Status of Proof-of-Principle demonstration of 400 MeV H^- stripping to proton by using only lasers at J-PARC

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H. Yoneda, Y. Michine (UEC, Tokyo)

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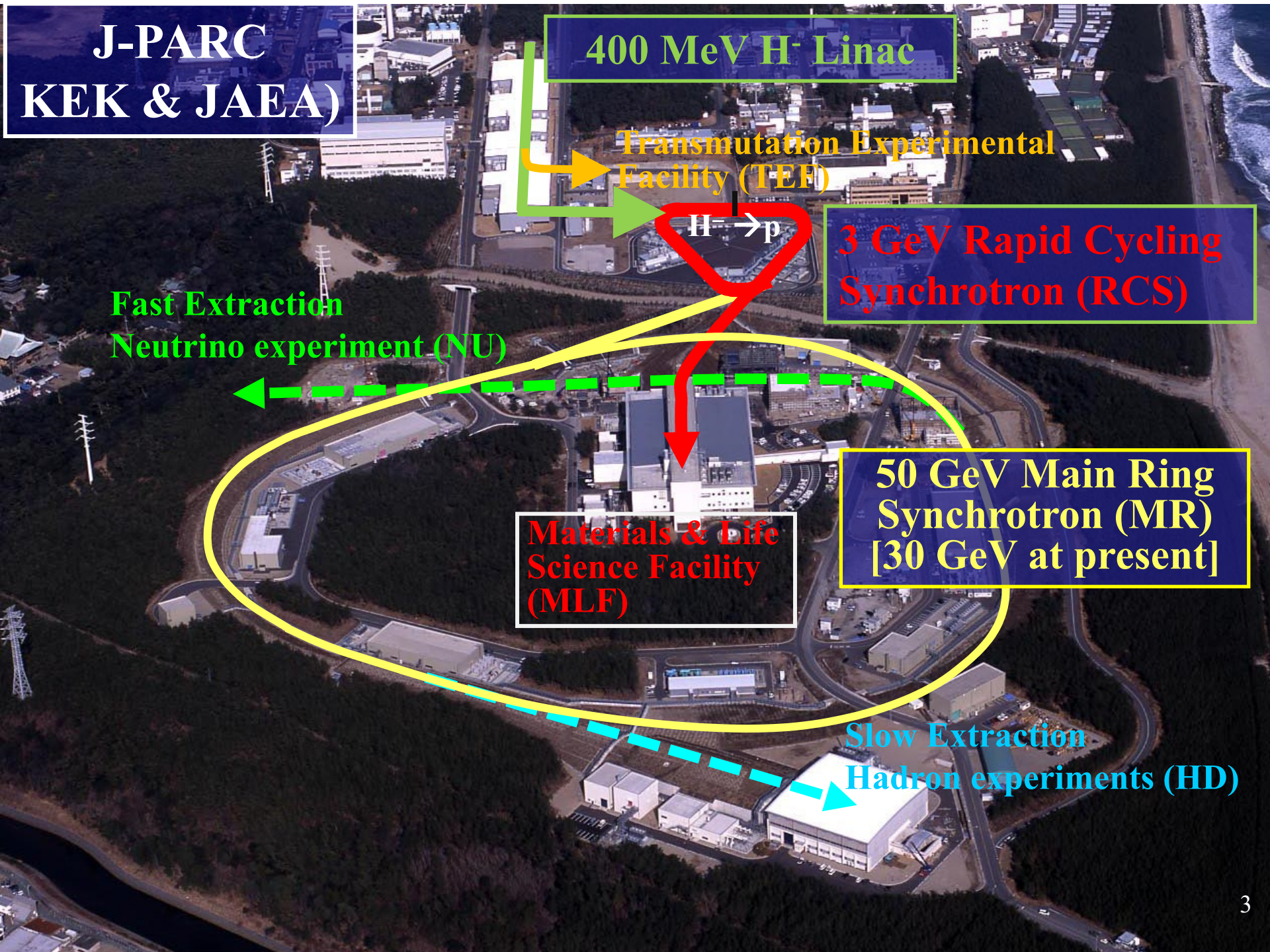
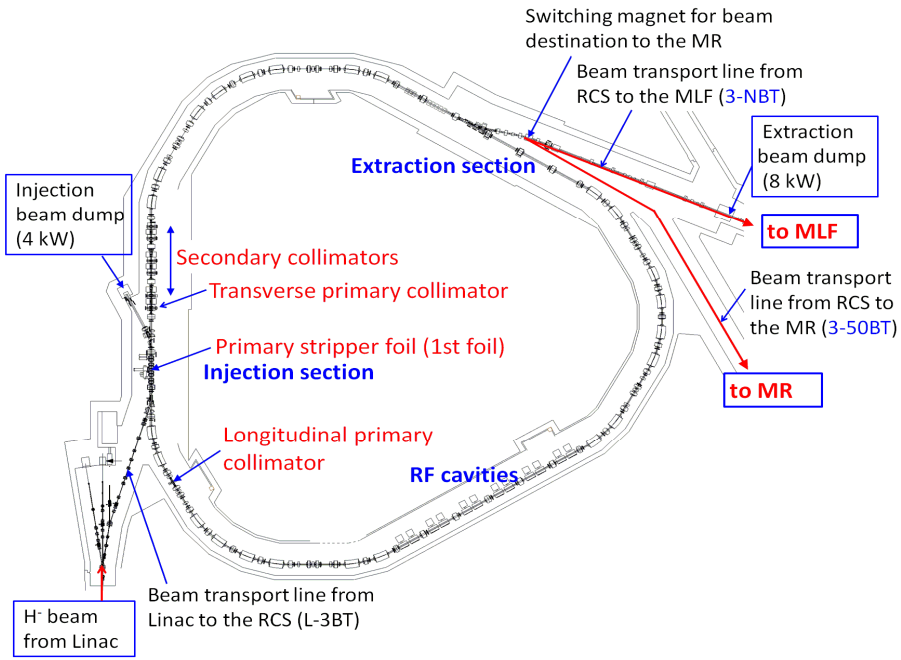
Outline:

1. Brief introduction of J-PARC and the RCS
2. Stripper foil issues
3. Principle of H^- stripping by only lasers
4. Experimental strategy, expected results, present status and schedule
5. Discussion on laser energy reduction
6. Summary and outlook

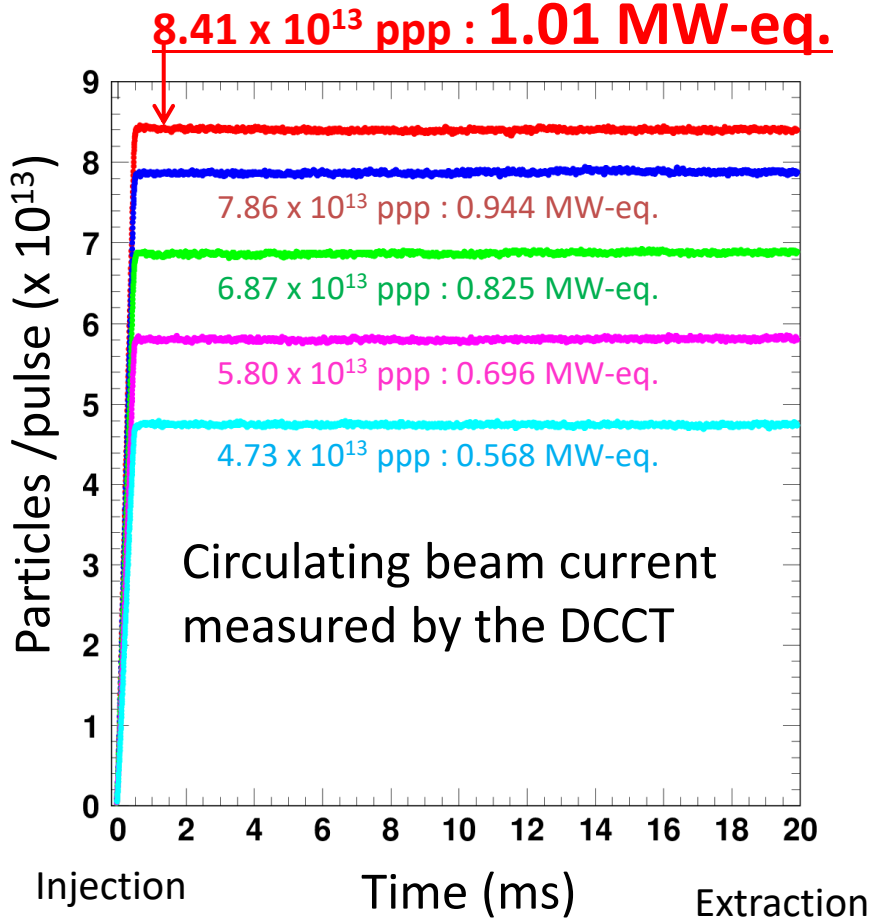

J-PARC
KEK & JAEA)
400 MeV H- Linac
Transmutation Experimental Facility (TEF)
H- →p
3 GeV Rapid Cycling Synchrotron (RCS)
Fast Extraction
Neutrino experiment (NU)
50 GeV Main Ring Synchrotron (MR) [30 GeV at present]
Materials & Life Science Facility (MLF)
Slow Extraction
Hadron experiments (HD)

Introduction of J-PARC 3-GeV RCS



Layout of J-PARC 3-GeV Rapid Cycling Synchrotron (RCS)

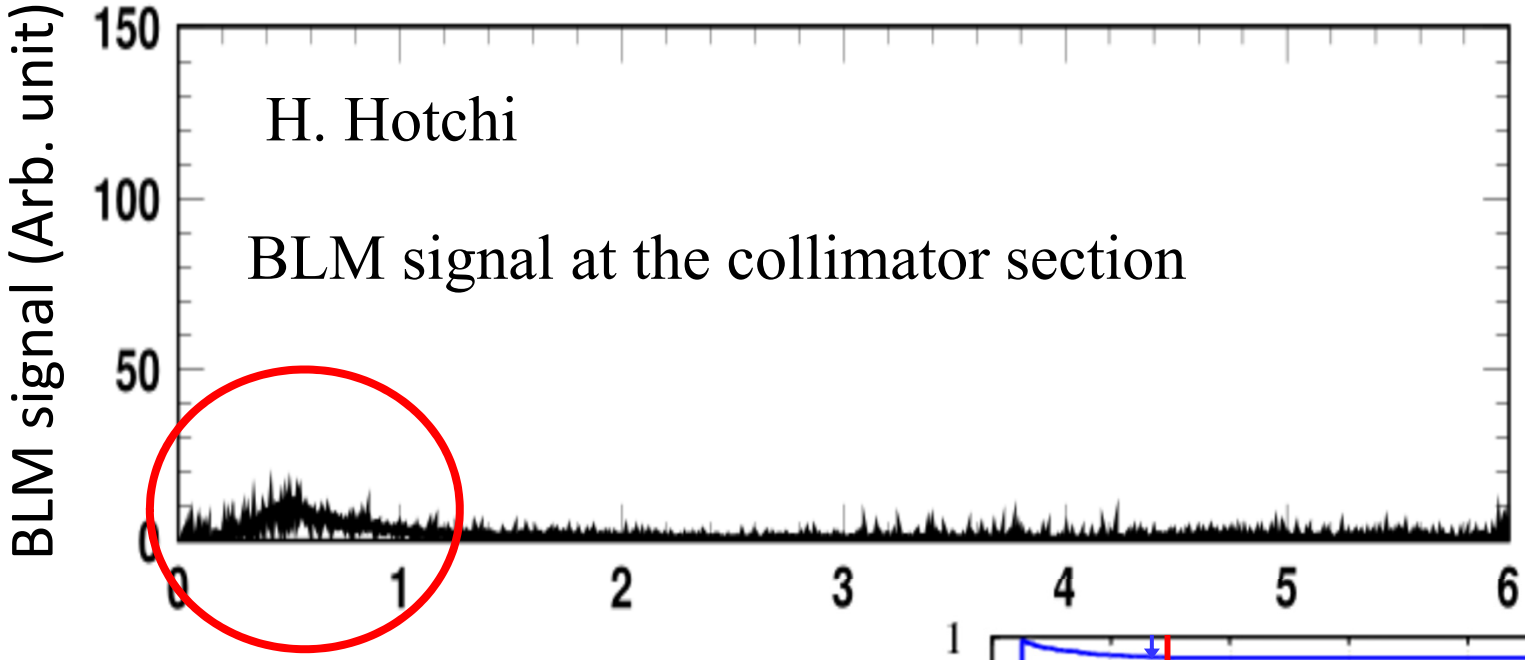
- *Multi-turn H^- stripping injection.*
- *Injection Energy: 400 MeV*
- *Extraction Energy: 3 GeV*
- *Repetition: 25 Hz*



- **Beam power (design): 1MW**

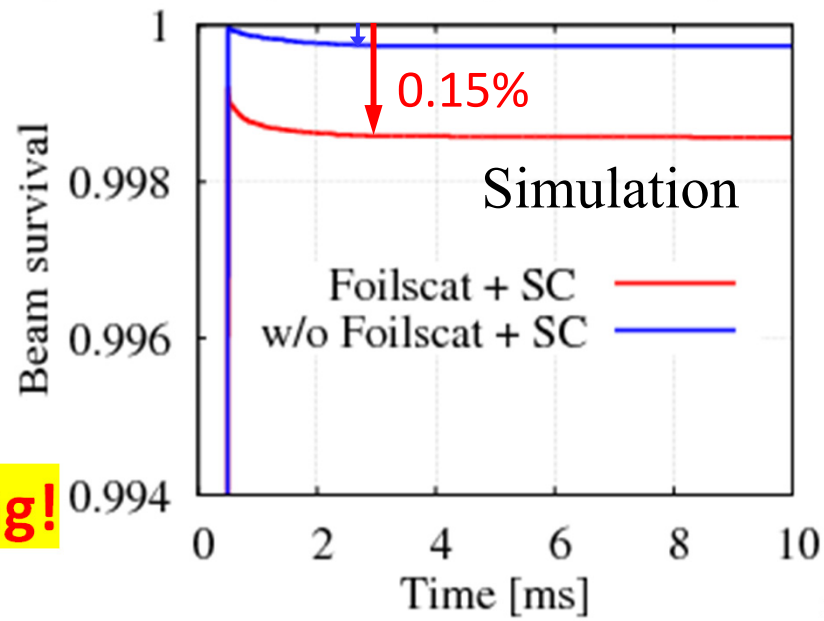
Successfully demonstrated acceleration of the designed beam intensity.

Beam loss at 1 MW beam power



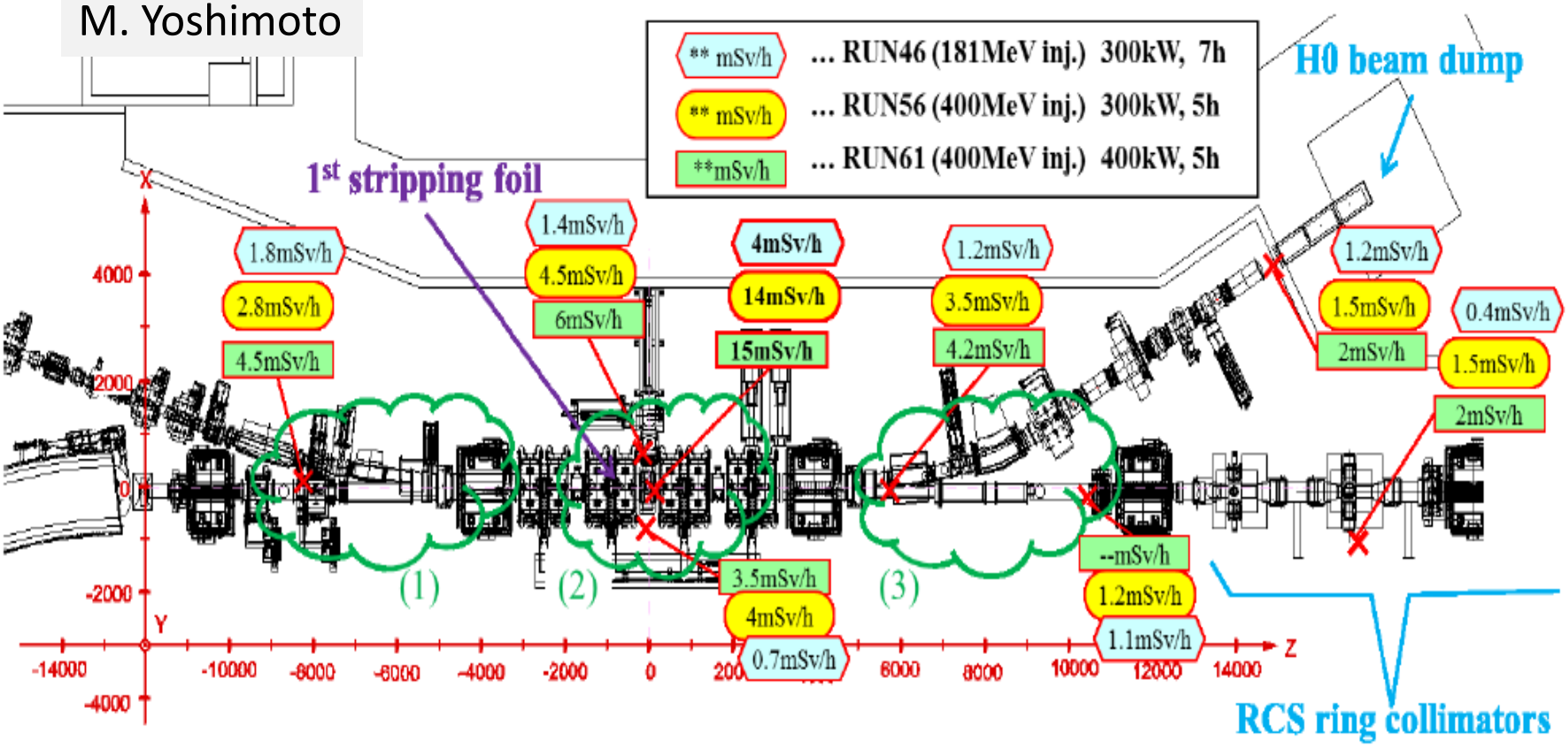
- Beam loss at 1 MW: ~0.2% and localized at collimator section (<< 3% of collimator limit)
- Beam loss occurs mainly at injection energy

→ **mostly due to the foil scattering!**



Residual radiation at the RCS injection area

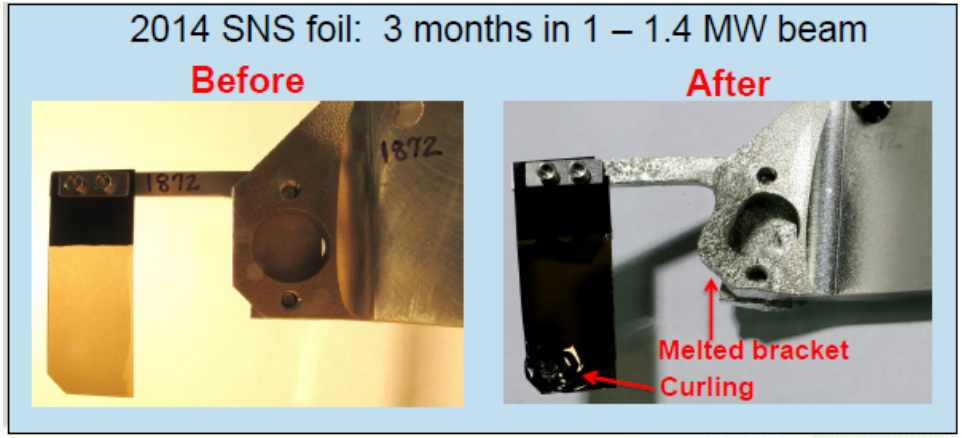
M. Yoshimoto



Residual radiation near the stripper foil is as high as **15 mSv/h** on contact, 4 hours after 0.4 MW routine operation!

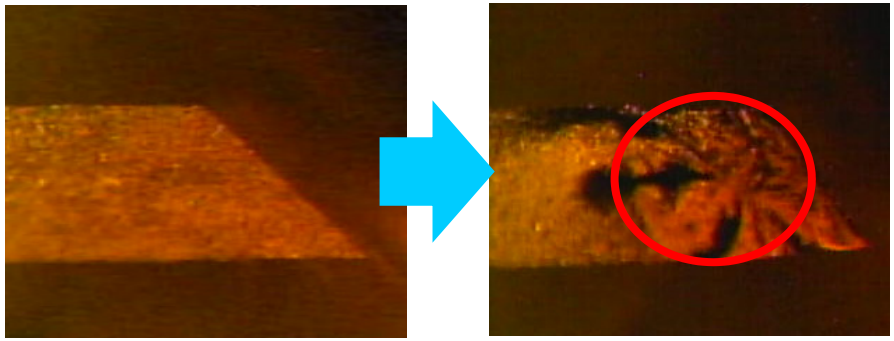
Experience of stripper foil behaviors at the SNS and J-PARC

S. Cousineau (HB2014)



J-PARC: 0.3 MW operation

Avg. foil hit: 10



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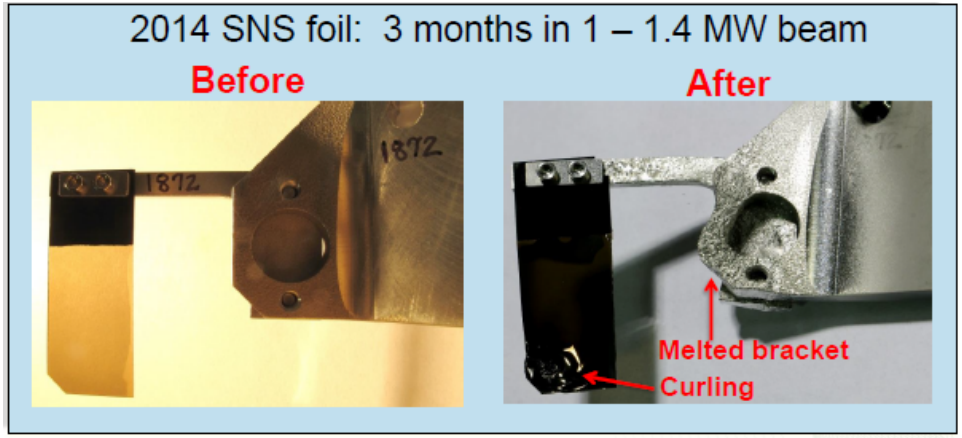

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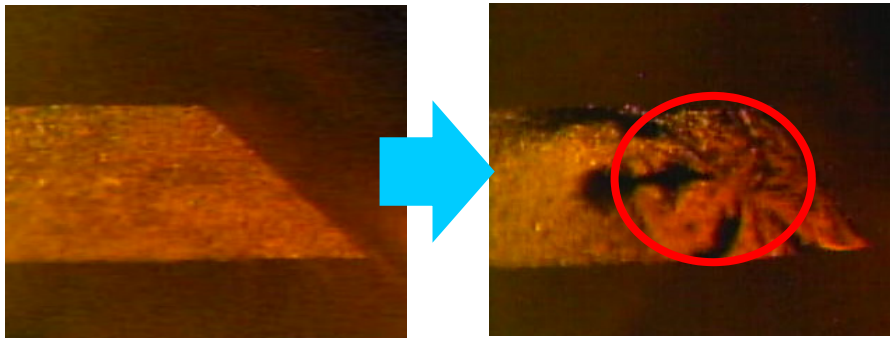

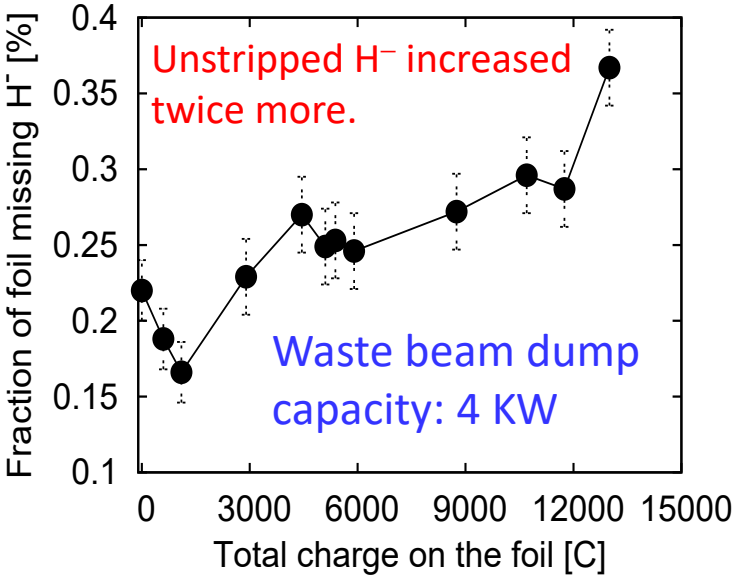

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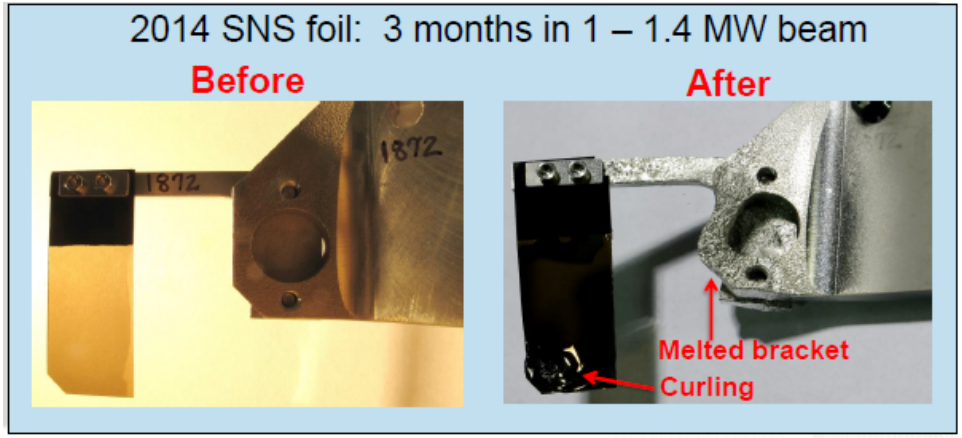

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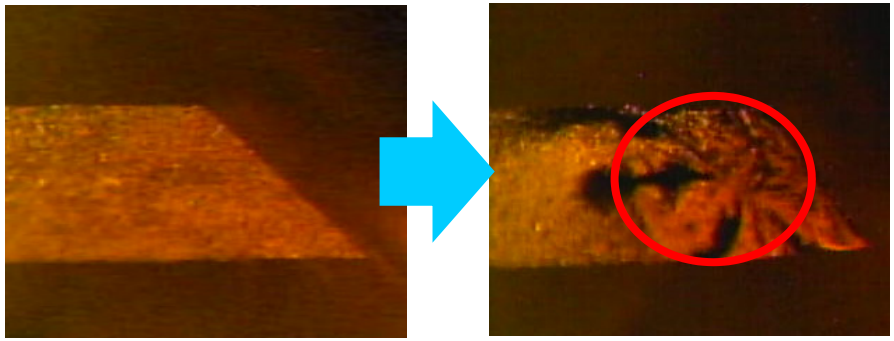
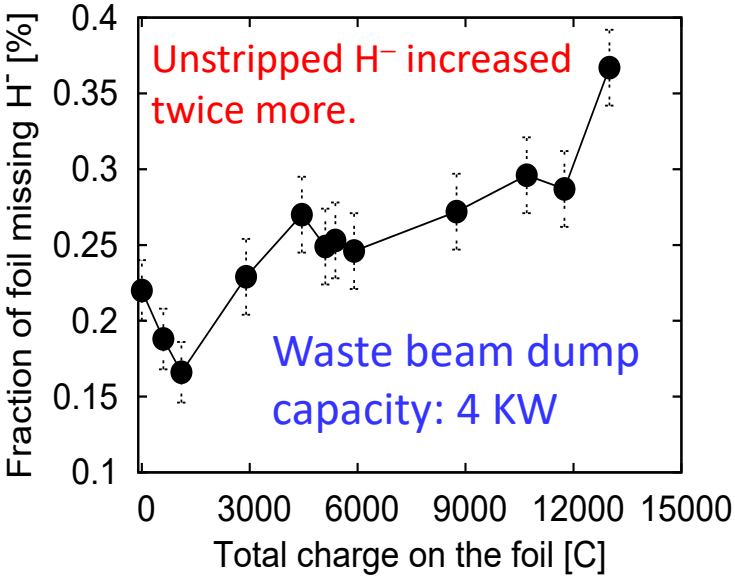


Foil hit at 1 MW operation (estimation)

To	P_{beam} (MW)	Beam sharing(%)	ε_painting (π mm mrad)	Foil hit
MLF	1	84	200	10
MR	1	16	50	70



Normalized avg. foil hit: ~20 but instantaneous foil heat for MR cycle is extremely high!

If the total charge limit on foil is 10000 C

→ Foil lifetime at 1 MW: 2 weeks!

RCS beam power at present and upgrade plan

RCS beam power to date:

To MLF: 500 kW

To MR: > 750 kW-eq.

Beam power to the MLF will be gradually increased to the designed 1 MW.

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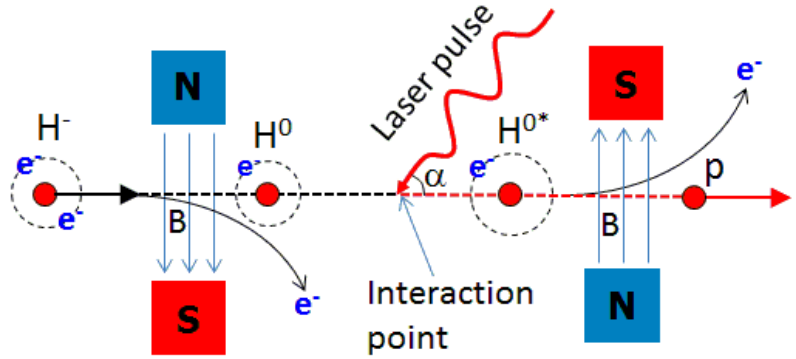
- Laser stripping of H^- holds the promise of eliminating the limitation and issues involved with using the stripper foil.
- We aim to establish the method even at 400 MeV H- energy.

Difficulties of laser assisted H⁻ stripping at 400 MeV



Step 1:
Lorentz stripping
$H^- \rightarrow H^0 + e^-$

Step 2:
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$H^0 + \gamma \rightarrow H^{0*}$ (n≥3)

Step 3:
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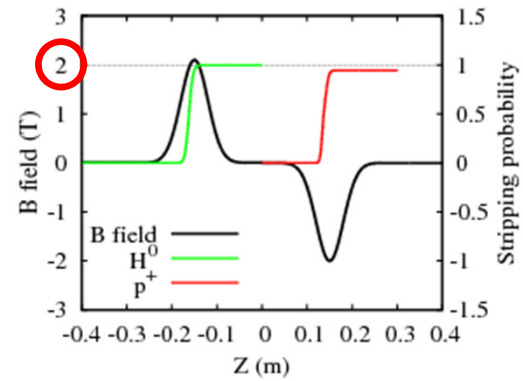
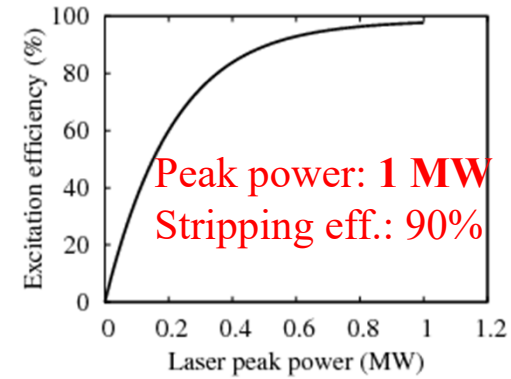
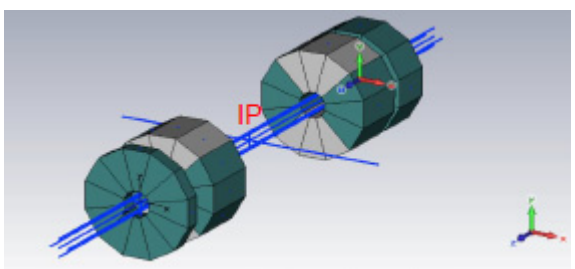
P.K.Saha et. al, IPAC15







A. Aleksandrov, HB2014
For SNS 1 GeV H-: B=1.2T
Inner radius: 15 mm

Magnetic field issues:

- *In the practical application, the magnets should have larger radius.*
- *For 400 MeV H⁻, hard to realize over 2 T magnetic field.*
- Circulating beam size after injection is quite big!
  r ~5 cm!

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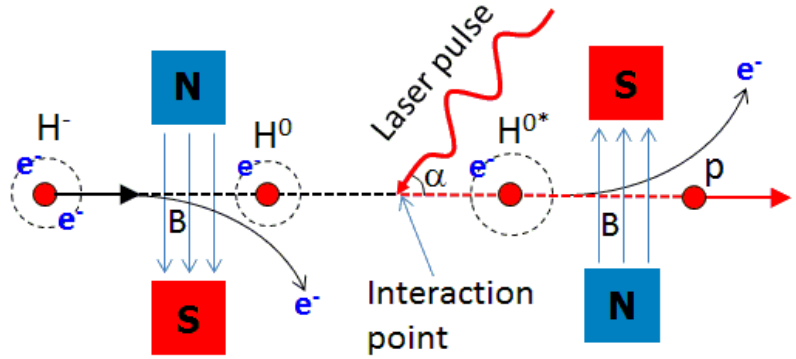

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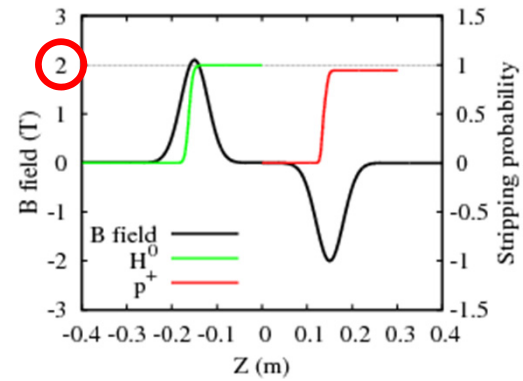
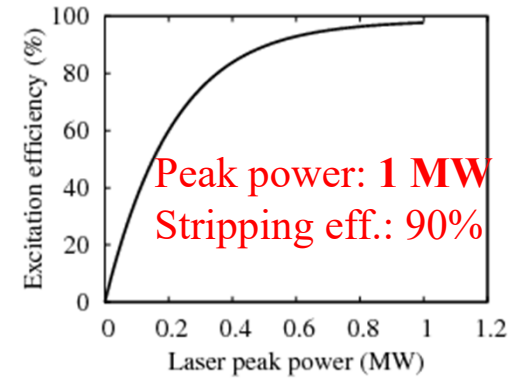
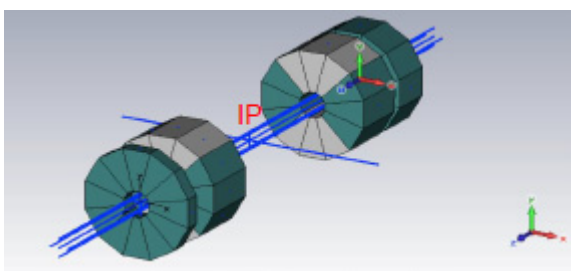
P.K.Saha et. al, IPAC15







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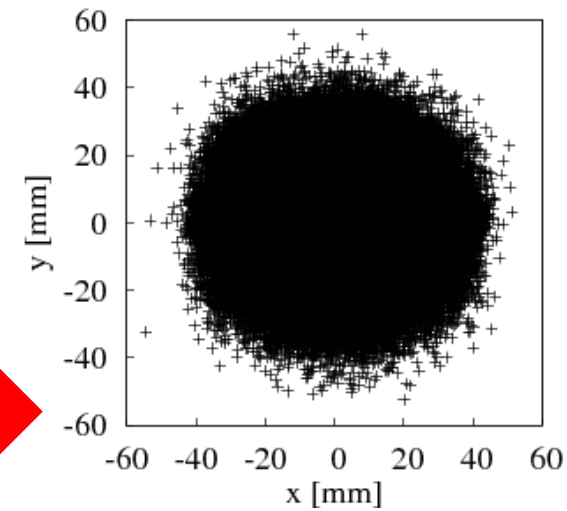

J-PARC RCS: 400 MeV inj. for 1 MW
Trans. dist. at the end of injection.
(Simulation: TP: none, LP: full)

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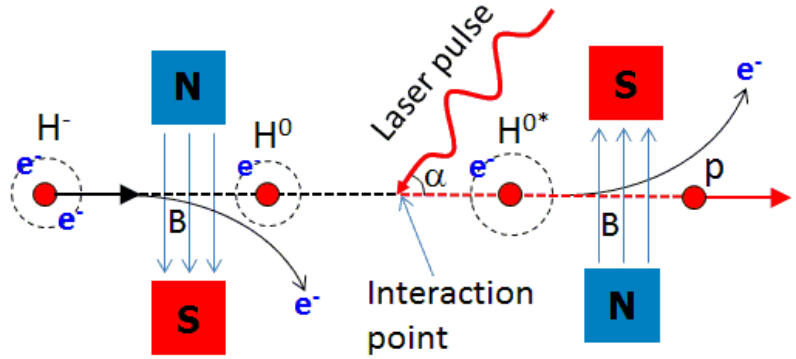

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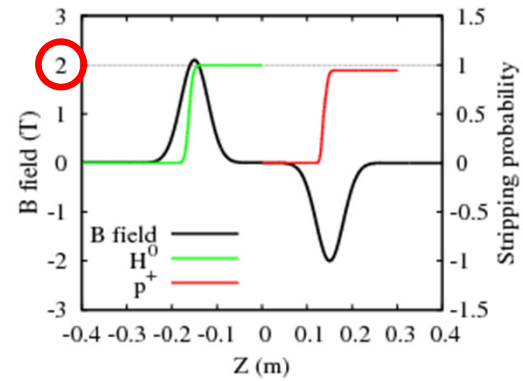

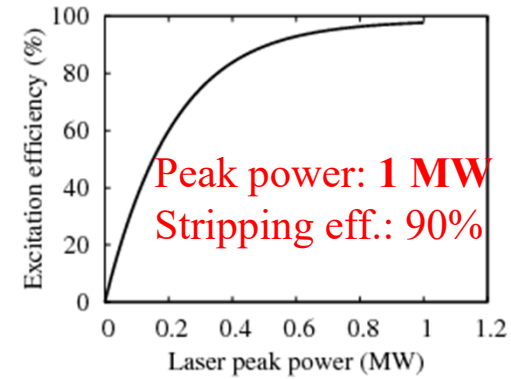

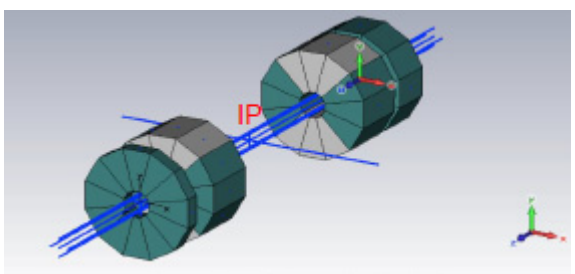

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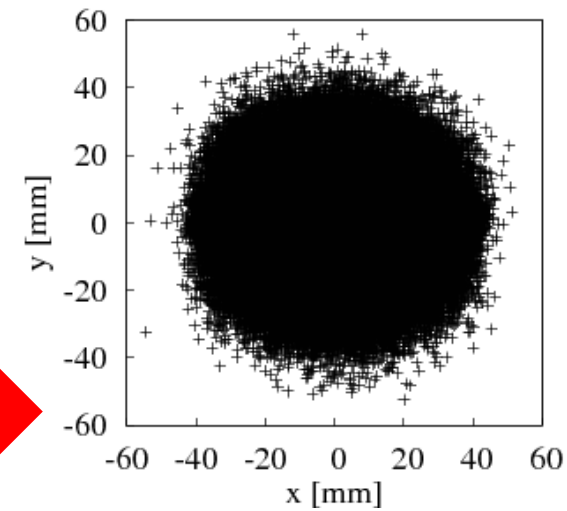
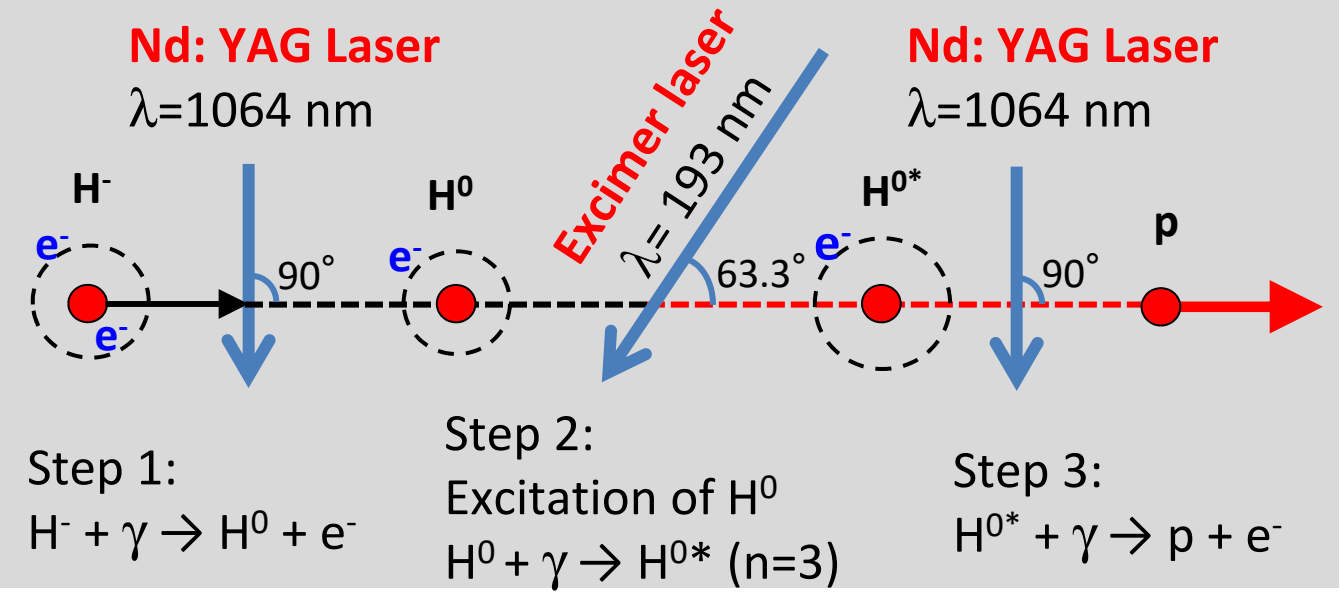


J-PARC RCS: 400 MeV inj. for 1 MW
Trans. dist. at the end of injection.
(Simulation: TP: none, LP: full)

One should concern about the emittance growth and also the lifetime of H0* (~5ns).

Principle of H^- stripping by using only lasers at J-PARC

Isao Yamane, Hiroyuki Harada, Saha Pranab and Shinichi Kato
PASJ, Vol. 13, 2016, 1-11 (in Japanese)



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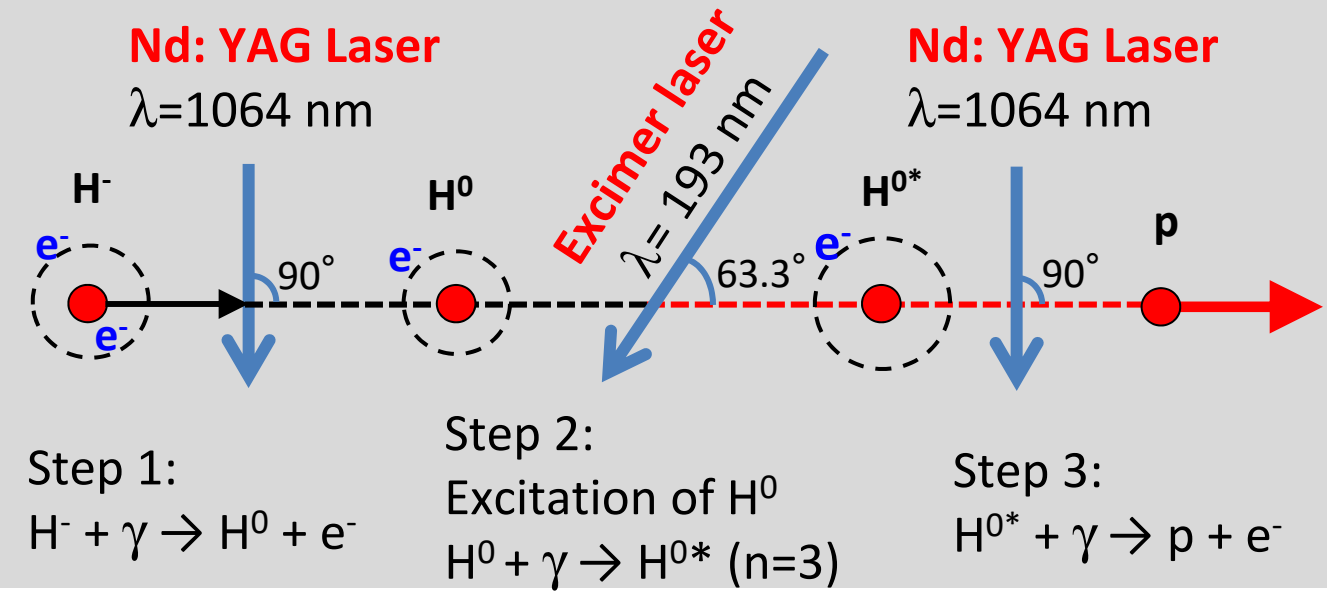

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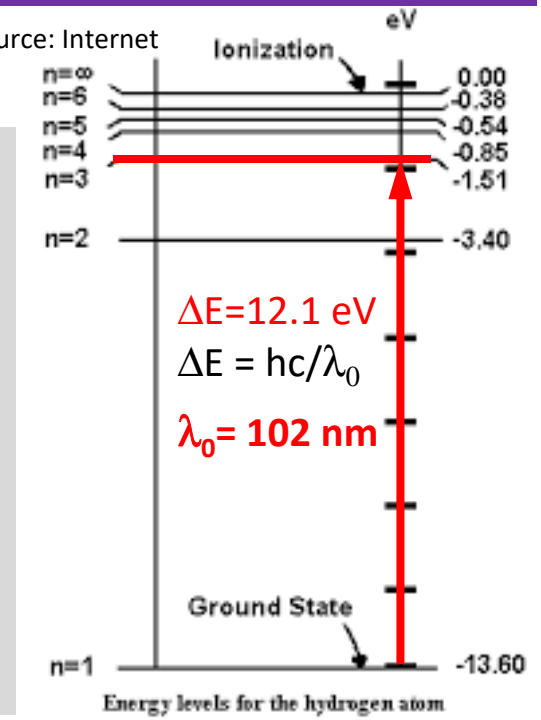

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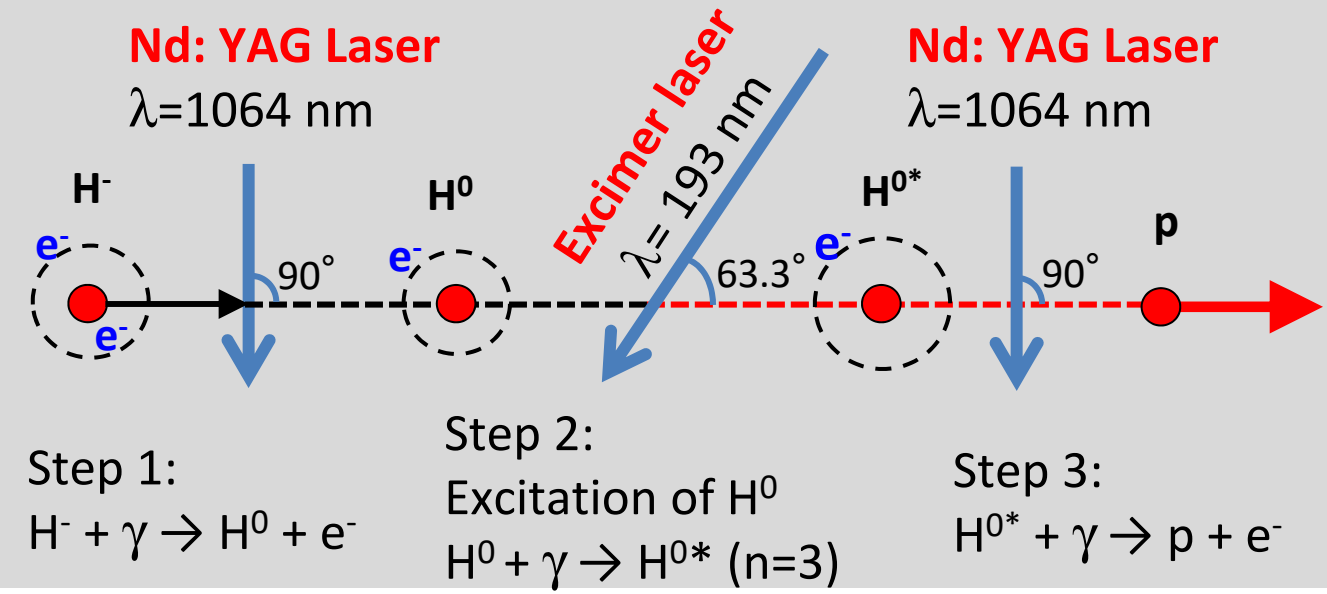

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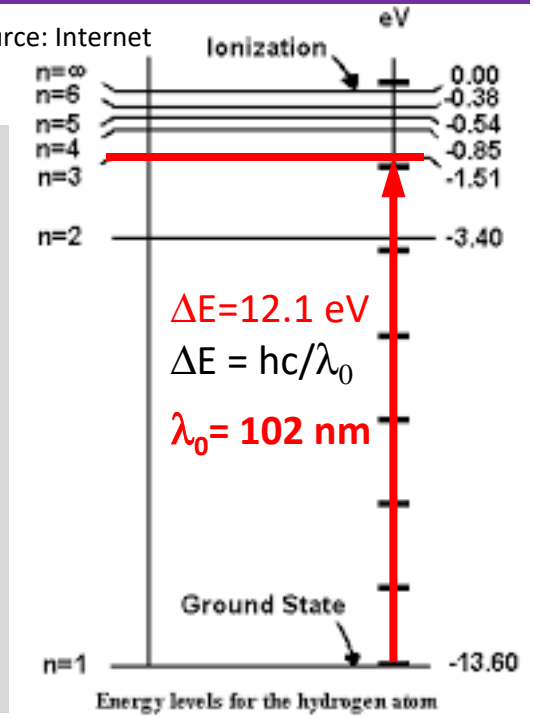


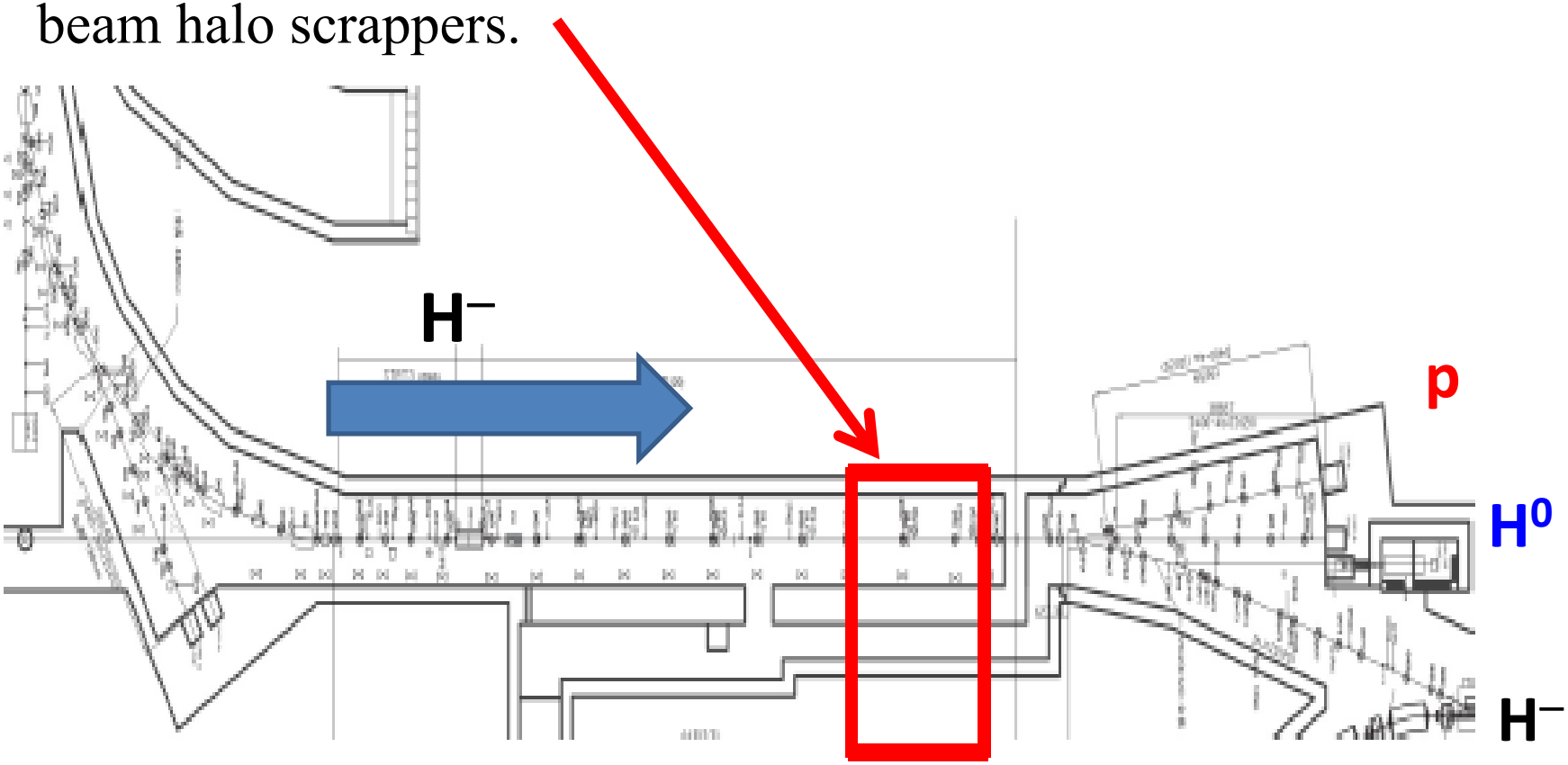
Process	E_{ph} (eV)	λ (nm)	α (deg.)	λ_0 (nm)	Laser
$H^- \rightarrow H^0$	1.67	1064	90	743	Nd:YAG
$H^0 \rightarrow H^{0*}$	12.1	193	63	102	Excimer (ArF)
$H^{0*} \rightarrow p$	1.67	1064	90	743	ND:YAG

Doppler effect of the 400 MeV H^- beam:
$\beta = 0.713$, $\gamma = 1.426$
$\lambda = \lambda_0 (1 + \beta \cos\alpha)\gamma$

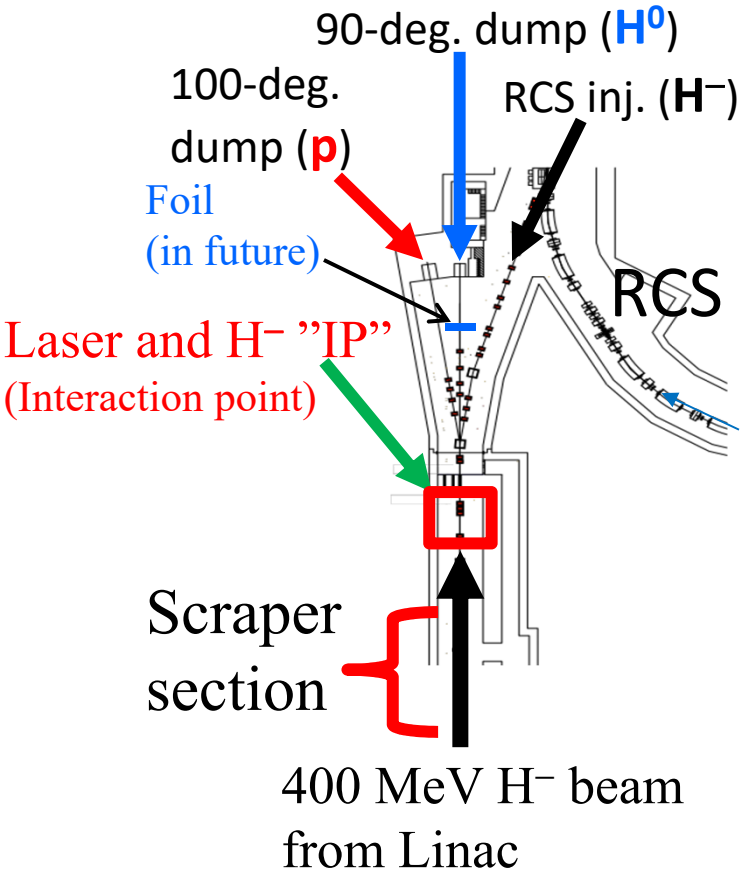
Experimental area, beamline

■ The POP demonstration will be performed at the end section of J-PARC L-3BT straight section.

■ The place is just downstream of the charge-exchange type beam halo scrappers.



Experimental Setup and strategy



- All three charge fractions can be measured in the downstream of IP.
- We will installed a foil at the 90-deg dump to strip H^0 to p for measuring.

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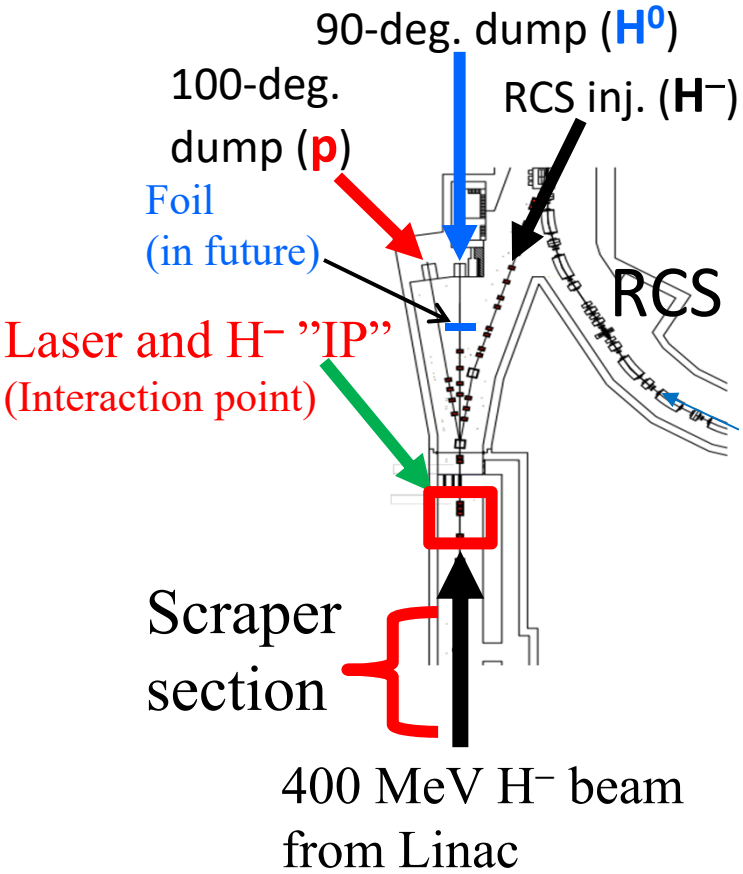

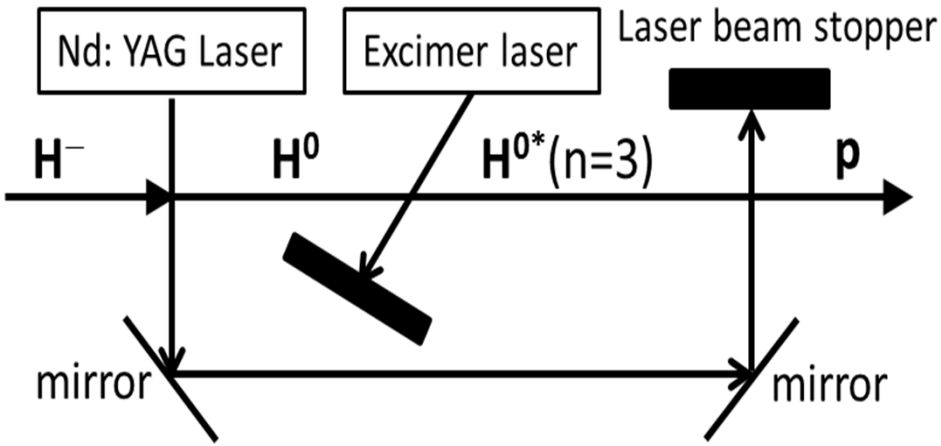

Setup for the POP experiment

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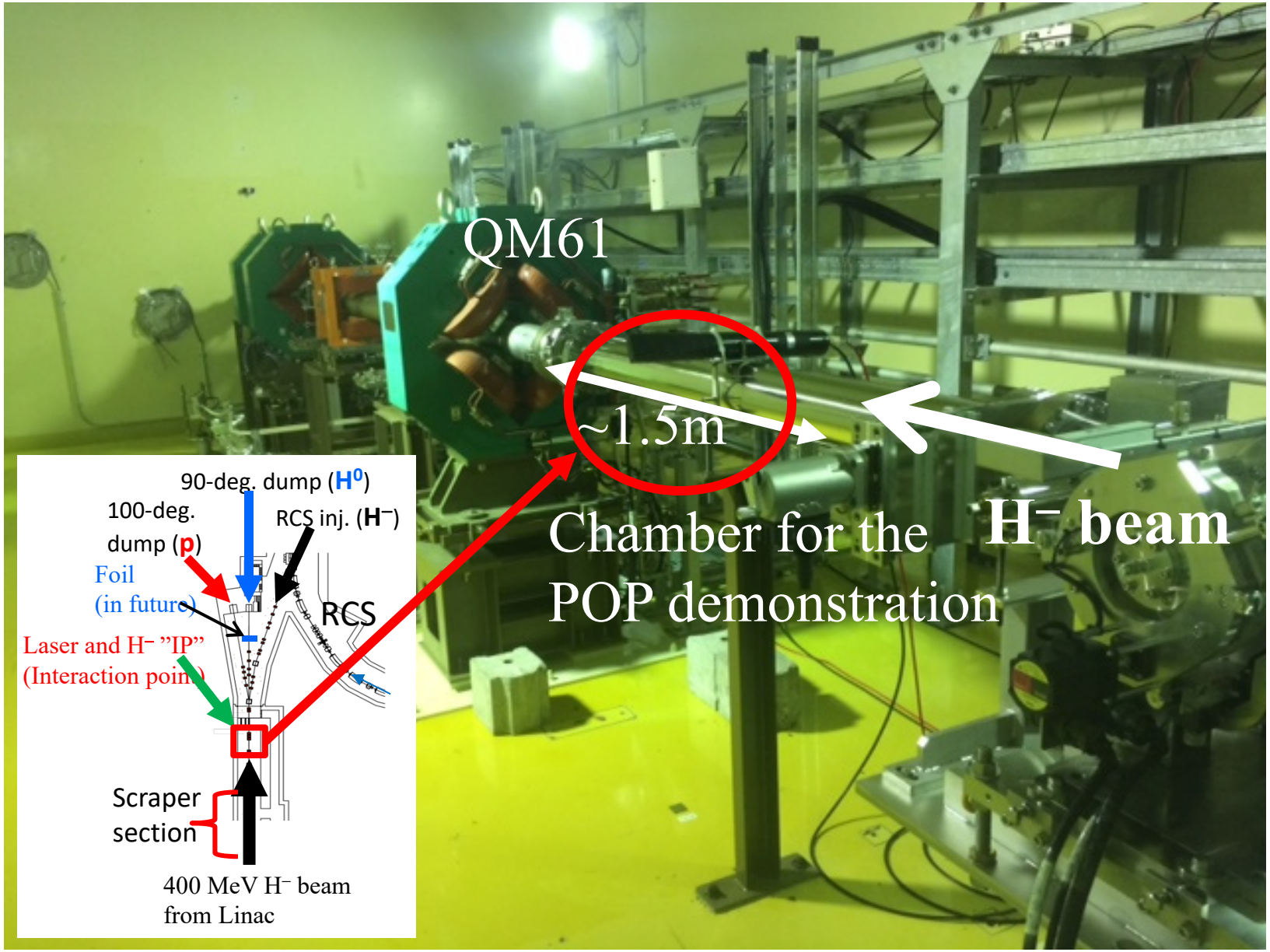
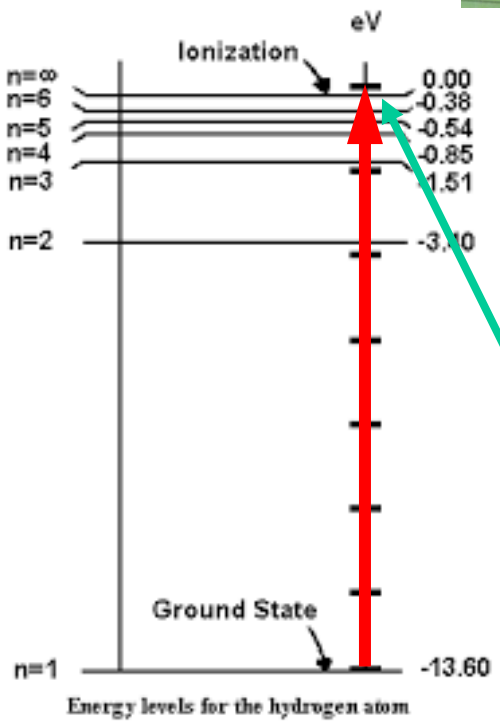
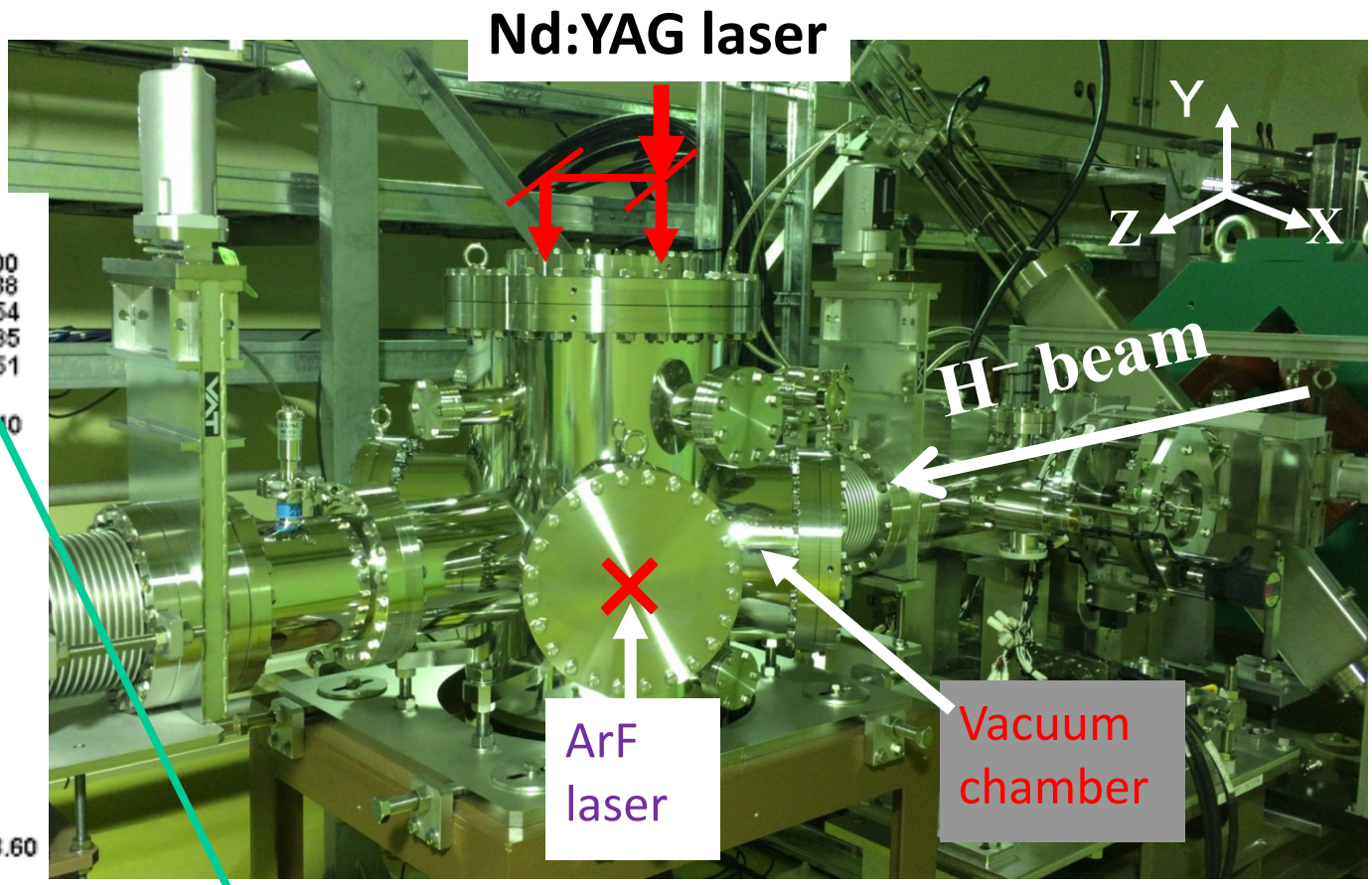
Beam line close view



Vacuum chamber for the POP demonstration ---- **Installed**

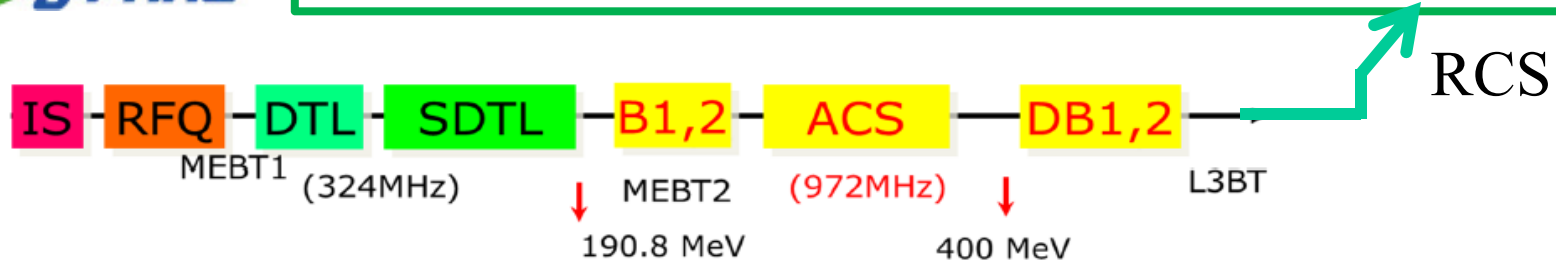


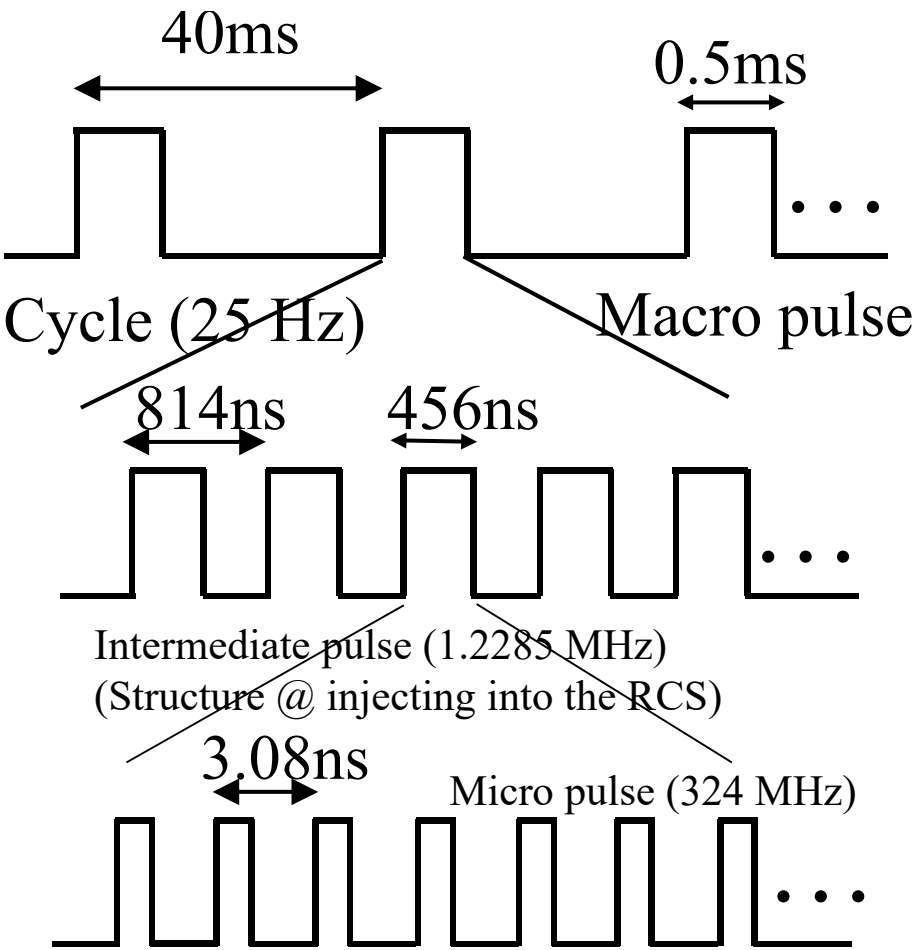


Excimer laser window size: Big enough for angle variation **67°<α<45°**

→ Try ionization of H0. **α = 47°, λ_0 = 91.2 nm** [$\lambda = \lambda_0(1 + \beta\cos\alpha)\gamma$]

LI beam structure and Measurement strategy





- For the POP demonstration, we concentrate stripping only a single micro pulse of ~100 ps.

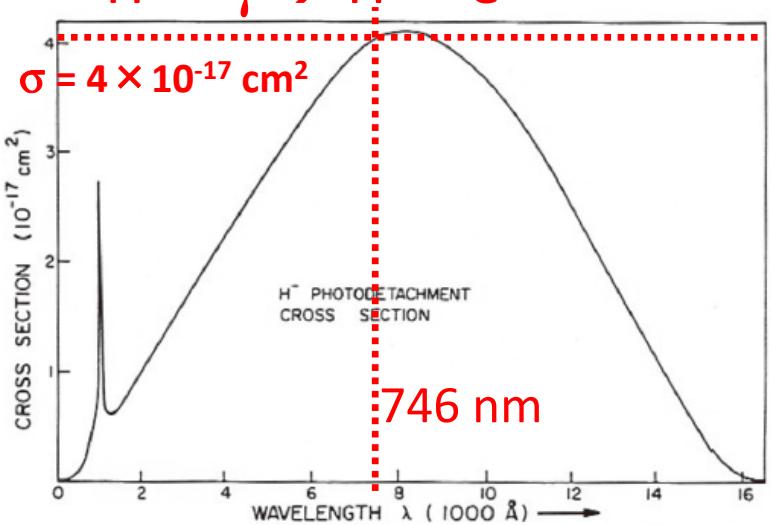
- We will use 324 MHz BPM electrode signal for the measurement.

Estimated Laser energy for stripping a micro pulse

Photo-detachment:

L. M. BRANSCOMB, "Physics of the One-And-Two-Electron Atoms", Edited by F. Bopp and H. Kleinpoppen, North-Holland, (1968)

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



E_{ph} = 1.67 eV, λ_0 = 746 nm

Saturation density Φ^s in PRF

$\Phi^s = (E_{ph}/\sigma) = 6.7 \times 10^{-3}$ J/cm^2

$r(H^-)$ = 2mm, $t(H^-)$=100 ps

t_i(collision) = 20 ps, t_l(laser) = (100+20) 120ps

$E(\text{laser}) = (\Phi^s/\gamma) \times (\pi r^2) \times (t_l/t_i)$

= **3.5 mJ**

Estimated Laser energy for stripping a micro pulse

Photo-detachment:

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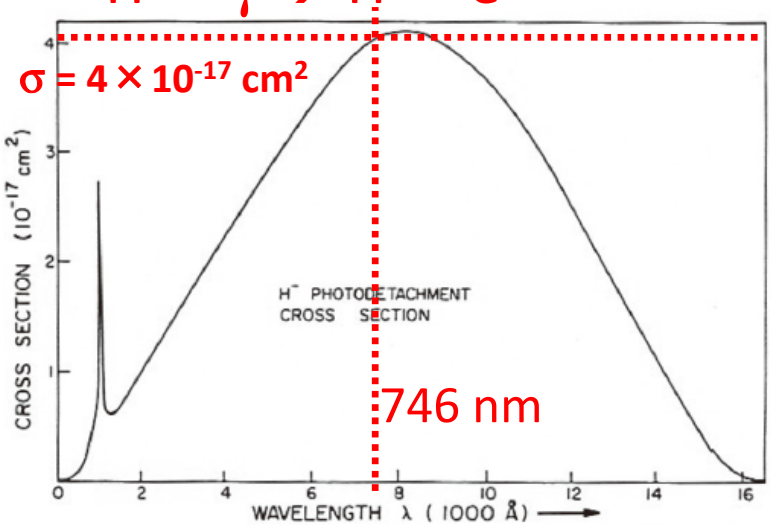

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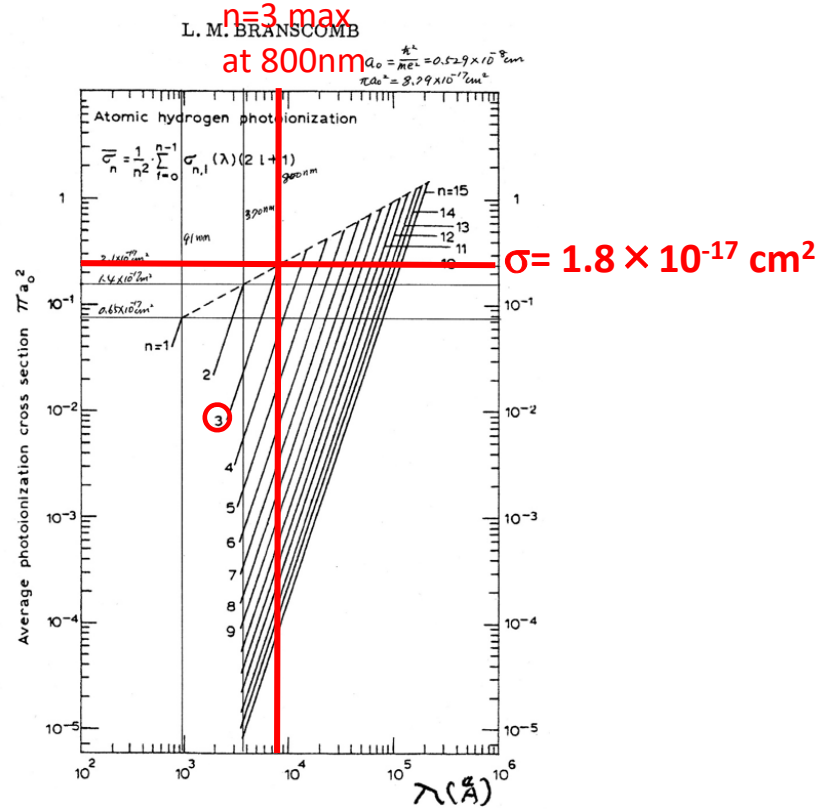
Photo-ionization:

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

n=3 max at 800nm



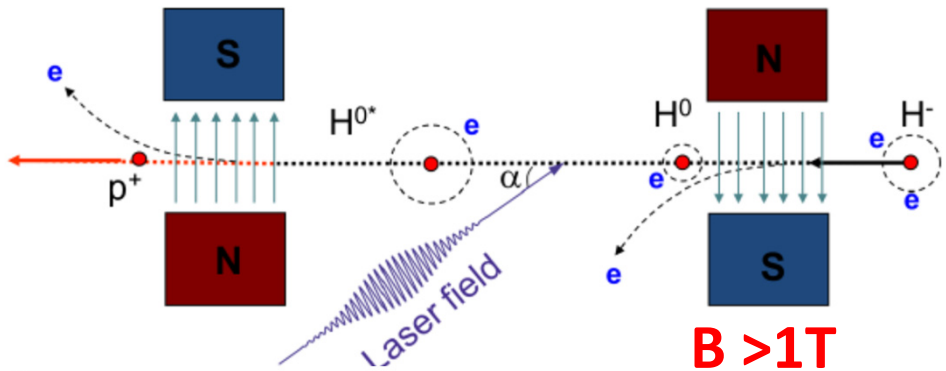
E(laser)= **7 mJ**

Laser energy for H0 excitation (n=3): SNS case

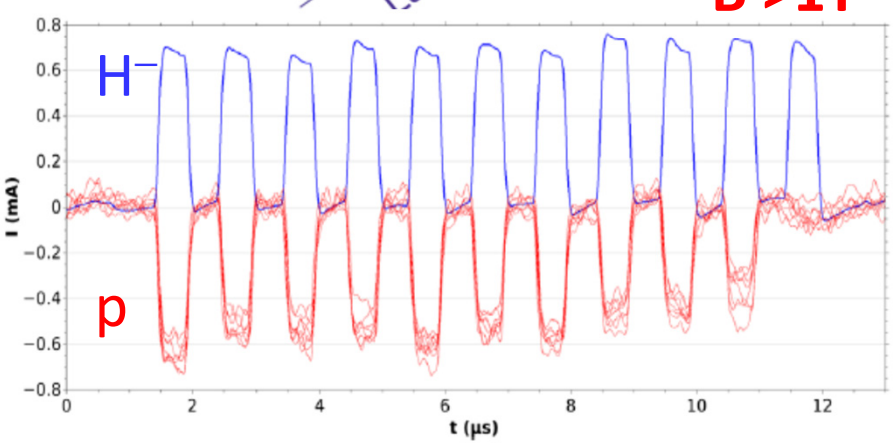
PRL **118,** 074801 (2017) PHYSICAL REVIEW LETTERS

SNS, Oak Ridge

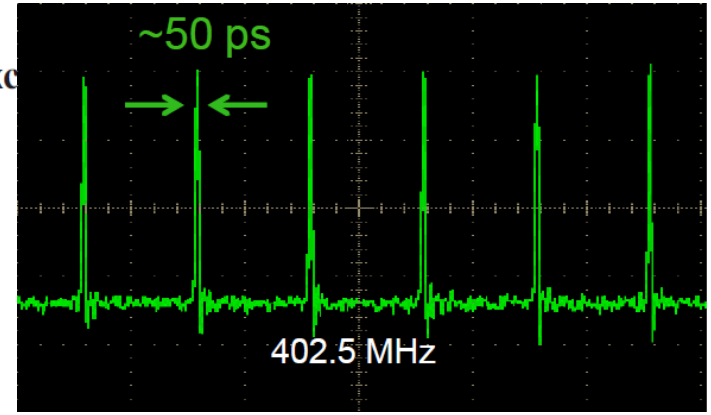
First Demonstration of Laser-Assisted Charge Exc
for Microsecond Duration H⁻ Beams



B >1T



Stripping efficiency: Achieved > 90%



Laser pulse and peak power:

Nd:YAG laser of 1064 nm
→ 3rd hc (355 nm)
Synchronized to 402.5 MHz
H^- pulses.
Laser pulse: 50μJ, 50ps
➔ Ppeak: **1 MW**

Lasers we have and expected stripping efficiency for the POP demonstration

1. YAG laser (1064 nm pulsed)

E = 0.2 ~ 0.6 J, 5~10 ns (FWHM)

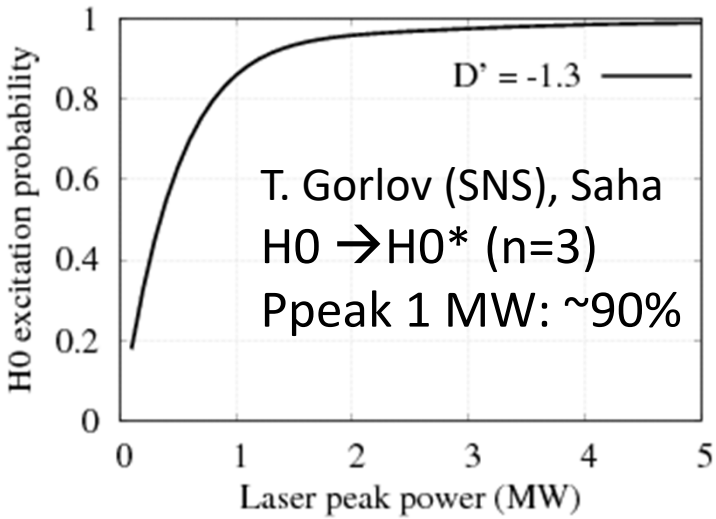
2. ArF Excimer laser (193 nm pulsed)

ArF 193 nm excimer laser (by Mlase)

E = 13 mJ, Pulse length = 5-10 ns (σ)

Bandwidth: ~4THz

➔ P_{peak} > 1 MW can be reached



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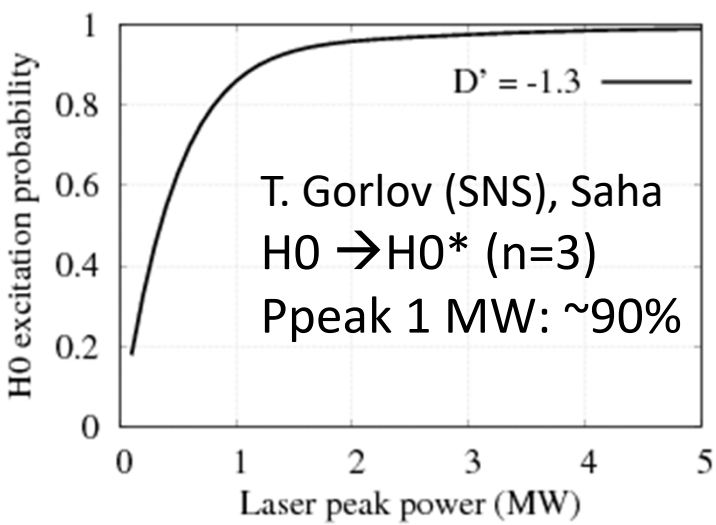

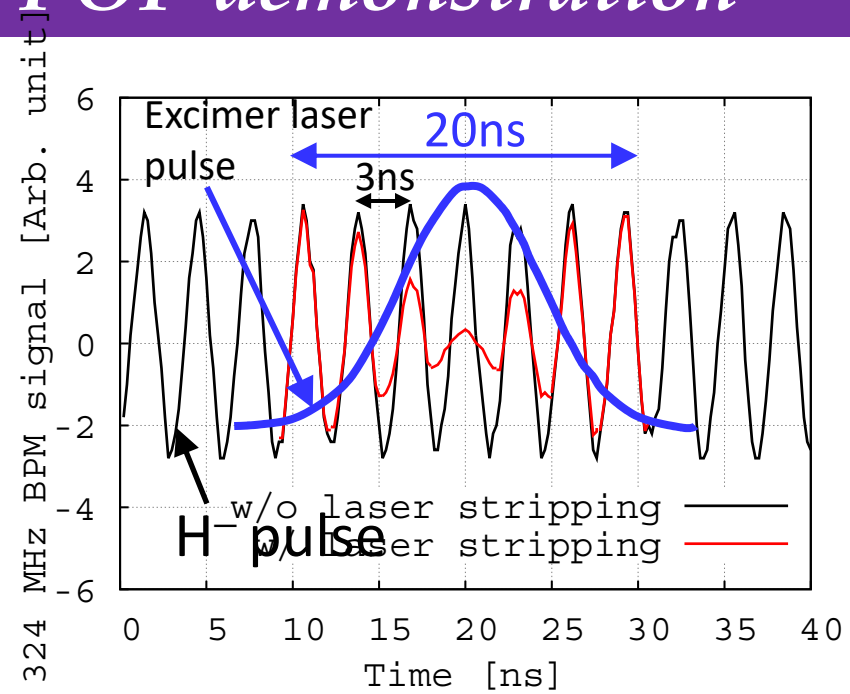

Typical 324 MHz BPM electrode signal. The red curve is an expected change of the H^- signal (black) due to its stripping to p.

We expect 90% stripping eff for at least one micro pulse which matches at the center of the laser pulses.

Manipulation of H- beam for reducing the laser power

Extensive manipulations of the H^- beam are very important to reduce the laser power, especially for the Excimer laser.

For us, the order might be as follows:

★ Dispersion derivative of the H^- beam
★ Minimization of the betatron angular spread
★ Shorter longitudinal beam size. σ_z <100 ps

. . . . . .

Dispersion derivative and minimize betatron angular spread to reduce the laser energy

Required maximum angular spread $(\Delta\alpha_l)_m$ of the laser pulse to cover ion beam (Ref: I. Yamane)

$$(\Delta\boldsymbol{\alpha_l})_{\boldsymbol{m}} = \left(\frac{\beta(\beta + cos\alpha)}{1 + \beta cos\alpha}\left(\frac{\boldsymbol{\Delta p}}{\boldsymbol{p}}\right) + \frac{\beta sin\alpha}{1 + \beta cos\alpha}(\Delta\boldsymbol{\theta})_m\right) \times \frac{1 + \beta cos\alpha}{\beta sin\alpha}$$

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Utilize dispersion derivative

V. Danilov, PRST-AB, 2003

Eliminate transition frequency spread

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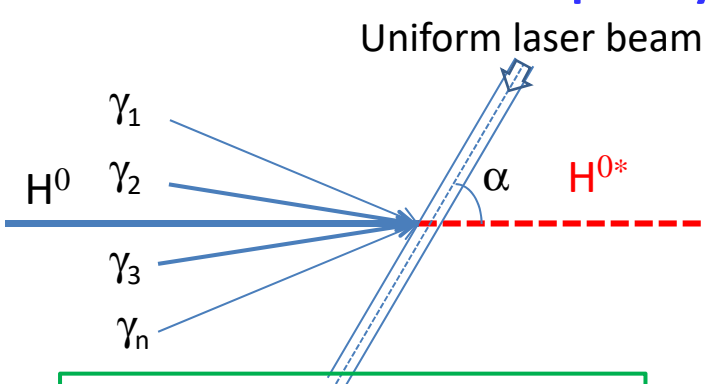

$$D' = -\frac{\beta+cos\alpha}{sin\alpha} = -1.3$$

- Hydrogen atom with different energies have the same laser light frequency in their rest frame.
- Uniform laser beam.

→ Gain on the laser peak power.

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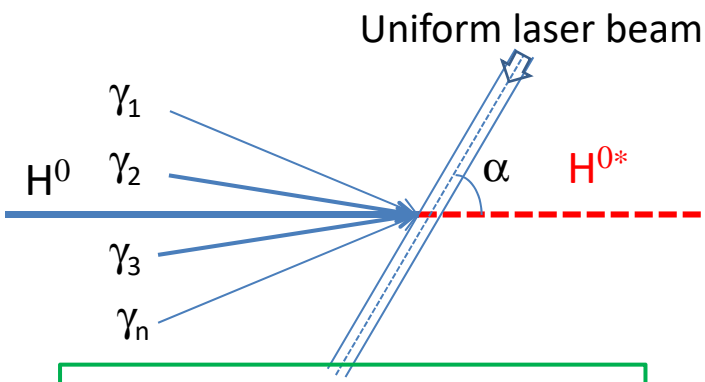
V. Danilov, PRST-AB, 2003

Reduce betatron angular spread

Eliminate transition frequency spread



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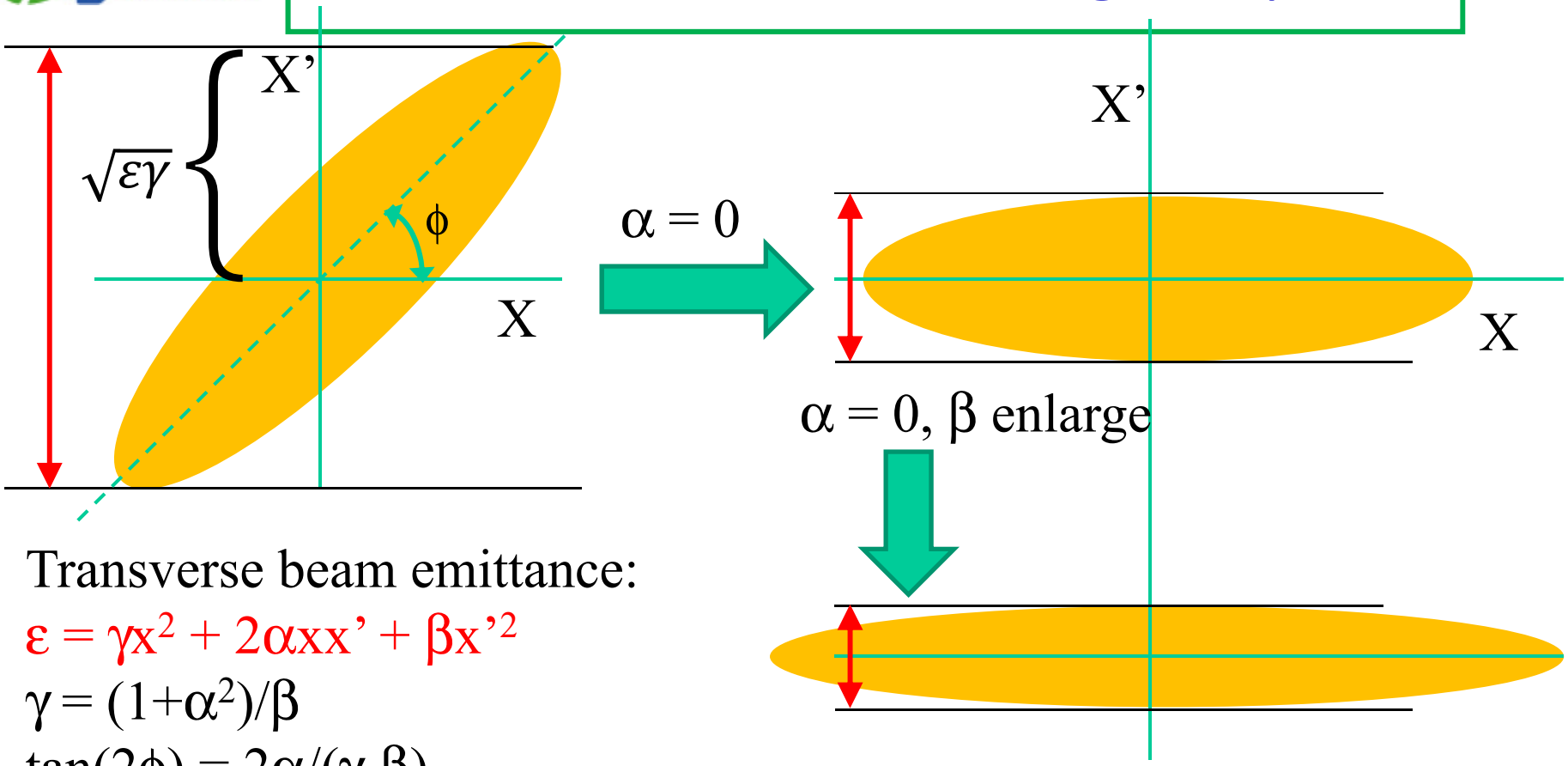
Minimization of betatron angular spread



Transverse beam emittance:

$\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2$

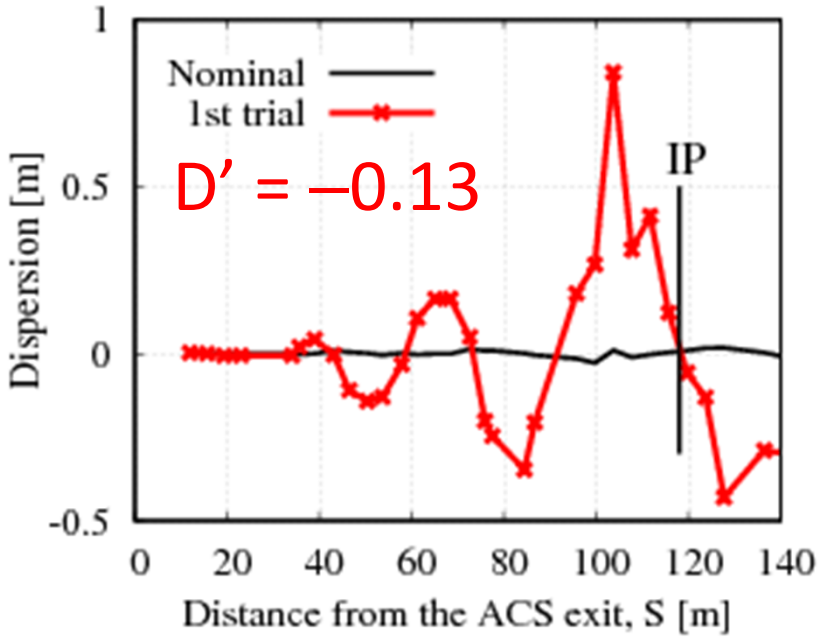
$\gamma = (1+\alpha^2)/\beta$

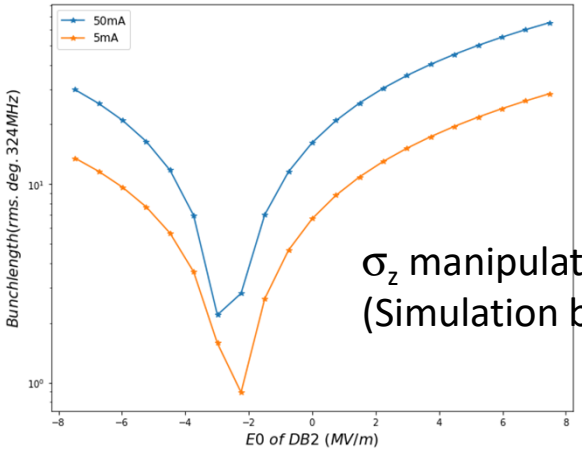
$\tan(2\phi) = 2\alpha/(\gamma-\beta)$

α, β, γ, ε are called twiss parameters

Angular spread is controlled by optimizing α to zero and also with large β.

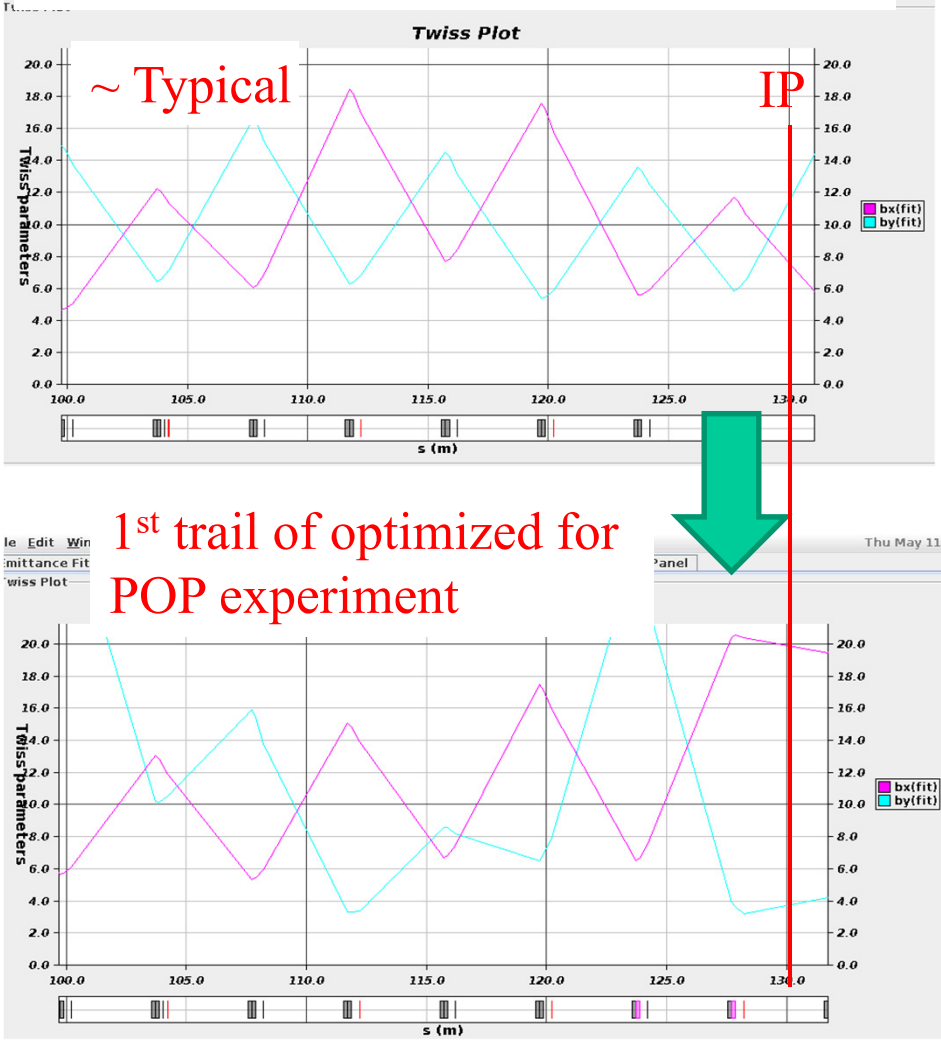
Trial manipulation of the H^- beam





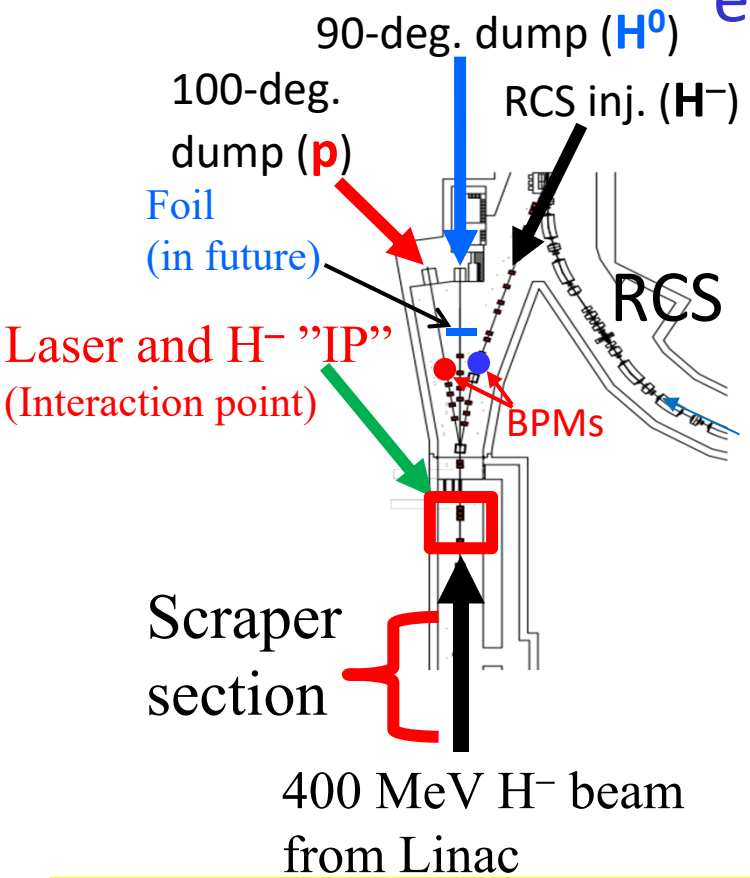
σ_z manipulation
(Simulation by Y. Liu)

Transverse beam optimization at the IP



Further studies are planned

Measurement method of stripping efficiency of a single micro pulse



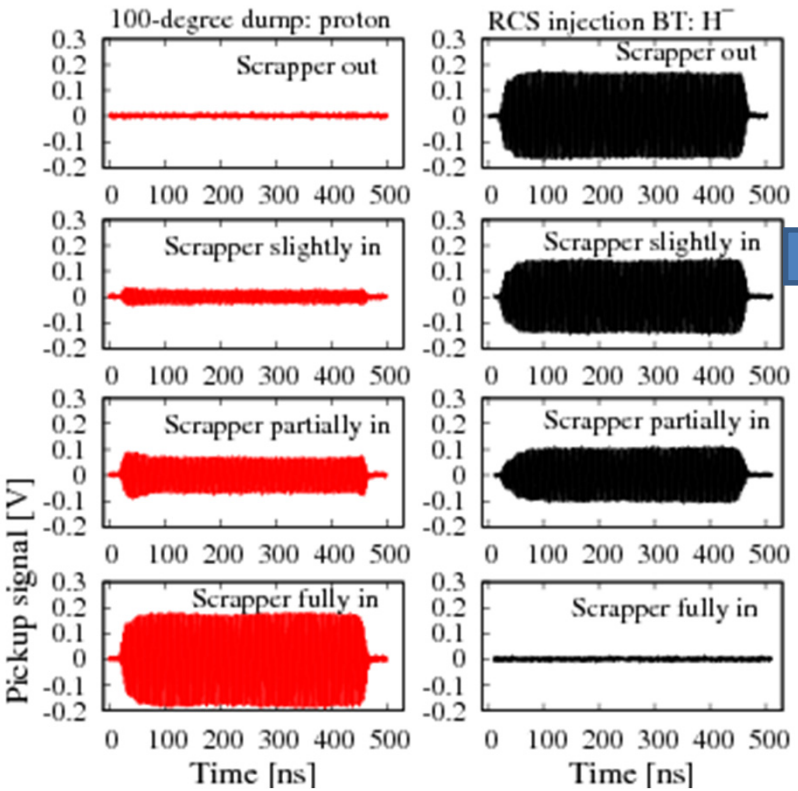
Scraper & Beam (y, x)	To 100-deg. Dump (p)	To 90-deg. Dump (H^0)	To RCS (H^-)
Scraper OUT; H^-	– – – ·	– – – ·	H^- 100%
Half IN	p 49.999%	1×10^{-3} %	H^- 50%
Fully IN	p 99.998%	2×10^{-3} %	$< 10^{-10}$ %

Checked by inserting L-3BT scraper at present

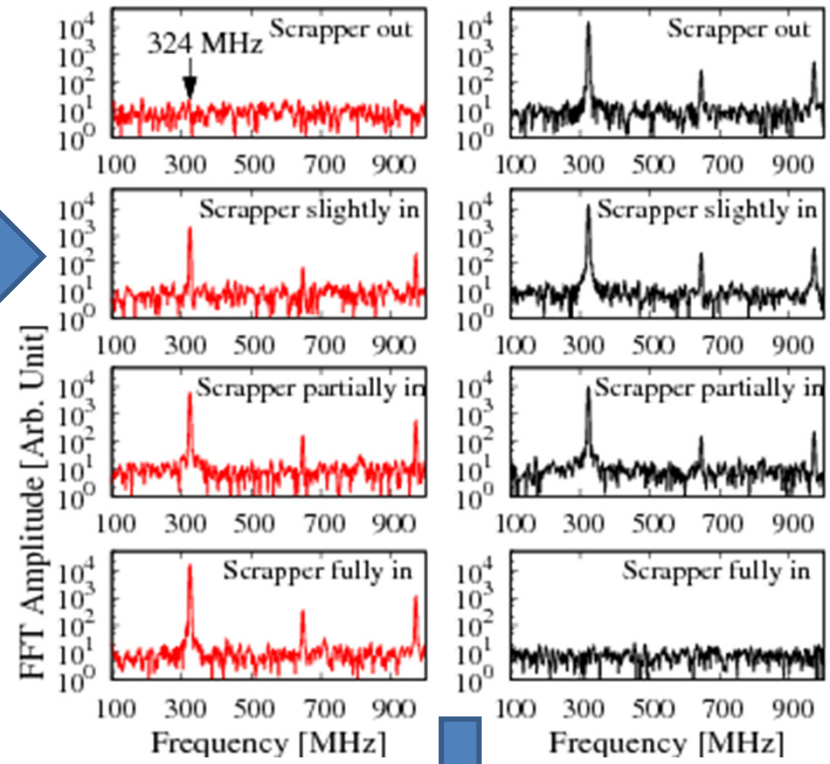
(Charge-exchange type transverse beam halo scrapper. Stripped protons go to the 100-deg. beam dump)

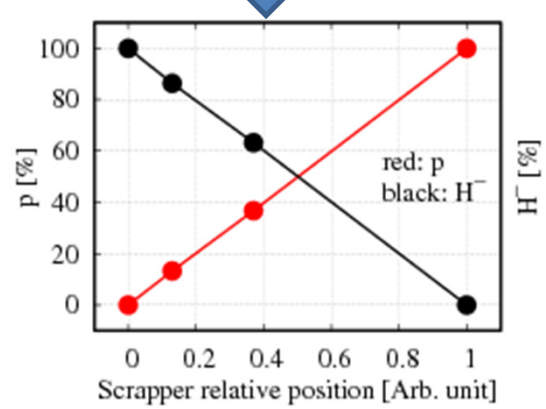
The 324 MHz BPMs electrode data was taken by a fast oscilloscope.

Measurement techniques: Experimental results



FFT



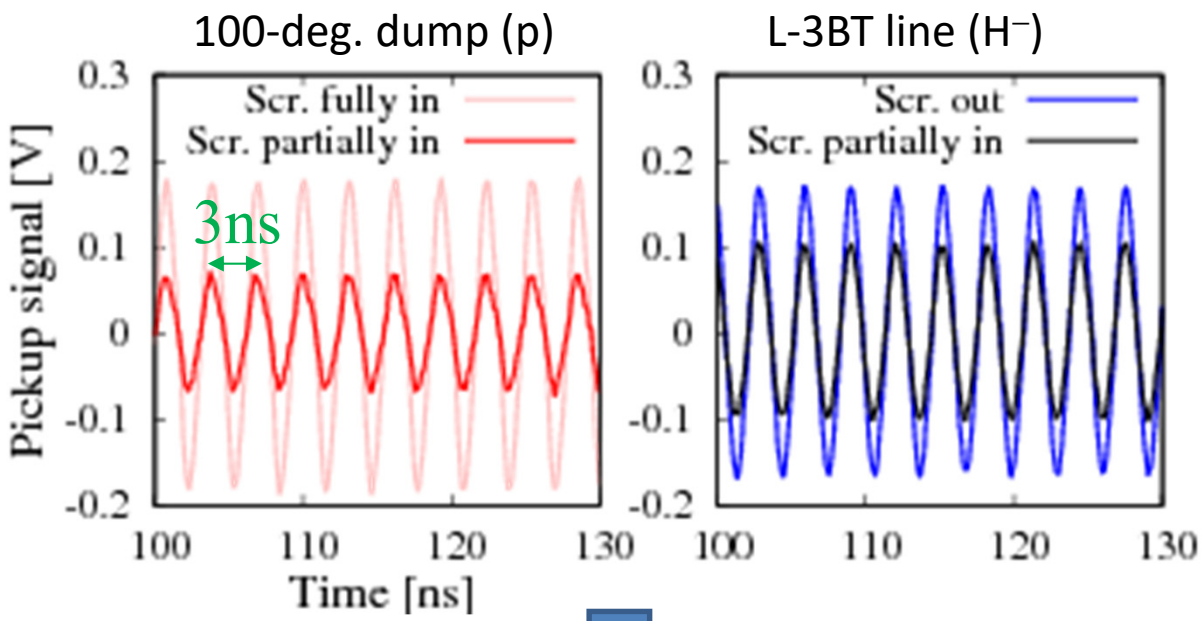


Stripping efficiency of single medium pulse can easily be obtained by using FFT analysis.

However, we have to obtain stripping efficiency of a single micro pulse of 324 MHz.

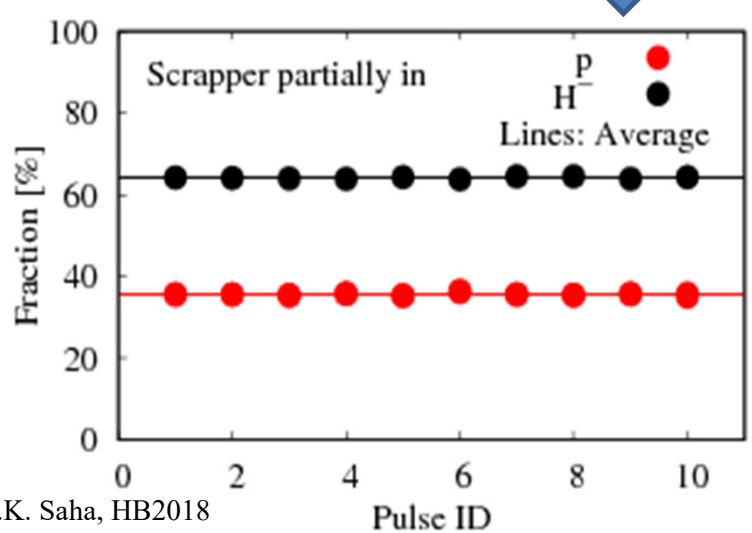
→ Analysis of individual micro pulse

Analysis of individual micro pulse



p fraction: pink to red

H- Fraction: black to blue

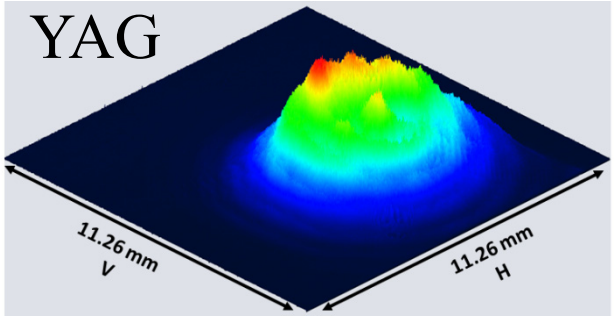


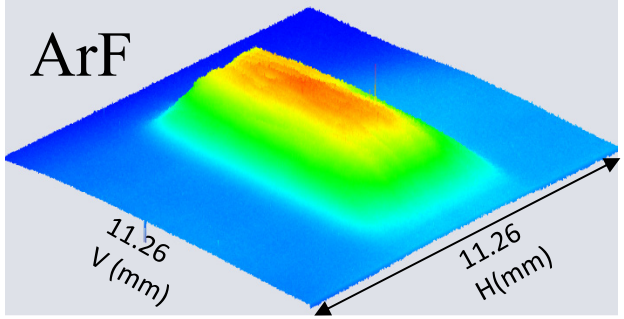
- Possible to measure stripping efficiency of individual micro pulses.
- Useful also for micro level check in long pulse/multiple pulses studies

P.K. Saha, HB2018

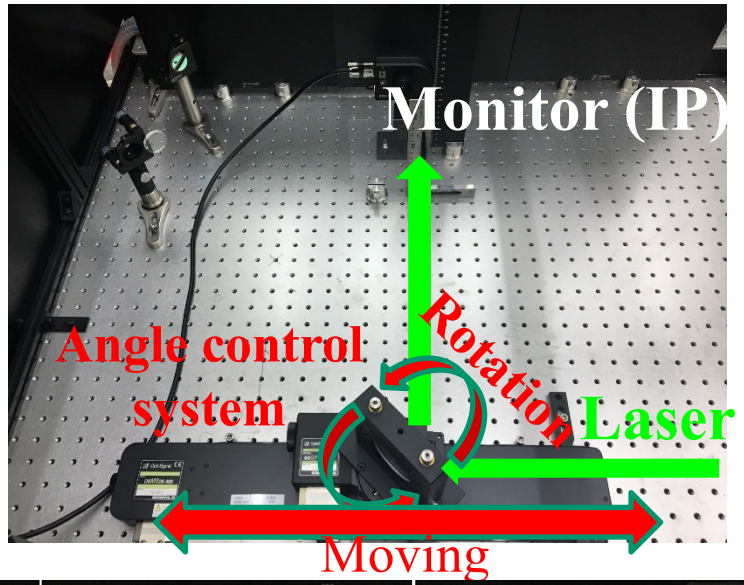
R&D Status of the Lasers

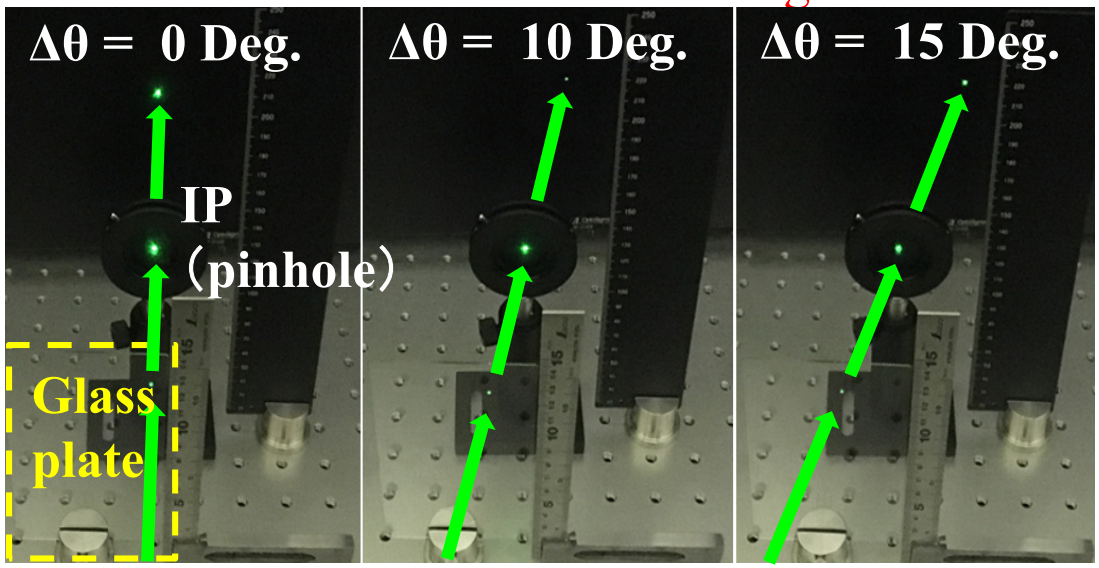
We have just started R&D of the lasers.
At present mainly for the Nd:YAG laser up to with 0.2J.





H. Harada



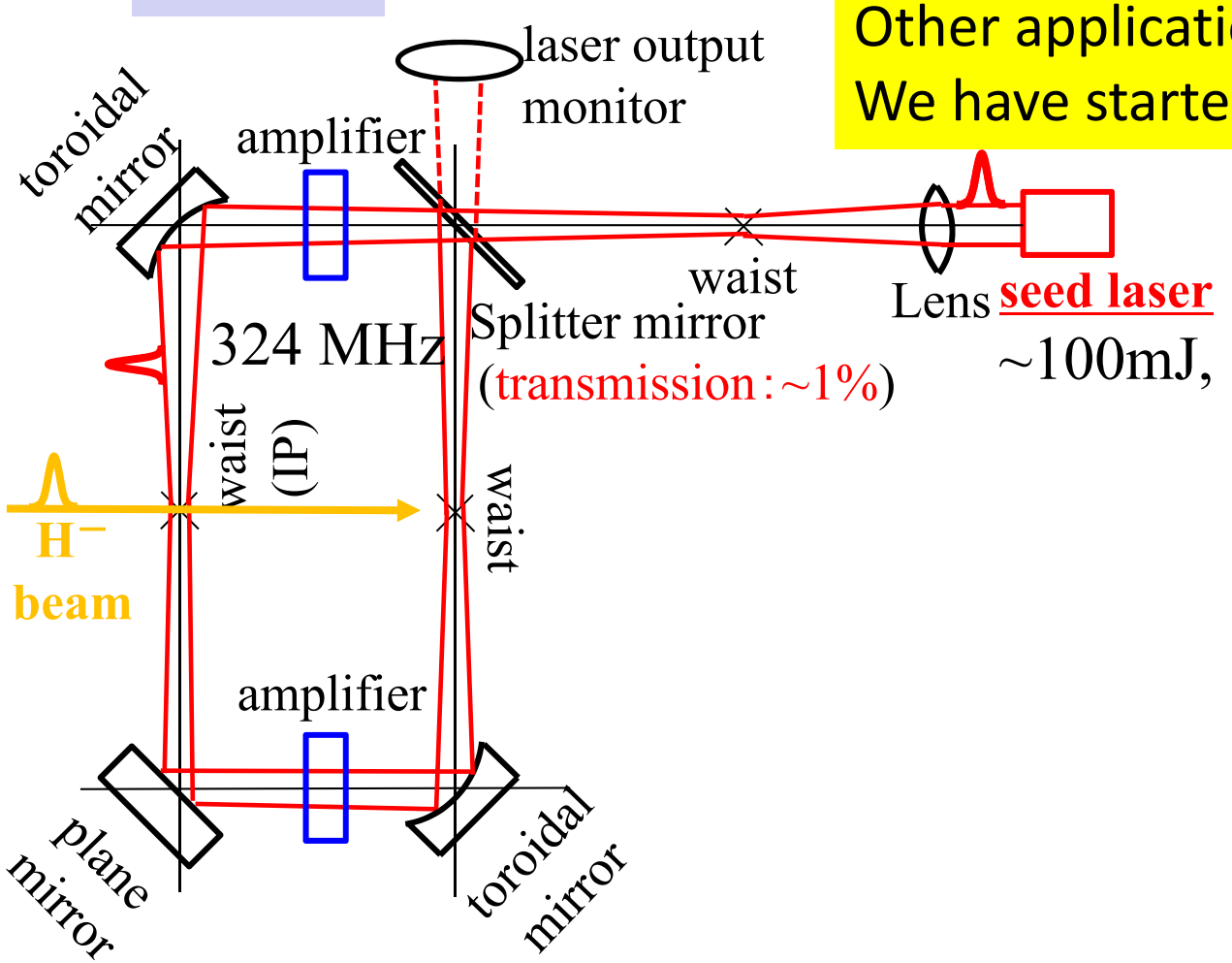


Angle control and optimization. Applicable for laser λ_0 change

How to cover 10^5 micro pulses (0.5 ms) for practical application?

H. Harada

Laser storage ring ? (Y. Yamane)
Other applications?
We have started R&D studies.



~100mJ, 100psec, 25Hz

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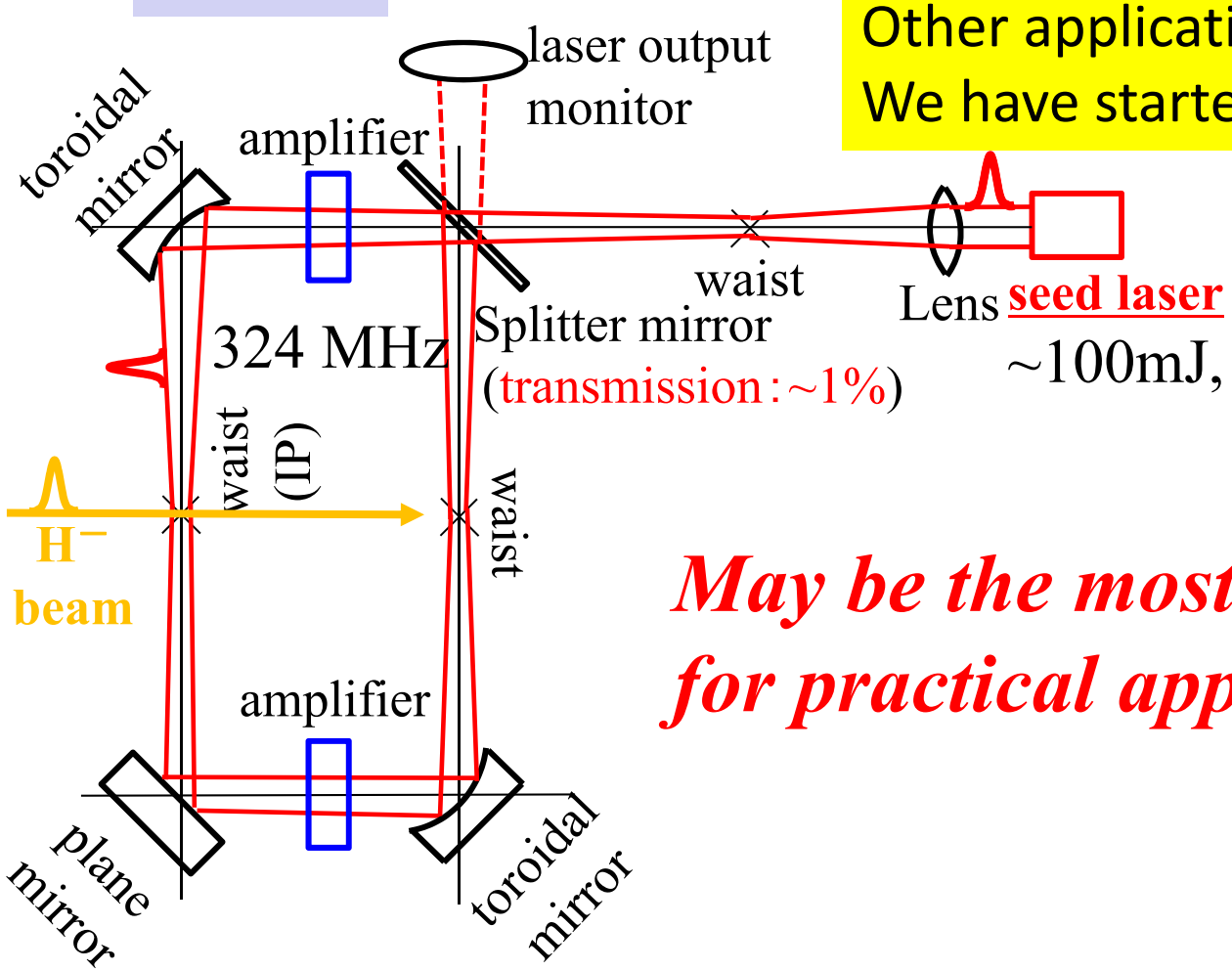
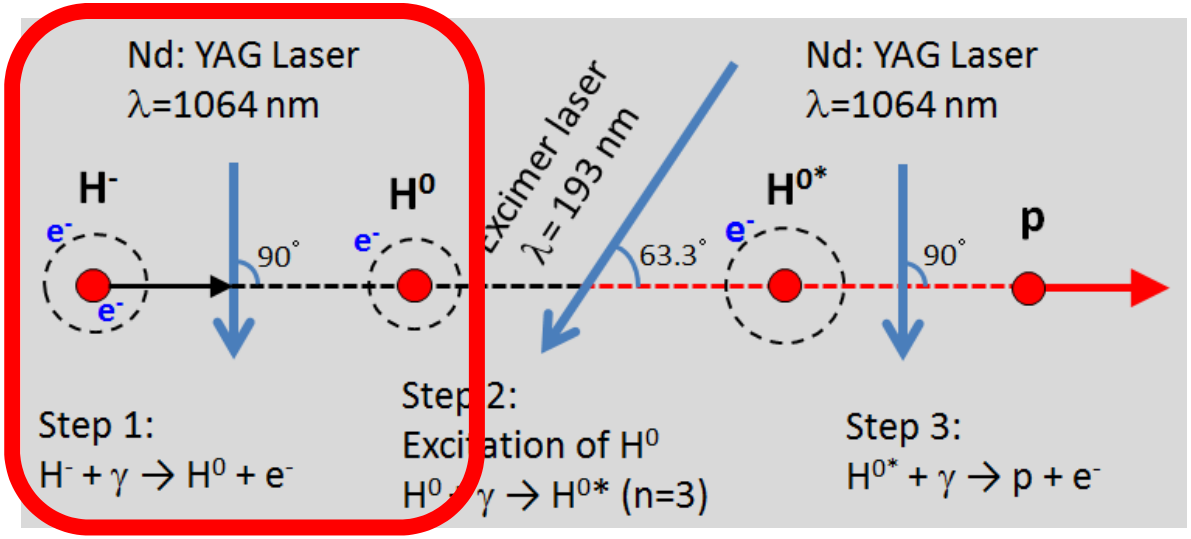


May be the most difficult part for practical application!!

Tentative schedule, steps

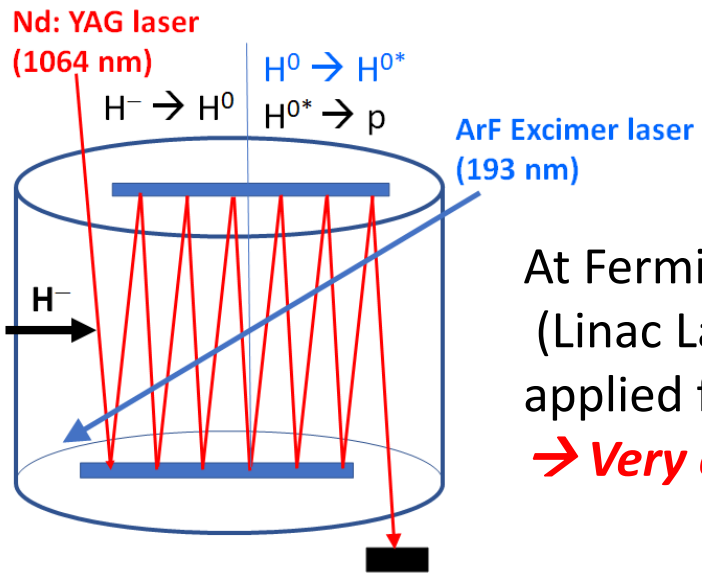


★ The H^- neutralization study first. JFY 2018 goal.

★ **Full scale experiment, POP demonstration: JFY 2019**

★ Setting/placing the laser station for the POP demonstration is one big issue.

Application of 2 mirror cavity (like Fermilab) for reducing individual laser pulse energy



David E. Johnson, Fermilab
Private communication

At Fermilab, 2 mirror cavity system also called zigzag cavity (Linac Laser Notcher) has been developed and successfully applied for the routine operation.

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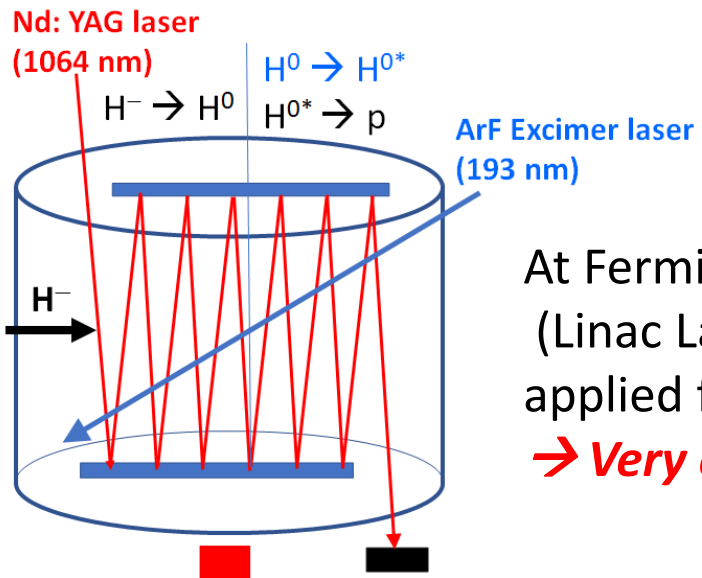

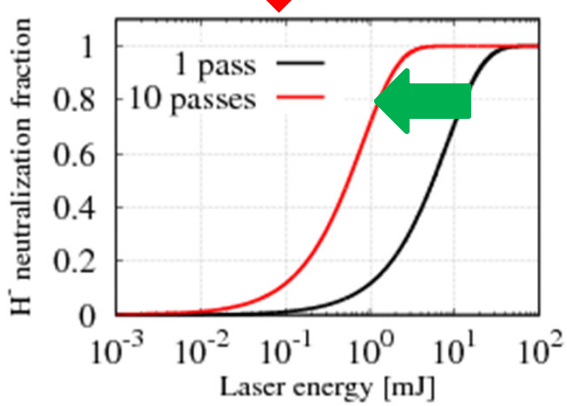

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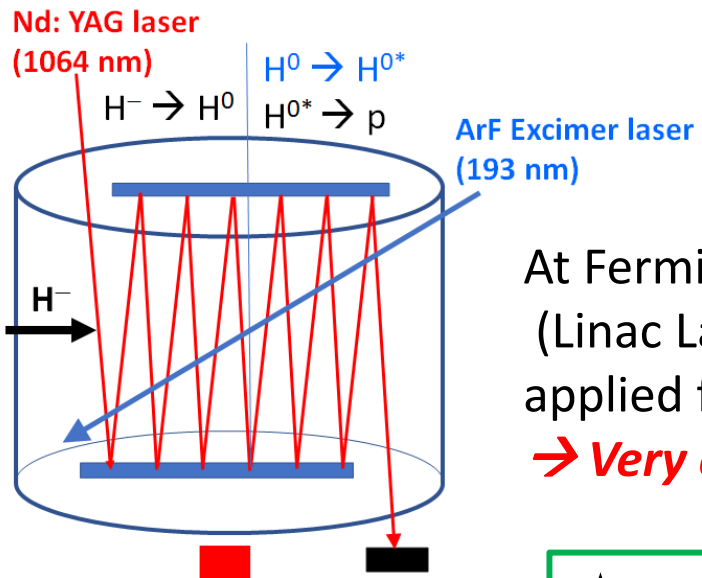

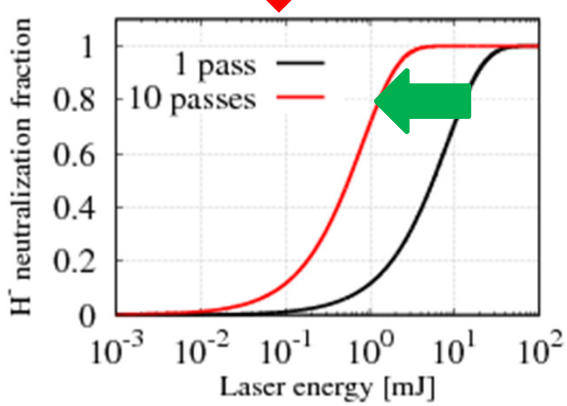

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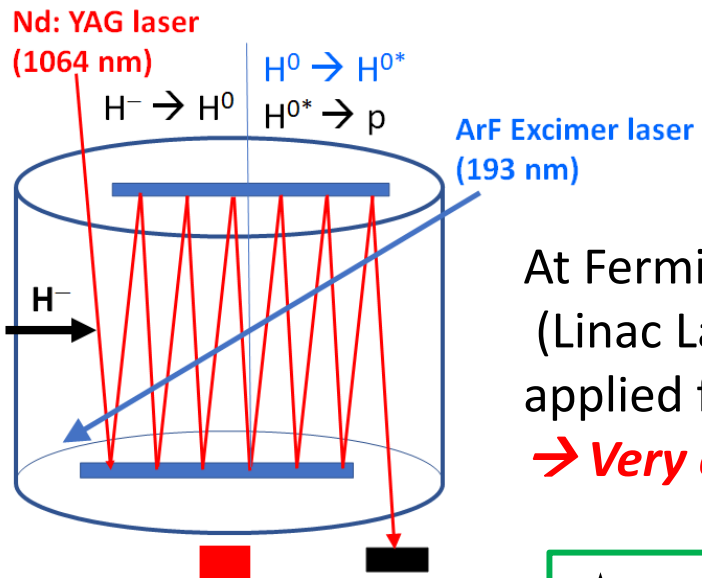

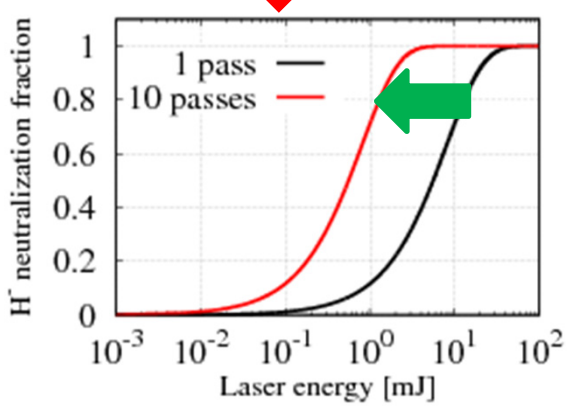

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We made collaboration with Fermilab for the "Laser manipulations of H- beams"

Summary and outlook

■ Preparation for a POP demonstration of 400 MeV H^- stripping to proton by using only lasers at J-PARC is in progress.

■ Laser R&D studies, H^- beam manipulations, numerical simulations are under progress.

■ A single micro pulse (100 ps) is expected to stripped with 90% eff.

■ Measurement technique for one micro pulse has been established.

■ Laser storage ring/other applications should be developed to cover the whole injection period.

■ **The H^- neuralization study in JFY 2018. POP demonstration in 2019.**

Application of Fermilab 2 mirror cavity can be considered to reduce individual laser pulse energy.

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Acknowledgement

We aknowledge many of our J-PARC colleagues for numerous support and encouragement.
K. Hasegawa, K. Yamamoto, N. Hayashi, H. Oguri, K. Kikuchi, K. Suganuma, H. Hotchi, K. Okabe, J. Kamiya, Y. Liu, S. Meigo, H. Takei …….
We thank *Dr. S. Cousineau, Dr. T. Gorlov, Dr. Y. Liu* of SNS and Mr. D. Johnson of Fermilab for their kind cooperation in this study.