First Simulation Results of Heavy-Ion Acceleration in the RCS of J-PARC

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Japan Proton Accelerator Research Complex (J-PARC)

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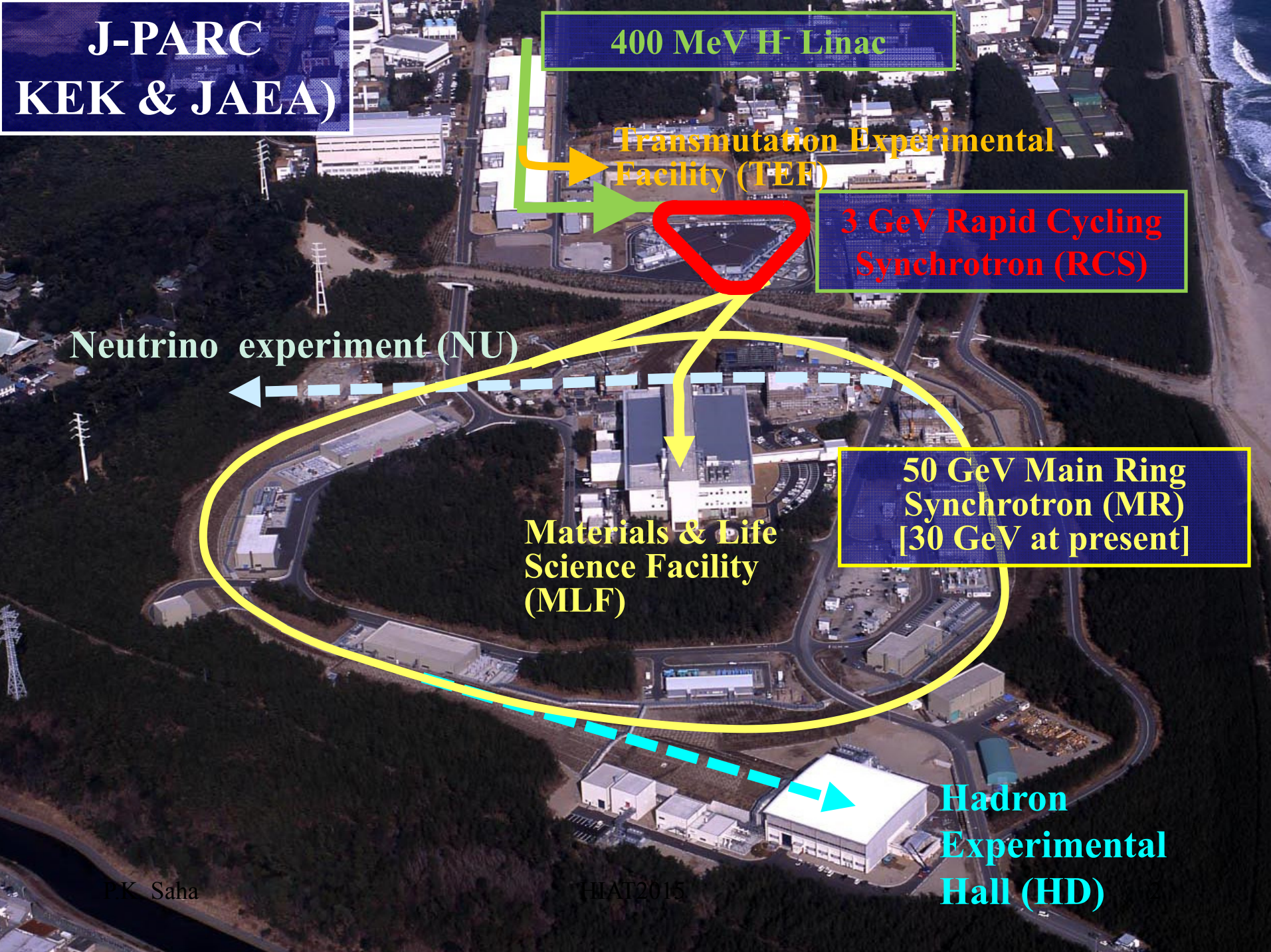

J-PARC
KEK & JAEA)
400 MeV H- Linac
Transmutation Experimental Facility (TEF)
3 GeV Rapid Cycling Synchrotron (RCS)
Neutrino experiment (NU)
50 GeV Main Ring Synchrotron (MR) [30 GeV at present]
Materials & Life Science Facility (MLF)
Hadron Experimental Hall (HD)

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.**
- Successfully demonstrated an acceleration and extraction of designed 1 MW-equivalent beam power in the RCS recently.
- *In response to the interesting HI physics program, we are considering to adapt a new accelerator scheme for HI in J-PARC.*
- ***This work studies the possibilities of HI acceleration in the RCS.***

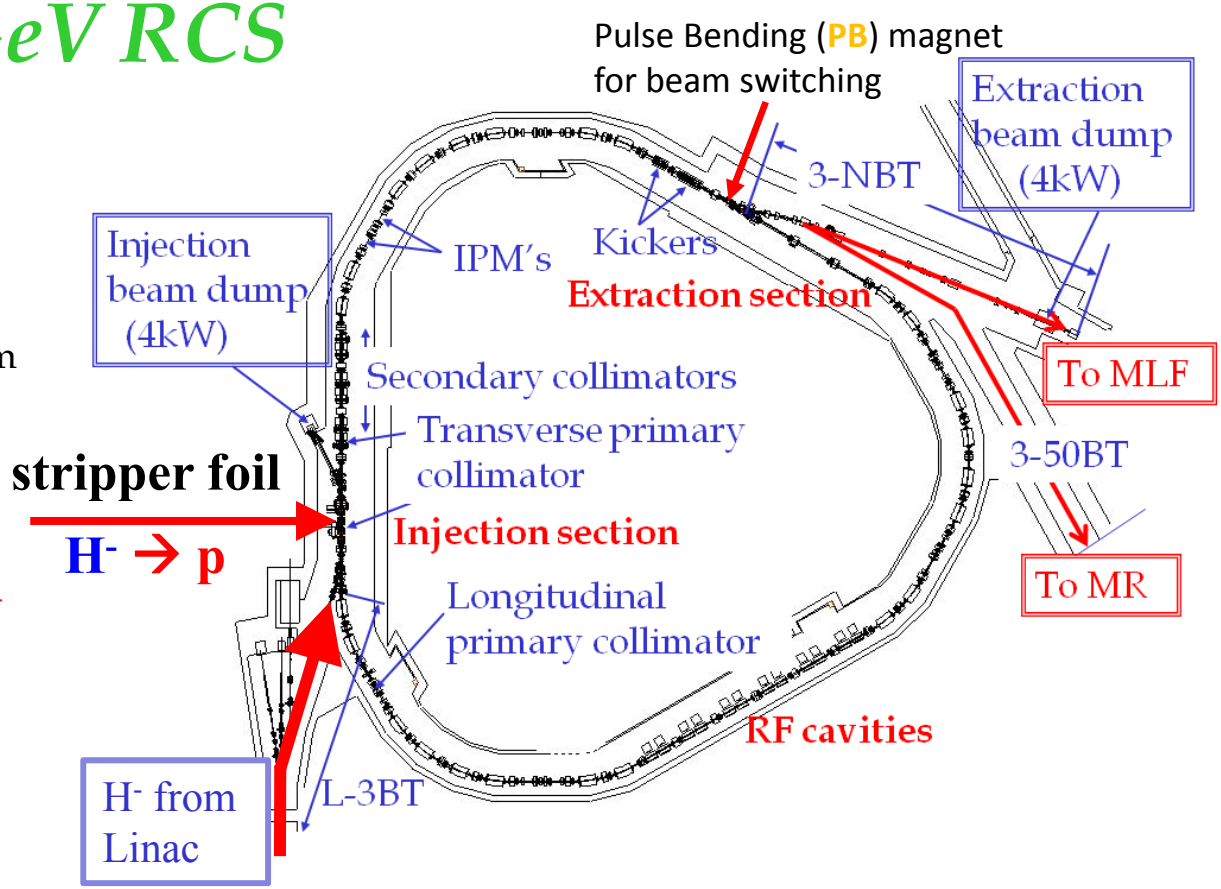
Outline:

1. **Overview of 3-GeV RCS**
2. **Overview of J-PARC HI physics program**
3. **Proposed HI accelerator scheme in J-PARC**
4. **HI acceleration strategy in the RCS**
5. **Simulation results of U^{86+} acceleration in RCS**
6. **Summary and Outlook**

Overview of 3-GeV RCS

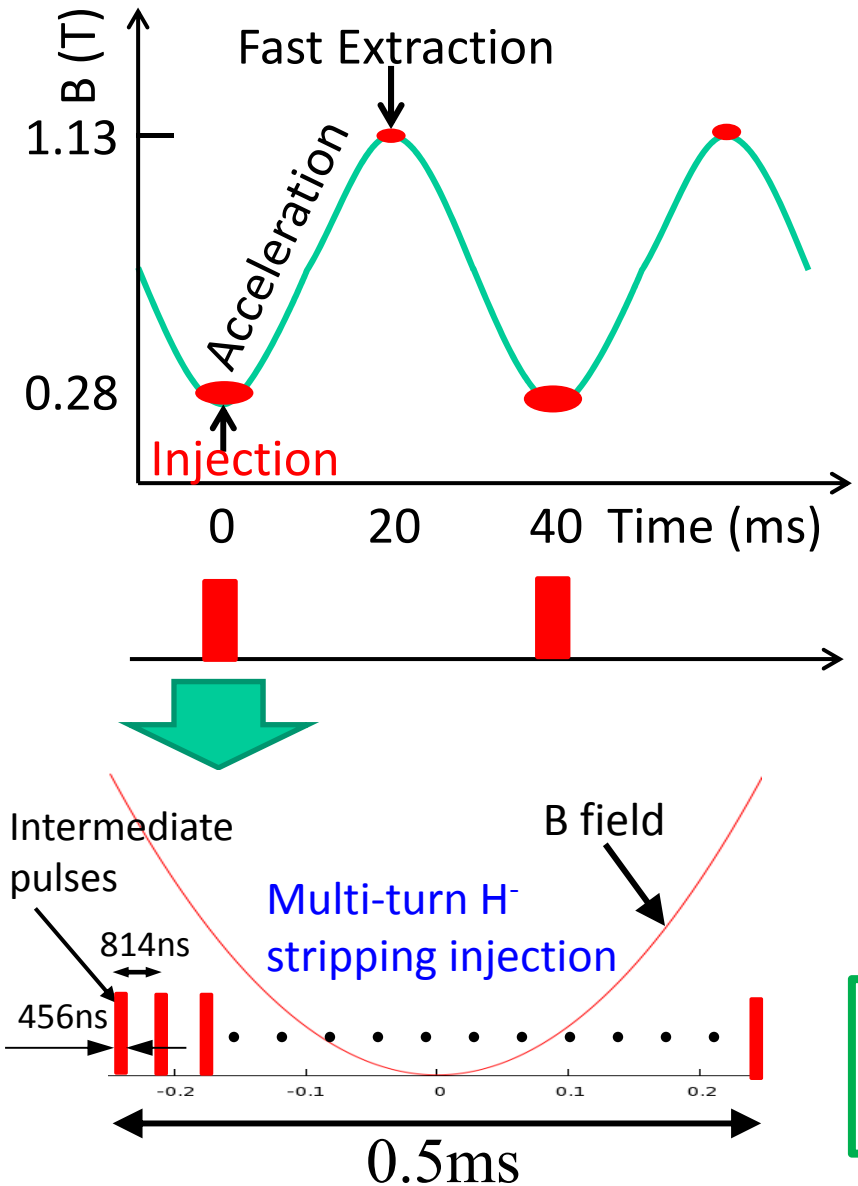
Design parameters:

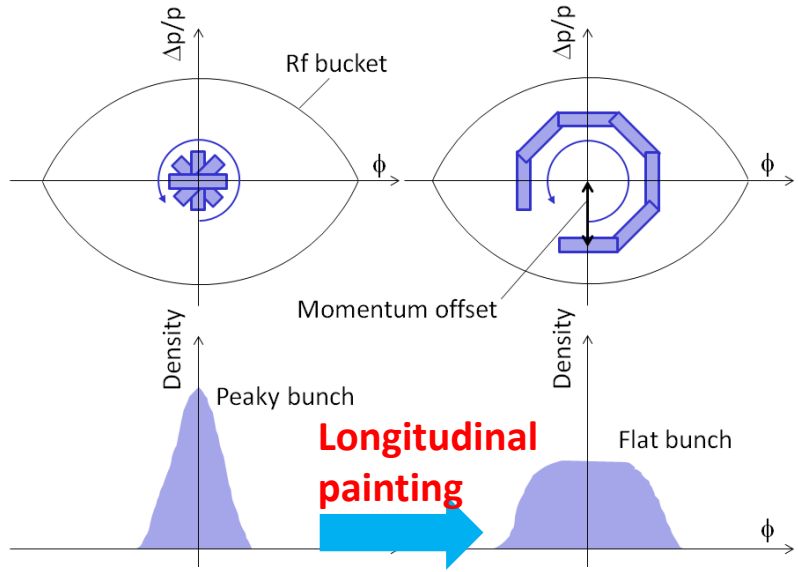
Particle	**p**
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
No of bunch	2
Injection energy	**400 MeV**
Extraction energy	**3 GeV**
Repetition rate	25 Hz
Particles per pulse	**8.3e13**
Output beam power	**1 MW**
Transition gamma	9.14 GeV
Collimator Limit	4 kW (3%@ inj. beam power)

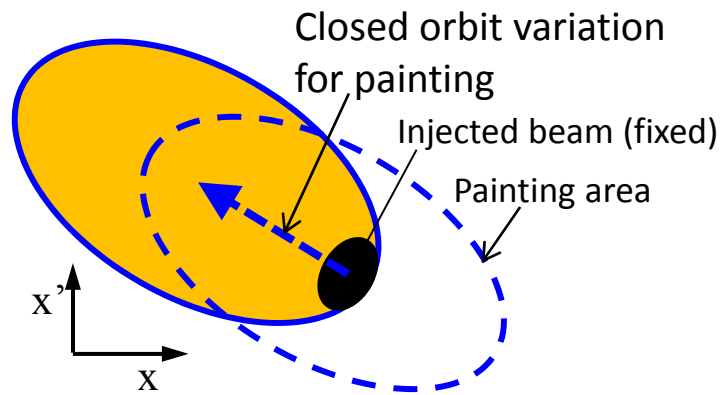


Extracted 3 GeV protons are simultaneously delivered to the neutron and muon production targets in the MLF as well as to the MR for beam injection.

RCS scheme for proton





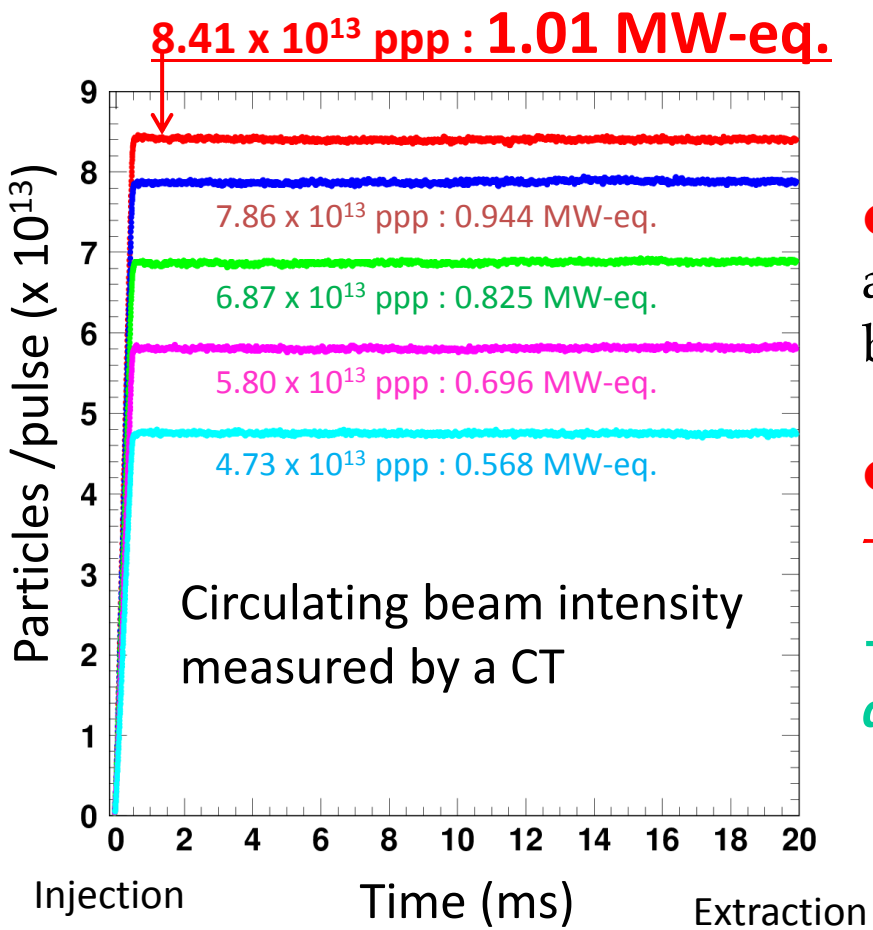


Transverse painting (H plane). Done in the V plane too.

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

RCS latest beam study results

Courtesy: H. Hotchi



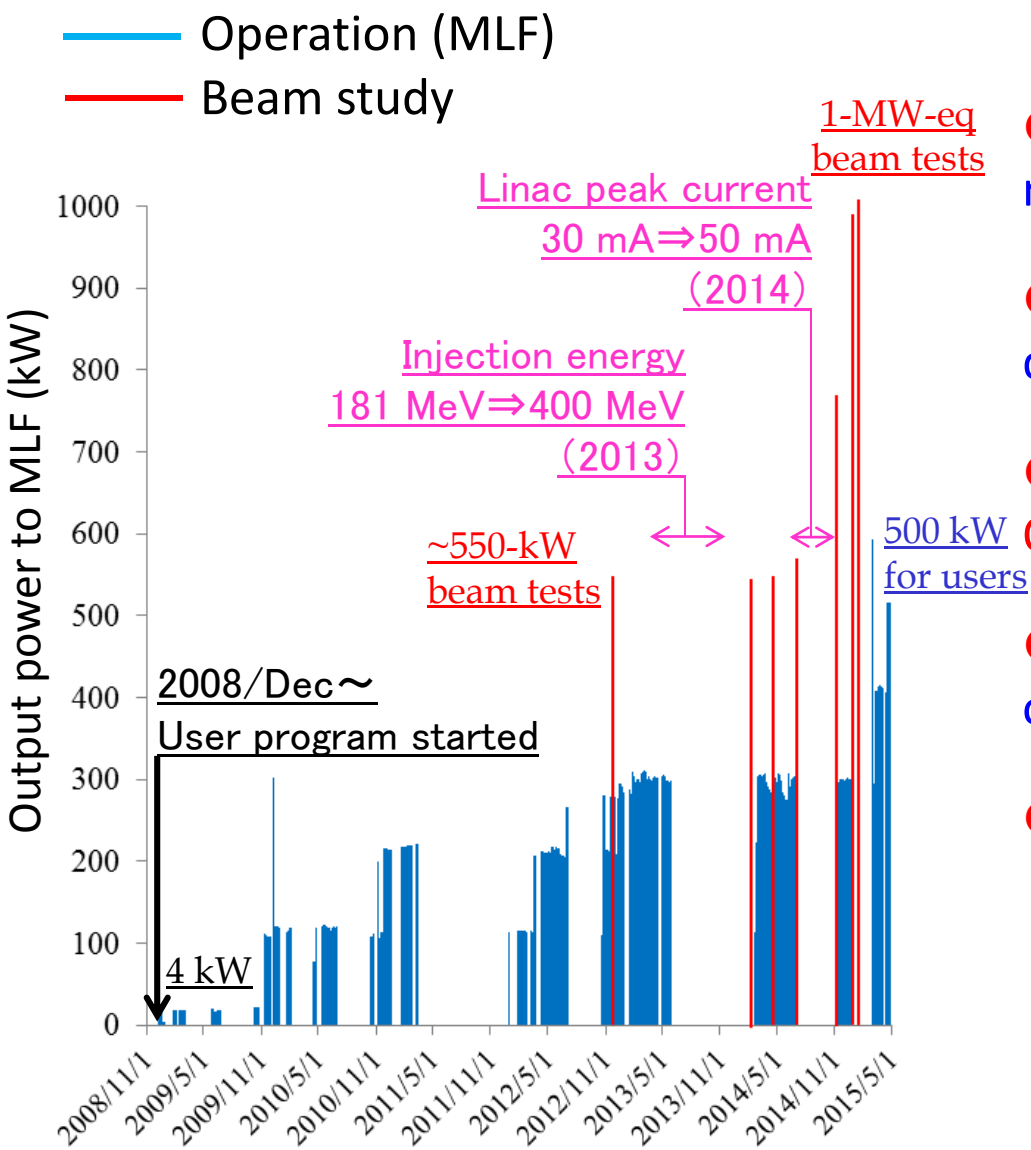
2015/Jan/10

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

- Beam loss at 1 MW: only 0.17%
-- mostly due to the foil scattering.

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

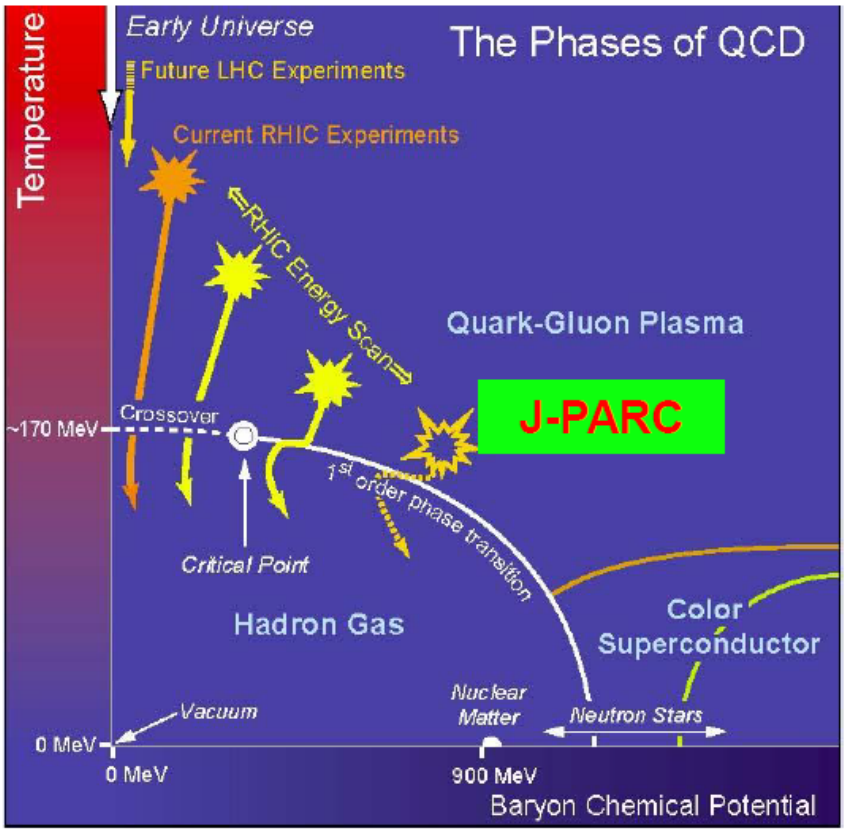
RCS beam power history to date



- Latest output beam power for routine operation: 500 kW.
- Beam power for operation mostly depends on the request from users.
- 1-MW beam tests started from October 2014.
- Parameters for up to 800 kW operation has already been fixed.
- Getting ready for 1 MW stable operation.

HI physics program at J-PARC

Low energy: 1-10 MeV/u (U) Linac beam for studying unstable nuclei.
High energy: 1-20 GeV/u (U) beam from the MR



- 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.

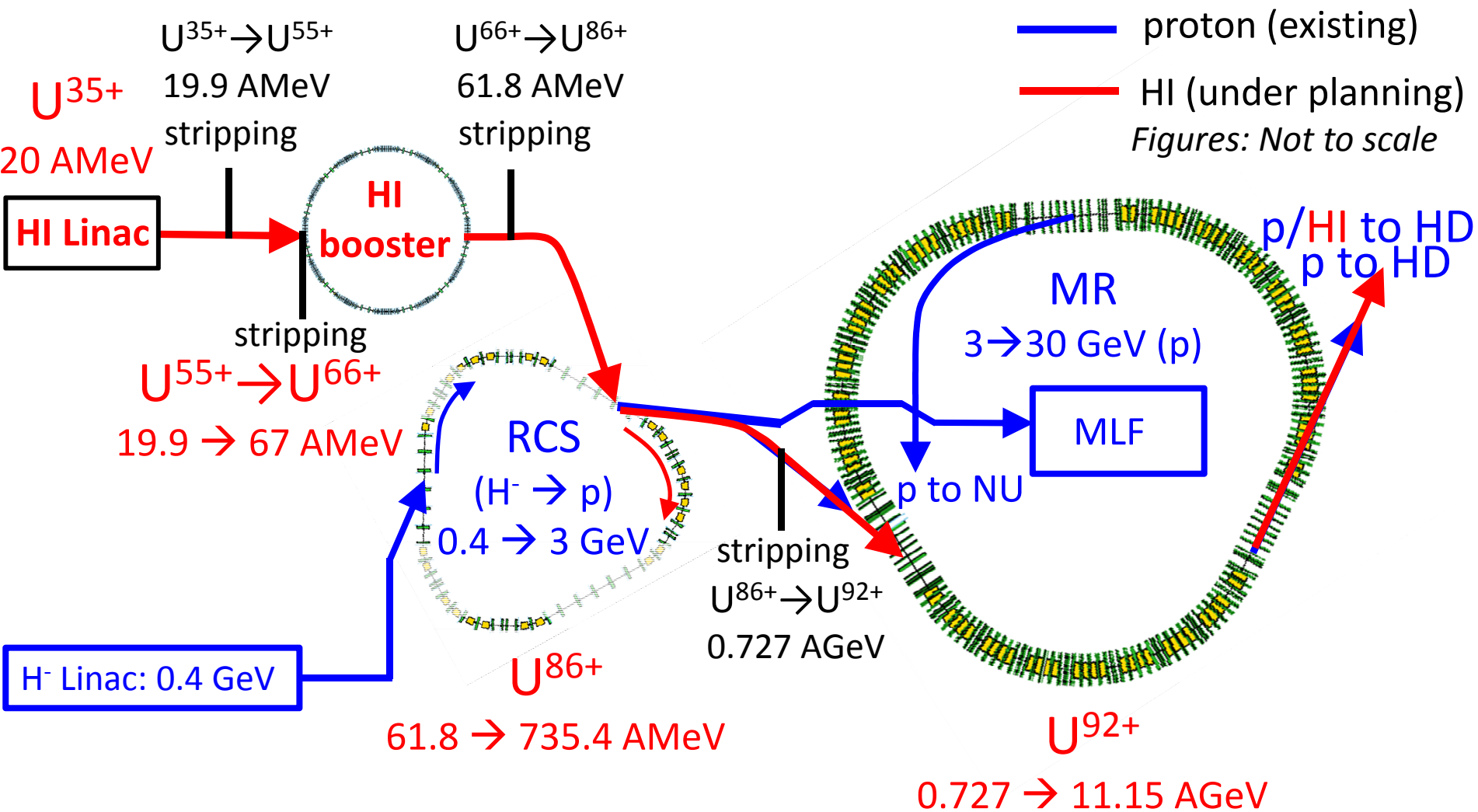
→ Fixed target collision by using slowly extracted HI beam of 1E11/cycle (6s) from the MR.

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

Big challenge for the accelerator people to meet the goal without intercepting any the of existing programs with proton beam.

HI Accelerator scheme in J-PARC

(Yet unofficial!)



Advantages and issues of HI scheme in the RCS

Advantages:

- Use existing building and devices.

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

- Large acceptance

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

- Well understood and optimized accelerator performance up to designed 1 MW.

-- Realistic discuss on beam dynamics issues and measures for high intensity HI.

. . . . . .

Issues:

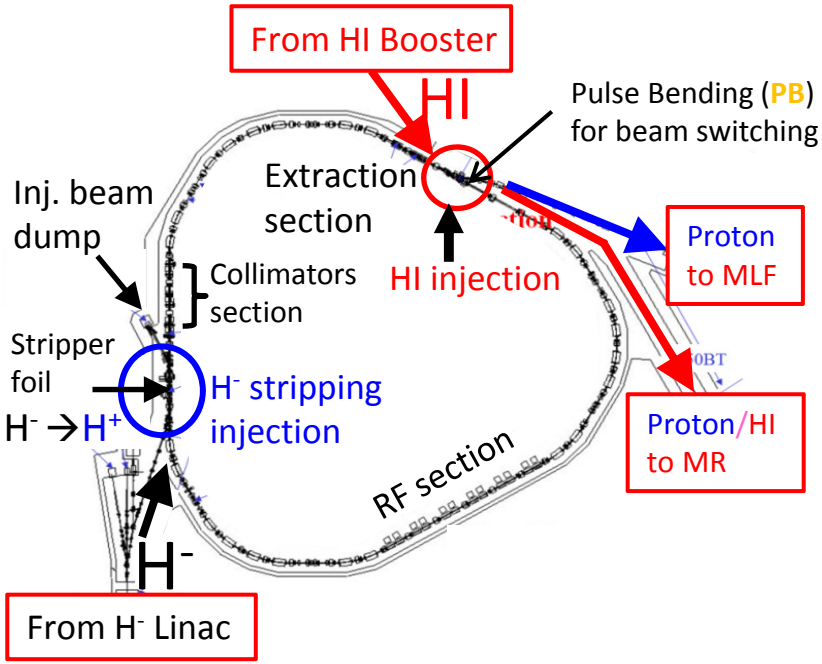
- Parallel operation between MLF and MR with **p** and **HI**, respectively must be done.
- Most of the machine parameters fixed for p must be used for HI

(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).

HI Scheme in RCS



HI injection system in the RCS:

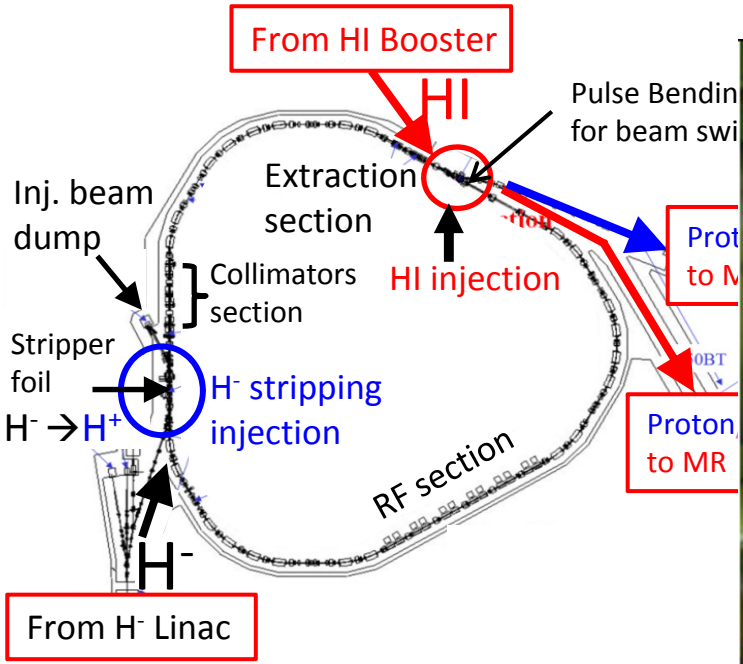
Place: At the end of extraction straight section

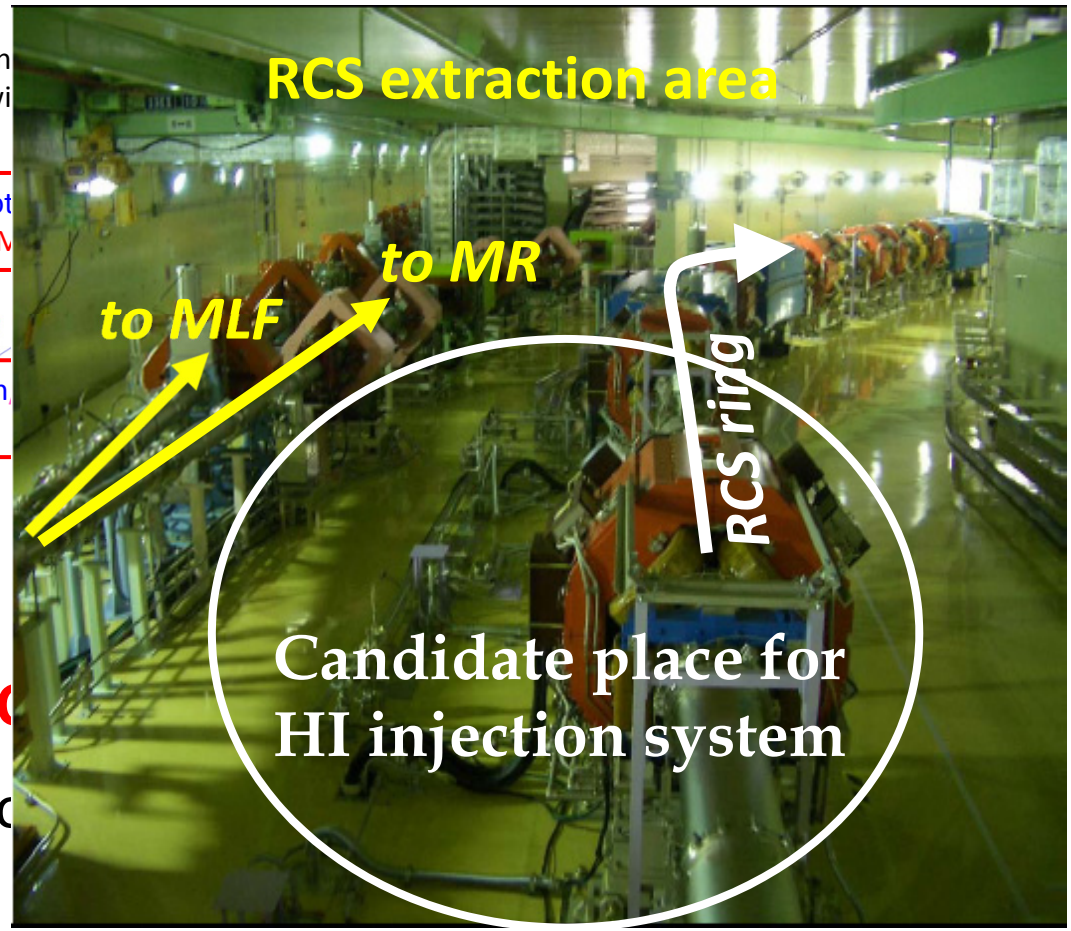
→ Only available space.

Scheme: One turn injection from the HI booster.

→ Simple injection system.

HI Scheme in RCS





HI injection system in the RC

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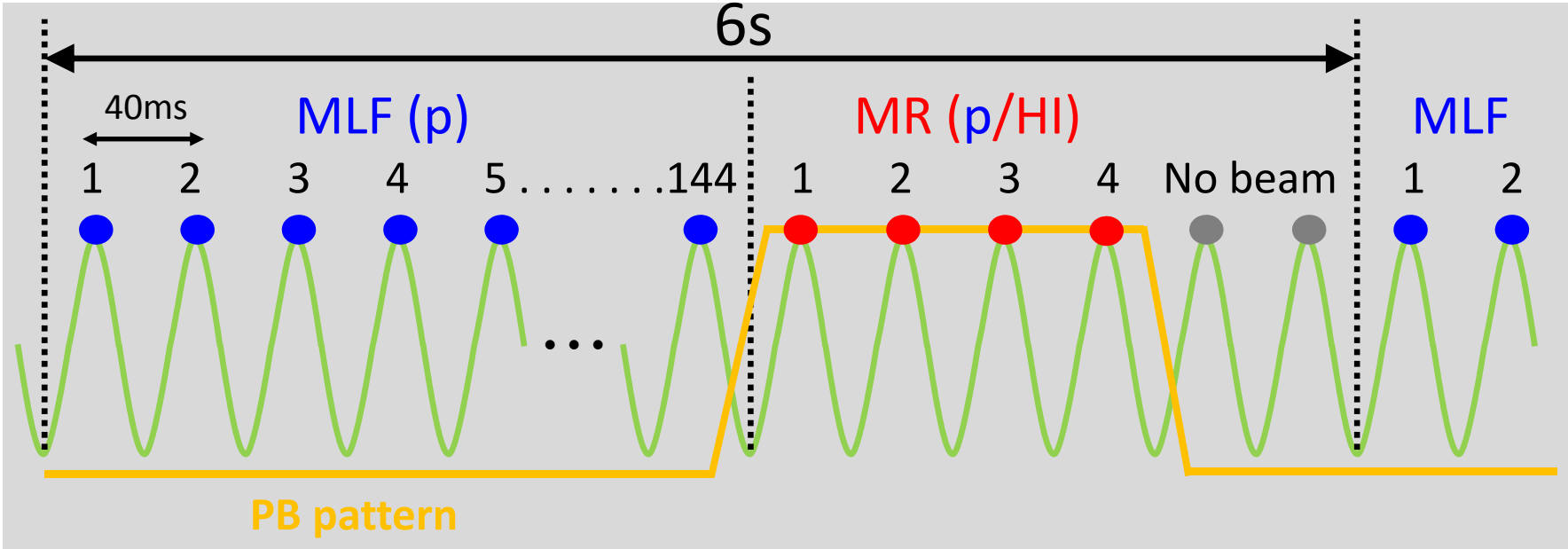
How HI scheme works in RCS

RCS beam delivery pattern



- MR operates for either NU or HD

  When MR operates for HD (6s), No. of RCS cycles: 25 × 6 = 150

  (144 RCS cycles to MLF, 4 to MR, 2 no beam (to avoid Eddy current effect of PB)

- Only when MR runs HI for HD, RCS injects HI in the MR cycle.

  → ***No conflict with MLF/NU***

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

Code: ORBIT-3D

Steps:

(1) Single particle w/o SC

(2) Multi-particle w/ SC

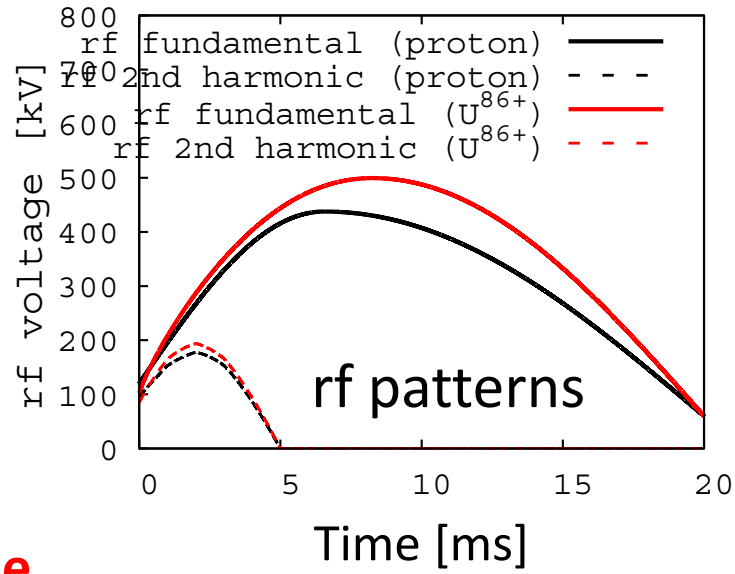
● BM, QM, Sextuples are kept unchanged as optimized for 1MW proton (for MLF).

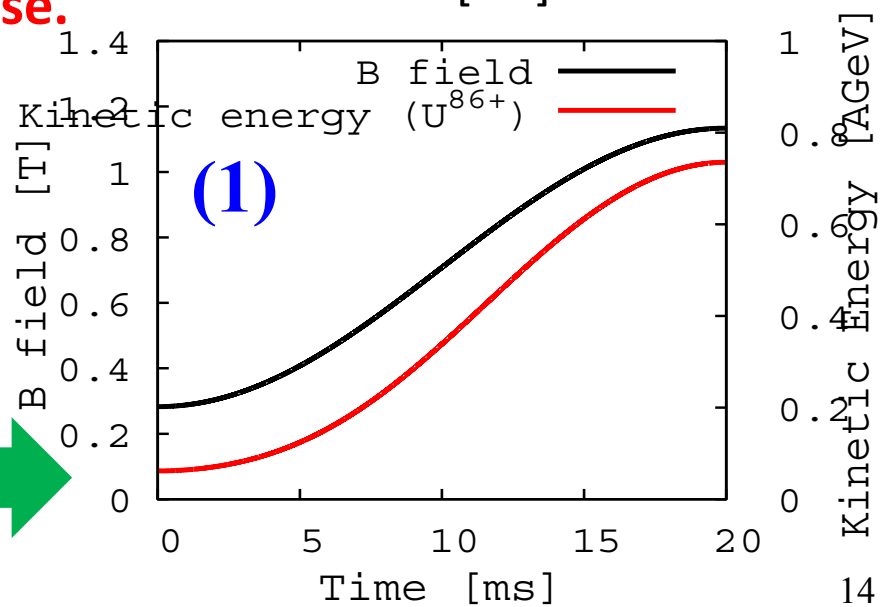
→Those can't be changed pulse-to-pulse.

● **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:

+ p : 4.2×10^{13} / bunch

x U^{86+} : 1.1×10^{11} / bunch

● Bare tune (6.45, 6.42)

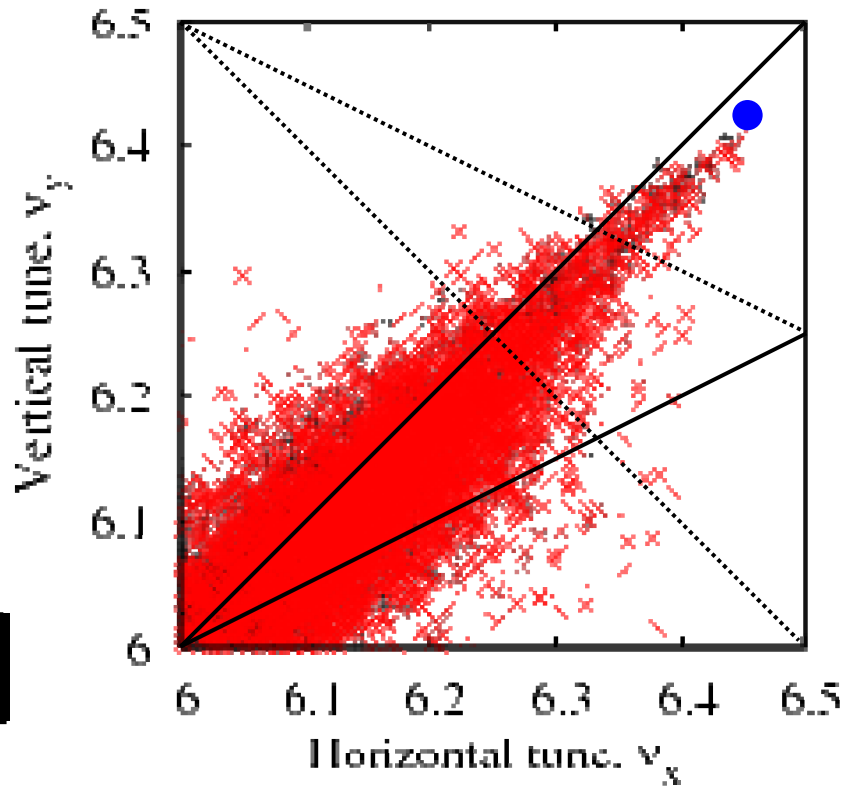
Laslett tune shift:

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

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**

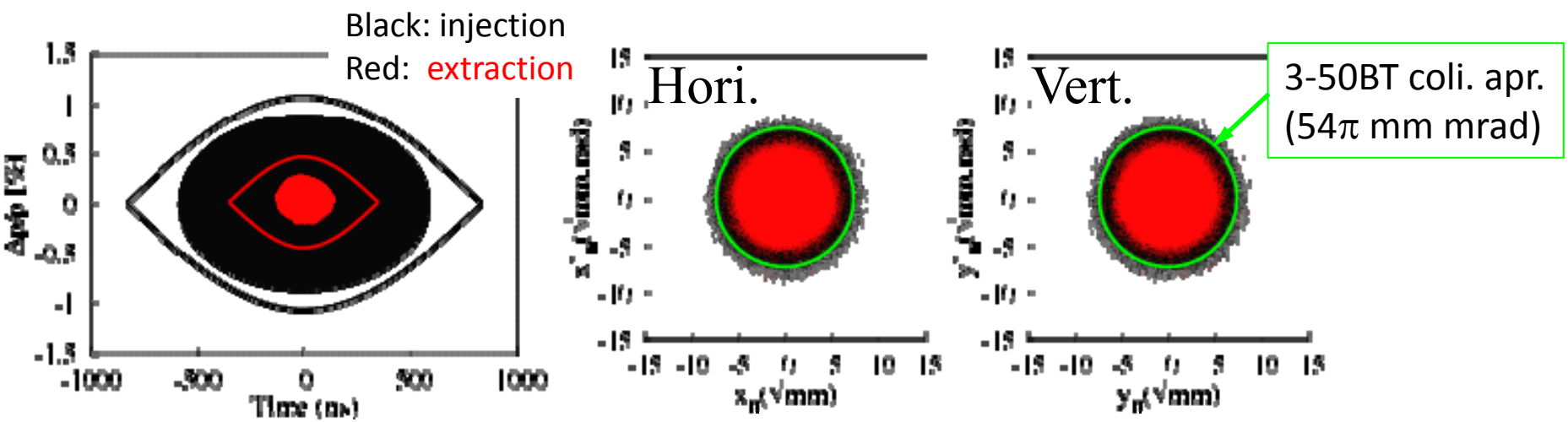


Consistent with numerical estimation!

(2) Transverse and longitudinal beam distributions

Inj. beam parameters:

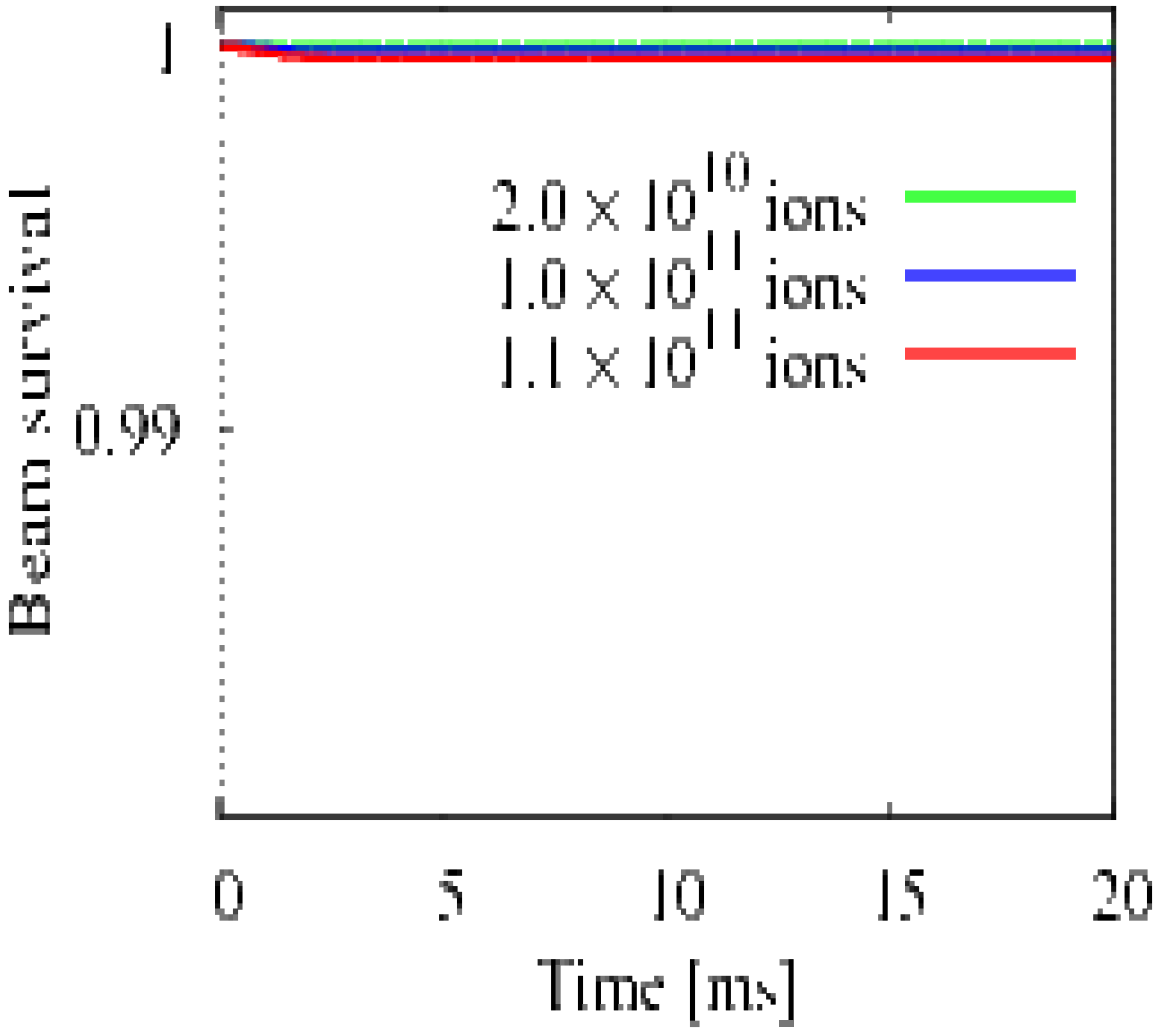
Inj. turn	No of bunch	**Intensity ($\times 10^{11}$)**	Beam shape	Δs (ns)	Δp/p (%)	ε_{tr} (π mm mrad)
1	1	**1.1**	Gaussion	1180	$\pm$0.9	100



>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



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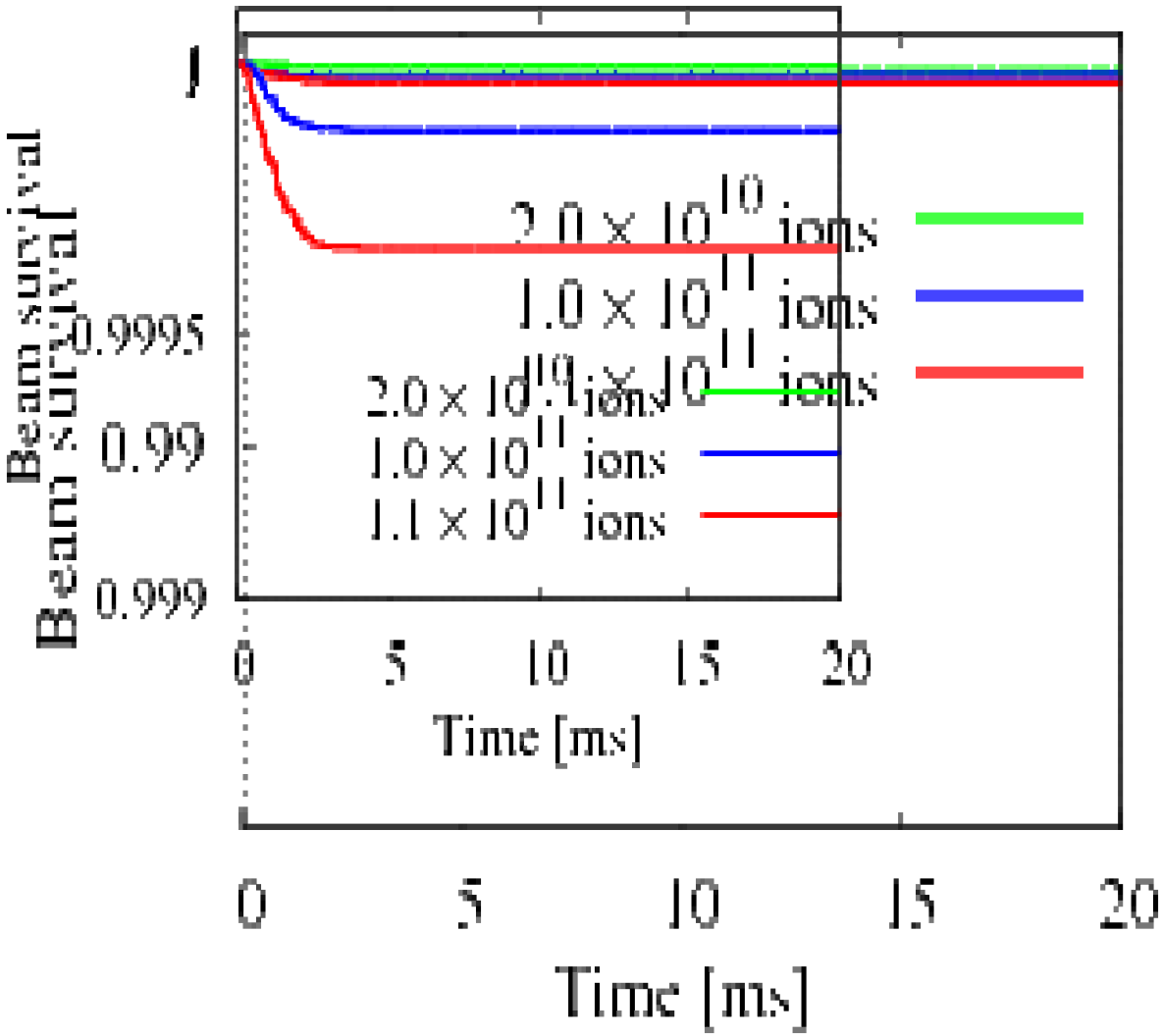

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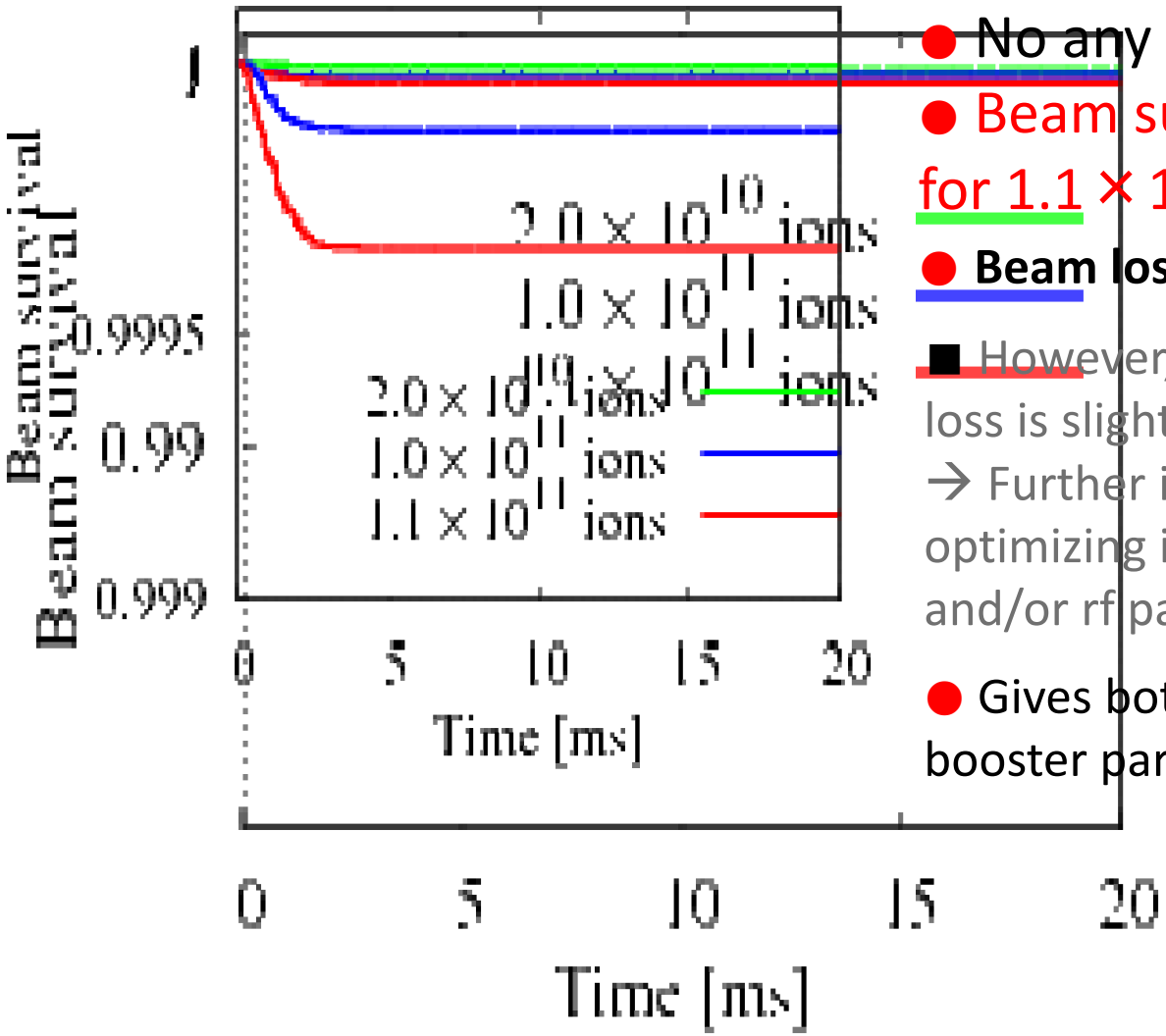

- No any unexpected beam losses.
- Beam survival > 99.95% even for 1.1 × 10^{11}/b of U^{86+} ions
- **Beam loss localizes at ring collimator.**
- However, intensity dependence beam loss is slightly non linear.
  → Further improvement is possible by optimizing injected beam shape and/or rf patterns.
- Gives bottom line for the new booster parameters.

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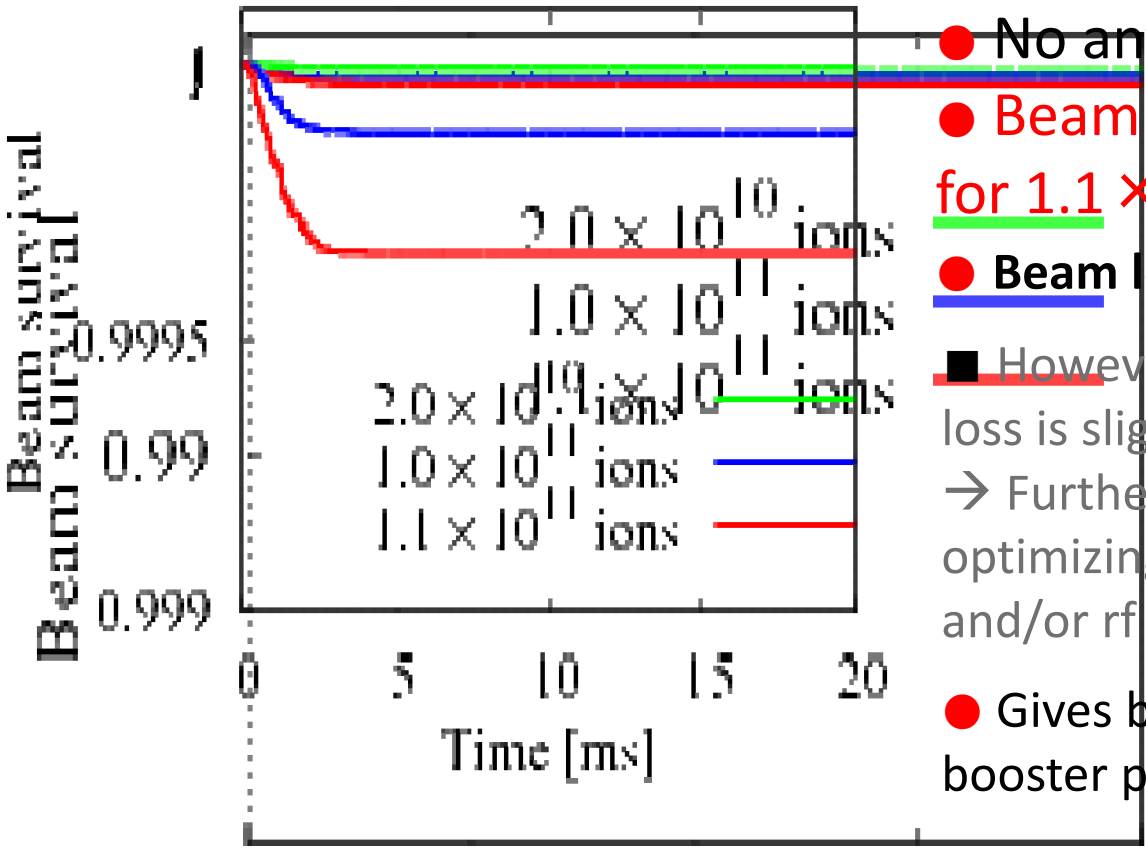

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U^{86+}: 1.1 × 10^{11} →stripping at 3-50BT → U^{92+}: ~1 × 10^{11}/RCS cycle

4 RCS cycles injection into the MR: 4 ×10^{11} /MR cycle (6s)!

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.

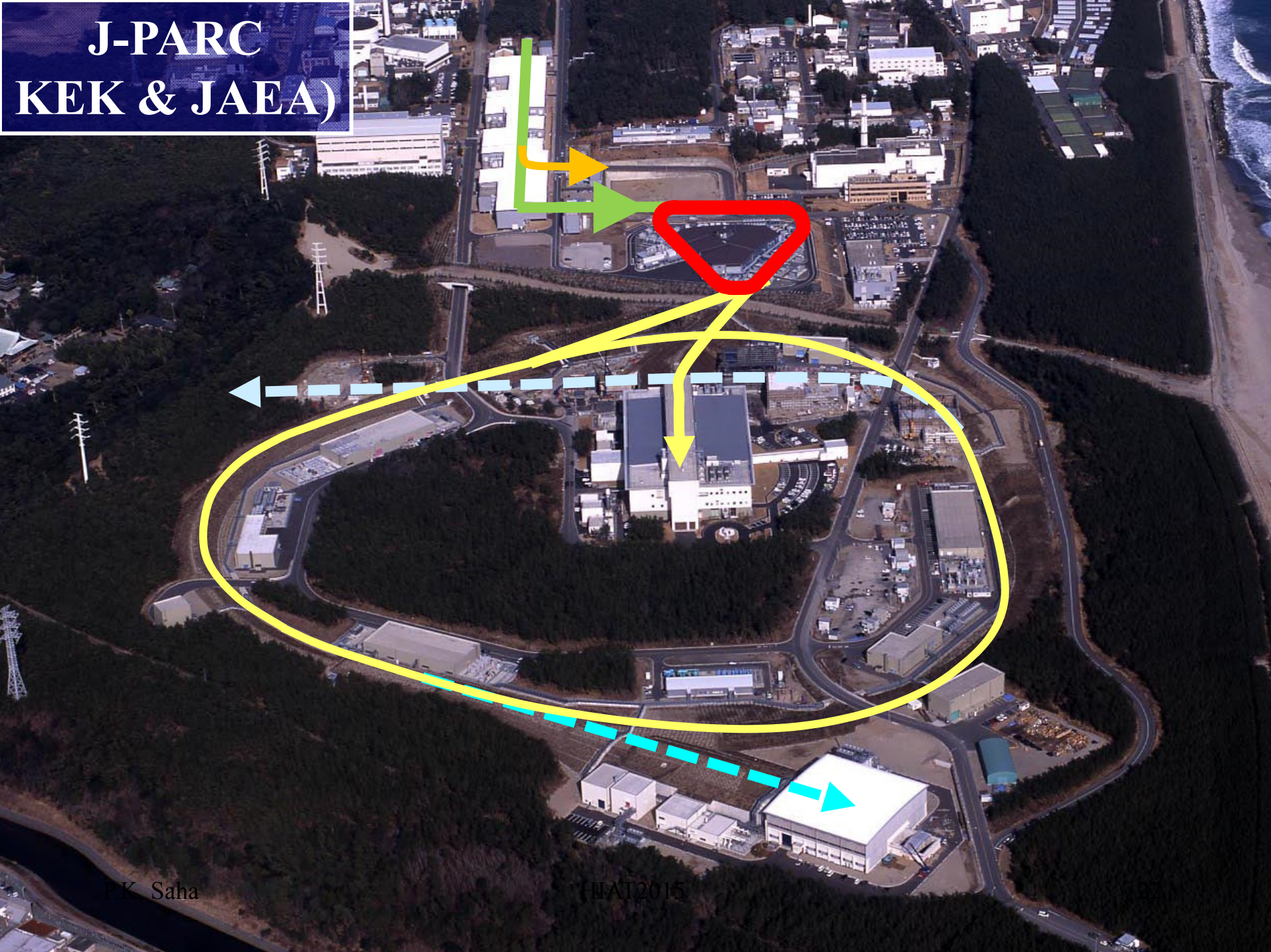
Studies are done within the designed and fixed frame for proton in the RCS.

- **A more than 10^{11} U^{86+} ions can be achieved with no significant beam losses.**
- No serious beam dynamics issues even up to such an intensity.

→ Gives 4×10^{11} U^{92+} ions/cycle (6s) in the MR and quite more than experimental requirement at present.

Design of the new Booster is in progress.
Further detail studies have to be done with realistic booster parameters.

The RCS including proposed new HI accelerator scheme has no interference/conflict with existing programs that make use of proton beams.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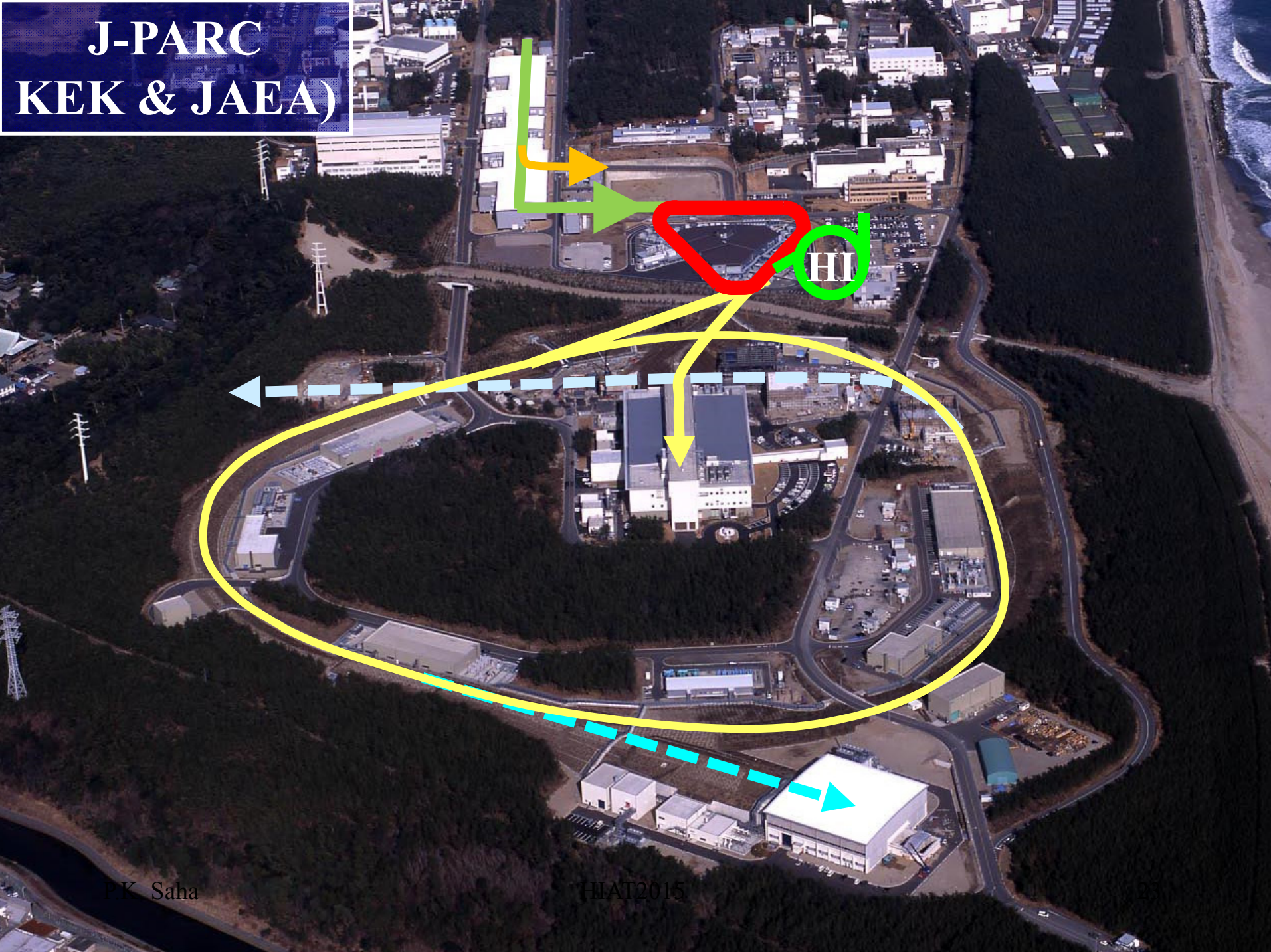
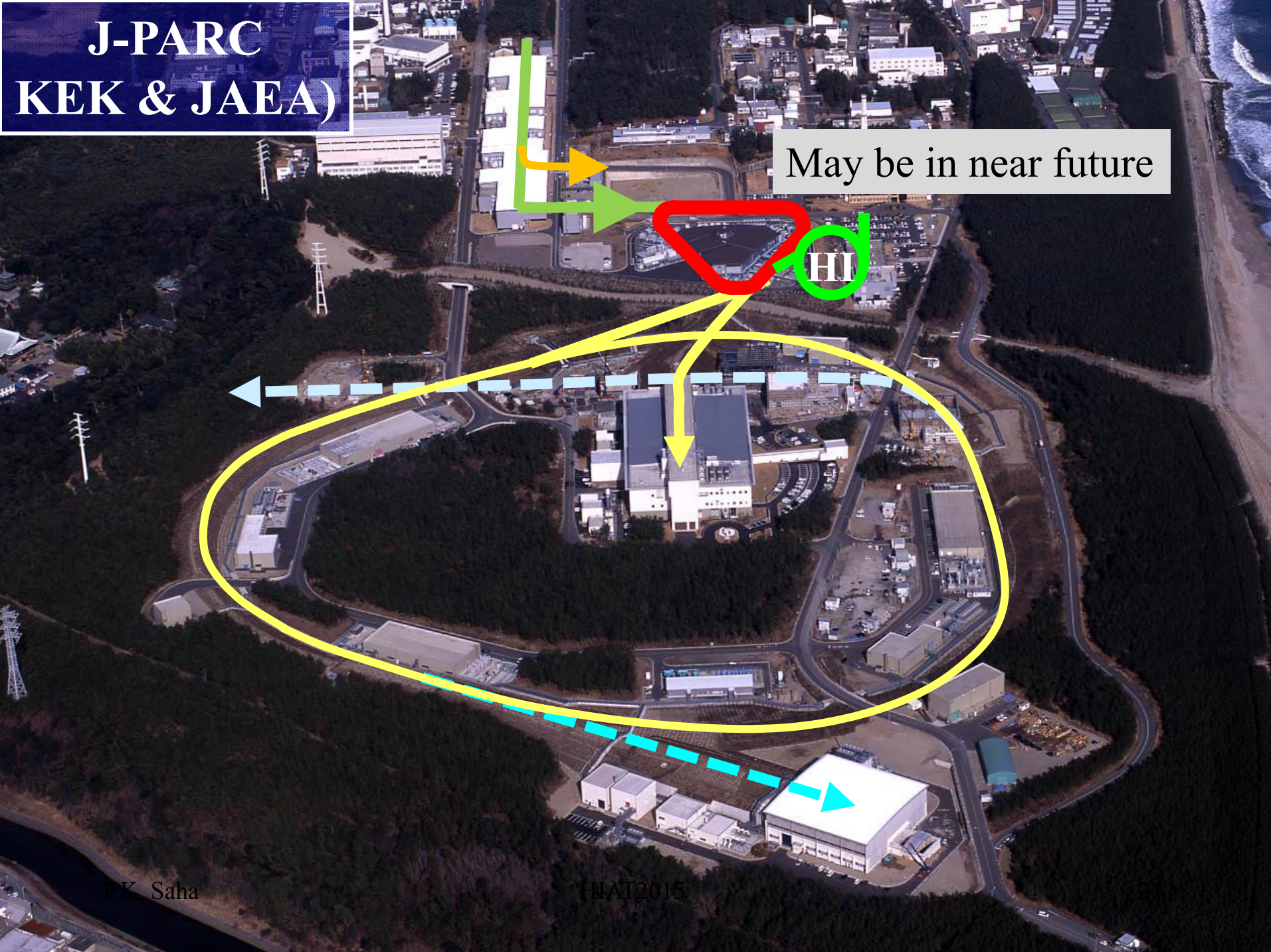
KEK & JAEA)


J-PARC
KEK & JAEA)
HI


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