Laser System Design and Operation for SNS H^- Beam Laser Stripping

Y. Liu, A. Aleksandrov, S. Cousineau, T. Gorlov, A. Menshov, A. Rakhman, A. Webster

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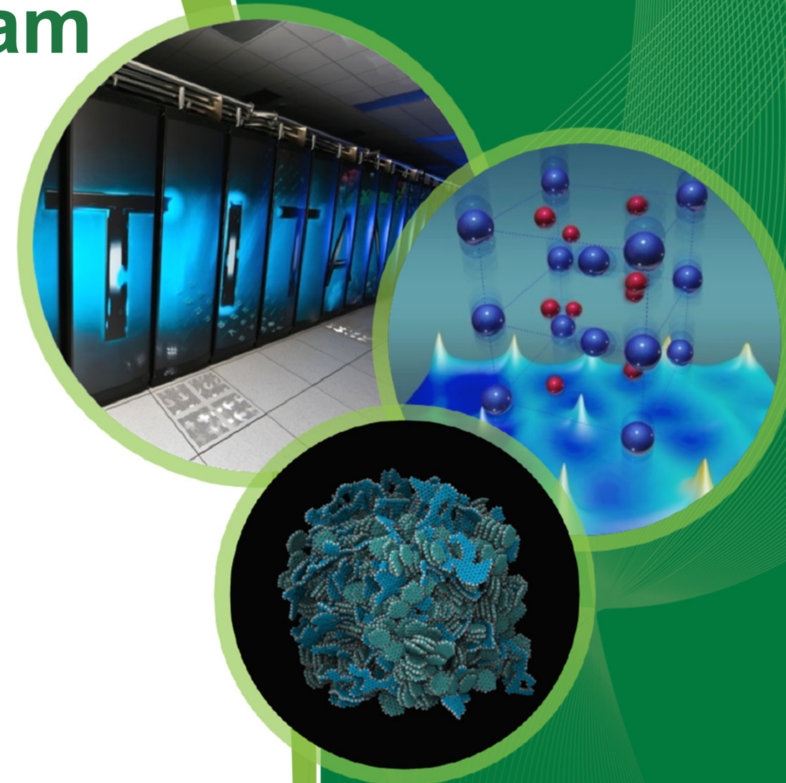

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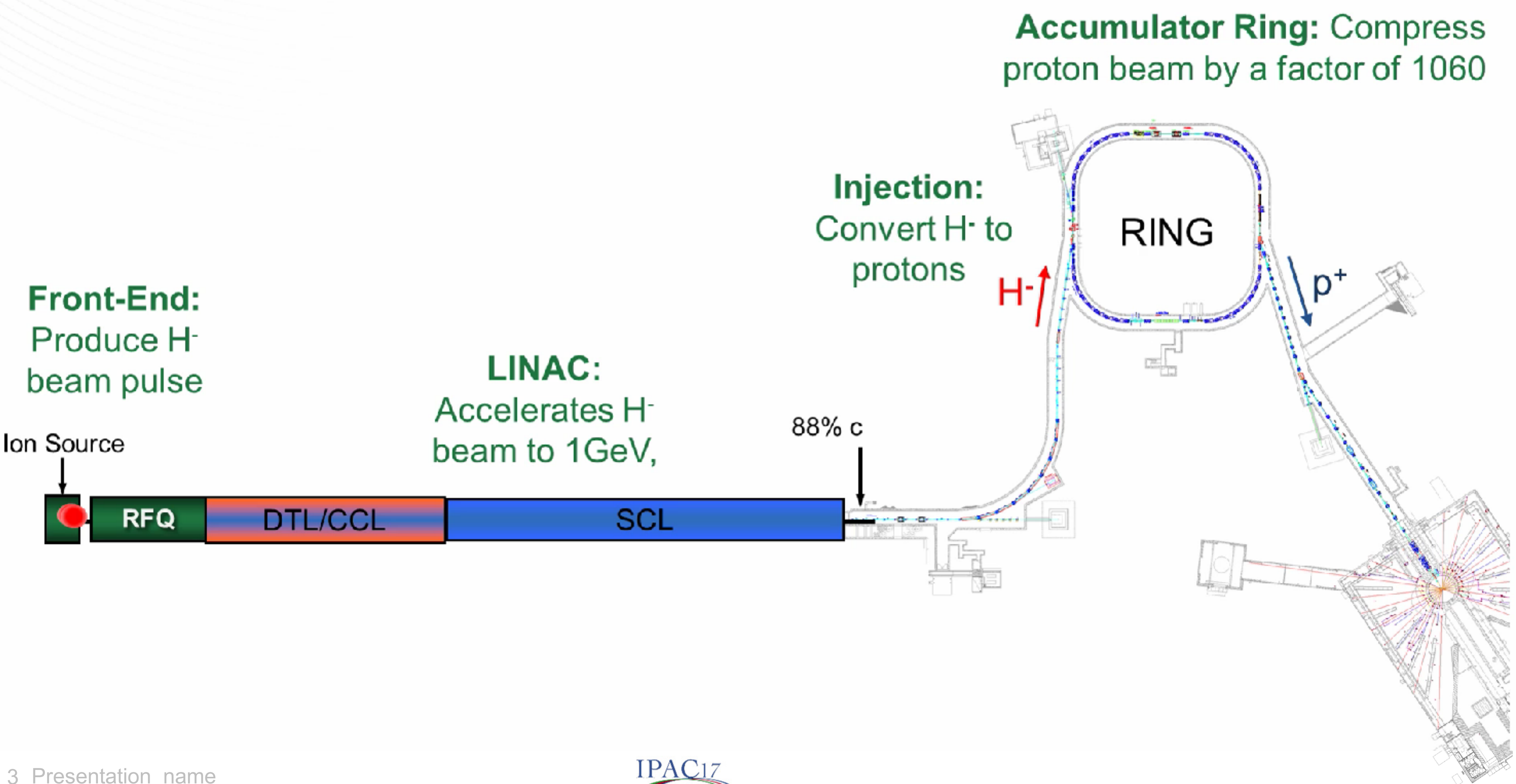
Outline

- Laser stripping principle and first stripping experiment
- Goal of the second laser stripping experiment and technical challenges on laser optics
- Laser system and operation for 10-μs macropulse H^- beam stripping
- Stripping experiment result
- Summary

Charge Exchange Injection Scheme in SNS Accumulator Ring



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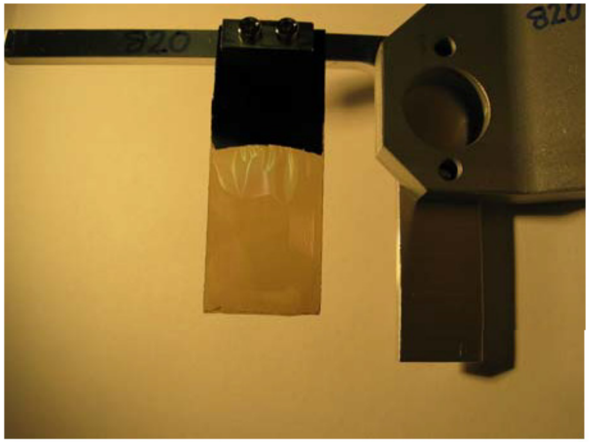
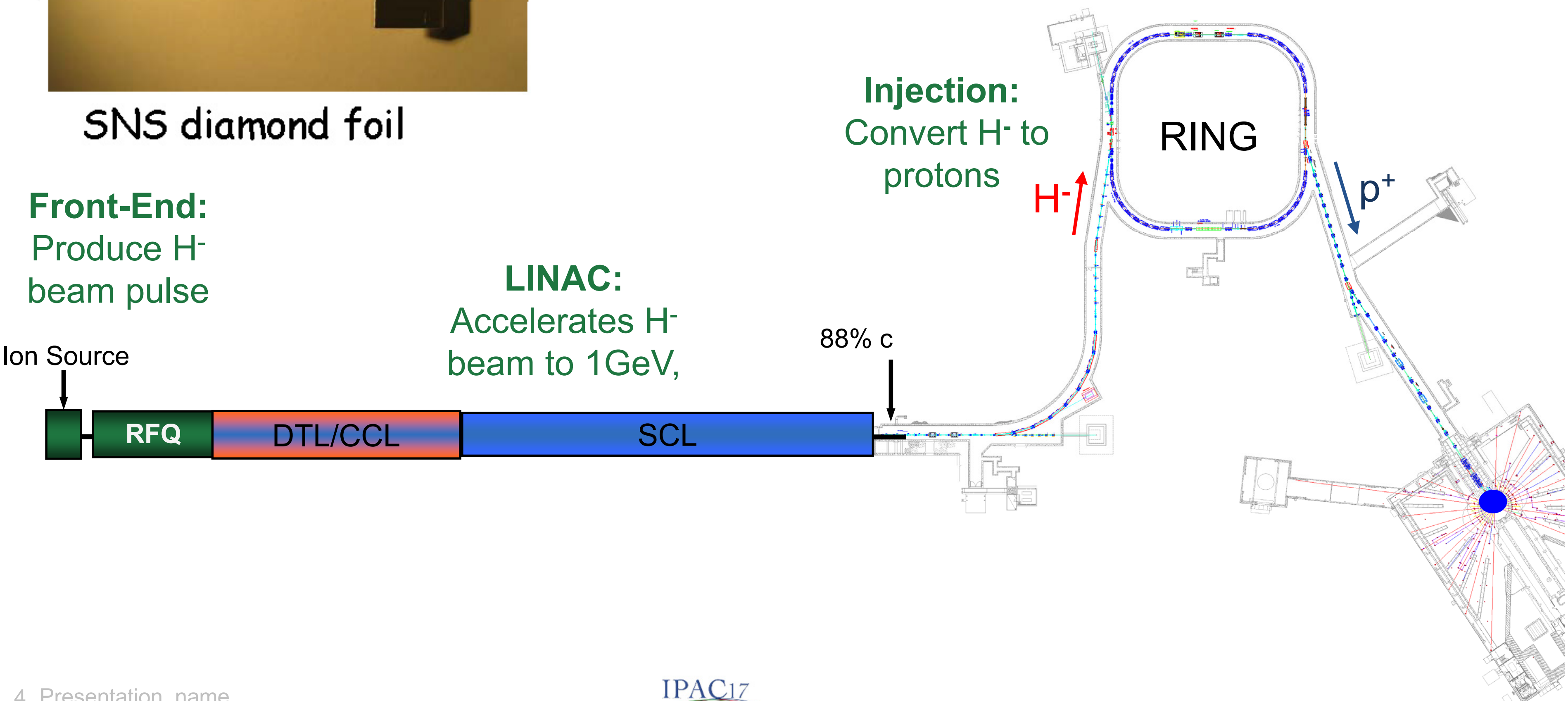


SNS diamond foil

Accumulator Ring: Compress proton beam by a factor of 1060



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Charge Exchange Injection Scheme in SNS Accumulator Ring

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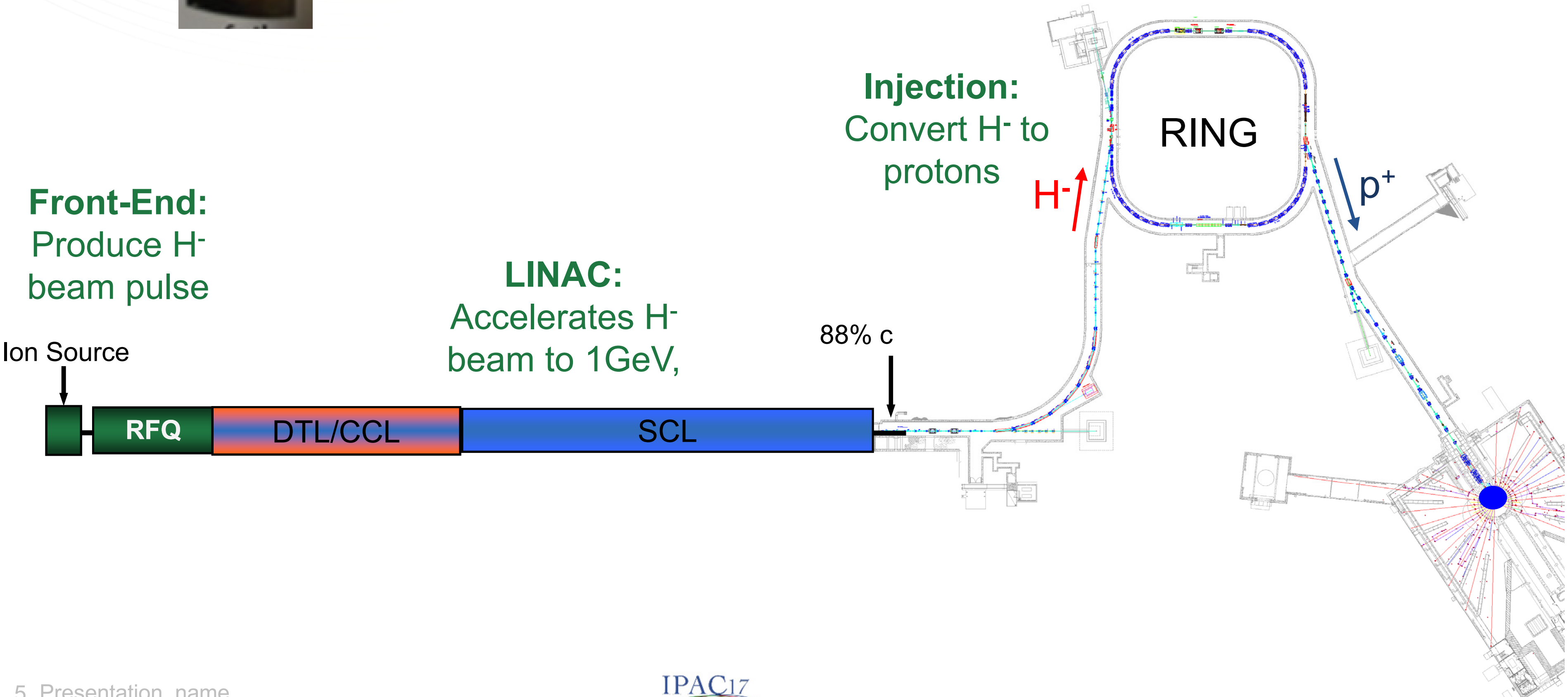
Injection: Convert H^- to protons

Front-End: Produce H^- beam pulse

LINAC: Accelerates H^- beam to 1GeV,



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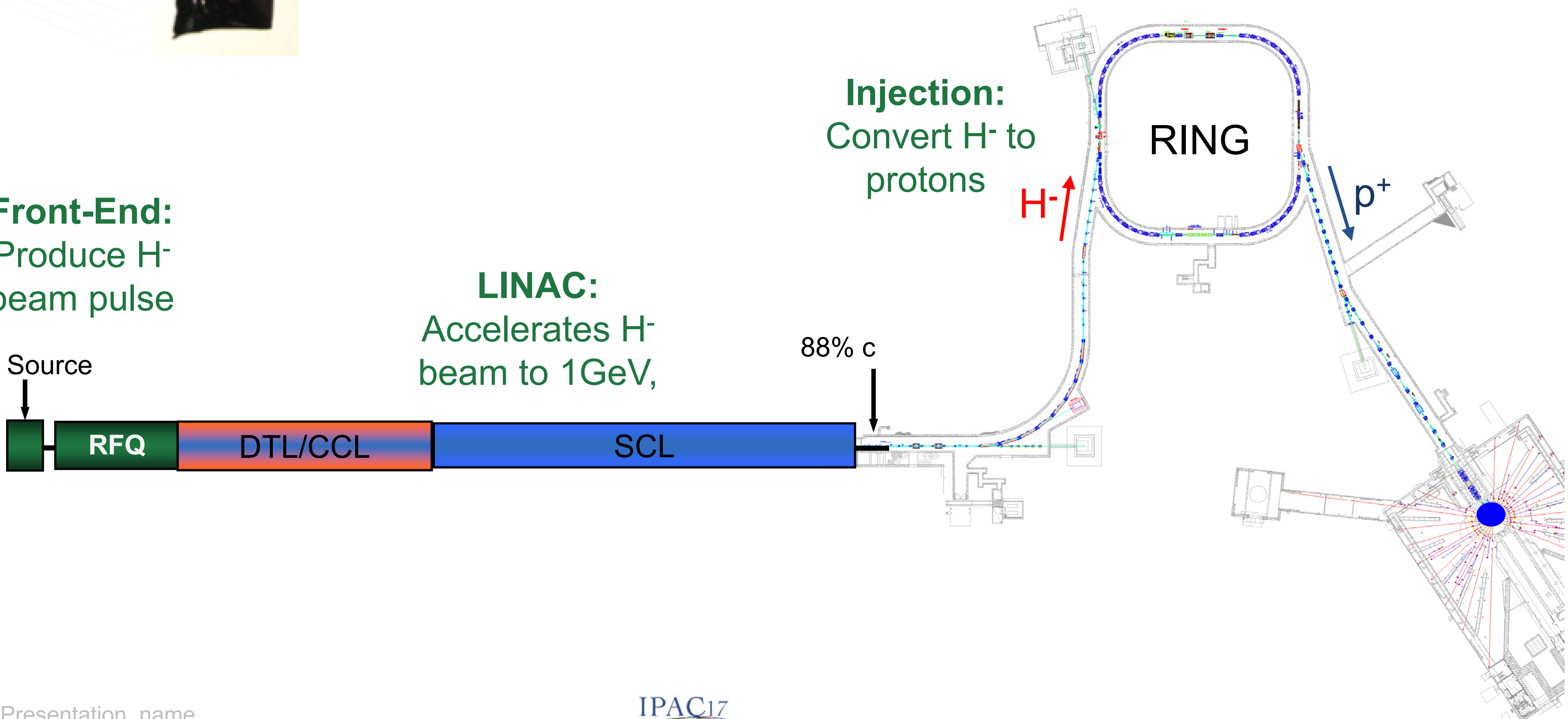

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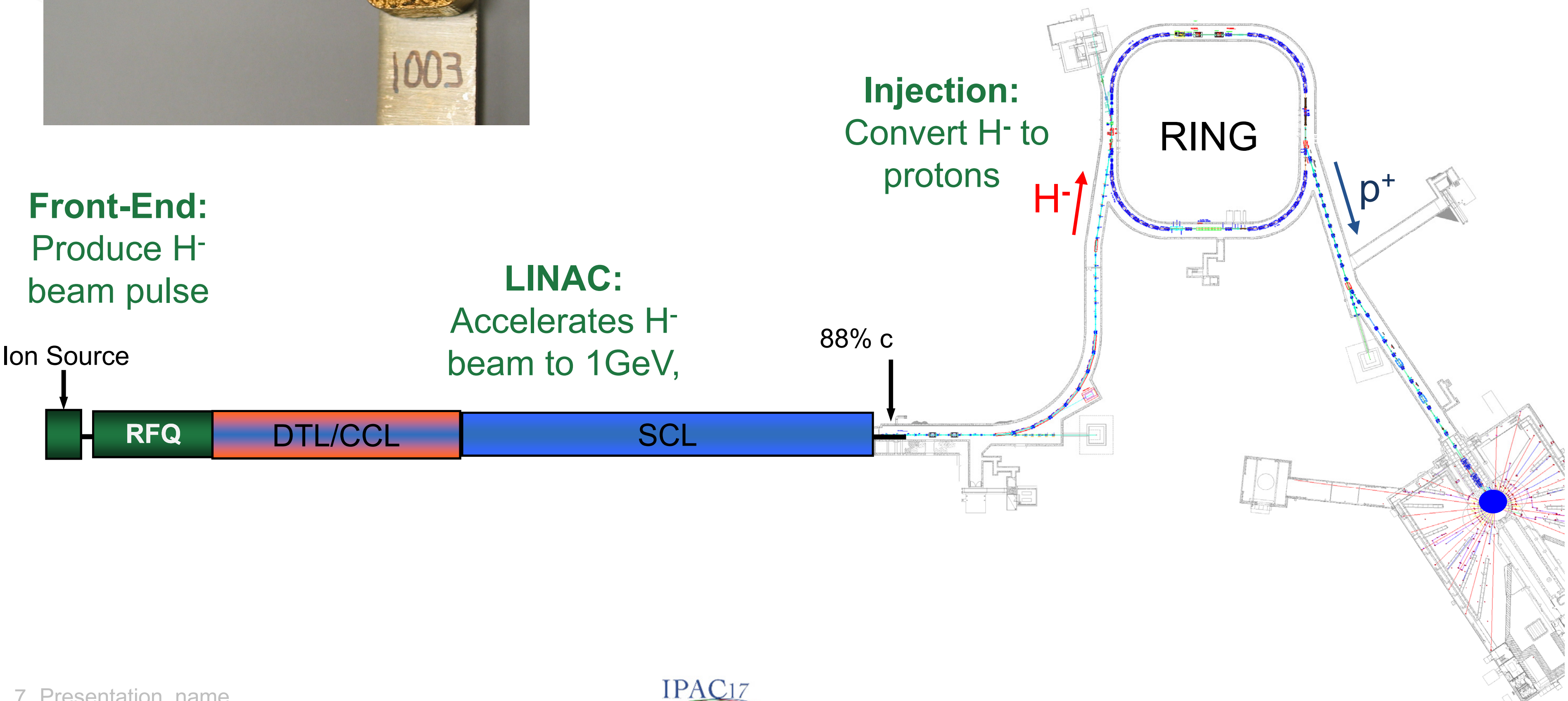

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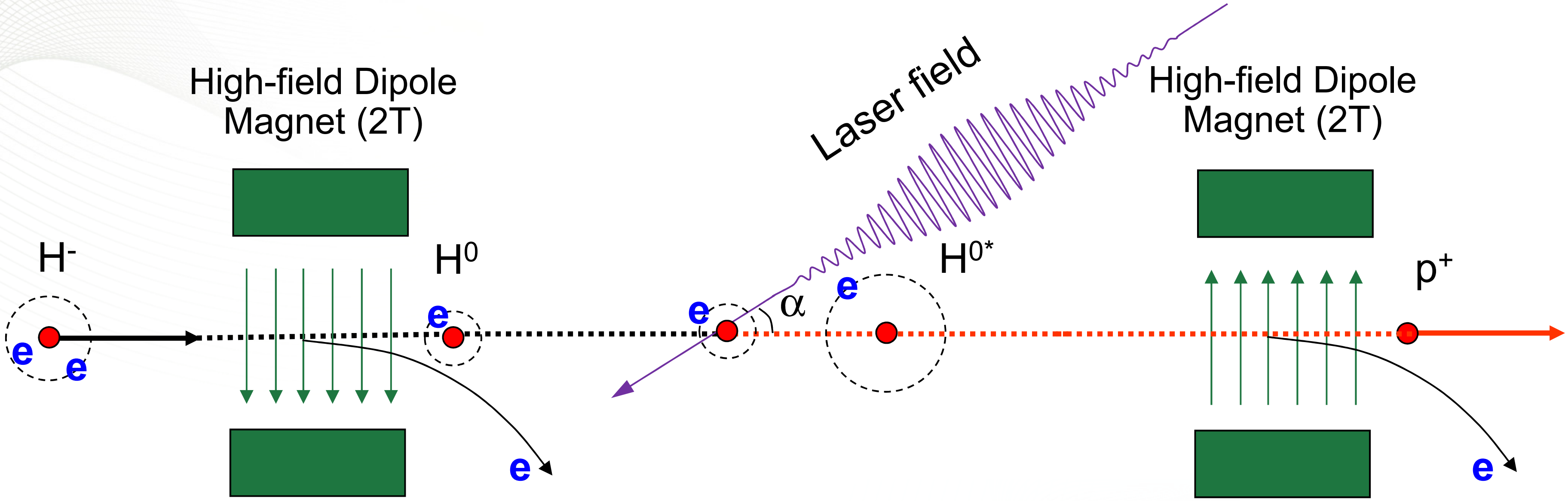
SNS Laser Stripping Concept



Step 1: Lorentz Stripping

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

Step 2: Resonant Laser Excitation

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

Step 3: Lorentz Stripping

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

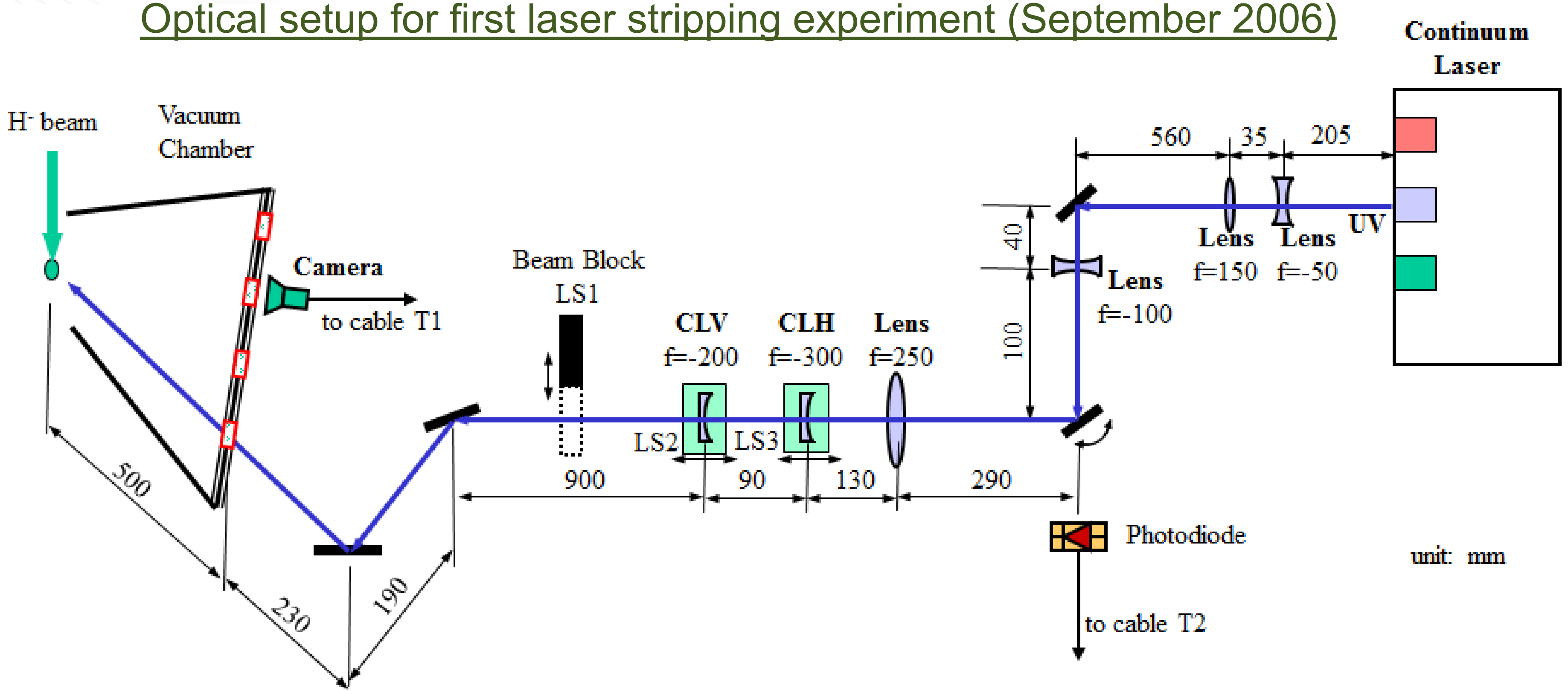
12.1 eV (102.6 nm)

$$\lambda_{laser} = \lambda_{1->3} \times \gamma\left[1 + \frac{v_{beam}}{c}\cos(\alpha)\right], \qquad \gamma = \frac{1}{\sqrt{1-(v_{beam}/c)^2}}$$

$$\lambda_{1->3} = 102.6\text{ nm}, v_{beam} = 0.87c, \gamma = 2.05, \alpha = 37.5°, \lambda_{laser} = 355.5\text{ nm}.$$

Proof-of-Principle Experiment (2006)

Optical setup for first laser stripping experiment (September 2006)



Danilov et al., **PRSTAB (2007)**

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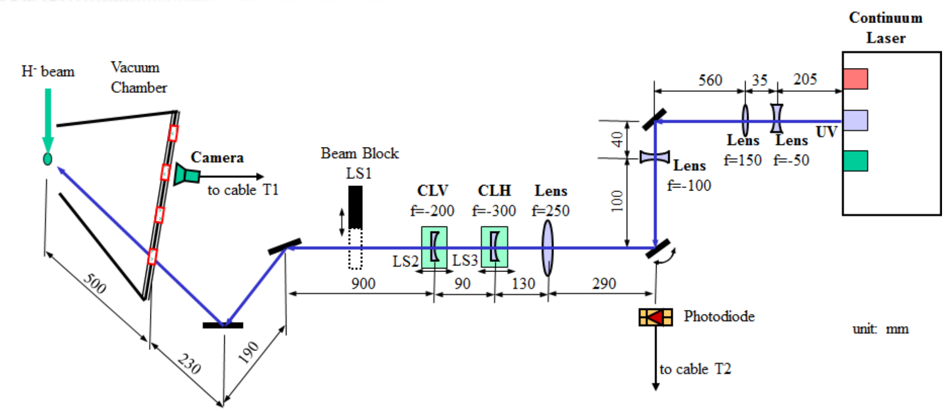
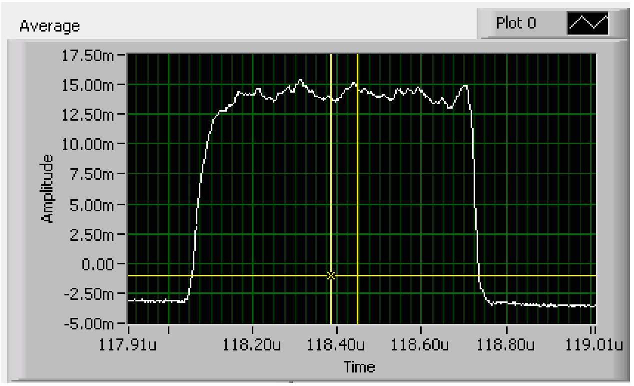
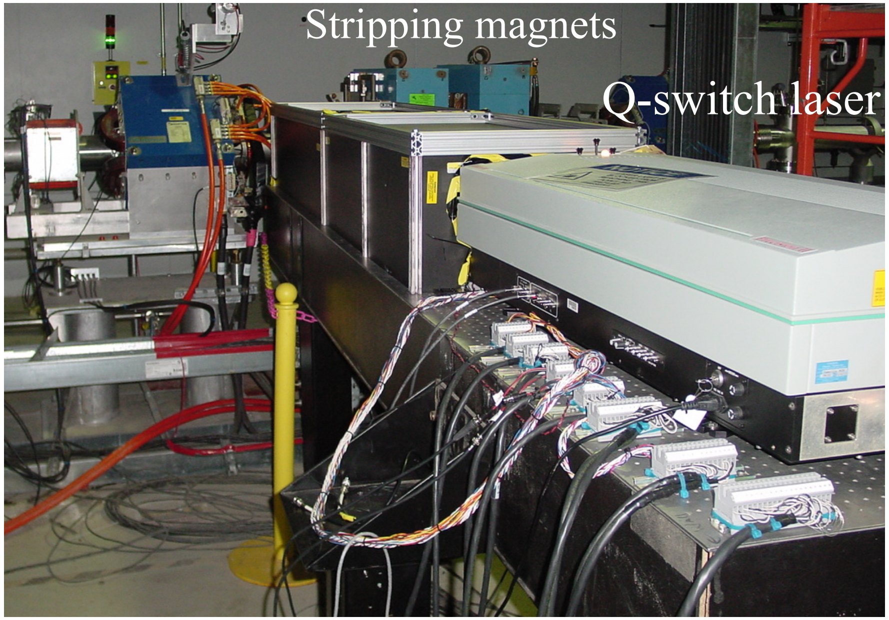
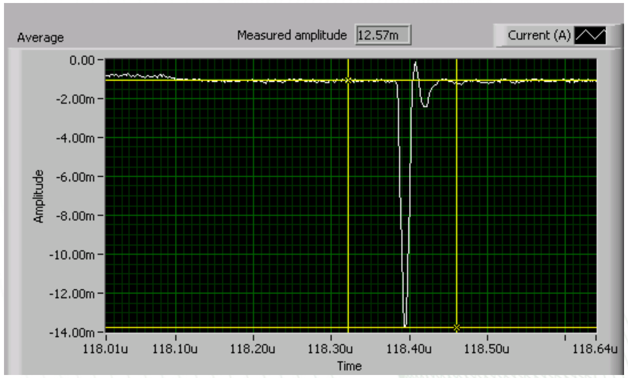


H^- beam current





Stripped electrons by laser



Stripping efficiency: 90%

Danilov et al., **PRSTAB (2007)**

Laser Stripping on 10-μs Macropulse

Goal: To demonstrate high-efficiency laser stripping on 10-μs macropulse which consists of 4,000 micro bunches of H^- beam.

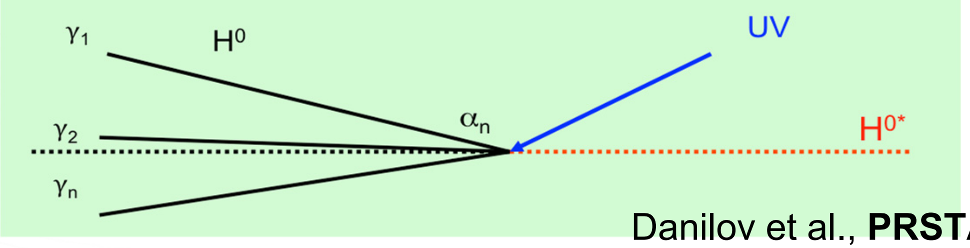
Technical challenges

- **Laser power**
- **Pulse structure and control**
- **Experiment in a highly radioactive environment**

Laser Power Mitigation

- Apply dispersion tailoring to reduce transition frequency spread

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

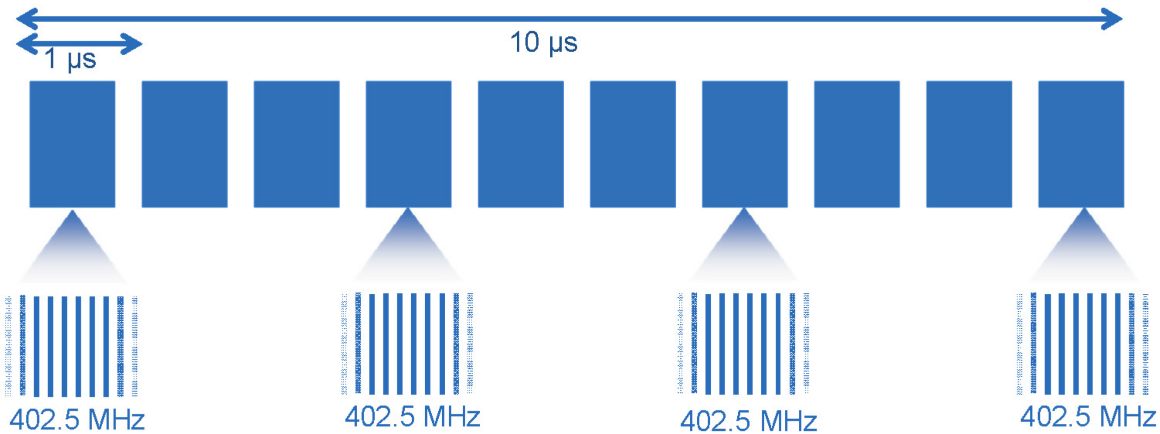


Danilov et al., **PRSTAB (2003)**

- Squeeze particle beam longitudinally and vertically to maximize beam density within the photon-particle overlap area

Results in factor ~10 reduction in required peak laser power

- Matching time structure of laser pulses to ion beam

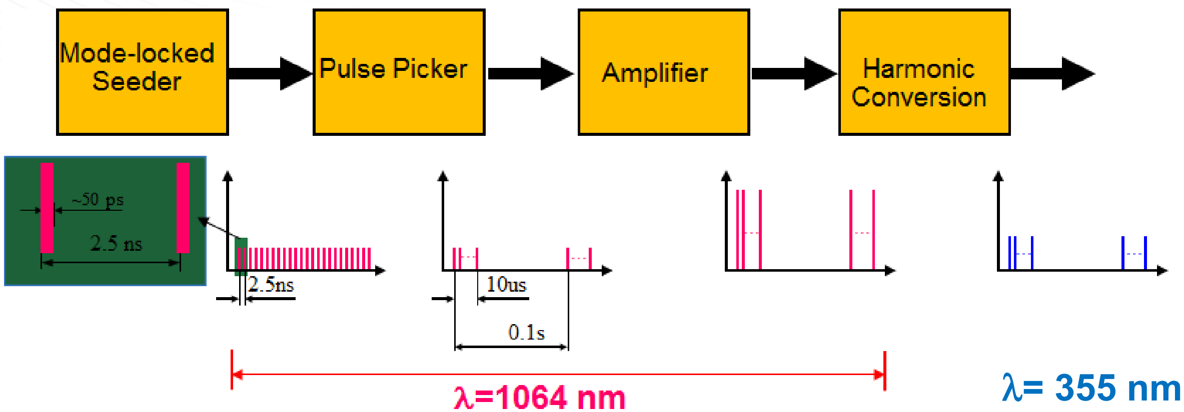


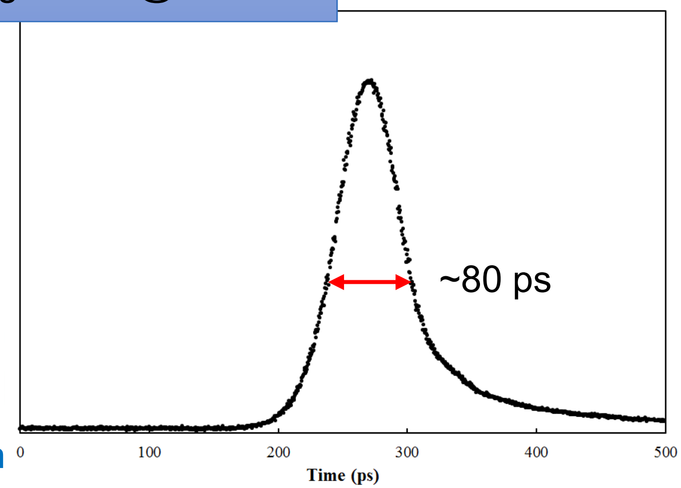
Macropulse Laser – Master Oscillator Power Amplifier (MOPA)

Seeder: generate micro-pulses matching micro-bunch structure of ion beam

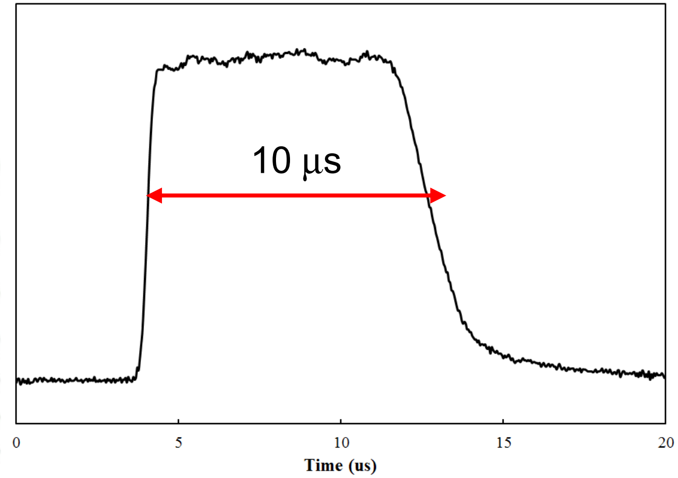
Pulse Picker: provide macro-pulses matching macro-bunch structure of ion beam

Amplifier & Harmonic Converter: boost power to the required level, e.g. 1MW @ 355 nm



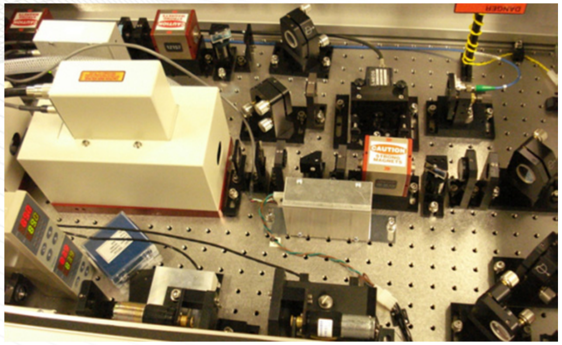


Output wavelength:	**355 nm**
Micropulse:	**30 – 50 ps @ 402.5 MHz**
Macropulse:	**10 μs @ 10 Hz**
Peak power:	**2 MW**
Average power:	**4 W**

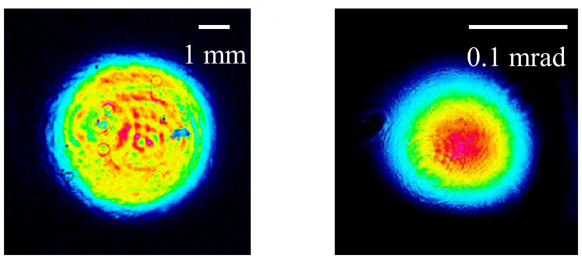


C. Huang, C. Deibele, and Y. Liu, **Opt. Exp. 21, 9123 (2013)**

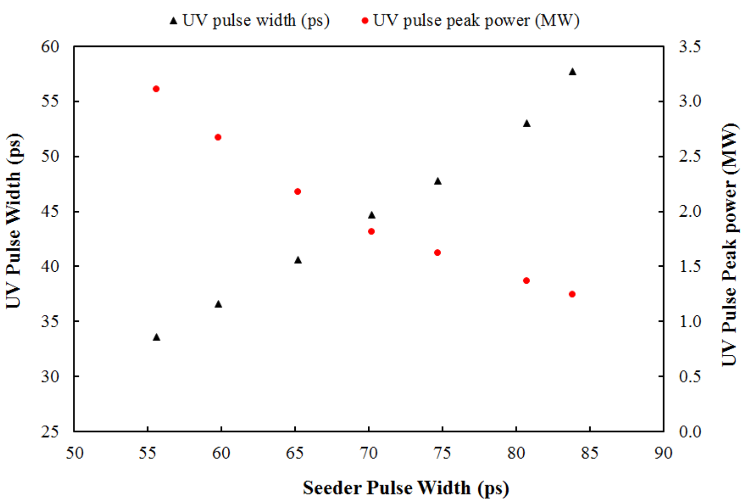
Macropulse Laser Setup

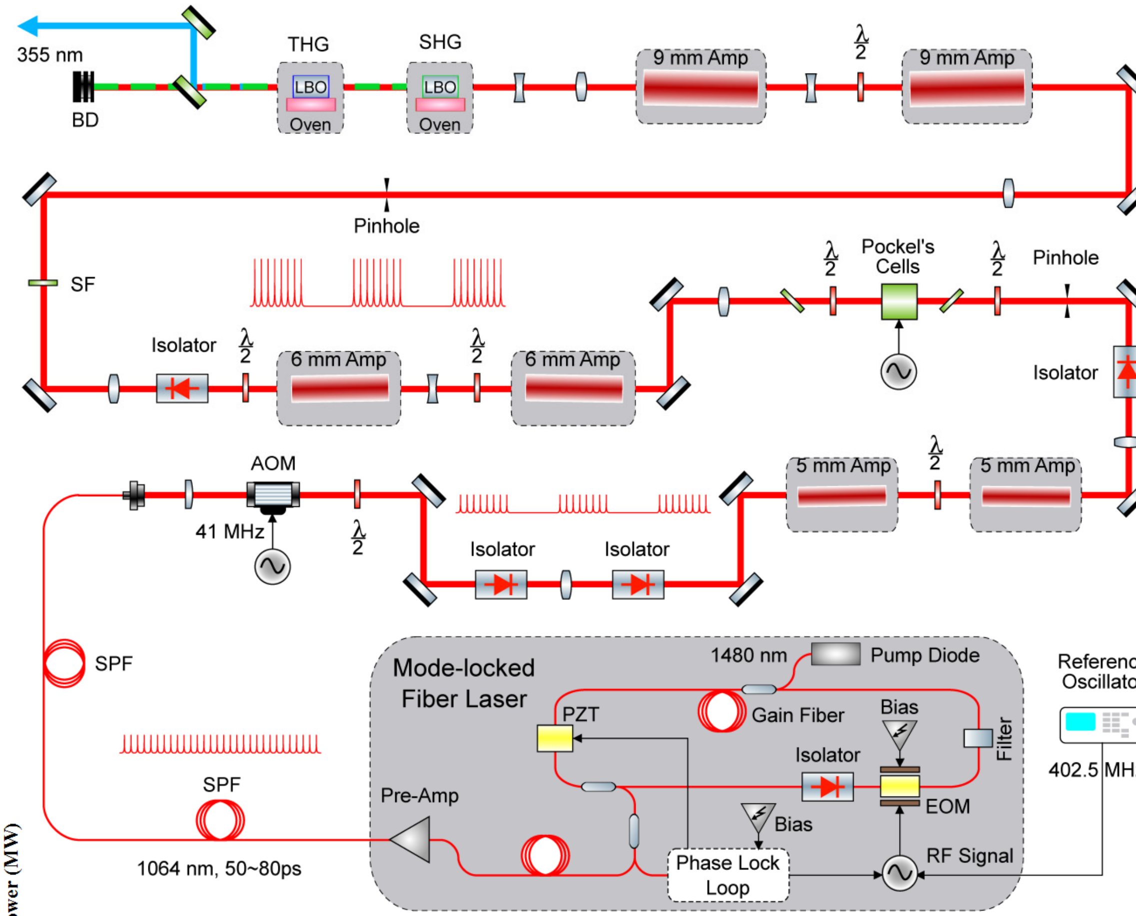


Spatial profiles



UV pulse width and peak power





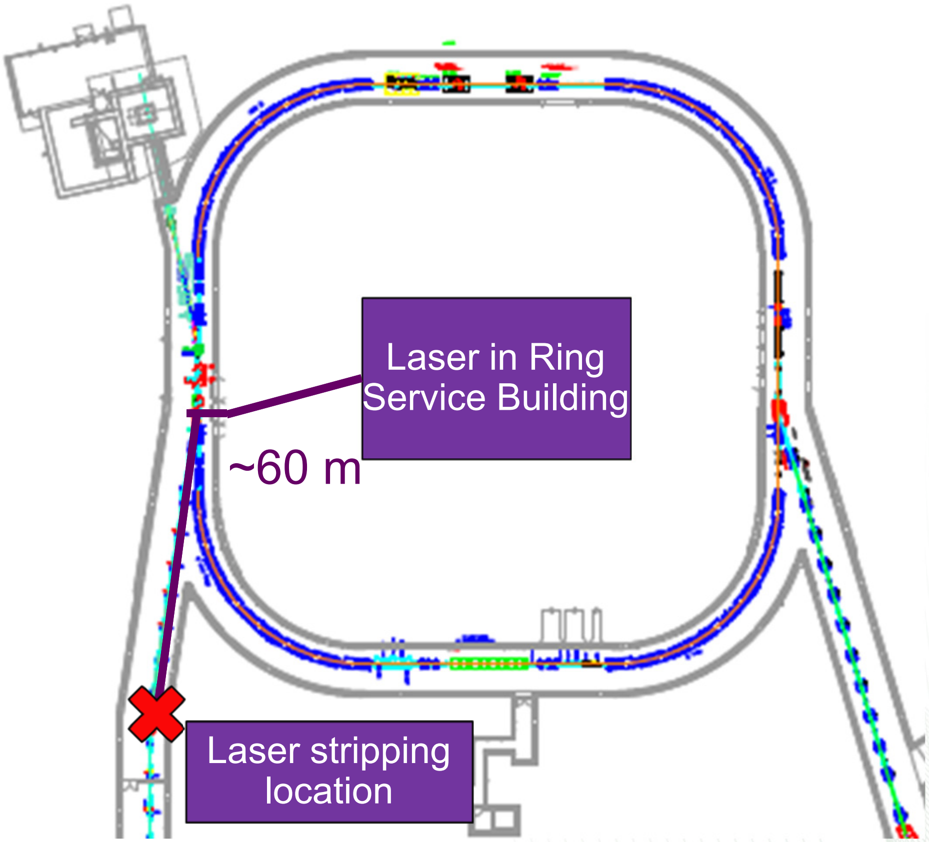
A. Rakhman *et al.* **Appl. Opt. 53, 7603-7609 (2014)**

Layout of 10 μs Stripping Experiment

- Experiment is in the transport line to the Accumulation Ring
- Laser is located remotely in Ring Service Building
- Laser transport line has to be installed

Concerns:

- Laser power loss
- Pointing stability



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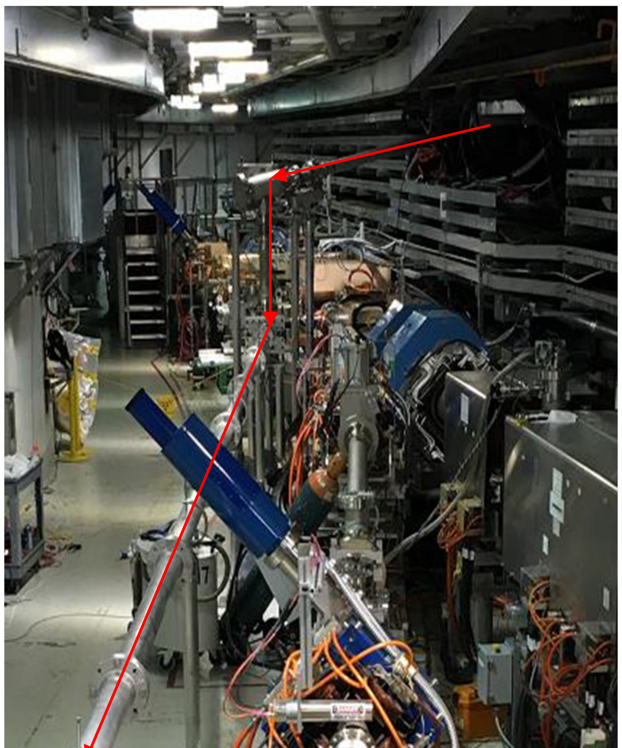
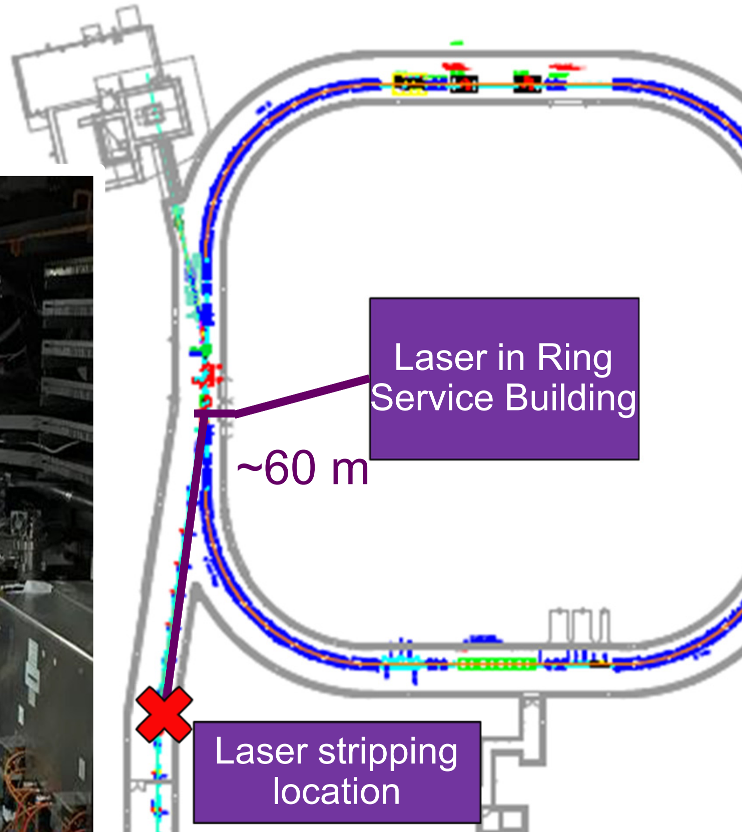
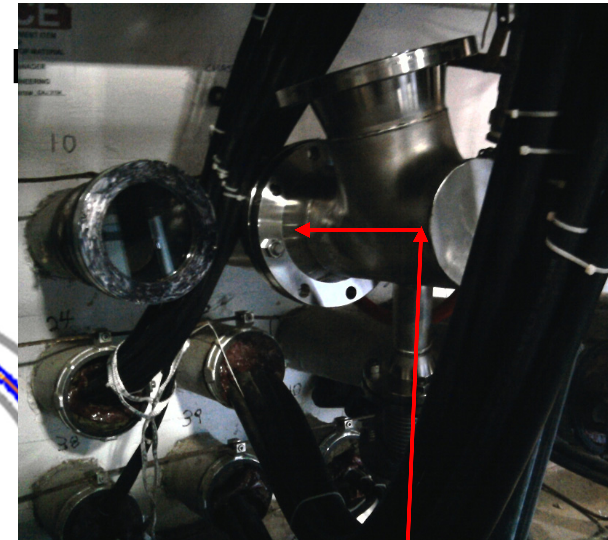
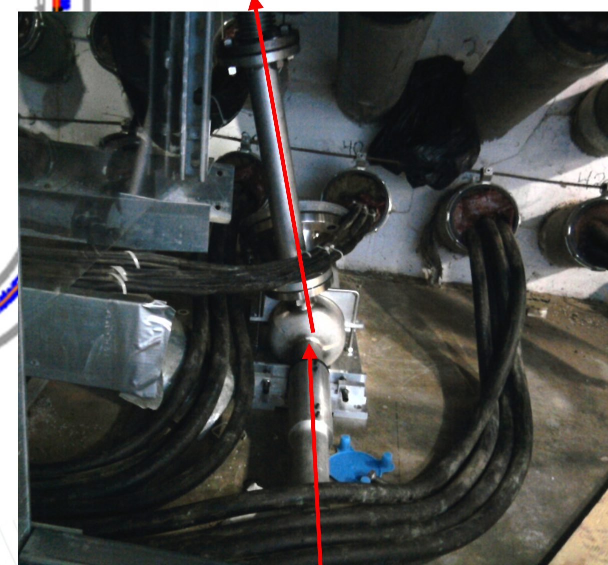
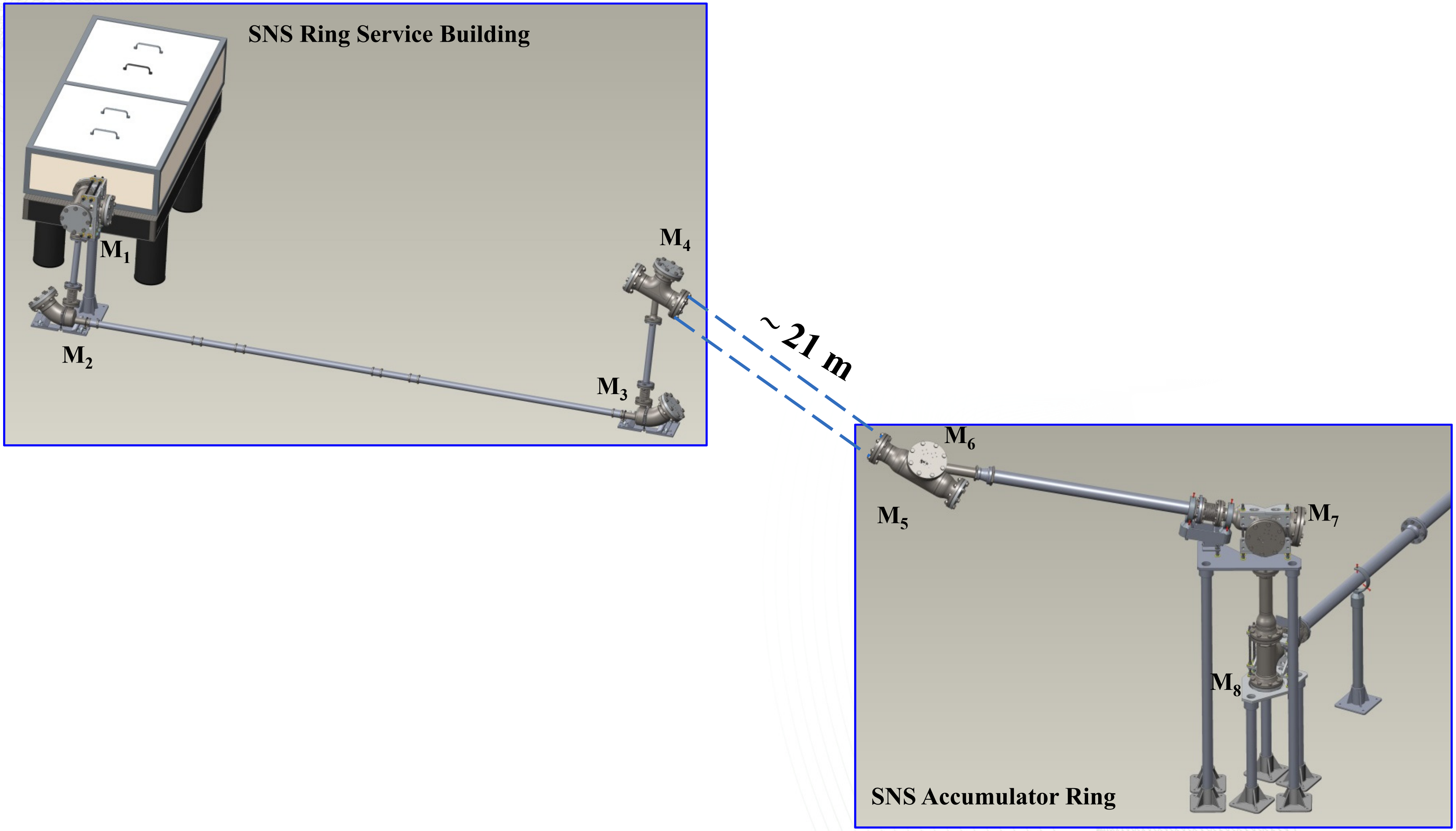








Laser Beam Transport Line



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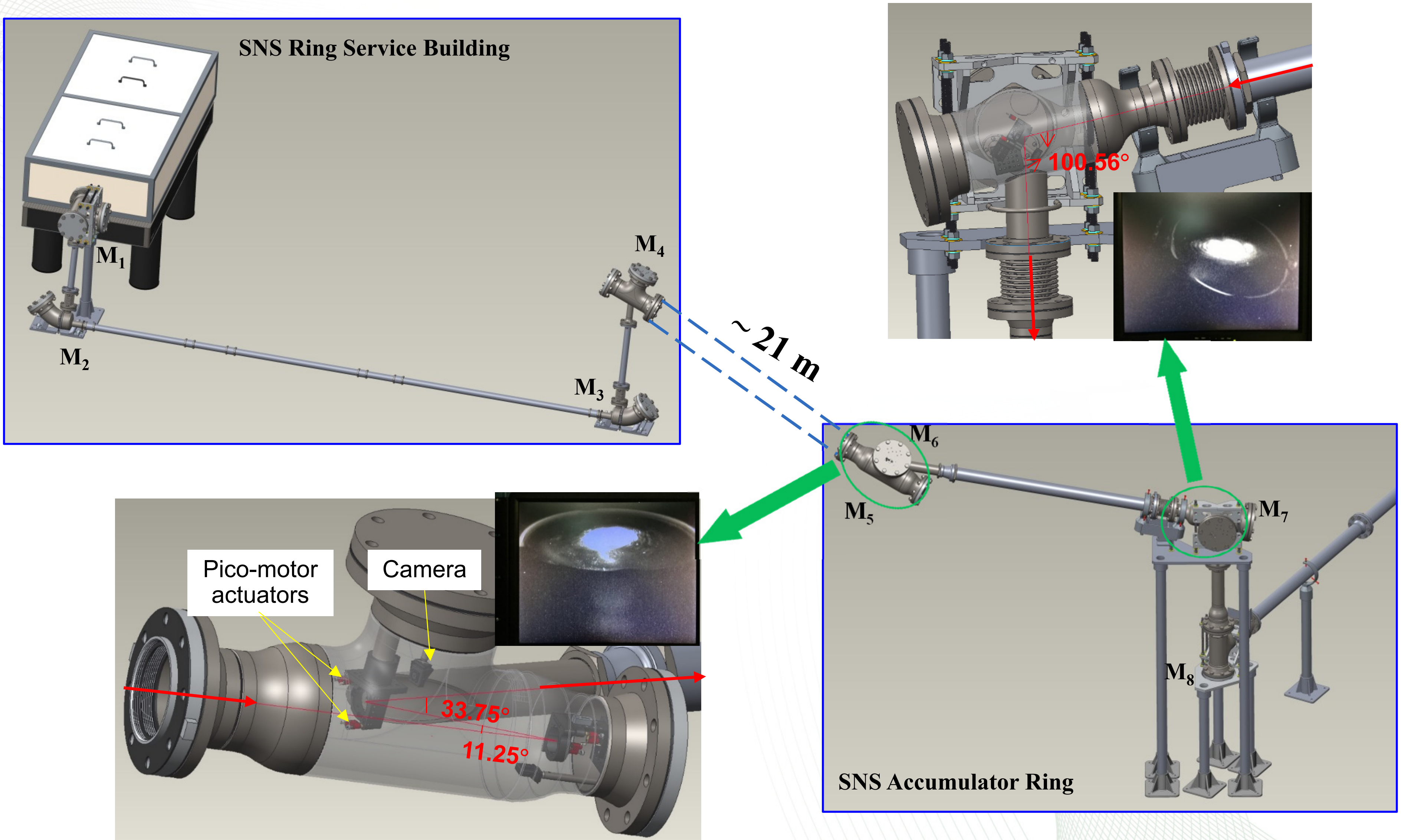
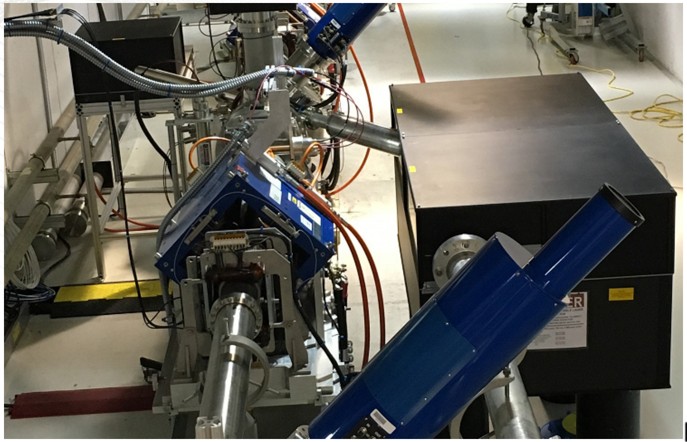
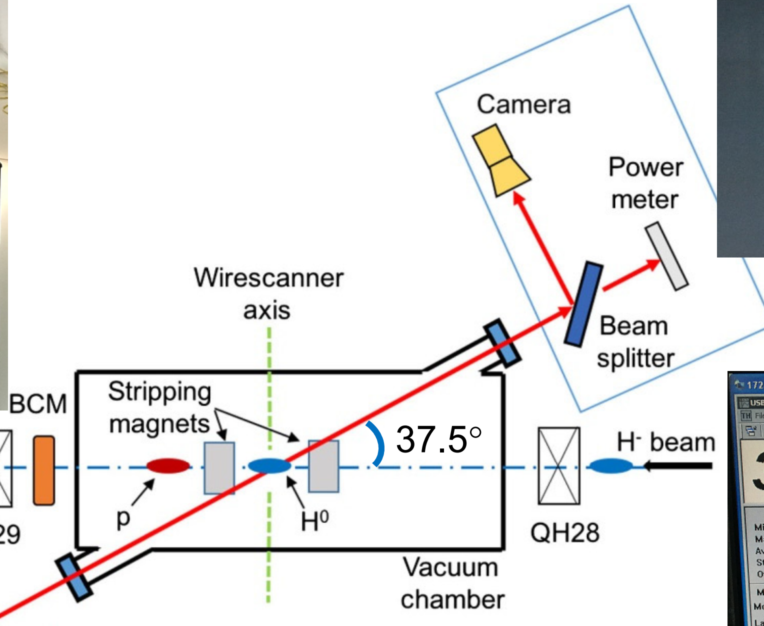
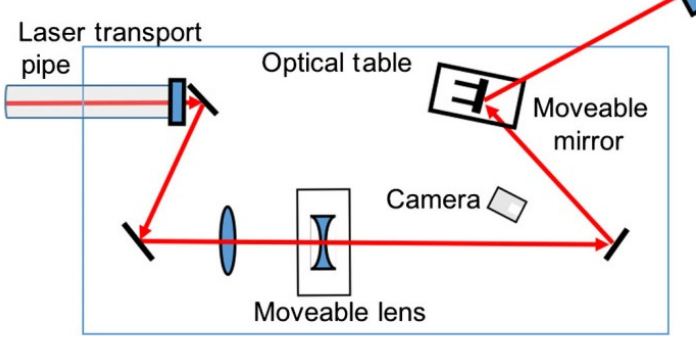
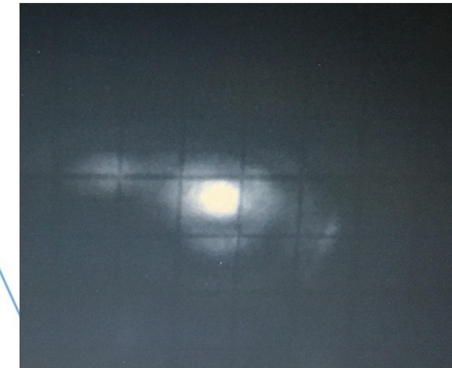


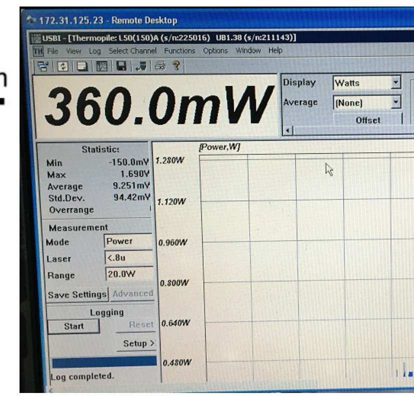
Optics around the Stripping Chamber





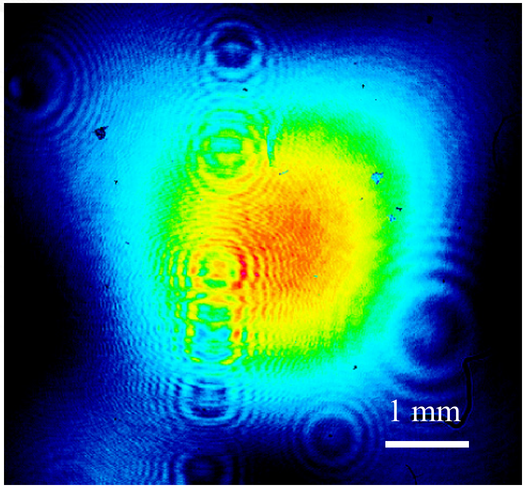




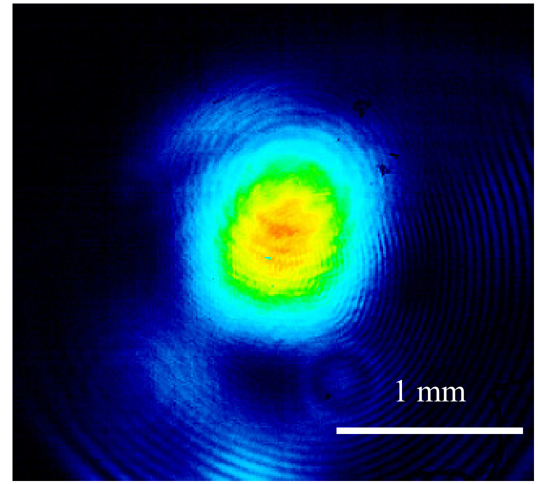


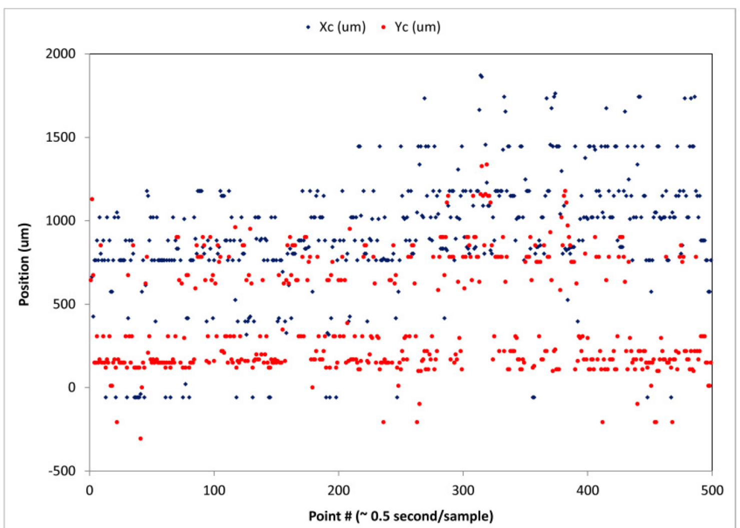
Laser Beam Pointing Stability

Laser beam after LTL

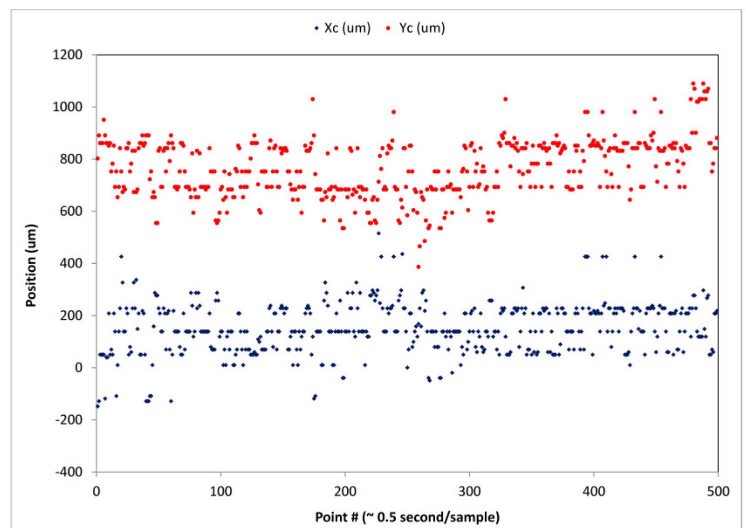


Laser beam at IP





Position variation: ± 0.37 mm (H) × ± 0.33 mm (V)



Position variation: ± 0.10 mm (H) × ± 0.11 mm (V)

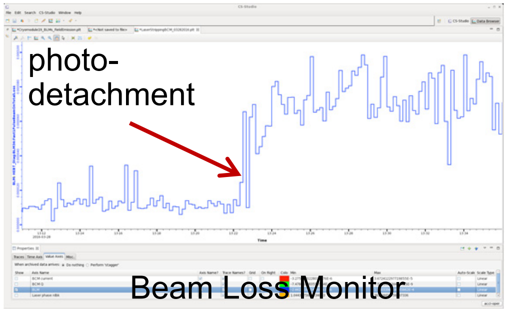
Primary Laser Beam Parameters for the Laser Stripping Experiment

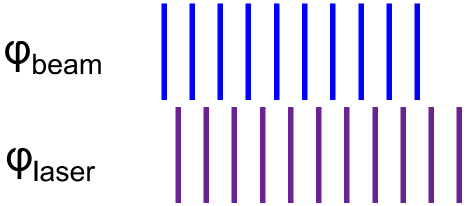
	Required	Delivered
Laser output specifications		
Macro-pulse length	10 us	10 us
Micro-pulse width	> 30 ps	30 – 50 ps (adjustable)
Peak power	1.5 MW	2.5 MW (at pulse width 35 ps)
Laser Transport Line (LTL) performance		
Transmission efficiency	60%	70%
Maximum power delivered on optical table in tunnel	> 1 MW	2 MW
Maximum power delivered to stripping chamber	1 MW	1.2 MW (limited to 1 MW at experiment)
Pointing stability at the exit of LTL		± 0.37 mm (H) × ± 0.33 mm (V)
Laser beam parameters at the photon-H^- interaction point (IP)		
Horizontal beam divergence (4σ)	2 mrad	2.6 mrad
Vertical beam size (4σ)	0.8 mm	1.1 mm
Maximum power delivered	1 MW	2 MW
Pointing stability at the IP		± 0.10 mm (H) × ± 0.11 mm (V)
Laser beam size and intensity on vacuum windows*		
Beam size (4σ) on entrance vacuum window at the default position		3.4 mm (H) × 3.1 mm (V)
Beam size (4σ) on exit vacuum window at the default position		2.7 mm (H) × 2.9 mm (V)

Y. Liu *et al*., **NIMA 847, 171-178 (2017)**

Laser-Ion Beam Alignment

- Vertical position alignment of laser beam based on photo-detachment measurement
- Phase matching between laser and ion beams
- Final steps:
  - Insert stripping magnets, confirm H^0 conversion.
  - Vary laser incoming angle to fine tune resonant frequency.
  - Only indication of correct angle is stripped beam (sensitivity ~0.1°).





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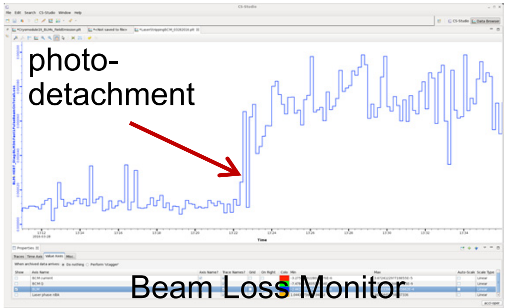

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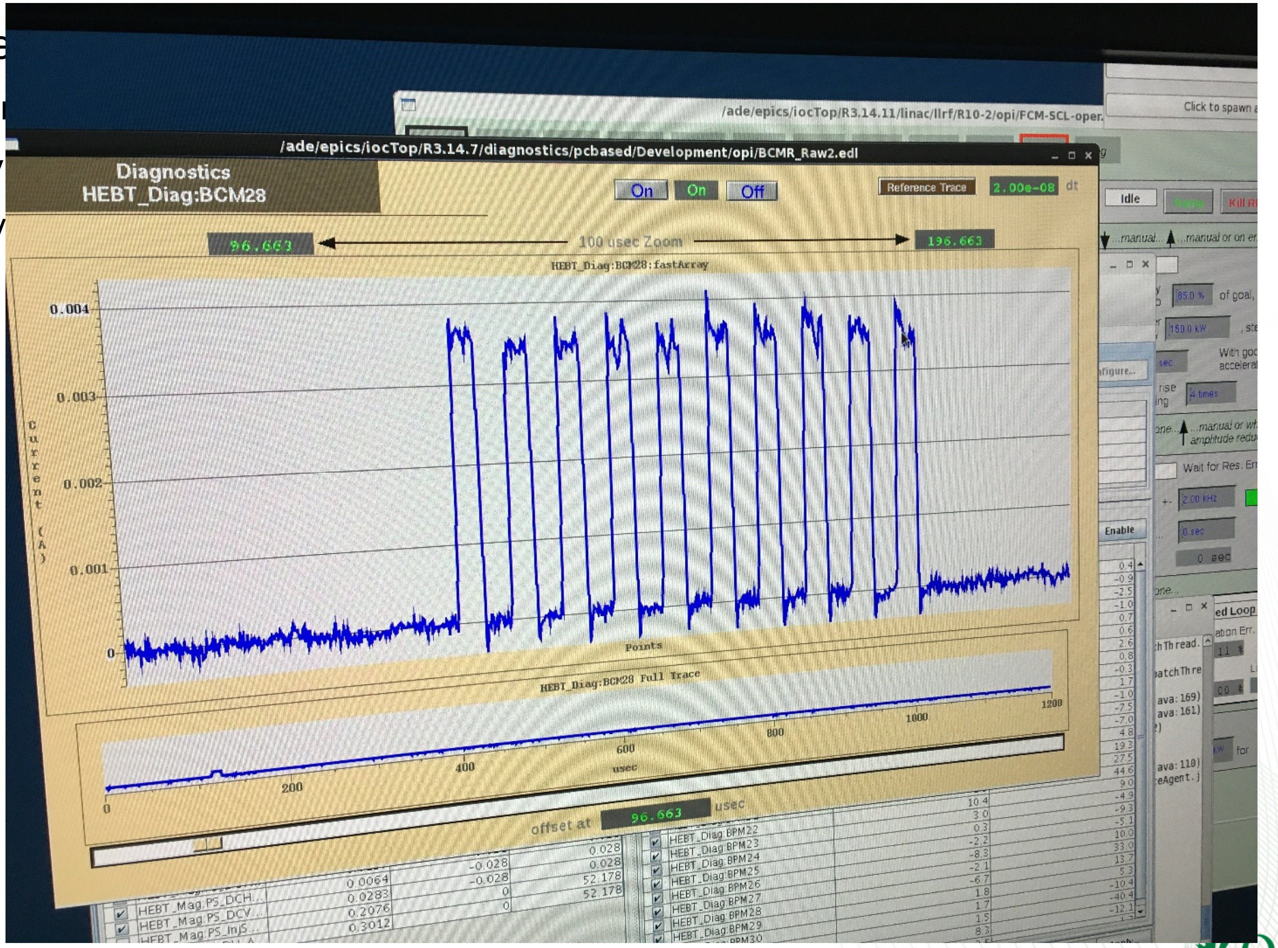
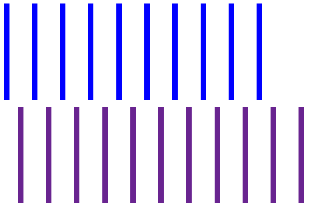
  – Vary
  – Only





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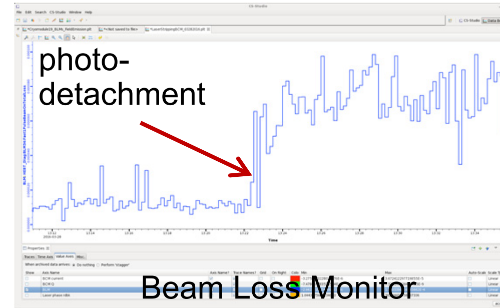

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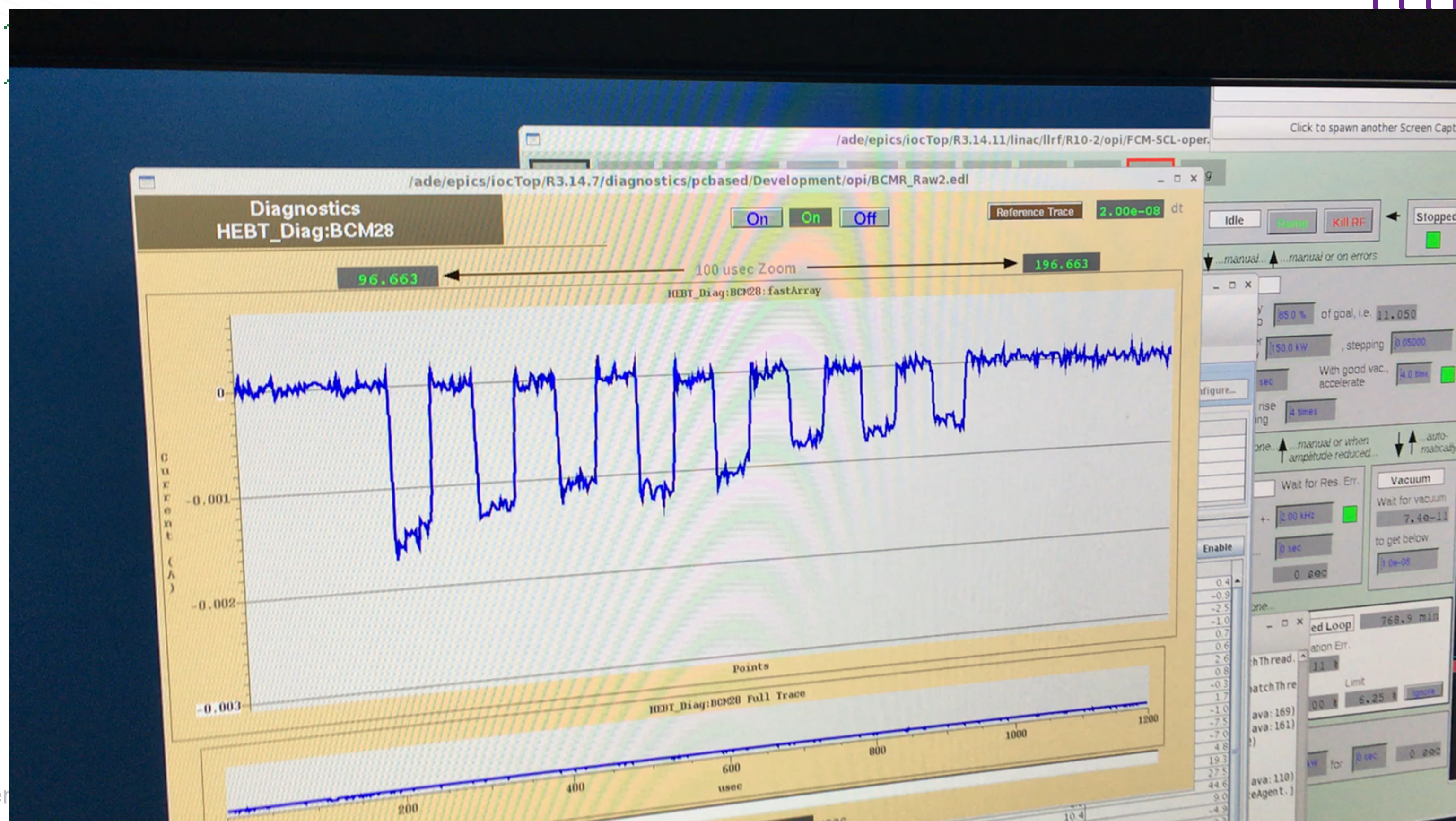
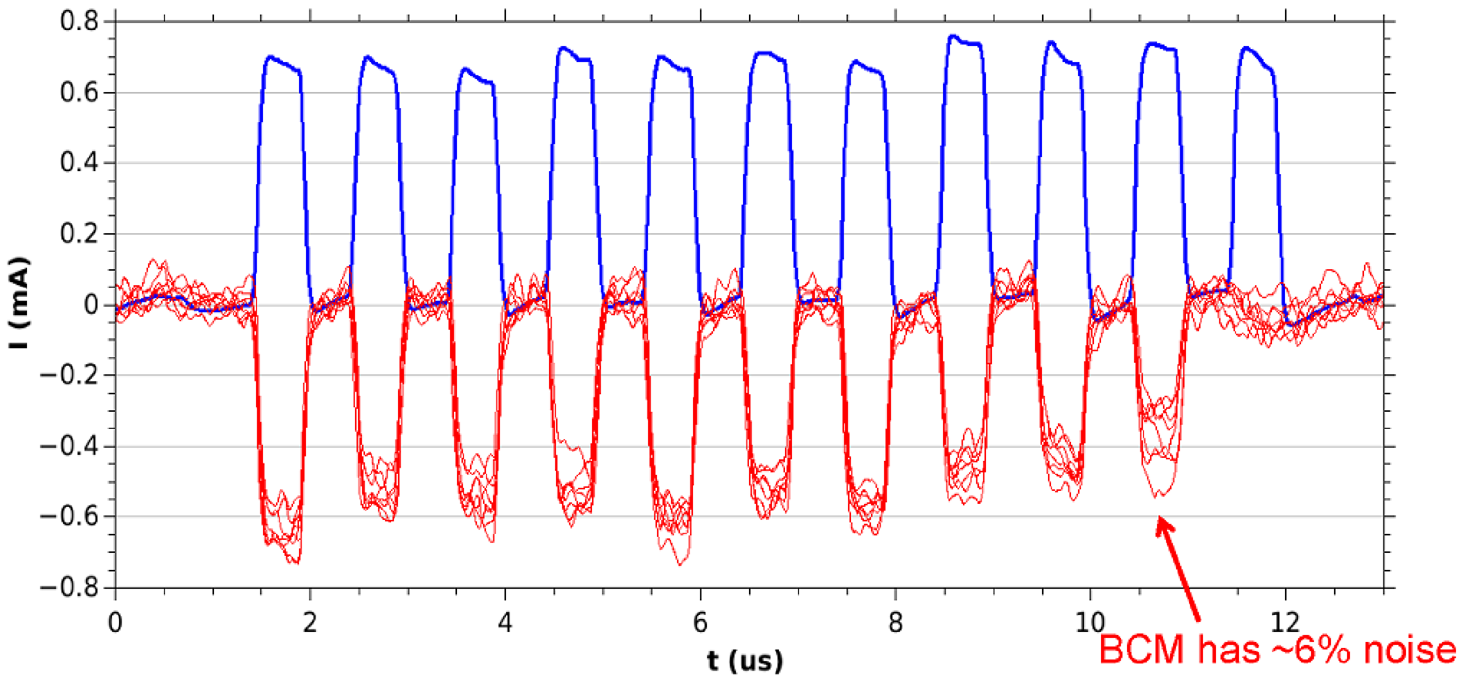


Final Stripping Results

March 28, 2016



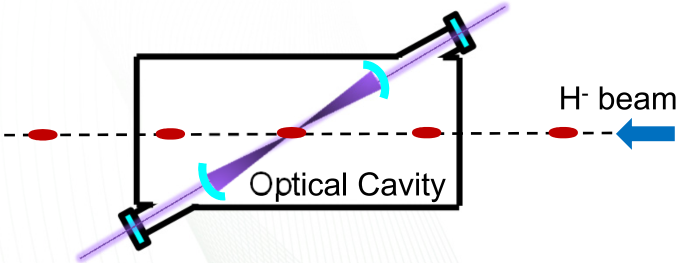
Stripping efficiency > 90%

Cousineau et al, PRL (2017).

Future Work – Scalability to 1-ms/60-Hz Laser Stripping

- Macropulse laser amplifier
  - Current flash-lamp pumped Nd:YAG amplifier can produce UV pulses over 30 – 50 ps with max peak power 3.5 MW at 10 μs.
  - Macropulse duration is limited to 30 μs.
  - Fiber amplifier has excellent beam qualities but no macropulse amplification available.
  - Solid-state amplifiers with 1 ms burst duration are needed.

- Laser stripping in optical recycling cavity
  - Photons/Electrons: ~ 10^7. Very low photon loss in the laser stripping process.
  - It is highly desirable to enhance and recycle the laser power with an optical cavity.
  - We developed a novel technique to solve this problem.



A. Rakhman, M. Notcutt, and Y. Liu, **Opt. Lett. 40, 5562 (2015)**

Summary

- Laser assisted hydrogen beam stripping method has been developed at SNS for high intensity proton beam production
- We have successfully demonstrated laser stripping on 10-μs H^- macropulses
  - Manipulation of ion beam parameters
  - Development of macropulse laser system
  - Installation of laser transport line
- Research on laser stripping in a power recycling optical cavity is on going.