Status of the laser stripping of H^- beam at J-PARC RCS

[J-PARC 3GeVにおける負水素イオンのレーザー荷電変換の状況]

Pranab K. Saha, H. Harada, M. Kinsho (JAEA/J-PARC)

H. Yoneda, Y. Michine (ILS, UEC), A. Sato (NAT), T. Shibata (J-PARC/KEK)

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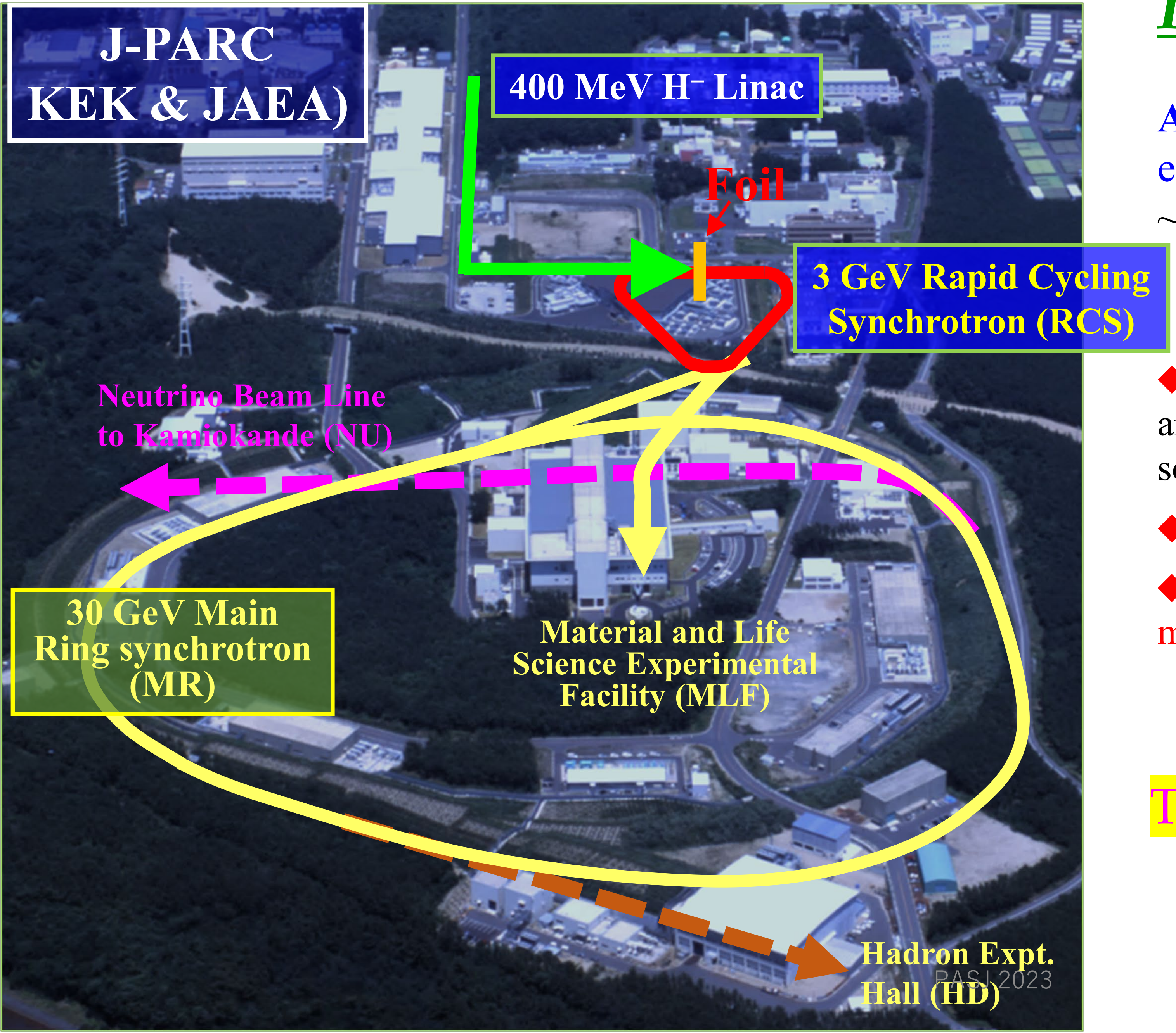
Outline:

- Introduction
- Laser stripping scheme and experimental setup
- Overview of the laser system and the laser cavity
- Results of 3 MeV H^- neutralization study
- Laser power reduction scheme
- Summary and outlook

J-PARC accelerators



Introduction:

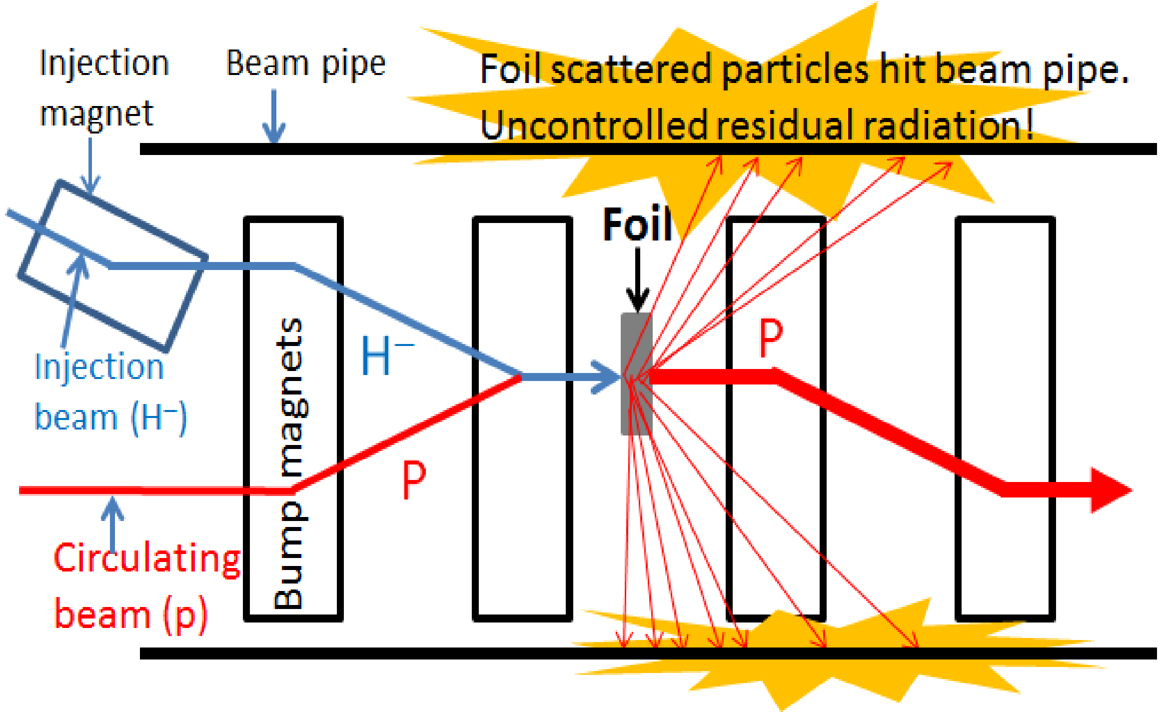
A stripper foil is need for multi-turn H^- charge-exchange injection (CEI) at RCS to accumulate ~10^{14} ppp for **1 MW beam power.**

- However, foil scattering **uncontrolled beam losses** and the corresponding **high residual radiation** is a serious issue at high-intensity operation.
- ***A shorter foil lifetime*** is also another big issue.
- These issues become further complicated at multi-MW beam power.

To overcome these issues, we are developing a ***foil-less H^- CEI by using lasers.***

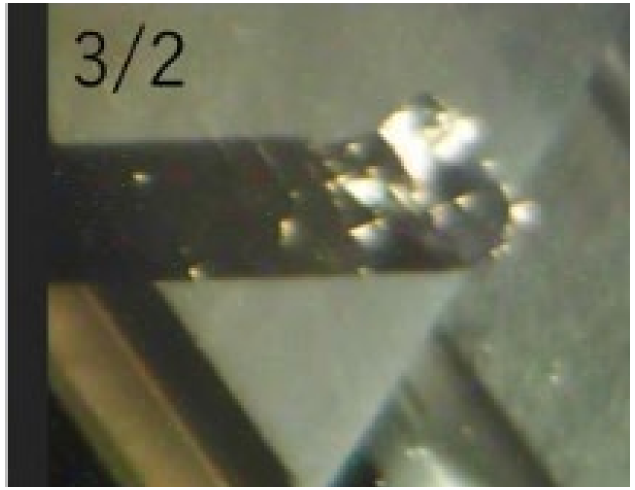
Stripper foil issues:

I. Foil scattering uncontrolled beam losses:
→ Extremely high residual radiation at the injection area.

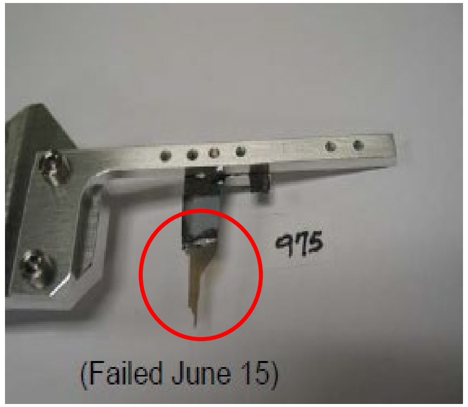


II. Short lifetime and foil failure:
→ Serious issues at high-intensity operation.

J-PARC foil degradation
@ 800 kW (1 Month)



Foil failures at the SNS, Oak Ridge.

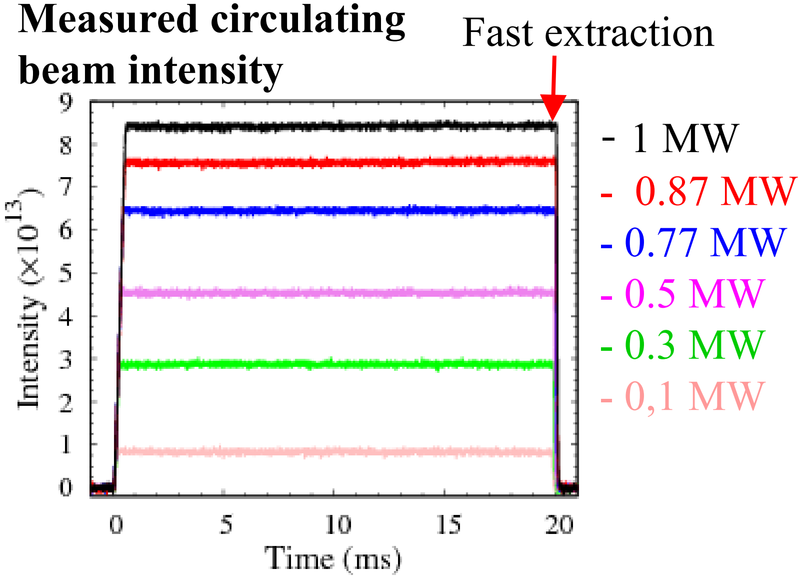


A foil-less H^- charge-exchange injection has to be realized!

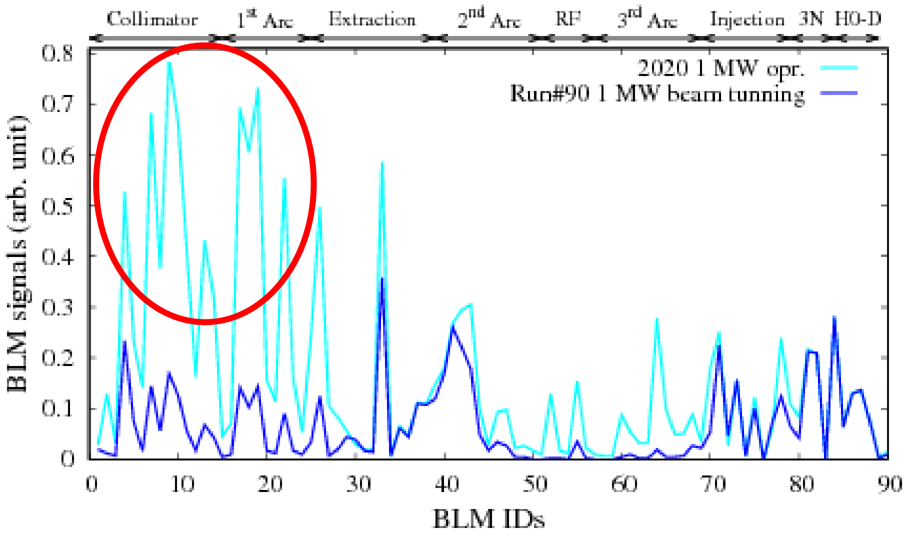
RCS beam loss mitigation at 1 MW

Until laser stripping is established, we continue our effort to minimize the beam losses including foil scattering ones by using a smaller size foil, optimizing transverse and longitudinal paintings....

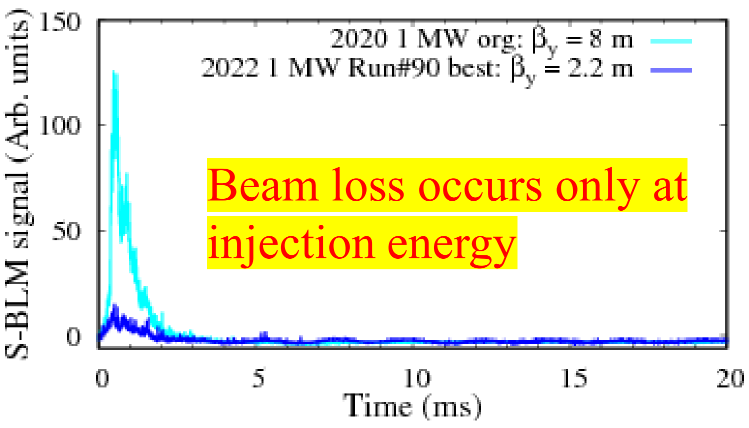
Measured circulating beam intensity



Beam loss throughout the ring



Time structure of the beam loss



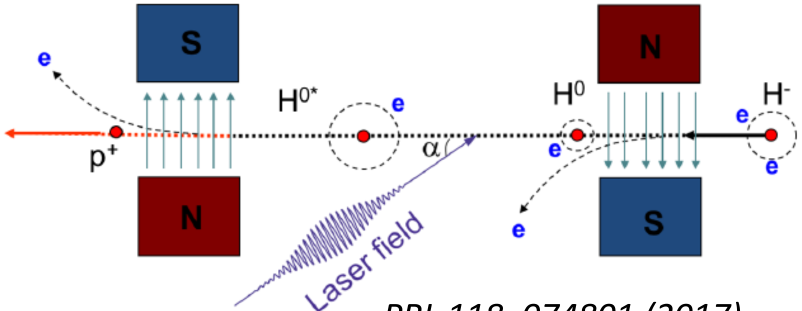
- ◆ The beam loss at 1 MW until 2020 was only 0.2%, well mitigated and controlled.
- ◆ We have further reduced (~80%) **to remain now only ~ 0.05%.**

→ Dominated by the foil scattering beam loss.

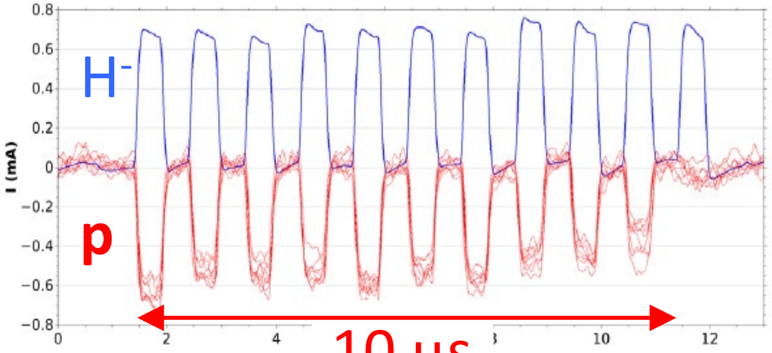
→ ***A laser stripping can give almost no beam loss at 1 MW in the RCS!***

Laser stripping schemes

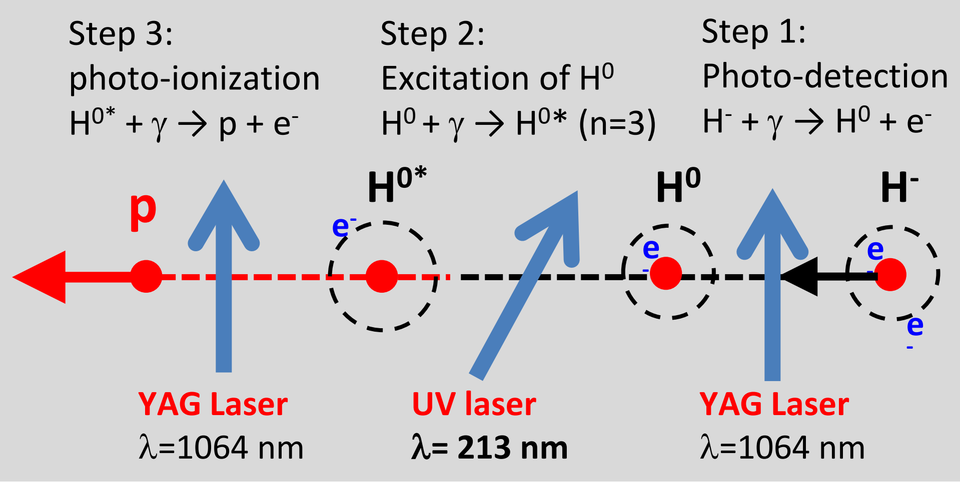
SNS (Oak Ridge) scheme:
Laser assisted
High magnetic fields for stripping
Laser for H0 excitation

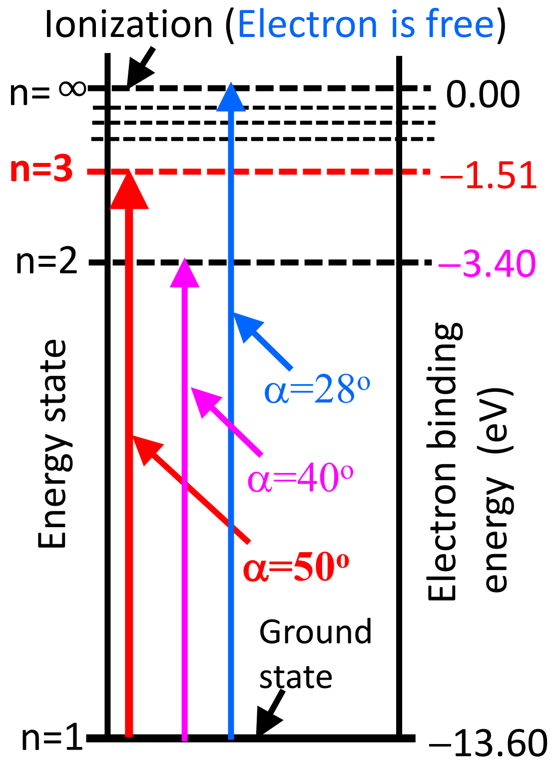


PRL 118, 074801 (2017)



J-PARC Scheme: Only lasers





J-PARC strategies:

- Avoid **difficulties and issues** with high magnetic field.
- Sufficient reduction of the laser power.

SNS achieved 10μs stripping in 20 years.
(Requirement: 1000 μs)
Laser power is the main limitation!

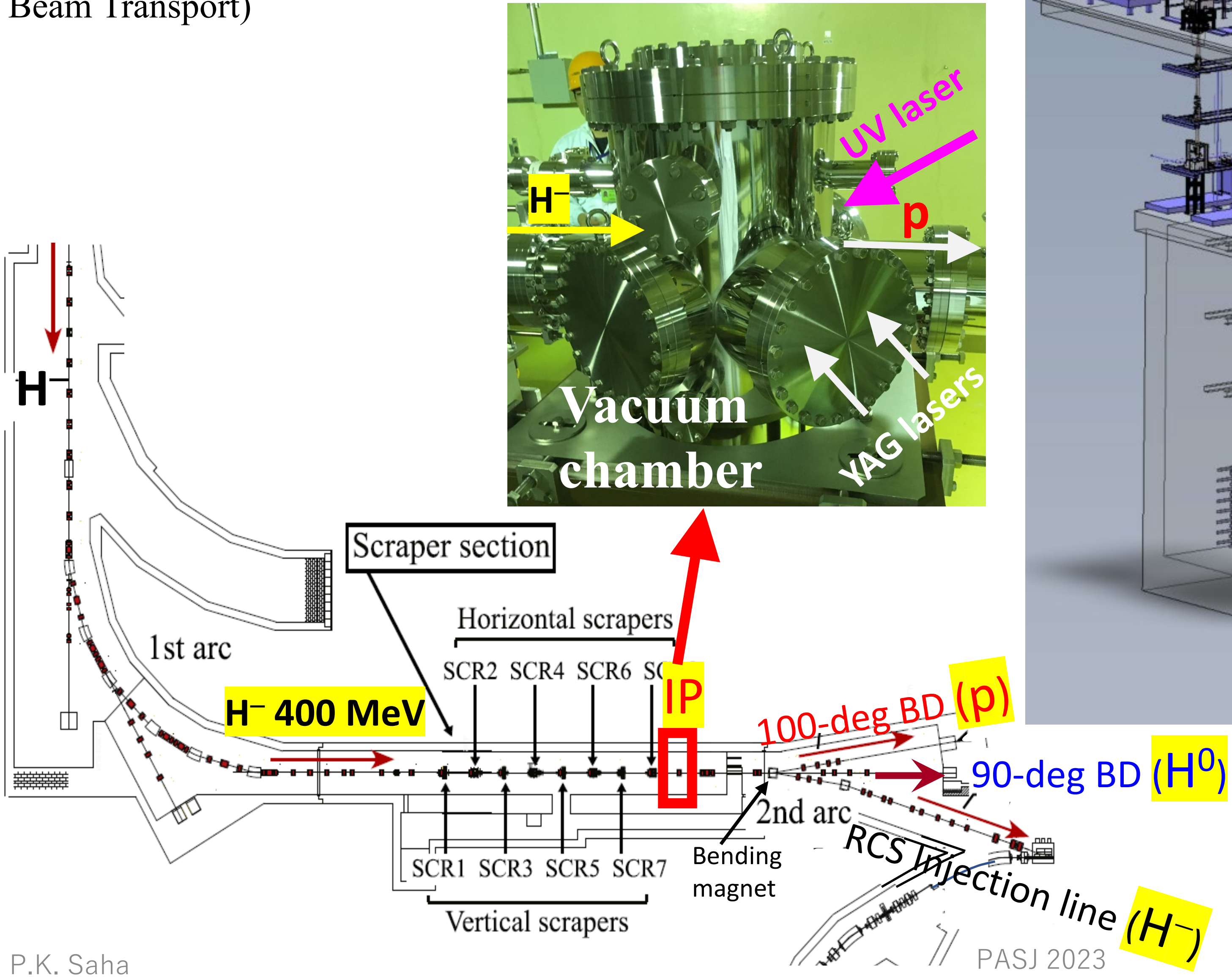
We are preparing a POP demonstration of 400 MeV H^- stripping by using only lasers.

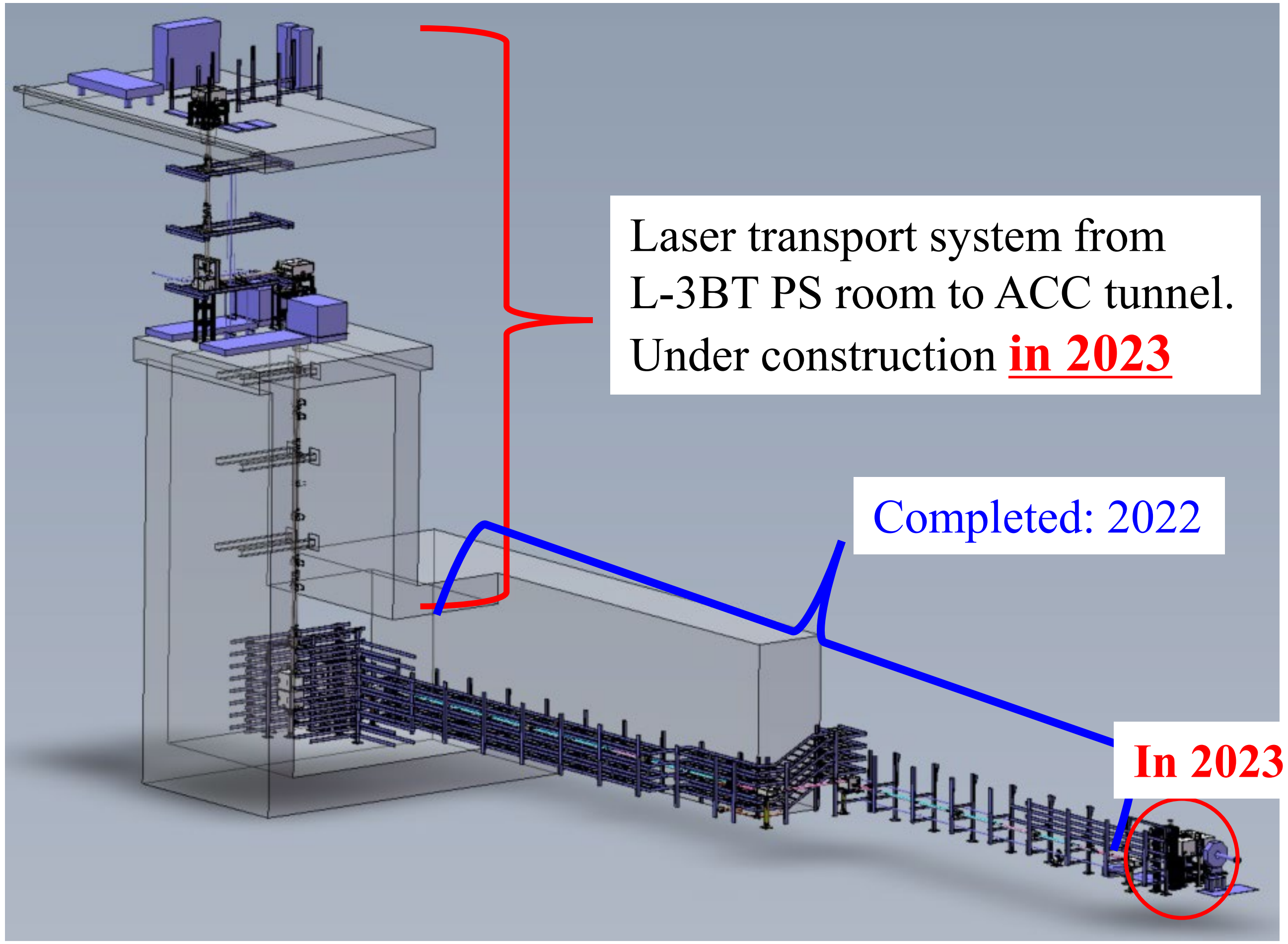
External funds:

- US-Japan Collaboration: (2018 ~ present)
- JSPS grants-in-aid: (2016~2019), (2019~2024 J-PARC, UEC, KEK)
- JAEA director's Houga fund: 2018-2020, 2020-2022, 2023-2025

Setup for POP demonstration at 400 MeV

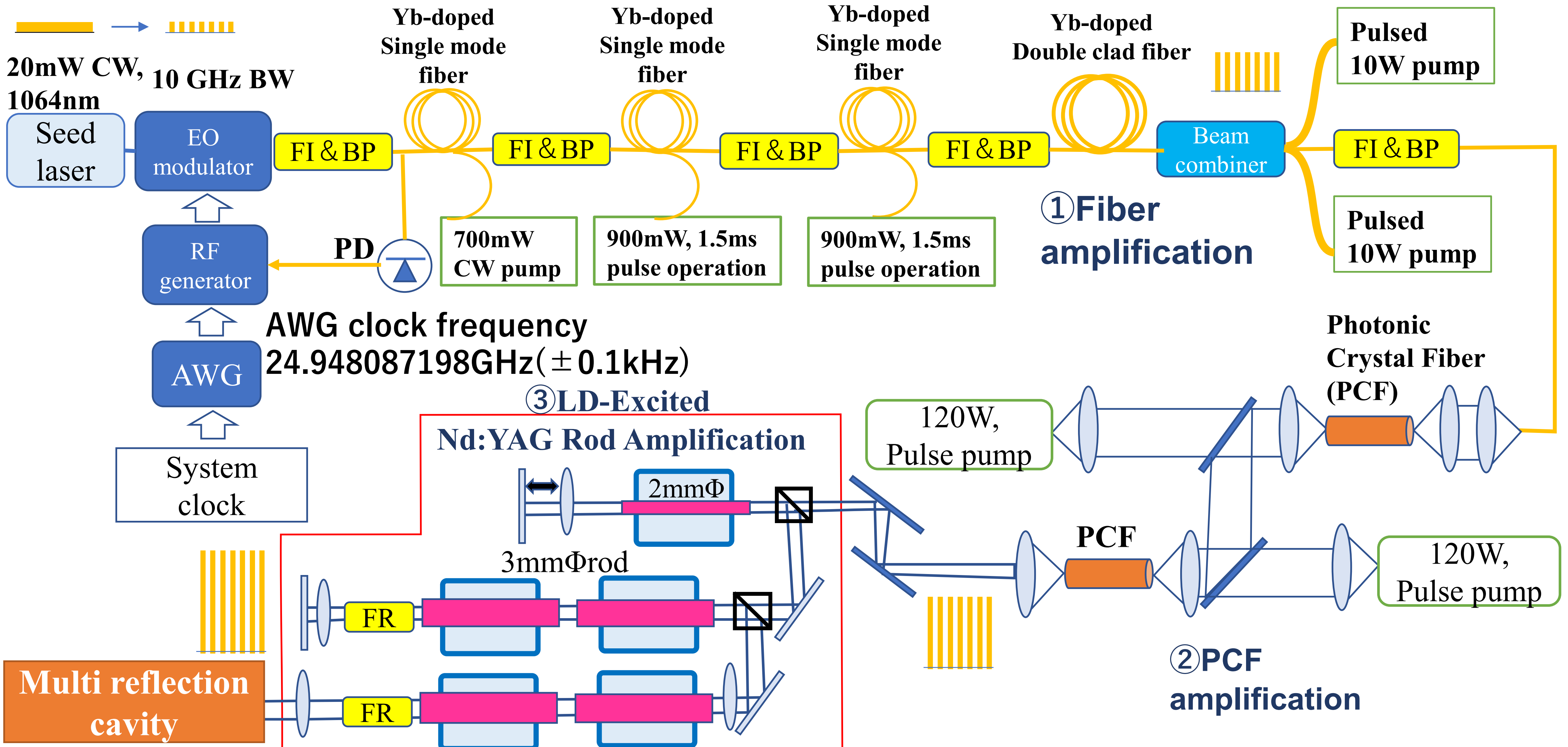
Place: J-PARC L-3BT (Linac to the 3-GeV Beam Transport)





- All charge fractions can be separately measured
- Each step can be separately studied and optimized.
- BPM electrode signals will be used (already tested)

YAG Laser system developed at the UEC



Multi-reflection cavity system
to reduce the seeder energy

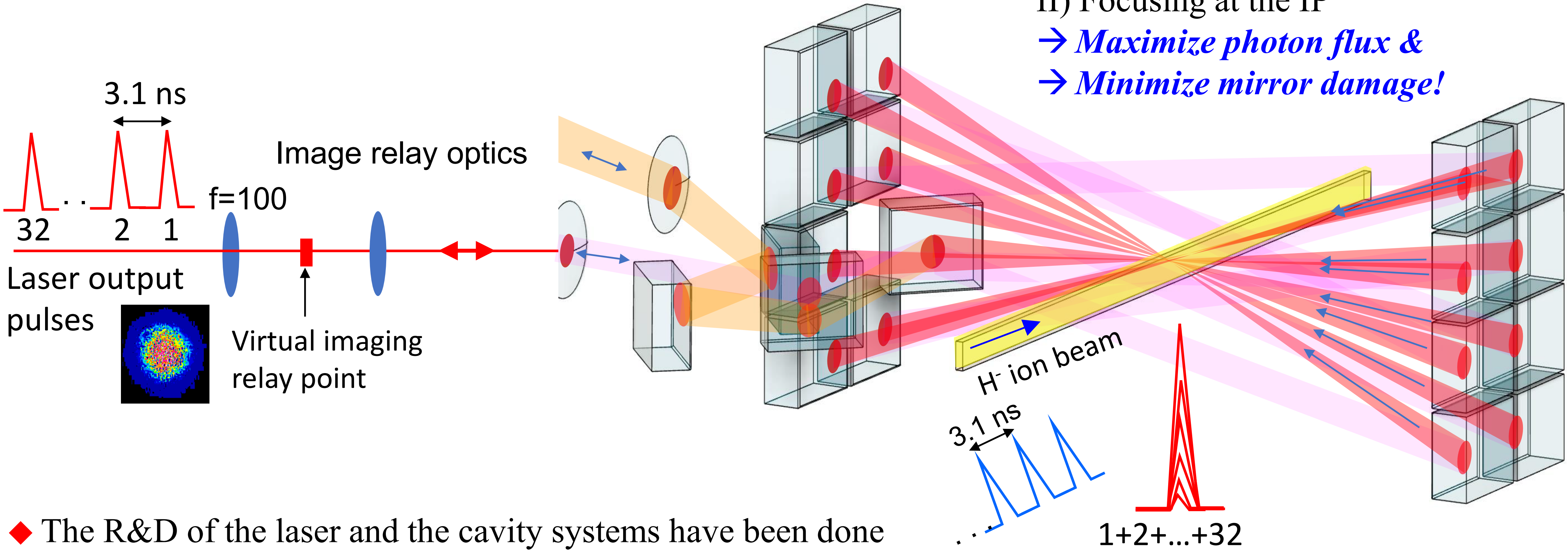
Key features:

I) Image transfer optics,

II) Focusing at the IP

→ Maximize photon flux &

→ Minimize mirror damage!



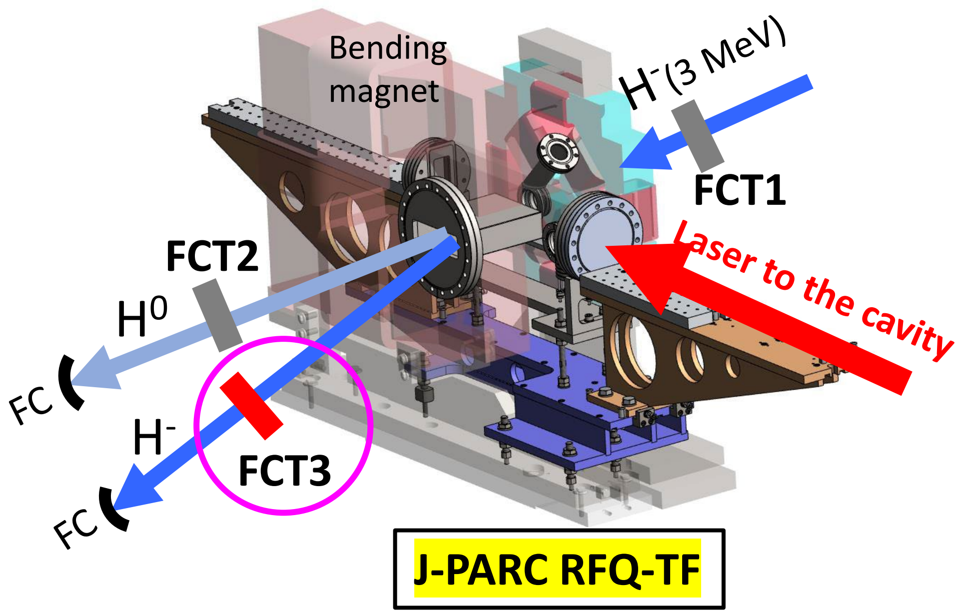
- The R&D of the laser and the cavity systems have been done through 3 MeV H^- neutralization studies at J-PARC RFQ-TF.
- Also demonstrated non-destructive H^- beam diagnostic systems.

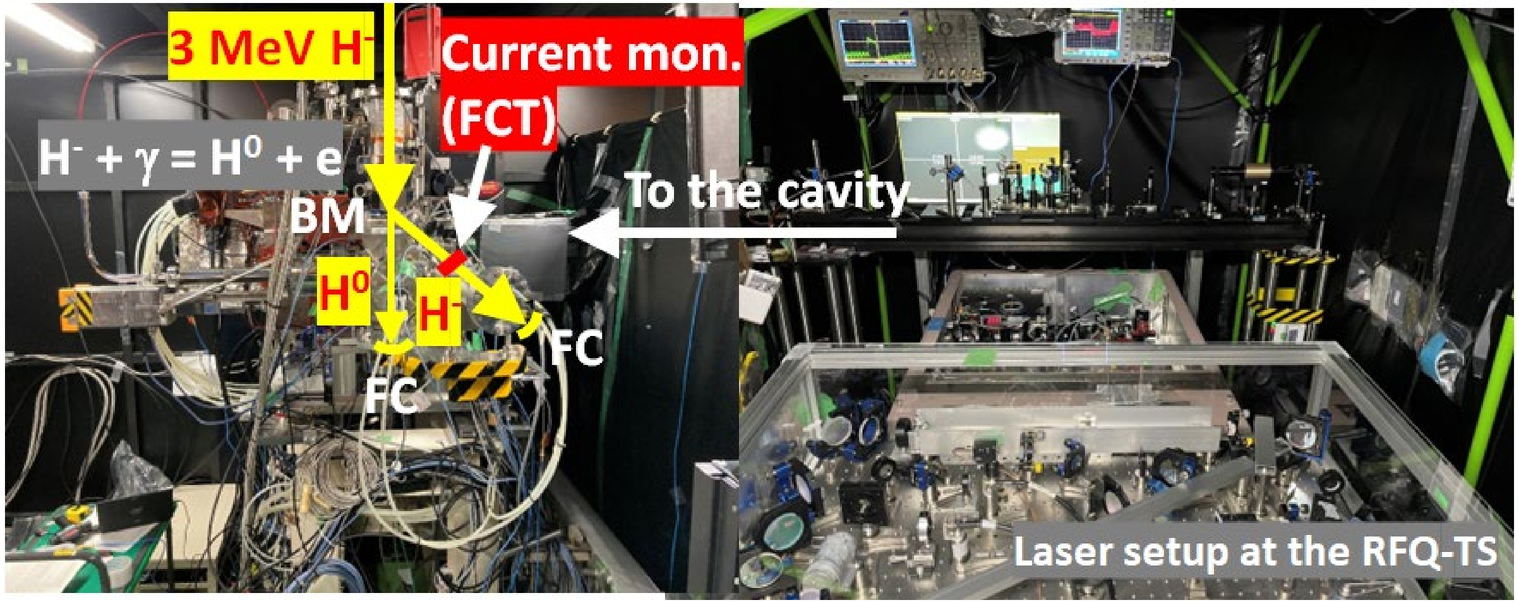
Reduction of the seeder energy: ~1/32

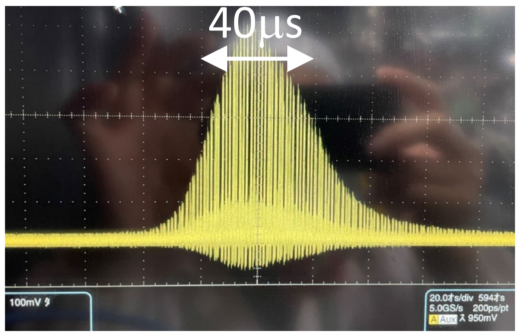
Further reflections possible.

Goal for seeder pulse: mJ → ~μJ

Study of 3 MeV H^- neutralization







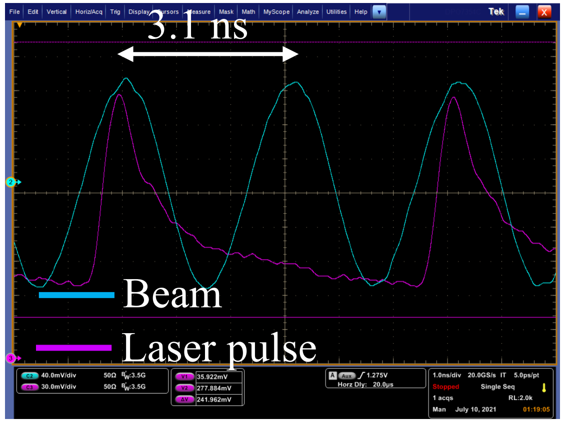
Typical laser pulse

- Pulse energy: 150 mJ @ 40 μs.
- Energy/micro pulse: 24μJ

→ 380μJ @ 32 passes (50%)

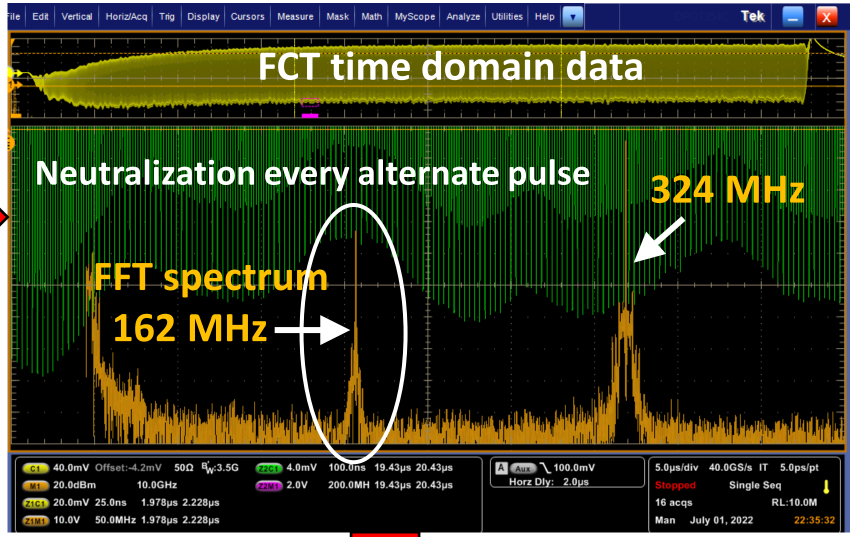
- Micro pulse width : 100ps
- Spot size : 0.1mm

Results of 3 MeV H^- neutralization

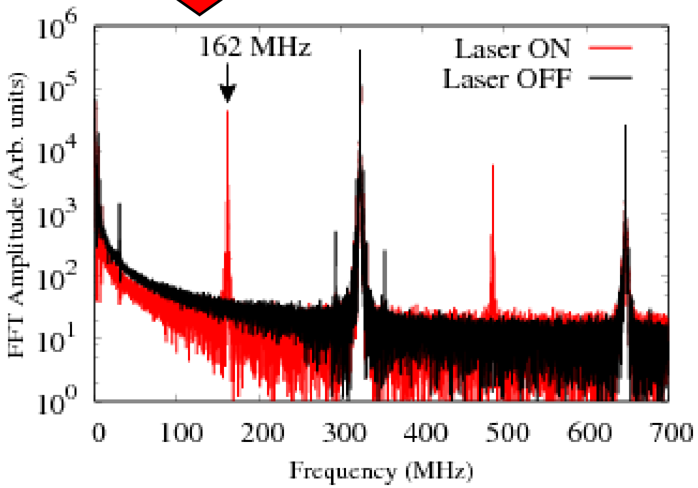


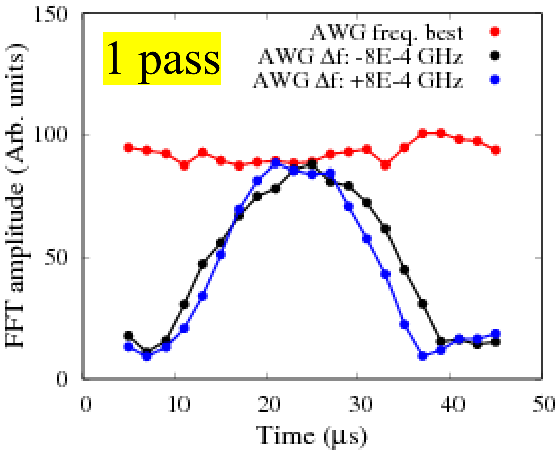
- H^- beam interval: 3.1 ns
- Laser pulse interval: 6.2 ns

→ Interaction @ alternate H^- pulses
→ **Neut. freq. : 162 MHz**
→ ***Unique!***

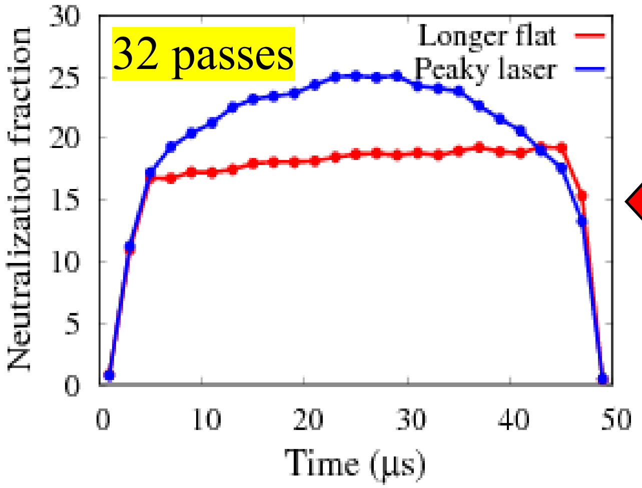


Offline analysis





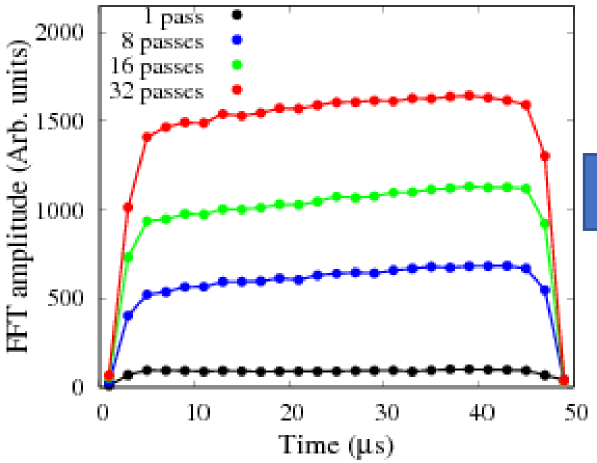
AWG tunning precision: ～10^{-4} GHz

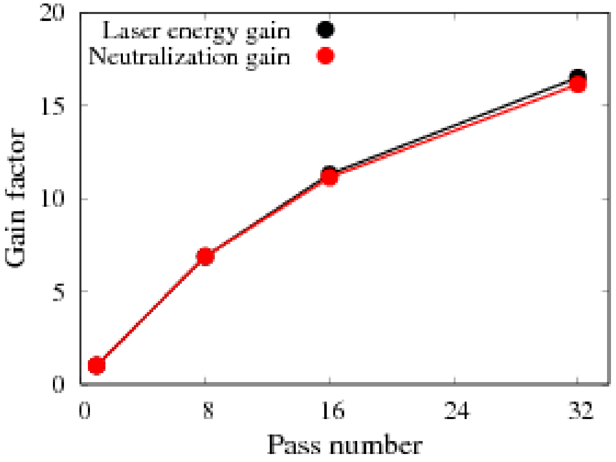


- **Obtained 18% neutralization.**
- **Flat over 40μs.**

Cavity pass dependence & longer pulse neutralization

Pass dependence



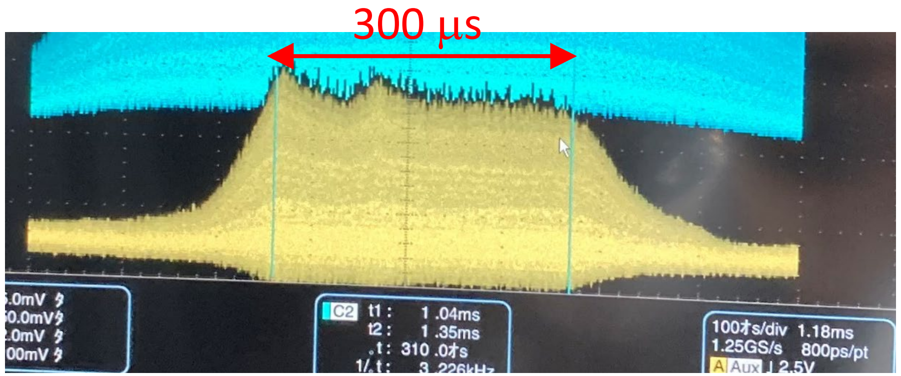


Achieved cavity gain: ×16

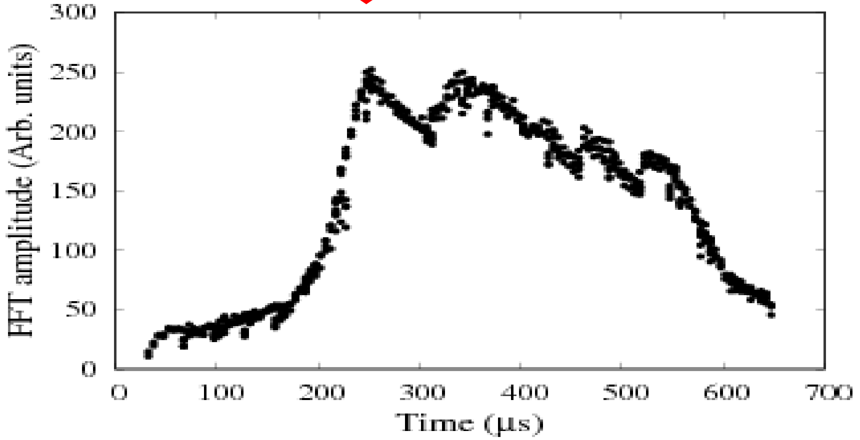
・Photon losses, especially at the vacuum windows are relatively high.

・R&D of low loss windows are manufactured.

Longer pulse neutralization



Neutralization

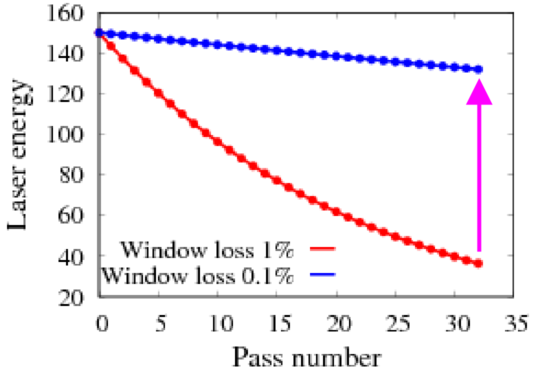


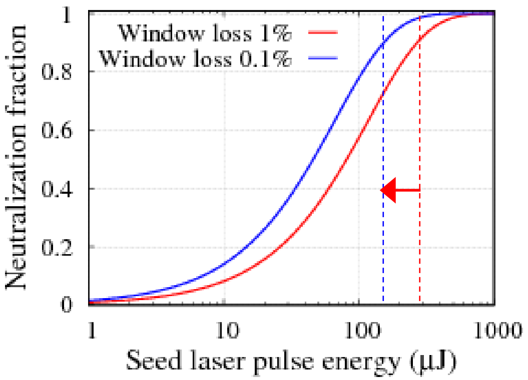
・Lower pulse energy, but approaching to J-PARC full injection pulse length of 500μs.

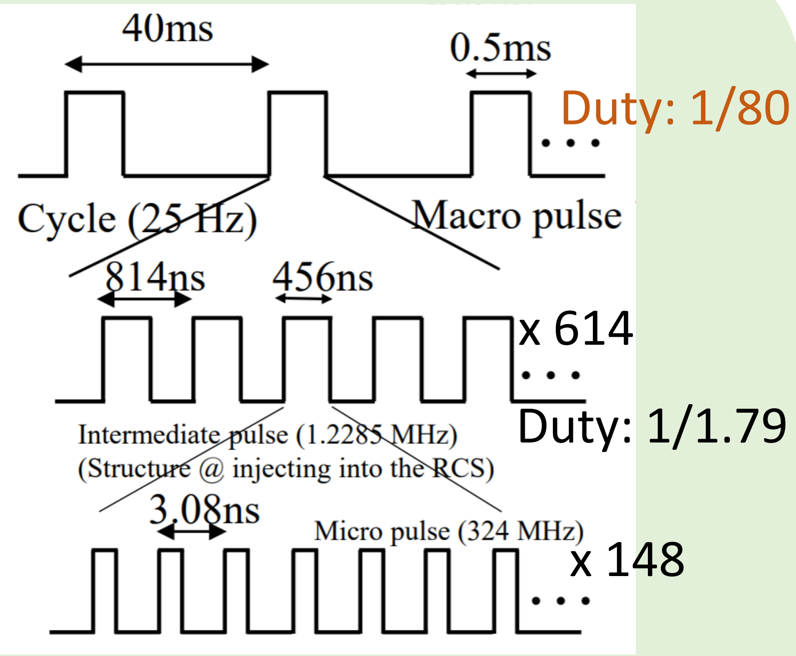
・Next step: Higher pulse energy

Low loss vacuum window & seeder power reduction scheme

◆ Low loss windows **(loss rate 1% → <0.1%)** are manufactured.







J-PARC beam structure.

→ Laser pulse should be at 324 MHz

● ~1/32 reduction of the seeder pulse.

→ 0.15 mJ/pulse → 4 mJ @ 32 reflections→ 90% neut.

● Reflections 32 → 64 and more are also in consideration.

→ Seeder: 0.1 mJ/pulse ***→ Easily achievable!***

For > 90% efficiency

Process	Laser	Pulse energy (mJ)
$H^- \rightarrow H^0$	YAG	6 → **0.09**
$H^0 \rightarrow H^{0*}$	UV	10 → **0.16**
$H^{0*} \rightarrow H^+$	YAG	11 → **0.17**

6 mJ × 324 MHz = 2 MW

↓

With duty ratio at 25 Hz:

2 MW × 1/80 = 25 kW

↓

With pulse recycling: 32

25 kW × 1/32 = 0.8 kW

↓

With pulse recycling: 64

25 kW × 1/64 = 0.4 kW

↓

More essential for the UV laser!

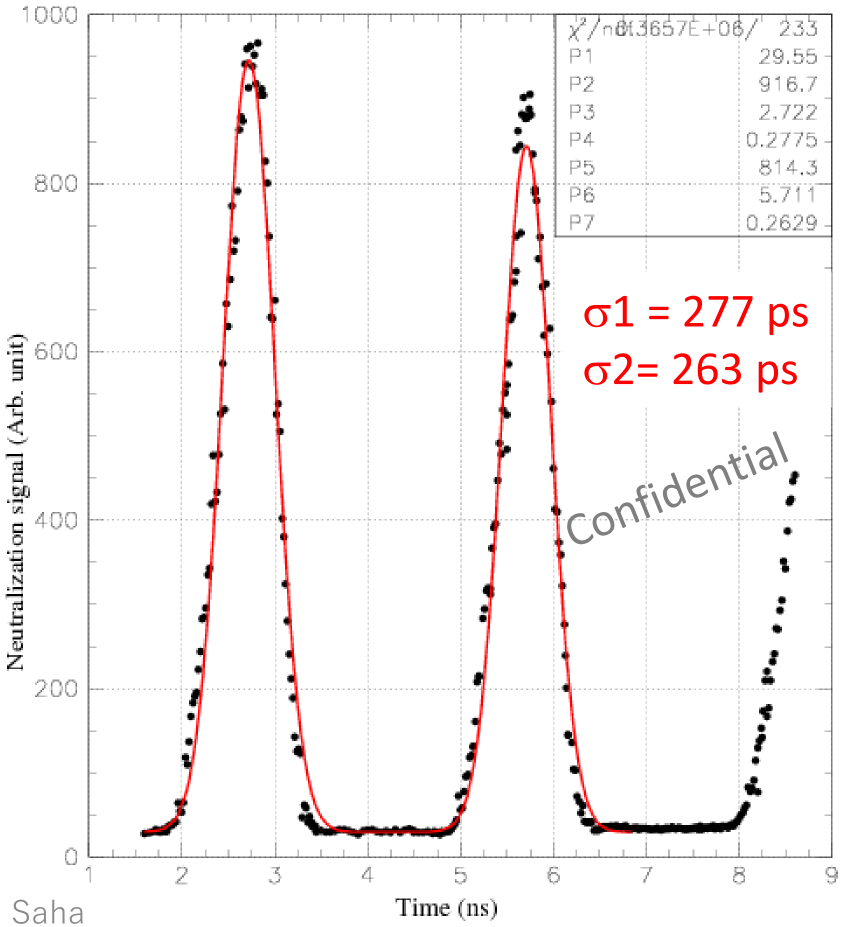
Demonstration of non-destructive H^- beam diagnostics

Longitudinal:

Laser time scan through the H- micro pulse.

→ **Laser time** vs. neutralization yield

→ Longitudinal H- micro bunch profile

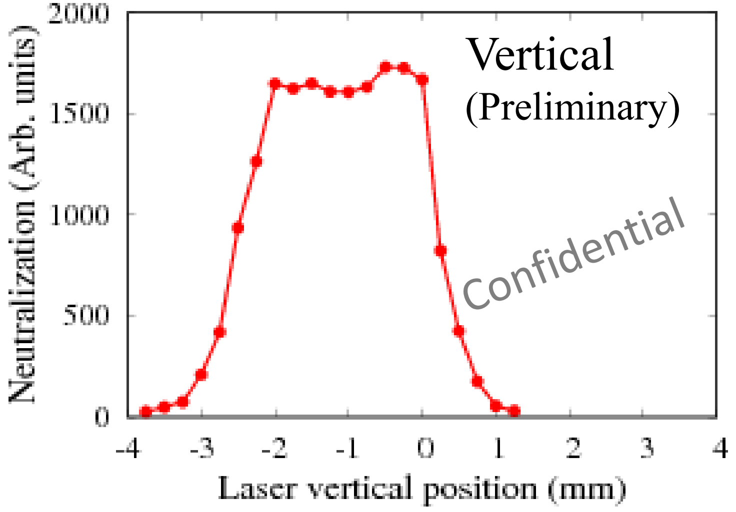


Transverse:

Laser position scan through the H- micro pulse.

→ **Laser position** vs. neut. Yield

→ Transverse H- beam profile



Summary and outlook

- To overcome the issues and limitations associated with a stripper foil, a laser stripping H^- CEI is under studied at J-PARC RCS.
- A POP demonstration of 400 MeV H^- stripping by using only lasers is under preparation.
- A prototype YAG laser system and also a multi-reflection cavity system to significantly reduce the seed laser power has been developed.
- The laser and the cavity systems have been successfully tested for 3 MeV H^- beam neutralization and further upgrades are in progress.
- High-reflective vacuum windows have been developed to achieve a negligible light losses.
→ *We expect ~3 orders of magnitude reduction of the seeder power.*
- **We have also demonstrated non-destructive H^- beam diagnostics at 3 MeV.**
- The laser system setup for 400 MeV test are in progress.
- **The POP test will be started in 2024.**