An Experimental plan for 400 MeV H^- stripping to protons by using only laser system in the J-PARC RCS

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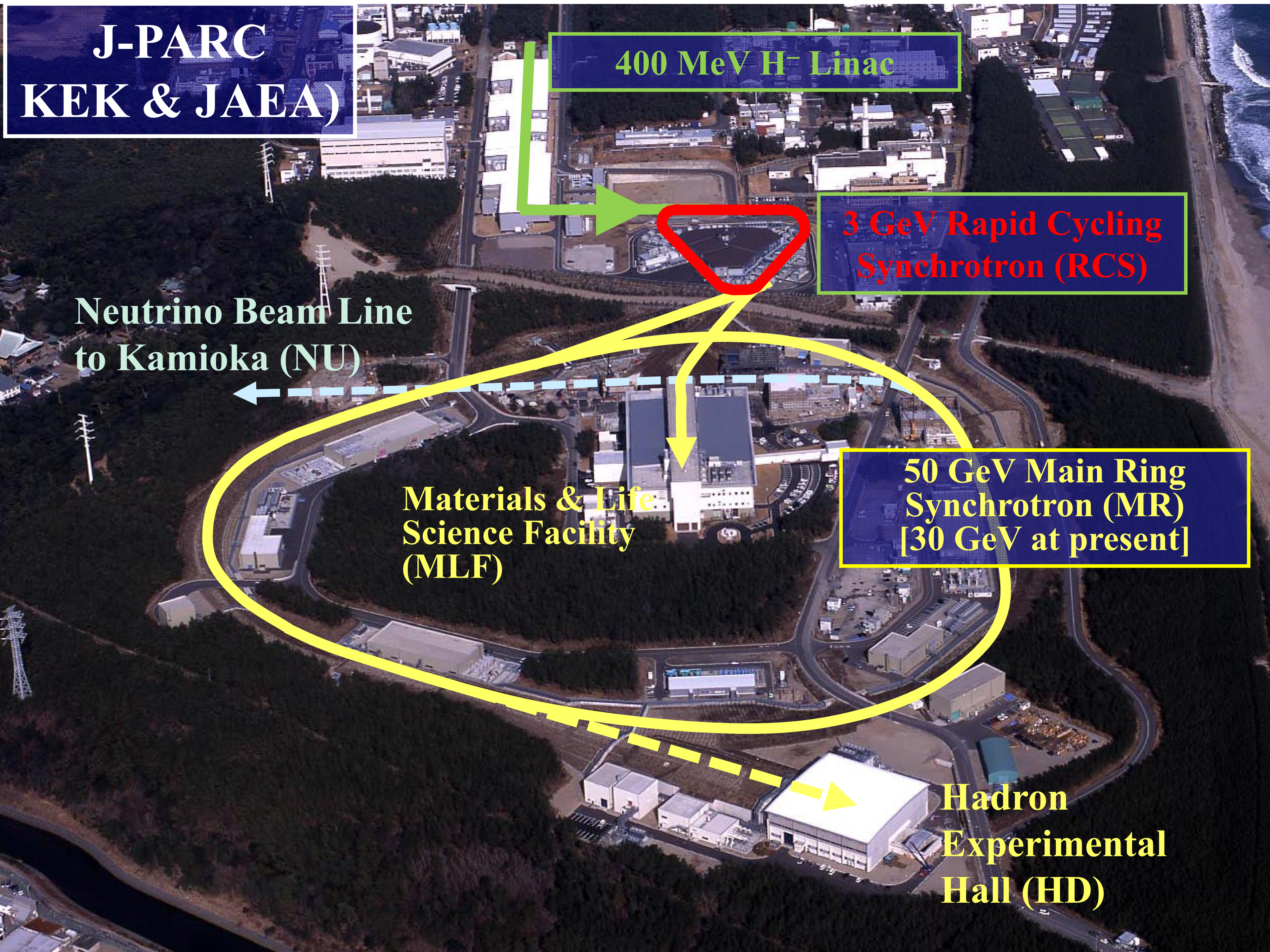
J-PARC (KEK & JAEA), Japan

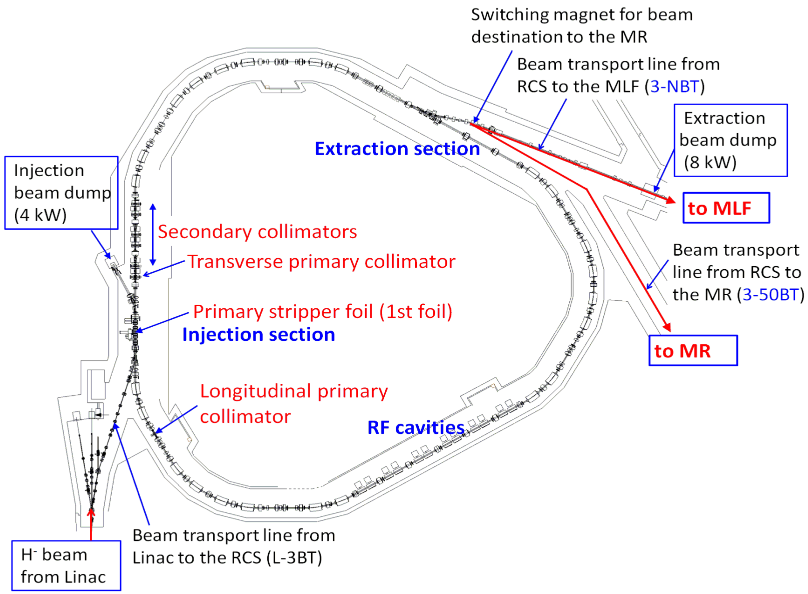
HB2016 @ Malmö, Sweden, 3-8 July 2016

Outline:

1. Brief introduction of J-PARC and the RCS
2. Motivation of H^- laser stripping
3. Principle of H^- stripping by only lasers
4. Experimental strategy, schedule and expected outcome
5. Summary and outlook


J-PARC
KEK & JAEA)
400 MeV H⁻ Linac
3 GeV Rapid Cycling
Synchrotron (RCS)
Neutrino Beam Line
to Kamioka (NU)
Materials & Life
Science Facility
(MLF)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Hadron
Experimental
Hall (HD)

1. Introduction of 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 in the beam studies!

Mid-term plan for beam power upgrade: 1.5 MW

Two big reasons:

① RCS beam sharing to the MLF and MR.

When MR runs at 1s cycle (~2018), RCS beam sharing to MLF becomes: (25-4)/25 = 0.84

RCS equivalent beam power to the MLF should be 1.0/0.84 = 1.2 MW!

② Also planning for a second neutron production target station at MLF.

● Feasible scenario:

Peak current: 50 → 60 mA

Injection pulse: 0.5 → 0.6ms

Stripper foil lifetime may be the most concerning issue!

Motivation

An alternate H^- stripping method other than using stripper foil.
→ Laser stripping of H^- holds the promise of eliminating limitation and issues involved of using stripper foil.

■ *May be hard to maintain stable and longer foil lifetime for 1 MW routine operation at J-PARC RCS.*

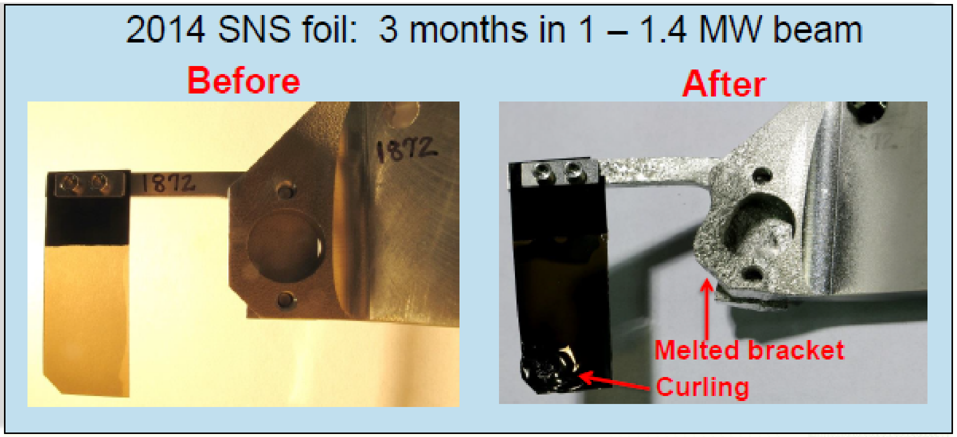
■ *Foil may not survive at 1.5 MW beam power.*

■ Foil scattering beam loss and the resulting high residual radiation at the injection area is already a serious concern for hardware maintenance even at lower beam power.

★ Additional collimators had to placed in the downstream of stripper foil.
★ New design of the injection chicane magnets to install radiation shielding surrounding the foil are in progress.

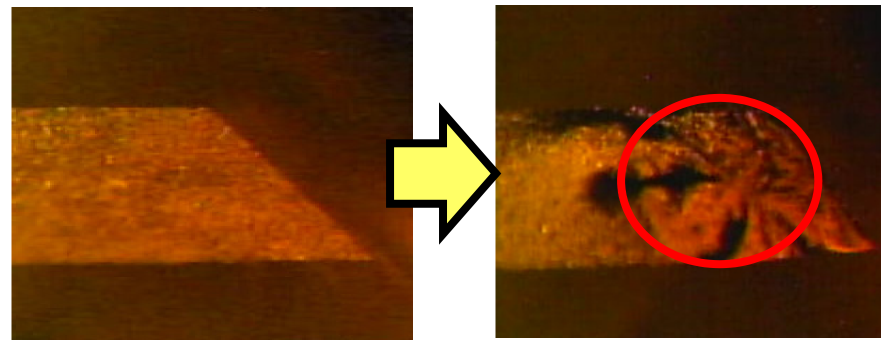
Experience of stripper foil behaviors at the SNS and J-PARC

S. Cousineau (HB2014)



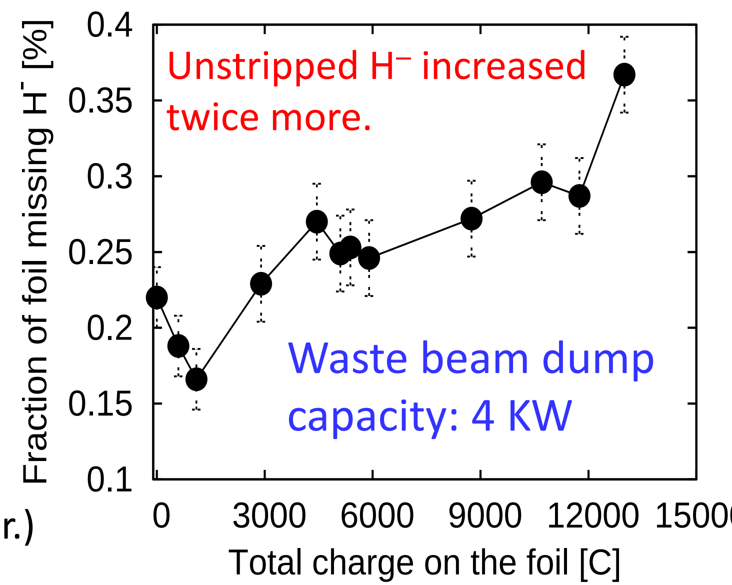
J-PARC: 0.3 MW operation

Avg. foil hit: 10



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 5000 C (based on latest opr.)

→ **Foil lifetime at 1 MW: 8 days!**

Energy deposition and foil temperature
(Comparison between RCS and the SNS for 1 MW beam power)

Accelerator	T [GeV]	tinj [ms]	Foil thickness [μg/cm²]	Avg. foil hit	Energy Depo. (dE) [J]	W_{peak} (DE/t_{inj}) [Watts-peak]
J-PARC RCS	0.4	0.5	340	10	0.2598	**276**
SNS-AR	1	1	300	6	0.0712	**71**

W_{peak} and foil temperature (T):

$W_{peak} \propto T^4$

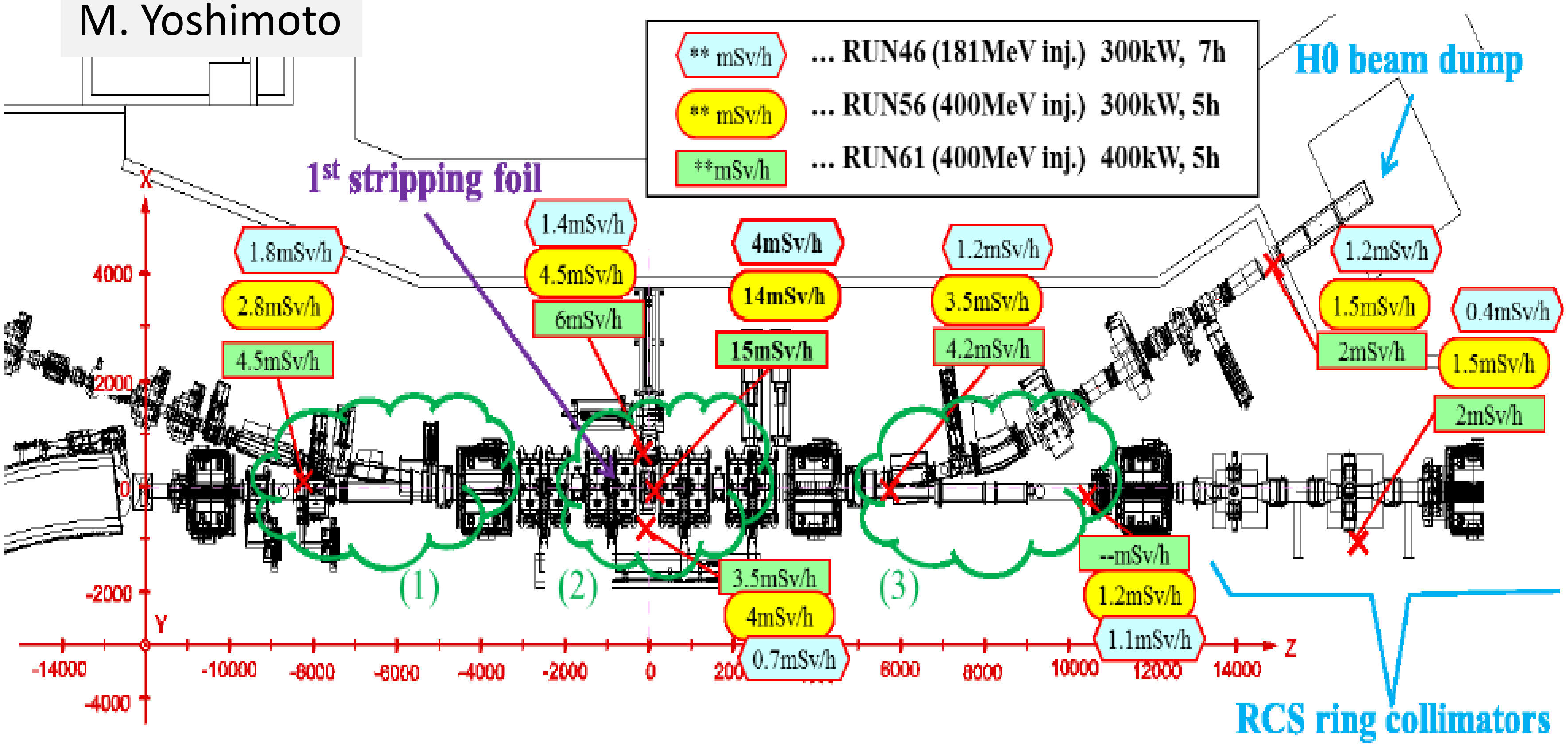
W_{peak} (RCS) / W_{peak}(SNS) = 4

T (RCS) ≈ 1.4 x T (SNS)?

If stripper foil limits the beam power to 1.5 MW at the SNS, it is then may be 1 MW in J-PARC RCS!!

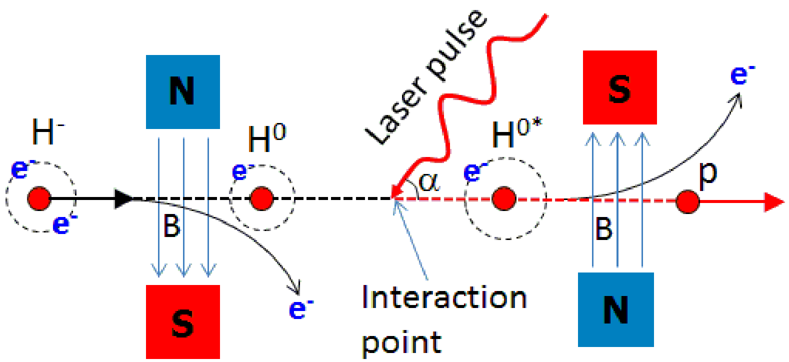
Residual radiation at the RCS injection area

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!

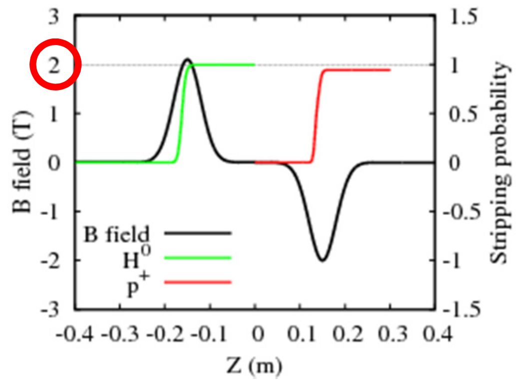
Review of our earlier study for laser assisted H^- stripping at 400 MeV (same as SNS framework)

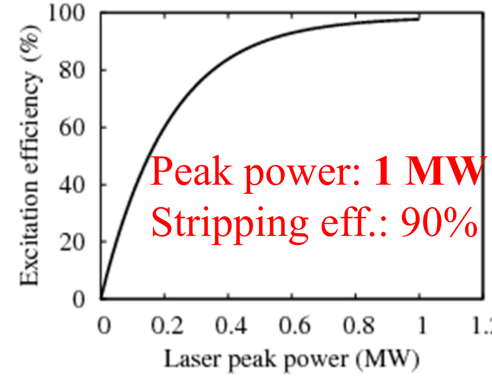


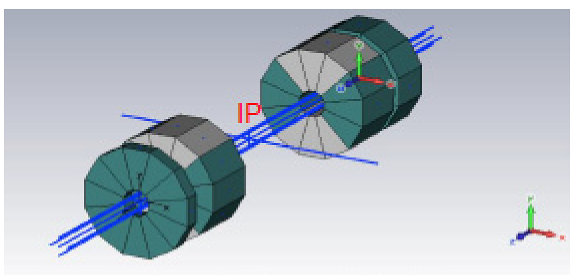
Step 1:
Lorentz stripping
$H^- \rightarrow H^0 + e^-$

Step 2:
Excitation by Laser
$H^0 + \gamma \rightarrow H^{0*}$ ($n \geq 3$)

Step 3:
Lorentz stripping
$H^{0*} \rightarrow p + e^-$





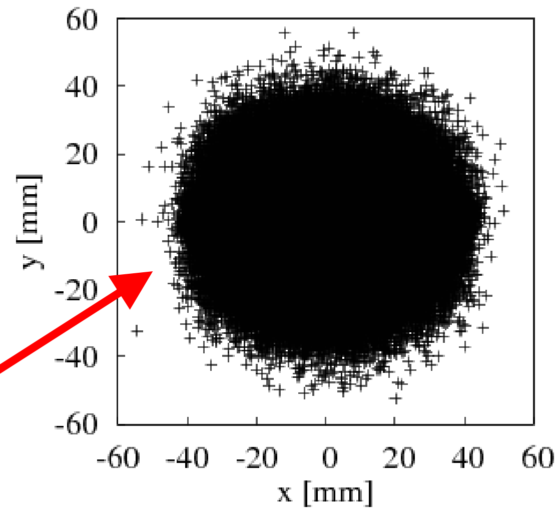


A. Aleksandrov, HB2014
For SNS 1 GeV H^-
Magnetic field 1.2T
Inner radius: 15 mm

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 large!

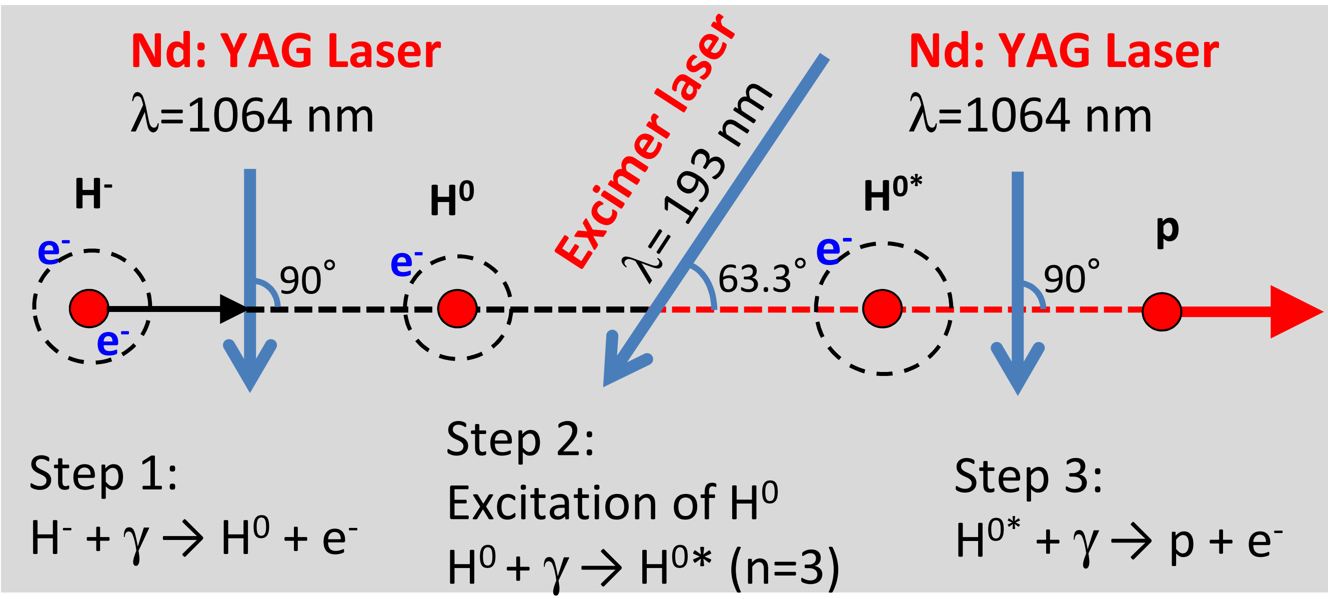
r ~6 cm!

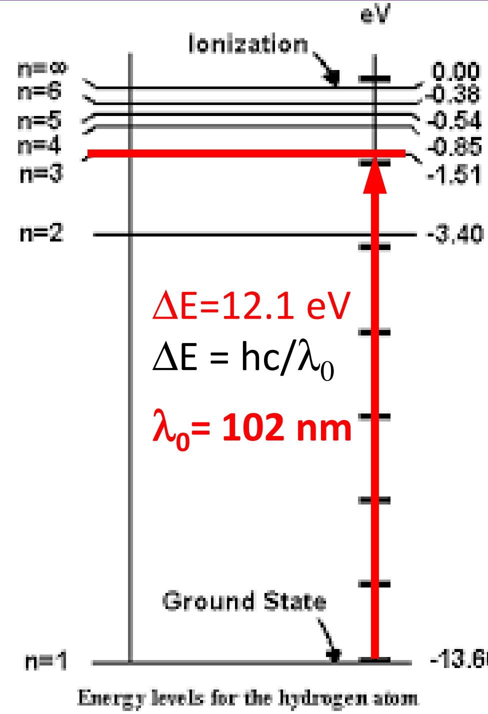


J-PARC RCS: 400 MeV injection for 1 MW.
Beam distribution at the end of injection.
(Simulation: TP: none, LP: full)

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

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



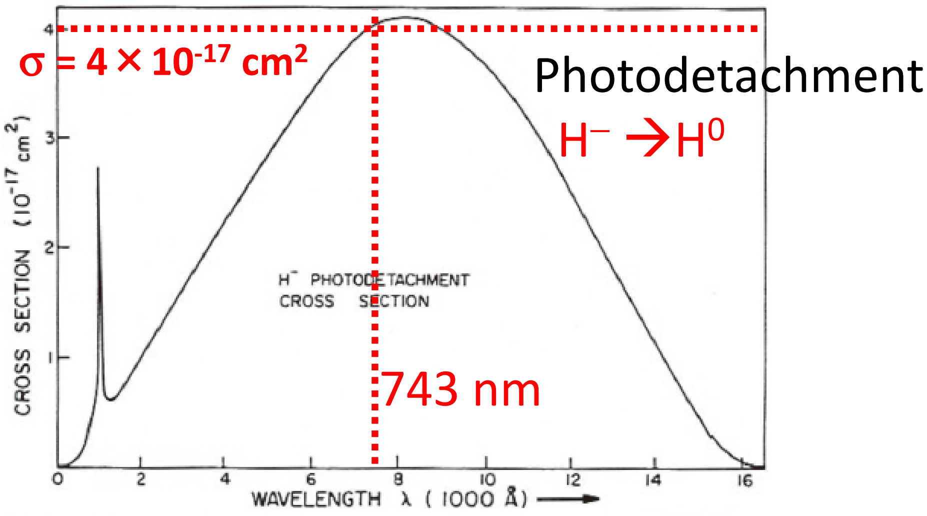


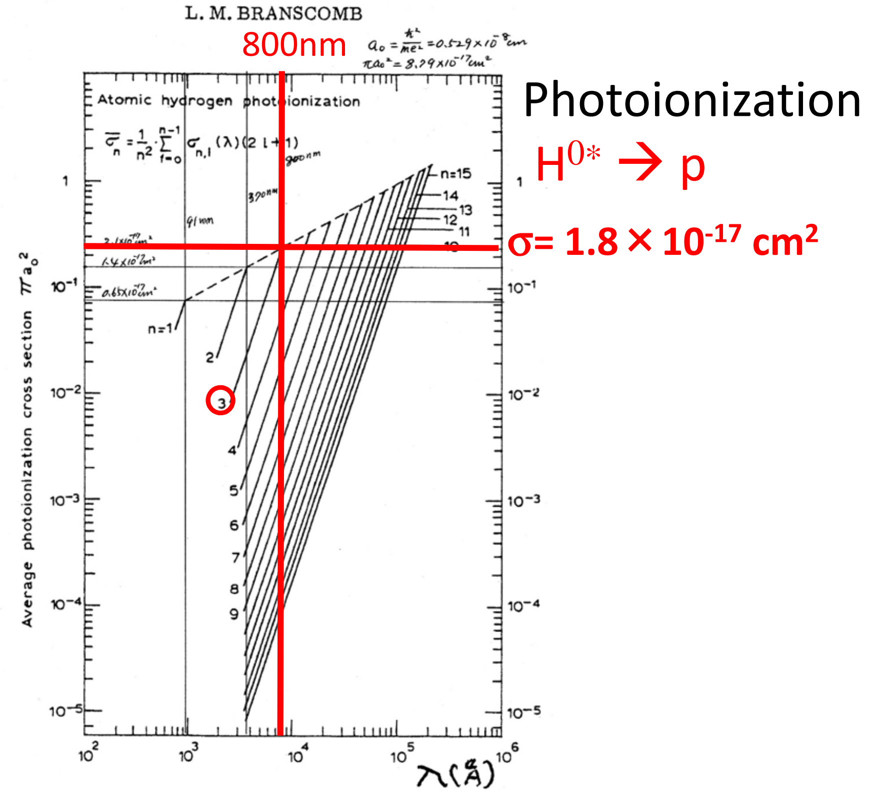
Process	E_{ph} (eV)	λ (nm)	α (deg.)	λ_0 (nm)	Laser
$H^- \rightarrow H^0$	1.67	1064	90	743	Nd:YAG
$H^0 \rightarrow H^{0*}$	12.1	193	63	102	Excimer (ArF)
$H^{0*} \rightarrow p$	1.67	1064	90	743	ND:YAG

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

Photodetachment, Photoionization cross sections and the corresponding laser power

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





E_{ph} = 1.67 eV @ 743 nm

Saturation density Φ^s in PRF

$\Phi^s = (E_{ph}/\sigma) = 6.7 \times 10^{-3}$ J/cm²

r(H⁻) = 1mm, τ(H⁻)=30 psec

τ_i(collision) = 10 psec, τ_l(laser) = 40 psec

E(laser) = $(\Phi^s/\gamma) \times (\pi r^2) \times (\tau_l/\tau_i)$

= **0.6 mJ → 15 MW**

E(laser) = **1.3 mJ**

→ 33 MW

Excitation of H^0 (n=3)

Laser peak power for H^0 excitation:

-- S. Danilov, PRST-AB 6, 053501 (2003)

$$P_{peak} = \ln(1/\delta)\hbar^2\varepsilon_0 c^2 \kappa \omega_0 \sin\alpha \Delta / 2\mu^2_{1\to n}\gamma(1+\beta\cos\alpha)^2$$

Where, δ= ratio of unexcited and excited atoms.

For 400 MeV H^-:
P_{peak} = ×2 of SNS
= 2 MW!

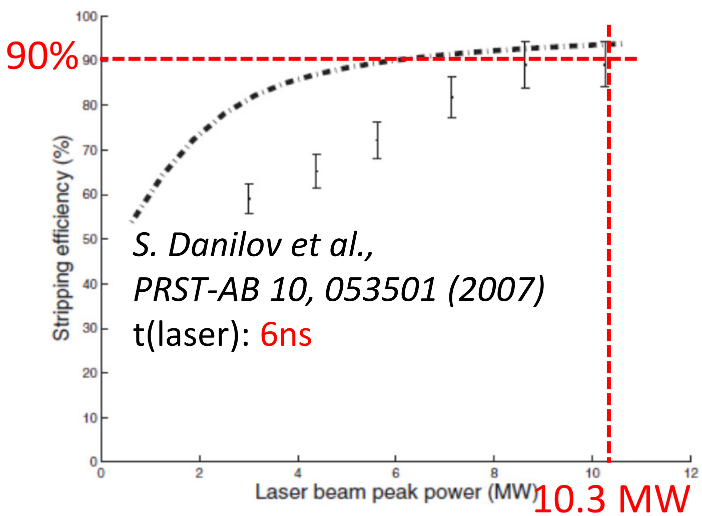
$$P_a = 10^6\ \mathrm{W} \times 50 \times 10^{-12}\ \mathrm{s} \times 40.25 \times 10^6\ \mathrm{Hz} \times 0.06$$

Laser peak power (1MW)

-- S. Danilov, PRST-AB 10, 053501 (2007)

By utilizing dispersion derivative.

D' = – (β + Cosα)/Sinα = –2.55



Choice of the laser for the POP experiment:

-- Excimer laser by GAM LASER INC.

http://www.gamlaser.com/EX350laser.htm

EX350A ArF Excimer laser specifications:

λ = 193 nm, Pulse length = 20 ns (σ= 8ns)

Energy (max): 150 mJ

➔ P_{peak} > 7.5 MW

Alternate option: 5th harmonic Nd:YAG laser beam. UV light power could be dropped to 1/10 IR light but recently high power lasers are commercially available.

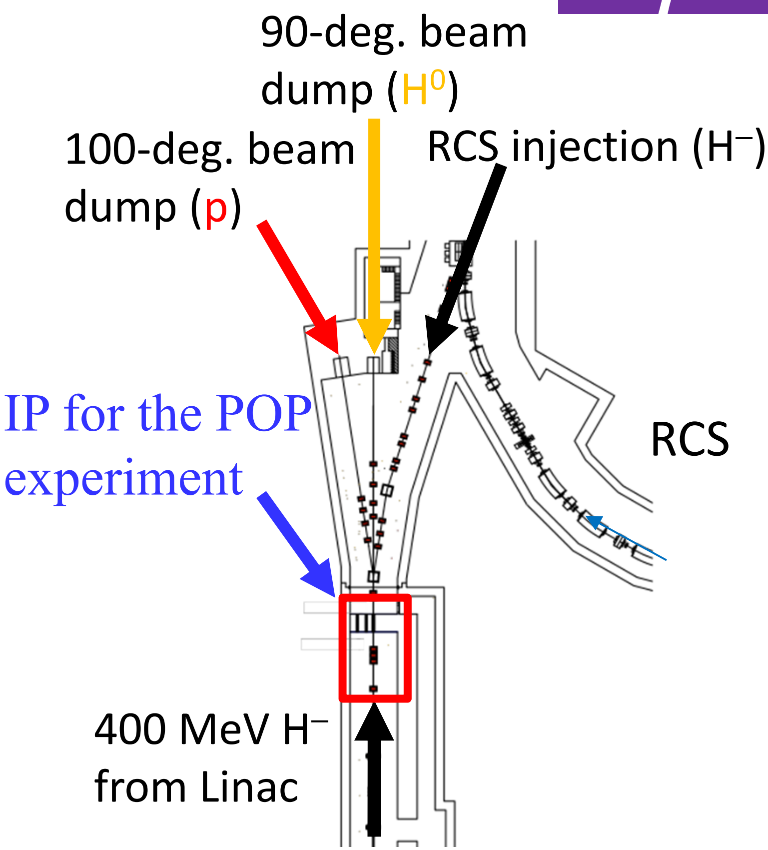
Table of required laser parameter in many labs
Courtesy: David E Johnson, FNAL
J-PARC parameters added (Pranab)

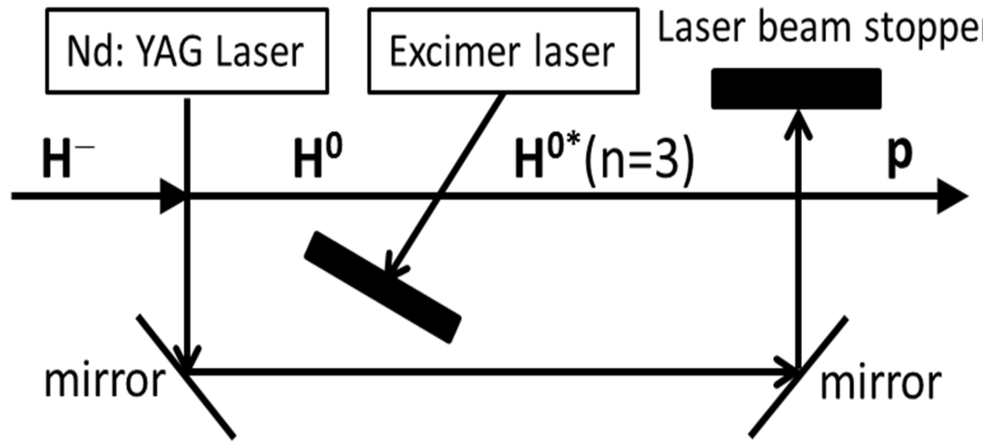
Typical Laser System Requirements (*preliminary*)

Parameter / Facility	SNS LS	CERN LS	FNAL LS	J-PARC	FNAL Notching	Chopper	H- beam laser Diagnostics
Time Frame/status	Current / R&D	Future	Future	Future	Current/R&D	Conceptual	Current
H- beam energy	1 GeV	4 GeV	8 GeV	400 MeV	750 KeV	Few MeV	varies
Wavelength	355 nm	1 um	1 um 2 um	<230 nm	1 um	1 um	typically 1 um
Micropulse Frequency	402.5 MHz	352 MHz	162.5 MHz	324	201.25 MHz	162.5 MHz 325 MHz	few hundred MHz
Micropulse duration	~50 ps	90 ps	~30 ps	~50ps	1.5 ns	1 -2 ns	fs (longitudinal) ns (transverse)
Micropulse energy	~300 uJ(IR) 50 uJ (UV)	450 uJ	400 uJ 80 uJ	50uJ (UV)	2 mJ	260 uJ	10's uJ to 10's mJ
Micropulse Peak power	1 MW	5 MW	5.5 MW 1.1 MW	1MW	1.3 MW	210 kW	1 -10 MW
Burst Frequency (rep rate)	60 Hz	1 Hz	10 Hz	25 Hz	458 kHz	~ CW	10's Hz to MHz
Macropulse width	1 ms	2.4 ms	4.3 ms	0.5ms	60 ns	NA	NA
Macropulse energy	120 J (IR) 20 J (UV)	300 J	~250 J ~50J	8.3 J (UV)	27 mJ	NA	NA
Macropulse (average) power	7.2 kW (IR) 1.2 kW (UV)	10 kW	65 kW 13 kW	0.21 kW (UV)	11 kW	42 kW @162 kHz 84 kW@325kHz	10 W to 1 kW

We are planning for a proof-of-principle demonstration!

Setup and schedule for the POP experiment





Setup for the POP experiment

We can simultaneously measure all three charge fractions in three separated beam lines in the downstream of IP.

Tentative schedule: October, 2017

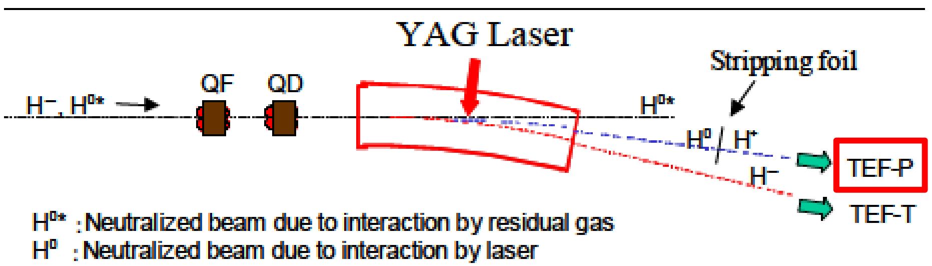
Available lasers for the POP experiment

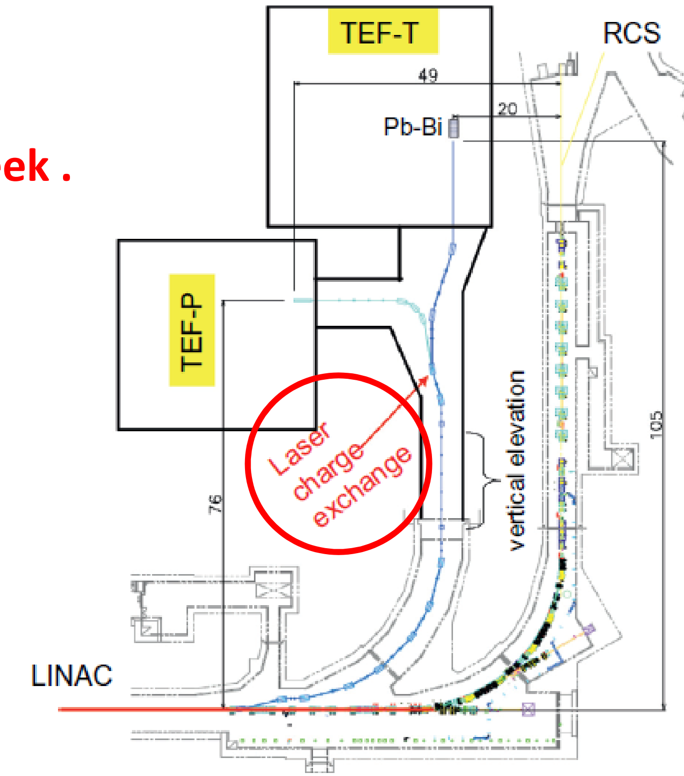
1. Nd: YAG 1064 nm, 5-9 ns (FWHM), 600 mJ
-- Under repair
Purpose: 1st ($H^- \rightarrow H^0$) and 3rd ($H^{0*} \rightarrow p$) conversions.

J-PARC ADS facility beamlines
Shin-ichiro Meigo
J. of Nucl. Mat. 450, (2014) 8-15

2. TEF-P of ADS facility. Using for $H^- \rightarrow H^0$
Nd: YAG 1064 nm, 5-9 ns (FWHM), 1.6 J
Test experiment for 3 MeV H^- just carried out last week .
$H^- \rightarrow H^0$ at the exit of test RFQ. *(S. Meigo, H. Takei..)*
→ *Has to be tested at 400 MeV*

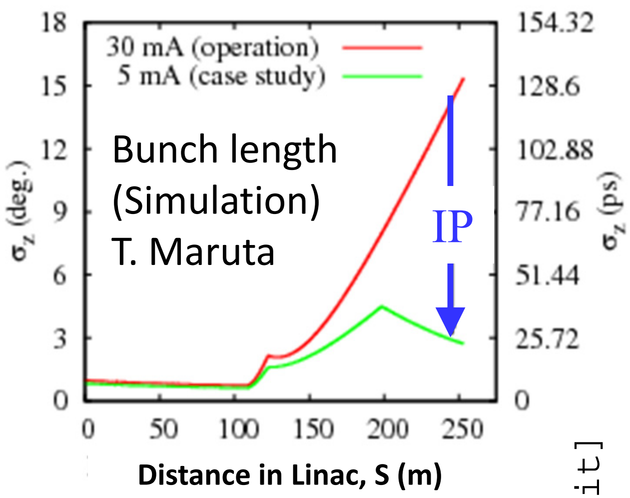
Our purpose: $H^0 \rightarrow H^{0*}$ by using 5th harmonic beam

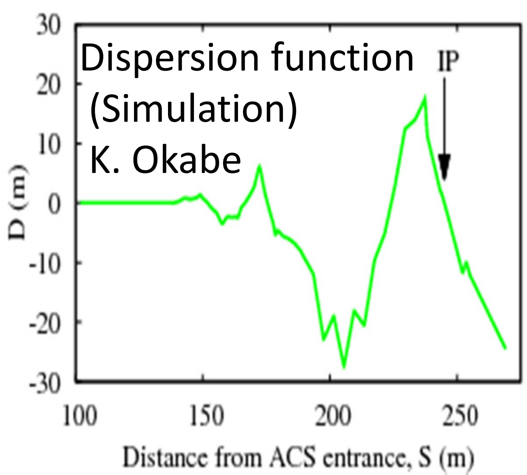




We also plan to buy an excimer laser to use for the H^0 excitation.

H^- beam optimization and expected stripping efficiency



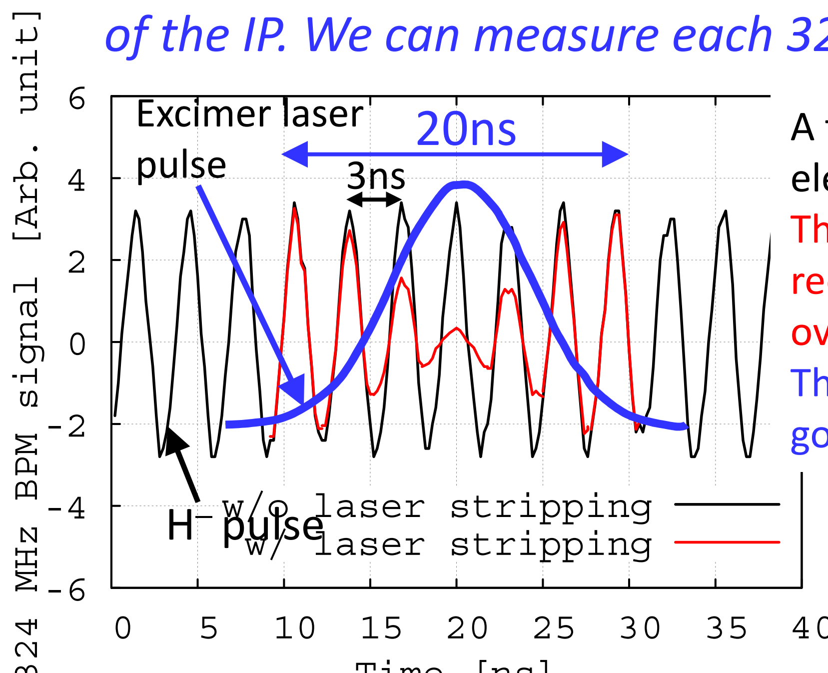


Scenario:

- TEP-P Nd:YAG laser (1.6J) for the 1st and 3rd steps.
- Excimer (EX350A) ArF laser (150mJ) for $H^0 \rightarrow H^{0*}$

Expect 90% overlap efficiency for at least 1 micro pulse (30 psec) of the H^- beam.

There are 324 MHz BPMs, FCTs and SCTs downstream of the IP. We can measure each 324 MHz pulse.



A typical 324 MHz BPM electrode signal.

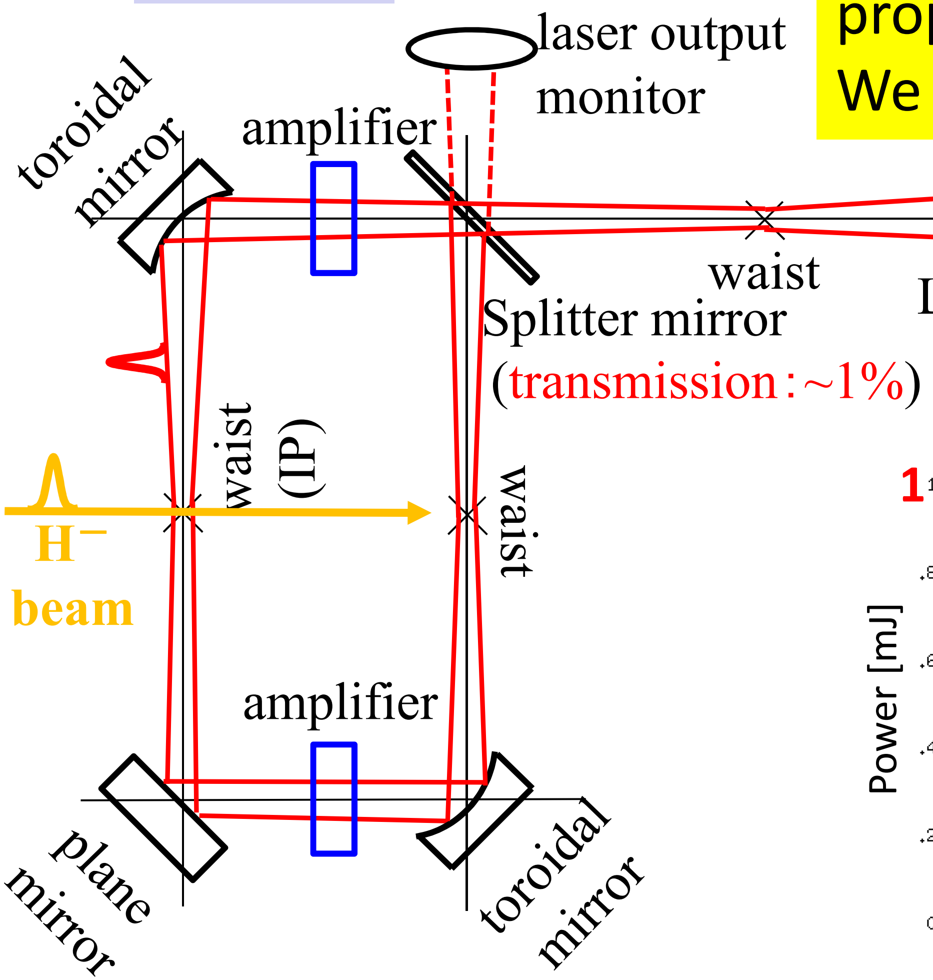
The H^- beam signal will be reduced in the laser pulse overlapping region.

The stripping H^- in the L3BT goes to the 100 deg. dump.

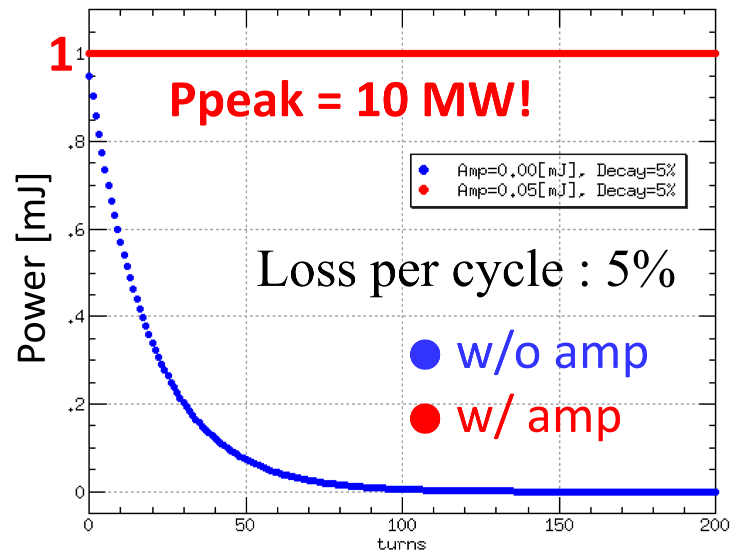
How to cover 0.5 ms (~10^5 micro pulses) for practical application?

H. Harada

Answer: Laser storage ring, originally proposed by I. Yamane.
We have started detail R&D studies.



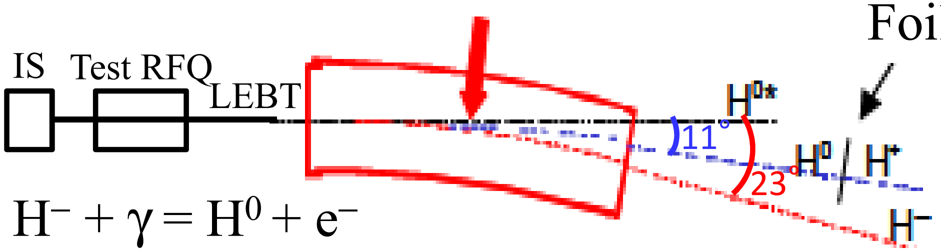
100mJ, 100psec, 25Hz



May be the most difficult part for practical application!!

TEF-P progress
Photodetachment of 3 MeV H⁻ (first data)

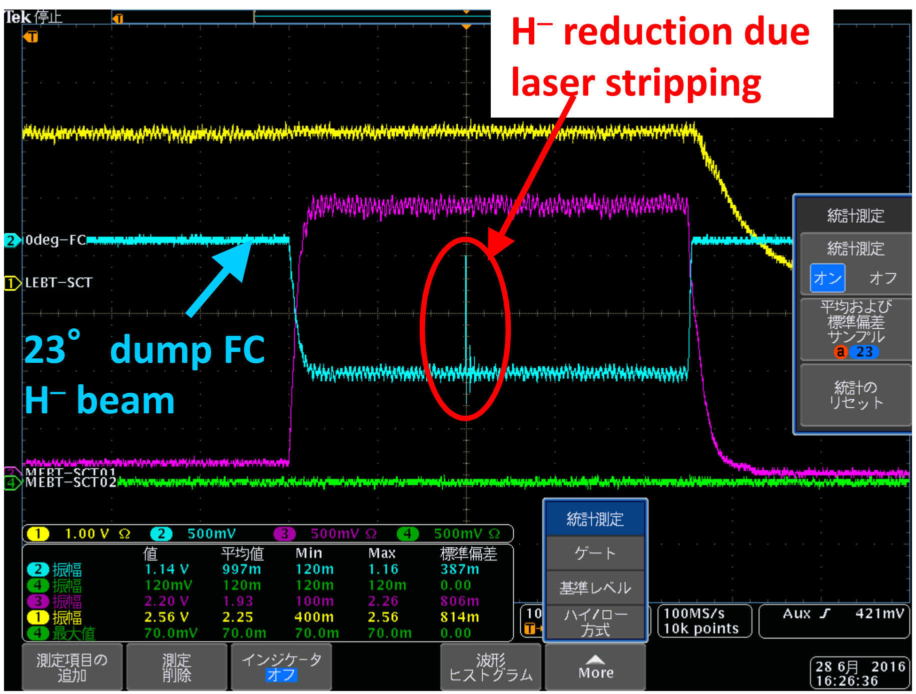
Courtesy: S. Meigo, H. Takei..

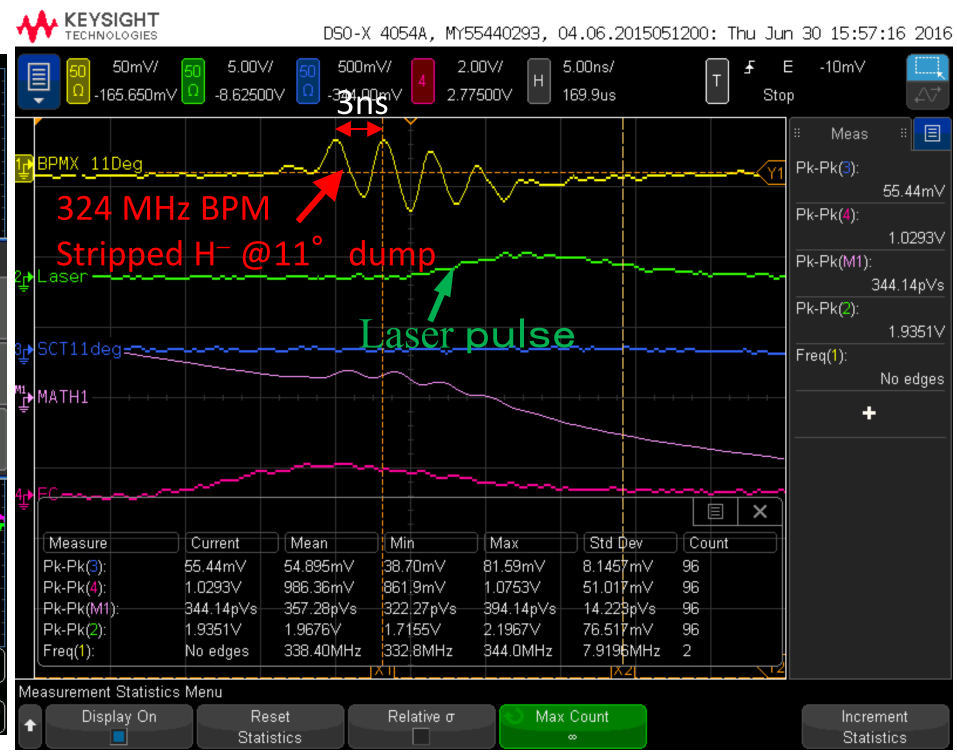


$$H^- + \gamma = H^0 + e^-$$

Nd: YAG laser: 0.8 J, 20 ns

Successfully demonstrated single electron stripping of H⁻ for several micro pulses!





Summary and outlook

■ We proposed an effective way to realize H^- stripping to protons by using only laser system.

■ We have also planned for a proof-of-principle demonstration for 400 MeV H^- at J-PARC RCS.

■ At least a single micro pulse of 30 psec is expected to stripped with 90% efficiency.

■ Laser storage ring could be the ultimate solution to cover the whole injection period.

◎ First successful trial of H^- Photodetachment by laser is a very good sign for us.

Acknowledgement

It's our opportunity to acknowledge many of our J-PARC colleagues for support and encouragement on the present work and our future plan.

K. Hasegawa, K. Yamamoto, K. Kikuchi, K. Suganuma, N. Hayashi, H. Hotchi, M. Yoshimoto, K. Okabe, J. Kamiya, Y. Miura, T. Maruta, Y. Liu, S. Meigo, H. Takei….

We thank *Dr. S. Cousineau, Dr. T. Gorlov and Dr. Y. Liu* of SNS for many fruitful discussions and advices on our present effort.