J-PARC Heavy-Ion Acceleration

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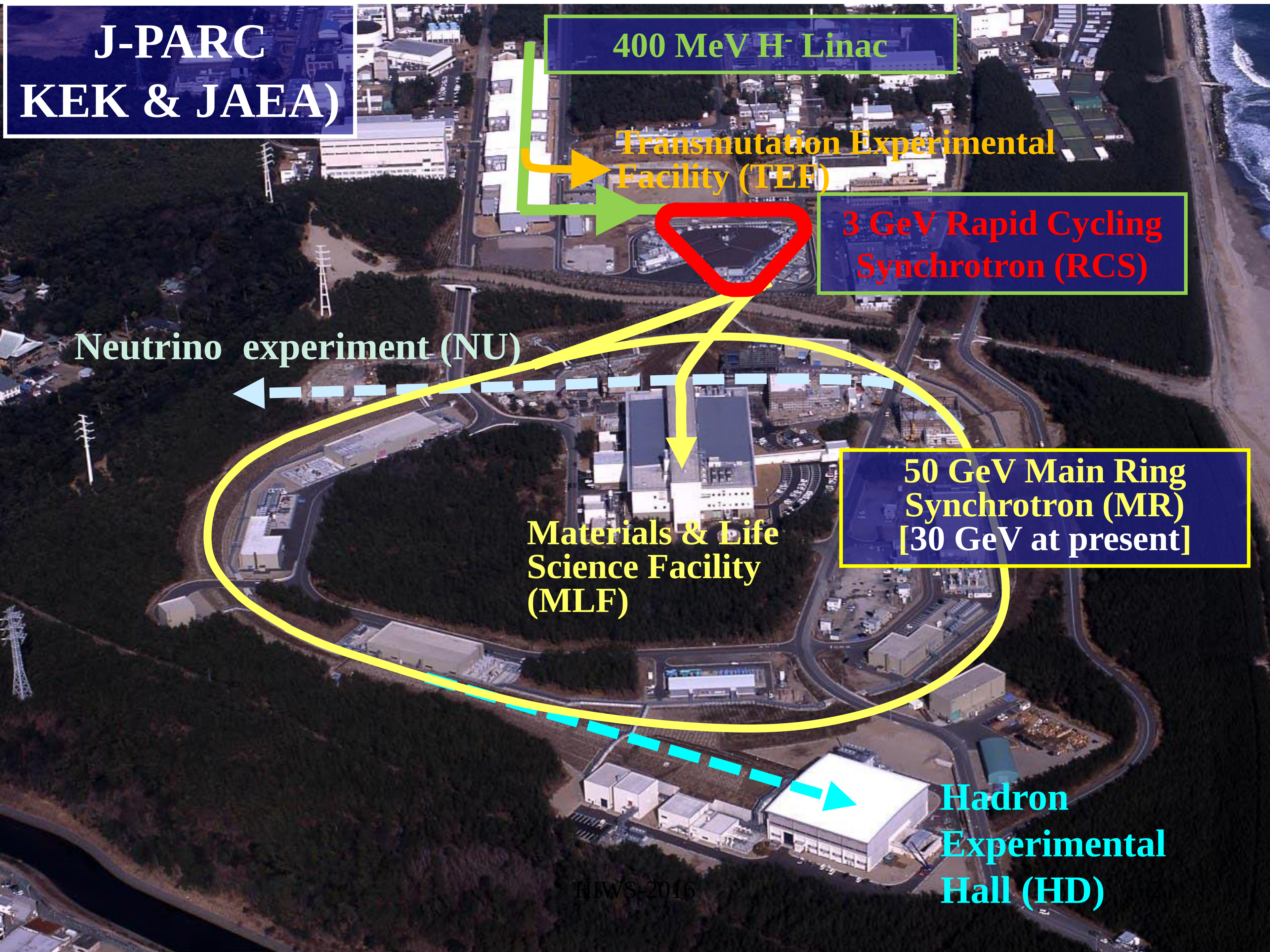

J-PARC
KEK & JAEA)
400 MeV H- Linac
Transmutation Experimental
Facility (TEF)
3 GeV Rapid Cycling
Synchrotron (RCS)
Neutrino experiment (NU)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Materials & Life
Science Facility
(MLF)
Hadron
Experimental
Hall (HD)
HIWS-2016

Introduction and Outline

- J-PARC is a multi-purpose research facility consists of 3 accelerators and several experimental facilities that make use of high intensity **proton beams.**
- RCS already achieved acceleration of designed 1 MW-eqv. beam power.
- MR also approaching towards the designed beam power.

- *In response to the interesting HI physics program, we are considering to adapt new accelerator scheme for HI in J-PARC.*
- ***Studies of HI acceleration in the RCS is the main topic in this talk.***

Outline:

1、Overview of J-PARC HI physics program

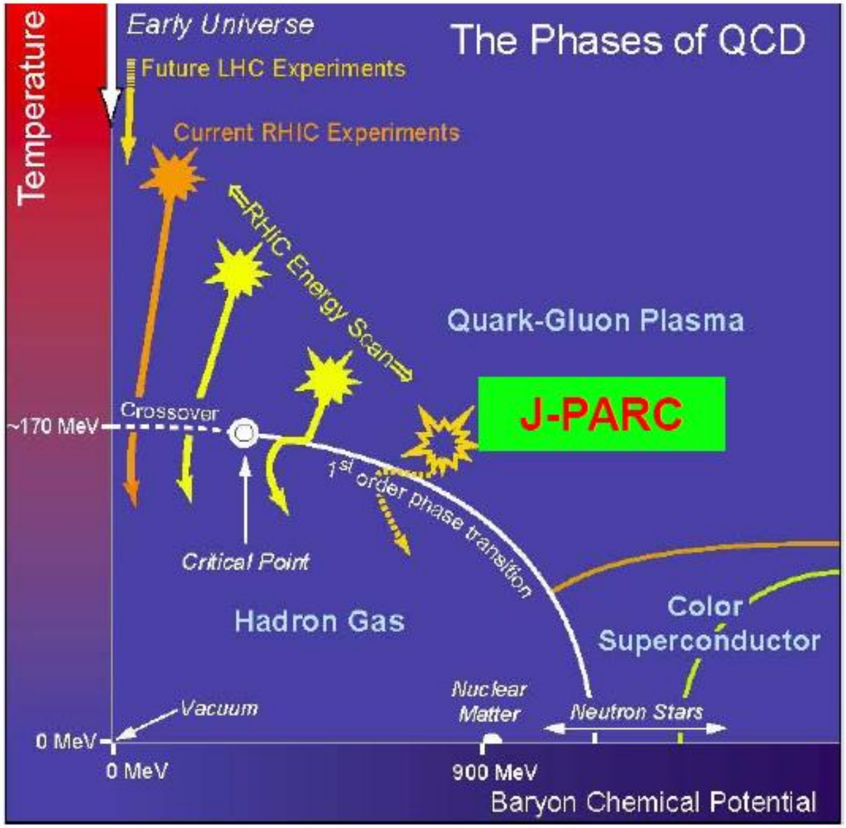
2、HI acceleration strategy and accelerator scheme

3、Overview of 3-GeV RCS and latest performances

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

5、Summary and Outlook

HI physics goal at J-PARC



- ♦ 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 of 1E11/cycle (6s) from the MR.

- ♦The HD programs should also have 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 (~6s)

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

HI Acceleration strategy in J-PARC

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

■ The RCS can be a suitable HI injector for MR for the final acceleration up to ~20 GeV/u (@50 GeV for p).

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

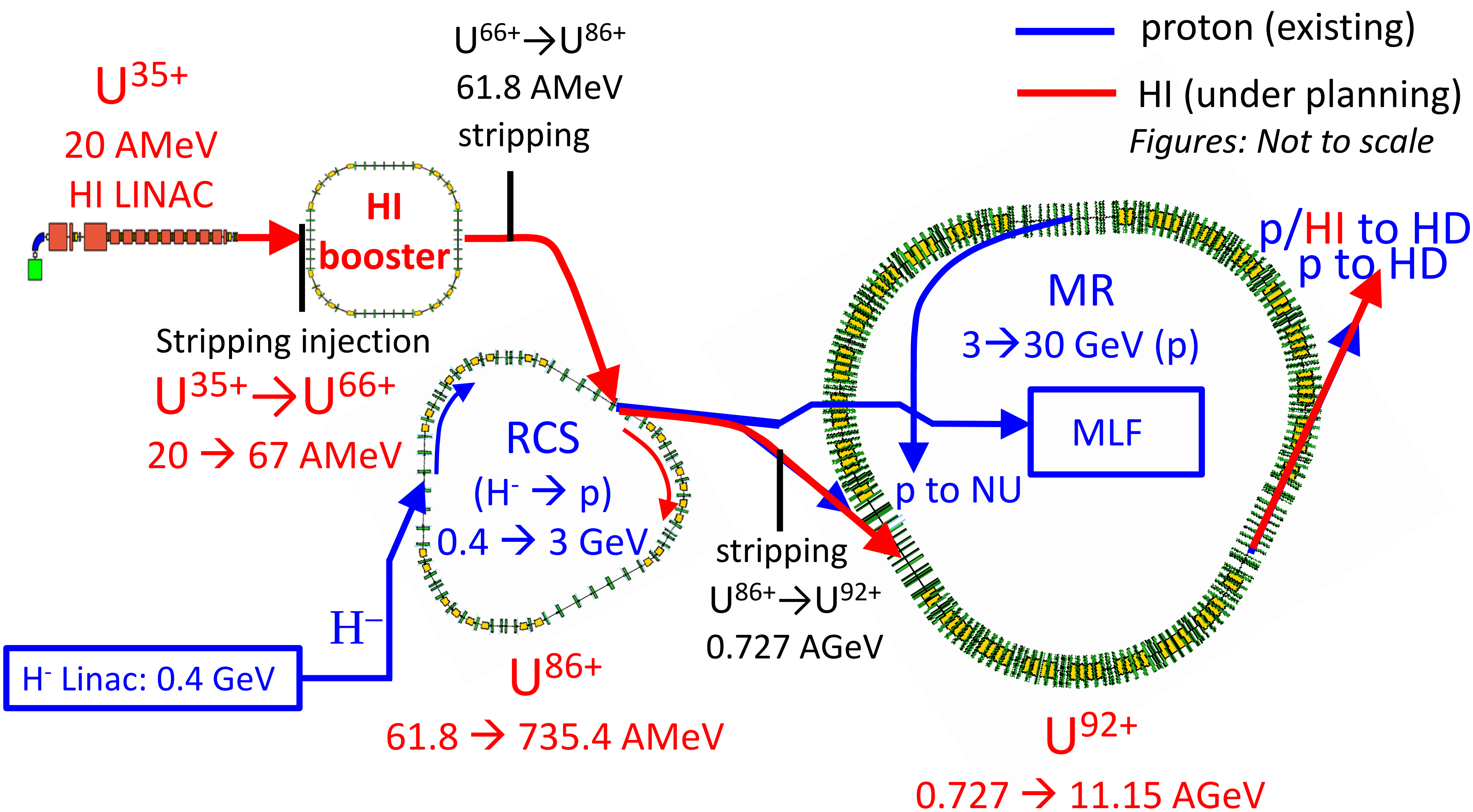
◎ Well understood and optimized accelerator performances.
--- Enable realistic discussion on beam dynamics issues and measures for high intensity HI beam.

◎ Use existing building and devices.
-- Reduction of space and budget to accelerate up to ~GeV/u (U) for MR injection.

◎ RCS has Large acceptance
-- transverse (ε_{tr}) > 486π mm mrad, longitudinal ($\Delta p/p$) > ±1%

HI Accelerator scheme in J-PARC

(Yet unofficial!)



Key issues to realize HI acceleration

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

Four following serious issues, particularly with RCS must be cleared.

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

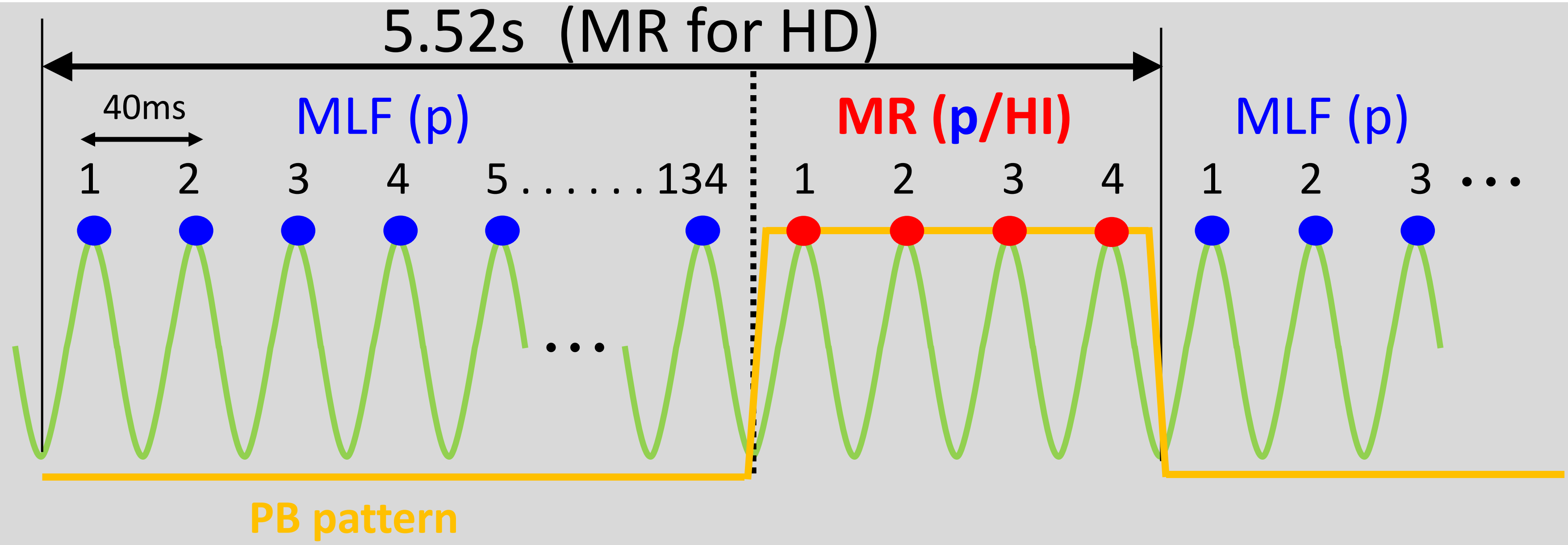
● Most of the machine parameters fixed for p must be used for HI
(At present, no choice for changing most of the parameters between cycles).

● Vacuum pressure level: ~10^{-8} Torr (no problem for p).
Not satisfied for HI w/ lower charge states (U^{86+} is thus considered).

■ **New HI injection system**

How HI scheme works in RCS

RCS beam delivery pattern



MR operates for either NU or HD

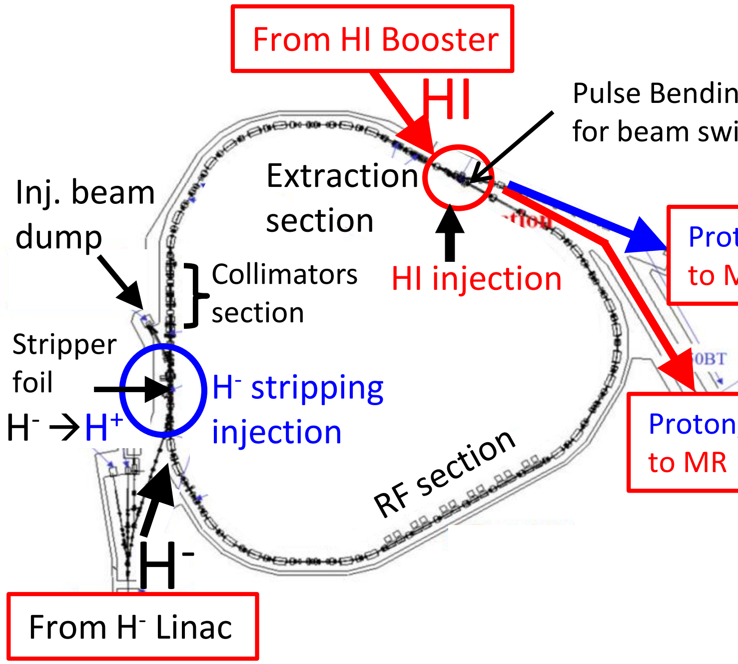
When MR operates for HD (5.52s), No. of RCS cycles: 25 × 5.52 = 138

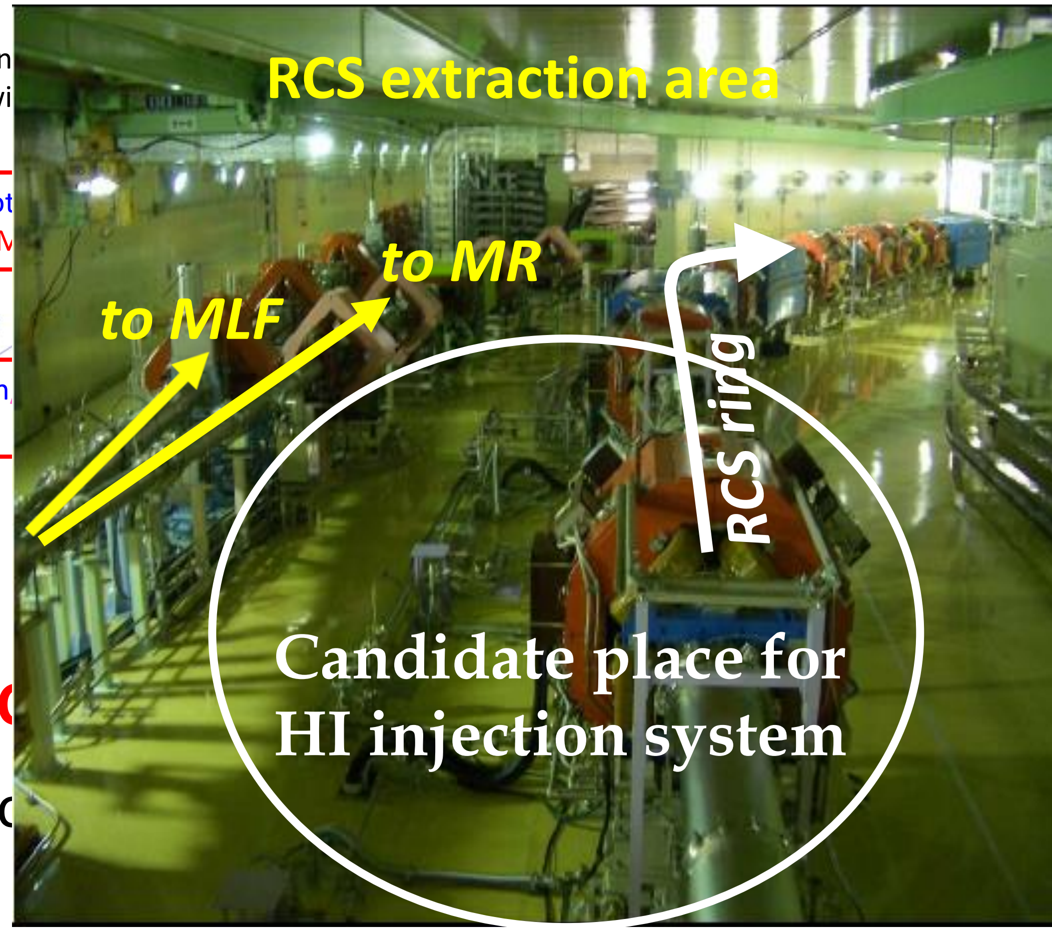
→ 134 RCS cycles to MLF, 4 to MR

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

→ No conflict with MLF/NU

Location for RCS HI injection Scheme





HI injection system in the RC

Place: At the end of extractio

→ Only available space.

Scheme: One turn injection from the HI booster.

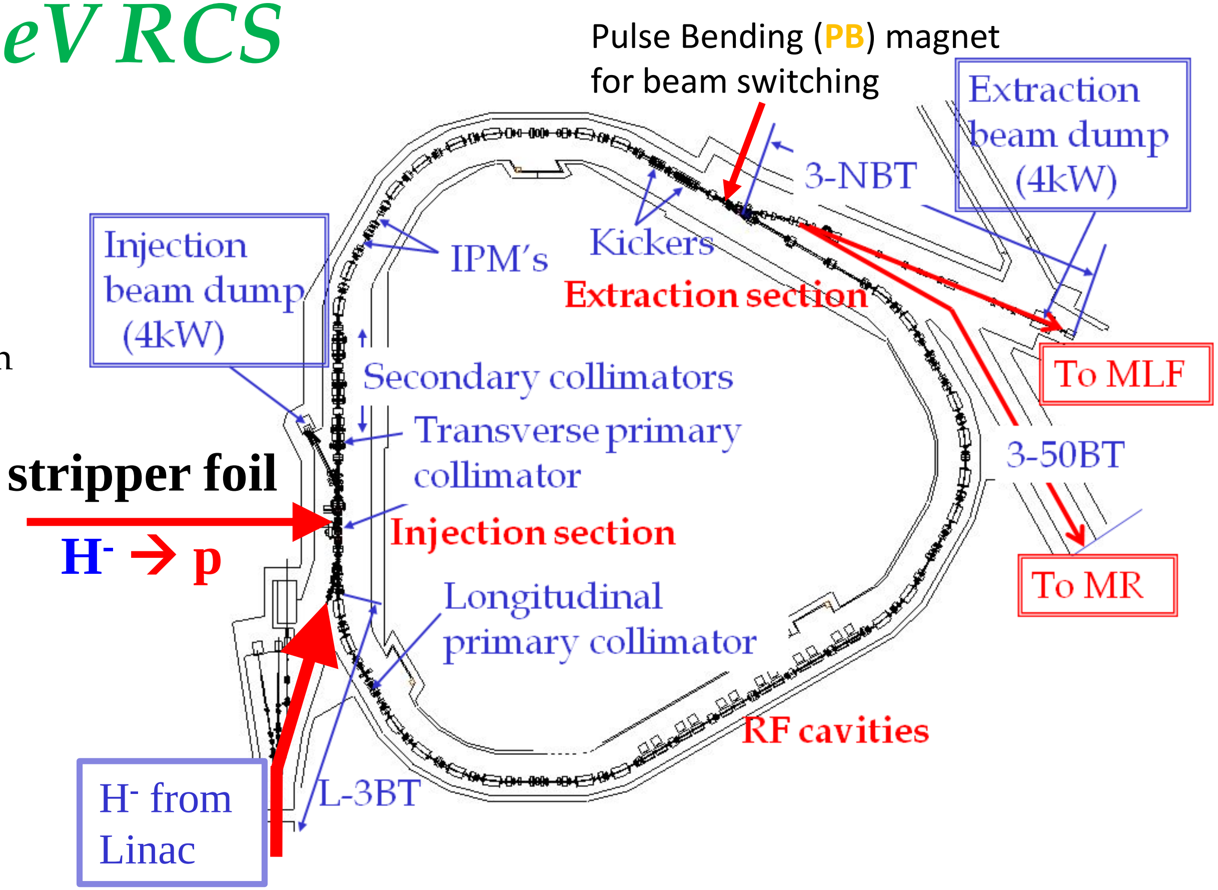
→ By using 1 or 2 kickers. Simple injection system.

Overview of the RCS and latest performance with proton beam

Overview of 3-GeV RCS

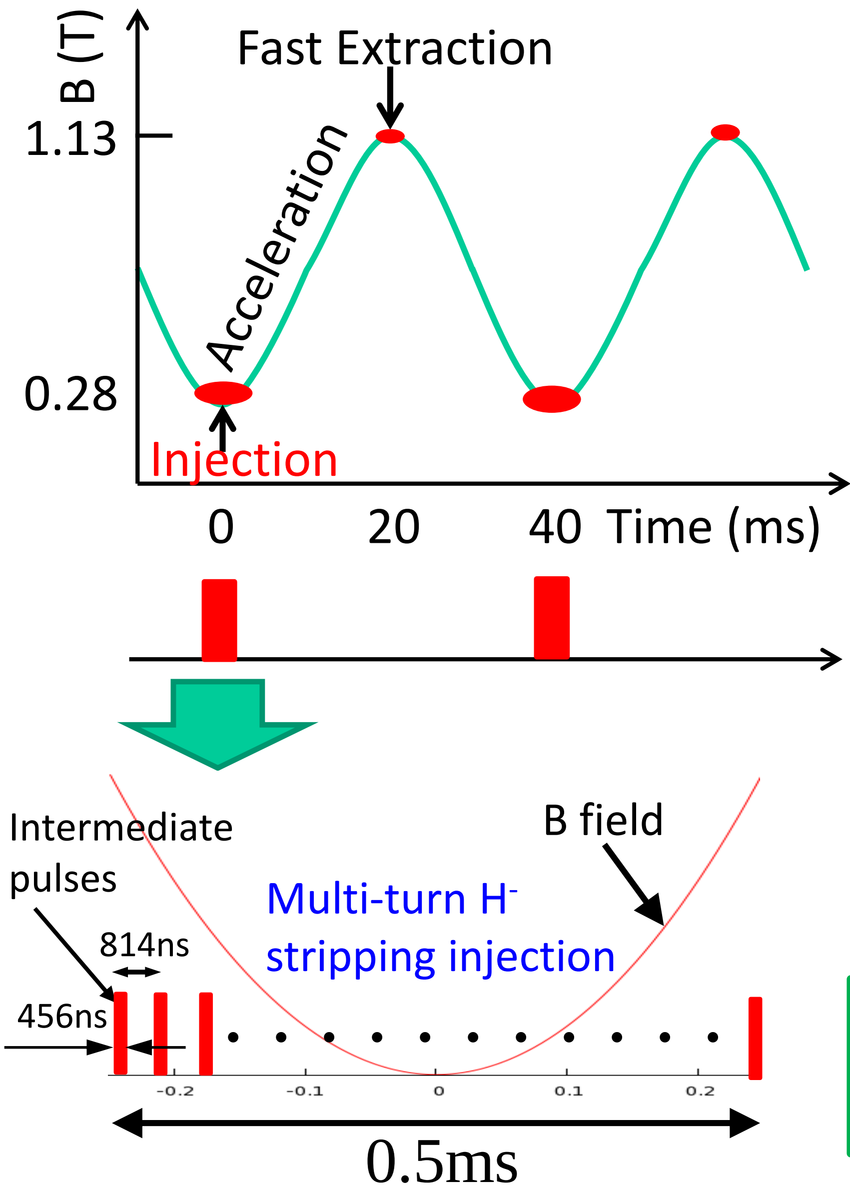
Design parameters:

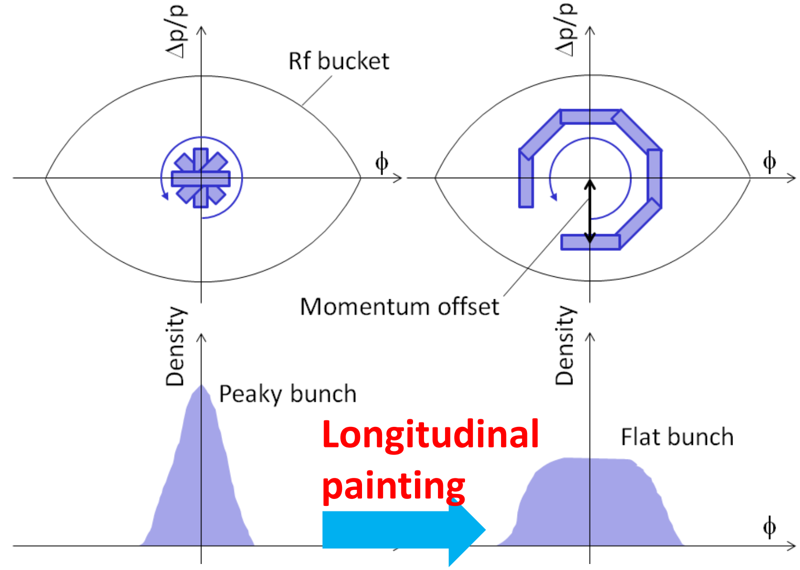
Particle	**p**
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
No of bunch	2
Injection energy	**400 MeV**
Extraction energy	**3 GeV**
Repetition rate	25 Hz
Particles per pulse	**8.3e13**
Output beam power	**1 MW**
Transition gamma	9.14 GeV
Collimator Limit	4 kW (3%@ inj. beam power)

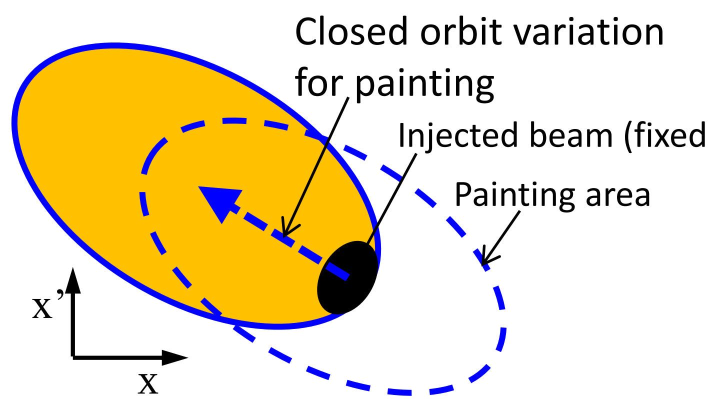


Extracted 3 GeV protons are simultaneously delivered to the neutron and muon production targets in the MLF (97%) as well as to the MR (3% @HD opr.)

RCS scheme *for proton*





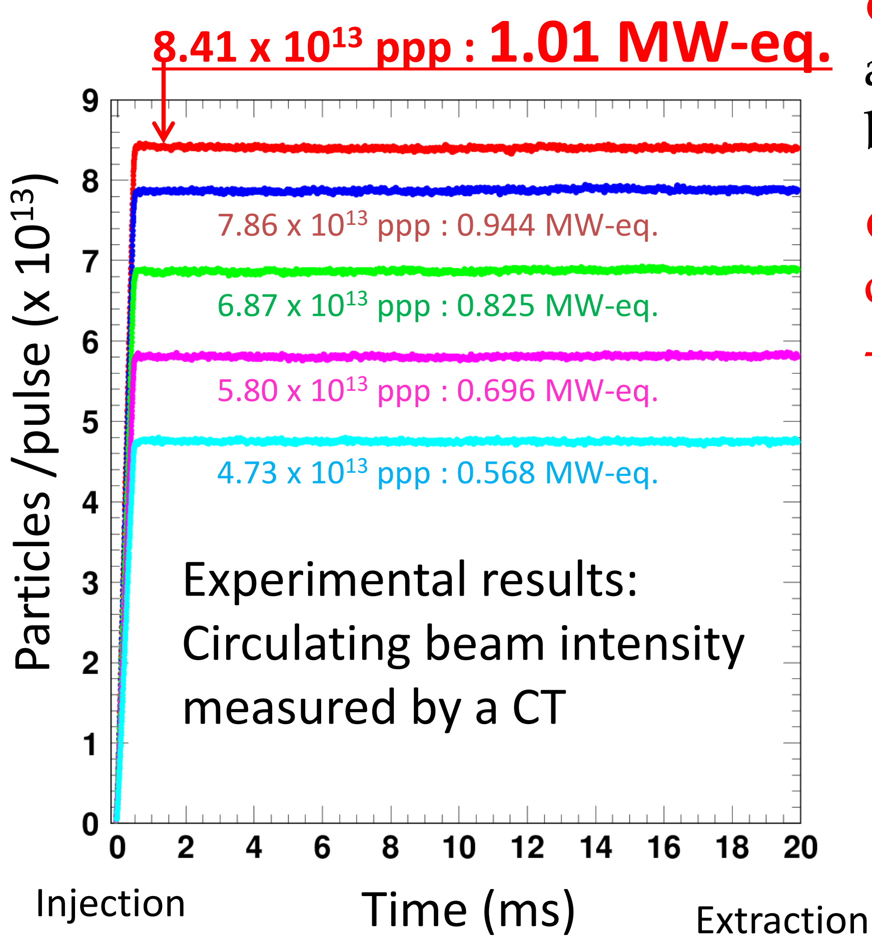


Transverse painting (H plane). Done in the V plane too.

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

RCS 1 MW beam study results

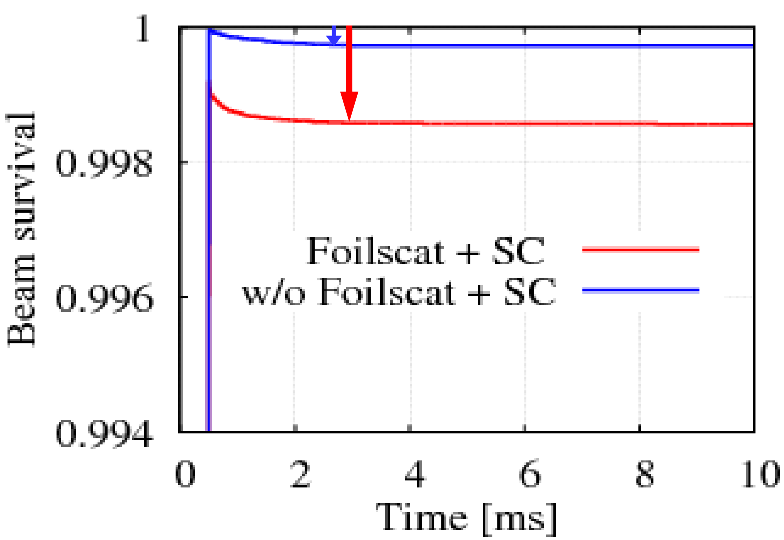
Courtesy: H. Hotchi



● Successfully demonstrated acceleration and extraction of **1 MW**-equivalent beam power.

● Beam loss at 1 MW: <0.2% and only at injection energy
-- mostly due to the foil scattering.

Simulation 1MW: ORBIT



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

RCS proton beam power capability --- Space charge limitation

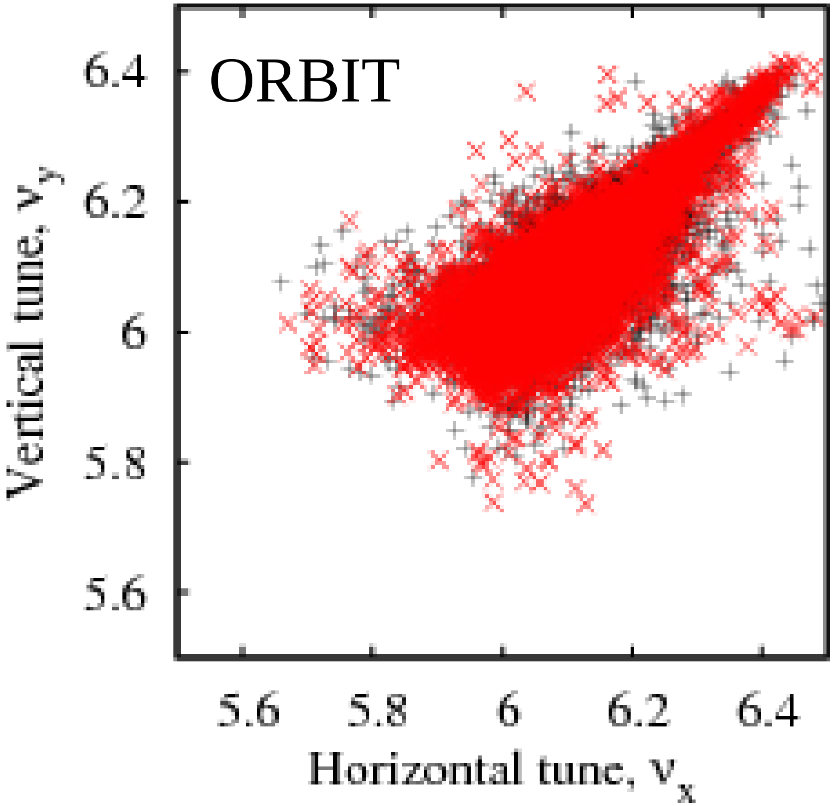
Laslett tune shift at injection energy:

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

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

Tune footprint (Simulation)



Trans. painting (ε_{tr}) = 100π mm mrad
Longitudinal painting: Full (B_f=0.4)
V2/V1 =0.8%, Δp offset =-0.2%
ϕ2= -100deg.

Black: 181 MeV injection
4.5E13/pulse (**0.54 MW**)

Red: 400 MeV injection
12.5E13 /pulse (**1.5 MW**)

Simulation for U^{86+} acceleration in the RCS

Code: ORBIT-3D

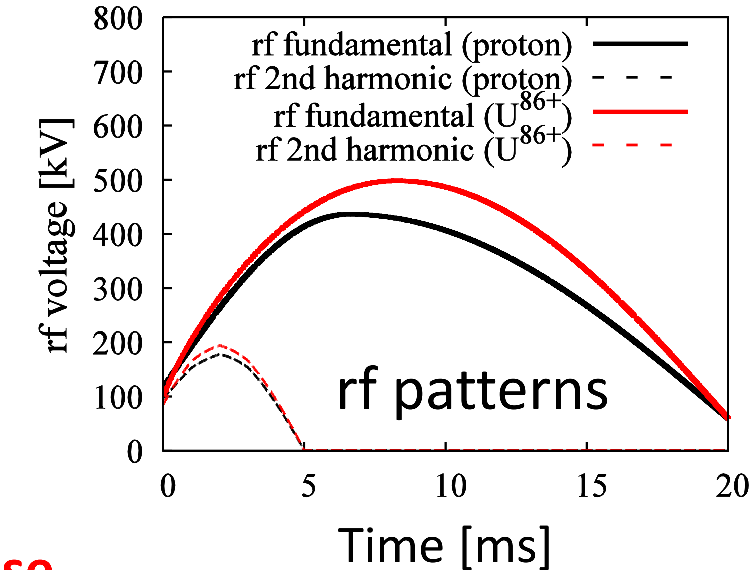
Steps:

(1) Single particle w/o SC

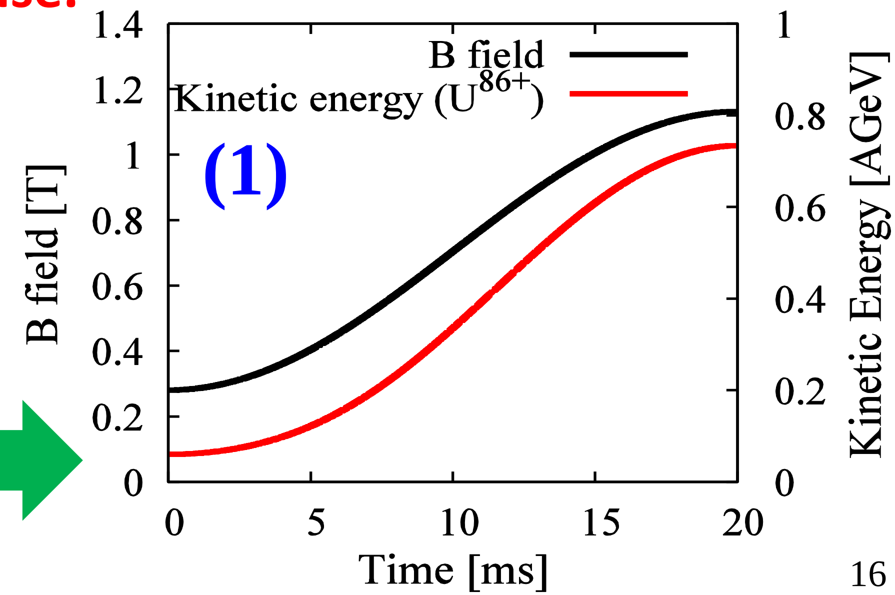
(2) Multi-particle w/ SC

- BM, QM, Sextuples are kept unchanged as optimized for 1MW proton (for MLF).
→**Those can't be changed pulse-to-pulse.**

- **rf patterns are differently used.**
→ *Upgrades might be 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:

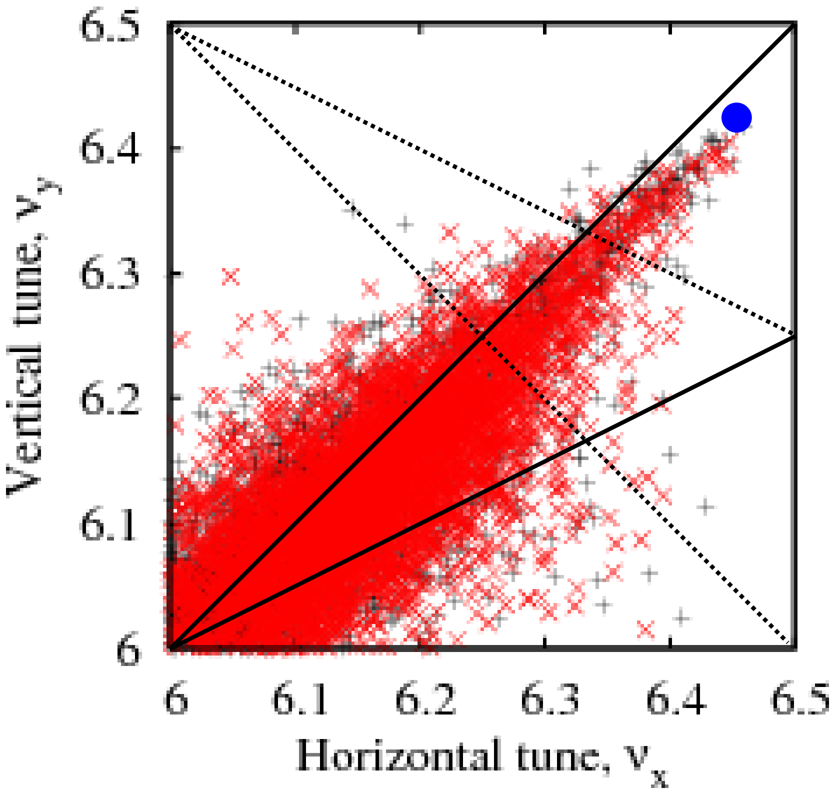
Laslett tune shift:

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

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

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

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

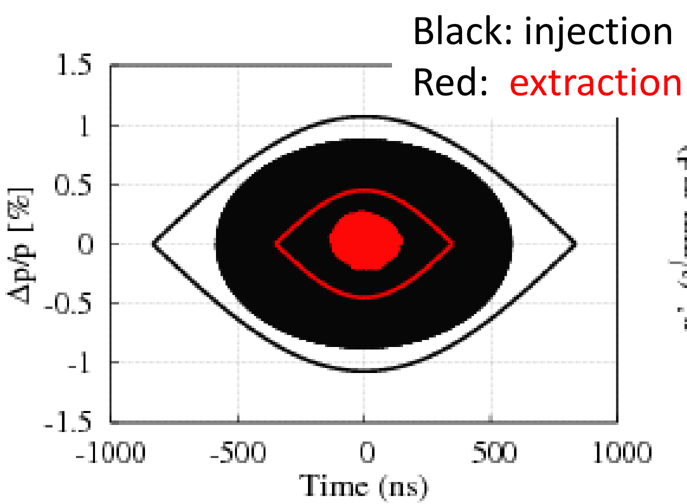


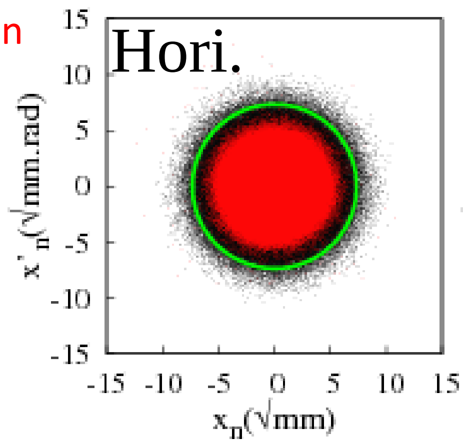
Consistent with numerical estimation!

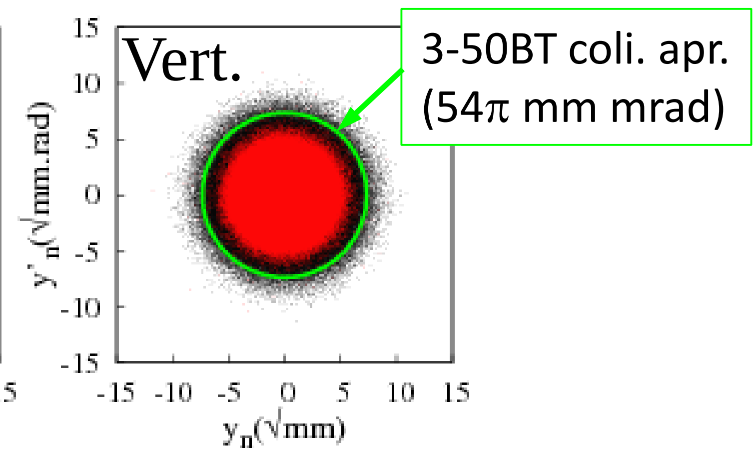
(2) Transverse and longitudinal beam distributions

Inj. 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	100



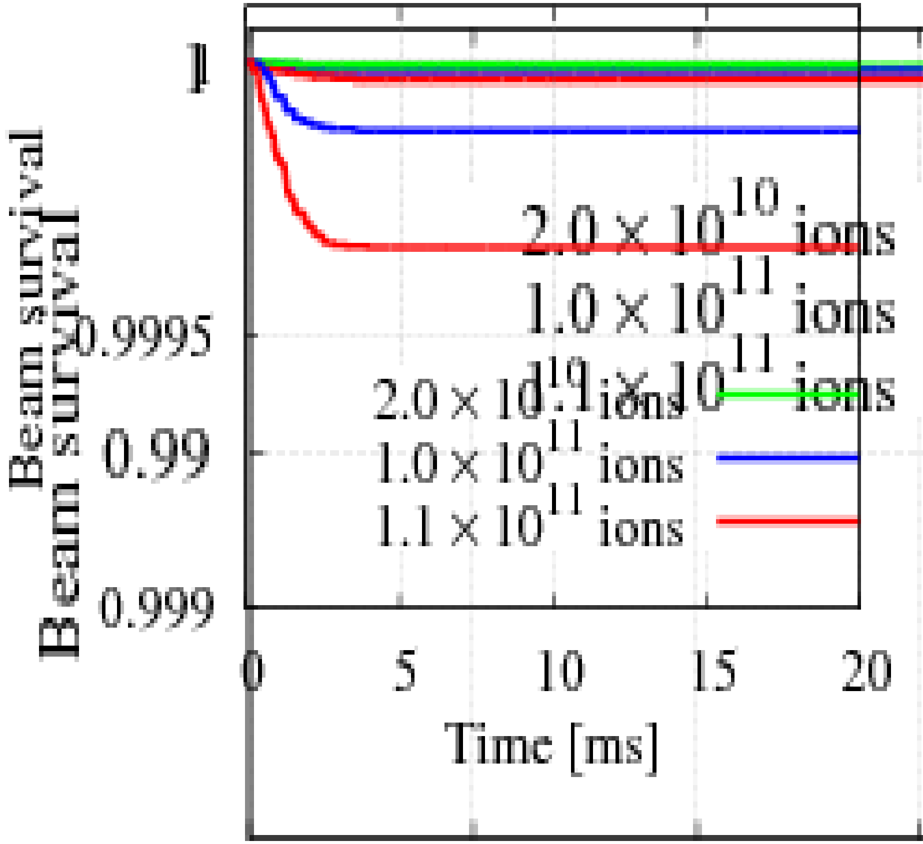




>99.9% transverse emittances of the extracted beam are within 3-50BT collimator aperture.

- ✓ **Collimated beam power << Collimator limit**
- ✓ **Satisfy very strict beam quality for MR injection.**

(2) Beam survival



- No any unexpected beam losses.
- Beam survival > 99.95% even for 1.1 × 10^{11}/b of U^{86+} ions
- **Beam loss localizes at ring collimator.**

■ However, intensity dependence beam loss is slightly non linear.
→ Further improvement is possible by optimizing injected beam shape and/or rf patterns.

- Gives bottom line for the new booster parameters.

U^{86+}: 1.1 × 10^{11} →stripping at 3-50BT → U^{92+}: ~1 × 10^{11}/RCS cycle
4 RCS cycles injection in the MR: 4 ×10^{11} /MR cycle !

Summary

In order to realize HI physics program in J-PARC, 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.
Possibilities of HI acceleration in the RCS are reported.

Studies are done within the designed and fixed frame for proton in the RCS.

- **More than 10^{11} U^{86+} ions can be achieved without any significant beam losses.**
- No serious beam dynamics issues even up to such an intensity.

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

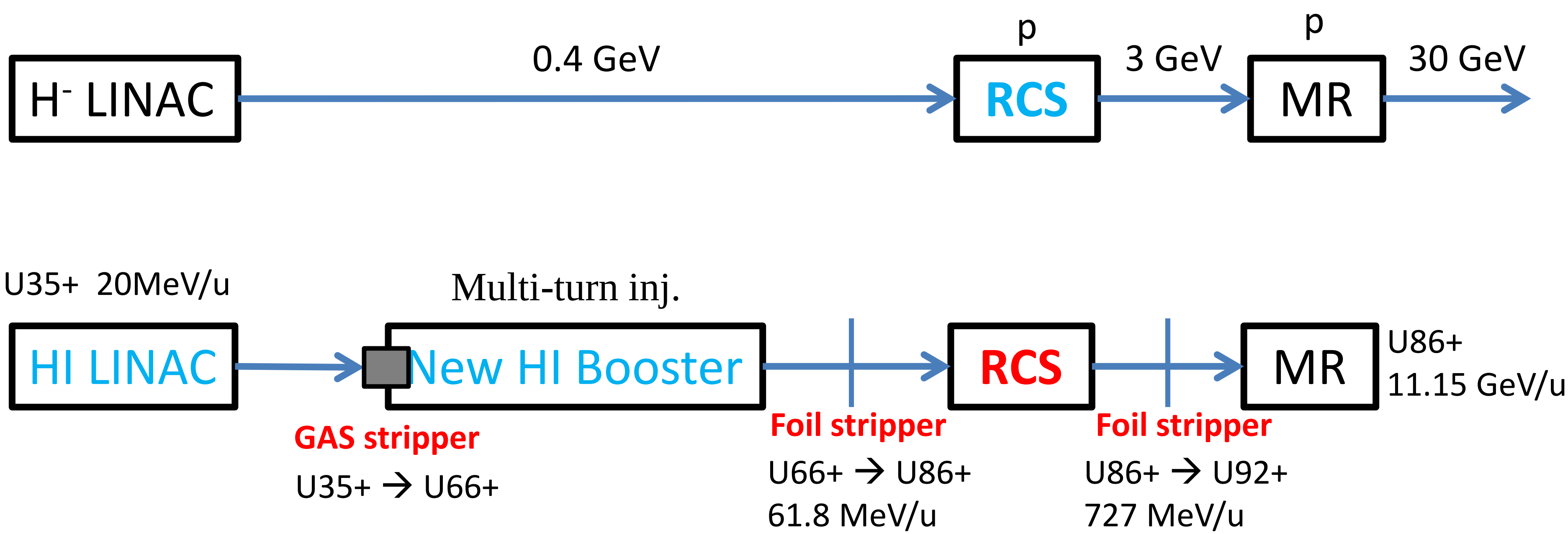
Design studies of new HI Booster is in good progress.
→ Harada-san (Tomorrow)

The RCS including proposed new HI accelerator scheme has no interference/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	Booster out	Stripper 2 Carbon	RCS out	Stripper 3 Cu<Z_T<Ta	MR out
E (MeV/u)	20	67.0	61.8	**735.4**	727.0	11.15 GeV/u
Q	35	66+-2	86	86	92	92

Present simulation background

Tool: ORBIT 3-D space charge code:

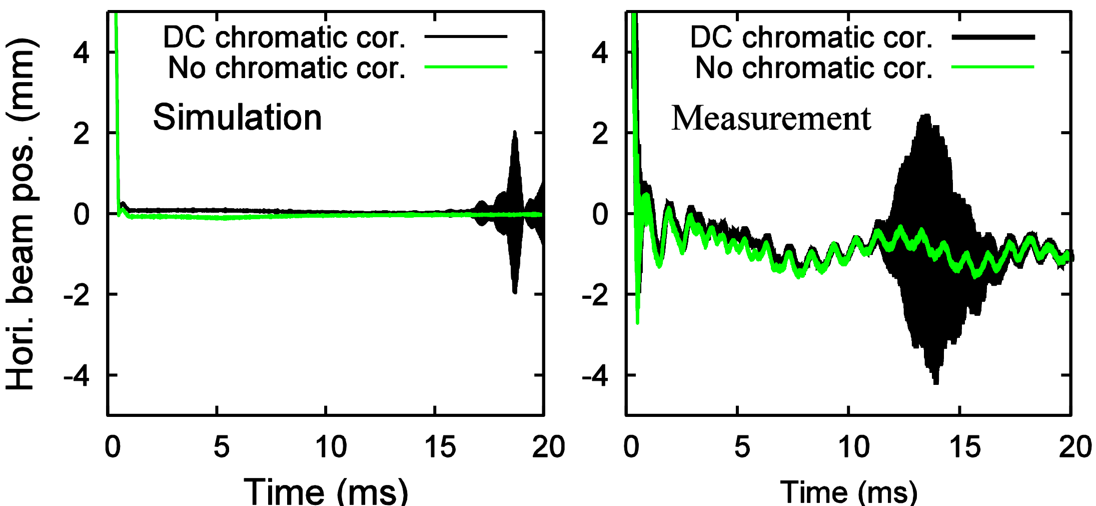
→ Originally developed at the SNS in Oak Ridge.

→ 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