H^- stripping: Operational issues and Challenges at high-energy, high-intensity stripping

International MUON Collider Collaboration

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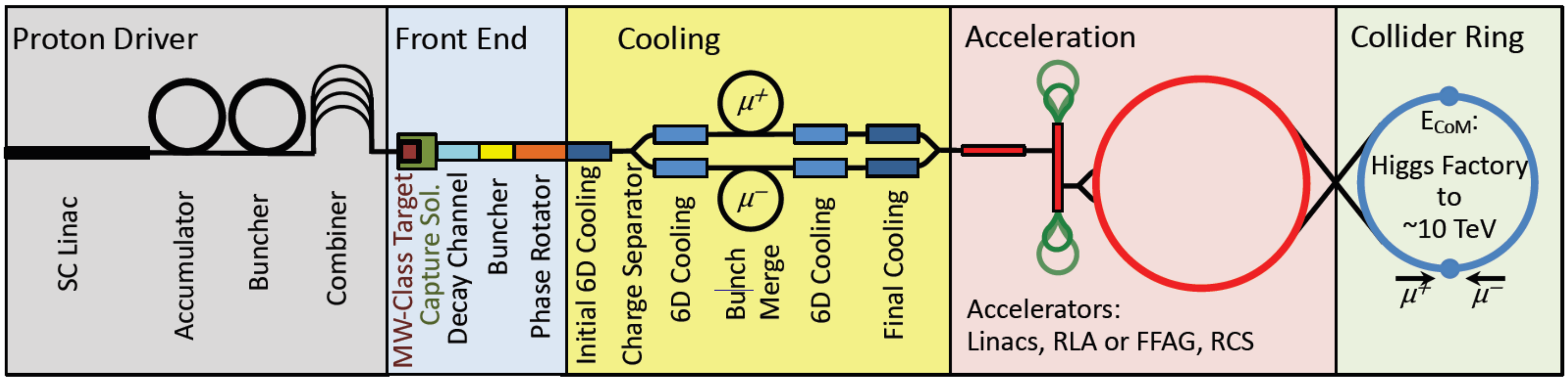
Background of this talk

A high intensity proton driver is needed for the Muon Collider.
Intensity: ~ 2 MW → Higher than existing to date.
The challenges are thus beyond those facing in the running machines to date.



A high-energy and high-intensity SC H^- linac with successive charge-exchange injection into a storage ring* are in consideration.
(* A rapid cycling synchrotron (RCS) could also be an option)

Overview of the operational issues in a high-intensity proton driver (J-PARC RCS) and high-energy stripping challenges are presented.

High-power H^- charge-exchange challenges

The H^- charge exchange injection (CEI) is an efficient way to increase the proton beam power with multi-turn injection into a synchrotron or storage ring.
The beam loss can be kept sufficiently lower as compared to p injection.

A stripper foil is conventionally used for an H^- stripping to proton.
However, this becomes complicated and have several following issues, especially dealing with high-intensity beam.

- Lifetime of the stripper foil.
- Maintaining and controlling the partially stripped (H^0) and unstripped H^- and their proper disposal.
- Excited state of H^0 and the beam loss from H^{0*} decays outside the aperture.
- Stripped electron collections.
- Beam loss, especially uncontrolled ones caused by the foil scattering.

→ An optimum transverse painting (TP) at injection is needed to minimize foil hitting of the circulating beam during multi-turn injection.

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Overview of running high-intensity (MW class) proton machines

- SNS in Oak Ridge: 1.4 MW designed
- RCS at J-PARC : 1 MW designed

Parameter	SNS in Oak Ringe	J-PARC RCS
Type	Storage ring	Synchrotron
H^- IS peak (mA) & inj. beam power (MW)	**< 40** **1.4**	**> 50** **0.133**
Inj. pulse (ms)	1	0.5
H^- stripping type & stripping efficiency (%)	Multi-turn H^- CEI by foil 95%	Multi-turn H^- CEI by foil **99.7%**
Ein / Eout (GeV)	1 / 1	0.4 / 3
Beam power (MW)	1.4* (1.5 E14/pulse)	~1** (~1E14/pulse)
SC tune shift	**~0.1**	**~0.15**

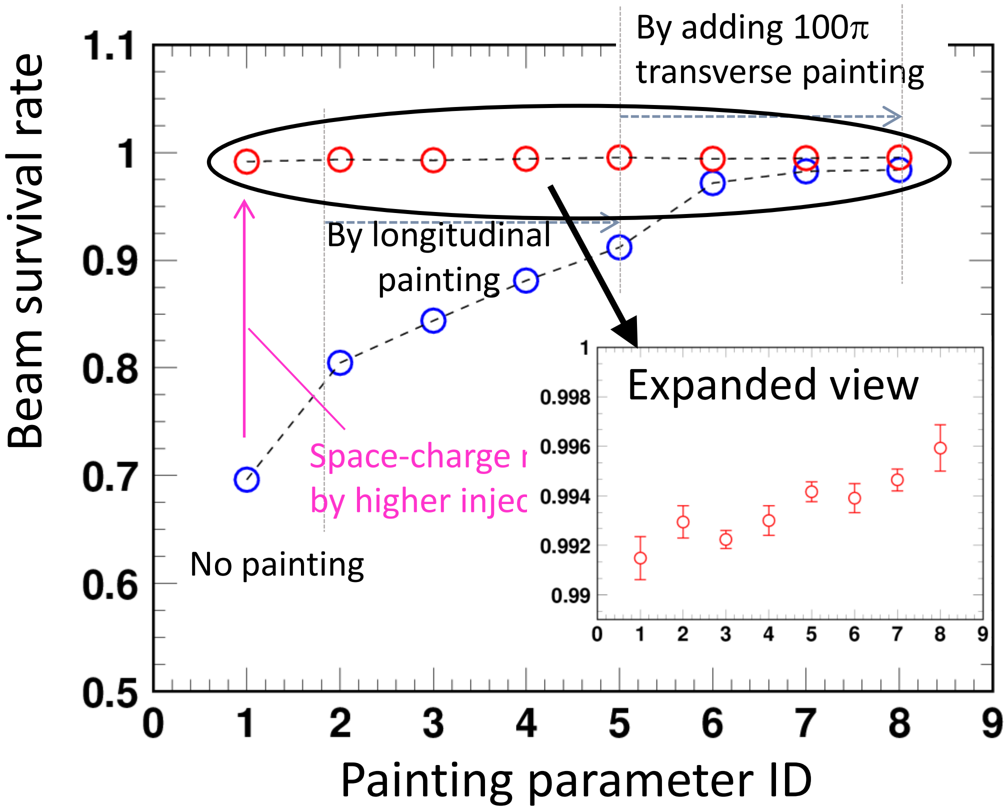
* 1.55 MW to date. Upgrading for > 2 MW (By increasing inj. beam energy and peak current)
** ~ 1 MW to date. Demonstrated 1.5 MW potential. Studying towards 2 MW!
(By increasing injection pulse length & peak current)

- ***A multi-MW beam power is thus not that far!***
- ***A higher injection energy has a significant benefit for SC mitigation.***

Higher injection energy benefits for SC mitigation

○ E_{inj}=181 MeV, 539 kW-eq. intensity

○ E_{inj}=400 MeV, 553 kW-eq. intensity



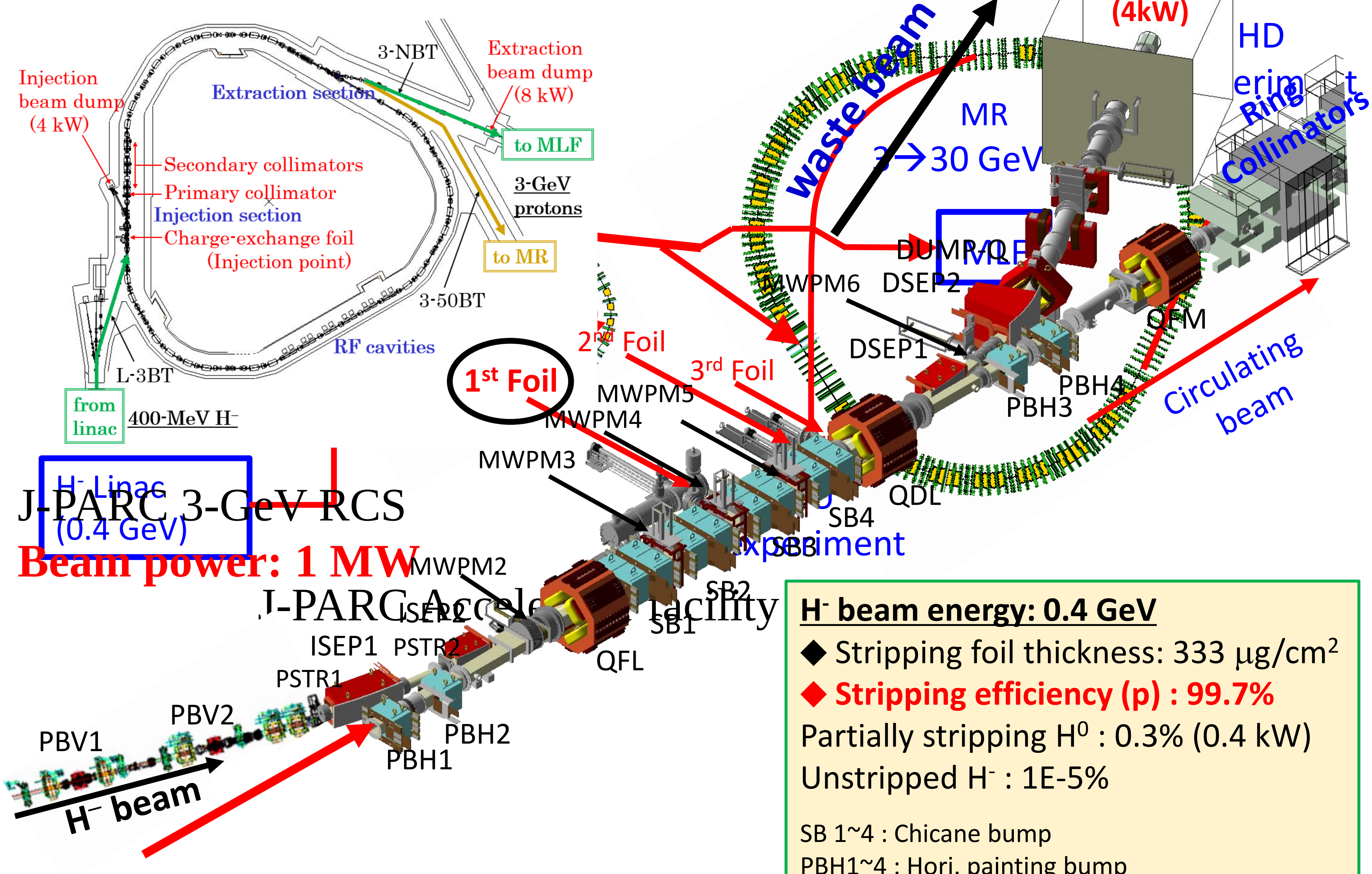
Laslett tune shift at inj. energy:

$$\Delta\nu = \frac{n_p r_p}{2\pi \boldsymbol{\beta^2} \boldsymbol{\gamma^3} \varepsilon} \frac{1}{B_f}$$

ID	ε_{tp} (π mm mrad)	RF V_2/V_1 (%)	f_2 (deg)	Δp/p (%)
1	-	-	-	-
2	100	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100	80	-100	-0.0
7	100	80	-100	-0.1
8	100	80	-100	-0.2

✓ This experimental data clearly show a significant gain from a higher injection energy as well as excellent ability of injection painting.

H^- stripping injection at J-PARC



H^- beam energy: 0.4 GeV

- ◆ Stripping foil thickness: 333 μg/cm²
- ◆ **Stripping efficiency (p) : 99.7%**

Partially stripping H^0 : 0.3% (0.4 kW)

Unstripped H^- : 1E-5%

SB 1~4 : Chicane bump
PBH1~4 : Hori. painting bump
PBV1~2 : Vert. painting bump

J-PARC H^- stripping issues at high-intensity operation

- Unstripped H^- (Controlled)

Determine by the foil thickness and those missing the foil.
Initially negligible (1E-5%), but problems when a foil degradation occurs and using a smaller size foil. Operational limit from the waste beam dump temperature.

- Partially stripped H^0 and their excited states (H^{0*}) losses (Partially uncontrolled):

H^0 yield depends on the foil thickness. H^{0*} decays determined by the injection chicane design.
H^0 yield: 0.3% (400 W). H^{0*} decay outside the aperture : 6W (Extreme case)
Recently chicane bump field is reduced by 20%.
At the SNS: Foil inside a magnet. Decays immediately. Loss negligible.
Otherwise > 2000 W loss could occur!

- Stripped electron collection (Controlled):

No issues so far. (SNS had problems at earlier commissioning stage)

- Foil lifetime (Controlled so far) *P.K. Saha et al., PRAB 23, 082801 (2020)*

Foil degradation determines the practical foil lifetime.
Temporary solution: Inserting the foil more to the beam. Foil hitting (scattering) rate increases.
At present ~1 month at 0.9 MW opr. Foil magazine can hold 15 foils.

◆ **Foil scattering beam losses (Partially uncontrolled):**

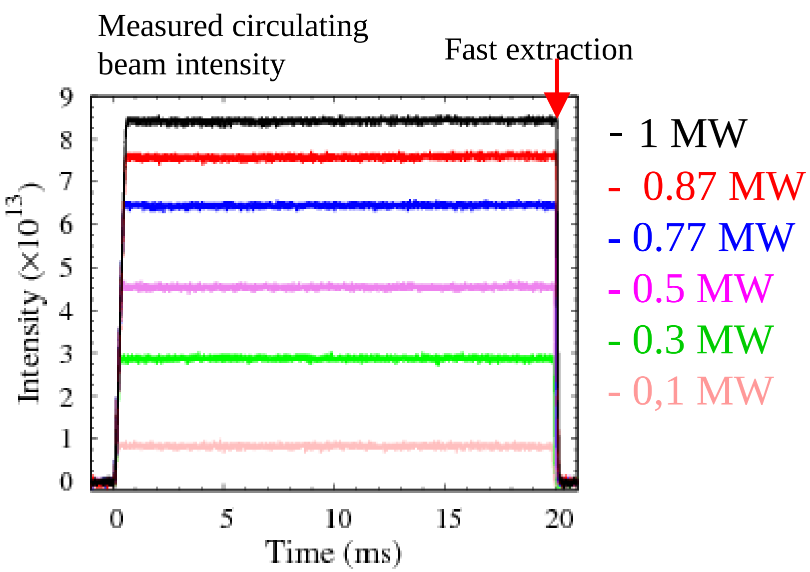
Several sources/mechanisms. Determined by the foil thickness & size, and foils hits.
TP minimizes the foil hits.
— Single Large angle Coulomb scattering: An additional injection collimator was installed in J-PARC.
— Energy straggling, Multiple scattering, Nuclear interaction: Determined by the foil thickness.
— Foil hitting rate of the circulating beam: Minimized by the trans. inj. painting and the foil size.
→ **One of the main issues at J-PARC at high-intensity operation.**

Foil scattering beam loss issues

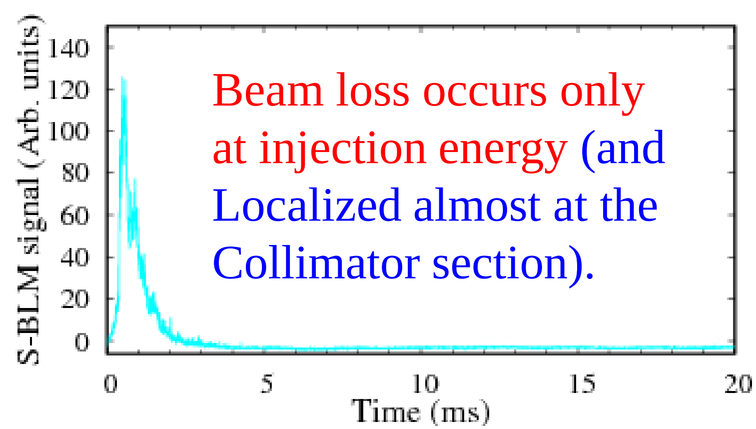
- Already achieved the designed 1 MW beam power and tested for a short time operation.
- Maximum Longitudinal and Transverse paintings (LP and TP) are applied for SC mitigation.
- The TP creates uniform beam distributions and also minimize foil hitting rate.

→ A higher TP reduced foil hitting rate, but TP area depends on the machine aperture, lattice design, realistic machine errors and imperfections.

→ Barely reached to the design TP of 216π mm mrad. **The average foil hits/proton is ~ 7.**



Time structure of the beam loss



● Estimated beam loss at 1MW: ~0.2% (0.3 kW) << Collimator limit (4 kW)!

◆ However, residual radiation at the injection area caused by the uncontrolled beam loss due to foil scattering of the circulating beam is rather high.

◆ ***Reduction of the foil scattering beam loss is a top priority!***

Reduction of the foil scattering beam losses

・Minimize vert. inj. beam size by manipulating vert. beta (β_y) of the injection beam.
・Minimize vertical size of the stripper foil.

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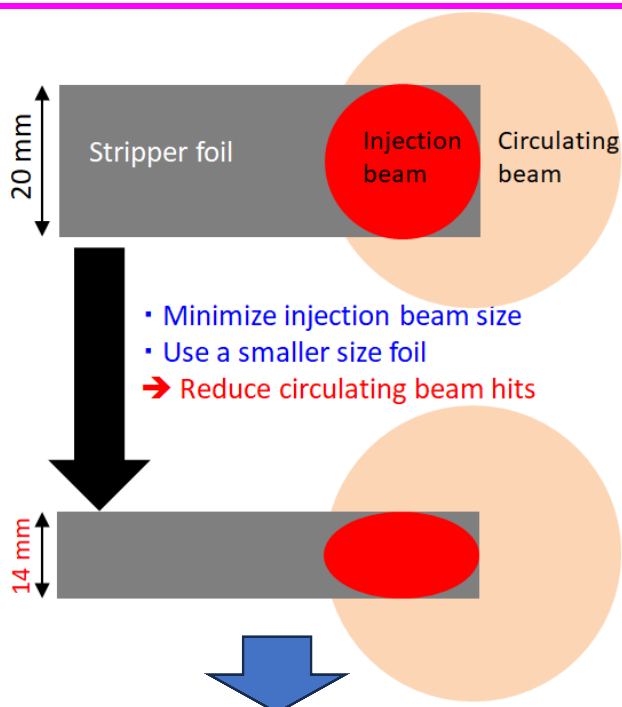
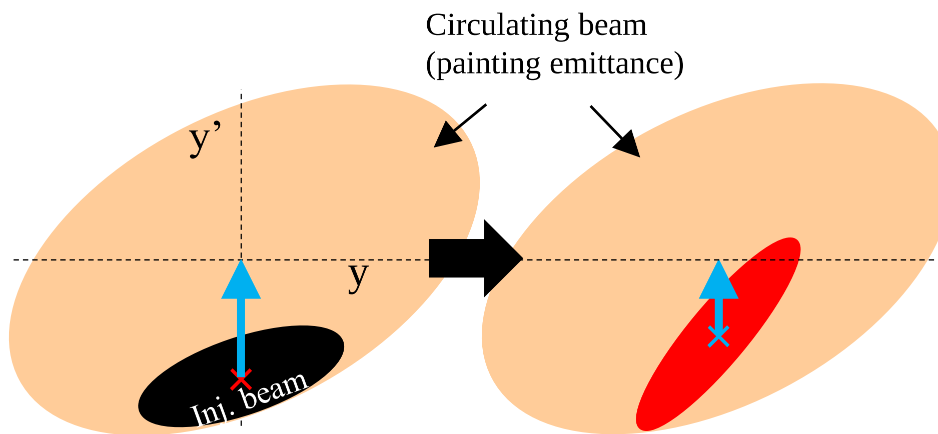
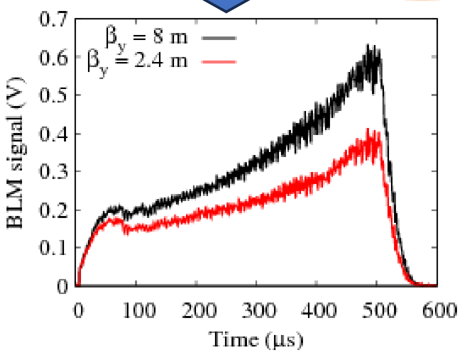
Optimize vert. transverse painting w.r.t. the smaller inj. β_y.





Optimization of vertical painting matching with injection beam. (y' : -3.3 → 2.82 mrad)
→ Minimize number of large amplitude particles.
➔ Reduce beam loss.



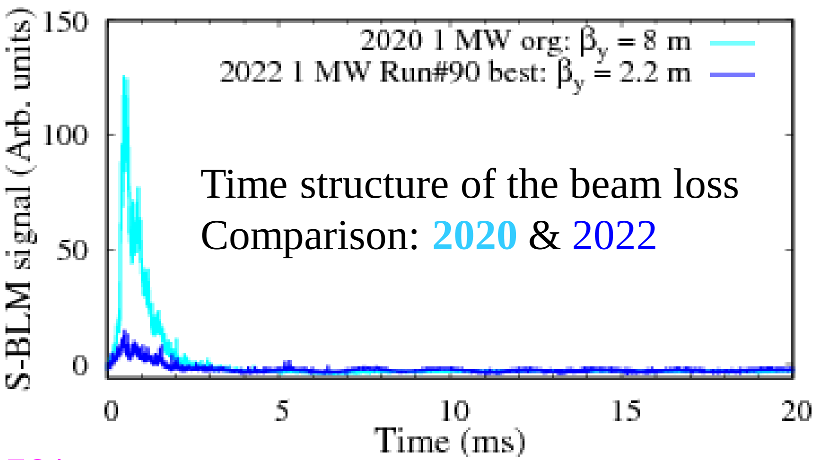
Measured foil scattering beam loss

Foil hitting rate (uncontrolled beam loss) 30% reduced.
The total beam loss at the injection, collimator and 1st arc sections are 40% reduced in average.

Latest beam loss mitigation at 1 MW

Based on numerical simulations and extensive beam studies following optimizations were implemented.

- ✓ Minimized injection beam and the foil sizes.
- ✓ Optimized betatron tunes.
- ✓ Optimized transverse and longitudinal paintings.
- ✓ Optimized correction of $\nu_x - 2\nu_y = -6$ resonance.
- ✓ Reduced $3\nu_x = 19$ effect by SB $\times$0.8 field
  (reduced K2 field intrinsic in the SB, H0* decays)



◆ The residual beam loss is estimated to be ~0.05%.

→ The residual beam loss is dominated by the foil scattering.

◆ We will try to further reducing the foil size.

→ Unstripped H^- beam power at the waster beam dump is an issue.

◆ To eliminate foil scattering beam losses and foil lifetime issues, we are **developing laser stripping of H^- charge-exchange injection.**

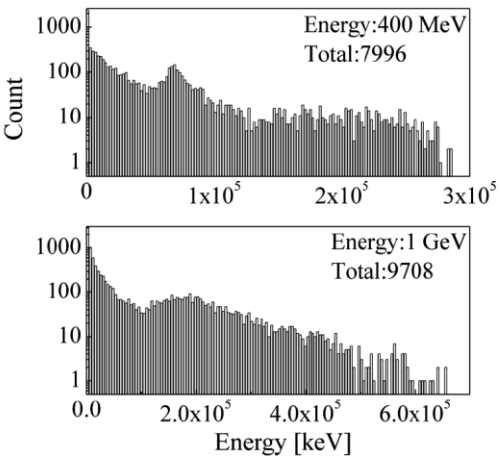
→ ***1 MW operation can be achieved with a negligible beam loss!!***

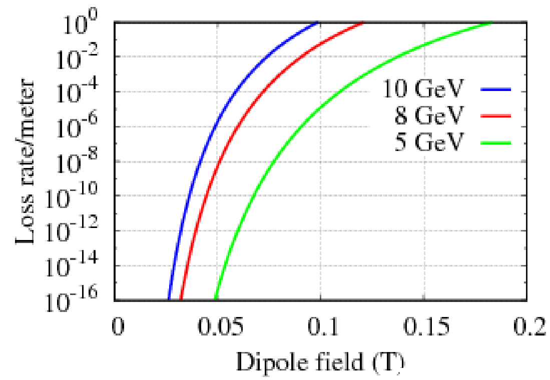
H^- stripping challenges at high-energy & high-intensity

MC case: 5-10 GeV, 2 MW

Earlier studies: Project-X design study at Fermilab (HB 2008, 2010 WS, David Johnson)
H- energy : 8 GeV with stripping injection

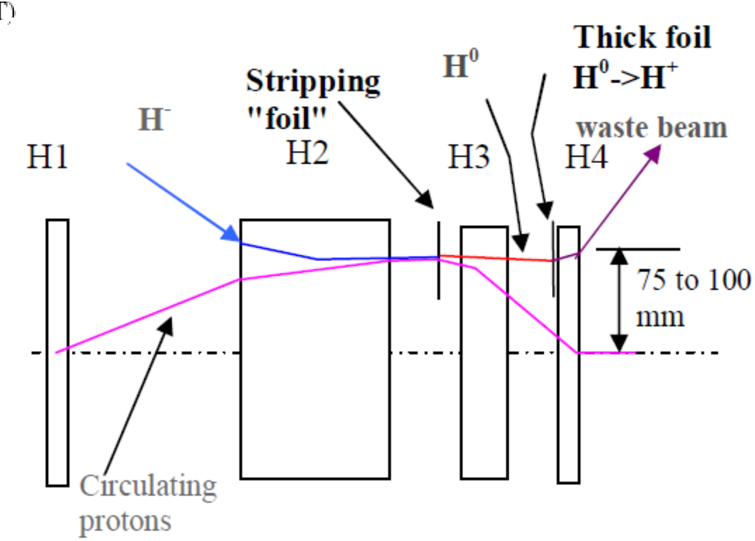
Additional concerns:





Lorentz stripping:
Curvature radius of the injection magnets should be long enough to keep a lower Lorentz stripping of the H^- beam.

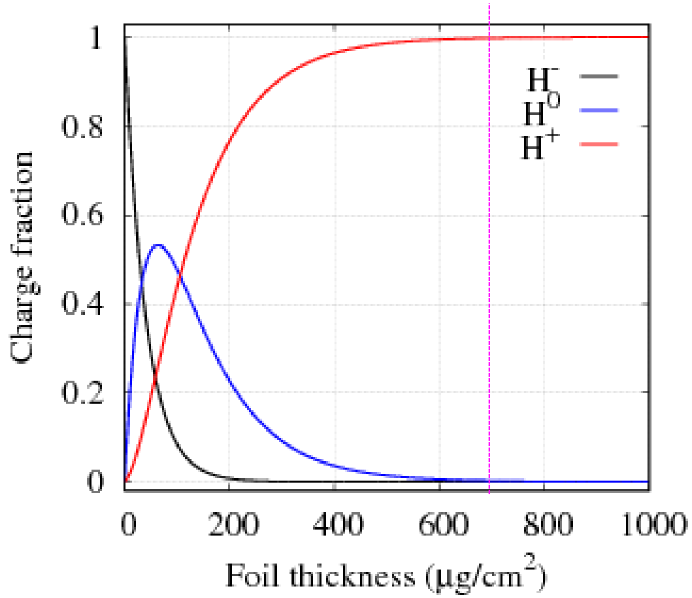
Kazami Yamamoto et al., PRAB15, 120401 (2012)
Higher secondary particles, hadronic flux at higher energy.
Residual dose rate around the foil:
1.6 times higher at 1 GeV as compared to 0.4 GeV!



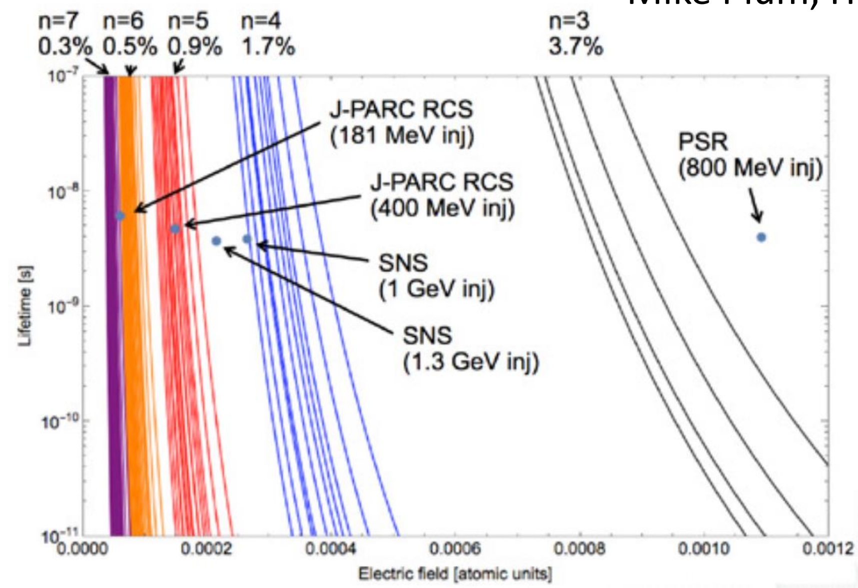
Foil scattering and foil lifetime issues should be further seriously concerned!

Needs careful injection design:
・Project-X (8 GeV) inj. case. David Johnson, HB 2008
・H2 should be moderate.
・H3 should be stronger to stripping H0* immediately.

Stripping efficiency and H^0 excited states loss



Mike Plum, HB 2016



Stripping efficiency of 8 GeV H- as a function of foil thickness
(Cross sections ref. W. Chou et al., NIMA 590, 1-12 (2008))

A foil thickness of 700 μg/cm² gives
H+ : 99.79%
H0 : 0.21%
H- : ~10-6%

Some of the H0 are in excited states (H0*).
Decays passing through a magnetic field due to $E = \beta \gamma c B$
E is higher for a high-energy beam.
The decay rates depend on the strength of the magnetic field.
→ Higher at higher H- energy
At 8 GeV, H0* > 2 are subjects to concern.

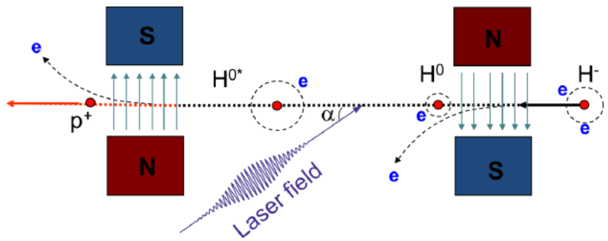
Next generation H^- stripping injection

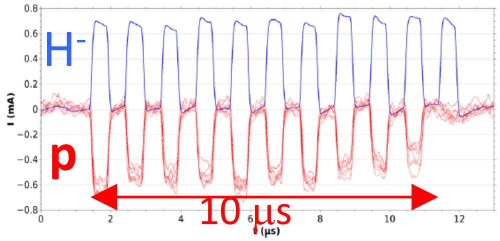
To overcome the issues and limitations associated with foil stripping as well as to realize next-generation multi-MW proton accelerator, we have to established an alternate method of H^- stripping.

→ ***Laser stripping?***

Laser stripping (LS) of H^- beam

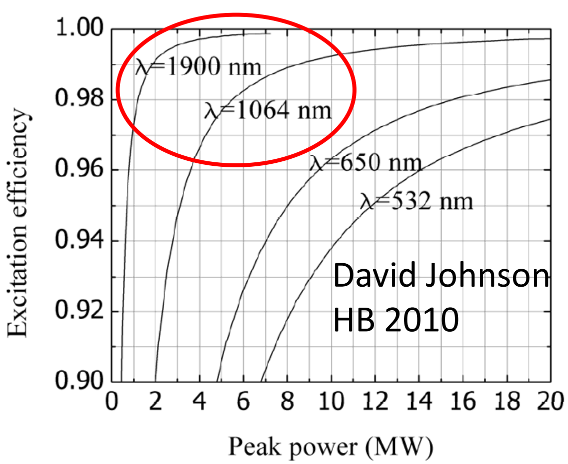
PRL 118, 074801 (2017)



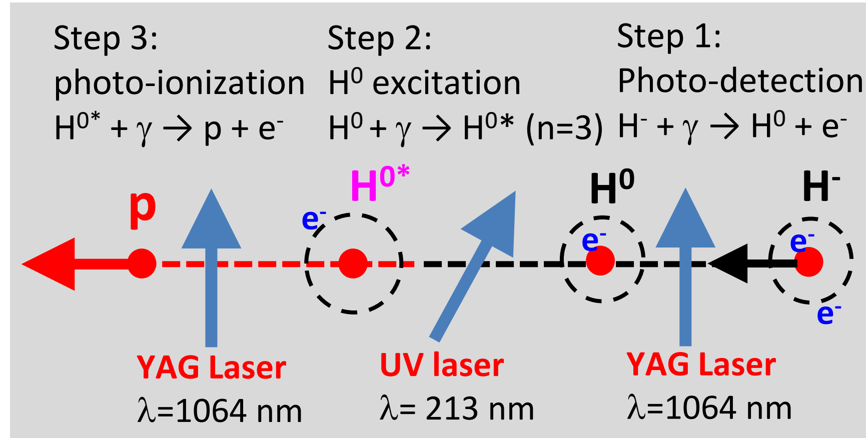


SNS (Oak Ridge): Laser-assisted H^- stripping

- High field magnets for stripping.
- UV laser (355 nm) for H^0 excitation.
- 10 μs stripping demonstrated.
- Studies for implementation are underway.



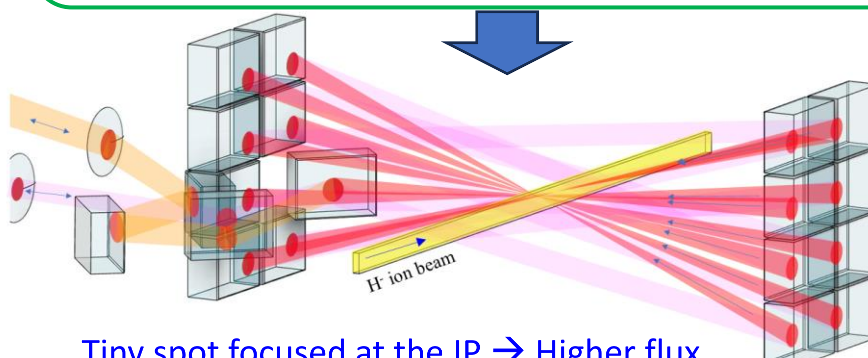
8 GeV H^0 excitation. Higher H^- energy is suitable.



J-PARC: H^- stripping by using only lasers

- IR lasers for stripping. Deep UV laser (~200 nm) for H^0 excitation.
- Demonstrated 40 μs H^- neutralization at 3 MeV.
- A POP test at 400 MeV stripping expected in 2024.

To reduced the laser energy, a multi-reflection cavity systems has been developed at J-PARC.
Seeder energy ～1/N, where, N = no. of reflections.
N = 32 achieved. Next trail for N = 64.



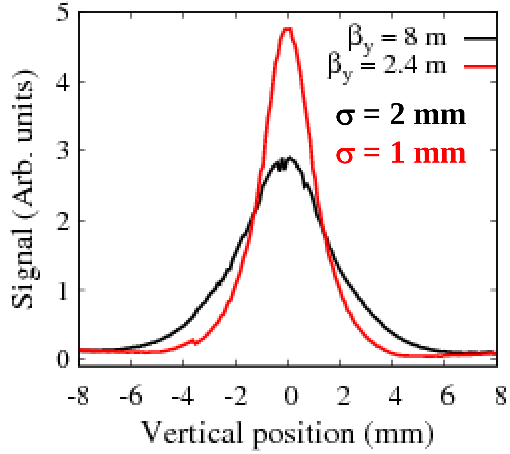
Tiny spot focused at the IP → Higher flux
Bigger spot at the mirrors → Reduce mirror damage

Summary

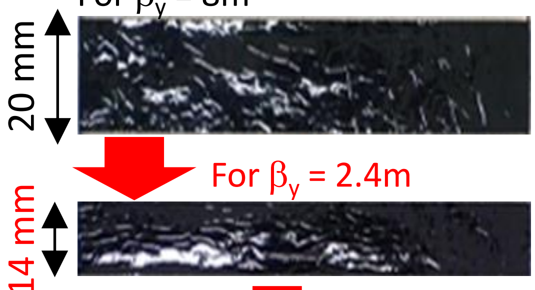
- The H^- stripping injection issues associated with stripper foil at J-PARC are discussed.
- The beam loss at the designed 1 MW has been reduced to an extremely low level to remain mainly the foil scattering beam losses.
- The foil scattering uncontrolled beam losses and the corresponding residual radiation at high-intensity operation is one of the concerning issues.
- To overcome the foil issues, a laser stripping of H^- is under development.
- Based on the J-PARC and SNS results so far, a multi-MW beam power for the MC can be achieved without serious issues.
- However, the H^- stripping at higher energy and higher intensity becomes more complicated and challenging.
- The injection system has to be designed more carefully.
- A laser stripping at higher H^- energies would be more feasible.

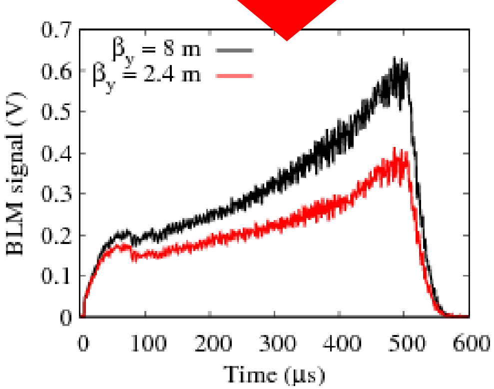
Extra slides

Implementation of a smaller β_y and a smaller foil

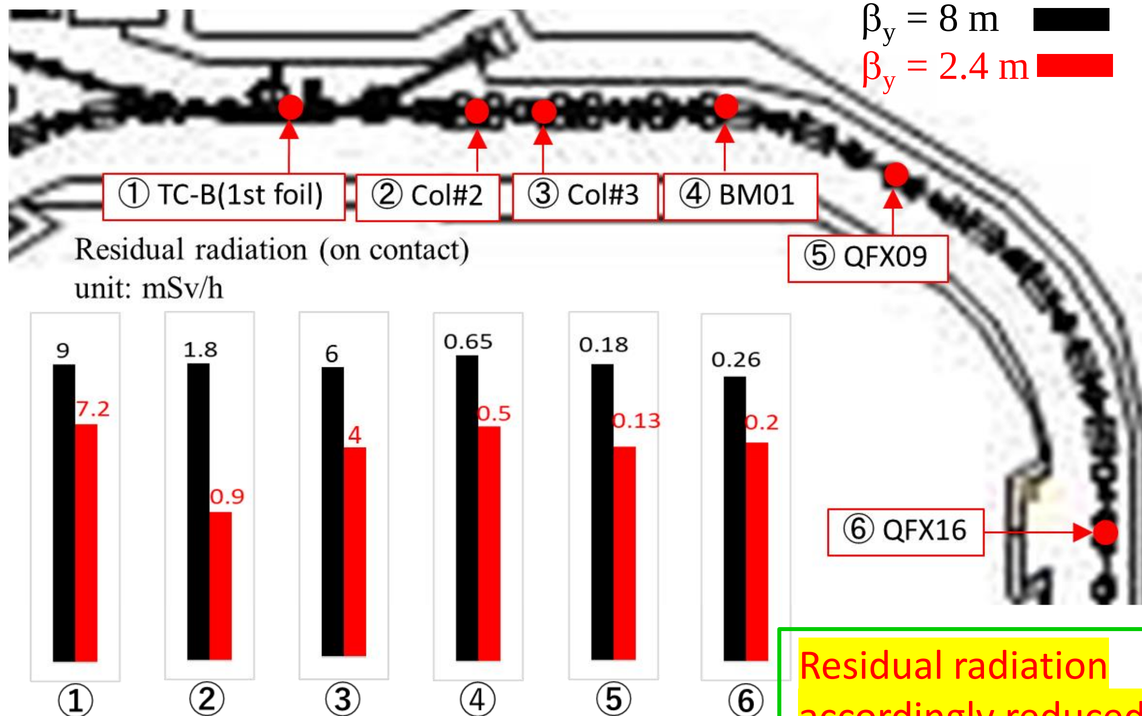


For β_y = 8m

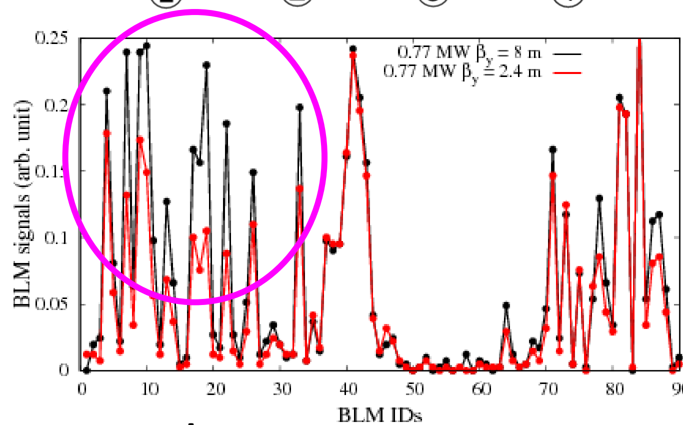




Measured foil hits: **30% reduced**



Residual radiation accordingly reduced



Implemented to RCS operation from 700 kW

Beam loss:

40% reduction at the injection, collimator and 1st arc sections.