US-Japan Collaboration on high intensity neutrino beams

● Laser manipulation of H^- beams

Brief status at J-PARC &

Progress of 400 MeV H^- striping to protons by using only lasers –

Pranab K. Saha

On behalf of J-PARC laser stripping group

US-Japan Collaboration meeting @ Fermi National Accelerator Lab, USA

2018/Mar/28-29

Laser manipulation of H^{-} beams

--- status at J-PARC

Three major activities:

-- Proof-of-principle (POP) demonstration for 400 MeV H- stripping to protons by using only lasers.
Goal to realize laser stripping H- charge exchange system.

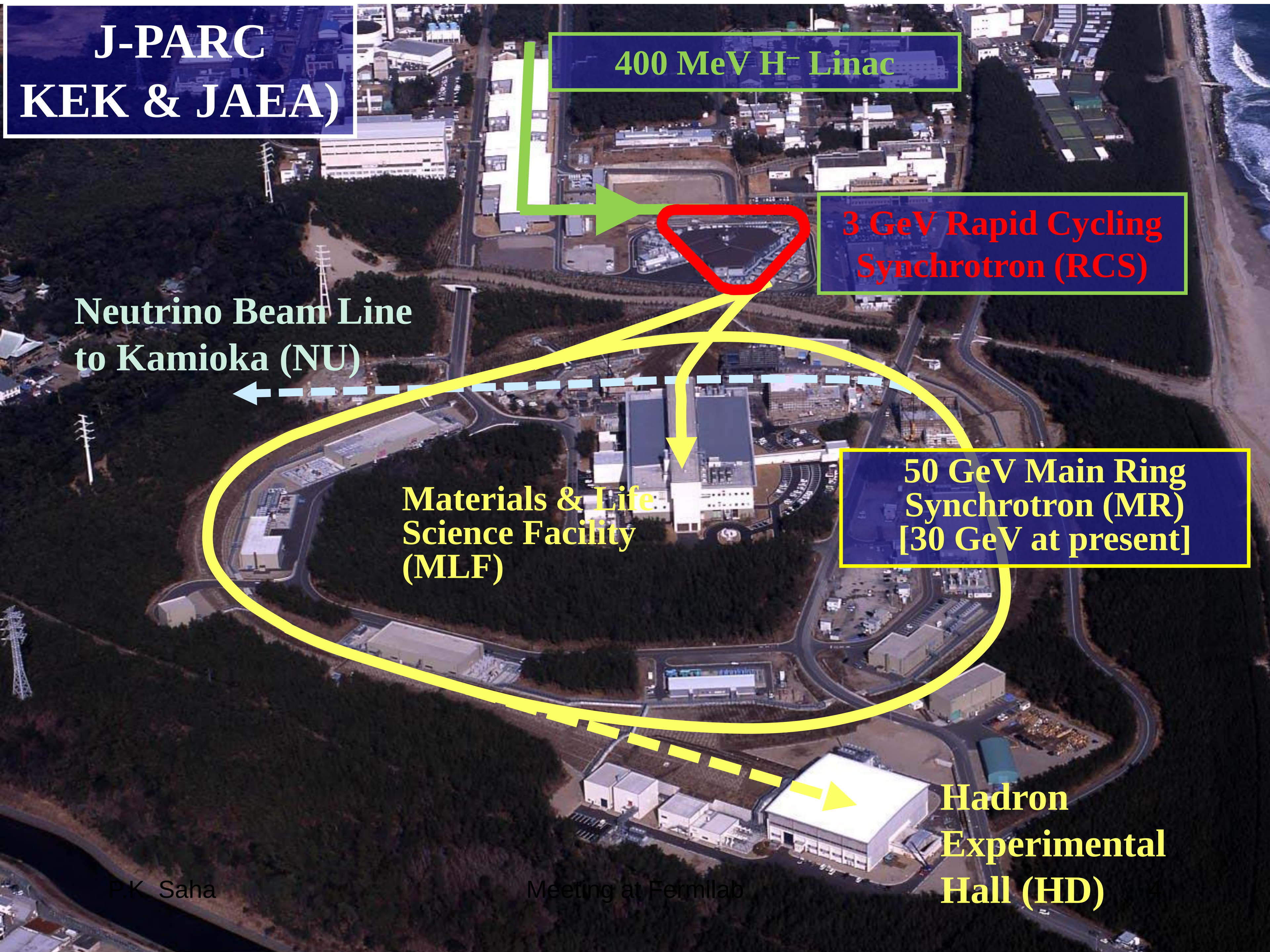
-- Developments of H^{-} neutralization system by using laser for J-PARC TEF.
R&D studies at 3 MeV H- now. To be tested for 400 MeV H- and put the system for operation.

-- Multi-laser-wire diagnostic system for measuring H^{-} beam profiles at J-PARC.
R&D stage, Laser stripping chamber will be used.

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, progress to date
5. Summary and outlook

J-PARC
KEK & JAEA)



400 MeV H⁻ Linac

3 GeV Rapid Cycling Synchrotron (RCS)

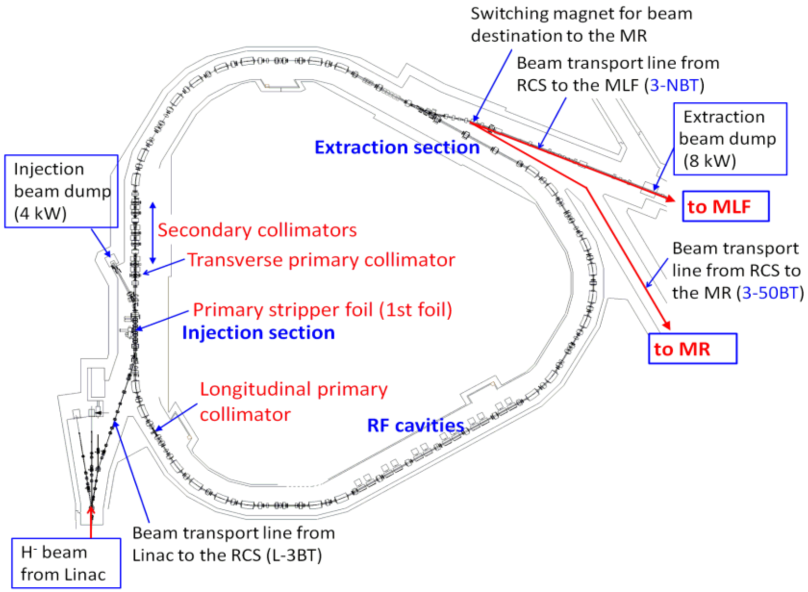
Neutrino Beam Line to Kamioka (NU)

Materials & Life Science Facility (MLF)

50 GeV Main Ring Synchrotron (MR) [30 GeV at present]

Hadron Experimental Hall (HD)

1. Introduction of J-PARC 3-GeV RCS



Layout of J-PARC 3-GeV RCS

- *Multi-turn H^- stripping injection.*

(stripping efficiency: 99.7% design)

- *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 to **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.

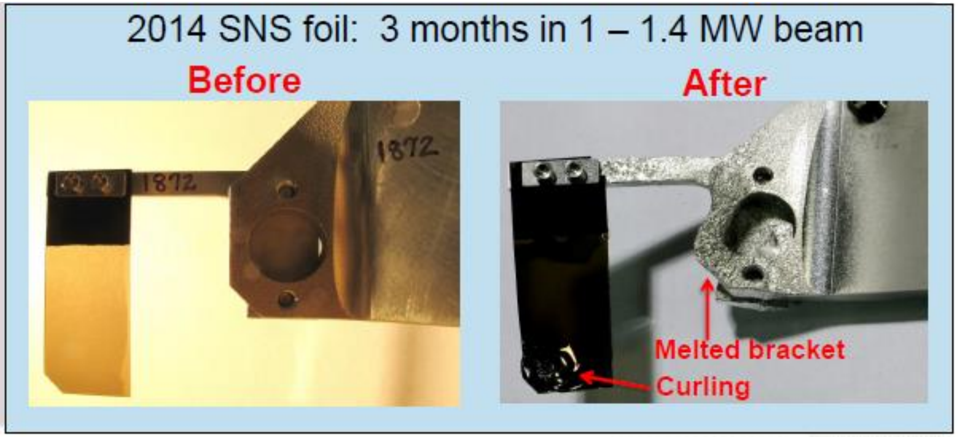
Reasons:

- ■ *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 installed at 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)

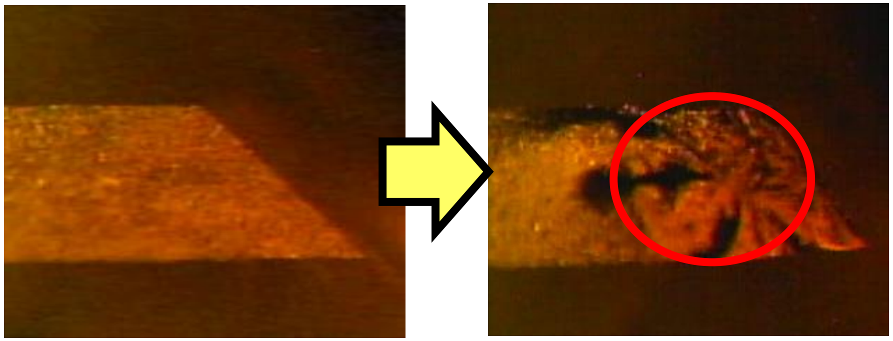


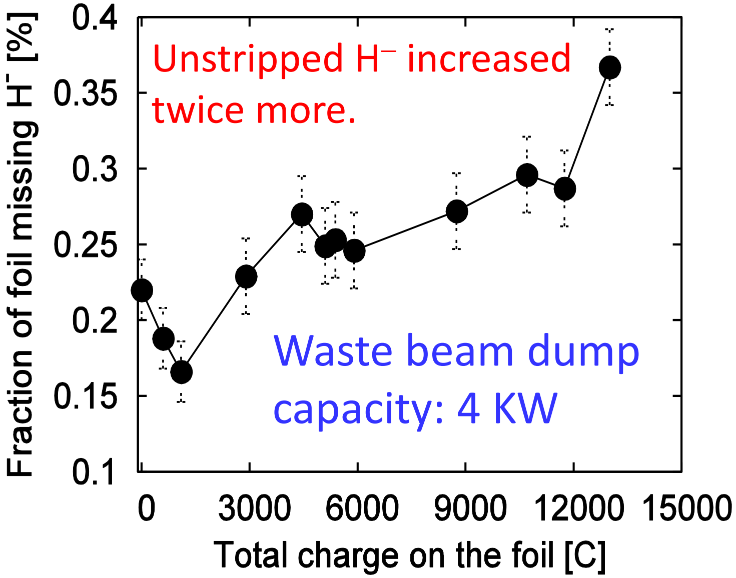
Foil hit at 1 MW operation (estimation)

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 at best!!**

J-PARC: 0.3 MW operation
Avg. foil hit: 10




Unstripped H^- increased twice more.

Waste beam dump capacity: 4 KW

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

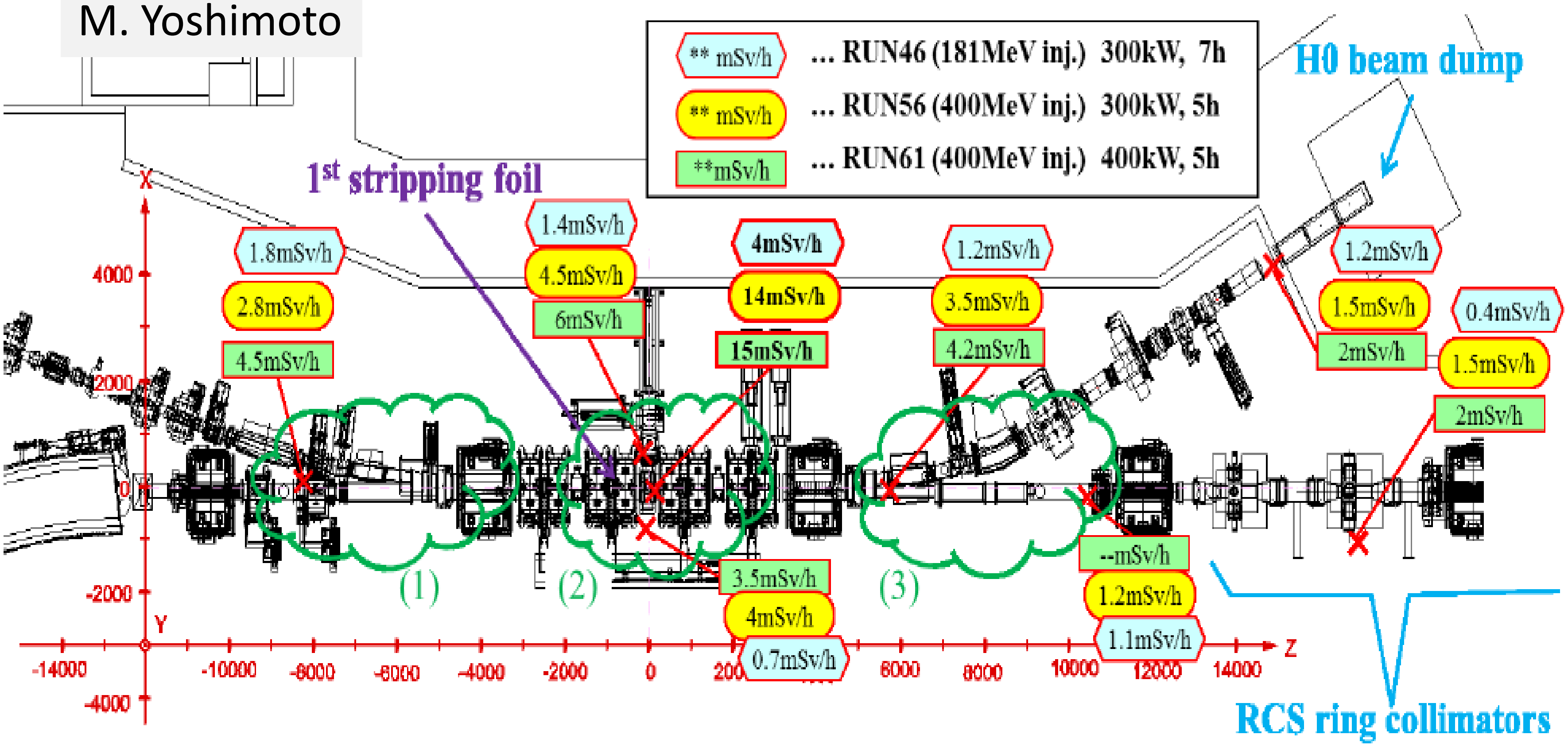
T (RCS) ≈ 1.4 x T (SNS)?

(Rep rate not taken into account)

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

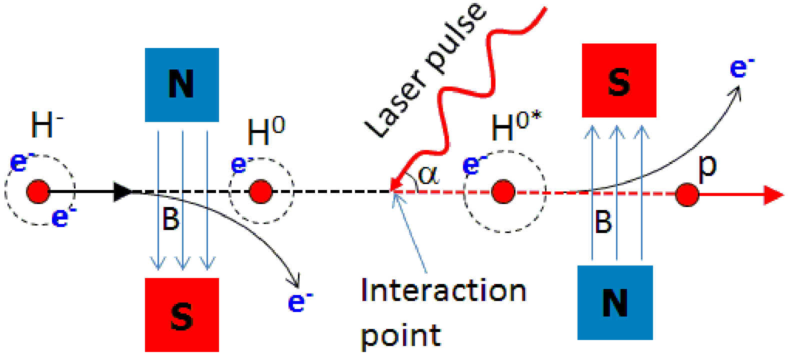
Residual radiation at the RCS injection area

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!

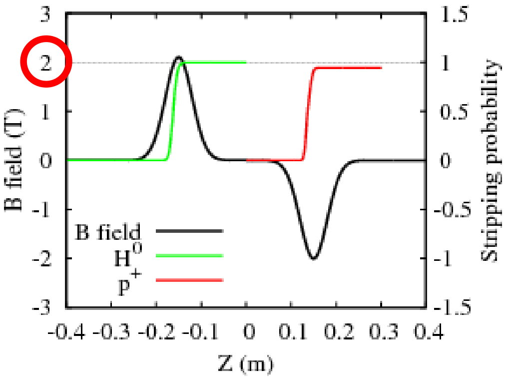
Review of our earlier study for laser assisted H^- stripping at 400 MeV (same as SNS framework)

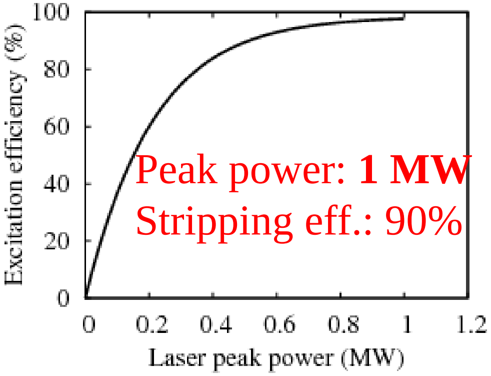


Step 1:
Lorentz stripping
$H^- \rightarrow H^0 + e^-$

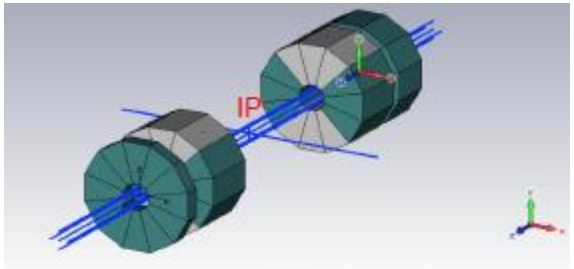
Step 2:
Excitation by Laser
$H^0 + \gamma \rightarrow H^{0*}$ (n≥3)

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





Peak power: **1 MW**
Stripping eff.: 90%

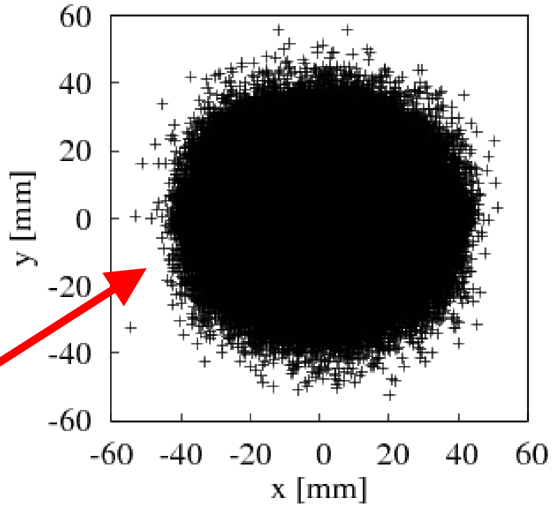


A. Aleksandrov, HB2014
For SNS 1 GeV H^-
Magnetic field 1.2T
Inner radius: 0.15cm

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!

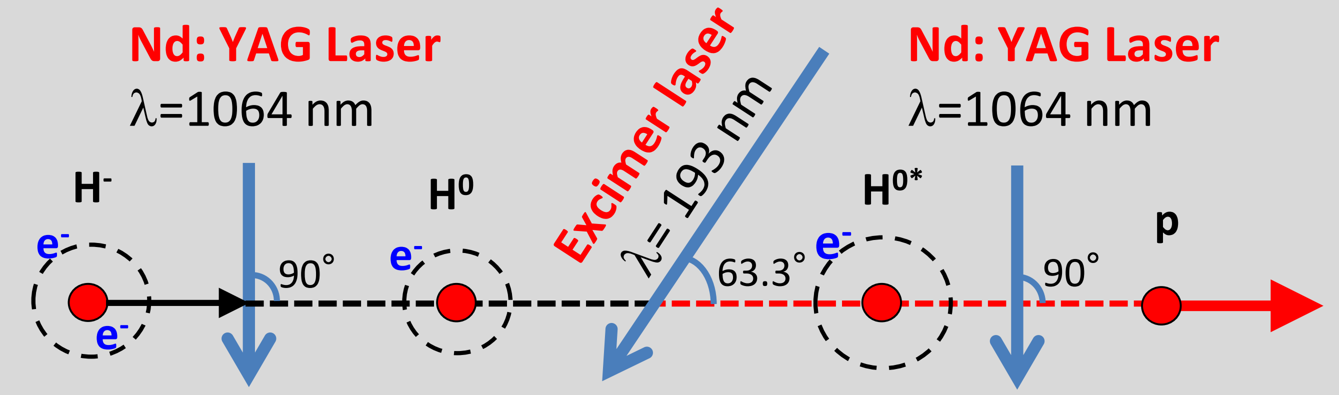
r ~5 cm!



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

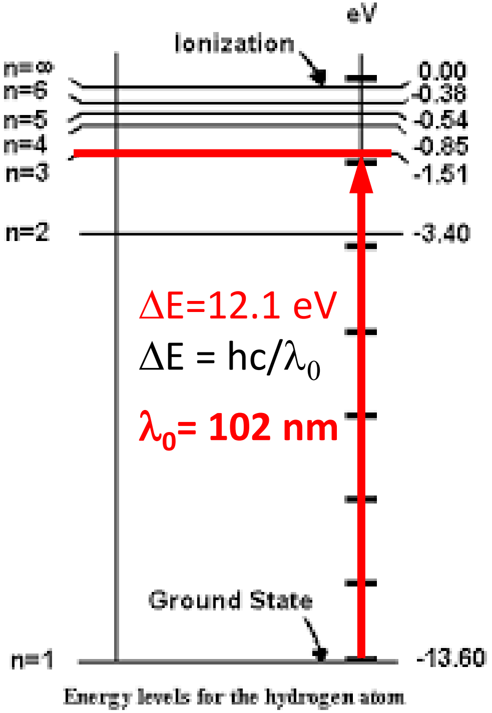
Isao Yamane, Hiroyuki Harada, Saha Pranab and Shinichi Kato
PASJ, Vol. 13, 2016, 1-11 (in Japanese)



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

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

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



ΔE=12.1 eV
$\Delta E = hc/\lambda_0$
λ_0= 102 nm

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

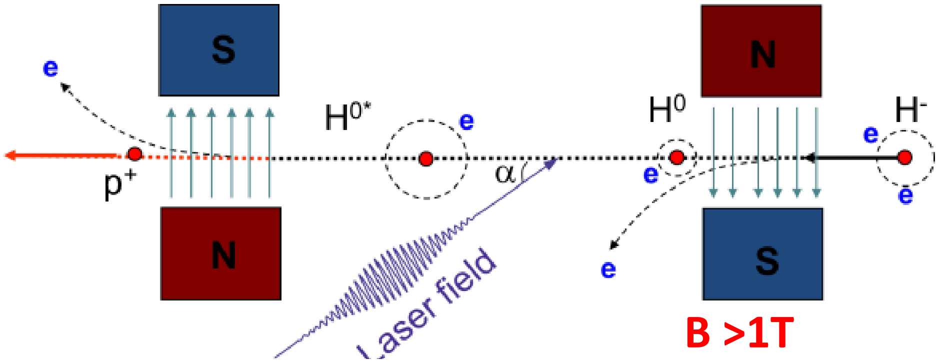
Doppler effect of the 400 MeV H^- beam:
$\beta = 0.713$, $\gamma = 1.426$
$\lambda = \lambda_0 (1 + \beta \cos\alpha)\gamma$

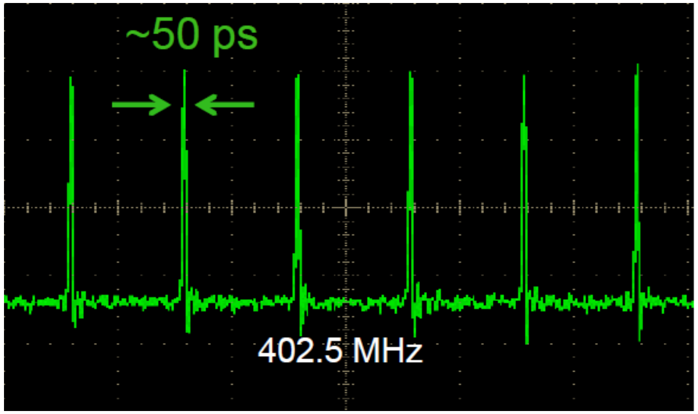
SNS demonstrated 90% stripping for 1 GeV 10 μs H^- pulse

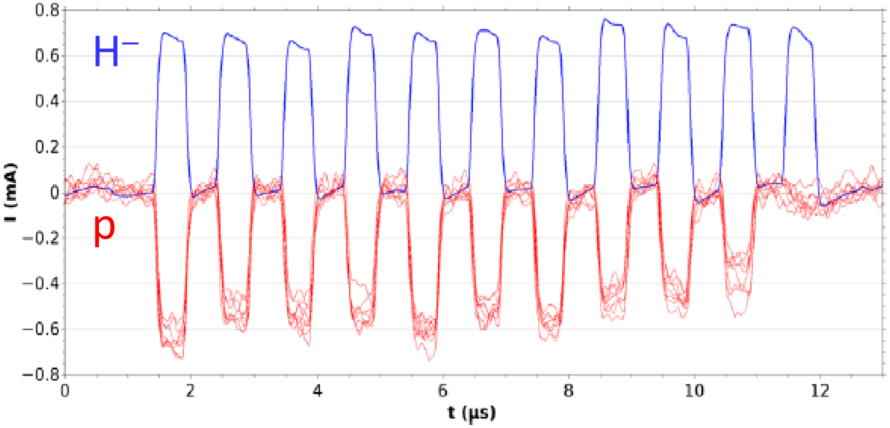
PRL **118,** 074801 (2017) PHYSICAL REVIEW LETTERS

SNS, Oak Ridge

First Demonstration of Laser-Assisted Charge Exchange for Microsecond Duration H^- Beams







Stripping efficiency: Achieved > 90%

Laser pulse and peak power:

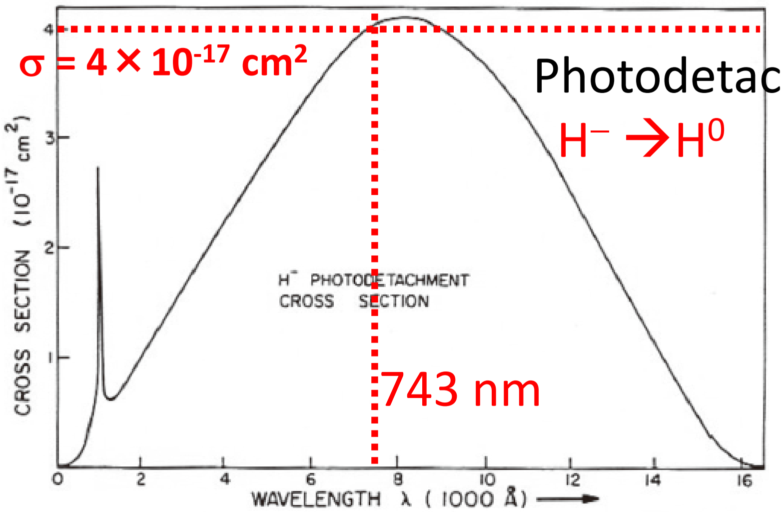
Nd:YAG laser of 1064 nm
→ 3rd harmonic conversion (355 nm)
Synchronized to 402.5 MHz H^- pulses.

Pulse energy and width: 50μJ, 50ps

➔ **Peak power: 1 MW**

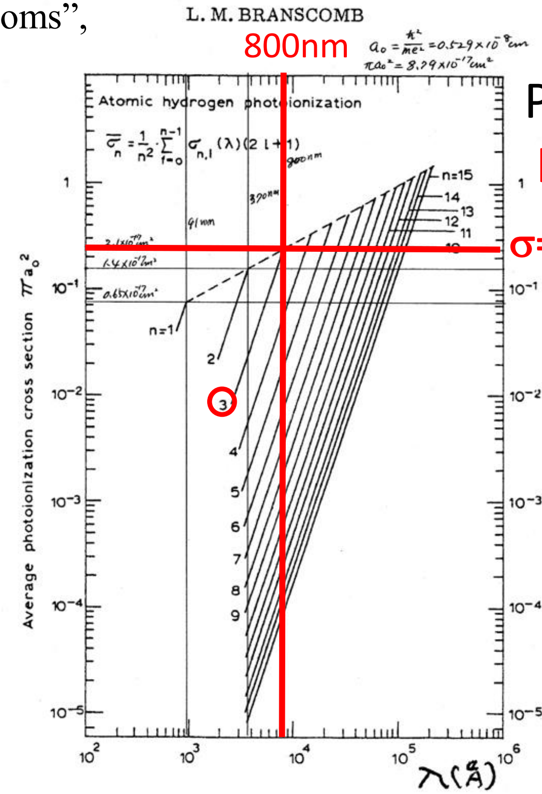
Photodetachment, Photoionization cross sections and the corresponding laser power

L. M. BRANSCOMB, "Physics of the One-And-Two-Electron Atoms",
Edited by F. Bopp and H. Kleinpoppen, North-Holland, (1969)



Photodetachment

$H^- \rightarrow H^0$



Photoionization

$H^{0*} \rightarrow p$

σ= 1.8 × 10^{-17} cm^2

E_{ph} = 1.67 eV @ 743 nm

Saturation density Φ^s in PRF

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

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**

H$^-$ neutralization is well studied in many places:
FNAL: Laser notcher system
J-PARC TEF: R&D studies for 3 MeV H$^-$.

Lasers we have for the POP demonstration

Two Nd: YAG lasers available:

Purpose: 1st ($H^- \rightarrow H^0$) and 3rd ($H^{0*} \rightarrow p$) stripping

1. Nd: YAG 1064 nm, 5-9 ns (FWHM), E= 0.2 ~0.6 J

-- Detail study under progress with 0.2 J

2. J-PARC TEF facility has one more powerful YAG laser
Nd: YAG 1064 nm, 5-9 ns (FWHM), 1.6 J
Test experiments done for 3 MeV H^- neutralization.

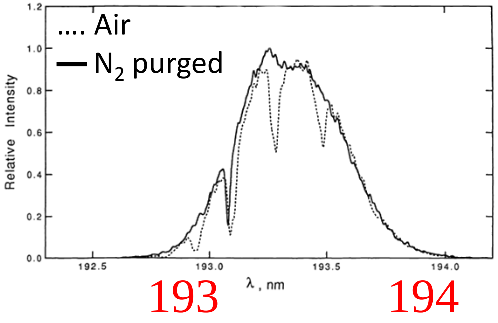
Excimer laser:

ArF 193 nm excimer laser (by Mlase)
Energy= 13 mJ, Pulse length = 5-10 ns (σ)
Bandwidth: ~4THz

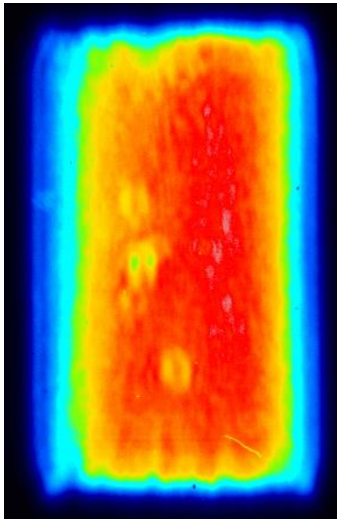
→ P_{peak} > 1 MW can be reached

→ **Excitation efficiency: 90% might be achieved.**

If we succeed pulse compression of the ArF laser, we can reach P_{peak} >> 1 MW



0.3 × 0.6 mm^2



ArF 193 nm excimer laser
Manufacturer data

JFY 2017 progress highlights

1. Preparation of POP (Proof-of-principle) demonstration of 400 MeV H^- stripping to protons by using only lasers at J-PARC is under preparation.

--- Vacuum chamber in the beam line is installed.

--- R&D of the lasers are also in progress.

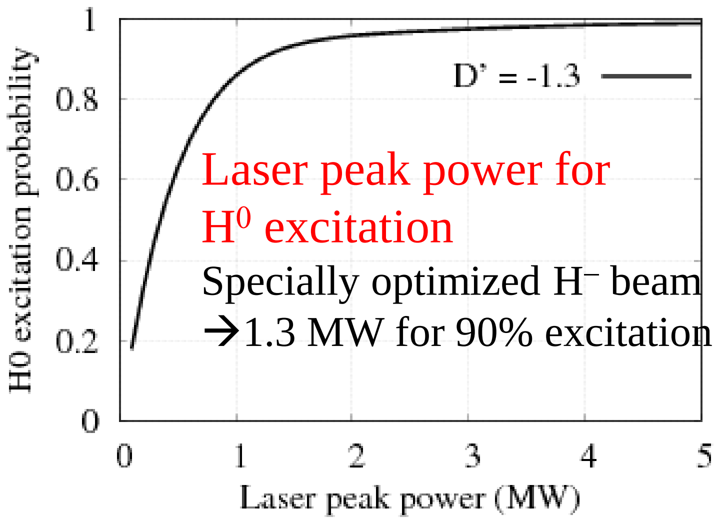
--- Simulation, H^- beam manipulations more details from now.

2. For R&D of the lasers we have new collaboration with Kyoto Univ. and the Univ. of Electro-communications, Tokyo (in progress). ---(H. Harada leading)

3. Dr. Timofey from SNS visited J-PARC for 2 weeks in March as an invited fellow.

-- Worked with Saha to develop pyORBIT code for 400 MeV H^0 excitation.

-- Discussion on the J-PARC laser stripping strategy, H^- beam manipulation, etc.



Laser peak power for H^0 excitation

Specially optimized H^- beam
→1.3 MW for 90% excitation

Recent status and the strategy in detail

We aim to demonstrate ~90% stripping efficiency for a single micro pulse.

To do

■ We should study about the expected laser power and effort to reduce the laser power.

■ Experimental strategy and the measurement techniques

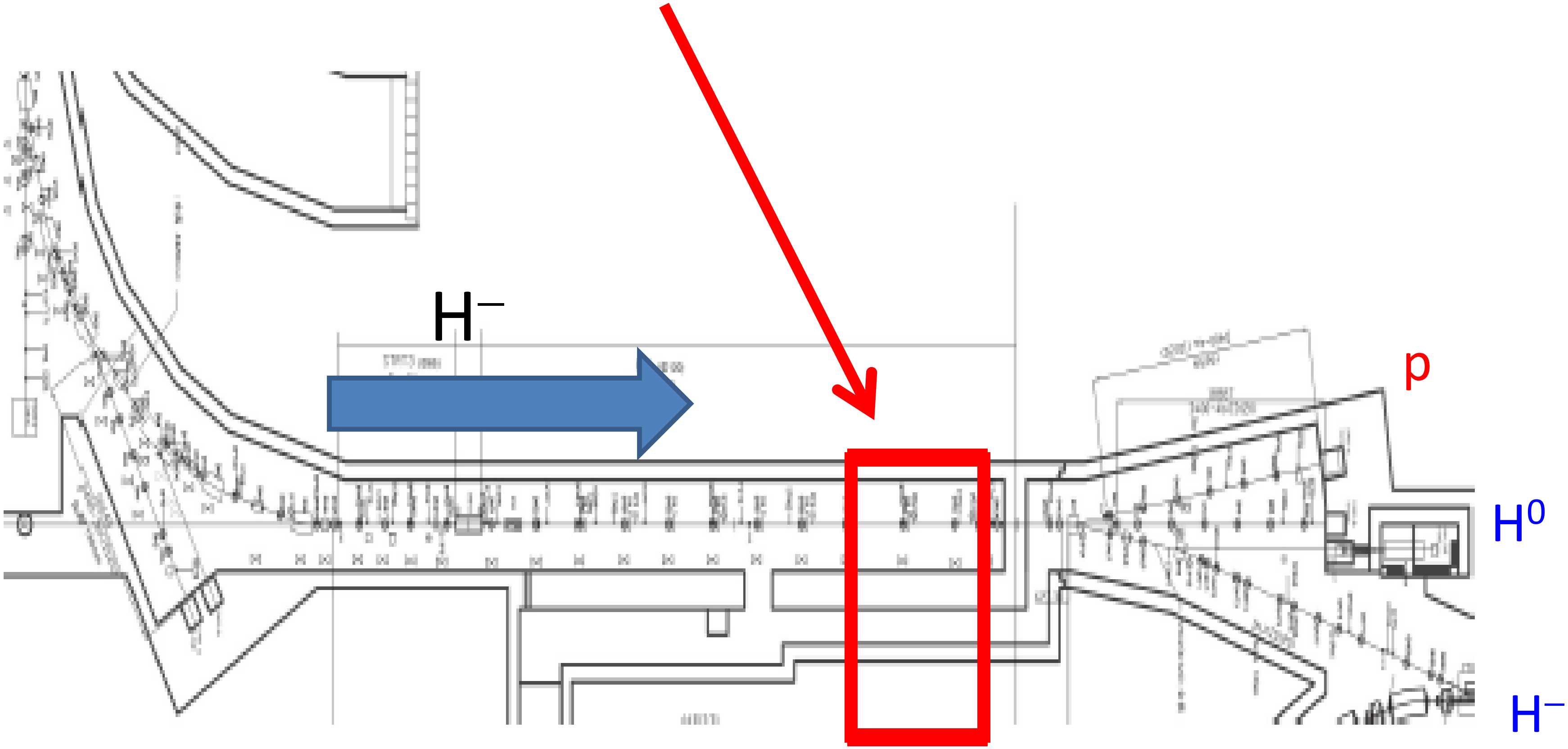
We should use existing devices and monitors for
the POP demonstration.

● Extensive R&D studies of the lasers:
H. Harada, P.K. Saha + other members..

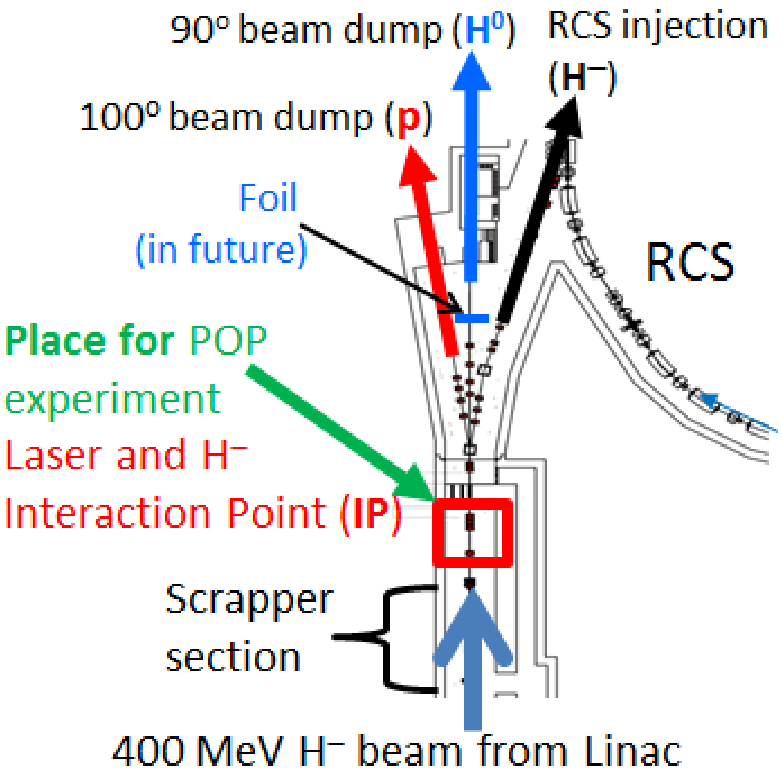
● H^- beam manipulation, measurement principles…
P.K. Saha, A. Miura, H. Harada + other members…

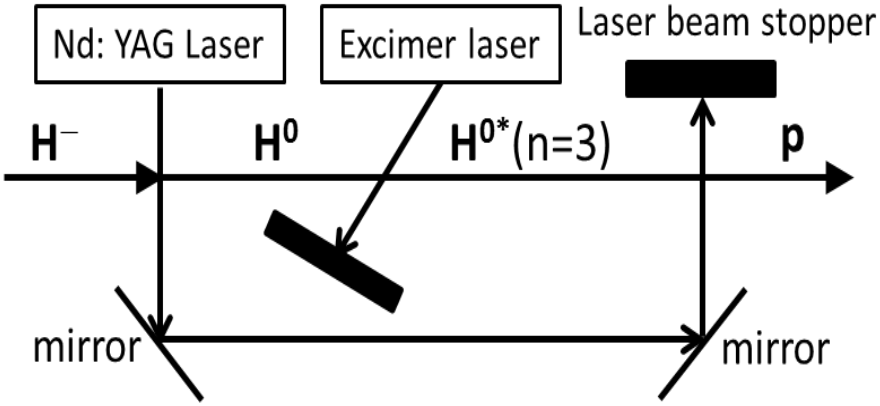
Experimental place, beamline

The POP experiment will be performed at the end section of L-3BT (Linac to the 3-GeV Beam Transport)



Experimental Setup and strategy





Setup for the POP experiment

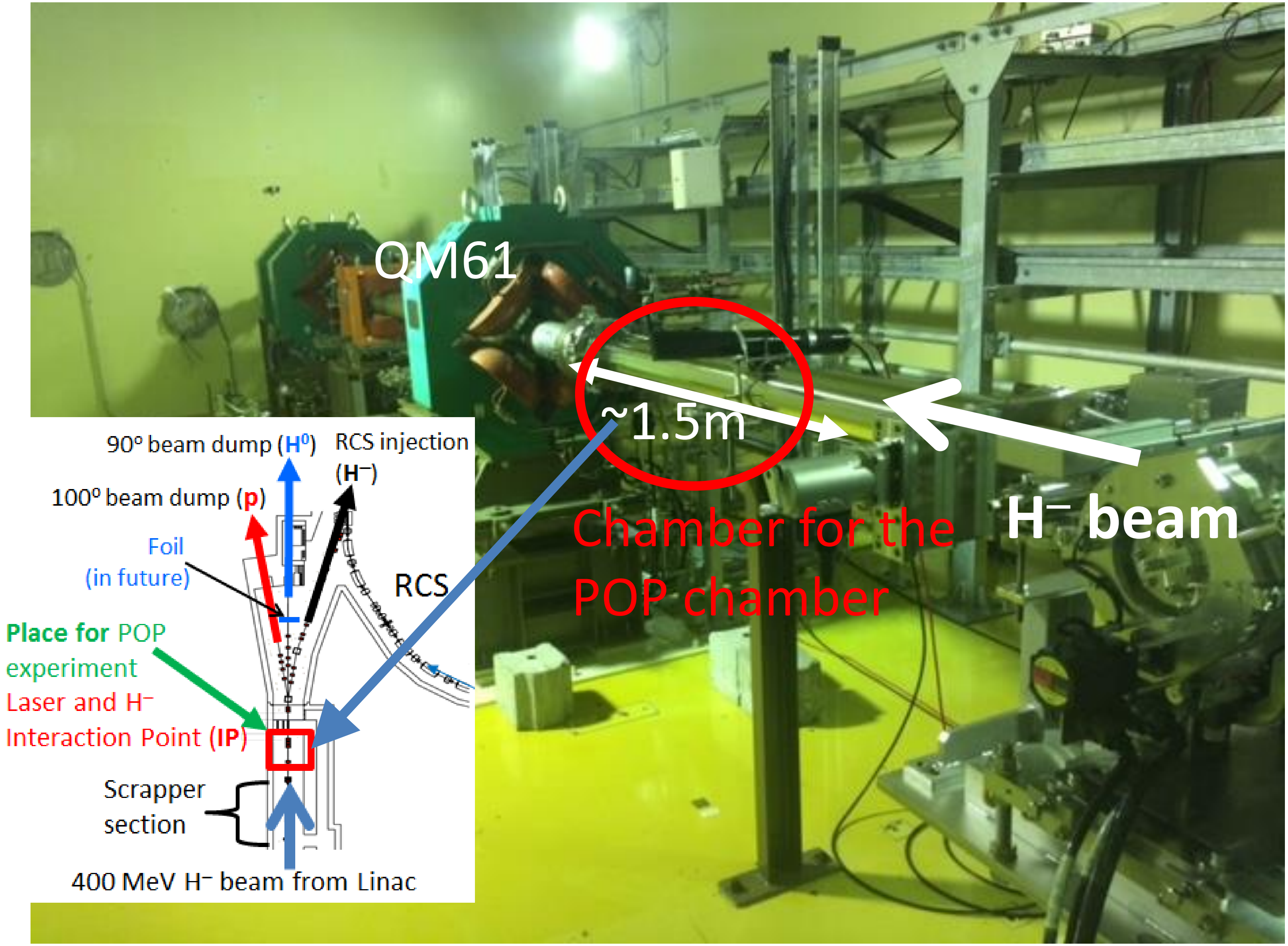
(Nd: YAG laser can also be splitted in the beginning for the 1st and 3rd steps)

- We can simultaneously measure all three charge fractions in three separated beam lines in the downstream of IP.
- A stripper foil will be installed near 90-deg dump to strip H^0 to p for measuring it.

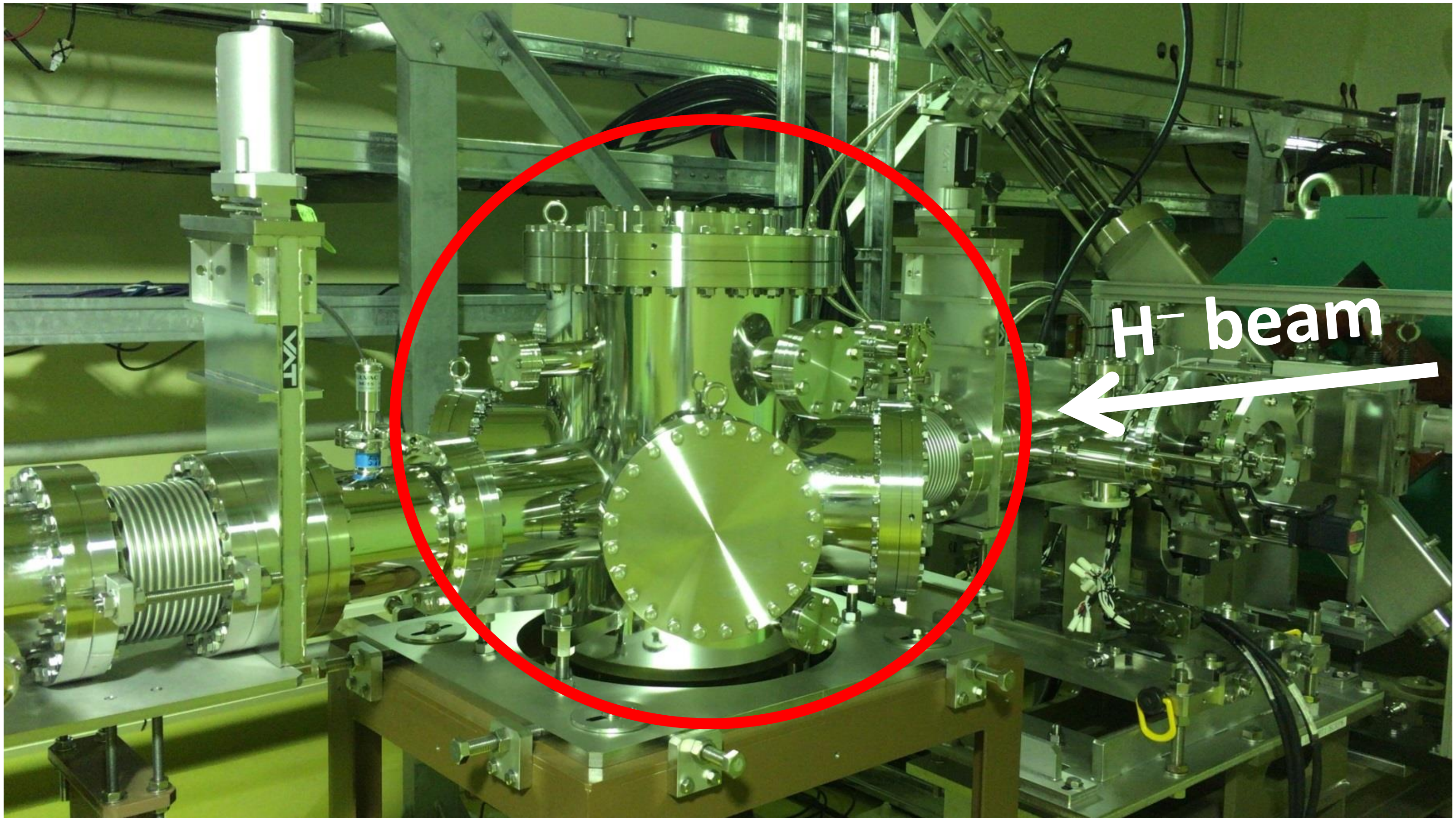
For confirmation of H0 excitation, we can also measure emitted lights from H0 decay.

POP experimental devices setup

End section of Linac to 3-GeV Beam Transport



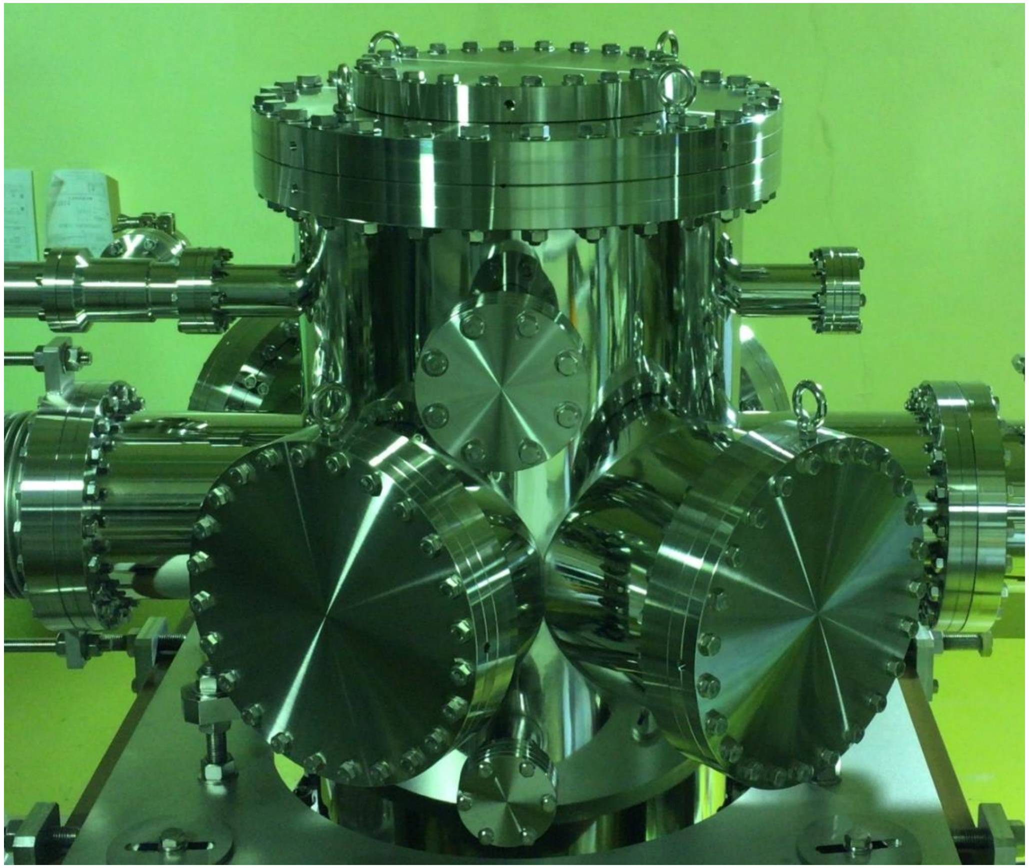
Vacuum chamber for POP experiment installed



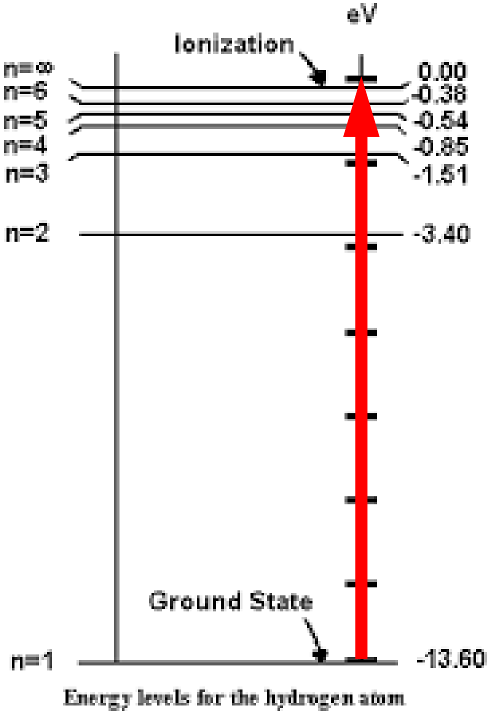
The chamber is designed for multi purpose laser manipulation of the H^- beam.

- Laser stripping of 400 H- beam.
- Multi-layer laser wire monitor.
- Electron impact on H-/p for beam for stripping, monitoring, SC neutralization, etc..

Vacuum chamber: close view



There are many windows on the chamber for multi-purpose uses.



Energy levels for the hydrogen atom

The excimer laser window is made large to try for direct ionization of ground state H0

λ_0 = 91.2 nm, λ = 193nm,

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

α = 47°

Variation range: 67°<α<45°

Laser power for 400 MeV H^0 excitation (n=3) at J-PARC: -- Based on SNS experience

Laser peak power, P_{peak} for H^0 excitation n=1→3

$$P_{peak} = \frac{\ln\left({}^{1}/_{\delta}\right)\hbar^2 \varepsilon_0 c^2 \, k \, \omega_0 sin\alpha \, \Delta}{2\mu_{1\to n}^2 \gamma (1+ \beta cos\alpha)^2}$$

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

Where, δ is the ratio of unexcited and excited atoms. δ <<1 is expected.

P_{peak} = 1 MW for 90% efficiency

At 400 MeV (β=0.713, γ =1.4263), Naively, P_{peak} ~1.7 MW is required 90% efficiency.

To reduce the laser power, extensive manipulations of the H^- beam were done at the SNS:

- ★ Shorter longitudinal beam size. σ_z = 30 ps → Not an issue for our POP expt.
- ★ Dispersion derivative of the H^- beam
- ★ Minimization of the betatron angular spread
- ★ Smaller vertical beam size

How much we can optimize these parameters?

Reduction of laser power

Let's take the equation of laser beam angular spread $\Delta\alpha_l$ (Yamane-san)

Required angular spread of the laser pulse:

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

Introduce dispersion derivative

Reduction of betatron angular spread (page 14)

$$(\Delta\alpha_l)_m = \left(\frac{\overbrace{\beta(\beta + cos\alpha + D' sin\alpha)}^{0}}{1+\beta cos\alpha}\left(\frac{\Delta p}{p}\right) + \frac{\beta sin\alpha}{1+\beta cos\alpha}(\Delta\theta)_m\right) \times \frac{1+\ \beta cos\alpha}{\beta sin\alpha}$$

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

Dispersion derivative of the H^- beam

In order to eliminate transition frequency spread, due to the momentum spread dp/p_0 in the H^- beam, dispersion (D) tailoring method is utilized.

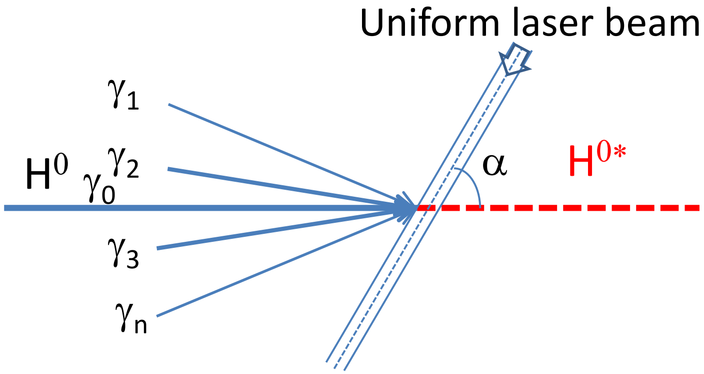
Due to the Doppler effect
$\lambda = \lambda_0 (1+\beta\cos\alpha)\gamma$
β, γ are Lorentz parameters
$\boldsymbol{\alpha = \alpha_0 - x'}$, $\boldsymbol{d\alpha = -x'}$

For reference particle ($dp/p_0=0$),
$\boldsymbol{\alpha = \alpha_0}$

For off-momentum particle,
$x = D(dp/p_0)$, $x' = D'(dp/p_0)$
From $dp/p_0 = (1/\beta^2)\, d\gamma/\gamma$
$d\alpha/d\gamma = -D'/\beta^2\gamma$

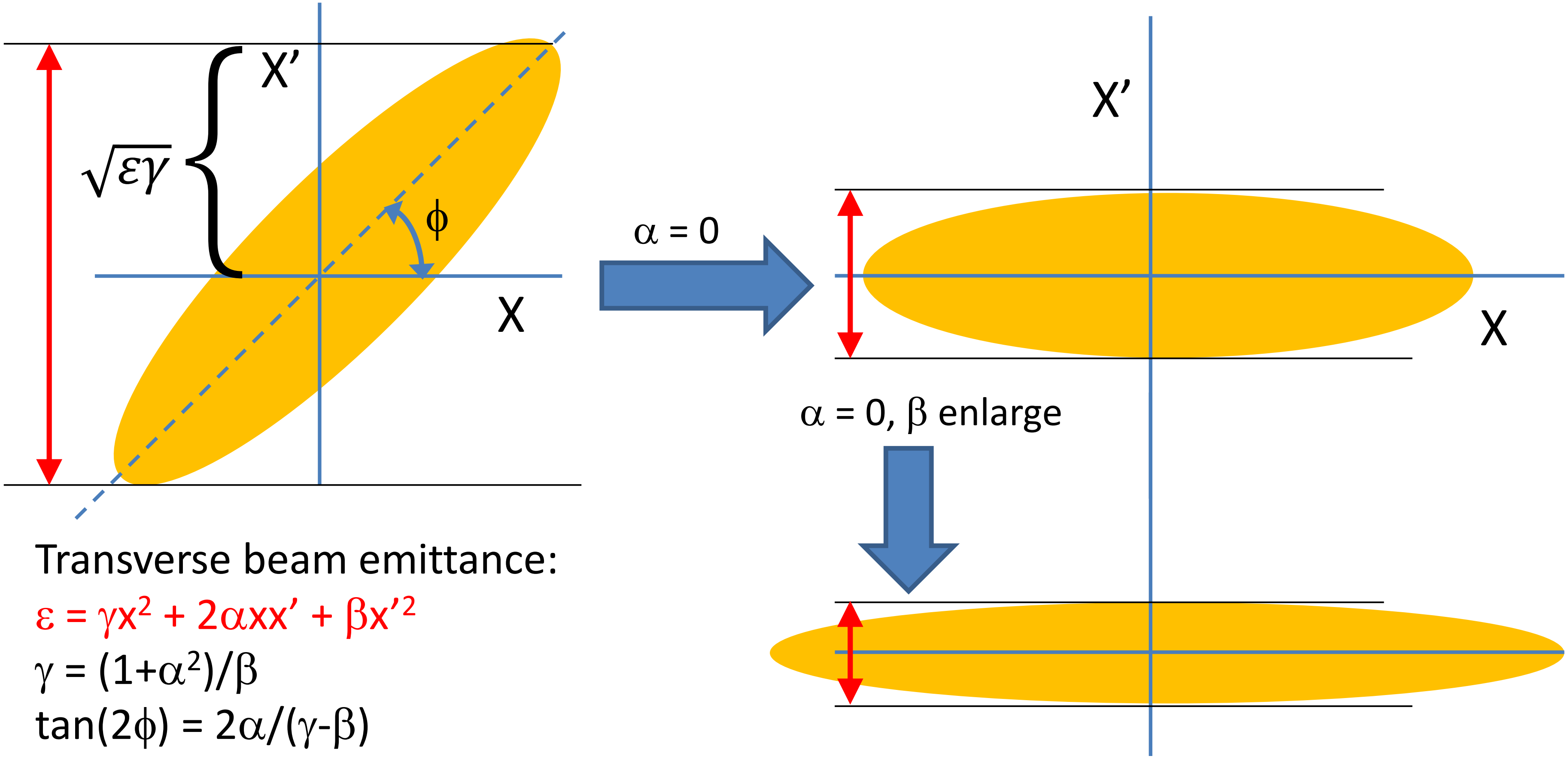
The dispersion relation becomes,

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



- ● Hydrogen atom with different energies have the same laser light frequency in their rest frame.
- ● Laser light does not have to have a divergence.
  → Gain on the laser peak power.

Optimization of betatron angular spread



Transverse beam emittance:

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

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

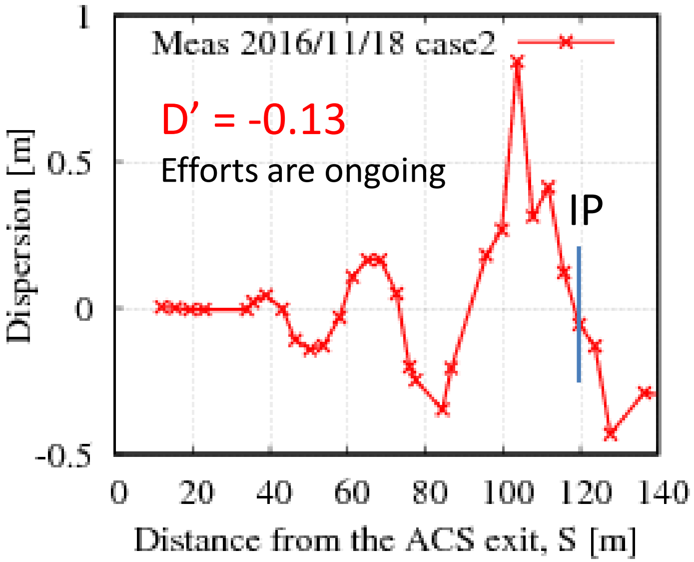
$\tan(2\phi) = 2\alpha/(\gamma-\beta)$

$\alpha, \beta, \gamma, \varepsilon$ are twiss parameters

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

As for the vertical size of the H^- beam, a smaller size is required to gain on the beam density. At SNS, $\sigma_v = 0.15$ mm achieved.

Trial optimization of the H^- beam

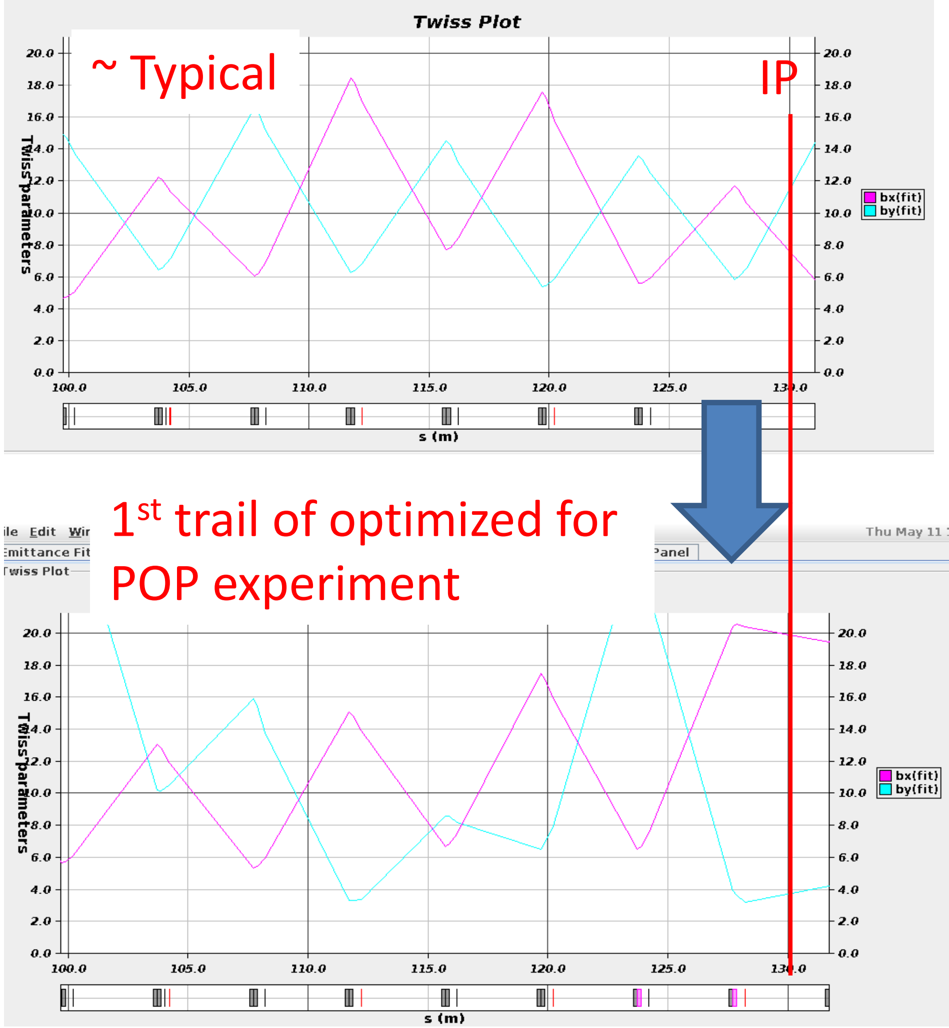


D' = -0.13

Efforts are ongoing

IP

Transverse beam optimization at the IP



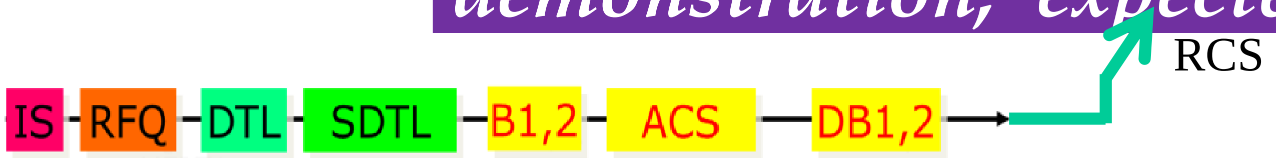
~ Typical

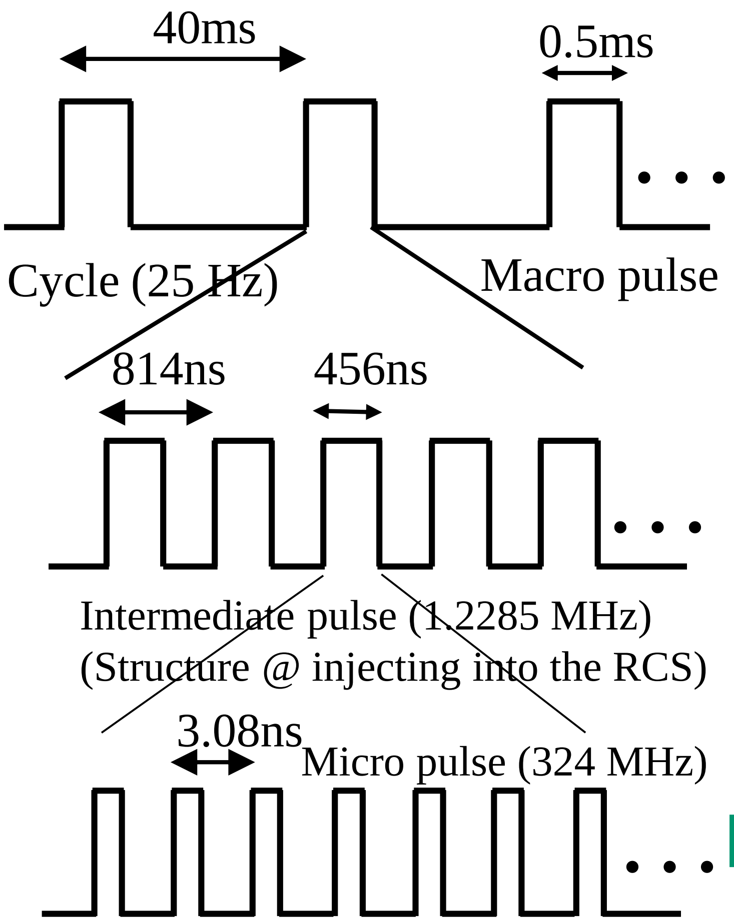
IP

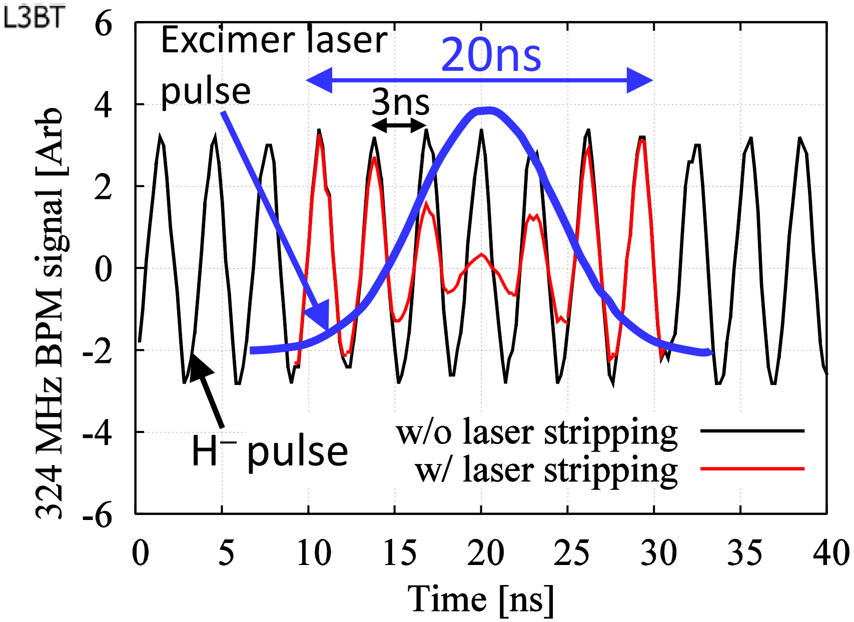
1^{st} trail of optimized for POP experiment

Further more studies needed

Measurement Strategy for POP demonstration, expected signal







Typical 324 MHz BPM electrode signal.

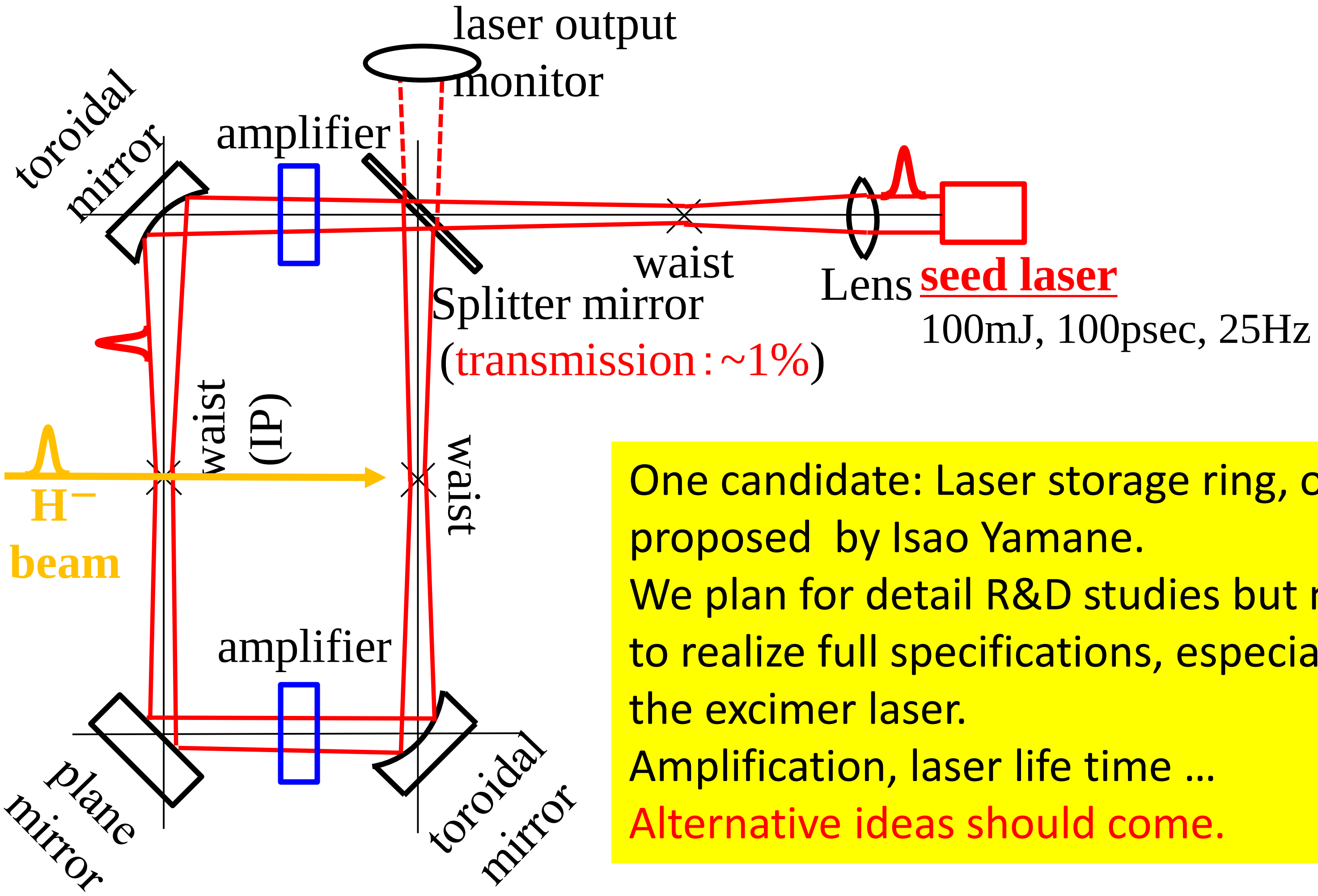
The H^- beam signal will be reduced in the laser pulse overlapping region.

The protons go to the 100 deg. dump.

We concentrate only on a single micro pulse.
Use stripline BPM signal.

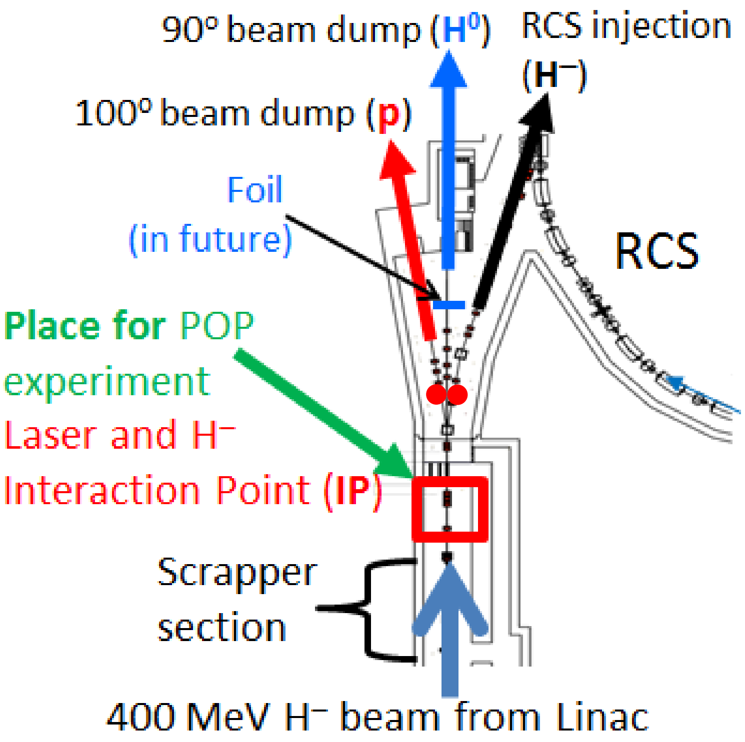
How to cover 0.5 ms (~10^5 micro pulses) for practical application?

H. Harada



One candidate: Laser storage ring, originally proposed by Isao Yamane.
We plan for detail R&D studies but many issues to realize full specifications, especially for the excimer laser.
Amplification, laser life time …
Alternative ideas should come.

Measurement method of stripping efficiency of a single micro pulse

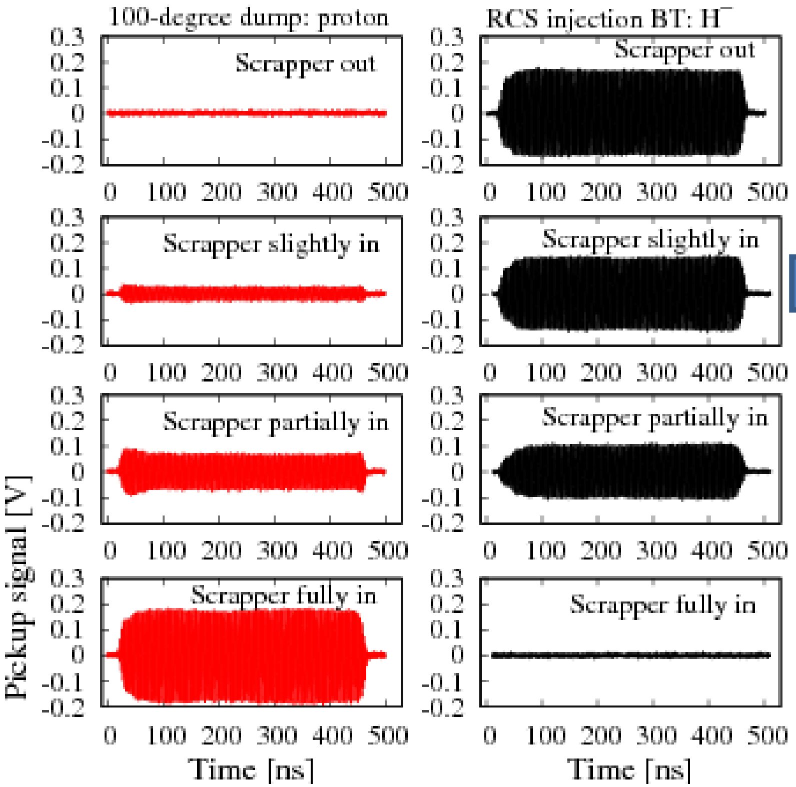


Scrapper & Beam (y ↑ x →)	To 100-deg. Dump (p)	To 90-deg. Dump (H^0)	To RCS (H^-)
Scrapper OUT H^-	- - -	- - -	H^- 100%
Half IN H^-	p 49.999%	1×10^{-3} %	H^- 50%
Fully IN	p 99.998%	2×10^{-3} %	$< 10^{-10}$ %

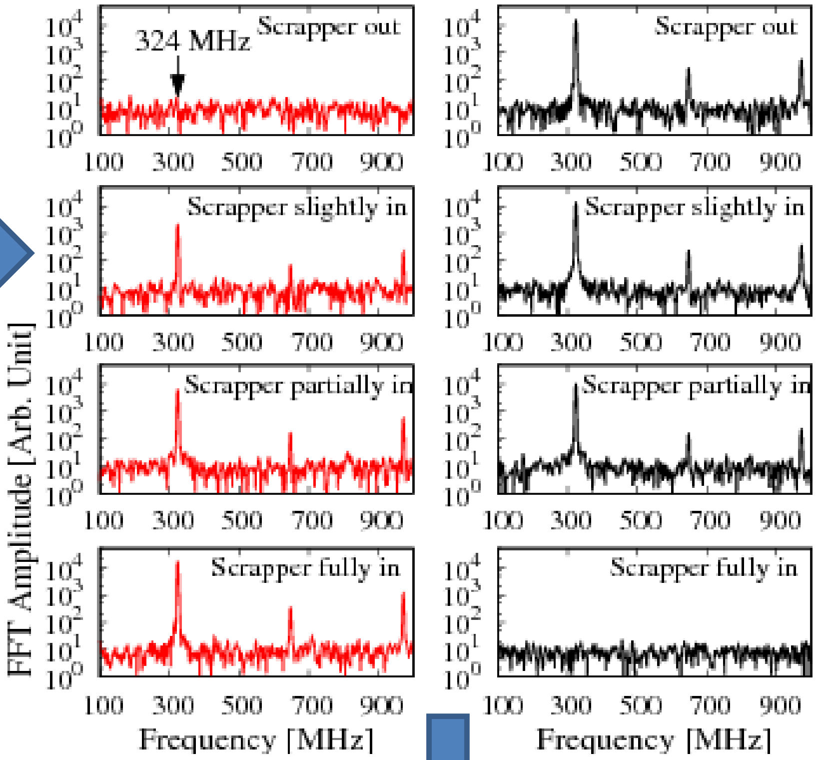
Checked by inserting L-3BT scrapper at present

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

Measurement techniques: Experimental results



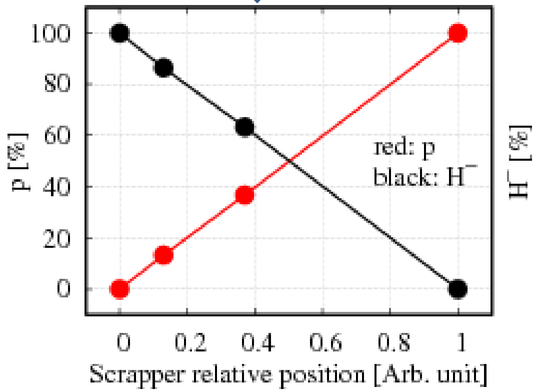
FFT



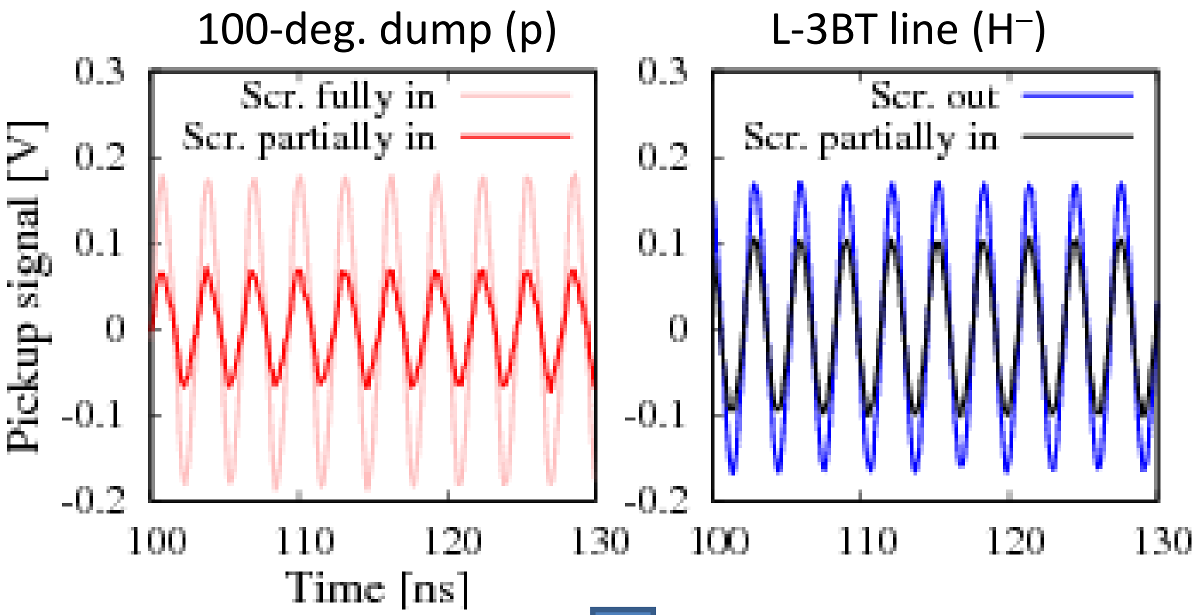
Stripping efficiency of single medium pulse can easily be obtained by using FFT analysis.

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

→ Analysis of individual micro pulse



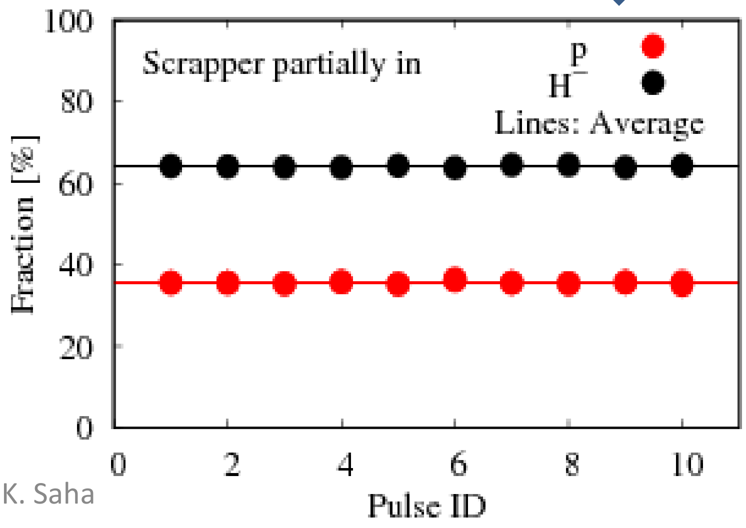
Analysis of individual micro pulse


100-deg. dump (p)

L-3BT line (H^-)

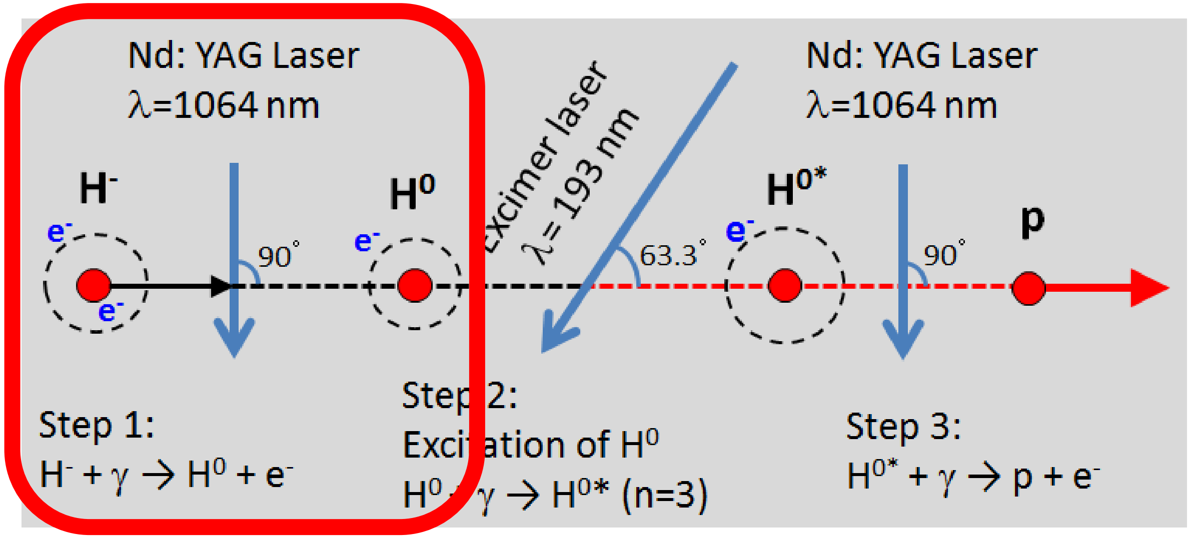
Fraction p : pink to red

Fraction H^- black to blue



- New effort to measure micro pulse stripping efficiency.
- Can be utilized also for micro pulse stability.

Laser stripping of 400 MeV H- beam
--- Scheduled step by step



H^- neutralization study first.

● The detail studies of ND:YAG laser are in good progress. At present detail of laser stability, pulse shape up to with 200 mJ are being studied.

★ The ArF excimer laser study just started.

★ We will work for pulse shortening of the lasers.

★ Placing lasers at the acceleration tunnel is big issue!

Summary

The preparation for POP demonstration of 400 MeV H- stripping by using only lasers at J-PARC is in progress.
The experiment will be carried out in steps.

First trial of complete set of experiment planned within JFY 2018.

Laser and H- beam manipulations more studies needed.

Measurement technique for even a single micro pulse established.

POP final goal: 90% stripping efficiency for a single micro pulse.

Next step, not straightforward to cover ~10^5 micro pulses.
Candidates:
Laser storage ring synchronized with 324 MHz H- micro pulse.
Many issues for realistic implementation with full specifications.
Other ideas have to come.

Collaboration outlook

■ Laser interaction of the H^- beam for utilization in stripping, chopping, beam diagnostic and other manipulations are an important subject for the present and next-generation high-intensity proton accelerators.

■ Non-destructive and highly required not only for the existing high intensity machines but also to realize multi-MW beam power.

The collaboration aims at

Developing a framework for an effective laser manipulation of the H^- beam

→ **Achieve maximum efficiency with a minimum laser power.**

→ **Explore for multi-dimensional application.**

. . . .