High efficient H⁻ beam stripping by multi-pulse train laser with multi-reflection imaging optics

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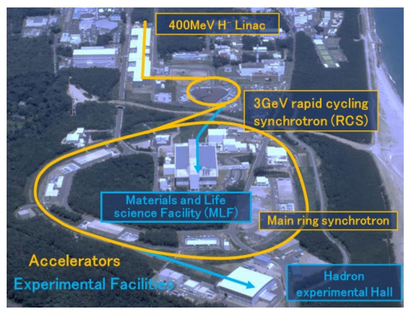
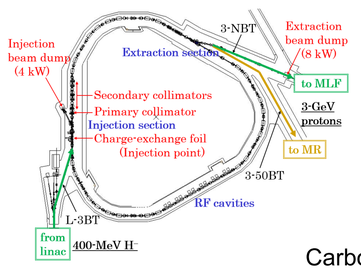
Background

Generation of intense proton beam (H+) by negative hydrogen ion (H-) charge exchange in J-PARC

J-PARC @ Ibaraki, Tokai village

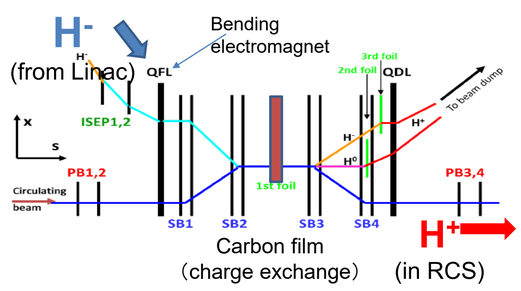


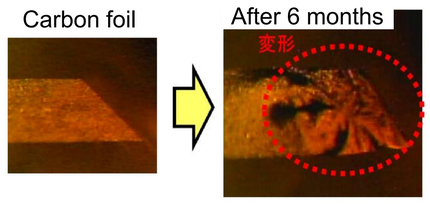


Extraction energy : 3 GeV
Repetition rate : 25 Hz
Particles per pulse : 8.33 x 10^{13}

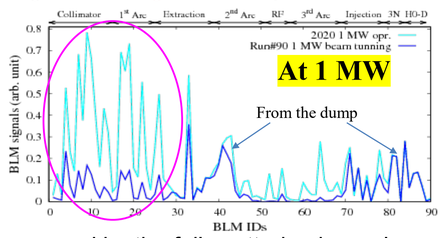
Average beam power : 1 MW

Charge exchange process by carbon film





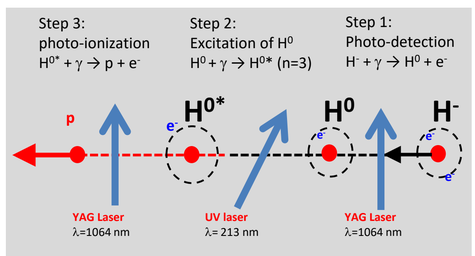
Large scattering loss → exposed to radiation



A short lifetime of the stripper foil and uncontrolled residual radiation caused by the foil scattering beam losses are two serious concerns for existing high-intensity proton accelerators as well as for considering next-generation multi-MW proton machines.

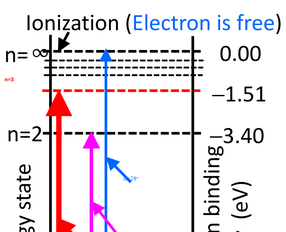
J-PARC laser stripping

Three step charge exchange process from H⁻ ion to H⁺ ion

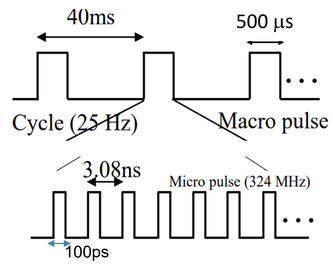


Principle of **400 MeV** H⁻ laser stripping at J-PARC

Process	E_{ph} (eV)	λ (nm)	α (deg.)	$λ_0$ (nm)
$H^- \rightarrow H^0$	1.67	1064	90	743
$H^0 \rightarrow H^{0*}$	12.1	213	50	102
$H^{0*} \rightarrow p$	1.67	1064	90	743



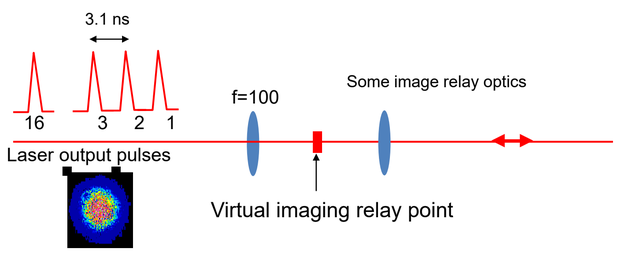
H- beam bunch structure (324MHz pulse train in 25Hz Macro pulse)

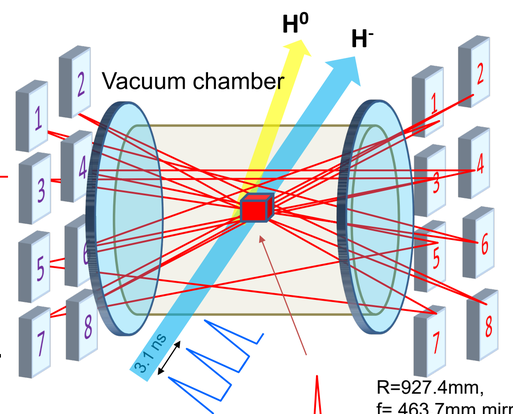


7mJ × 324MHz = 2.3 MW (impossible)

duty ratio at 25Hz
2.3 MW × 1/80 ≃ 28.8 kW
+ pulse energy recycling
(reasonable)

Multi–reflection laser cavity system (Pulse recycling)
⇒To significantly reduce the laser power

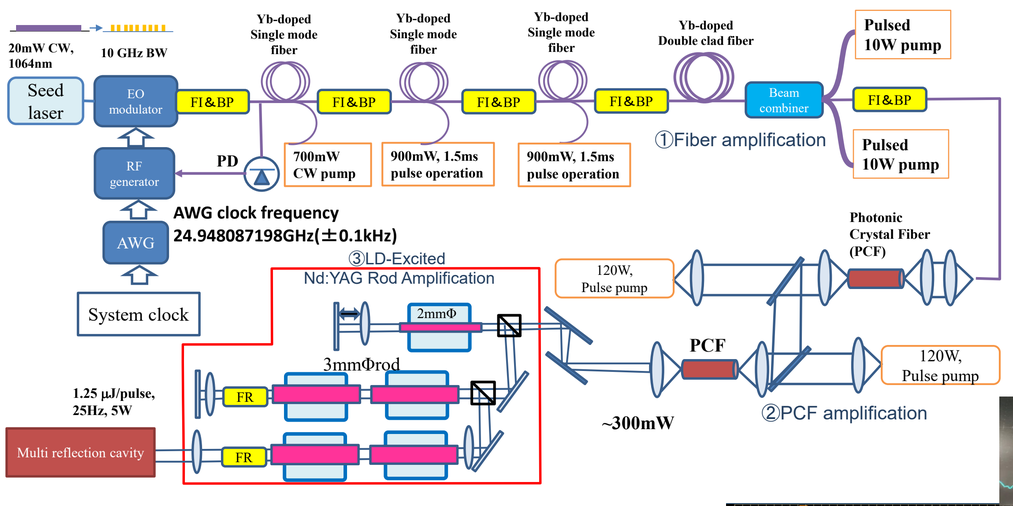


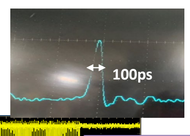


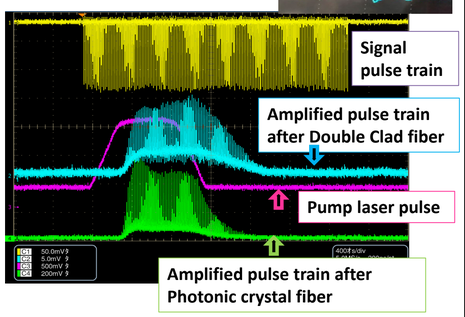
Key feature (achievement):
- Superimposition of 32 pulses at the ion beam interaction point. (using polarization)
- Imaging relay using by some image relay optics and cavity mirrors.

1+2+…+16 × 2
=32 times overlapping
(by using polarization)

Laser system for charge exchange



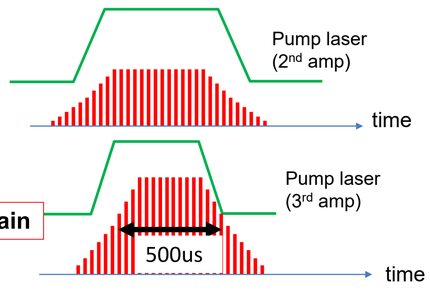




Point 1.
Input the slow-slope rectangular pump laser.

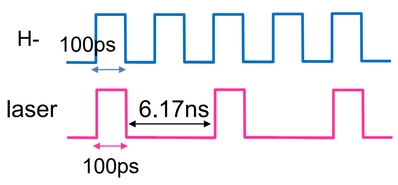
Point 2.
Seed pulse train should be longer than pump laser.

= **Uniform intensity pulse train**



3 MeV H⁻ neutralization study in 2022

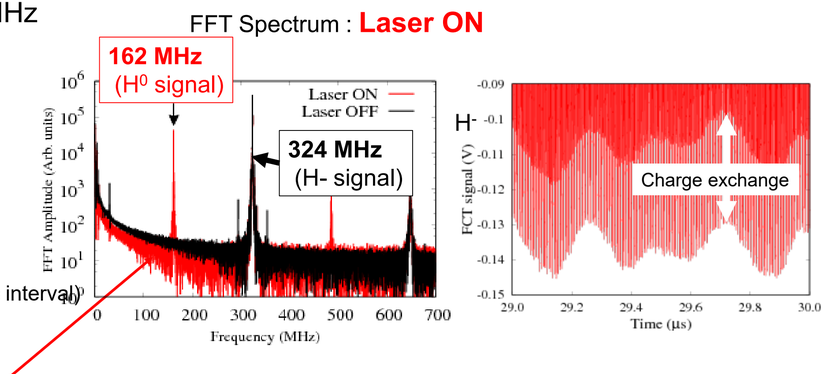
Laser operation at 162.00000 MHz for 324 MHz ion beam



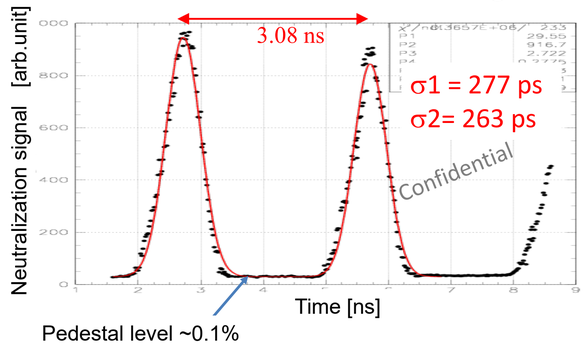
Laser pulse frequency synchronized to alternative H- pulse (6.17 ns interval)
→ Should appear signal at 162 MHz peak if H- stripping occurs.

= Easy to check exchange efficiency on-time.

FFT Spectrum : **Laser ON**



Measurement of longitudinal H⁻ bunch profile

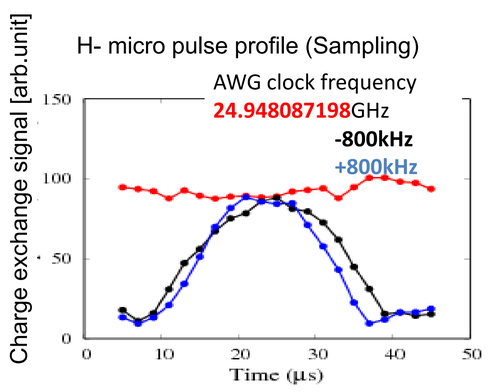


- ◆ Laser scanned through the H⁻ bunch with 20 ps interval.

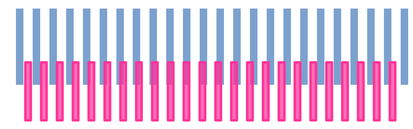
Bunch profile obtained from the neutralization yield.

- ◆ Potential application for simultaneous and online monitoring of the H⁻ bunch profiles throughout the linac.
→ **Next effort**
- ◆ Also, easily applicable to present FNAL Linac /PIPII linac.

Single shot measurement of H- micro pulse temporal profile: Sampling oscilloscope by the shift of laser repetition frequency



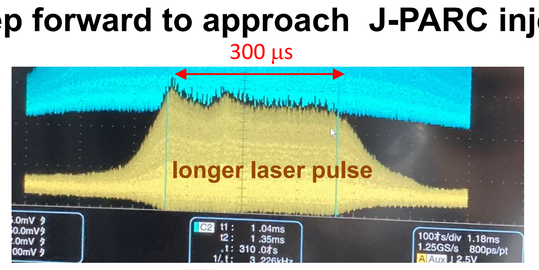
Measurement of charge exchange efficiency for each pulses ↓
H- micro pulse (324MHz fixed)



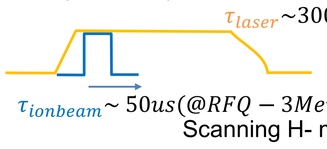
Laser pulse
(324±α MHz by AWG control)

→ *Real-time bunch shape monitor of H- macro pulses*

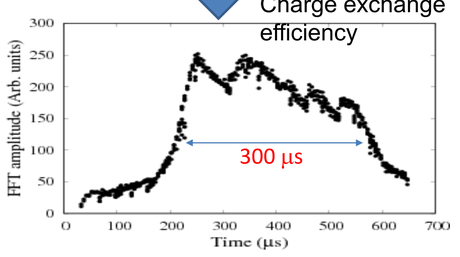
A step forward to approach J-PARC injection pulse length of 500 μs



- Laser pulse length was extended by reducing the energy.
- Laser scanned at 30 μs step delay through the 50 μs ion beam pulse.

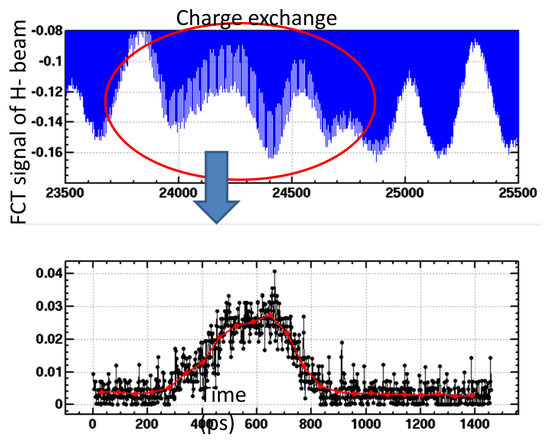


Charge exchange efficiency



・The charge exchange efficiency was lower but, obtained almost flat neutralization for about 300 μs pulse duration.
→ A step forward to approach J-PARC injection pulse length of 500 μs.

Single shot longitudinal profile measurement throughout the macro pulse by intentional (arbitrary) deviation of the laser pulse frequency



6.001 | 6.001 | 6.001 | ……..

Analysis method considered:
Raw data → FFT → Reverse FFT (Time domain)

Multiple profiles throughout the H- macro pulse have also been obtained.

Conclusion

- EO modulated ps pulse laser system are successfully developed.
- Accuracy in temporal axis is better than 10^{-8} in 25GHz.
- We obtained full flat neutralization for 50μs duration at RFQ test stand.
- 25% neutralization efficiency is achieved with only 1.25μJ pulse energy.
- New temporal bunch shape monitoring method for relativistic proton is demonstrated.

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