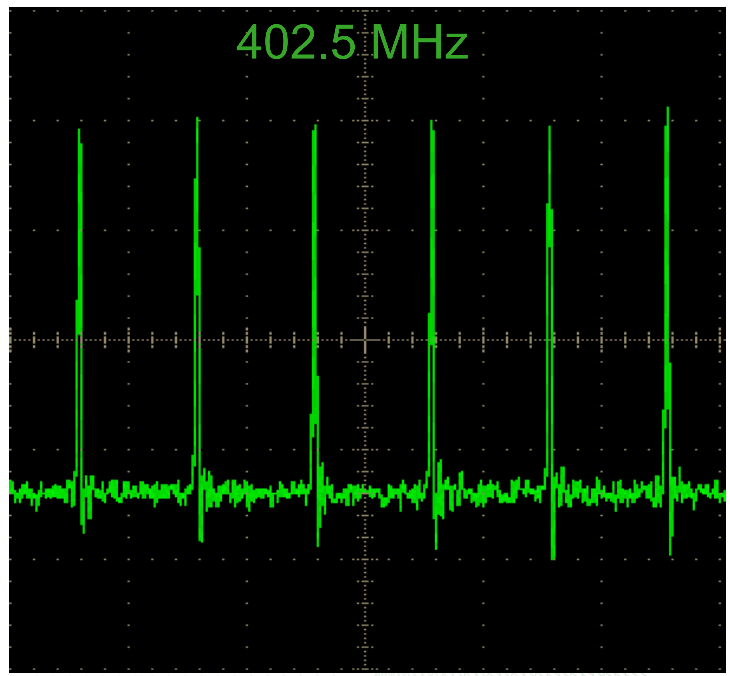
Laser-Ion Beam Temporal Matching

UV peak power achieved: 1.3 - 3.0 MW

Structure	Time	Frequency
Micropulse	30 – 55 ps	402.5 MHz
Macropulse	5 – 10 us	10 Hz

Master oscillator power amplification (MOPA) system



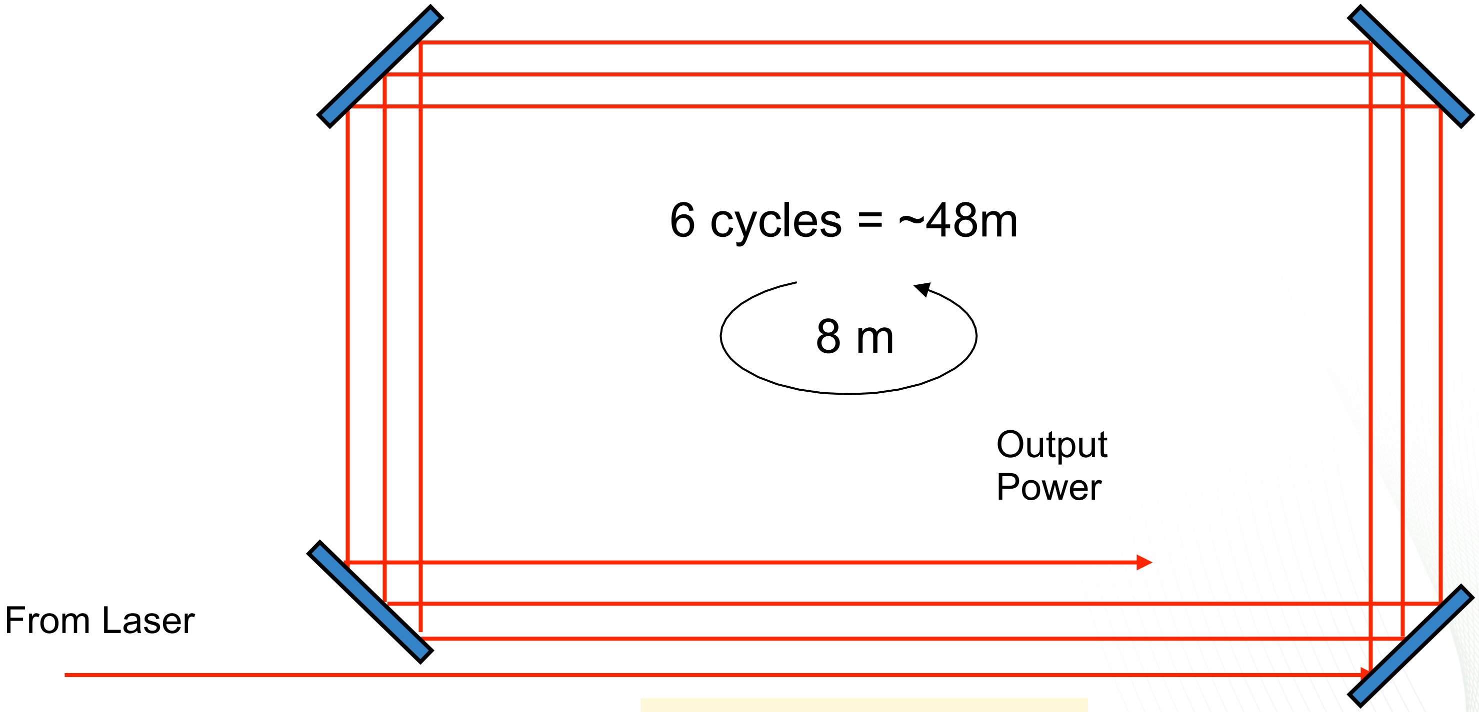


Y. Liu, A. Rakhman

Laser Transport Mock-Ups

- Piezoelectric tuner will stabilize laser against > 1 Hz drift. Higher frequency not expected.
- Mirror losses independently measured to be ≤1%.
- Expect ~ 1/3 power loss (Fresnel diffraction, higher order mode loss).

Conclusion: Remote laser placement is feasible.



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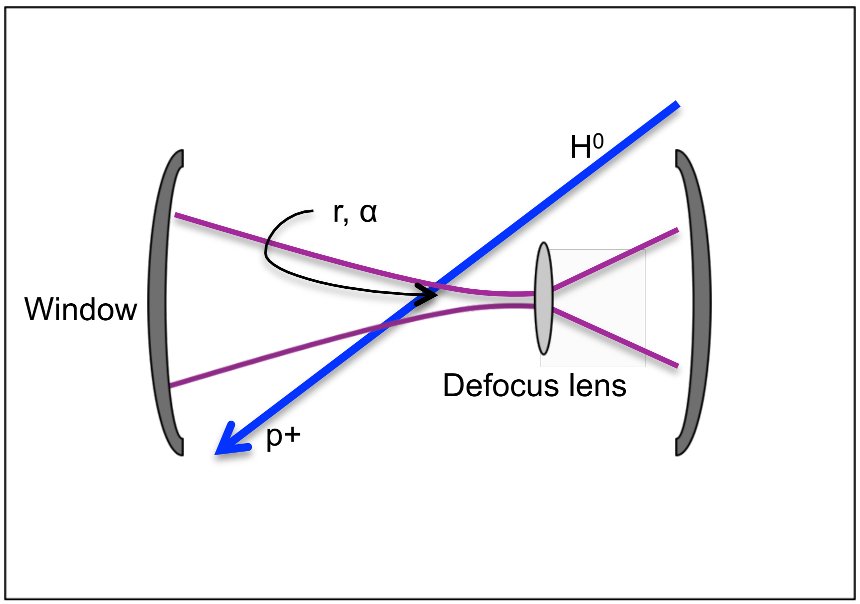
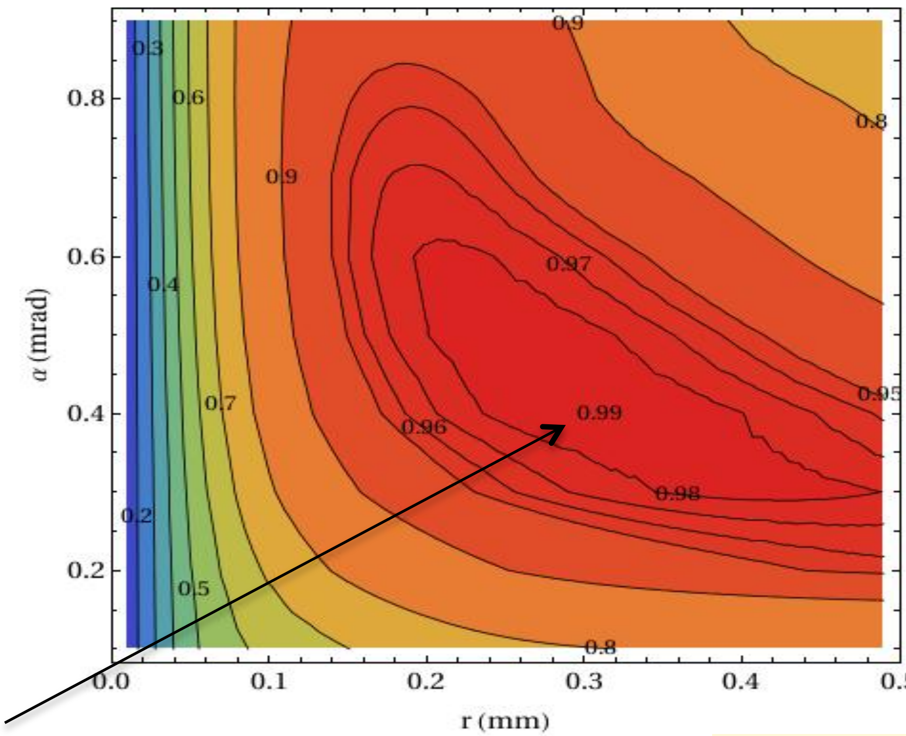
Laser Stripping Efficiency Calculation

- All ion and laser beam parameters achieved.
- Measured parameters used to calculate laser stripping efficiency (pyORBIT model)



Final Stripping Efficiency

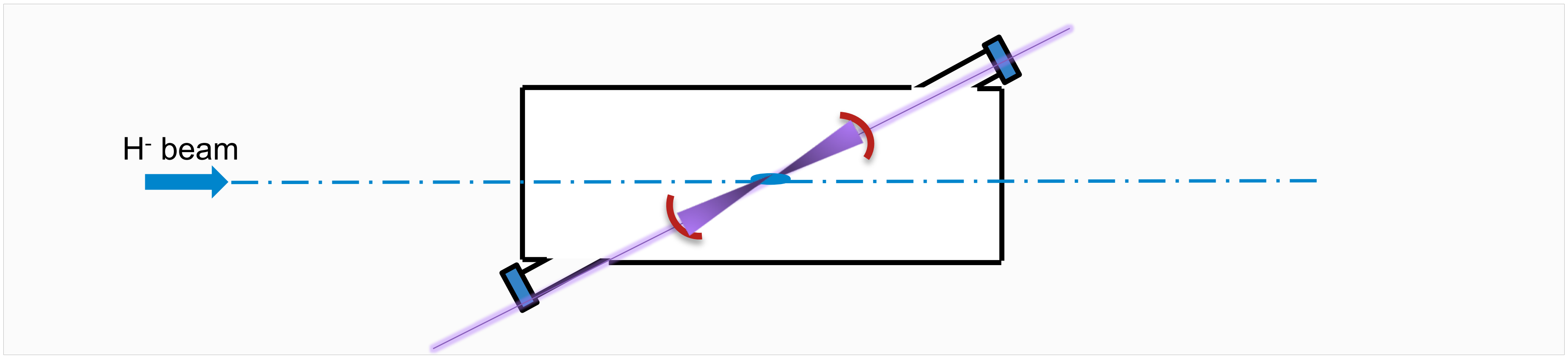


Concern about power density on window

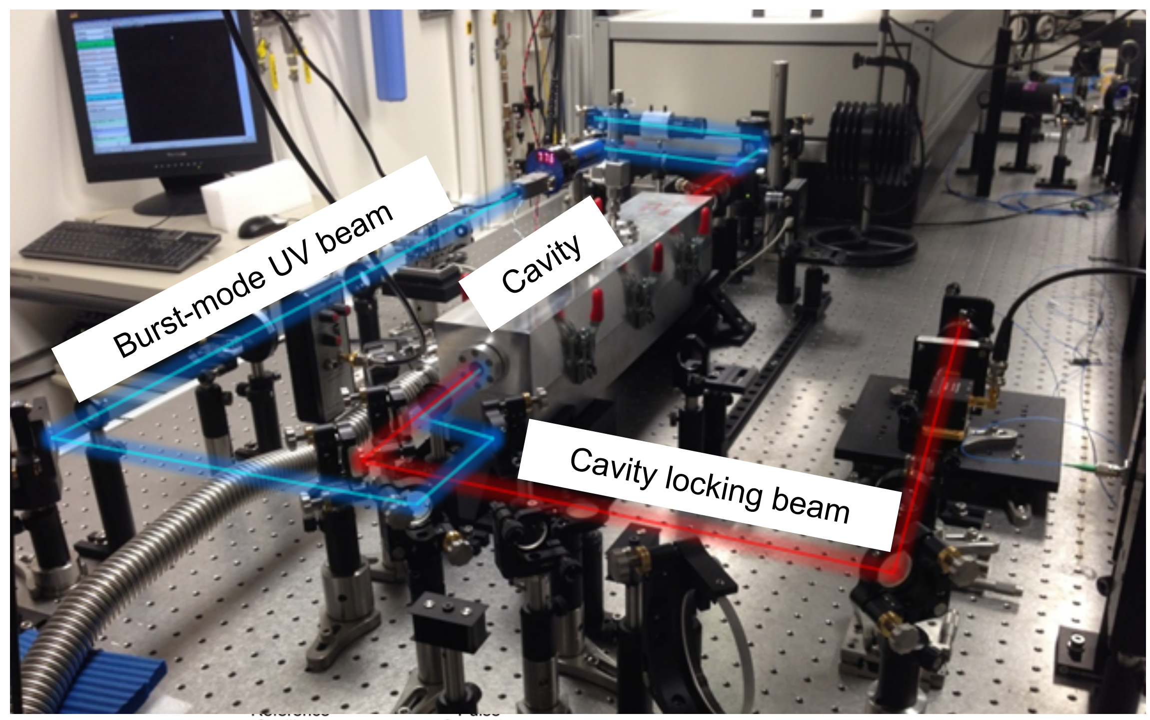
T. Gorlov

The Next Step: 1 ms

Add the recycling cavity to achieve 1 ms laser pulses



- Power recycling cavity relies on CW laser for stable lock.
- Amplification of burst mode laser.
- 50 times power enhancement demonstrated.



Other Observations of Note

1. Advantages and disadvantages of Laser Stripping:

Advantage

1. Virtually no injection beam loss
2. Higher density beams

Disadvantage

1. Cost
2. Complexity (foils are simple!)
3. Fragility of system components
4. No conceptual for operational system
5. Unforeseen problems.

Some of the disadvantages are problems that will resolve with time, experience

2. Laser stripping is more advantageous at high beam energies:

- Lower frequency laser required: Harmonic generation requires less peak power.
- Laser power density transformation scales as energy squared: $Q \propto Q_0 / \gamma^2$

Summary

1. Material free charge-exchange injection has major advantages over foil-based systems:
   - Virtually no injection beam loss
   - Allows direct accumulation of higher density beams

2. Laser stripping injection under development at SNS (UT-ORNL-Fermilab):
   - Demonstrate 10 us stripping, > 90% efficiency (2016)
   - Demonstrate 1 ms stripping, > 90% efficiency (~2019)