Investigation of charge strippers for high intensity uranium ions

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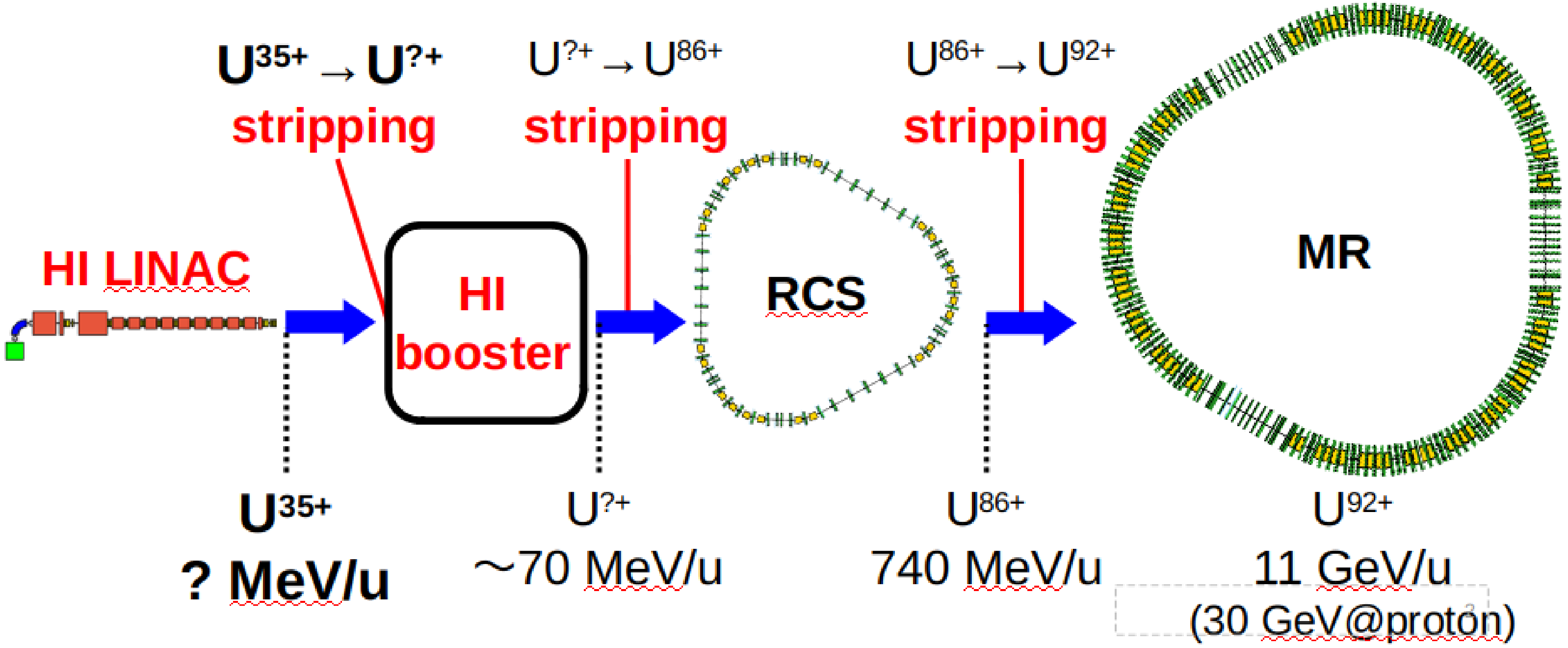
J-PARC Heavy Ion (HI) accelerator scheme



$U^{35+} \rightarrow U^{?+}$ stripping

$U^{?+} \rightarrow U^{86+}$ stripping

$U^{86+} \rightarrow U^{92+}$ stripping

HI LINAC

HI booster

RCS

MR

U^{35+}
? MeV/u

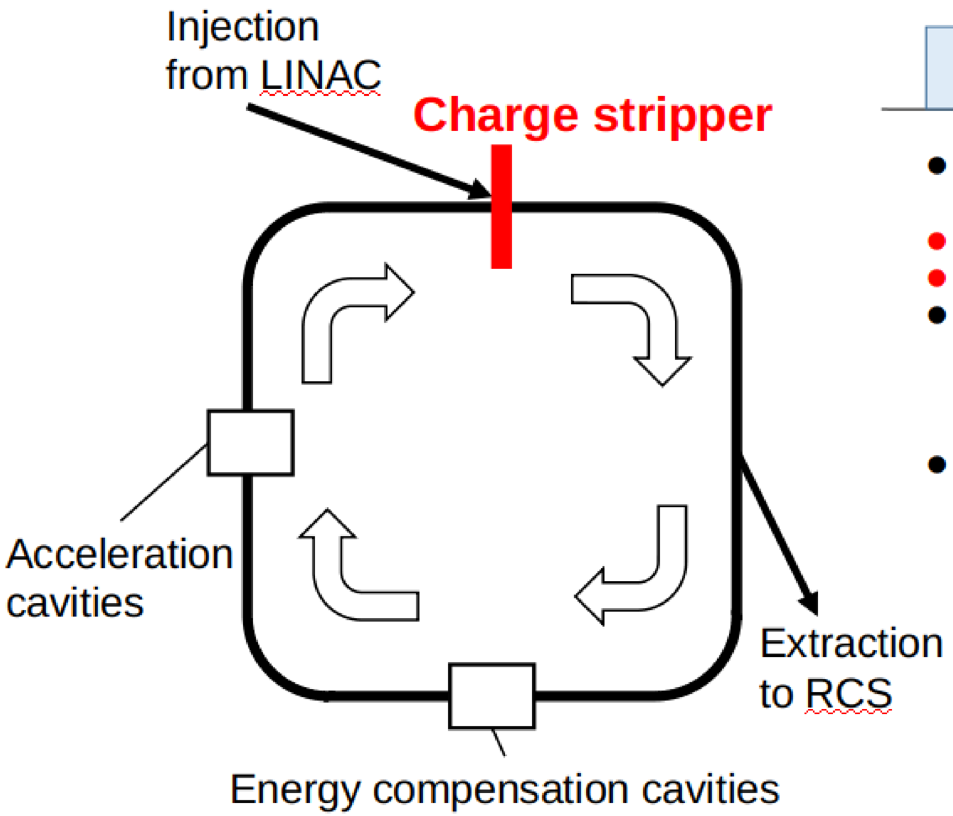
$U^{?+}$
~70 MeV/u

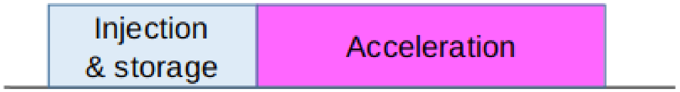
U^{86+}
740 MeV/u

U^{92+}
11 GeV/u
(30 GeV@proton)

[1] P.K. Saha et al., HIAT2015.
[2] H. Harada et al., to be published.

Stripping section at beam injection to the booster





- Both injected beam and circulating beam pass through the stripper every turn
- Compensation of energy deposit in the stripper
- Multi-charge acceleration ±2 charge states
- No change of the charge state distribution of the circulating beam

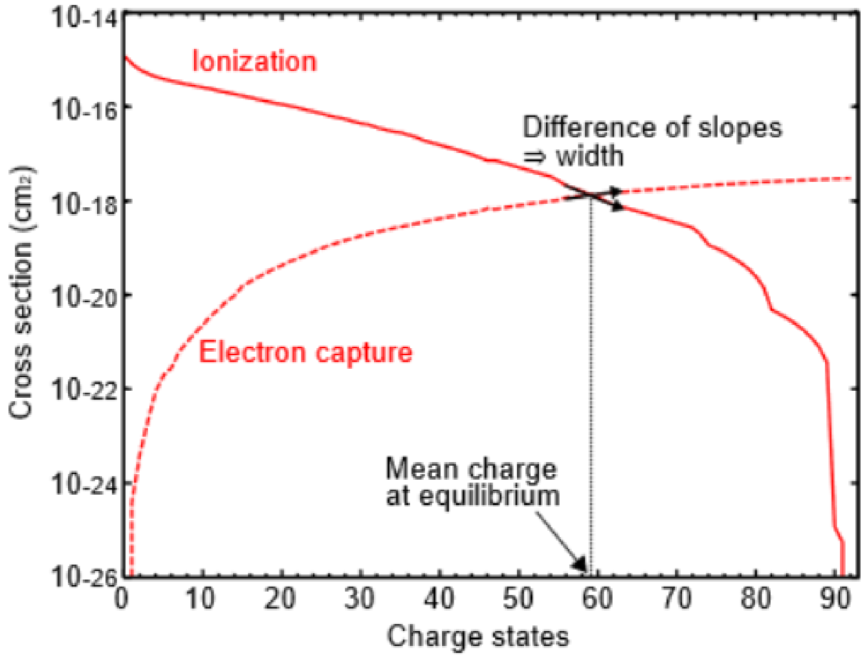
  Charge state is desired to be equilibrium by one path through the stripper
- Higher charge state is not required

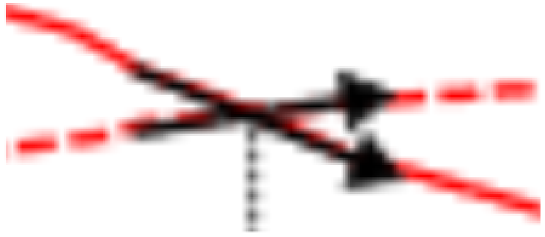
Thin stripper & narrow width are required.

[2] H. Harada et al., to be published.

Mean charge & distribution width

- Charge changing cross section **ionization σ_{ion}** and **capture σ_{cap}**





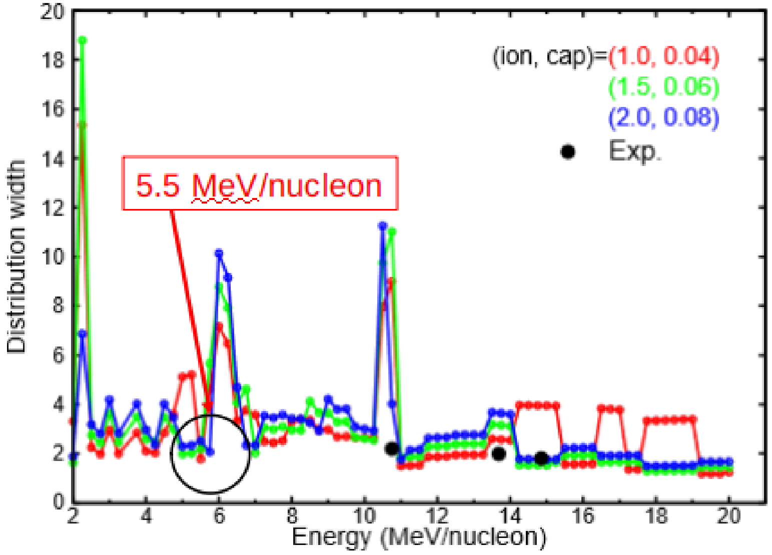
$$\sigma_{ion}(q,q+1) = \sigma_{ion}^{0}\exp[-c_{ion}(q-q_0)]$$
$$\sigma_{cap}(q,q-1) = \sigma_{cap}^{0}\exp[c_{cap}(q-q_0)]$$
$$width = \sqrt{\frac{1}{c_{ion}+c_{cap}}}$$

- Distribution width at the equilibrium charge state is determined by the *slopes* of the charge changing cross section

[3] Kuboki et al., INTDS meeting 2016.

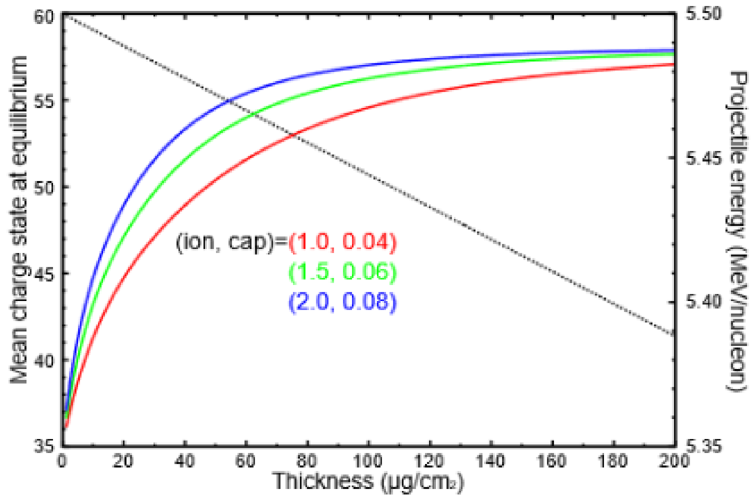
Width search

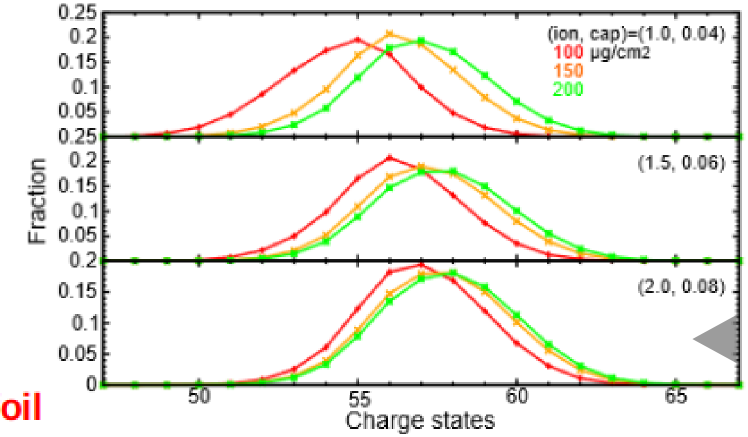
- Incident energy was searched so that the distribution width becomes narrower.
    - Scaling factor set for the cross sections was optimized by fitting the experimental data

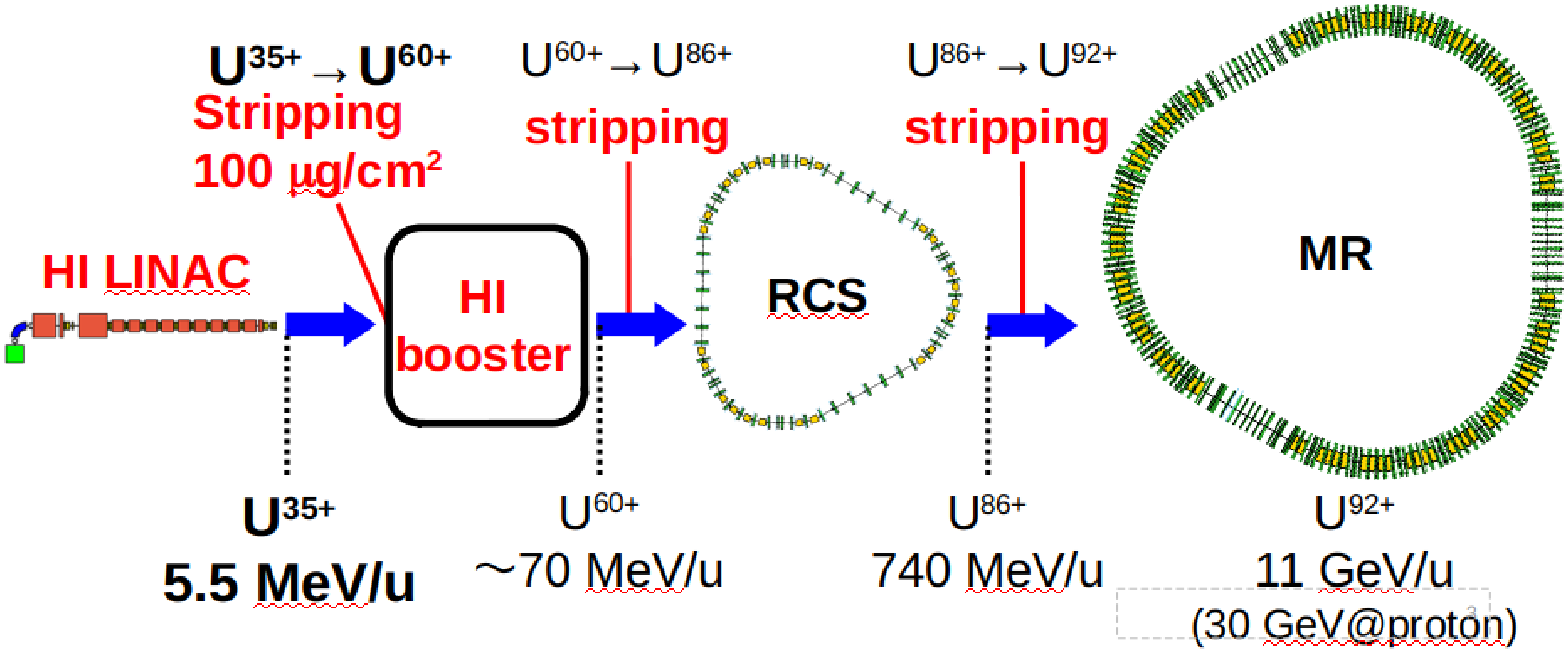


	From cross section	Calc. of distribution
1.0, 0.04	1.8	2.0
1.5, 0.06	2.2	4.3
2.0, 0.08	**2.5**	**2.1**

5.5 MeV/nucleon with 100 μg/cm² (0.45 μm) C-foil







$U^{35+} \rightarrow U^{60+}$

Stripping

100 μg/cm²

HI LINAC

HI booster

$U^{60+} \rightarrow U^{86+}$

stripping

RCS

$U^{86+} \rightarrow U^{92+}$

stripping

MR

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5.5 MeV/u

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Foil temperature calculation

Simplyfied model

- In advance of detailed realistic calculation.
    - Ignoring heat conduction
    - Constant temperature is assumed inside the beam pipe
    - Foil is cooled by radiation only

Differential equation to be solved

$\rho V c \frac{dT}{dt} = -2\sigma f \epsilon A_s \left(T^4 - T_0^4\right) + P A_s$

[4] C.j. Liaw et al., PAC99

P: Power input [W/m^2]	$P = 4.6939e + 11 \times d \times I$ (6837551 H 1 GeV in C)
$\frac{dE}{dx}$ [MeV/(g/cm^2)]	132972 (at U 5.5 MeV/u in C), 1.937 (at H 1 GeV in C)
d: Foil thickness [g/cm^2]	100 μg/cm^2 →0.5 μm
I: Beam current density [A/m^2]	
T: Foil temperature [K]	
t: Time [sec]	
ρ: carbon density [kg/m^3]	2000
c: Heat capacity [J/(kg·K)]	Another slide
A_s: Spot area [m^2]	$r_{\text{spot}} = 5$ mm was assumed.
V: Volume of the carbon foil [m^3]	Thickness 0.5 μm are assumed.
f: Radiation view factor	1
ϵ: Radiation emissivity	0.8
T_0: Room temperature [K]	300

Heat capacity & Thermal conductivity calc.

- Heat capacity c and thermal conductivity k depend on the temperature *T*.
- [5] Brady, Clauser, and Vaccari, "Materials Handbook" 14th Ed., McGraw Hill Book Company
  [6] "Handbook of Materials Science", CRC Press, 2nd Ed., Vol III.

In [4]:

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pio.write_image(fig,filename)
Image(filename)
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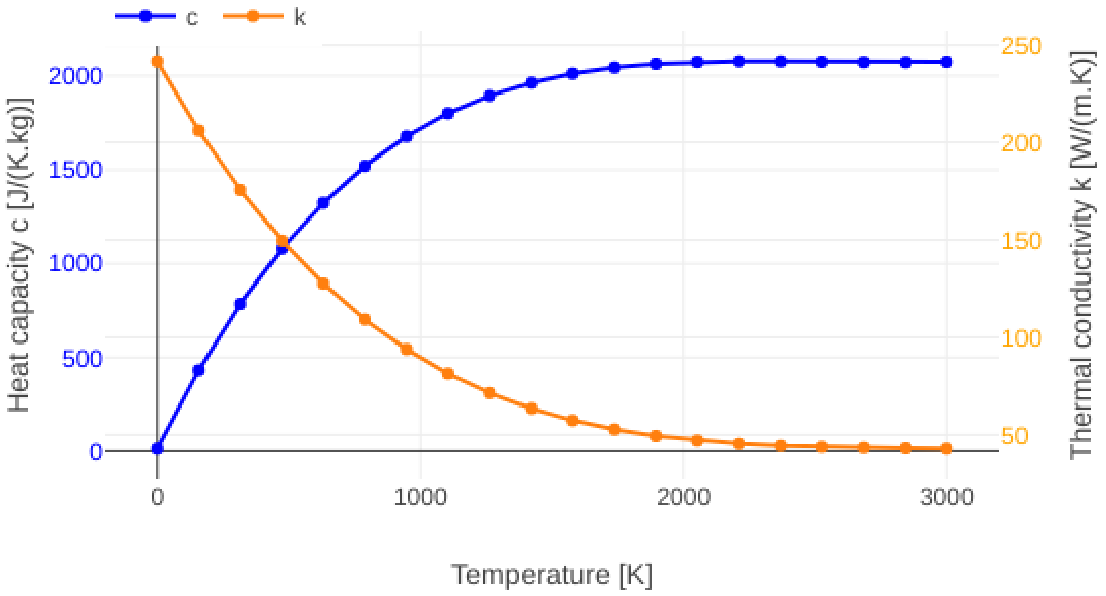
Out[4]:



Calculation condition

Repetition rate [Hz]	25 (same as J-PARC RCS)
Pulse length [msec]	0.5 (same as J-PARC operation)
Particles/pulse	1.0e+12 - 2.0e+13

In [12]:

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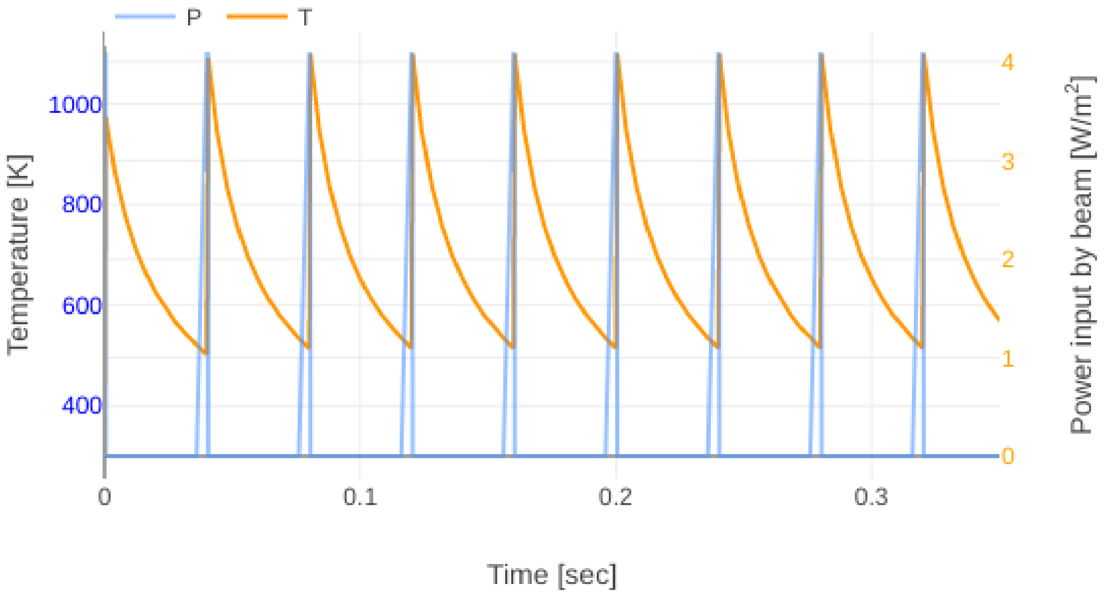
Out[12]:



Beam intensity limit: 1.3×10^{13} particles/pulse

Particle/pulse	Max. Temperature [K]
1.0e+12	1098
5.0e+12	2559
1.0e+13	3541
1.2e+13	3790
1.3e+13	3897
1.4e+13	3995
1.5e+13	4085
2.0e+13	4458

- Carbon melting point: 3973 [K]

Summary

- Condition for the 1st stripper of J-PARC HI booster: 5.5 MeV/u, C 100 μg/cm^2
- Temperature rise by the beam load was estimated in a simplified model (severe condition).
- Static carbon foil stripper can withstand up to 1.3×10^{13} particles/pulse

Future

- Rotating stripper or other stripper (fluid) should be considered as a candidate.
- Thermal analysis for rotating strippers and liquid strippers should be performed with realistic models (cooling system, ANSYS etc.).