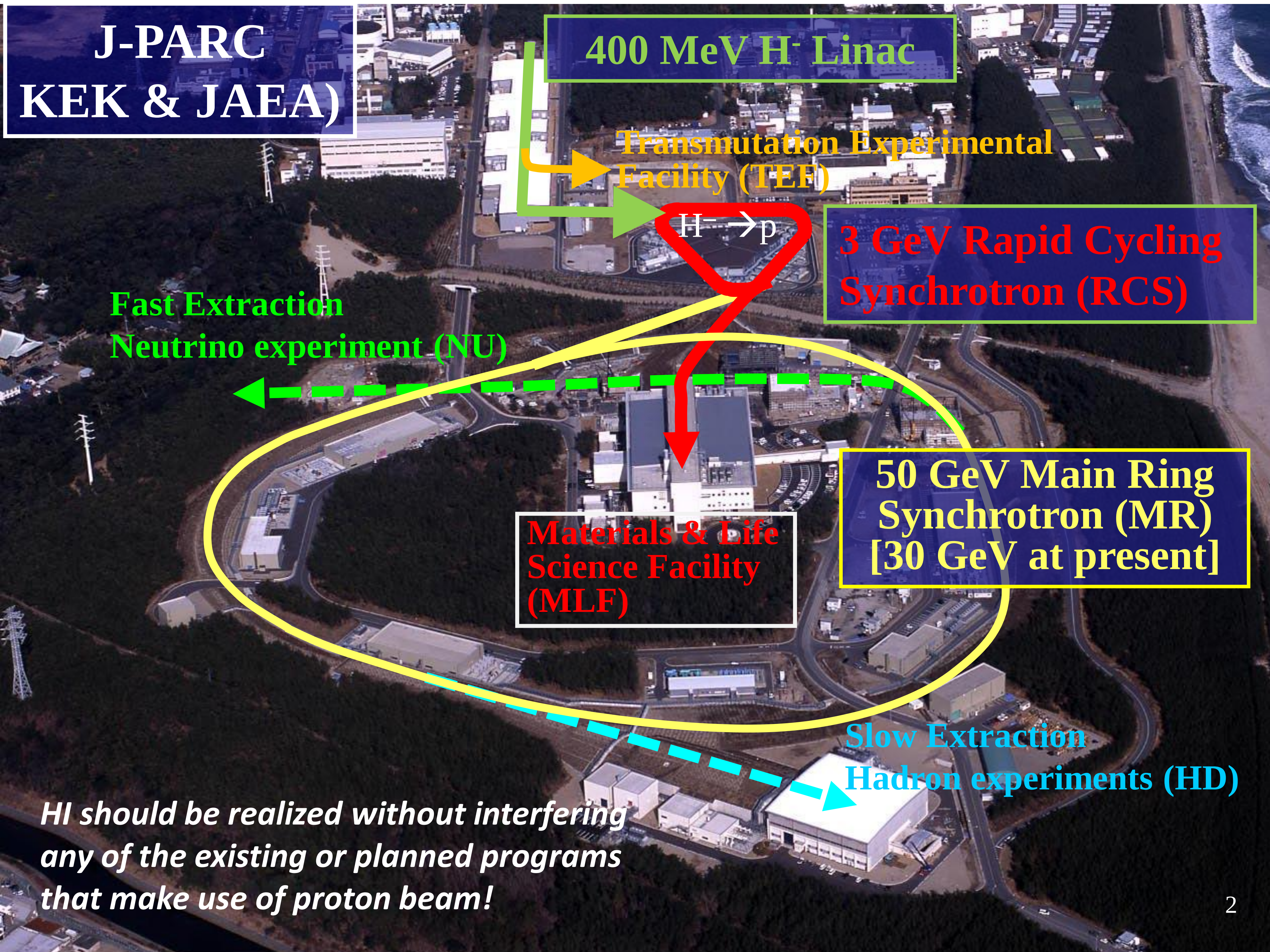
Feasibility studies of High-Intensity Heavy-Ion Beam Acceleration in J-PARC

P.K. Saha, H. Harada, M. Kinsho and M. Yamamoto

Japan Proton Accelerator Research Complex (J-PARC)

International Workshop on Strangeness Nuclear Physics 2017

Osaka E-C Univ. 12-14 March, 2017



HI should be realized without interfering any of the existing or planned programs that make use of proton beam!

Introduction

J-PARC is a multi-purpose research facility consists of 3 accelerators and several experimental facilities that make use of high intensity **proton beams.**

- The RCS successfully demonstrated 1MW beam acceleration.
  (At present, 0.15 MW beam to the MLF and 0.72 MW-equivalent beam to the MR)

- The MR is approaching towards the designed beam power.
  FX operation: 470 kW at present
  SX operation: 42 kW at the latest

In the next plan of J-PARC, HI program is one of the candidates.
Therefore, we have started feasibility studies to adapt HI acceleration scheme in J-PARC by utilizing the RCS and MR.

- RCS plays the key role to realize HI beam in J-PARC.

- *In this presentation, feasibilities studies for high intensity HI beam acceleration mainly in the* ***RCS*** *are reported.*

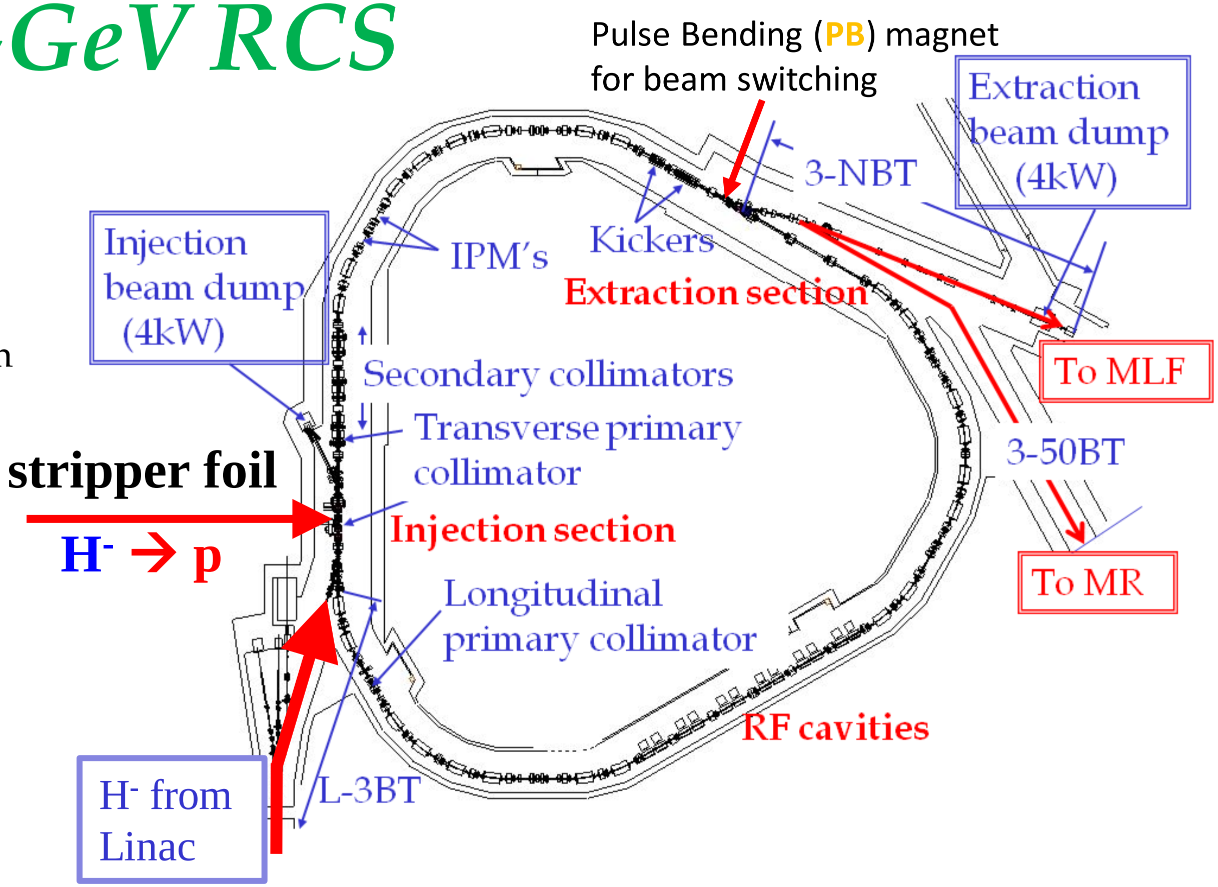
Outline:

1. Overview of J-PARC 3-GeV RCS
2. Brief introduction of J-PARC HI physics program
3. HI acceleration strategy, an accelerator scheme
4. Feasibilities and numerical simulation results of U^{86+} acceleration in the RCS
5. Expected beam intensity in the MR
6. Summary and Outlook

Overview of 3-GeV RCS

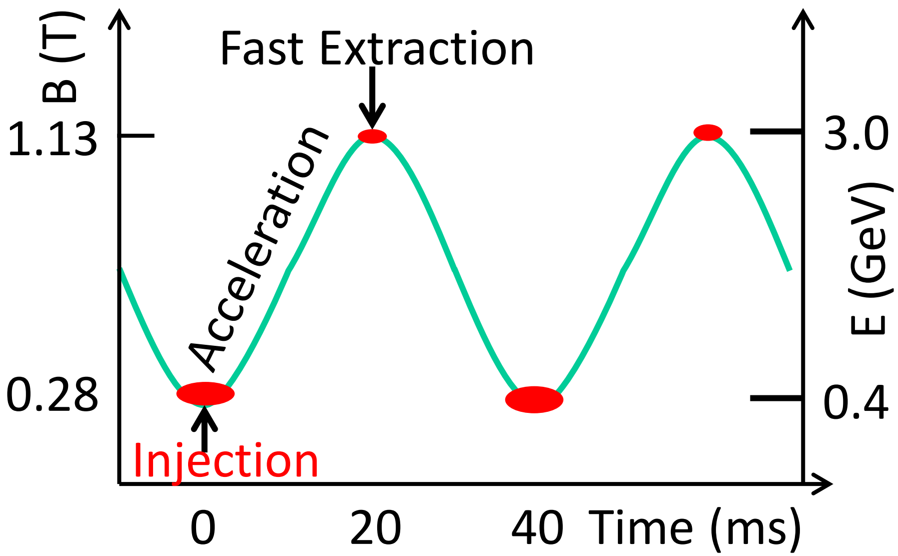
Design parameters:

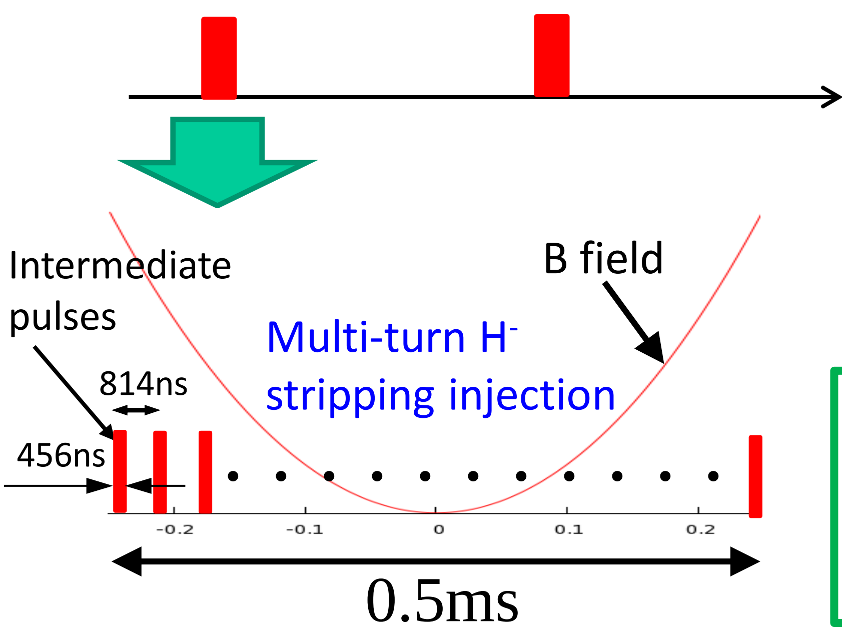
Particle	**p**
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
No of bunch	2
Injection energy	**400 MeV**
Extraction energy	**3 GeV**
Repetition rate	25 Hz
Particles per pulse	**8.3e13**
Output beam power	**1 MW**
Transition gamma	9.14 GeV
Collimator Limit	4 kW (3%@ inj. beam power)

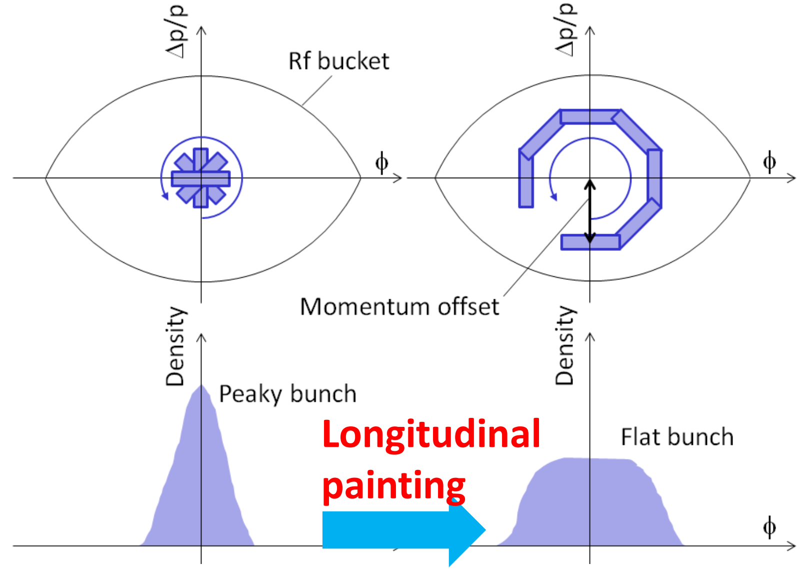


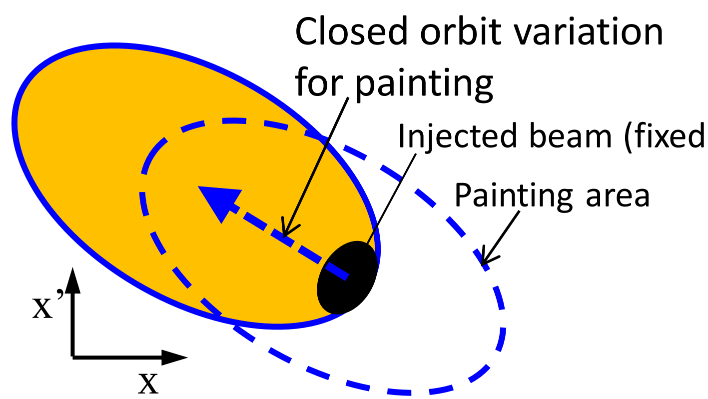
Extracted 3 GeV protons are simultaneously delivered to the neutron and muon production targets in the MLF as well as to the MR for beam injection.

RCS scheme for proton









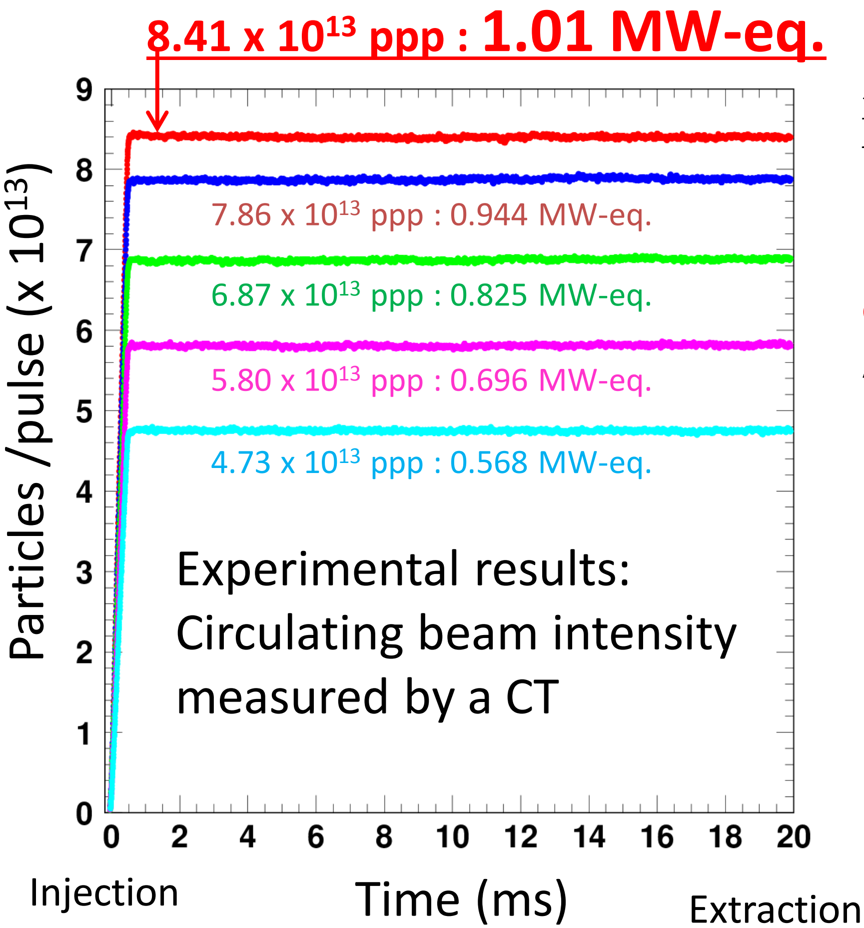
Transverse painting (H plane). Done in the V plane too.

Large acceptance:

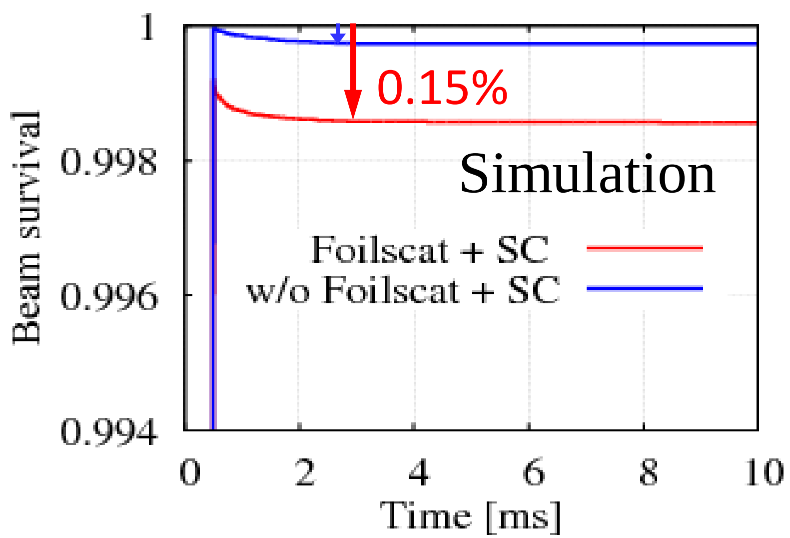
$\varepsilon_{tr} > 486\pi$ mm mrad, $\Delta p/p > \pm 1\%$

→ **Important for low energy HI beam**

RCS latest performance and path to realize high intensity HI beam



- Successfully demonstrated and ready for user operation with 1 MW beam power.
- Beam loss at 1 MW: <0.2% and only at injection energy
-- mostly due to the foil scattering.



→ ***Demonstrates RCS potential to achieve a rather high intensity HI beam too.***

RCS proton beam power capability --- Space charge (SC) limitation

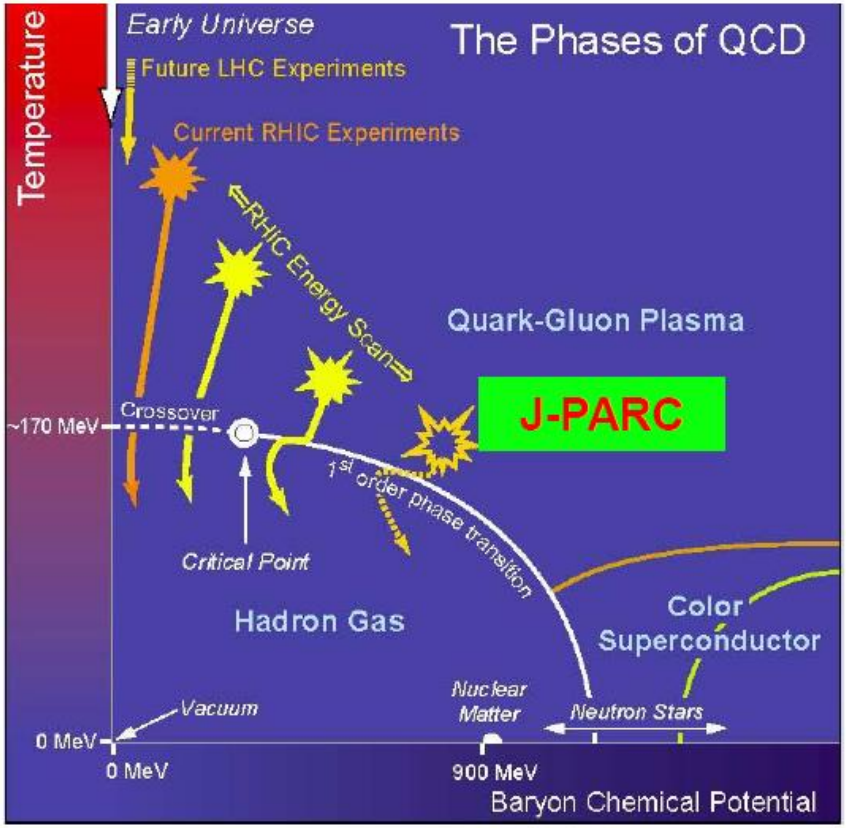
Laslett tune shift at injection energy:

$$\Delta\nu = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\varepsilon B_f}$$

r_p: classical radius of proton
n_t: no. of protons in the ring
β, γ: relativistic parameters
ε: transverse painting emittance (100π mm mrad)
B_f : Bunching factor (0.4)

E_{inj} (MeV)	ppp ($\times 10^{13}$)	Beam power at E_{ext} (MW)	Δν	Comment
181	**4.5**	**0.54**	**-0.53**	**Achieved**
400	**8.33**	**1**	**-0.33**	**Achieved**
400	11.0	1.3	-0.43	Reasonable
400	13.3	**1.6**	-0.53	Reasonable

J-PARC HI physics program (in brief)



- ♦ To study QCD phase structures (critical point and phase boundary) in high baryon density regime of 8-10ρ_0 (U+U system).
- ♦ Study the properties of high baryon density matter.

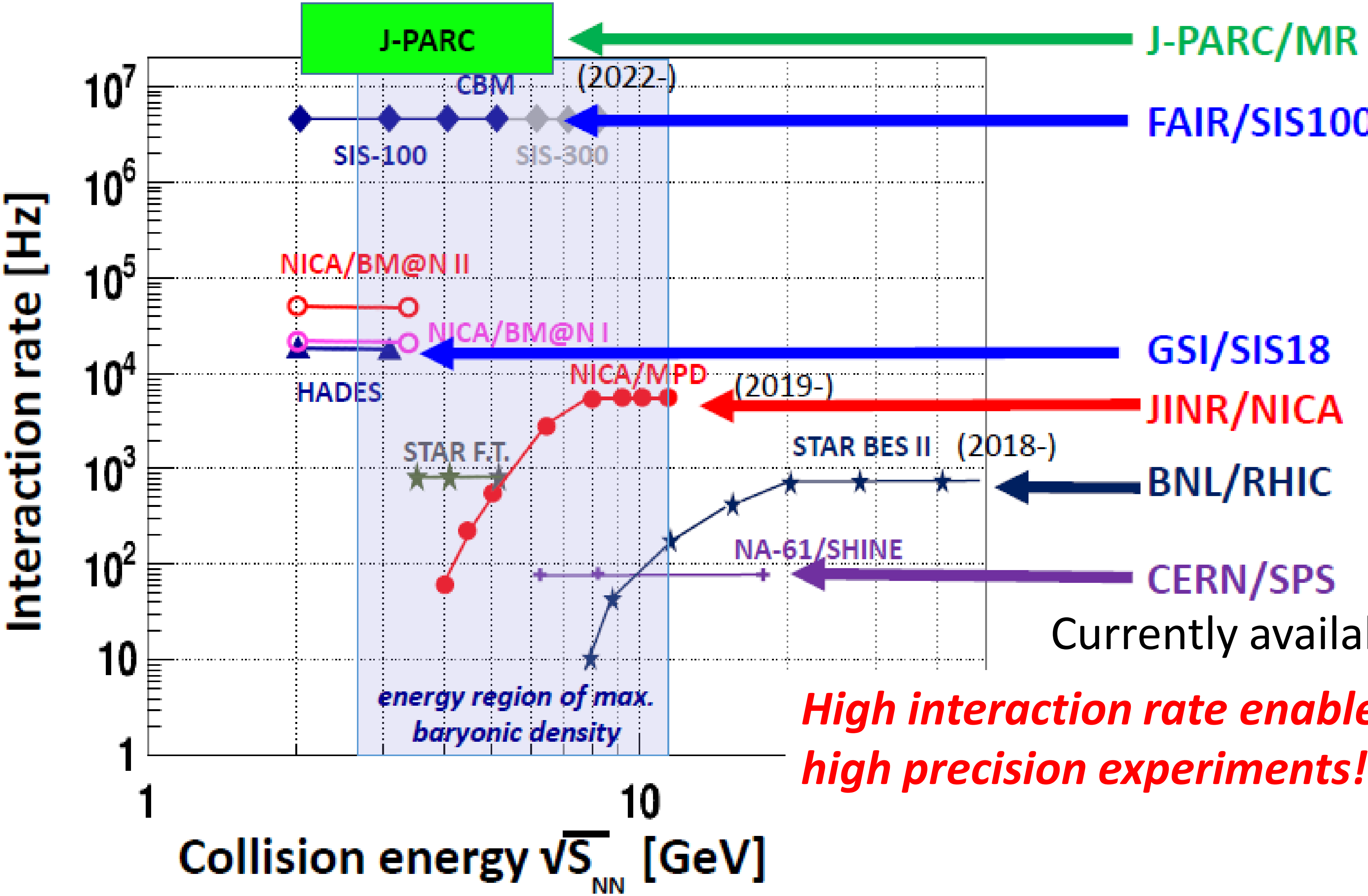
→ Fixed target collision by using slowly extracted HI beam from the MR.

- ♦The HD programs also have many advantages by using HI beam.
  - *Hypernuclear production rate*
  - *S=-3 sector (only possible by HI collisions)*

- ● Beam energy: 1-20 GeV/u (U) beam from the MR
- ● Beam intensity: 1E11/cycle (~4s)

To adapt such a high intensity HI scheme in the already running proton machines and moreover without intercepting any existing or planned programs is surely a big challenge!

Present and future HI experiments/machines



Currently available

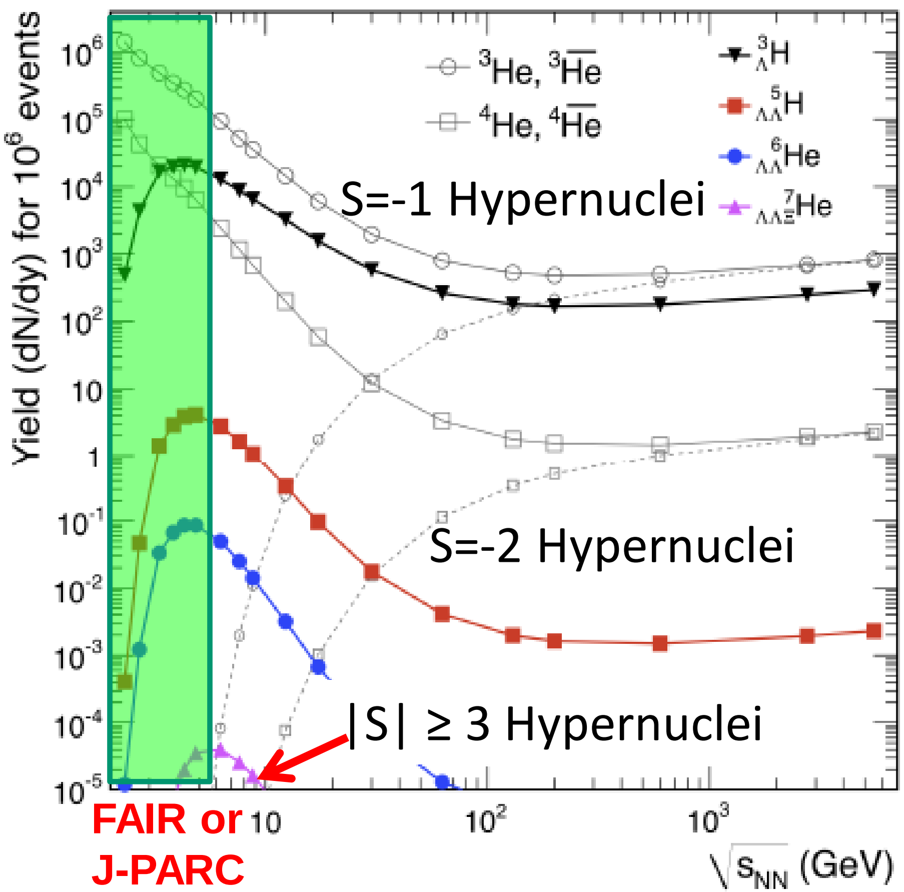
High interaction rate enables high precision experiments!

H. Sako -- Reimei WS, 2016

Mass production of hypernuclei and also Multi-strangeness hypernuclei?

A. Andronic, PLB697 (2011) 203

Pb + Pb (Central collision)



Hypernuclear production rate is maximum at J-PARC energy.

Production of Multi-strangeness hypernuclei possible at $\sqrt{S_{NN}}$ <10 GeV?

HI Acceleration strategy in J-PARC

■ Utilize existing high performance RCS and the MR for HI acceleration in addition to the proton.

■ RCS can be a suitable injector also for HI in the MR for final acceleration up to ~11 GeV/u at MR (@30 GeV for p).

RCS: Already achieved designed 1 MW-eq. beam power.
MR : Achieved up to ~5E13 protons/cycle for HD operation.

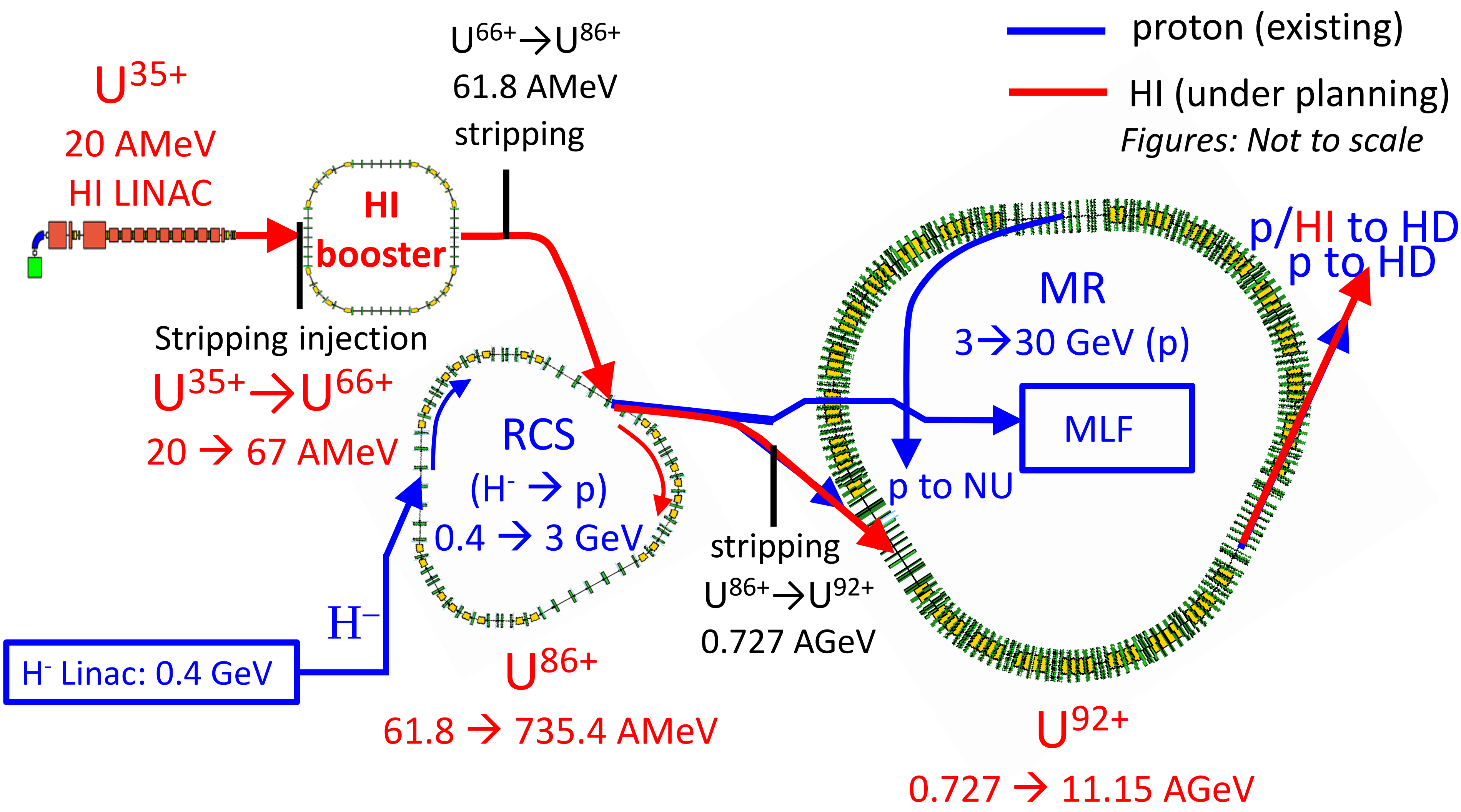
◎ Well understood and optimized accelerator performances.
--- Enable realistic discussion on beam dynamics issues and measures for high intensity HI beam.

◎ Use existing building and devices.
-- Highly reduced the construction budget.

◎ RCS has Large acceptance
-- transverse (ε_{tr}) > 486π mm mrad, longitudinal ($\Delta p/p$) > ±1%
Enables to achieve high intensity even at lower beam energy

HI Accelerator scheme in J-PARC

(Yet unofficial!)



Key issues to realize HI acceleration

We should meet the goal without intercepting any existing/planned programs utilize proton beam.

Following 4 issues, particularly at the RCS must be cleared.

1. Simultaneous operation with proton for MLF and HI for MR must be done.

2. New HI injection system.

3. Most of the machine parameters fixed for p must be used for HI

(At present, no choice for changing many parameters between cycles).

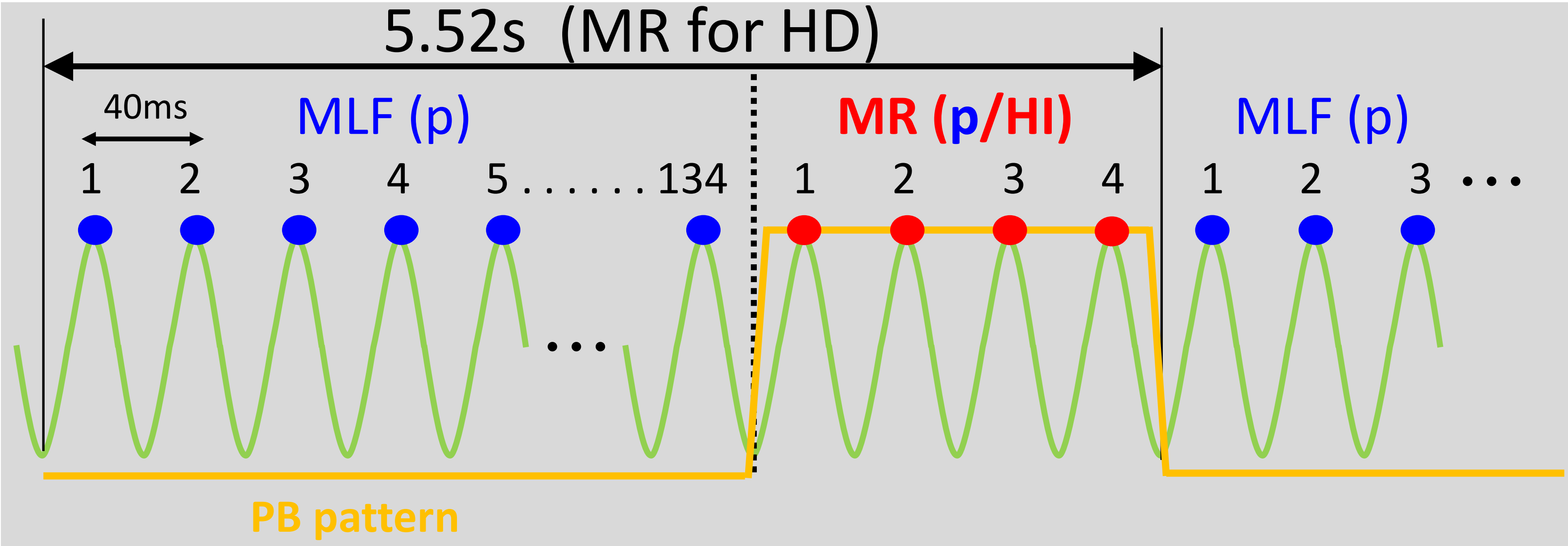
4. Insufficient vacuum pressure level: ~10^{-6} Pa, no problem for p but requires > 2 orders of magnitude better for HI with lower charge states.

We considered U^{86+} in the RCS.

However, higher charge states limit the beam intensity due to the space charge effect. Already established high performance RCS is thus a good choice.

How the HI scheme works

RCS beam delivery pattern



MR operates for either NU or HD

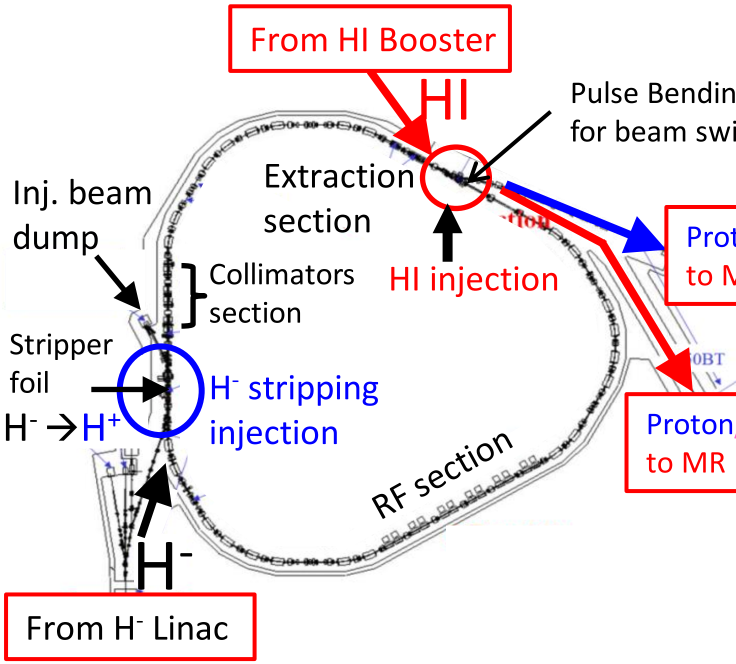
When MR operates for HD (5.52s), No. of RCS cycles: 25 × 5.52 = 138

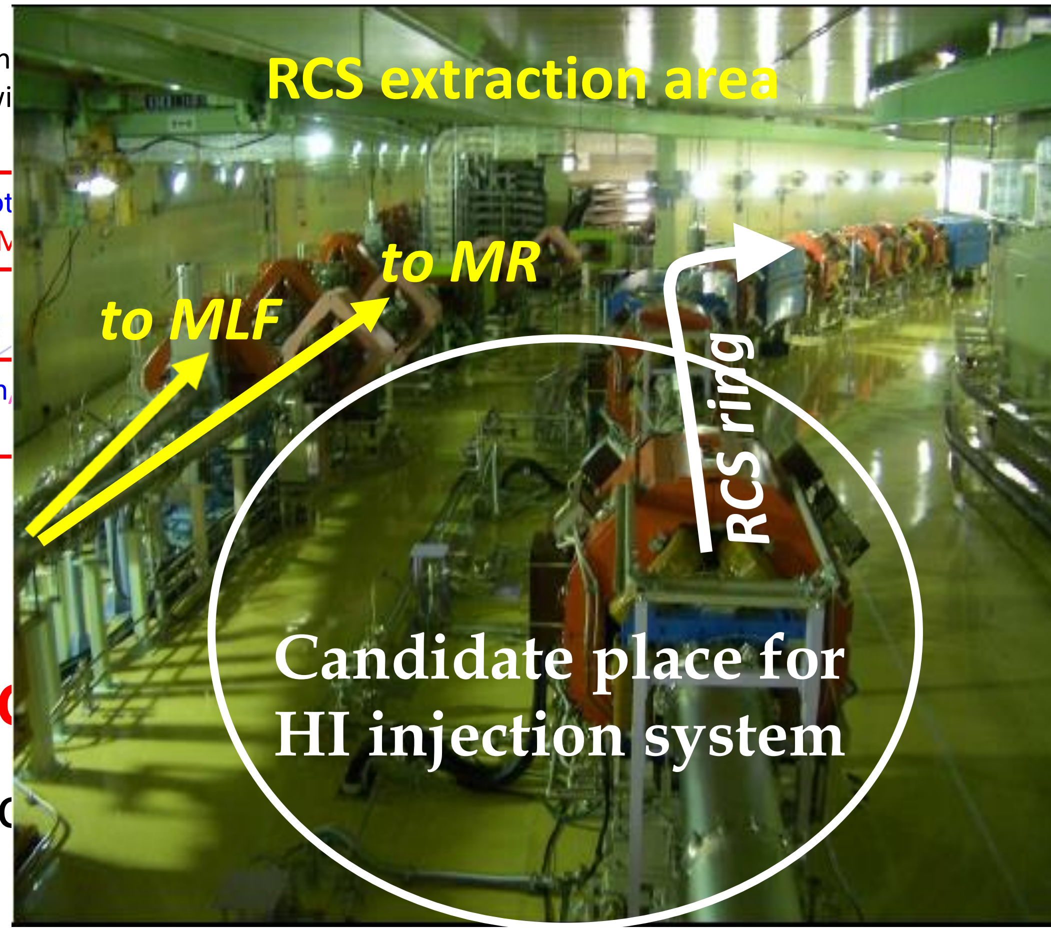
→ 134 RCS cycles to MLF, 4 to MR

◎ Only when MR runs HI, RCS injects HI in the MR cycle.

→ No conflict with MLF/NU

HI Scheme in the RCS





HI injection system in the RC

Place: At the end of extractic

→ Only available space.

Scheme: One turn injection from the HI booster.

→ Simple injection system.

Simulation results of U^{86+} acceleration in the RCS

Code: ORBIT-3D

Steps:

(1) Single particle w/o SC

(2) Multi-particle w/ SC

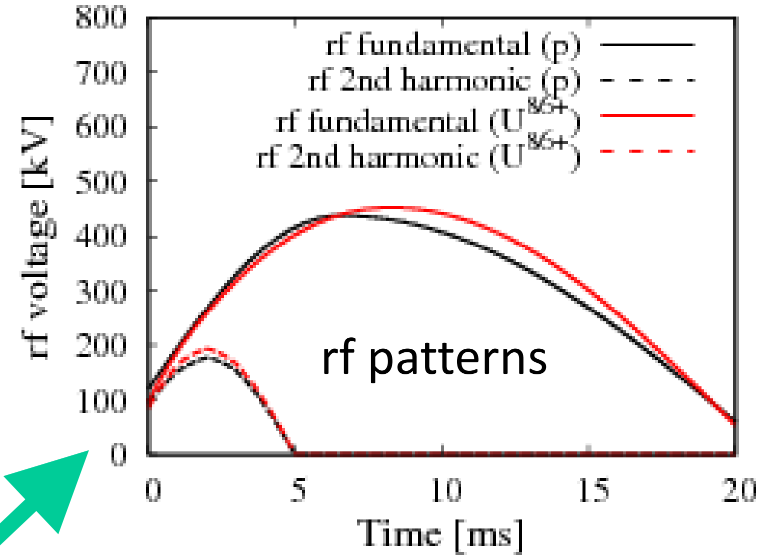
- BM, QM are kept unchanged as optimized for 1MW proton (for MLF).

→ **Can't be changed pulse-to-pulse .**

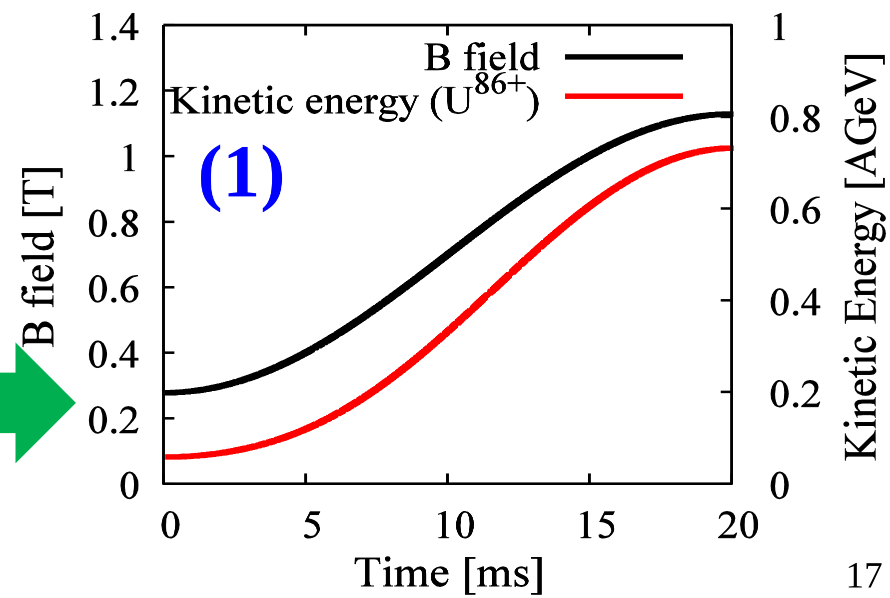
- **rf patterns are slightly different.**

→ System *upgrades is necessary.*

(may not be a big issue!)



Injection energy: 61.8 MeV/u
Extraction energy: 735 MeV/u
→ (1) **Successfully confirmed by the single particle simulation.**



(2) Multi-particle simulations w/ SC

Space charge limit:

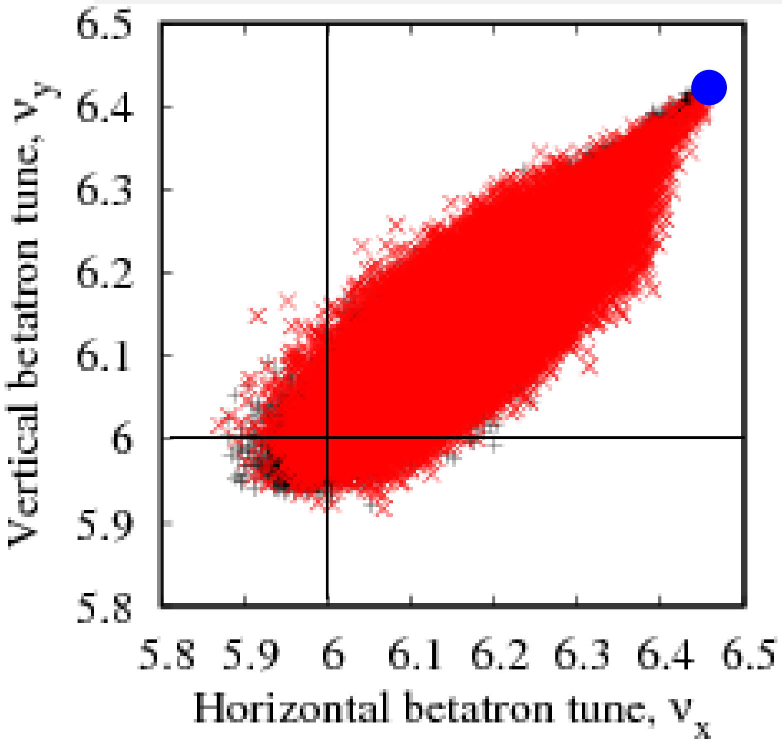
Laslett incoherent tune shift:

$$\Delta\nu \approx -\frac{q^2}{A}\frac{r_p n_t}{2\pi\beta^2\gamma^3\varepsilon B_f}$$

For 1 MW proton: 8.33×10^{13}/2b
→ 4.2×10^{13}/b

Particle	n_t (ppb)	Δν
P	4.2×10^{13}	-0.33
U^{86+}	1.1×10^{11}	-0.33

Tune footprint @ inj.
+ p : 4.2×10^{13} / bunch
x U^{86+} : 1.1×10^{11} / bunch
● Bare tune (6.45, 6.42)

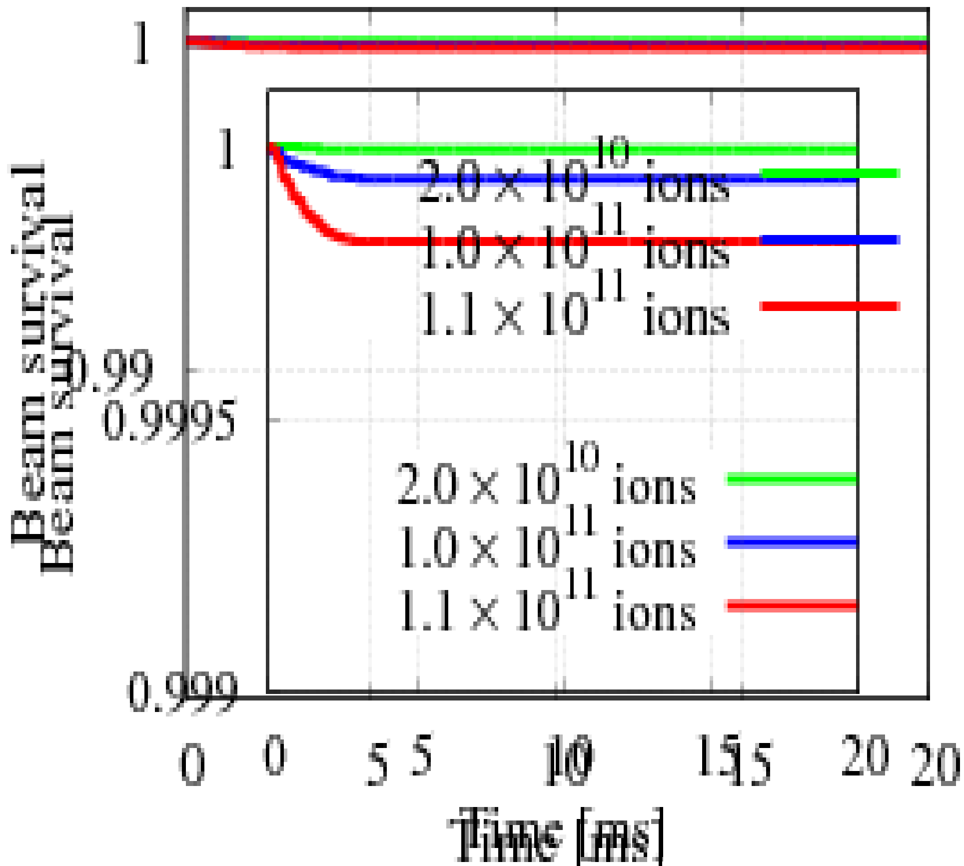


Consistent with numerical estimation!

(2) Intensity versus beam survival

Injected beam parameters:

Inj. turn	No of bunch	**Intensity ($\times 10^{11}$)**	Beam shape	Δs (ns)	$\Delta p/p$ (%)	ε_{tr} (π mm mrad)
1	1	**1.1**	Gaussian	1180	±0.9	60



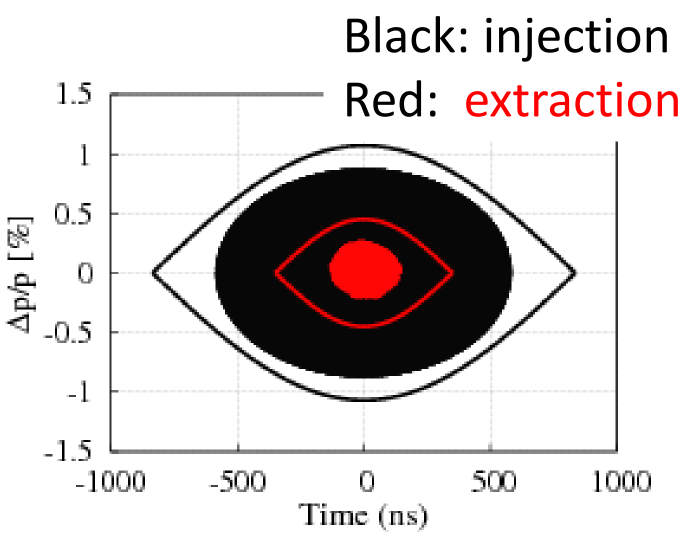
◎ **Beam survival: 99.98% even for 1.1 × 10^{11}/b of U^{86+} ions**

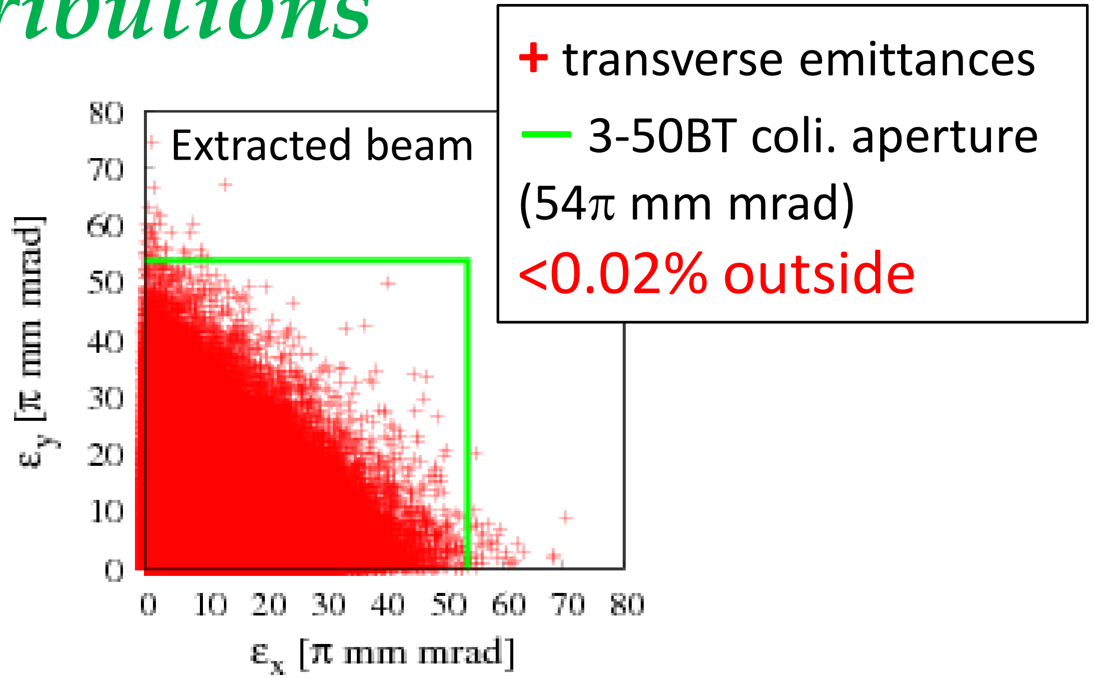
→ Consistent with 1 MW proton case, if no foil-scattering is considered.

◎ **Beam loss localizes at ring collimator.**

Beam loss can be kept <1% even for 1.5 × 10^{11}/b of U^{86+} ions.
(Collimator limit > 3%)

(2) Longitudinal and transverse beam distributions





◎ More than **99.98%** transverse emittances of the extracted beam are within 3-50BT collimator aperture.

✓ **Collimated beam power (<<100W) << Collimator limit (2kW)**

✓ **Highly Satisfy very strict beam quality for MR injection.**

● Gives bottom line for the new booster parameters.

Estimation of vacuum pressure related beam loss

Special thanks for suggestions:
Manfred Grieser, Max-Planck Inst.
H. Imao, RIKEN

Mechanisms: (1) Electron capture, (2) Electron loss ….

Electron capture cross section: (Schlachter's formula, Phys. Rev. A 27, (1983)3372)

$$\sigma_c = 1.1 \times 10^{-8} (Z_i^{3.9} \times Z_t^{4.2}/E_i^{4.8})$$

where, Z_i and Z_t are HI and target (gas molecule) charge numbers, respectively. E_i is the HI mass in keV/u.

$\sigma_c = 2.752 \times 10^{-20}$ cm^2 (For N_2 at inj.)

Electron-loss (stripping) cross section: (Modified Bohr's formula)

$$\sigma_s = 4\pi a_0^2 \left(\frac{\alpha^2}{\beta^2}\right)(Z_t^2 + Z_t) + \sum_{q_i}^{Z-1}\left(\frac{I_0}{I}\right)$$

Where, q_i is the ion charge state (86), z is the ion chare (proton number = 92)
a_0 = Bohr radius = 0.529 $\times 10^{-10}$ m, a = fine structure constant = 1/137
b = relativistic parameter =0.3473 at injection, Z_t = charge of residual gas atom (Z = 7 for N)
I_0 electron ground state energy = 13.6 eV, I is the binding energy of remaining 6 electrons in different orbital shell

$\sigma_s = 3.34 \times 10^{-20}$ cm^2 (For N_2 at inj.)

Ion beam lifetime:
$\tau = 1/(\sigma * n * v)$
σ= cross section, n = residual gas density and v = ion beam velocity

	E(GeV/u)	β	γ	P_{gas}(Pa)	σ_c (cm^2)	τ_c (s)	σ_s (cm^2)	τ_s (s)	τ_{tot} (s)
N_2	0.0618	0.3473	1.0664	10^{-6}	2.752E-20	14.44	3.34E-20	12	**6.5**
N_2	0.735	0.8293	1.7894	,,	1.898E-25	8.8E5	5.85E-21	28	**28**
H_2	0.0618	0.3473	1.0664	,,	7.766E-24	5.12E4	1.19E-21	334	**332**
H_2	0.735	0.8293	1.7894	,,	5.355E-29	3.11E9	2.09E-22	796	**796**

Beam loss by residual gas interaction cont'd

Beam loss: (Upper limit by using τ_{tot} at injection energy)

$$\frac{\Delta N}{N} = 1 - e^{-(t/\tau)}$$

ΔN (Beam loss) = 0.31%

Precise estimation:

(summing up turn-by-turn)

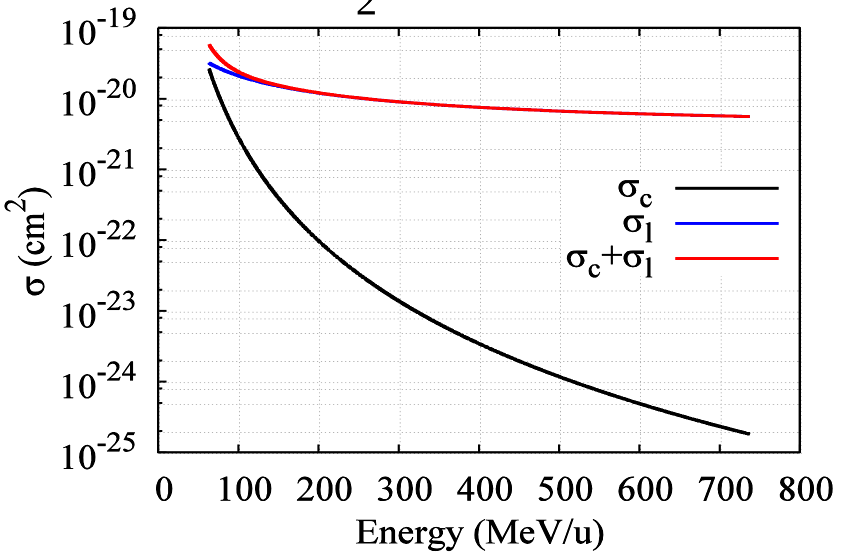
$$\frac{\Delta N}{N} = 1 - \sum_{1}^{n} e^{-(\Delta t/\Delta \tau)}$$

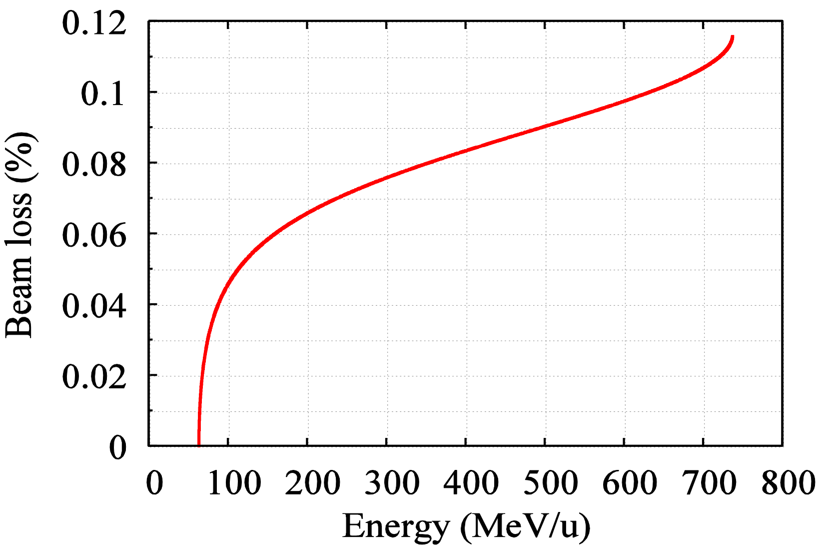
ΔN = 0.12%

Loss rate high than that of space charge induced beam losses, but it is fairly within acceptable range.

Detail of loss distribution has to be studied.

For N_2 with 10^{-6} Pa





Expected beam intensity in the MR

U^{86+} of 1.1 × 10^{11} from the RCS will be fully stripped (U^{92+}) at the 3-50 BT before injecting into the MR.

Stripping efficiency:~90% gives 1 × 10^{11} ions/RCS cycle

4 RCS cycles injection in the MR gives ***4 ×10^{11} /MR cycle***

→ 1 order of magnitude higher than any existing or planned HI accelerators in the world!

Main parameters of the MR for U^{92+} beam. (* if MR 50 GeV for proton)

Parameter	Value
Ion beam energy	0.727 ~ 11.2 (20*) AGeV
$\sqrt{S_{NN}}$	1.9 ~ 4.9 (6.2*) AGeV
MR cycle	~ 4s
Average beam rate	1 × 10^{11} Hz
Extraction scheme	Slow extraction

LOI for J-PARC HI program

Accelerator part: P.K. Saha, H. Harada, and M. Kinsho

HEAVY-ION ACCELERATION IN J-PARC

P.K. Saha, H. Harada and M. Kinsho
J-PARC Center, KEK & JAEA, Tokai-mura, Naka-gun, Ibaraki-ken, Japan

2.1 ACCELERATOR OVERVIEW

Figure 1 shows a feasible acceleration scheme for high intensity Heavy-ion (HI) beam in J-PARC along with existing proton one. The present J-PARC accelerator scheme and experimental facilities that make use of proton beam are shown in blue color. A possible HI program which is under discussion now is shown in red color. In order to achieve required world record high intensity at more than 10 AGeV (GeV/nucleon) in case of U^{92+} HI beam, we aim to utilize high performance 3-GeV Rapid Cycling Synchrotron (RCS) as well as the Main Ring (MR), approaching to the designed

Table 1: Key parameters and accelerator performance for the U^{92+} beam. The numbers in the parentheses are by considering the designed MR extraction energy of 50 GeV for proton.

Parameter	Value
Beam energy	0.727 ~ 11.2 (19.5) AGeV
$\sqrt{s_{NN}}$	1.9 ~ 4.9 (6.2) AGeV
Beam rate	10^{11}
MR cycle	~ 6 s
Flat top	~ 4 s

Letter of Intent for J-PARC Heavy-Ion Program
(J-PARC-HI)

J-PARC-HI Collaboration

http://silver.j-parc.jp/sako/letter-intent-v2.10-PAC.pdf

Summary

In order to realize HI physics program in J-PARC, feasibility studies and a new HI accelerator scheme by utilizing most of the existing facilities are proposed.

RCS plays the most important role to realize HI program in J-PARC.

Feasibility studies are done within the designed and fixed frames for proton in the RCS.

● **RCS can easily achieve > 1.1×10^{11} U^{86+} ions for the MR.**

→ Gives 4×10^{11} U^{92+} ions/cycle (5.52s) in the MR and is already higher than experimental requirement at present.

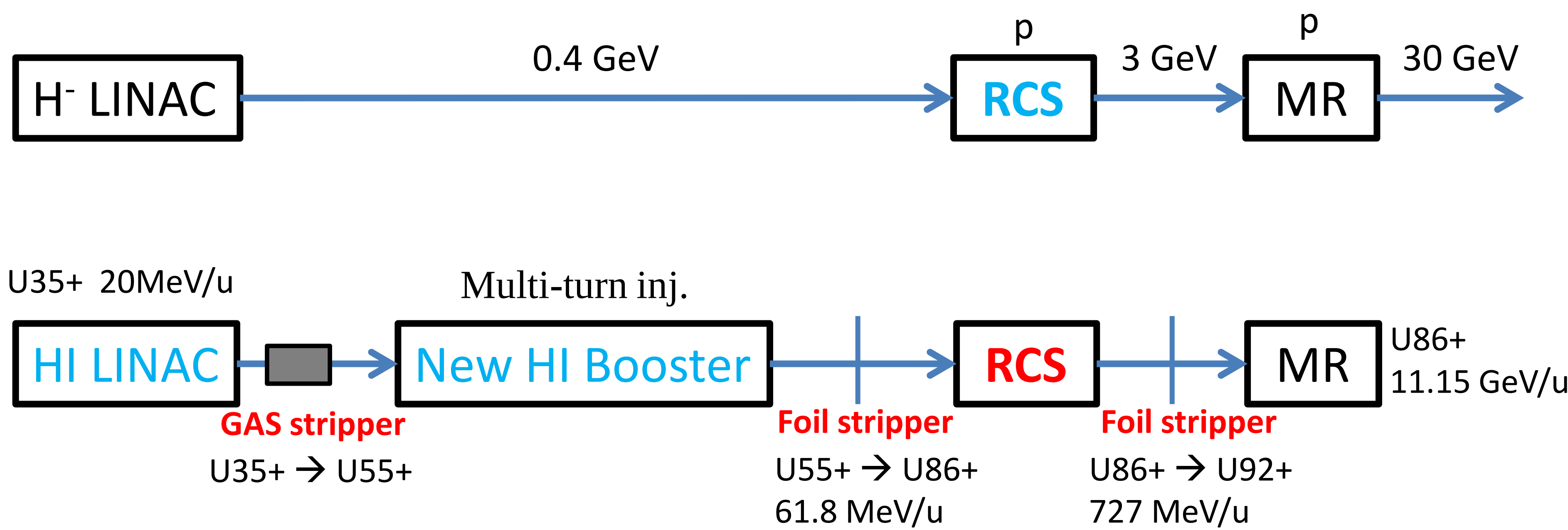
The RCS has potential to achieve further higher intensity HI beam.
HI for the neutron/Pion (for NU) productions can be considered?
An Ion source, short LI and a compact booster ring are only needed.
Design studies for the new HI Booster are also in progress.

The proposed new HI accelerator scheme has no interference or conflict with existing programs that make use of proton beams.


J-PARC
KEK & JAEA)
May be in near future
HI
Thank you for your attention!

Backup slides

HI Accelerator Scheme



	LINAC out	Stripper 1	Booster out	Stripper 2	RCS out	Stripper 3	MR out
		N_2 gas		Carbon		$Cu<Z_T<Ta$	
E (MeV/u)	20	19.86	67.0	61.8	**735.4**	727.0	11.15 GeV/u
Q	35	66+-2?	66+-2	86	86	92	92

Present simulation background

Tool: ORBIT 3-D space charge code:

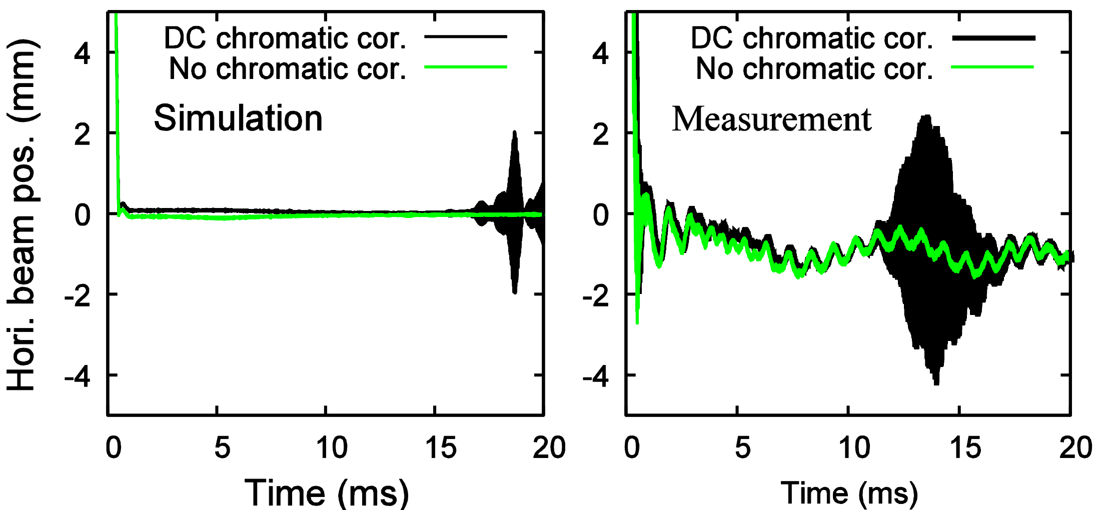
→ Originally developed at the SNS in Oak Ridge.

→ Successfully adopted in the RCS, especially for beam instability simulation.

(Ext. kicker impedance is a significant beam instability source in the RCS.)

● ***Space charge effect is strongly connected to the beam instability.***

-- First an accurate space charge simulation was demonstrated.



Beam instability at 1 MW:
Simulation vs. Measurement

● The next step was to determine optimum parameters to avoid beam instability at 1 MW.

Even DC chromatic correction gives beam instability at 1 MW!

→ Confirmed by measurements!!

ORBIT can be used HI beam simulation in the RCS