Manipulating H^- Beams with Lasers

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NAPAC2019, Lansing, MI

9/3/2019

Outlines

- Background
- H^- Photo-Detachment
  - Beam diagnostics
  - Laser notcher & momentum correction
  - Beam Extraction/Splitting
  - Laser sculpting
- H^- Charge Exchange Injection
  - Single-step excitation
  - J-PARC scheme
  - Sequential excitation
  - Laser crab-crossing
  - Enhancement cavity
- Perspectives (challenges & technology)
- Summaries

Why H^- Beams Need Lasers?

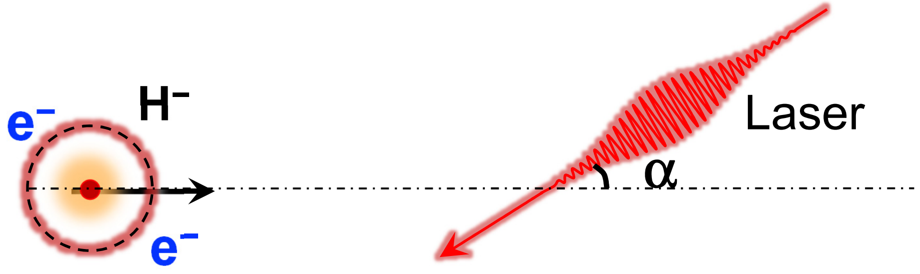
- Laser manipulations of the H^- beams are an important subject for the high-intensity proton accelerators with many purposes such as,
- Non-destructive beam diagnostics
  - nonintrusive beam profile and emittance measurements have little risk of causing equipment damage
  - can be conducted under operational particle beam conditions (high beam current, long pulse duration, and high rep. rates)
- Beam chopping and halo reduction
- Beam extraction, arbitrary beam pattern generation
- Beam carving (sculpting)
- Laser assisted charge exchange
- Laser systems have been in use at many major H^- beam facilities such as BNL, CERN, Fermilab, JPARC, LANL and SNS.

H^- Laser Beam Interaction

- Photodetachment: based on removing of electrons from ions by interactions with photons
- Yield is larger for low energy ion beams than higher energy beams
- Interaction cross-section is divided into three domains:

$$H^- + h\nu \begin{cases} \rightarrow H^0(1s) + e^-, & 0.75\ eV < E_l < 10.9\ eV \\ \rightarrow H^0(n \geq 2) + e^-, & 10.9\ eV < E_l < 14.35\ eV \\ \rightarrow H^+ + 2e^-, & E_l > 14.35\ eV \end{cases}$$

single photo-detachment
resonant excited state
double photo-detachment

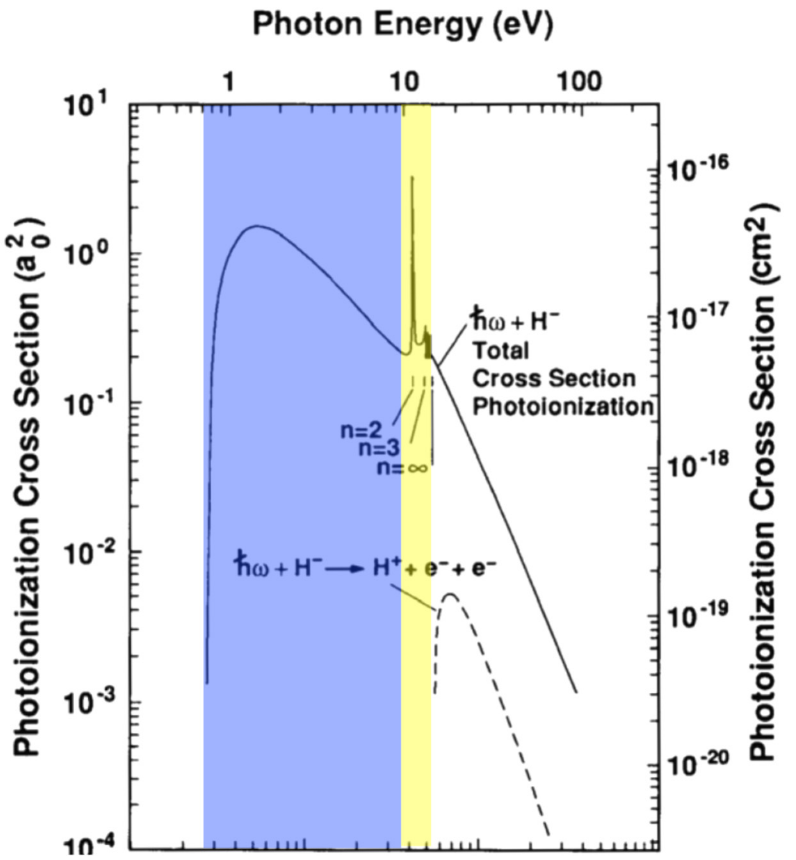


E_l: laser energy in ion beam rest frame

$$E_l^{cm} = E_l \gamma (1 + \beta \cos \alpha)$$

Single photo-detachment yield:

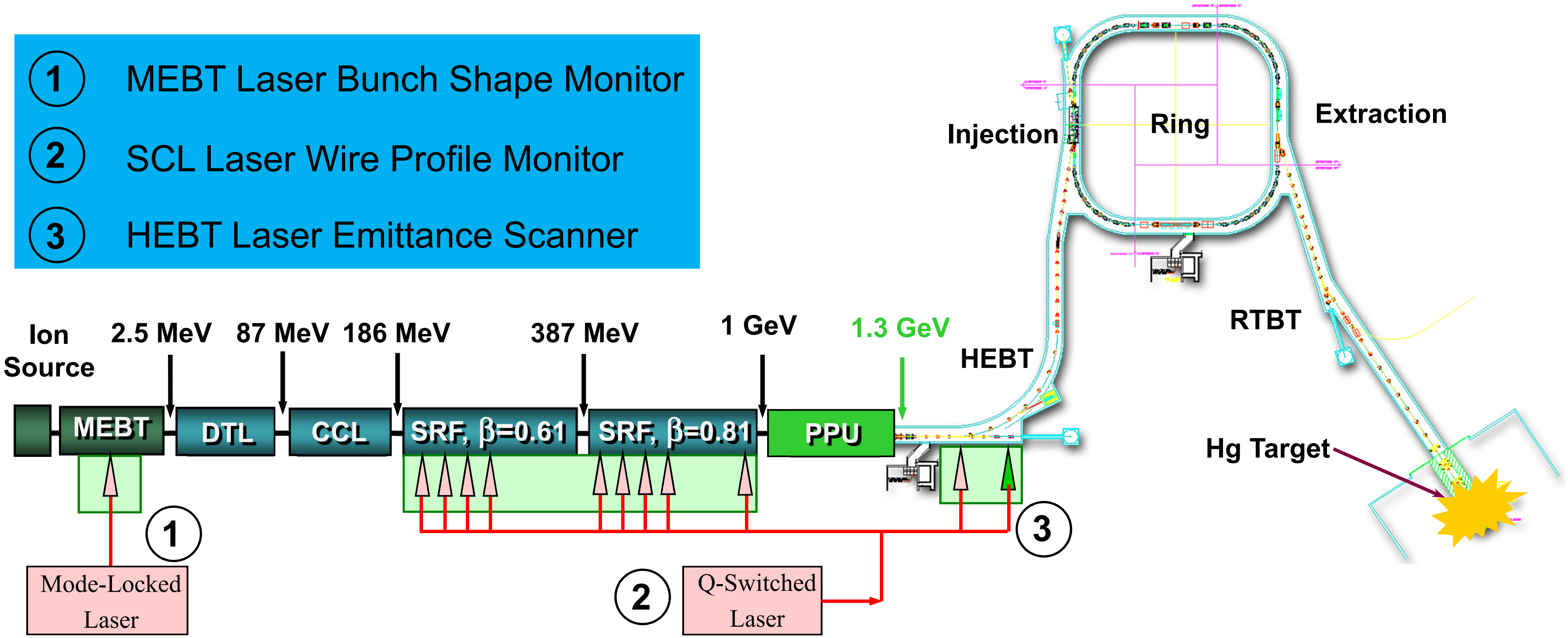
$$Y_l = \frac{I_b N_l}{\sqrt{2\pi} e \beta c} \frac{1 - \beta \cos \alpha}{\sin \alpha} \frac{\sigma_N(E_l)}{(\sigma_b^2 + \sigma_l^2)^{\frac{1}{2}}}$$



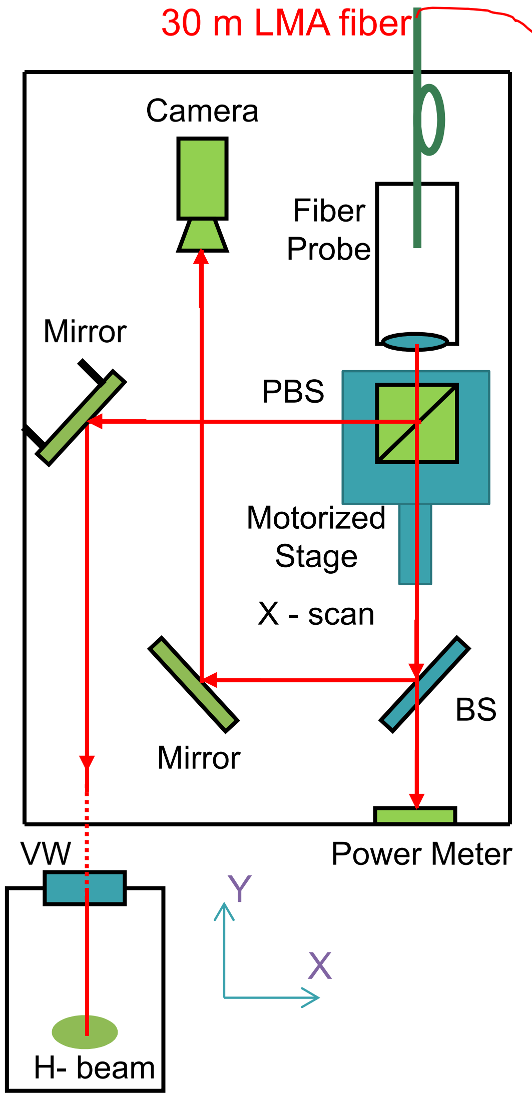
A. Rau, ***J. Astrophys. Astr.,*** 17:113–145, (1996)

Non-invasive Beam Profile Diagnostics at SNS

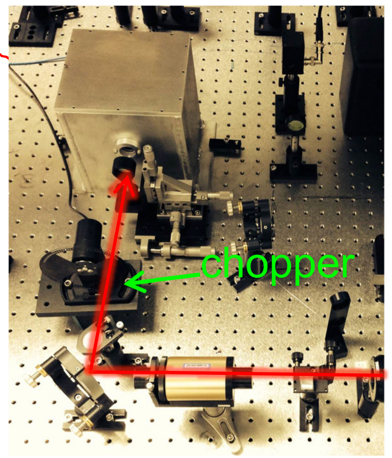
- In the photo-detachment process, the neutralized beam (H^0) maintains nearly the original phase-space parameters of the H^- beam from which it was extracted.
- The transverse spatial profile, transverse divergence, emittance, energy, energy spread, and phase spread characteristics of the H^0 and H^- beams are the nearly identical and can be deduced.
- Three types of laser-based diagnostics have been developed at SNS for measuring H^- beam.



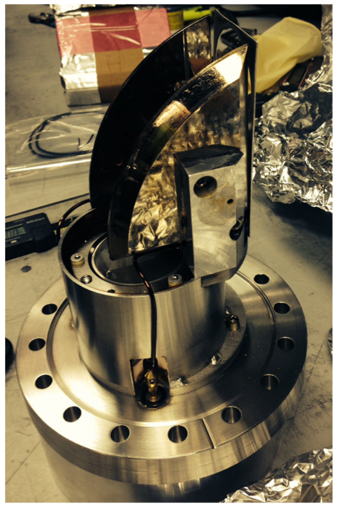
MEBT Longitudinal Bunch Shape Monitor



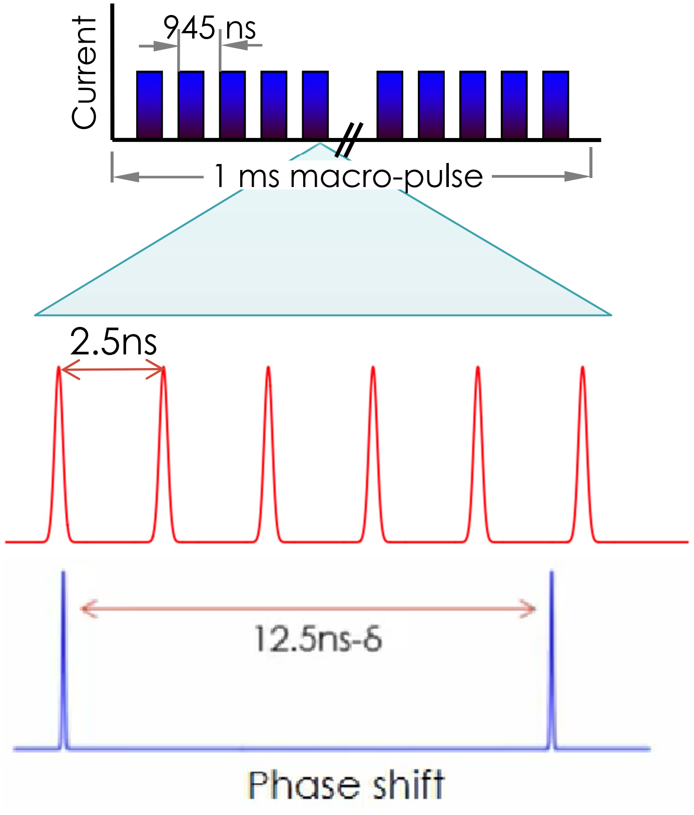
Laser table

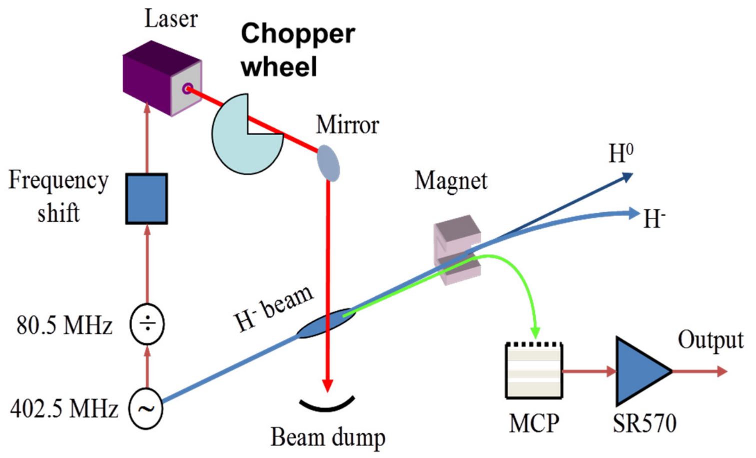


MCP & magnet

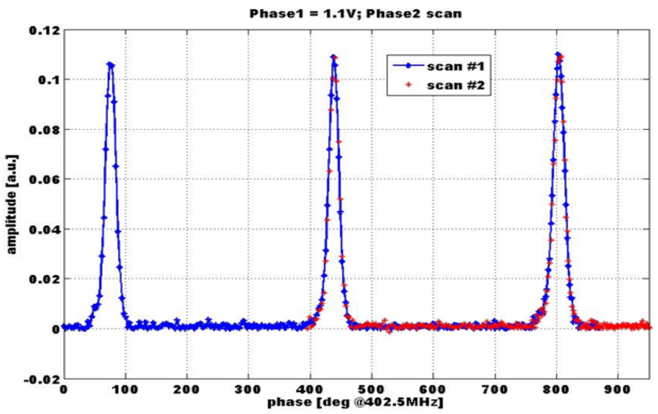


Laser detaches the electrons from the 2.5MeV negative hydrogen ions in the MEBT. The detached electrons are deflected by magnet to be collected by MCP.



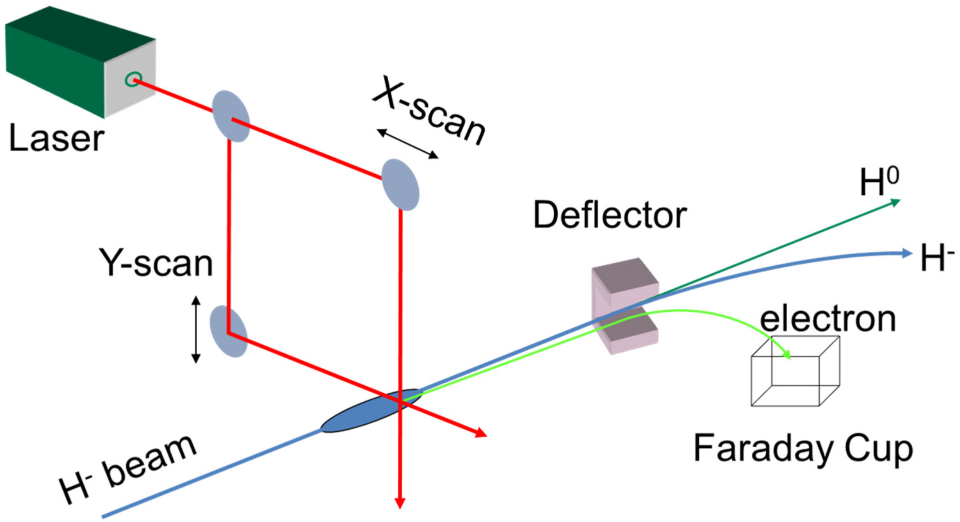


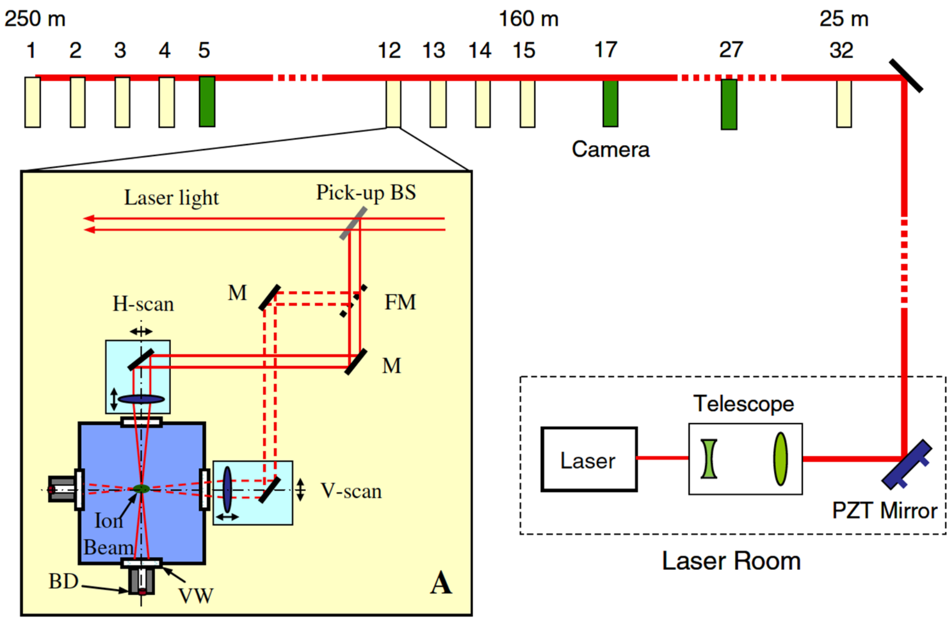
- Mode-locked Ti:S Laser
- λ = 800 nm
- f_{rep} = 80.5 MHz
- T_w = 2.5 ps (11.6 ps @ fiber end)



A.Zhukov, A. Aleksandrov, Y. Liu, *IBIC'14*, **MOCYB3**

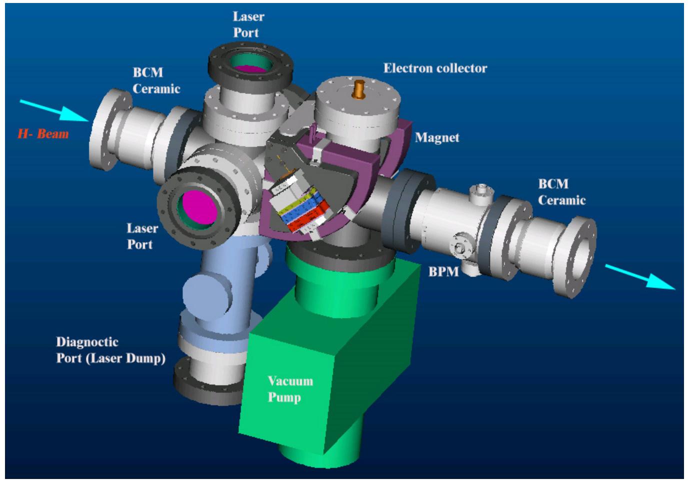
SCL Laser Wire Profile Monitor



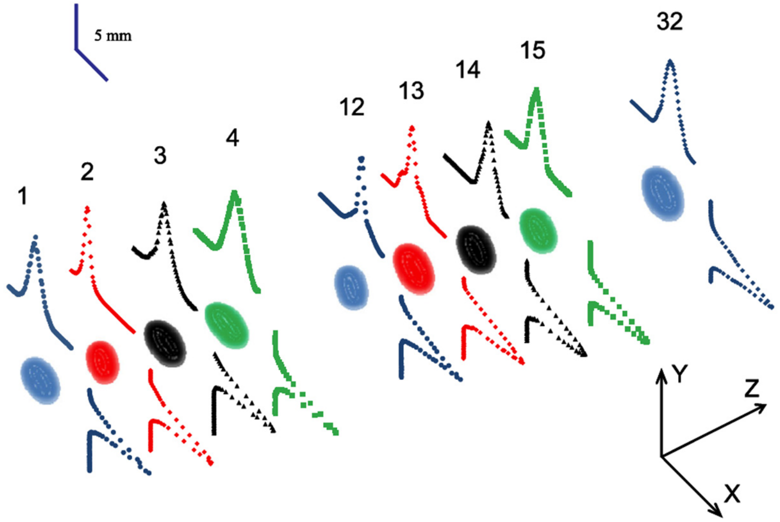


Q-switched Nd:YAG Laser

- λ = 1064 nm
- f_{rep} = 30 Hz
- T_w = 7 ns
- E_p = 1 J



- 9 pairs of profiles measured
- 4 LW from 200 MeV
- 4 LW from 450 MeV
- 1 LW at 1 GeV

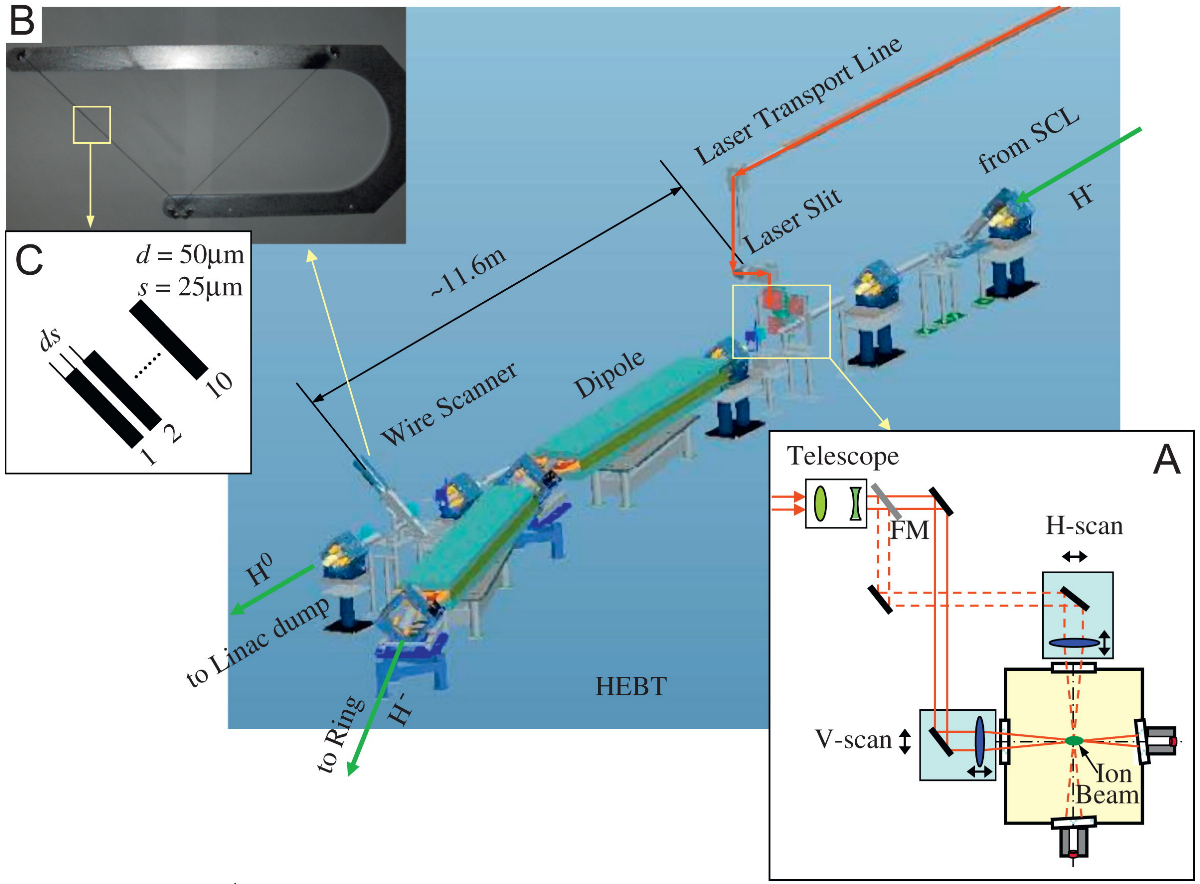


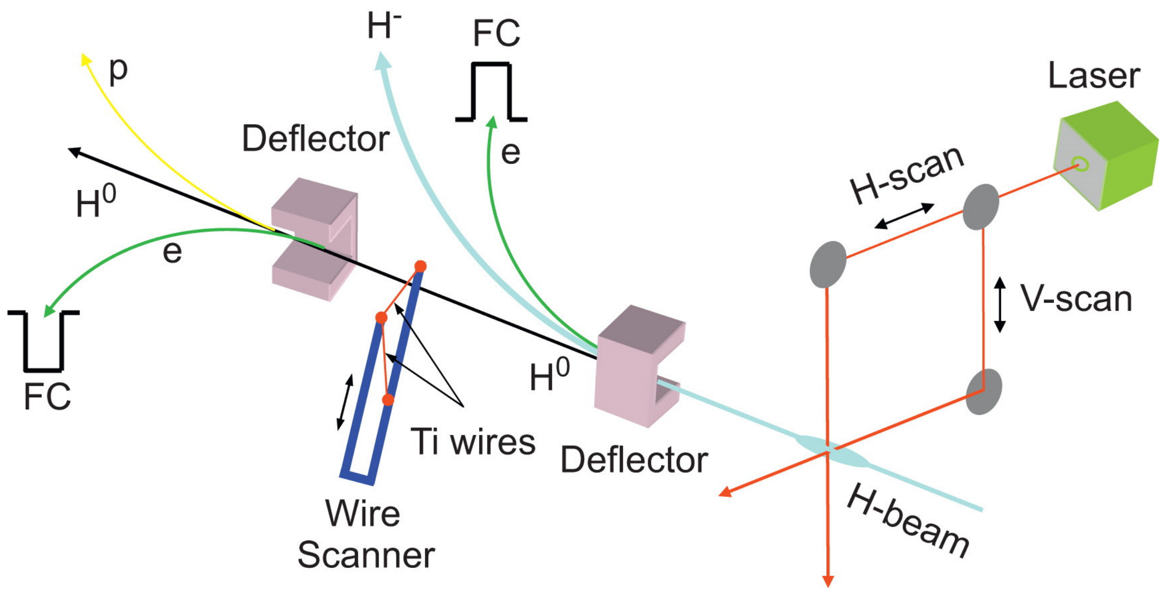
Y. Liu, *et al.*, ***Phys. Rev. STAB*** 16 (2013) 012801

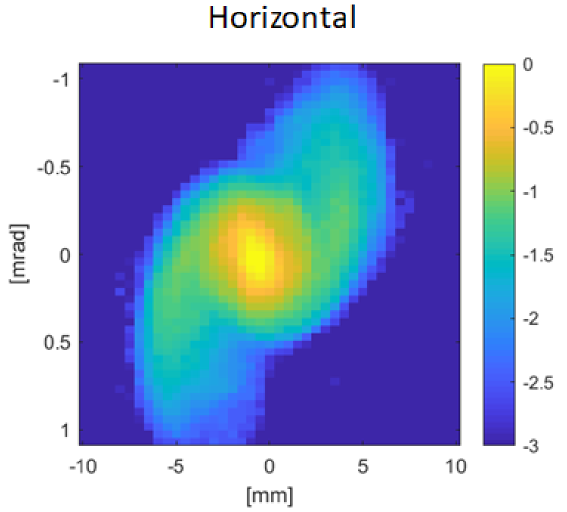
HEBT Emittance Scanner

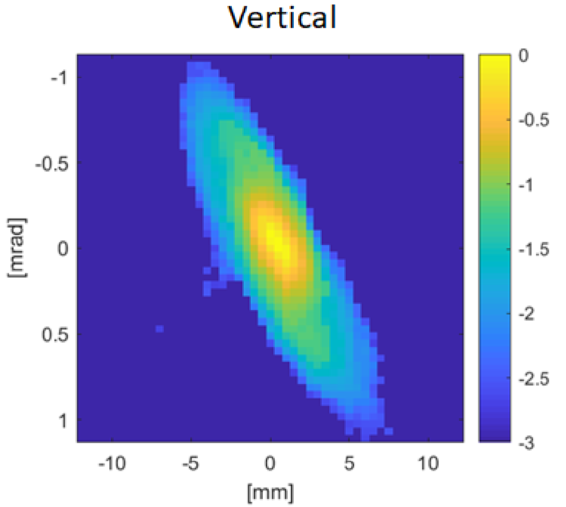
- 1064nm/200mJ laser pulse split from the same Q-switched laser line in LW

Φ50 µm Ti wire



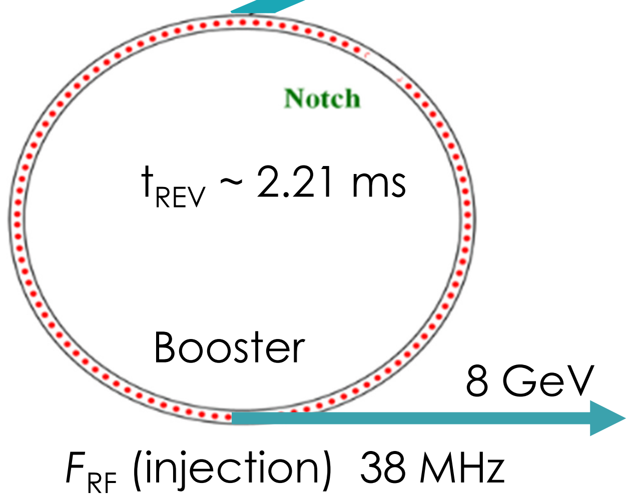






Y. Liu *et al.*, ***Nucl. Inst. Meth. A*** 675, 97-102 (2012)

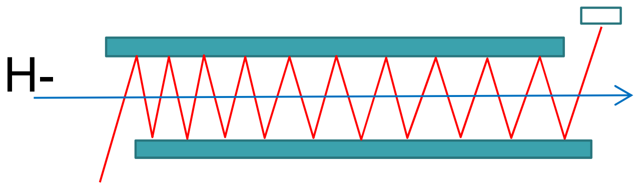
Fermilab Laser Notcher

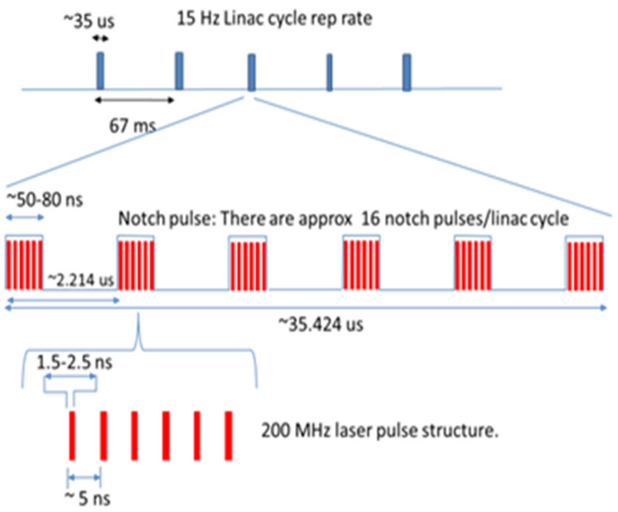


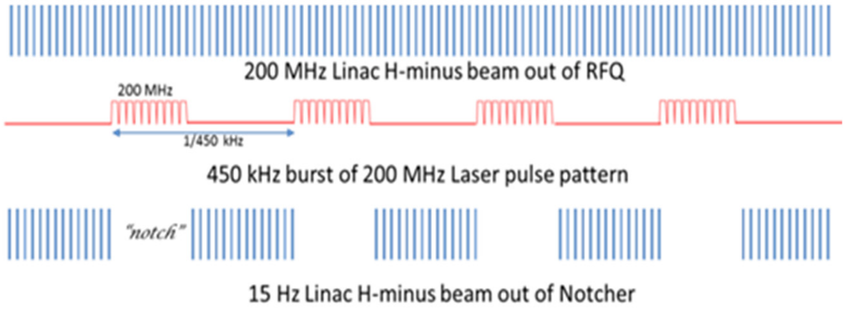
- Use laser to create notches (neutralize H^-) in linac at 750 keV
- Replace the notch created in Booster @400 MeV which has ~30% total power loss
- Match the H^- ion 201.25 MHz bunch structure exiting RFQ
- The width of the 201.25 MHz burst is 80 ns to allow for rise time of the Booster extraction kicker

Non-resonant optical cavity (zig-zag cavity)

$$F_N = 1-(1-F_{neut})^N$$

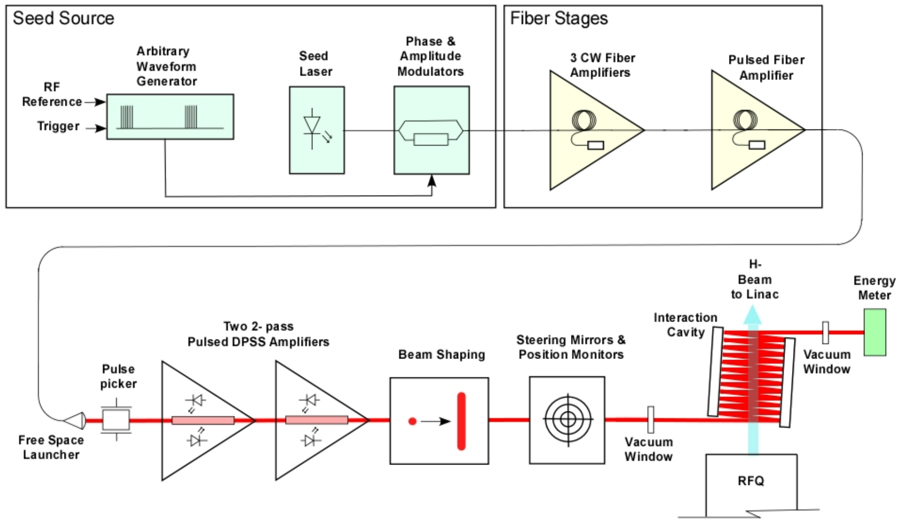






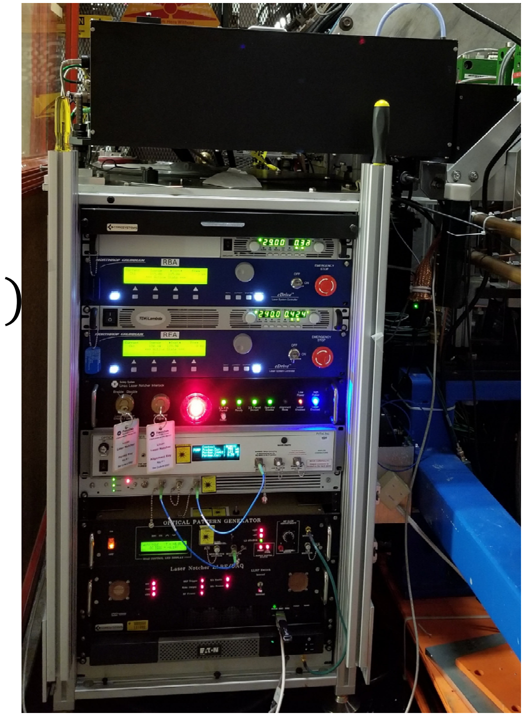
Courtesy: D. Johnson (Fermilab)

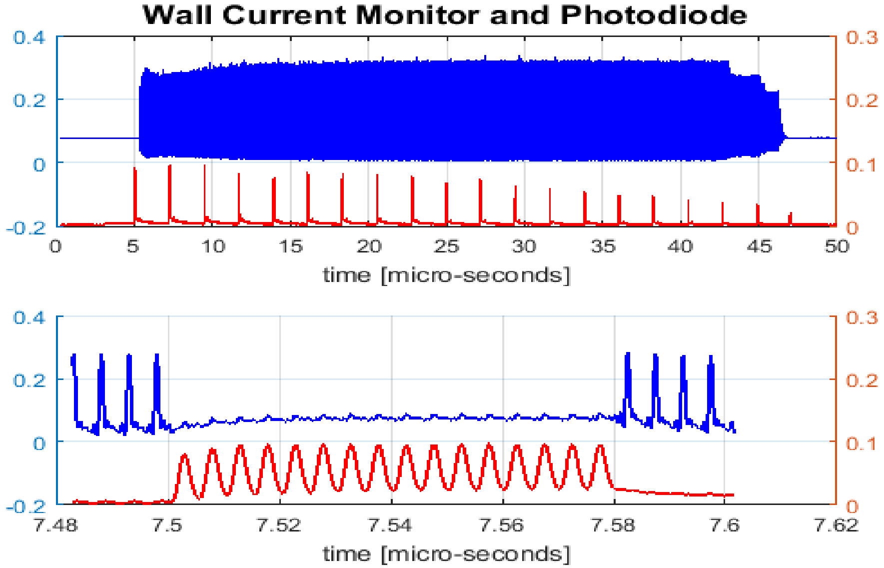
Fermilab Laser Notcher

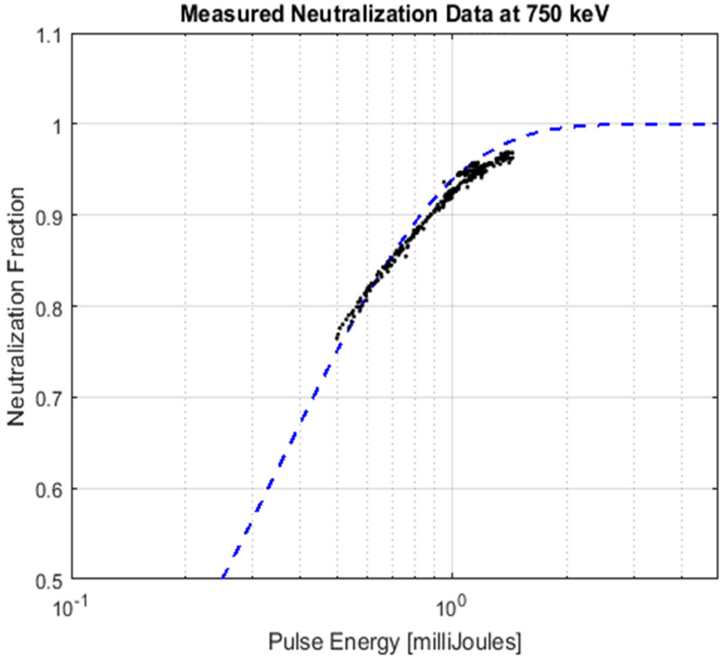


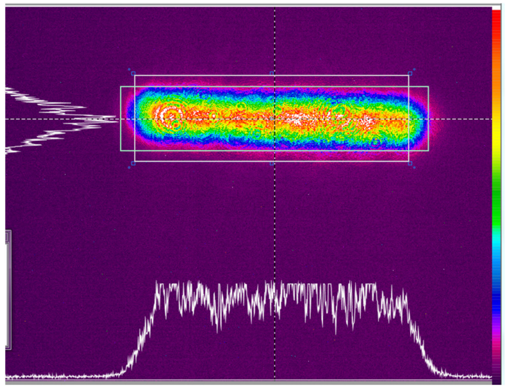
$$F_1 = N/N_0 = (1 - e^{-f_{CM} * \sigma(E) * \tau_{crossing}})$$

$$f_{cm} = \gamma \left(\frac{E_{laser}\lambda_{LAB}}{hc\tau_{laser}}\right)\left(\frac{1}{A_{laser}}\right)(1 - \beta\cos\theta)$$







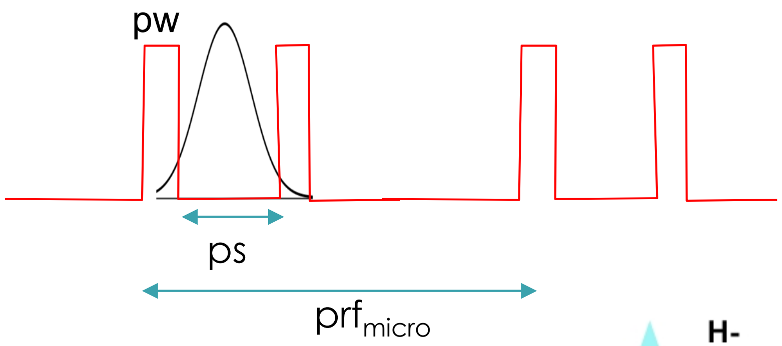


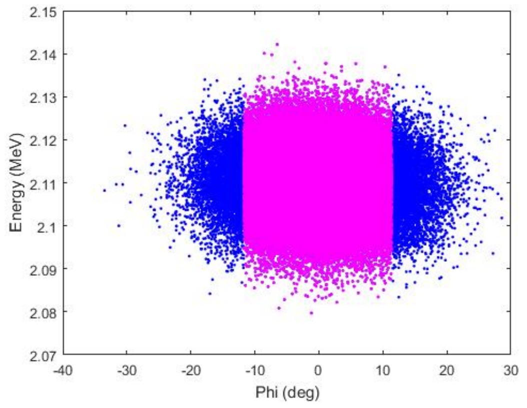
D. Johnson, *et al.*, *HB'2018*, **THP1WC01**

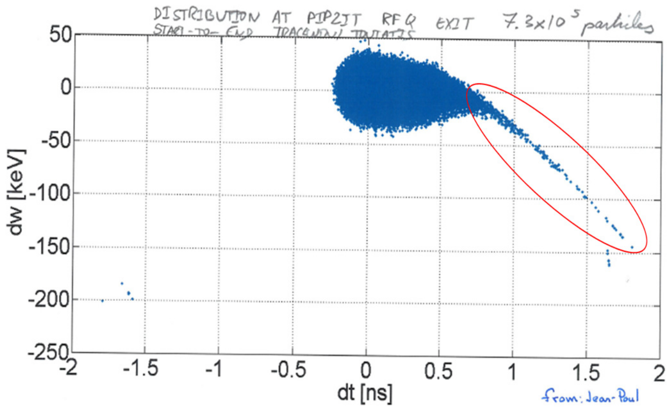
Fermilab PIP-II Momentum Collimation Concept

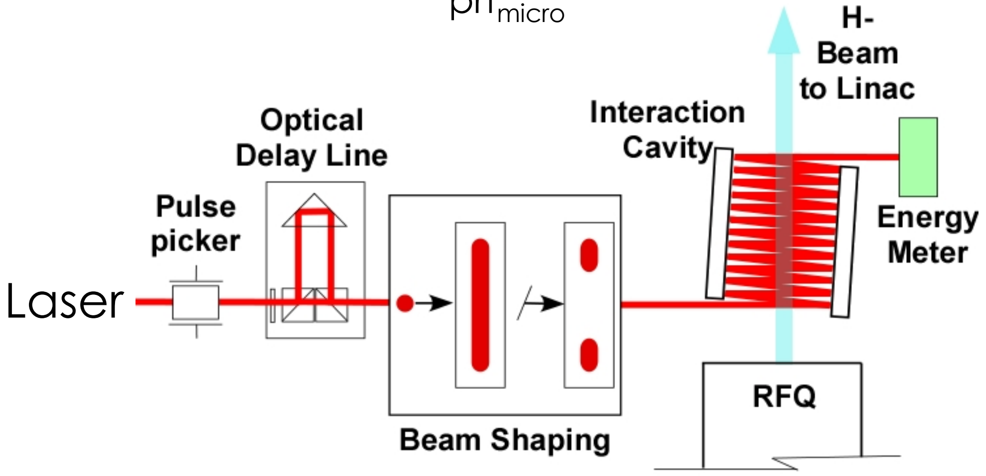
- Controlling the longitudinal emittance (including **halo**) in linacs
- To get >90% neutralization of the **head** and **tail** of all bunches in a 500 us PIP-II linac cycle out of the RFQ need about 80 -100 uJ laser pulses split between head and tail (i.e. 40-50 uJ)
- Split amplified pulse → delay line → recombine temporally with adjustable spacing (ps) create head/tail out of single amplified laser pulse
- Can be done for both transverse and longitudinal

pw = 50 ps each
pE = 15 uJ each
ps = 2 ns
prf = 201.25 MHz
DF = 0.016





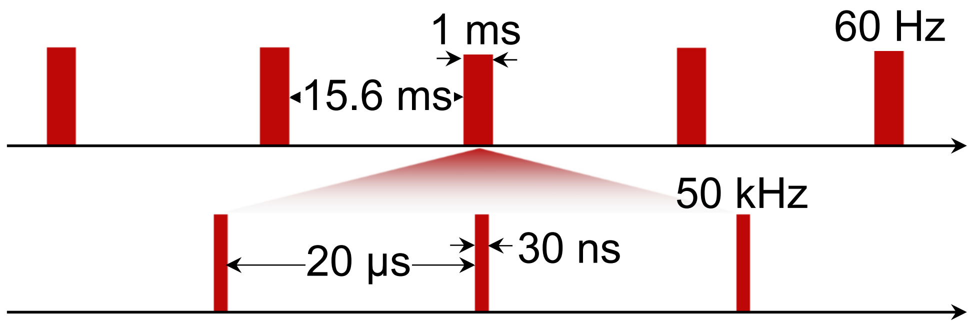


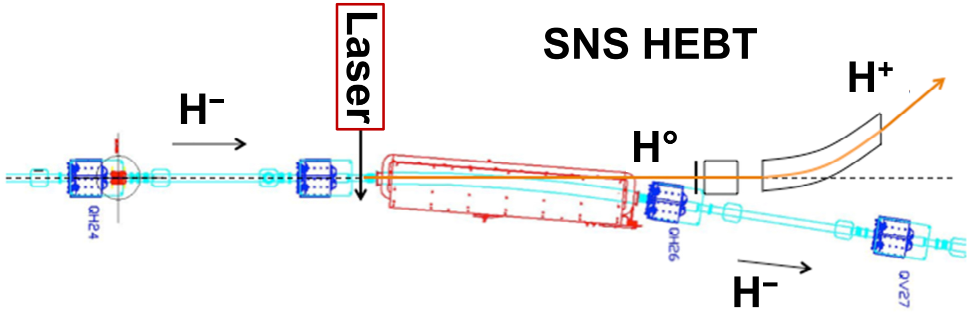


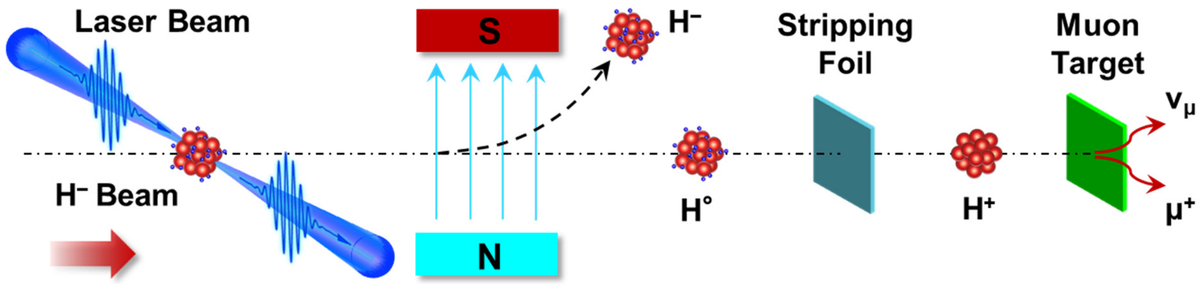
Courtesy: D. Johnson (Fermilab)

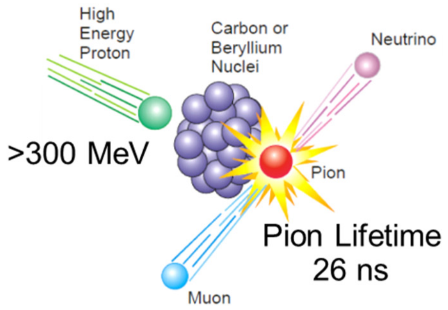
μSR - Muon Spin Relaxation/Rotation/Resonance*

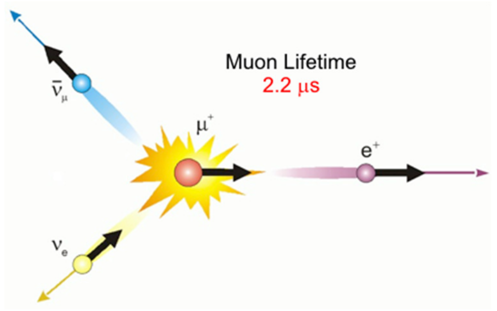
- Use a laser to neutralize the H^- beam to achieve the necessary timing characteristics for a future *μSR* facility
- ***Goal***:
  - *Develop a burst-mode laser system to neutralize 1.0 GeV H^-.*
  - *Generate* ***30 ns H°*** *pulses at* ***50 kHz*** *(optimal for a μSR facility).*
  - *Measure the neutralization efficiency for this system.*
- 100 % neutralization of 30 ns/50 kHz H^- pulses will only cause negligible (0.15 %) influence to the neutron production
- ***Can be:*** *Highest flux, highest resolution pulsed Muon source for materials research in the world.*







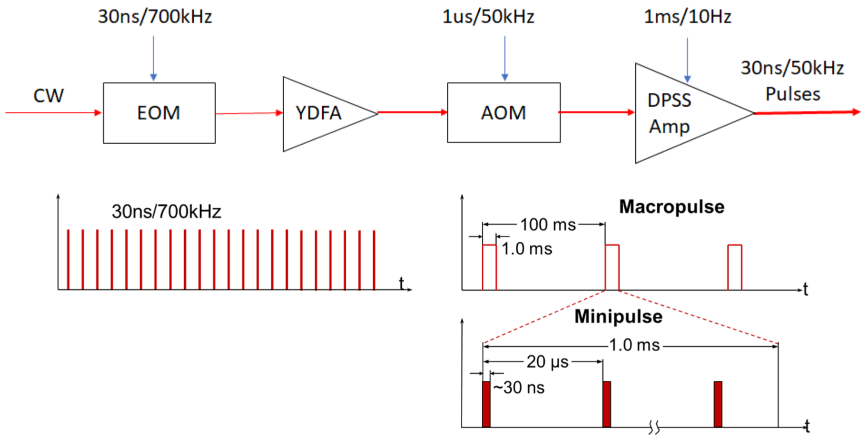




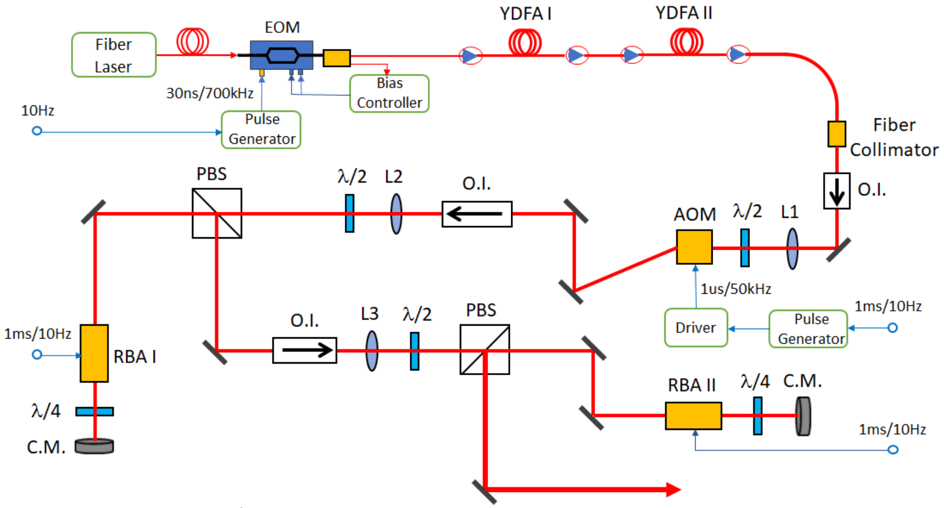
* ORNL LDRD SEED Money Project: "*Laser stripping for a next-generation Muon source at SNS*"

µSR Experimental Setup

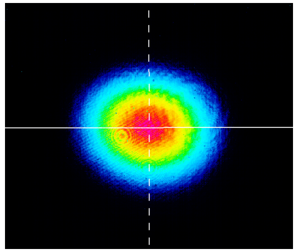
Block diagram of laser architecture



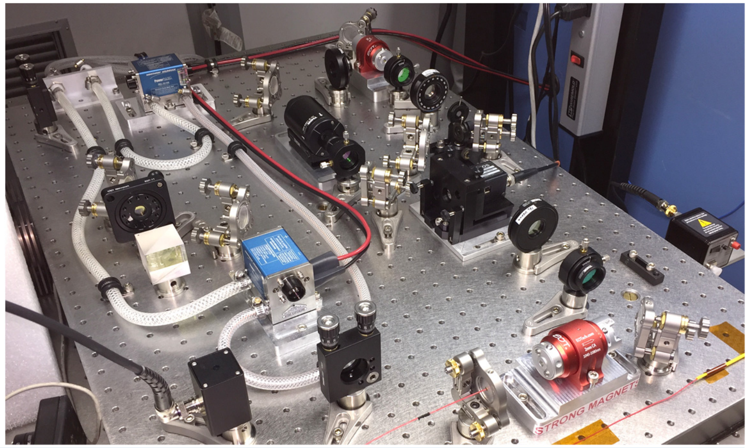
Schematics of laser system

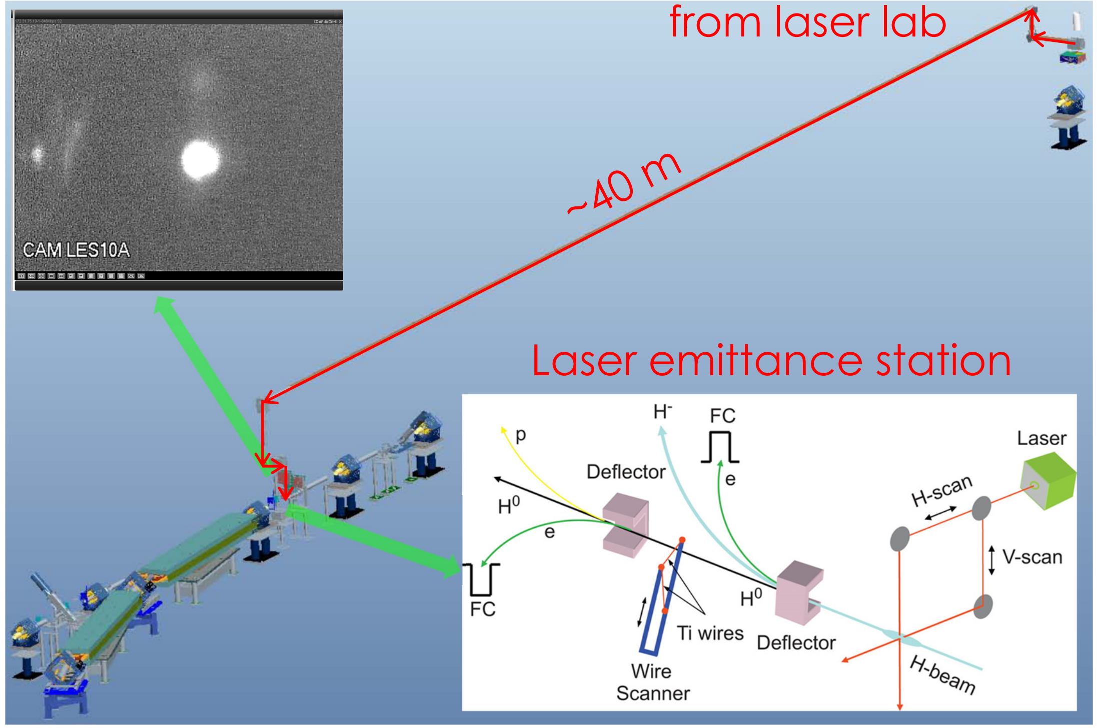


Laser Parameters:
30 ns, 7.6 mJ @50 kHz
1.0 ms, 380 mJ @10 Hz
Peak power: 250 kW
M^2: 1.1
Wavelength: 1064 nm



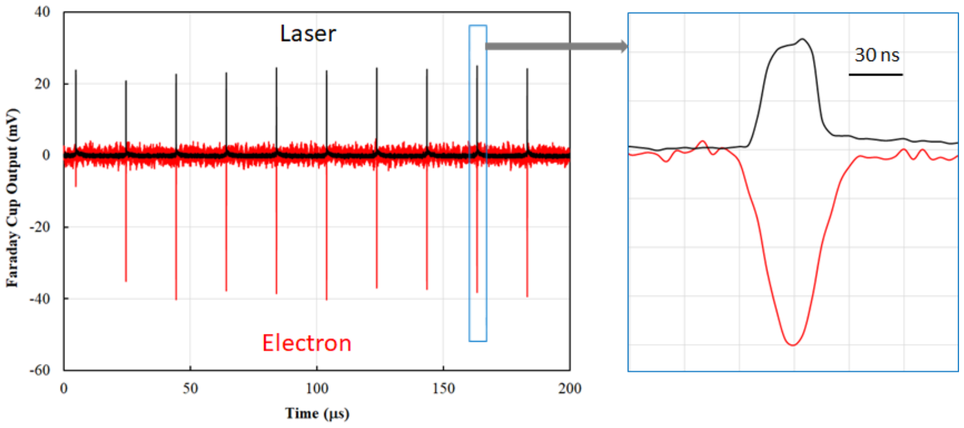
Far-field profile



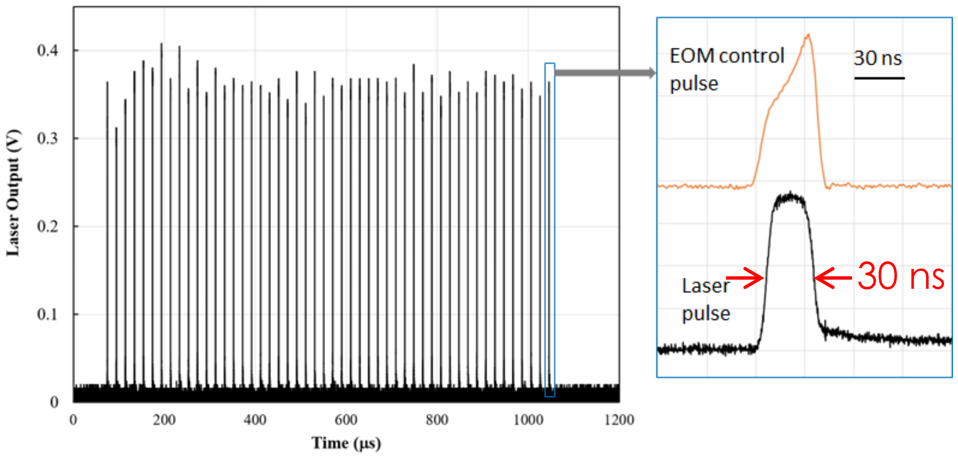


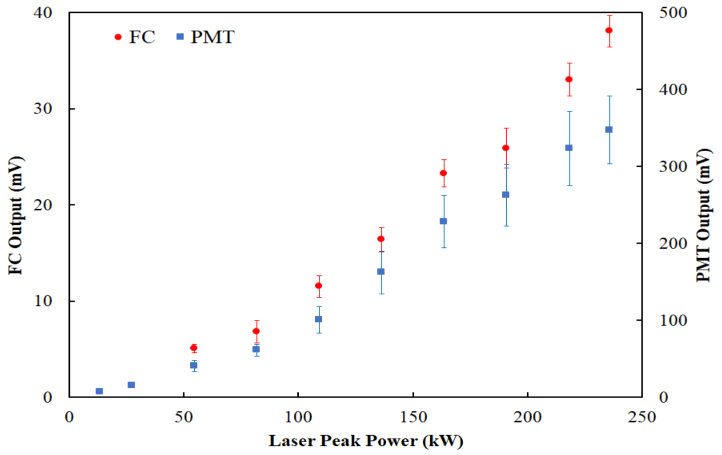
μSR Experimental Results

Electron and corresponding laser pulses



50 minipulses in a 1 ms bunch





Electron and H^0 signals w/ corresponding laser power

Estimated neutralization efficiency

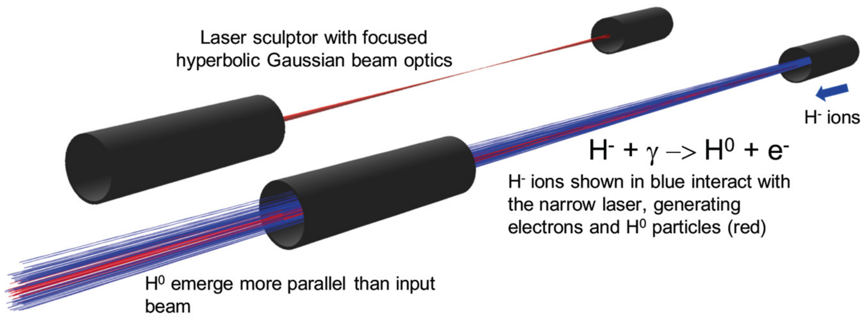
	Laser Pulse Width	Laser Peak Power	H^- Charge	Photo Detached Charge	Efficiency
Laser Wire	7 ns	14 MW	210 pC	8.5 pC	4.0%
1st Experiment	30 ns	225 kW	900 pC	0.87 pC	0.10%
2nd Experiment	30 ns	400 kW	900 pC	1.6 pC	0.18%

Next Steps:

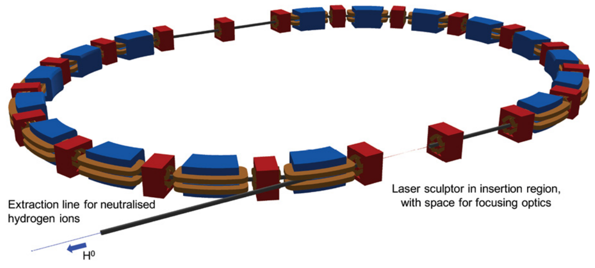
- Introduction of micro-bunch structure (200ps/402.5MHz to replace 30ns) will increase laser peak power (x10)
- Adding more stages of amplifiers to boost laser power (x10)
- Multiple reflection (non-resonant cavity) scheme will increase photodetachment efficiency (x5-10)

Laser Sculpting of H⁻ Beams (simulation)

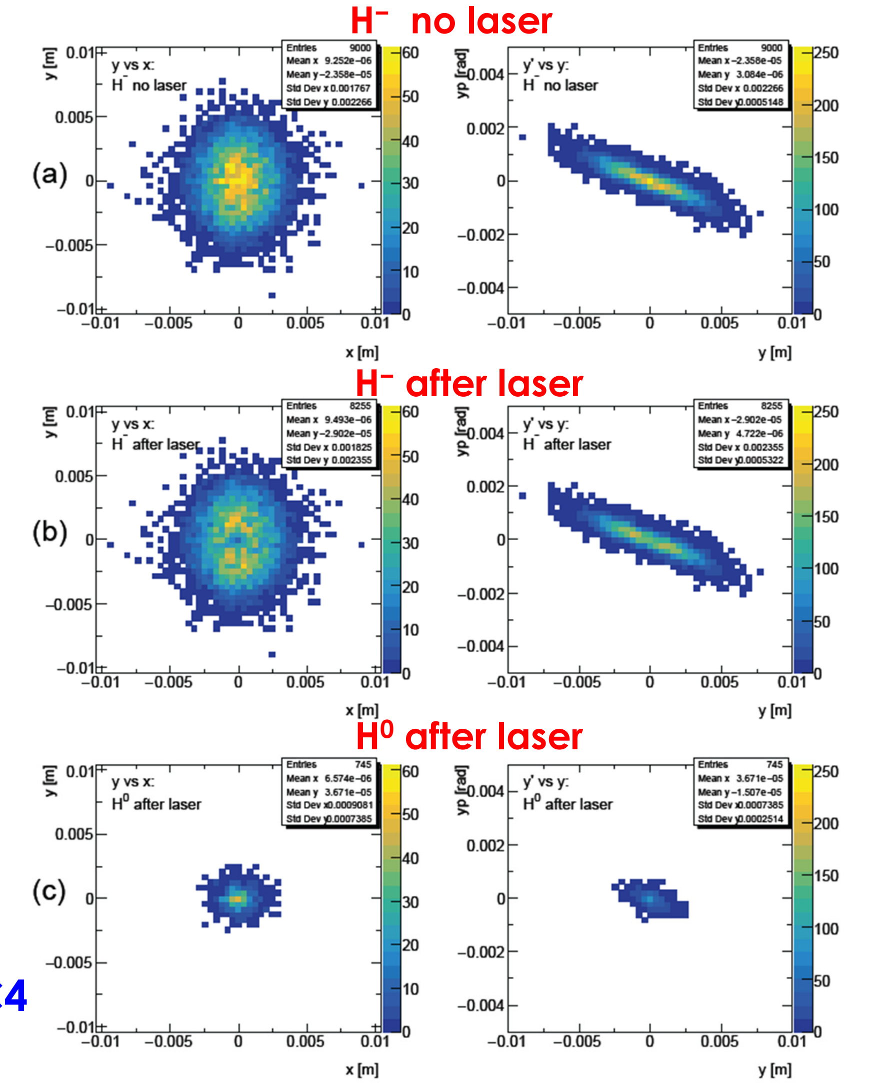
- Carve out narrow beam of H^0 from the core of H^- before it hits the foil.
- Significantly reduced emittance in resulting protons after the foil as compared to protons generated from parent H^-.
- Properties of the extracted proton beam can be precisely controlled and sculpted by the laser beam parameters and interaction geometry.
- Can be used to reduce the emittance of proton bunches injected into an accelerator.
- Inject the laser beam **antiparallel** to the ion beam.



Beam Delivery Simulation (BDSIM) of laser H⁻ sculpting

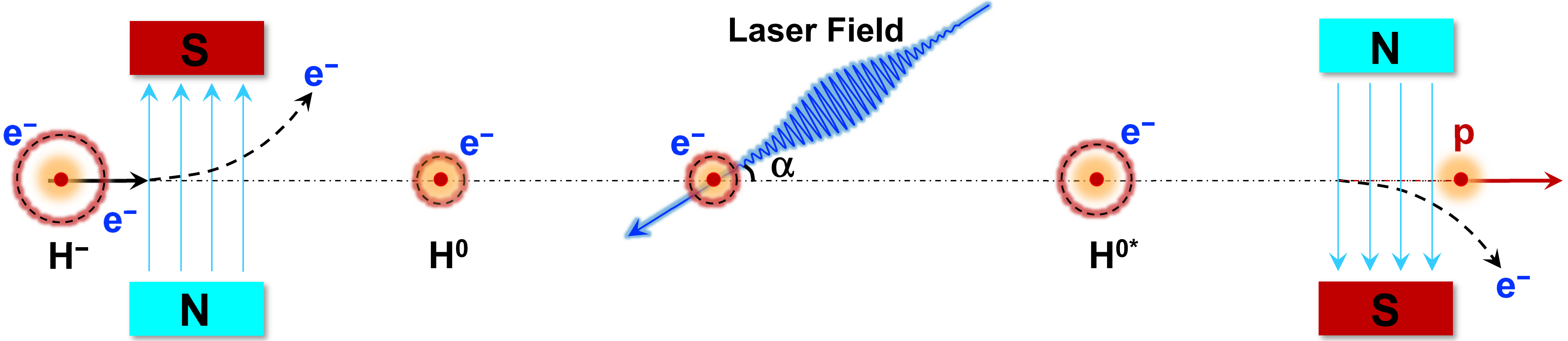


Simulation for 160 MeV LINAC4 at CERN



S.M. Gibson, *et al.*, *IPAC*2019, **MOPRB116**

Laser-Assisted Charge Exchange Injection (single-step excitation)



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

Resonant Laser Excitation
H^0 (n=1) + γ $\rightarrow$ H^{0*} (n=3)

12.1 eV (102.6 nm)

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

I. Yamane, ***Phys. Rev. STAB*** 1, 053501 (1998)

Demonstrated >90% stripping efficiency at SNS using a **6 ns** laser with **10 MW** peak power (2007)

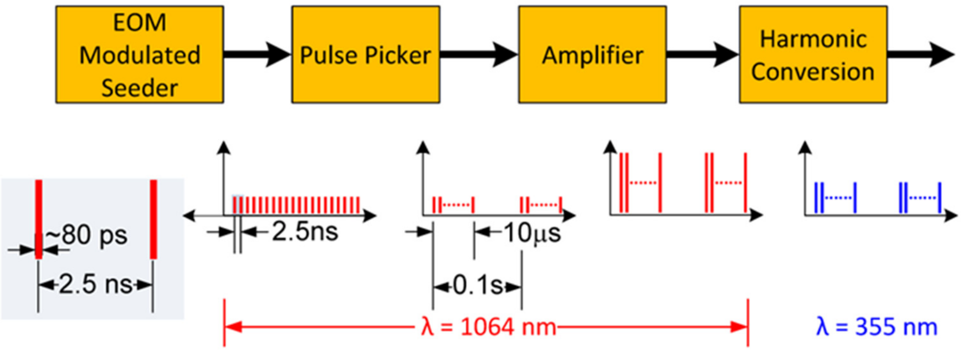
$$\lambda_{laser} = \lambda_{1\to3} \times \gamma\left[1 + \frac{\nu_{beam}}{c}\cos\alpha\right], \gamma = \frac{1}{\sqrt{1-(\nu_{beam}/c)^2}}$$

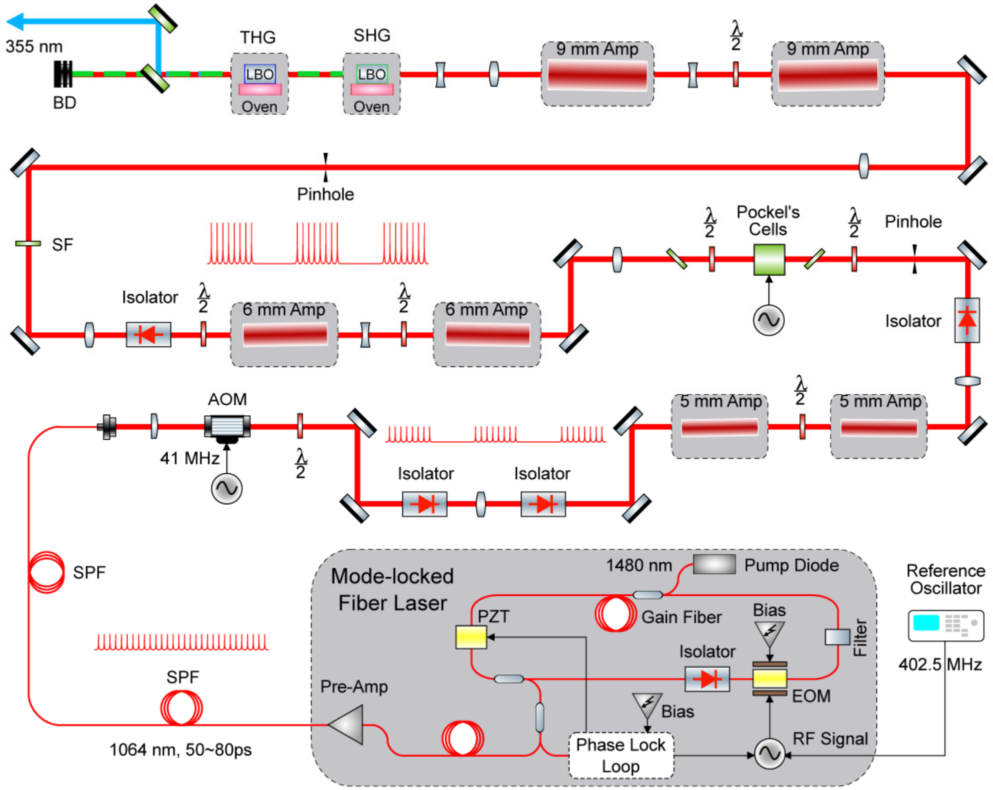
V. Danilov *et al*. ***Phys. Rev. STAB*** 10, 053501 (2007)

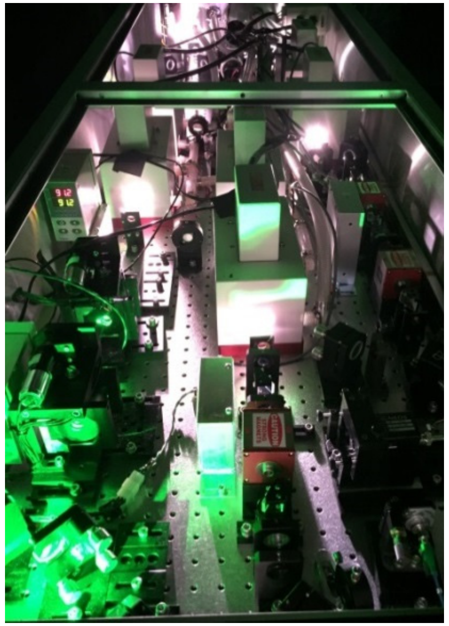
$$\lambda_{1\to3} = 102.6nm, \nu_{beam} = 0.87c, \gamma = 2.05, \alpha = 37.5^\circ, \lambda_{laser} = 355.5nm$$

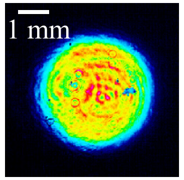
Burst-Mode Laser System for 10 μs Stripping Experiment

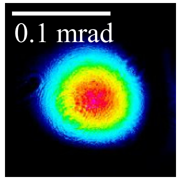
CW seeder:	linewidth <5 kHz
Output wavelength:	355 nm
Micropulse:	50 ps/402.5 MHz, 100 μJ
Macropulse:	10 μs/10 Hz, 400 mJ
Peak/Average power:	2 MW/4W

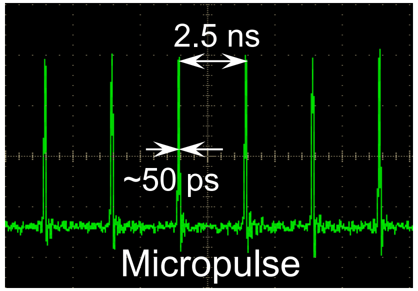


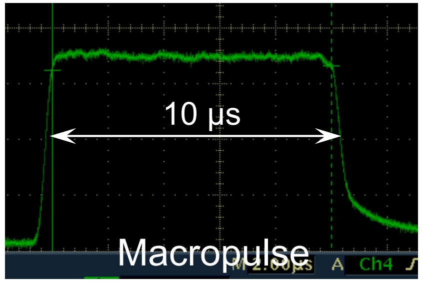












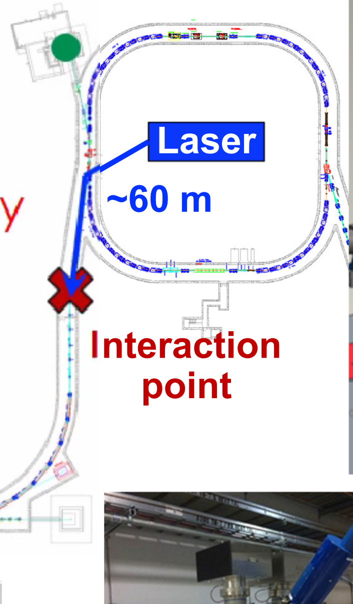
A. Rakhman *et al.*, ***Appl. Opt.*** 53, 7603-7609 (2014)

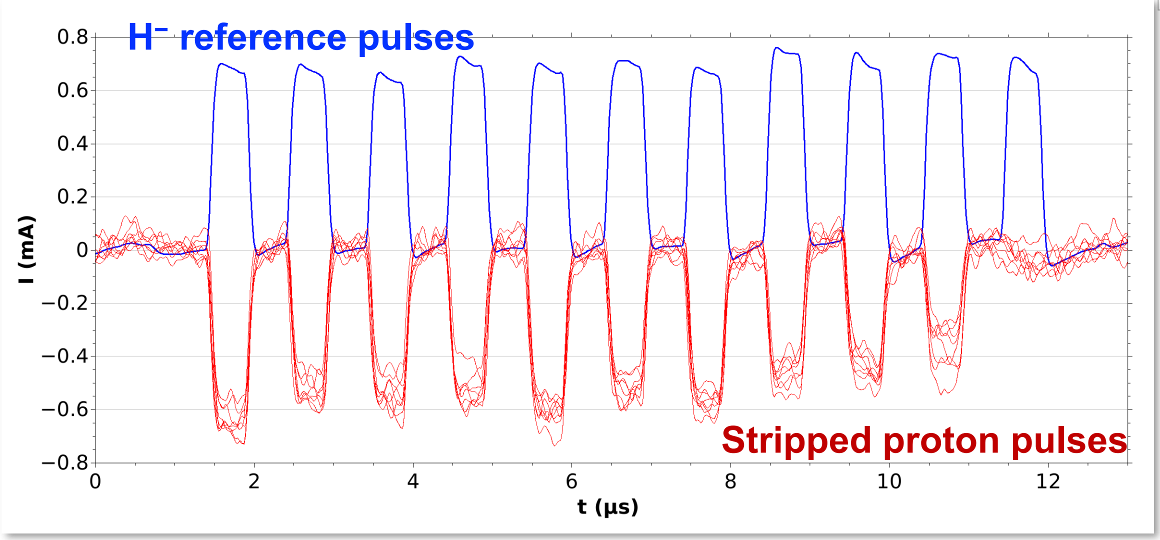
C. Huang, C. Deibele, and Y. Liu, ***Opt. Exp.*** 21, 9123 (2013)

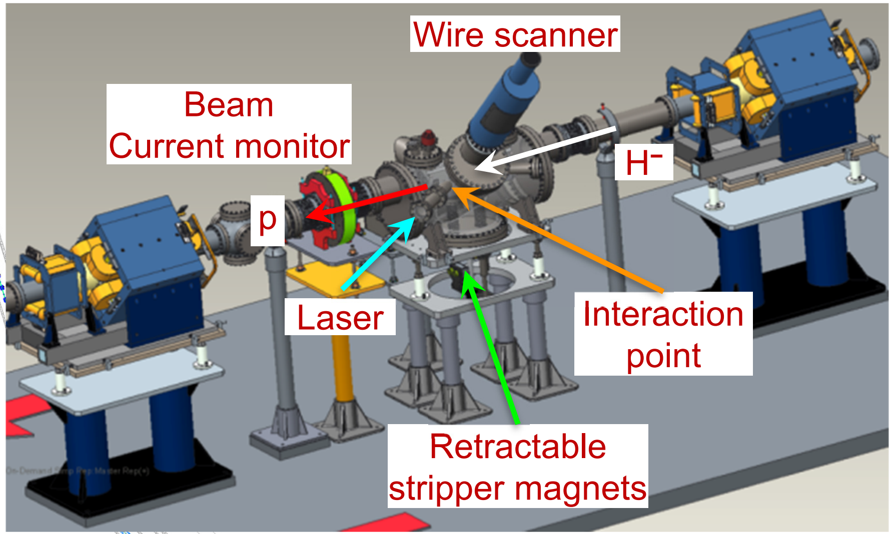
10 µs Laser Stripping Experiment

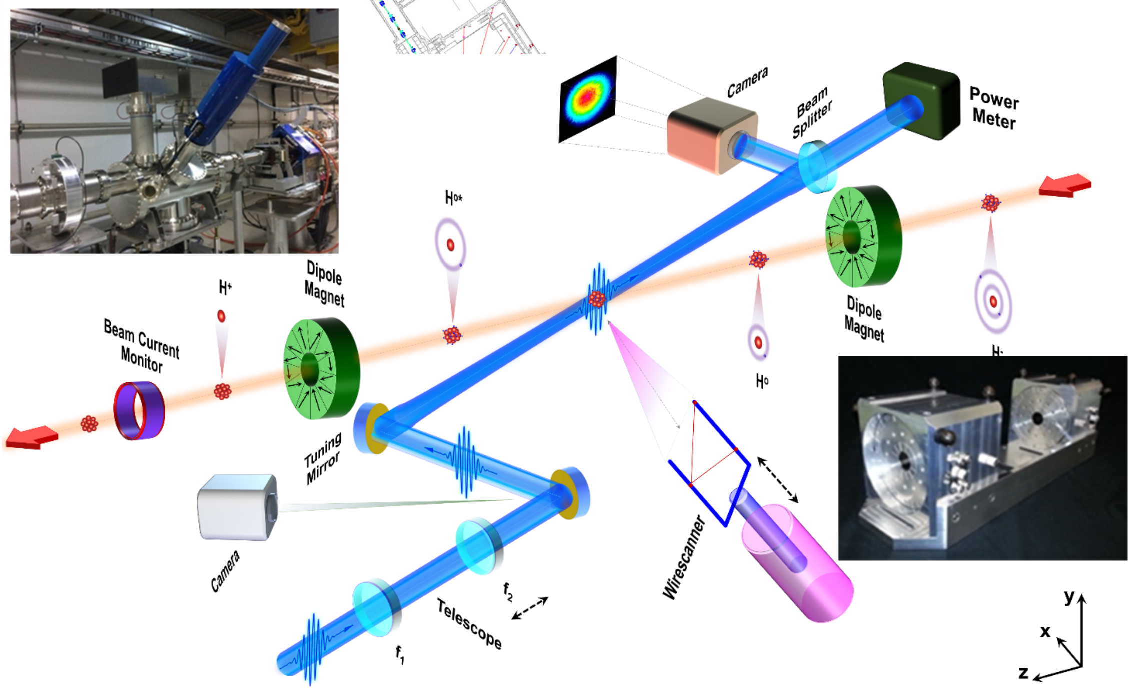
- Successfully stripped 10 µs, 1 GeV H^- pulse
- Demonstrated >95 % stripping efficiency
- Proof of principle (6 ns, 2007) → proof of practicality (10 µs, 2016)

S. Cousineau *et al.*, ***Phys. Rev. Lett.*** 118, 074801 (2017)
Y. Liu *et al.*, ***Nucl. Instr. Meth. A*** 847, 171-178 (2017)
S. Cousineau *et al.*, ***Phys. Rev. STAB*** 20(12), 120402 (2017)

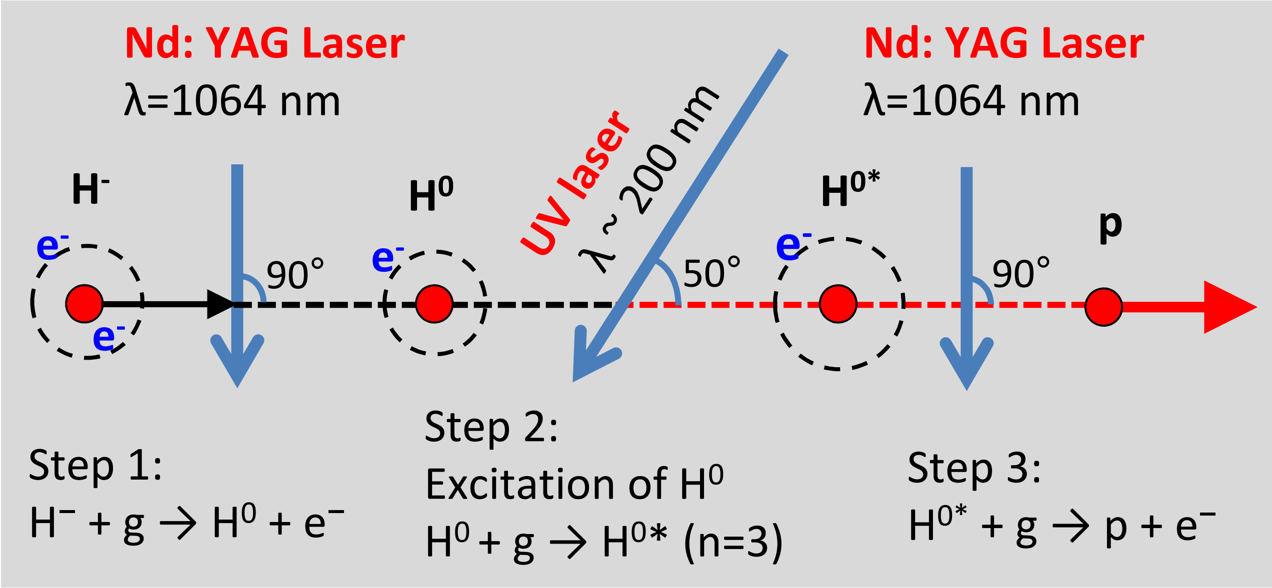


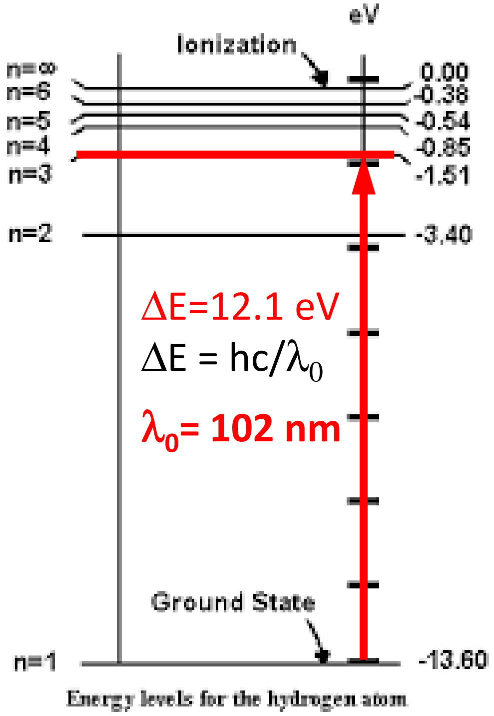


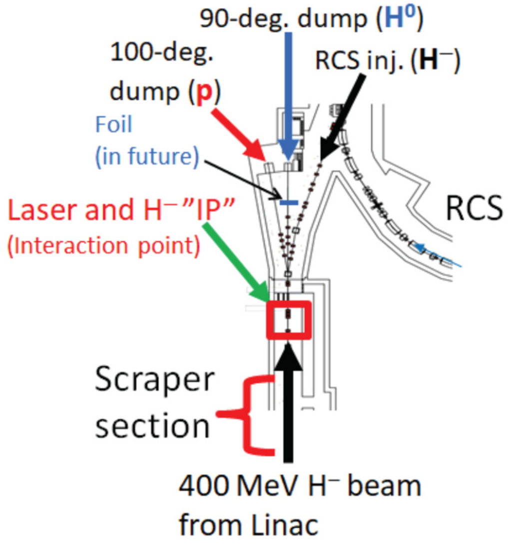




J-PARC Scheme: H^- Stripping by Only Lasers







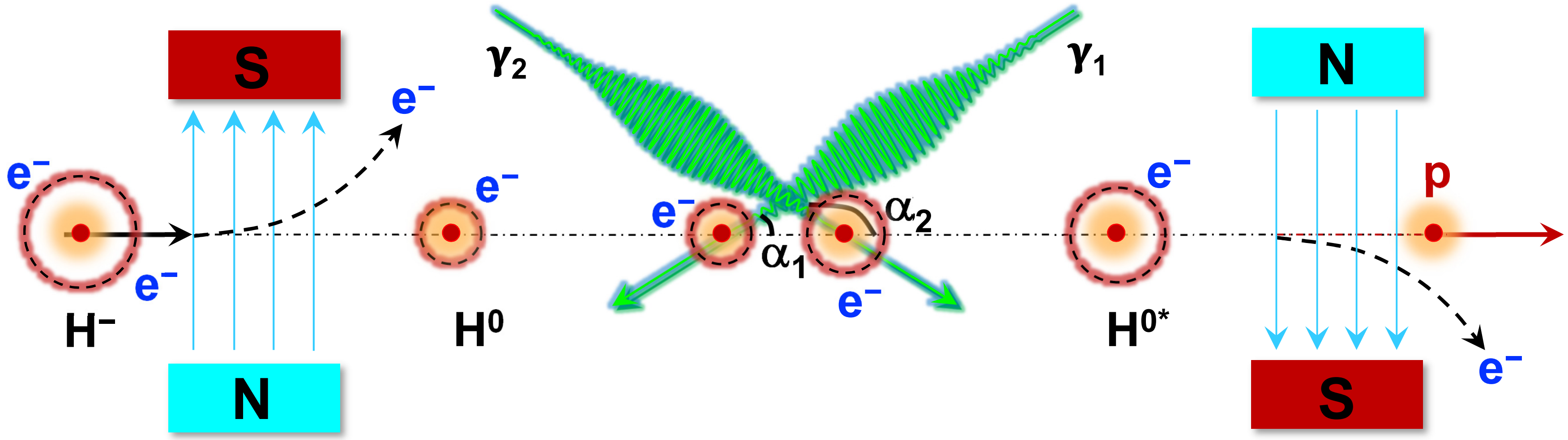
Process	E_{ph} (eV)	λ (nm)	α (deg.)	λ_0 (nm)	Laser
$H^- \rightarrow H^0$	1.67	1064	90	743	Nd:YAG
$H^0 \rightarrow H^{0*}$	**12.1**	**212**	**50**	**102**	**5th H of YAG**
$H^{0*} \rightarrow p$	1.67	1064	90	743	Nd:YAG

Doppler effect of the 400 MeV H^- beam:
$\beta = 0.713$, $\gamma = 1.426$

$$\lambda = \lambda_0 (1 + \beta \cos\alpha)\gamma$$

P. Saha, *et al.*, *HB2018*, **THP1WC02**

Sequential Excitation Reduces Required Laser Power

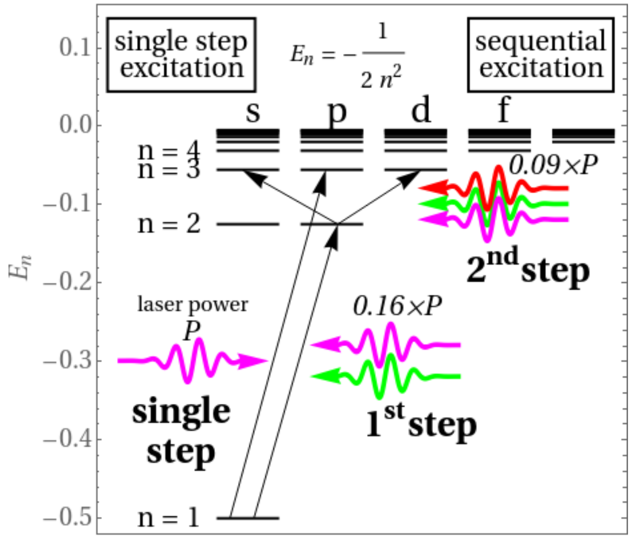


w/o sequential excitation, n = 3 excitation is required for H^- below 2 GeV !!

Lorentz Stripping
$H^- \to H^0 + e^-$

Sequential Excitation
H^0 (1s) + $\gamma_1 \to H^{0*}$ (2p)
H^{0*} (2p) + $\gamma_2 \to H^{0*}$ (3s + 3d)

Lorentz Stripping
$H^{0*} \to p + e^-$



- New sequential resonance scheme conceptualized
- Gives significant laser power gain by factor of 6-10
- Add flexibility of laser wavelength (green or UV) at 1.3 GeV

Next Steps:

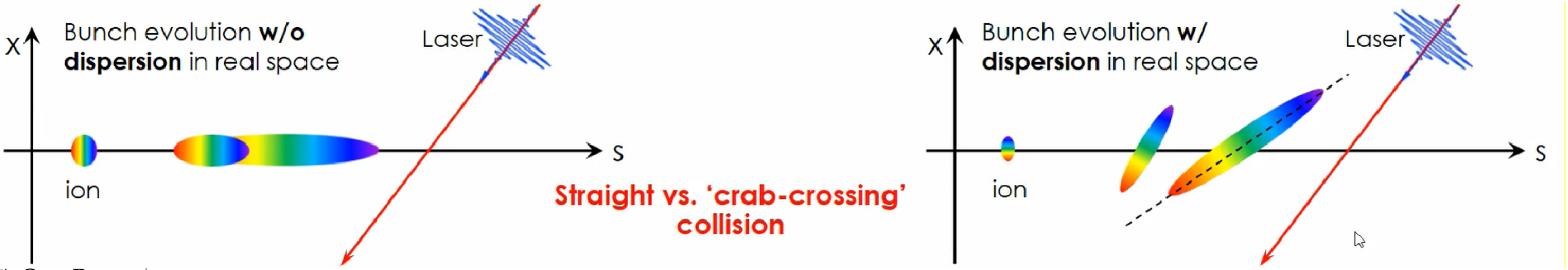
- Experimental demonstration of **sequential resonance** and **crab-crossing** schemes in winter 2020.
- Efforts to address laser pointing instability

T. Gorlov, "Efficiency Estimation for Sequential Excitation Laser Stripping of H^- Beam", *NAPAC2019*, **WEPLH10**

Crab-Crossing Scheme for Laser Stripping

- Space charge prevents focusing
  - SNS production bunch length (rms) at IP: **9 deg (31.05 ps) at 30 mA**
  - Laser stripping bunch length (rms) at IP: **3 deg (10.35 ps) at 1.0 mA**
- Ion bunch size must match laser pulse length
- Minimum vertical beam size is determined by the beam emittance
- Crossing angle must be precisely controlled to achieve efficient excitation
- Adding dispersion at IP allows crab-crossing collision

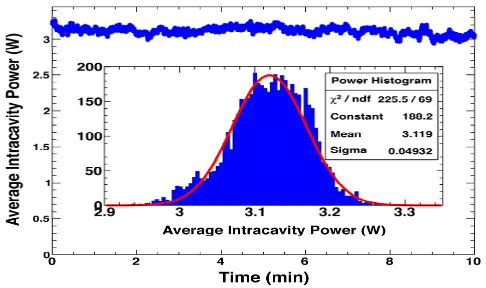
- Crab-crossing collision scheme
  - **Uses existing hardware without modifications**
  - **No beam current limit**
  - **No longitudinal bunch squeezing**
- SNS HEBT magnets have enough margins to achieve required dispersion
- **Practical implementation of laser stripping at SNS production beam condition now seems possible**

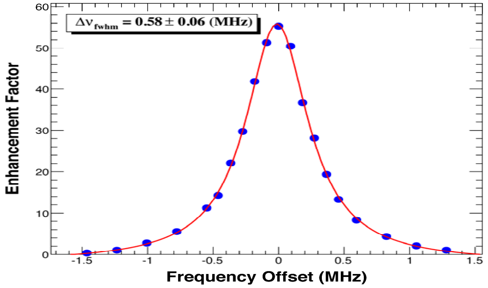


A. Aleksandrov, "A Crab-Crossing Scheme for Laser-Ion Beam Applications", *NAPAC2019*, **WEYBB5**

Burst-Mode Enhancement Cavity

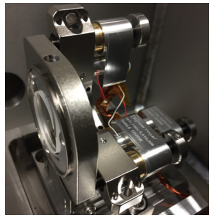
- Photons/Electrons: ~10^7 very low photon loss in the stripping process
- Highly desirable to enhance the laser power with an optical cavity
- How to do the enhancement of burst-mode pulses?
- We have developed a novel technique

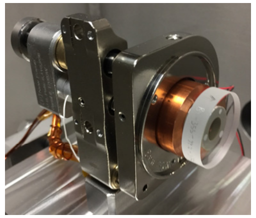


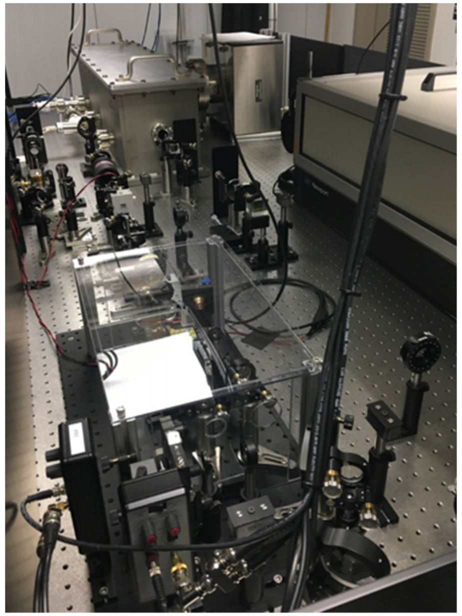


Pulses stored in cavity:

- 50 ps, 75 μJ @402.5 MHz
- 10 μs, 300 mJ @10 Hz
- Peak power: 1.5 MW
- Enhancement factor: 50
- Wavelength: 355 nm







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Optics Letters

Power enhancement of burst-mode ultraviolet pulses using a doubly resonant optical cavity

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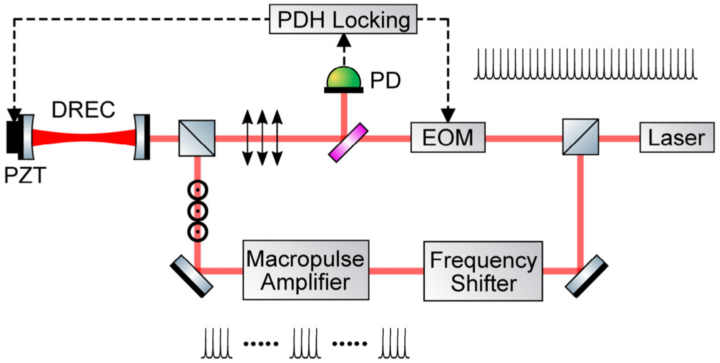
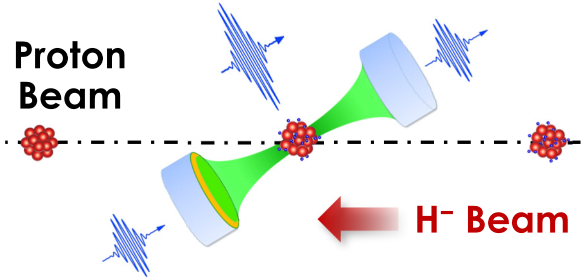
Received 10 September 2015; revised 28 October 2015; accepted 28 October 2015; posted 28 October 2015 (Doc. ID 249933); published 24 November 2015

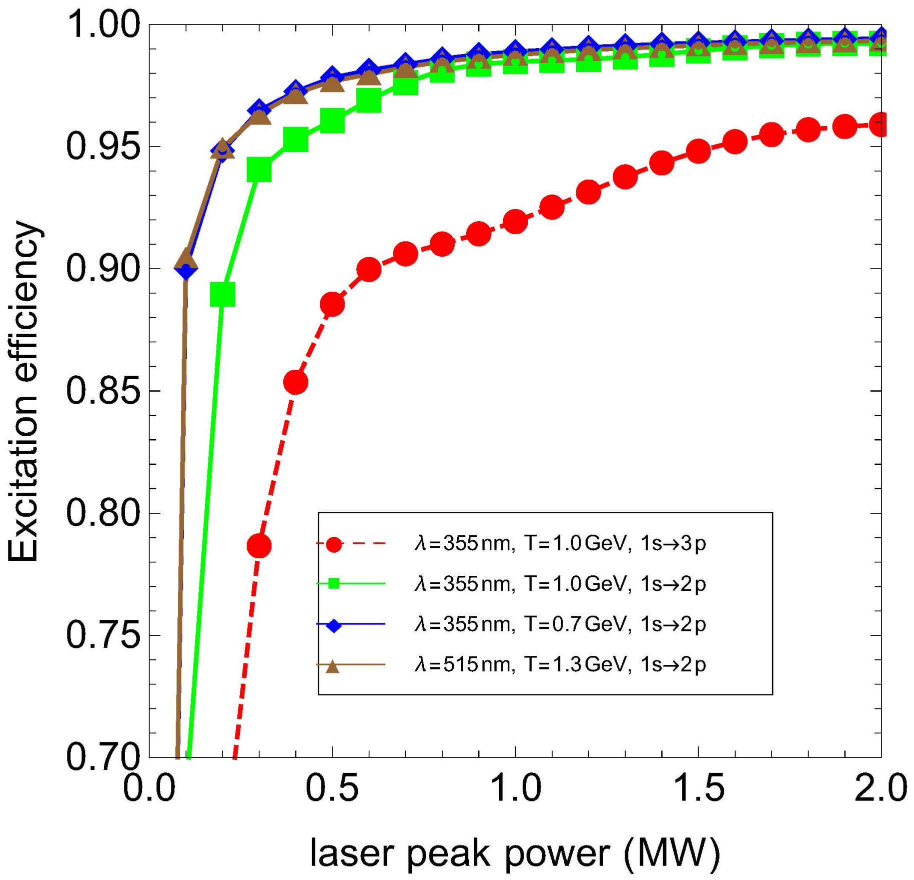




A. Rakhman, Y. Liu, *CLEO2019*, **JW2A. 120**

Perspectives of Laser Stripping at SNS

- Sequential excitation scheme allows reduction of average laser power by factor of 6-10 due to fundamental atomic parameters
- Laser choice of **532 nm or 515 nm** at 1-ms/60-Hz would need **300 kW** peak power (average power **360 W**) to achieve >90% stripping efficiency
- It is **6J** per macropulse and **15 µJ** per micropulses
- Combining fiber and diode-pumped solid-state laser amplifiers would bring the power up
- May still need cavity enhancement to achieve the required power
- Crab-crossing would make the laser stripping practical at production beam settings
- Proton Power Upgrade (PPU) will bring beam energy to 1.3 GeV and would offer new opportunities for laser stripping

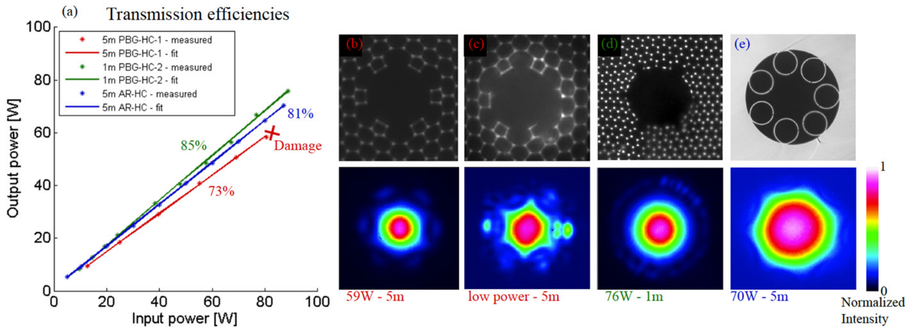


Courtesy: T. Gorlov (*NAPAC2019*, **WEPLH10**)

Challenges

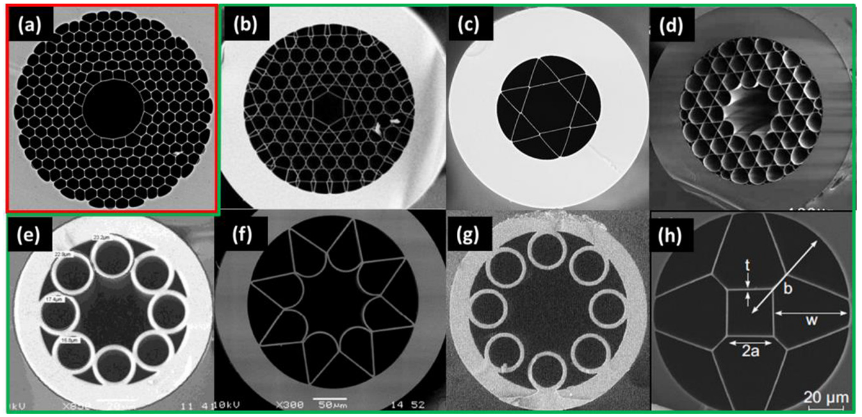
- Demand for high average, high energy, high repetition rate lasers (**very often burst-mode is required**)
- High radiation around beam lines always prevents us from placing lasers near the interaction point (IP)
- Laser beam stability
  - Angular & spatial pointing at IP
  - Phase & intensity noise
- Laser induced damage to accelerator vacuum windows
- **Solutions:**
  - Proper collimating optics
  - Active position feedback control
  - Dedicated laser beam transport line (vacuum or special gas filled)
  - Anti-resonant hollow core fibers
    - LMA fibers have been used for low power beam transport
    - Robust and alignment free
    - Dispersion, High nonlinearity, Polarization

Anti-resonant hollow-core PCF



Used as beam delivery for **100 µJ/200kW** peak power beam at 1064 nm

M. Michieletto *et al.*, ***Opt. Exp.***, 24-7-(2016) 7103



F. Poletti, ***Opt. Exp.***, 22-20-(2014) 23807

Summaries

- Lasers have been playing increasingly important role in H^- facilities around the world
- Photo-neutralization has been one of the most widely used applications of H^- manipulation with lasers
  - Beam diagnostics (partial detachment)
  - Beam chopping & halo reduction (nearly 100% detachment)
  - Beam extraction & arbitrary beam pattern generation (nearly 100% detachment)
  - Beam sculpting/carving (antiparallel injection to H^-, nearly 100% detachment)
  - New topics emerging
- New opportunities such as μSR, SEE (Single Event Effects) and other secondary beams driven by protons
- Proof-of-principle experiment for **practical implementation** of laser stripping at SNS being planned
- Laser-assisted charge exchange has the potential to make high-power (> 10 MW), high-brightness proton accelerators a reality
- H^- manipulation with lasers will be a major part of the future of high-intensity MW proton beams

Thanks for your attention!