Design and improvement of J-PARC 3GeV Rapid Cycling Synchrotron (RCS) for 1 MW

Accelerators Capabilities Enhancement Workshop

Jan. 30, 2023

Kazami Yamamoto

Accelerator Division

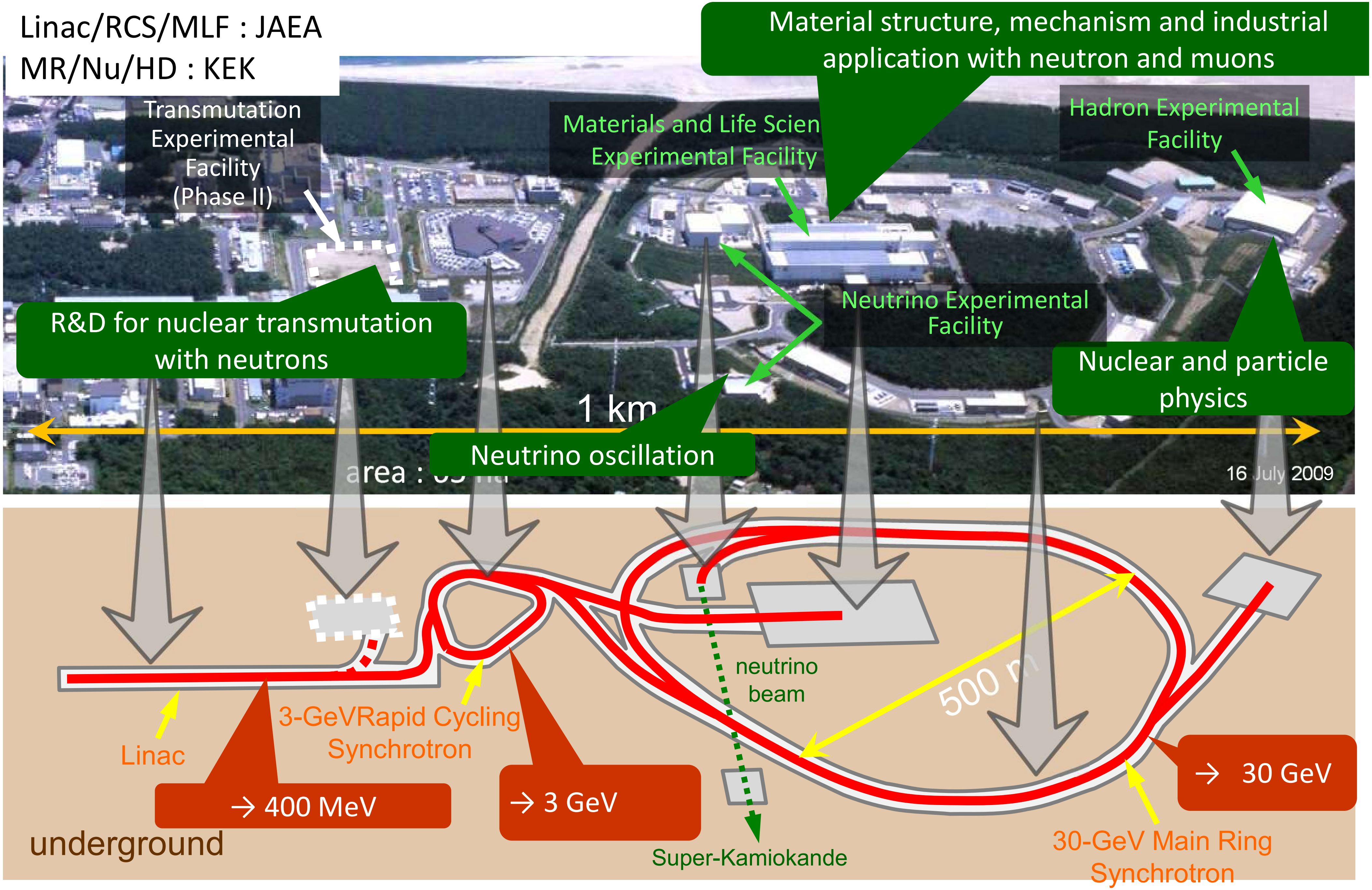
Japan Atomic Energy Agency (JAEA)

Contents

- Overview
- Design of J-PARC RCS
- Beam study and improvement

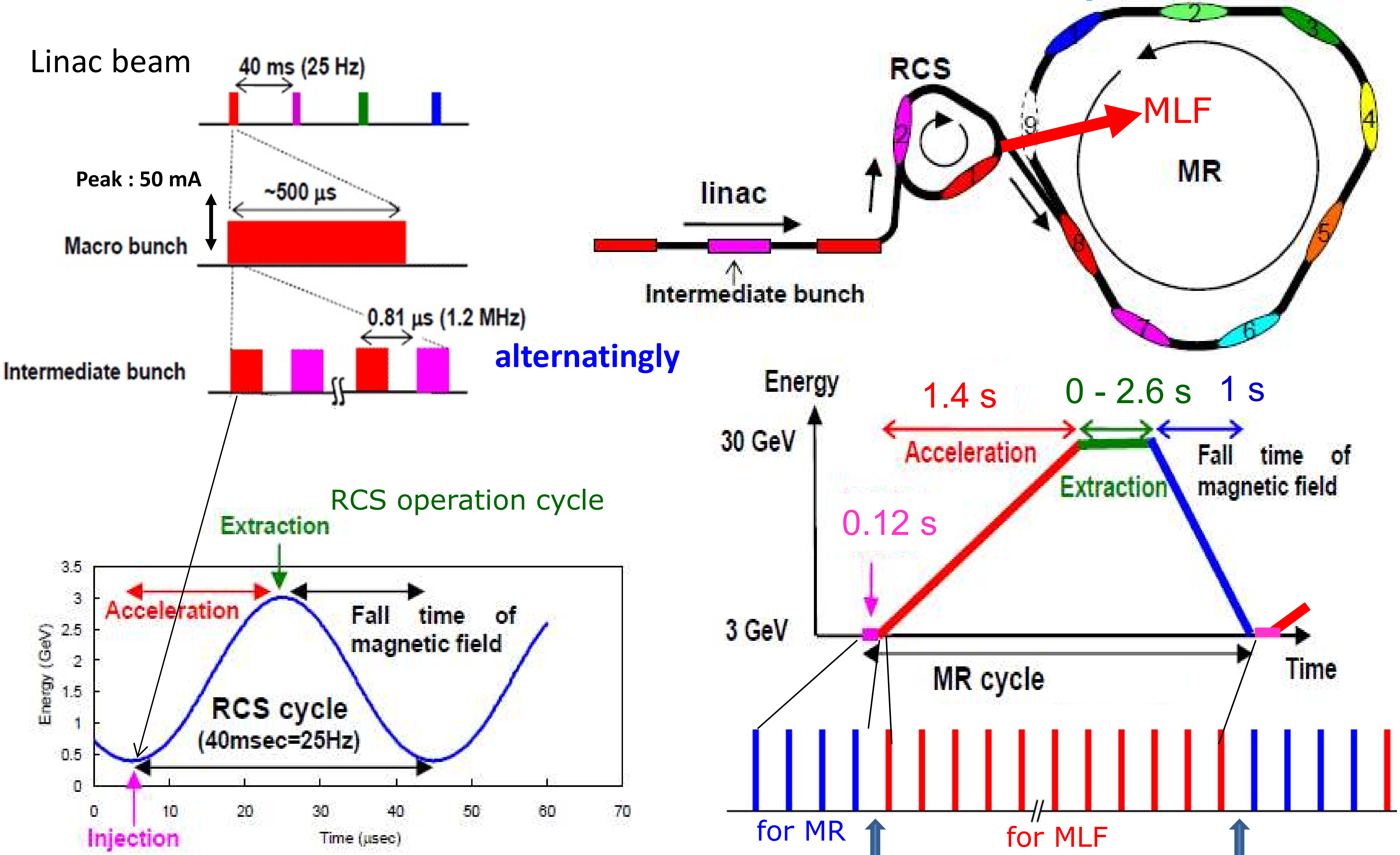

Fukushima
Power plant
Tokai-mura
Kamioka
Tsukuba
Tokyo
Osaka
Google Map - ©2013 Google

Japan Proton Accelerator Research Complex



3 proton accelerators and (3+1) experimental facilities

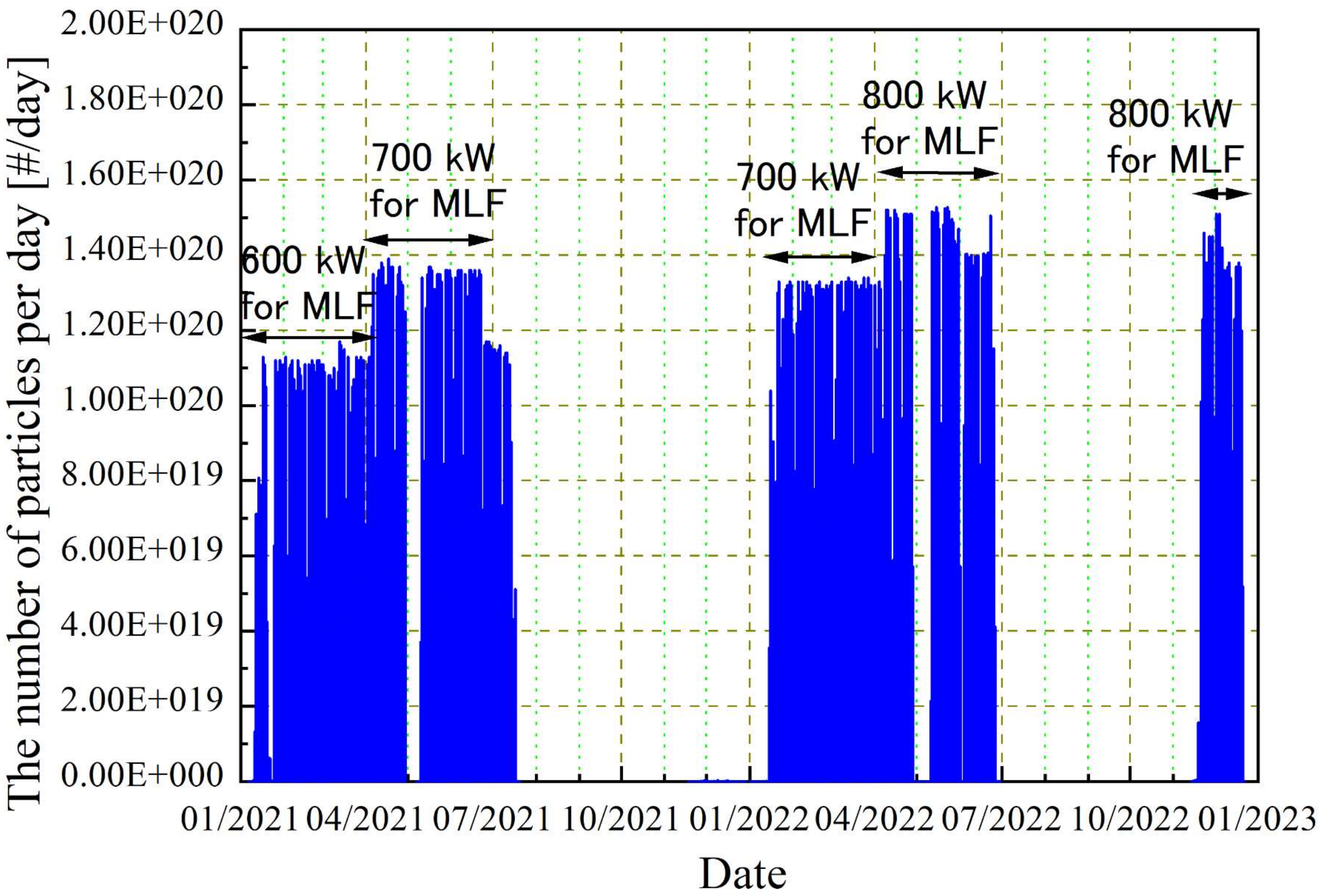
Time Structure of accelerator operation



Switch the parameters of RCS between MLF ~~MR~~ during 20 ms interval

MR operation cycle was shorten!
FX:2.48 s -> 1.36 s (MLF Duty 93.5%->88.2%)

User operation of RCS



Recent years, availability of MLF user operation is around 95 %.
We achieved quite stable operation.

Design of J-PARC RCS

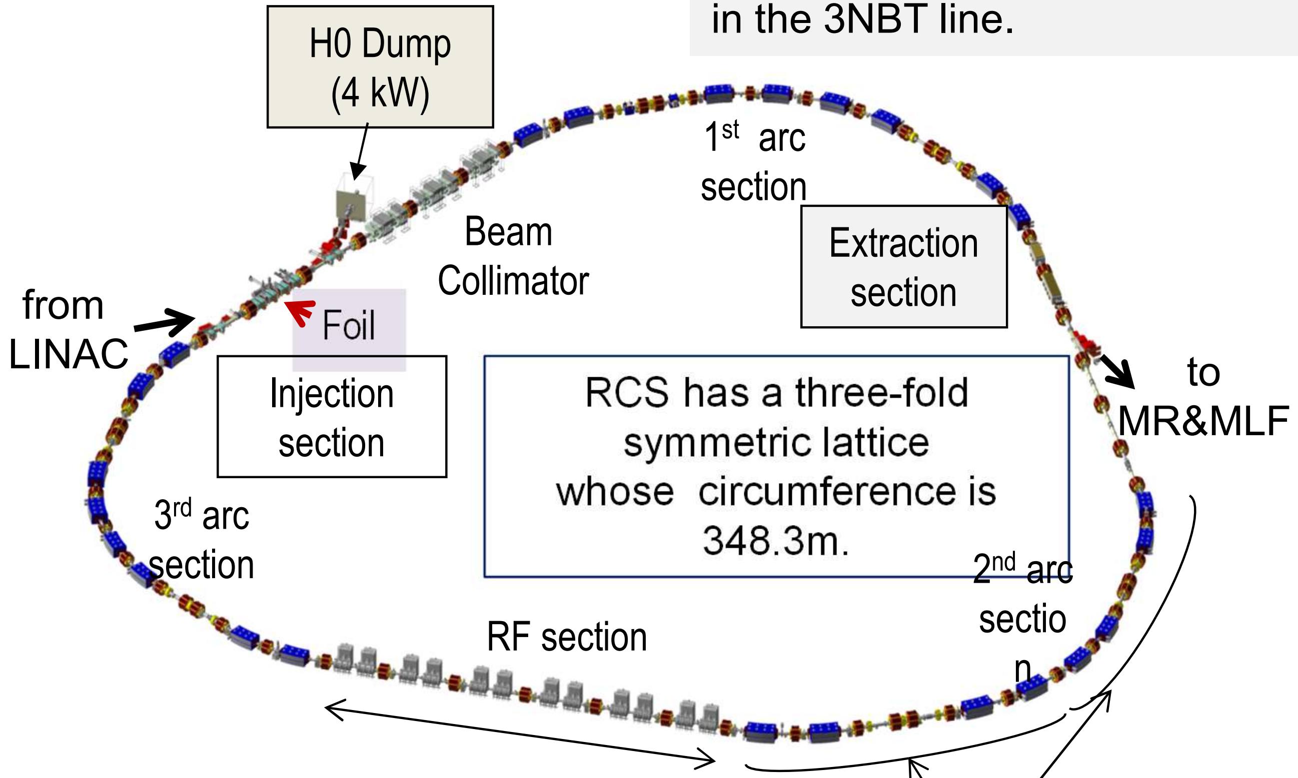
3GeV-RCS in J-PARC

Design parameters

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
F_{rev}	0.61-0.84 MHz
F_{rf}	1.23-1.67 MHz
Injection energy	400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	8.3e13 with 1 MW
Output beam power	0.5 MW (1 MW)
Transition gamma	9.14
Number of dipoles	24
quadrupoles	60 (7 families)
sextupoles	18 (3 families)
steerings	52
RF cavities	12

The H0 dump is used to dump unstripped beams at the stripping foil. The capacity is 4kW.

The beams are extracted by kicker magnets and DC septum magnets at the extraction section and then transported either to MLF or to MR with a pulsed bending magnet placed in the 3NBT line.



One of the three-fold symmetric lattice comprises two arc modules and a long straight insertion.

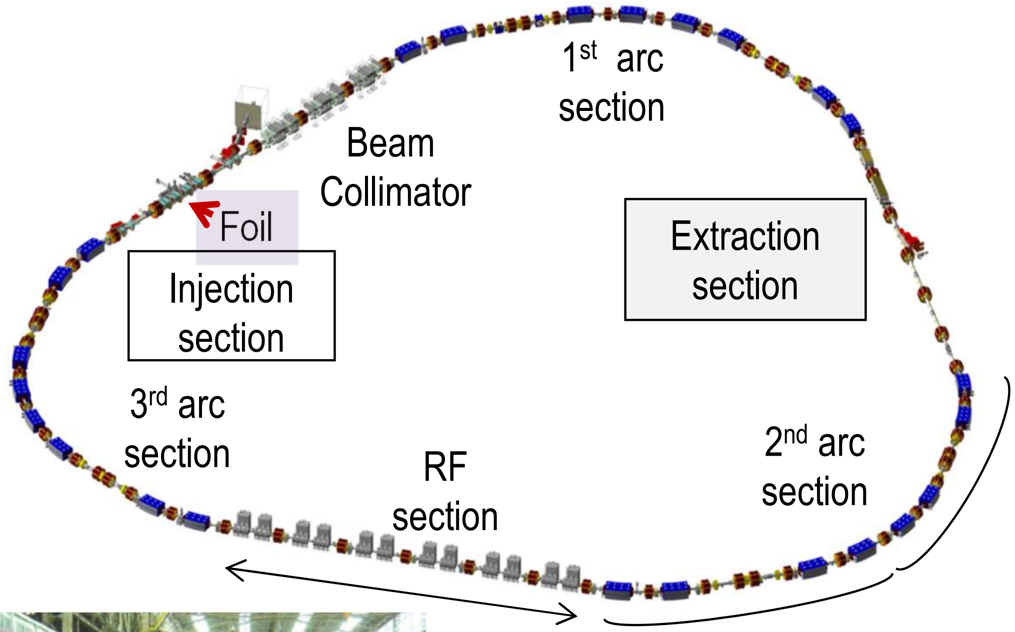
Each arc module has a missing-bend cell.

Concept of the lattice design

We have chosen the lattice with three-folding symmetry in order to keep three long straight sections.

- One is dedicated to the long RF acceleration section
- One for the injection and collimation, and the other for the extraction, both of which will be radioactive.

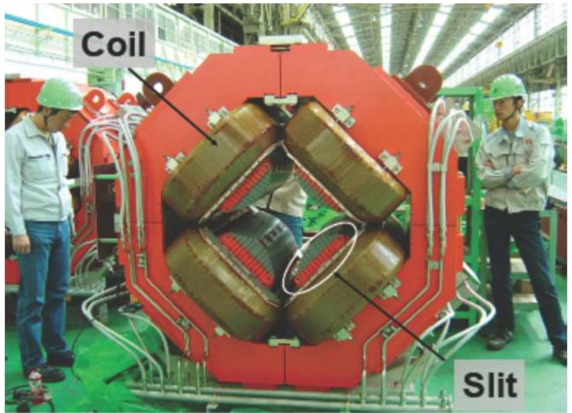
The circumference of the RCS is limited from the circumference of the MR. The ratio of those circumferences should be the rational number.
(348.333:1567.5 = 2/9)



Loss localization in the collimator to achieve 1 W/m criteria.

Keep enough Acceptance
->Large aperture magnet

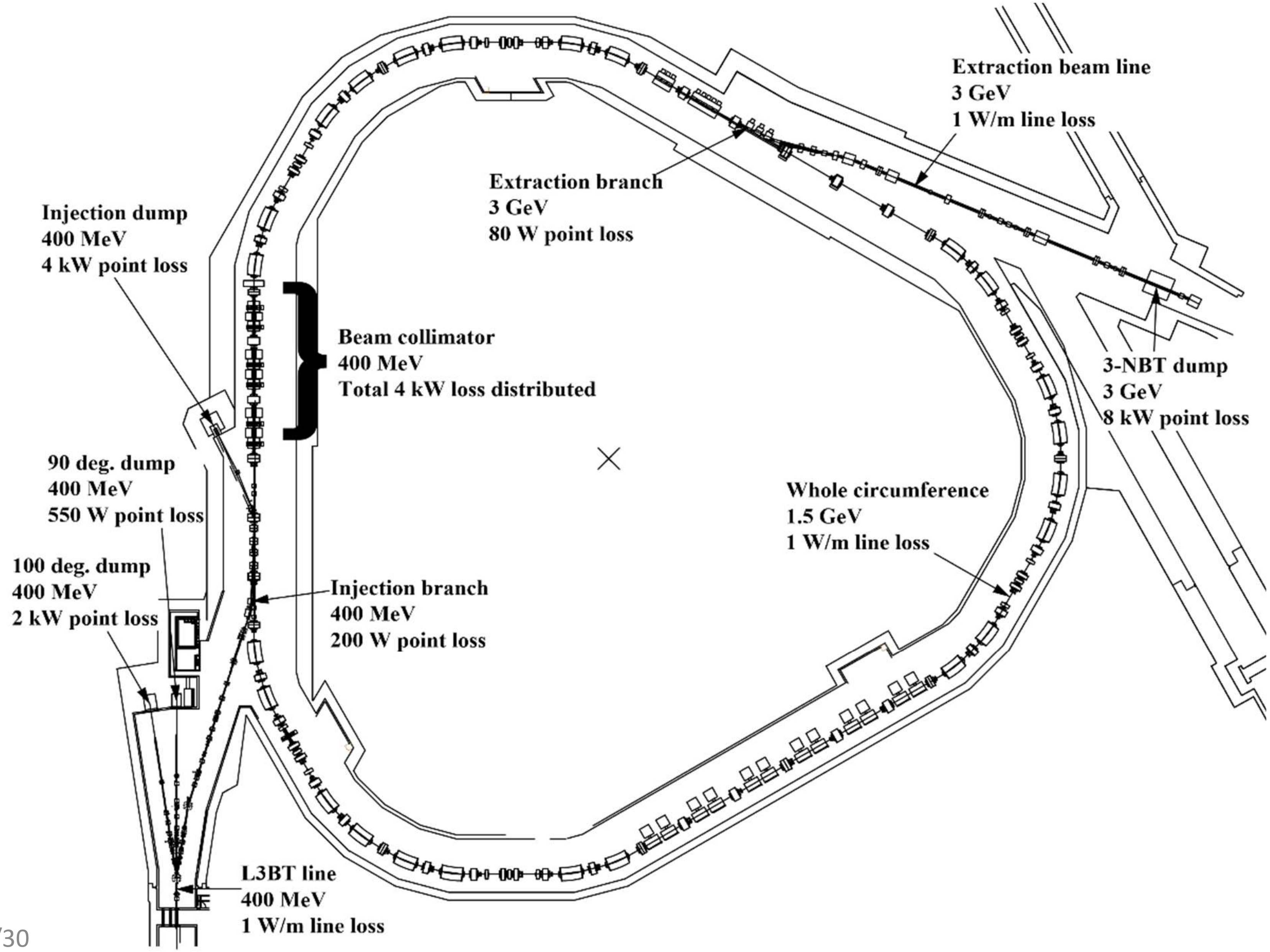
Painting	216 π mm-mrad
Collimation	324 π mm-mrad
Physical Aperture	>486 π mm-mrad



Concept of the lattice design -reduction of the uncontrolled loss-

- Large painting injection (216 π) to mitigate space charge effect and foil scattering effect.
- *The transition gamma (γt) is chosen enough high value than the operation gamma*. In RCS case Those are 9.14 of γt and 4.2 of 3GeV proton.
  - The beam loss inherent to the transition crossing will be thus avoided.
- The straight sections are made *dispersion free* in order to avoid the synchro-betatron coupling, and simplify injection and collimation.
- Bunch to Bucket injection to avoid loss adiabatic capture process.
- In the former ISIS synchrotron case, the acceptance of the extraction beam line was smaller than the ring collimator acceptance. Such situation made large amount loss at the extraction line.
  - Secure the same acceptance by the extraction beam line and the ring collimator(324 πmm-mrad). same acceptance is kept to the neutron target in MLF
  - However, due to the budget, MR could not secure same acceptance. It has only the acceptance of 84 πmm-mrad. (this value corresponds to the emittance after damping of 324 πmm-mrad at 400 MeV.)
    -> Collimator@3-50 BT is required.
  - RCS has deliver narrower beam for MR than MLF!
    -> swich the operation parameters

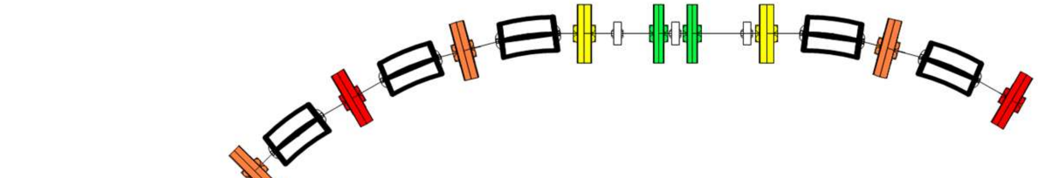
Beam loss budget in RCS

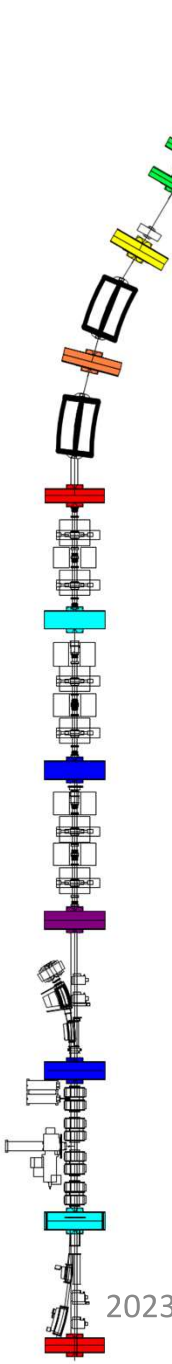


Symmetricity

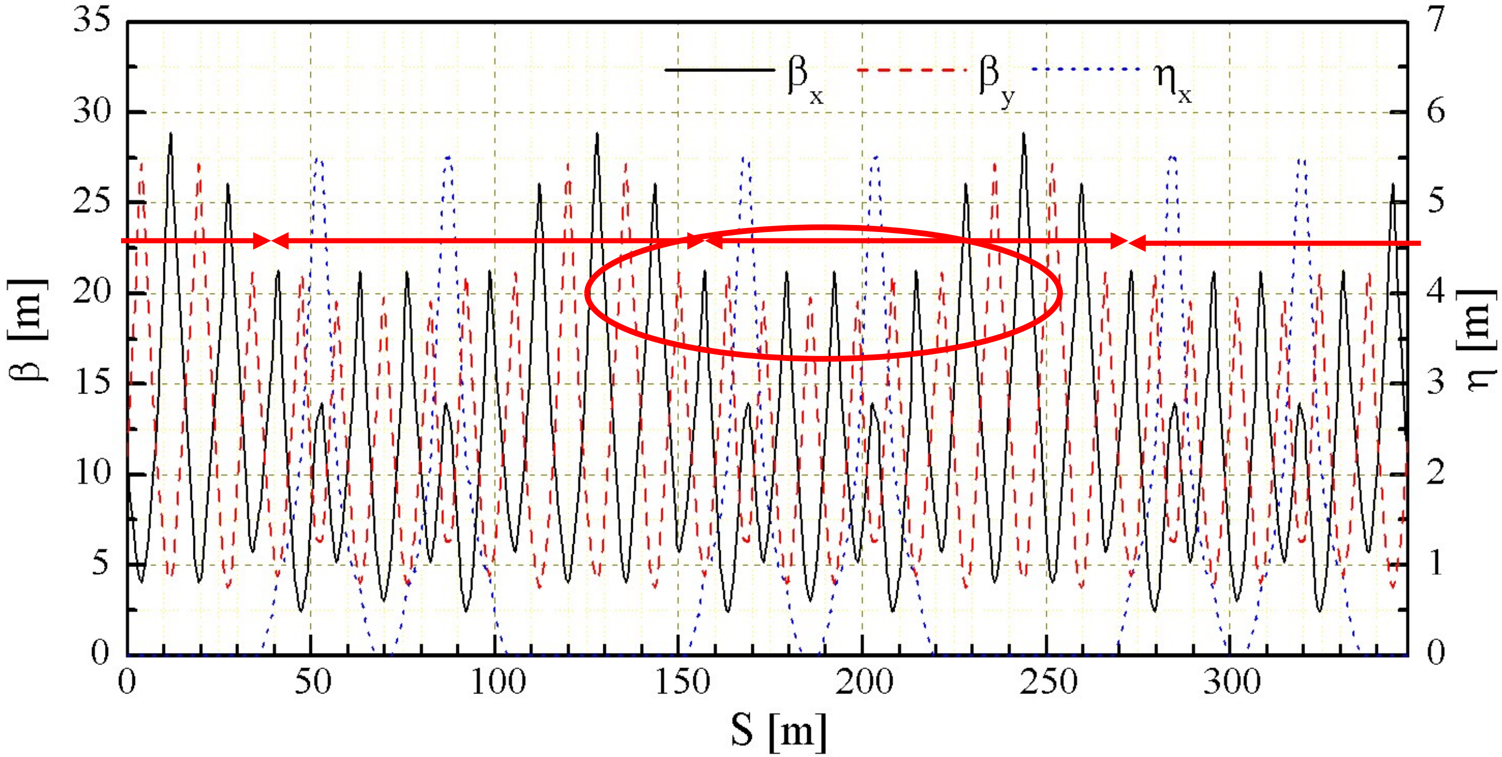
- 3-fold symmetry
- Arc and insertion are mirror symmetry
- Dispersion free insertion

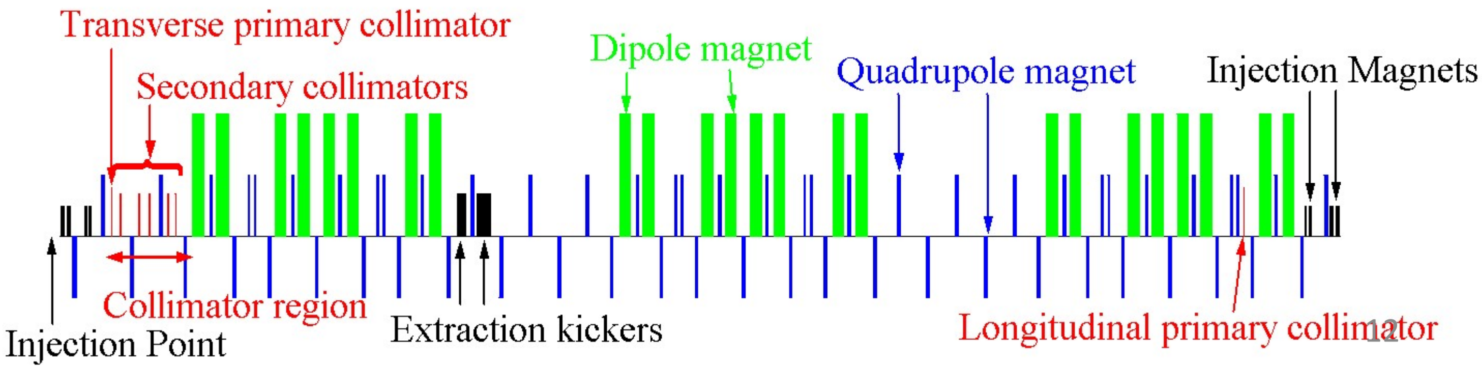
Especially β_y@Dipole should be suppressed to reduce the gap = excitation current!





- QDX
- QFN
- QDN
- QFX
- QFL
- QDL
- QFM

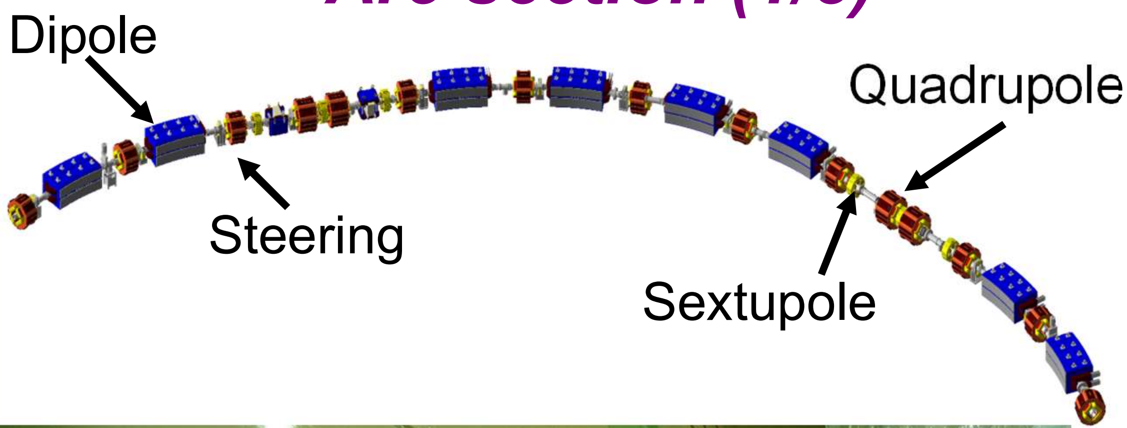


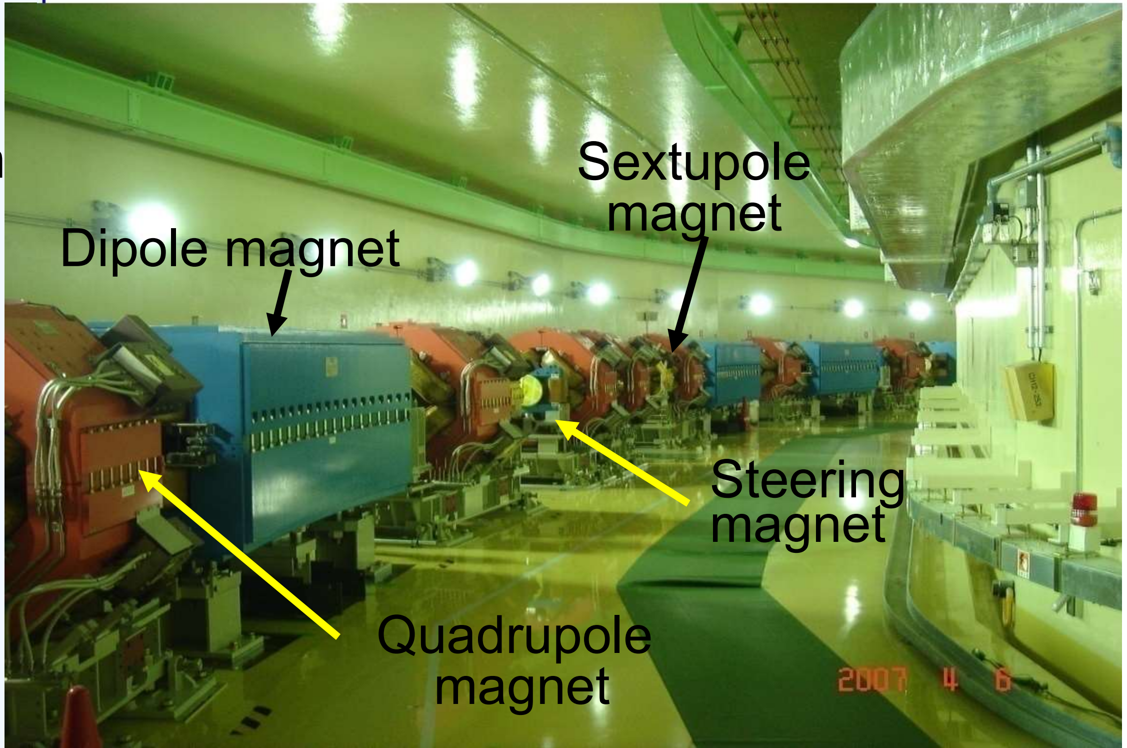


Arc section

- **Dipole magnet** *1 Power supply*
  - Number of magnet 24
  - Pole Gap 210 mm
  - Core Length 2770 mm
  - Field strength 0.27T ~ 1.1T
- **Quadrupole magnet** *7 families*
  - Number of magnet 60
  - Bore Radius 145~210 mm
  - Field gradient < 4.5 T/m
- **Sextupole magnet** *3 families*
  - Number of magnet 18
  - Bore Radius 140 mm
  - Field gradient 26.2T/m^2
- **Steering magnet** *independent*
  - Number of magnet 52

Arc section (1/3)



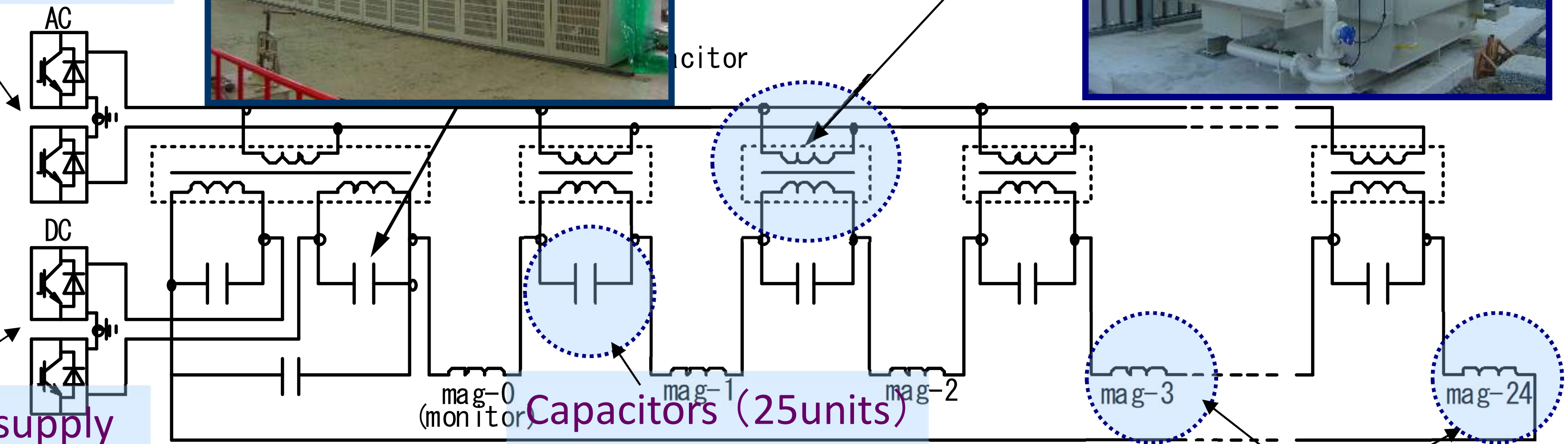


Resonant network and power supply for BM

AC power supply
Voltage : 5832 Vp
Current : 1587 Ap
Rating : 3273 kW

Chokes（25units）
Inductance : 62 mH
Mass : 42 ton

Parallel



DC power supply
Voltage : 2661 V
Current : 1667 A
Rating : 4436 kW

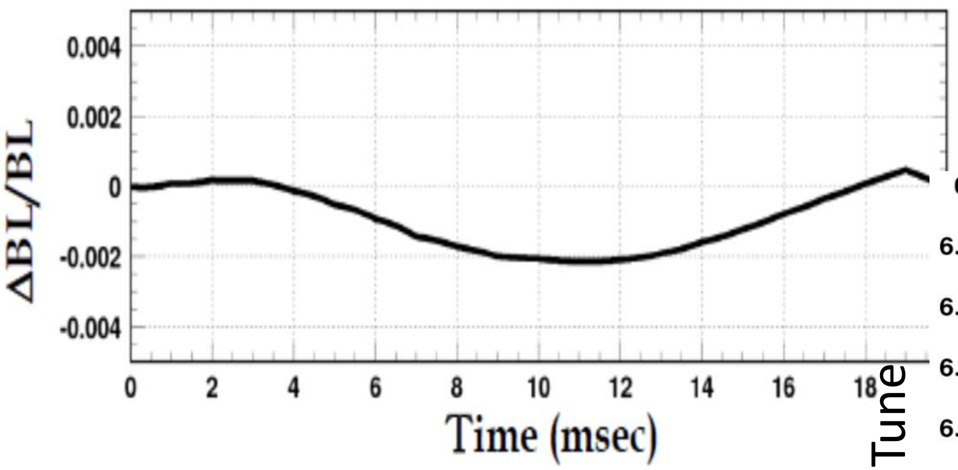
Capacitors（25units）
Voltage : 11108 Vp
Capacitance : 1325 uF
Mass : 11 ton

Bending Magnet

Accuracy of the magnetic field tracking

- Since the quadruple magnets were grouped into *7 families*, *totally 8* independent resonance circuits should be excited.
- *The precise control* is necessary for tracking *all the 8 families* of the magnets, in particular, in the present case that each family of the magnets has its own saturation effect.

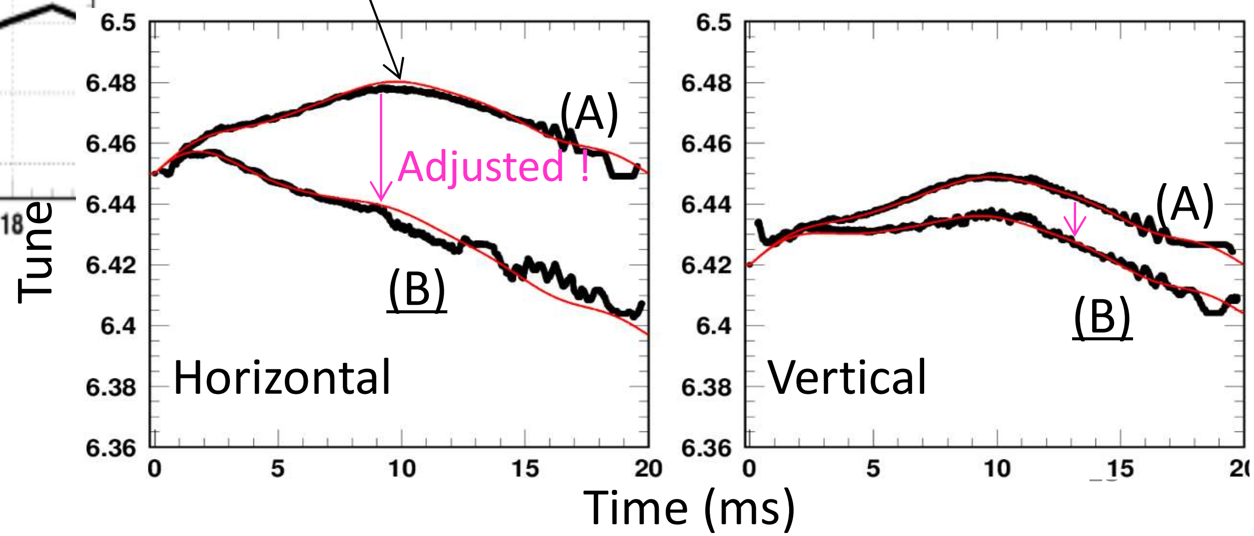
Deviation of the BM field pattern from *the ideal sinusoidal* curve



- In our system, the *accuracy of magnetic field* is *10^-3*.

- Tracking error between BM and QMs causes tune variation during acceleration.

Small loss appeared here due to the stopband of ν=6.5.=>Reduce the excitation current of some QM families



RCS injection scheme

3 strippers foils, Type: HBC

Primary (1st): 340 $\mu g/cm^2$

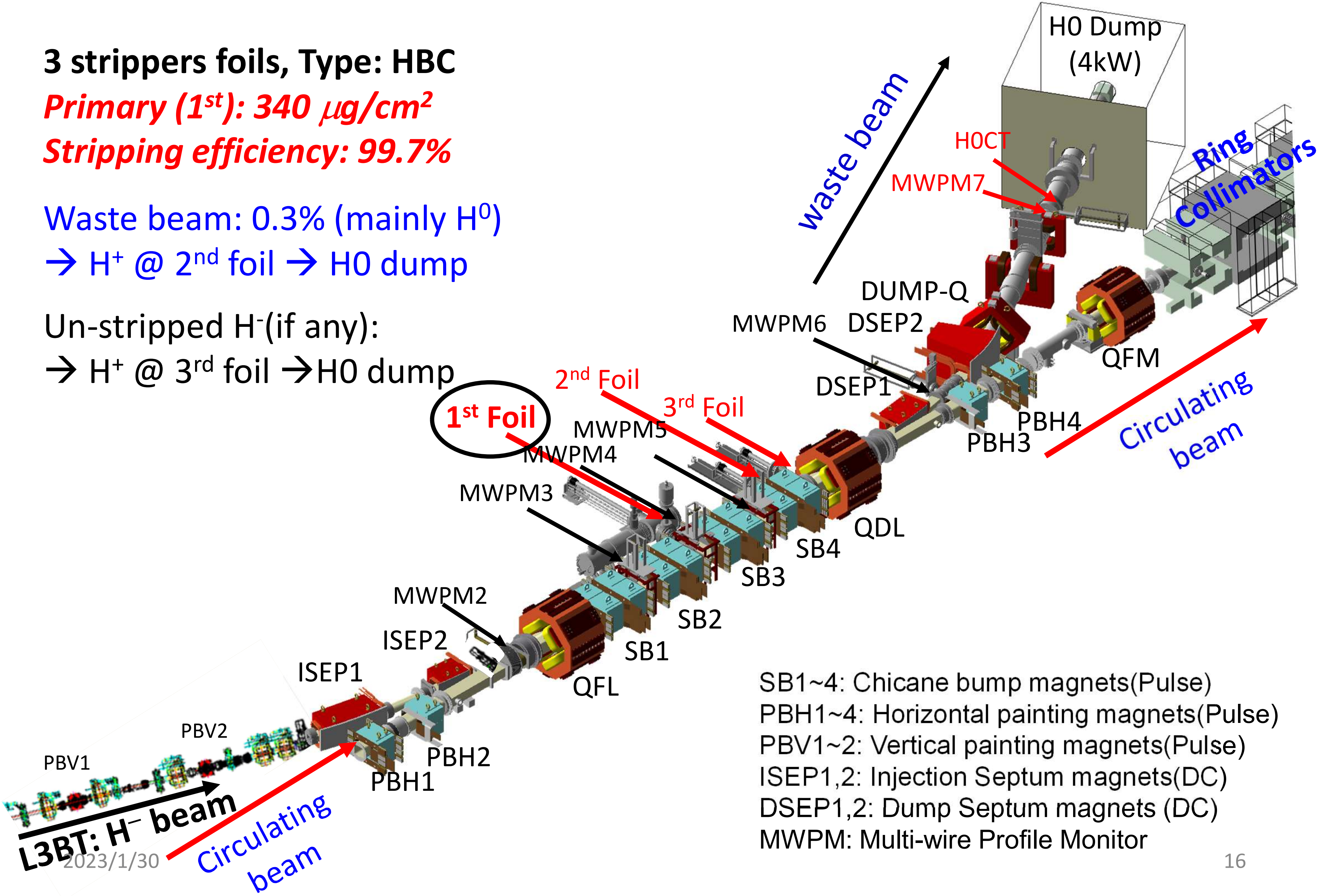
Stripping efficiency: 99.7%

Waste beam: 0.3% (mainly H^0)

→ H^+ @ 2nd foil → H0 dump

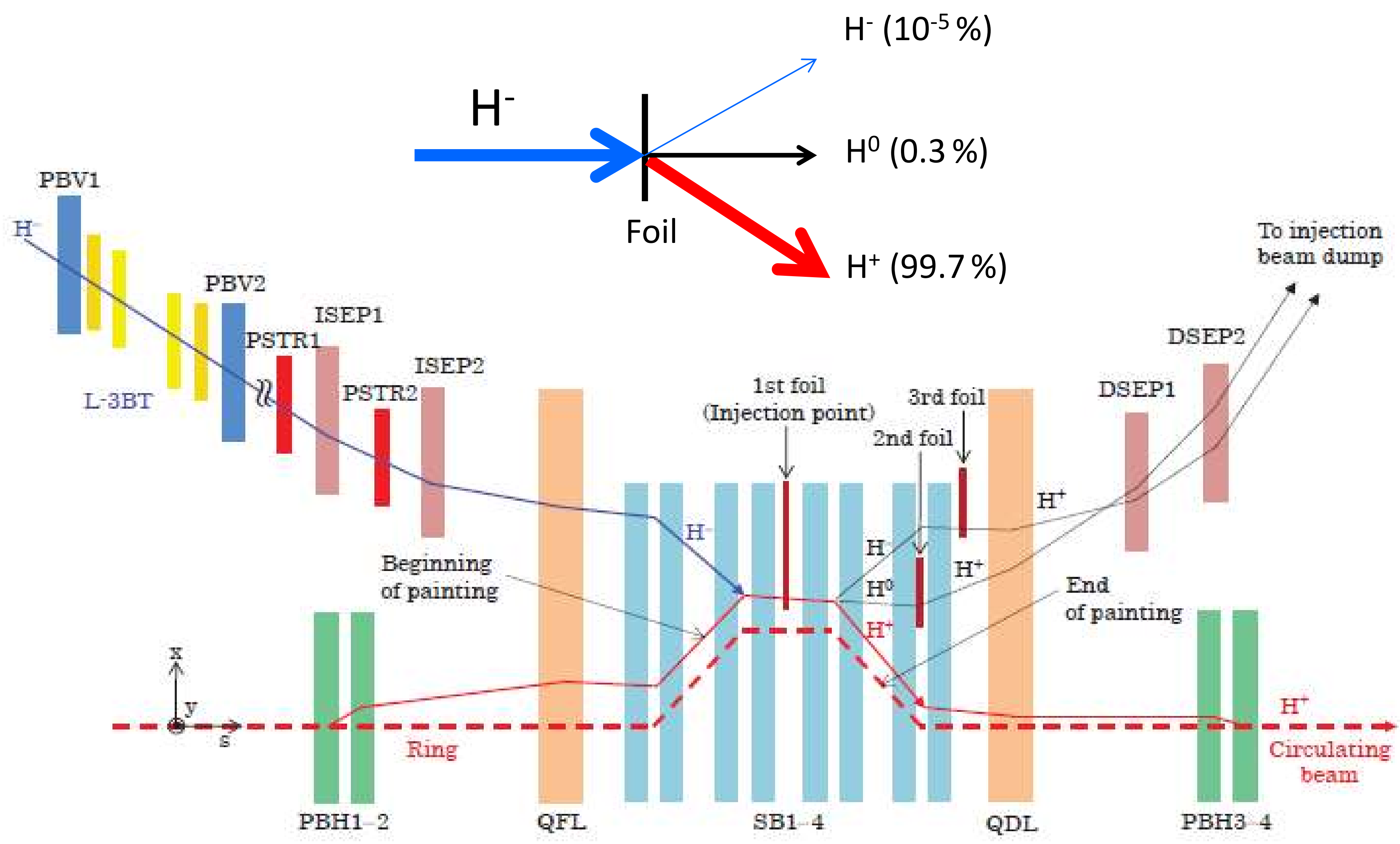
Un-stripped H^-(if any):

→ H^+ @ 3rd foil →H0 dump



SB1~4: Chicane bump magnets(Pulse)
PBH1~4: Horizontal painting magnets(Pulse)
PBV1~2: Vertical painting magnets(Pulse)
ISEP1,2: Injection Septum magnets(DC)
DSEP1,2: Dump Septum magnets (DC)
MWPM: Multi-wire Profile Monitor

Schematic view of the RCS injection area

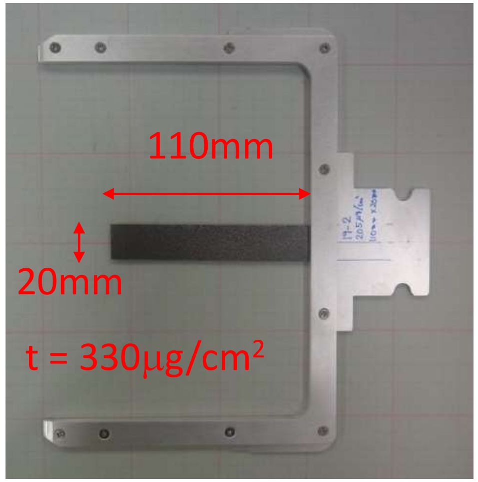


Foil production

Courtesy of T. Nakanoya

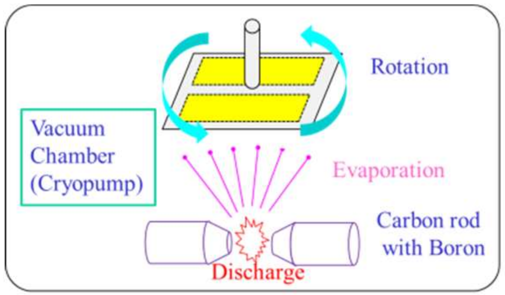
☐ Stripper foil in J-PARC RCS

- We use HBC Foil and it had produced by KEK lab.
- Due to retirement of an authority, foil deposition system was moved in J-PARC site.



HBC foil = **H**ybrid **B**oron mixed **C**arbon stripper foil
(C : B ≈ 80 : 20)

Deposition apparatus based on EBX-2000 system @ ULVAC

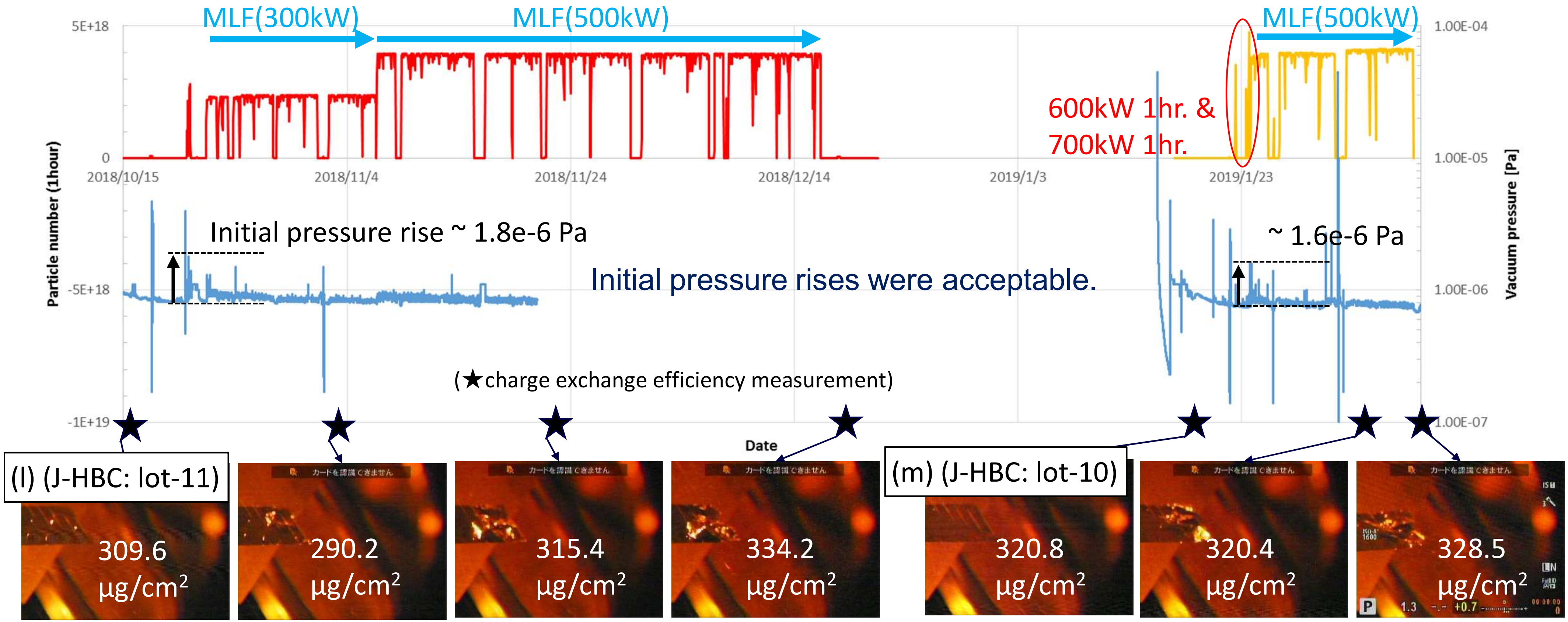


- The system was resumed successfully and we can fabricate a new HBC (J-HBC) foil in Tokai-site.

Foil production(Cont'd)

Courtesy of M. Yoshimoto

- We have started to use the J-HBC foil since last October.

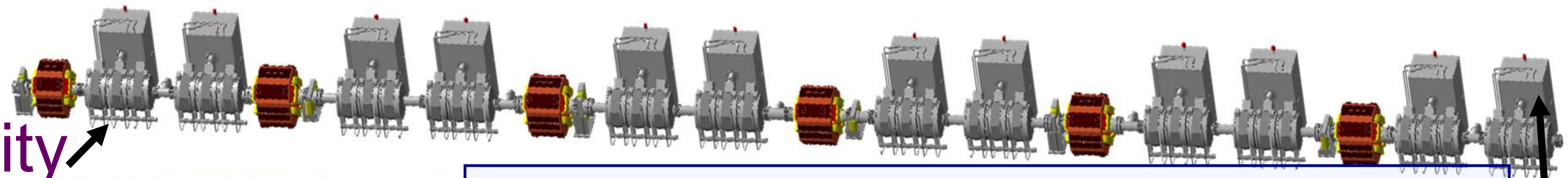


J-HBC foils are deformed and the thicknesses are varying during the beam irradiation, but it is allowable.

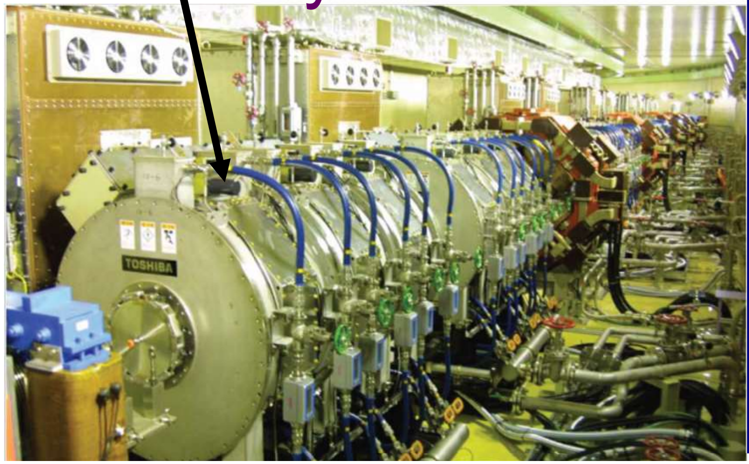
- At present, J-HBC foil seems to endure 500 kW operation.

(Now we achieve 800-kW user operation, and we give some sample to LANCE facility(800 MeV SR). J-HBC foil works in LANCE system.)

Straight section (RF section)



RF Cavity

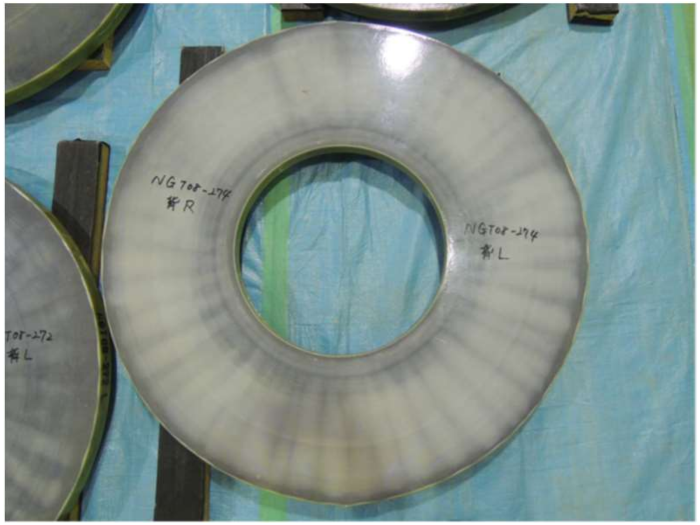


●RF Cavity

No. of RF Cavity	12
Length	1.65 m
Gap	3
F_{rf}	1.2-1.7 MHz(Fundamental)
Gap Voltage	43kV (14.4kV/gap *3)

Amplifier

RF Cavities installed in the RCS tunnel

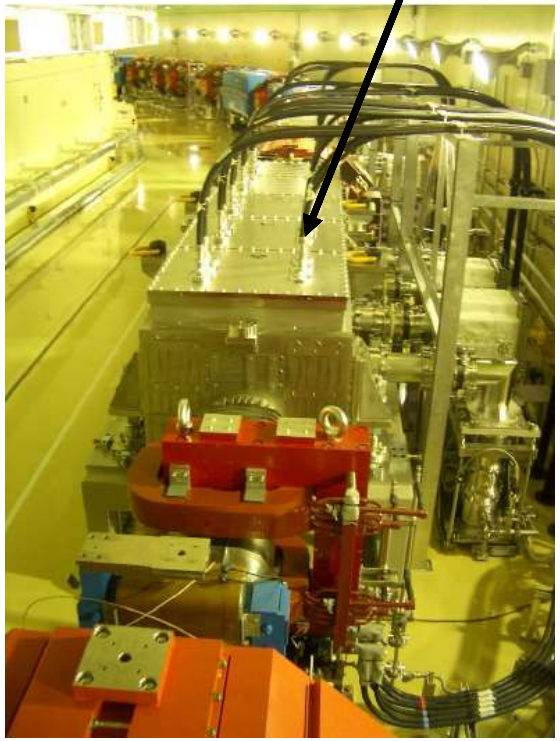


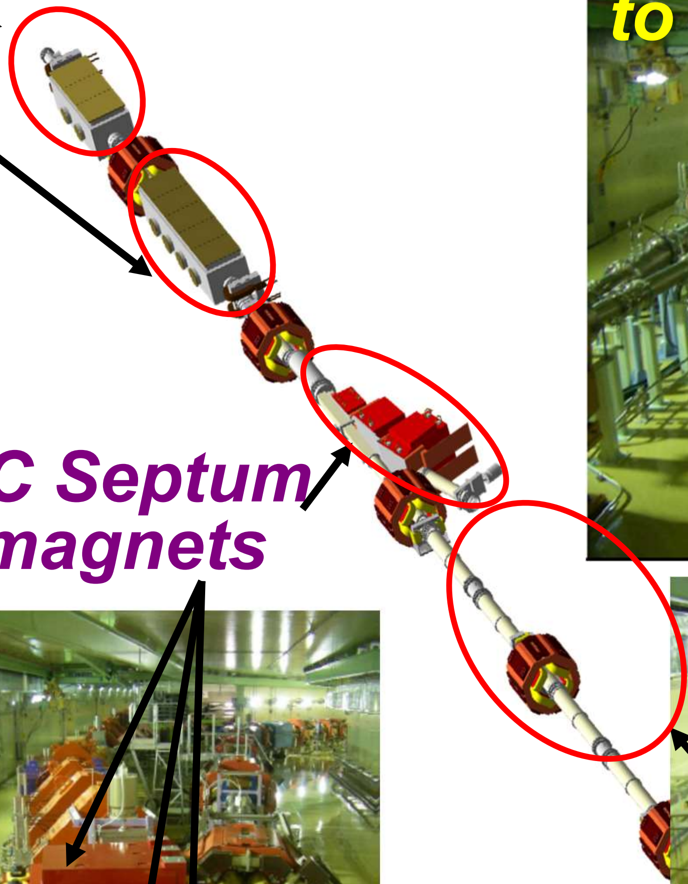
J-PARC ring RF adopted the magnetic alloy core except the ferrite
-> higher RF voltage and wider bandwidth

Okita-san will present in detail at the annual collaboration meeting on 1st March

Straight section (extraction)

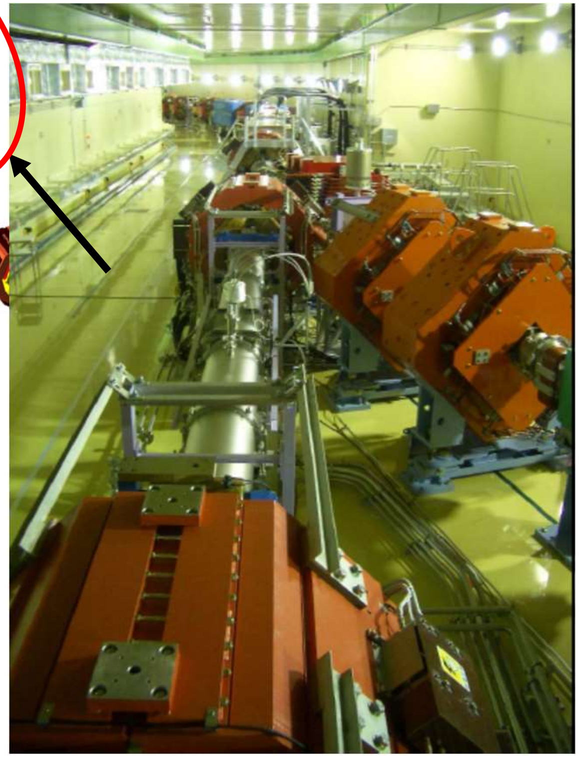
Kicker magnets





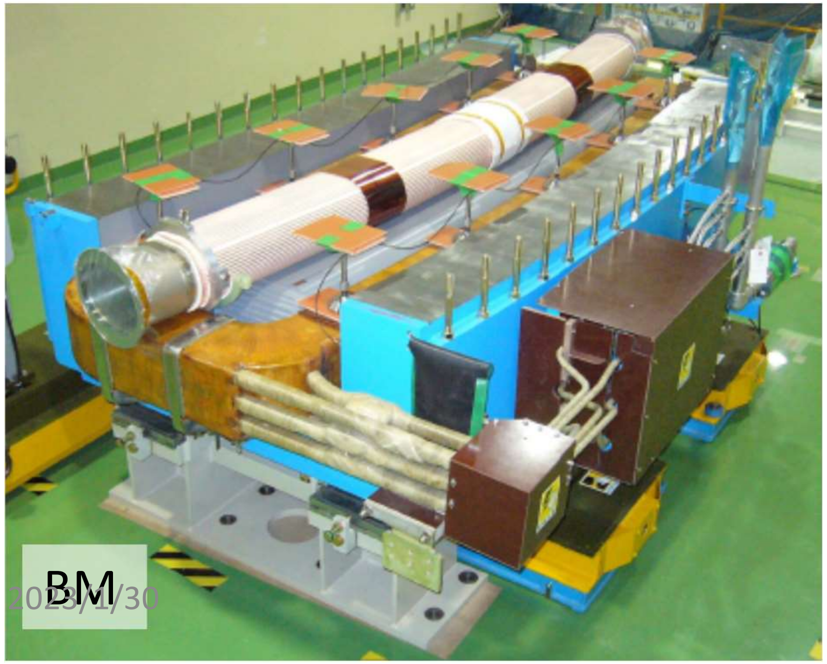
Beam transport lines

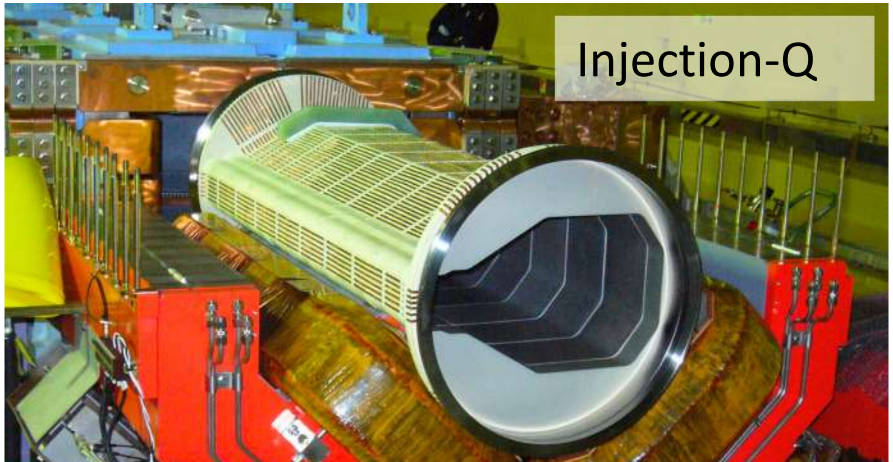
DC Septum magnets



Low-impedance ceramics vacuum chamber

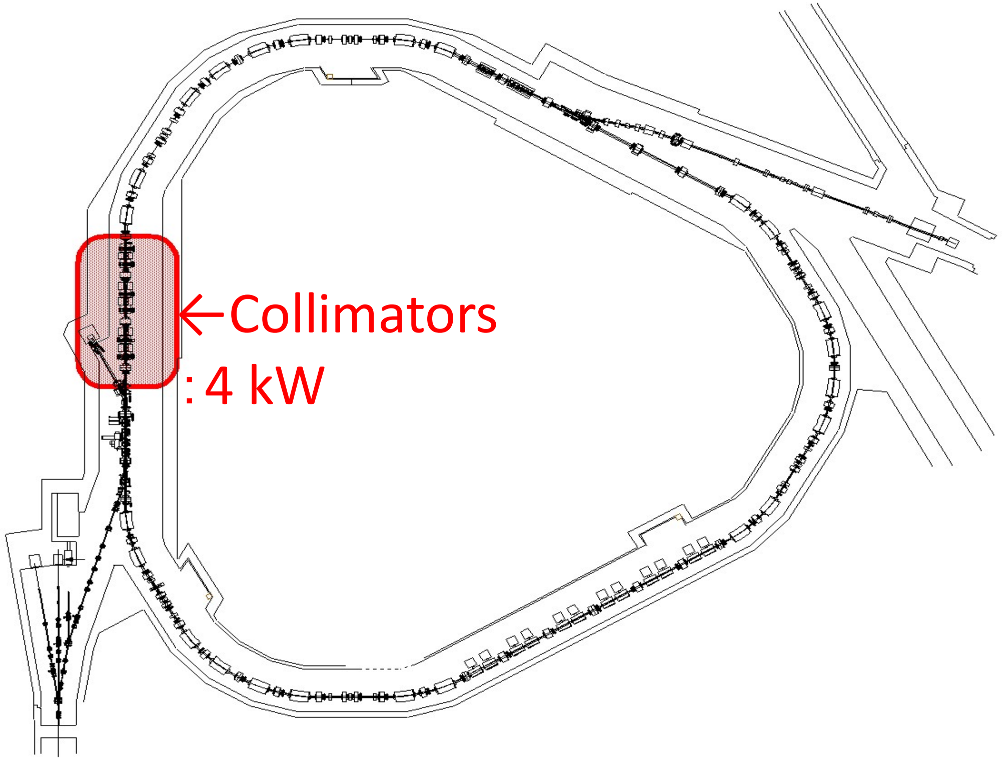
- For mitigating the eddy current effect, all the vacuum chambers exposed to the fast varying magnetic fields have been manufactured of *the alumina ceramics.*
- To use a ceramic chamber, *some electrically conductive layer* is necessary on the ceramics so that the *wall impedance* is *reduced* (and thus the beam is stabilized) and that the electromagnetic waves arising from the beam is prevented from radiating outside. *The RF shield* is thus designed as *a high frequency pass filter*, where eddy current cannot be generated.
- In order to keep the large aperture with the reasonable cost for the bending magnet (BM), we decided to choose the cross section of the *race-track shape* for the *BM* vacuum chambers. In addition, the special shapes (*rectangular and racket-shape cross sections*) of vacuum chambers have been produced for the *injection section*.

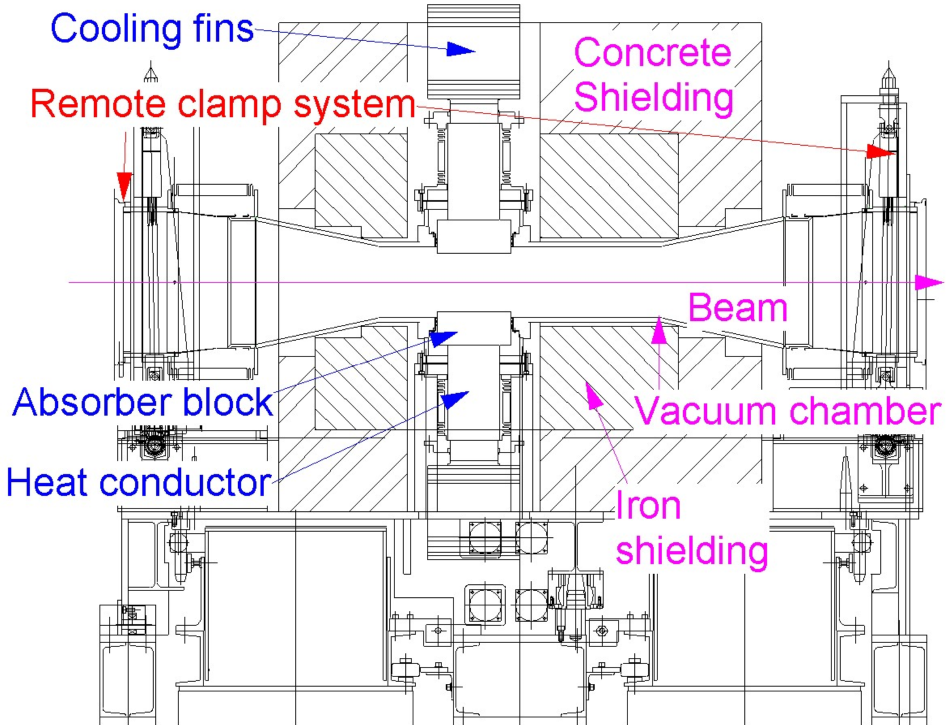




Yamada-san will present in detail at the annual collaboration meeting on 1st March

Beam collimator





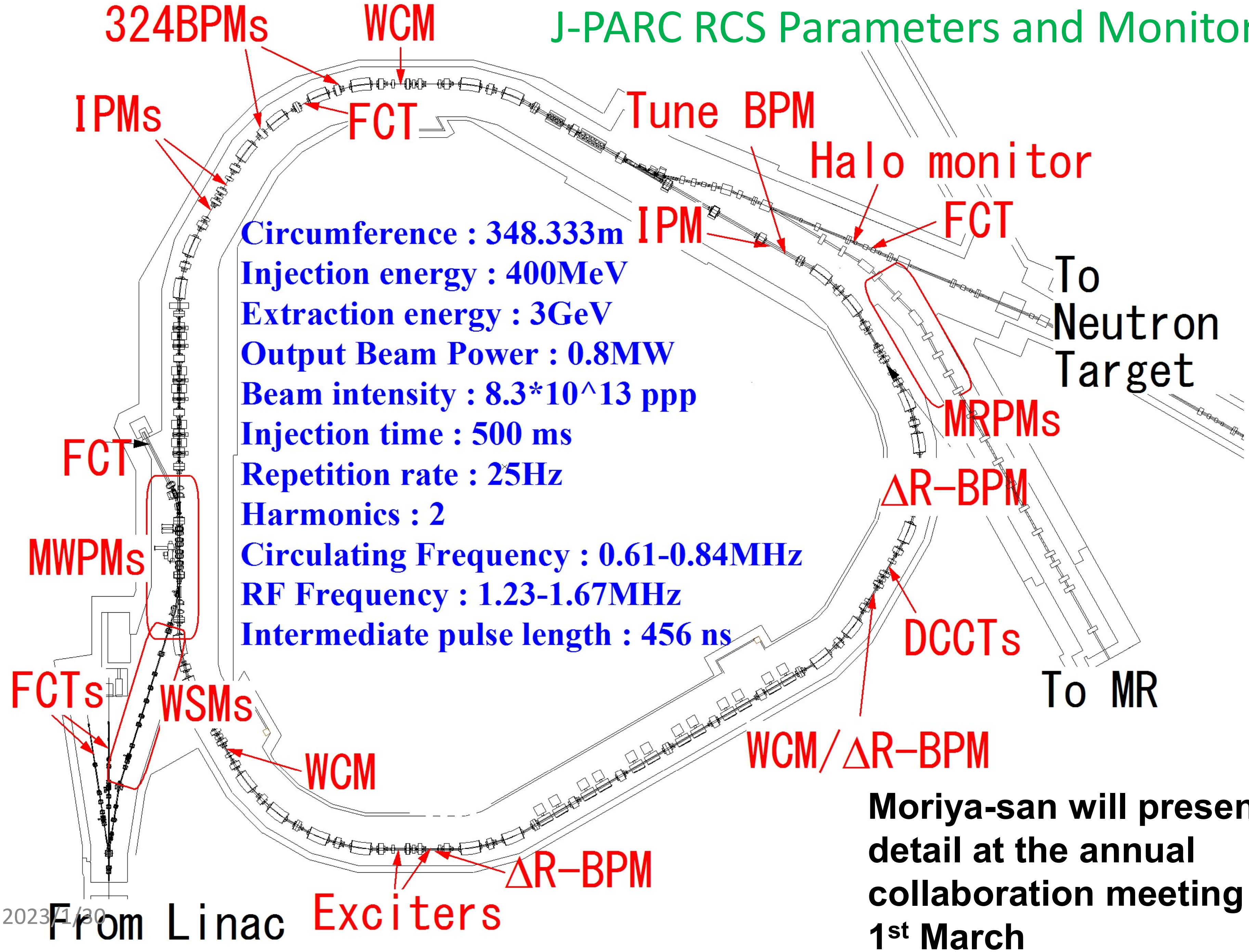
Emittance&Acceptance

Injection beam	4 π mm-mrad
Painting	216 π mm-mrad
Collimation	324 π mm-mrad
Physical Aperture	>486 π mm-mrad

Collimator aperture can adjust to 160～486 π mm-mrad.

Monitors

J-PARC RCS Parameters and Monitors



Circumference : 348.333m
Injection energy : 400MeV
Extraction energy : 3GeV
Output Beam Power : 0.8MW
Beam intensity : 8.3*10^13 ppp
Injection time : 500 ms
Repetition rate : 25Hz
Harmonics : 2
Circulating Frequency : 0.61-0.84MHz
RF Frequency : 1.23-1.67MHz
Intermediate pulse length : 456 ns

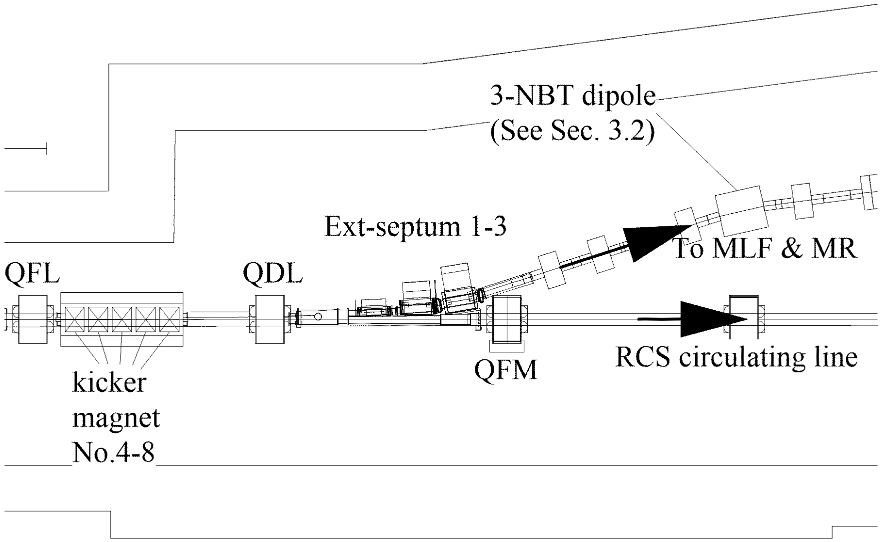
Moriya-san will present in detail at the annual collaboration meeting on 1st March

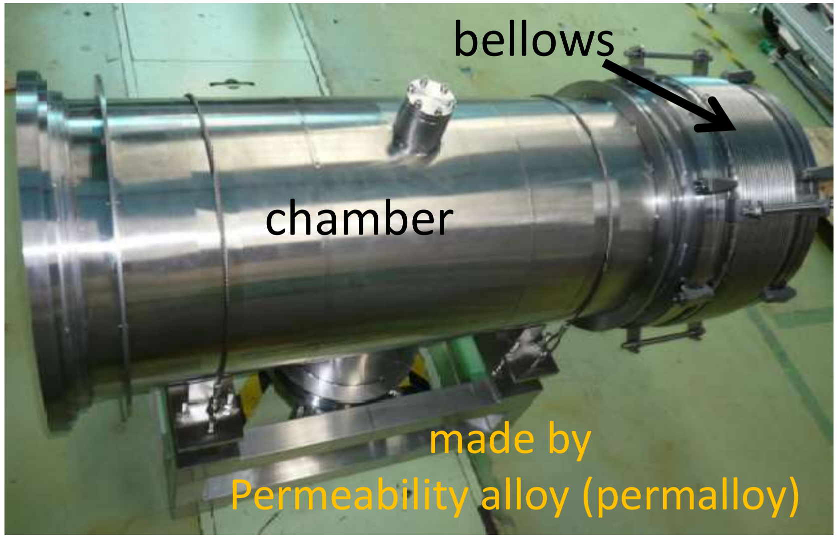
Beam study and improvement

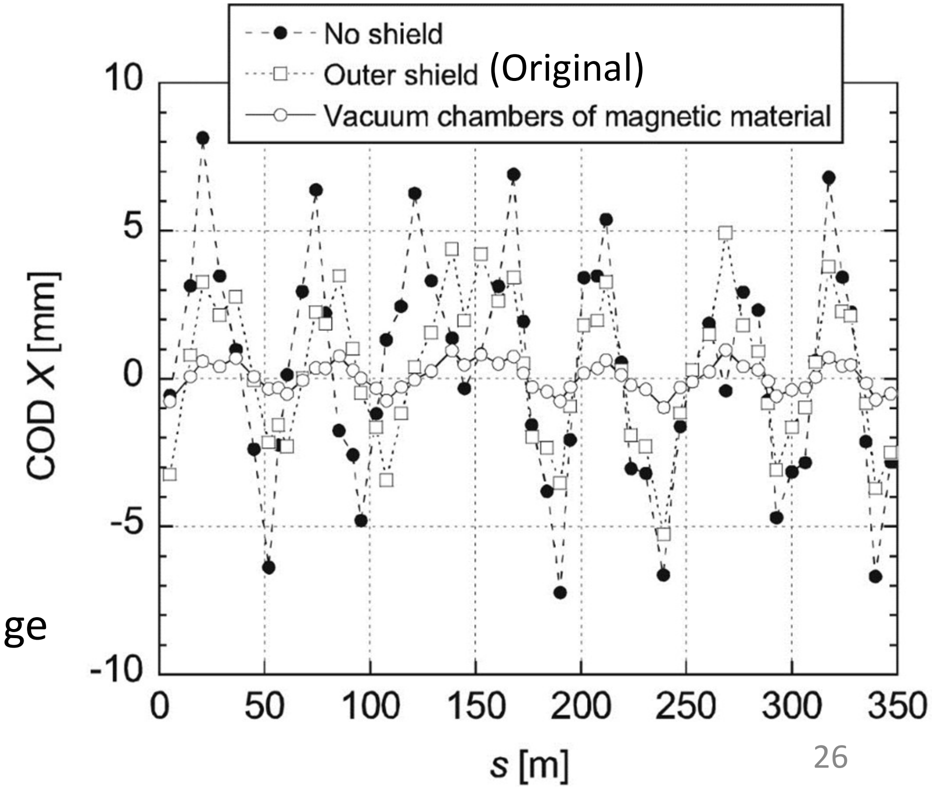
- Influence of the leakage field
- Chopping noise from magnet power supplies.
- Correction of the beta function due to Injection magnet
- MLF and MR parameter optimization
- Additional shielding and collimator

Influence of the leakage field

We investigated the effect of the leakage field, and found that not only the septum magnets but the dipole magnetin the 3-NBT line is also the source of the leakage field.
Regarding the septum, a magnetic shield had attached and a magnetic stainless steel had been used for its vacuum chamber from the beginning.
However, that had been not enough to completely suppress.
In addition, no measures had been taken against the dipole magnet in BT.





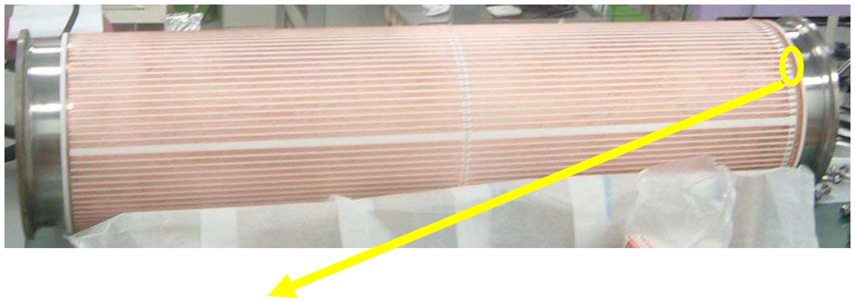


New vacuum chamber and bellows with permeability alloy (permalloy) have been developed to reduce magnetic leakage field from beam transport line at extraction area.

->Leakage field reduced < 1/10!

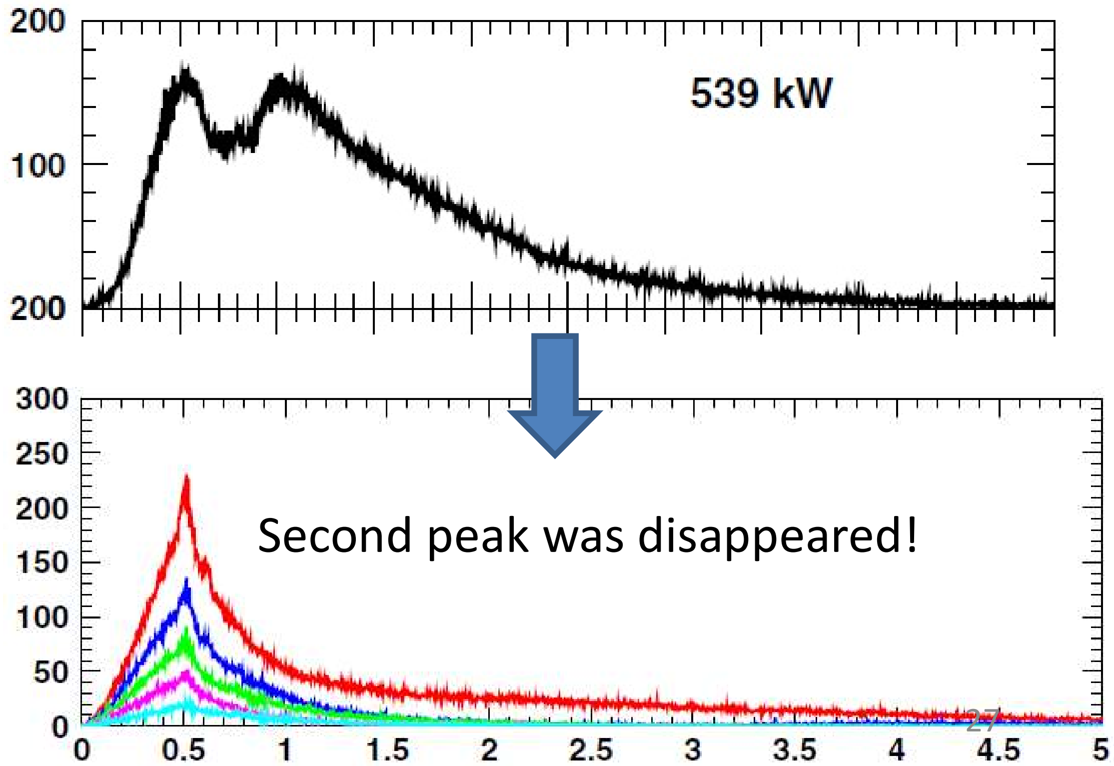
Chopping noise from magnet power supplies

- We found a beam loss which has a unique time structure; the beam loss has two peaks during first 3 msec. Our study results revealed that the cause of the first peak was foil scattering during charge exchange injection, and the second peak was caused by the magnetic field ripple of the shift bump magnets due to IGBT switching. The noise due to the switching was enhanced by the electric circuit made of the RF shields and capacitors.
- The error kick due to the switching noise brought out the second peak.
- RCS had increased the injection energy from 181 MeV to 400 MeV. At that time, the shift bump power supply was replaced with less noise system



Capacitors

Capacitance
: 330 nF

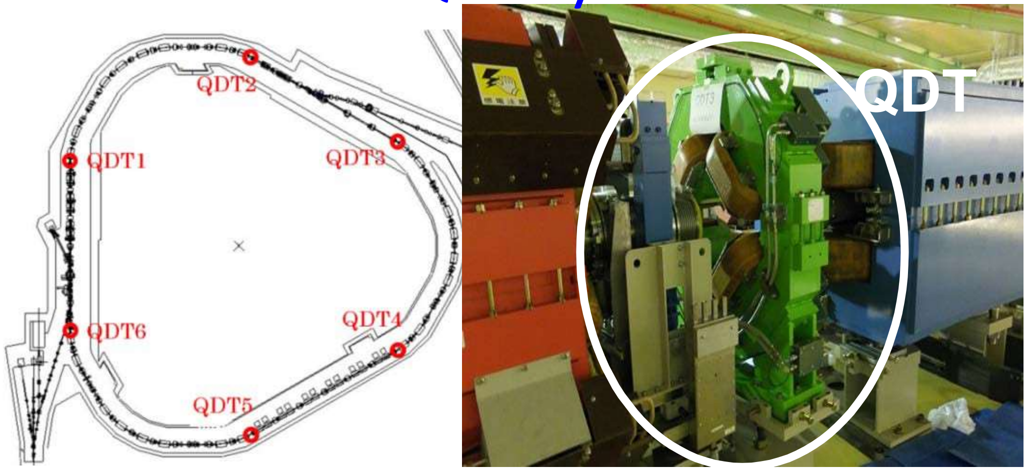


Correction of the beta function due to Injection magnet

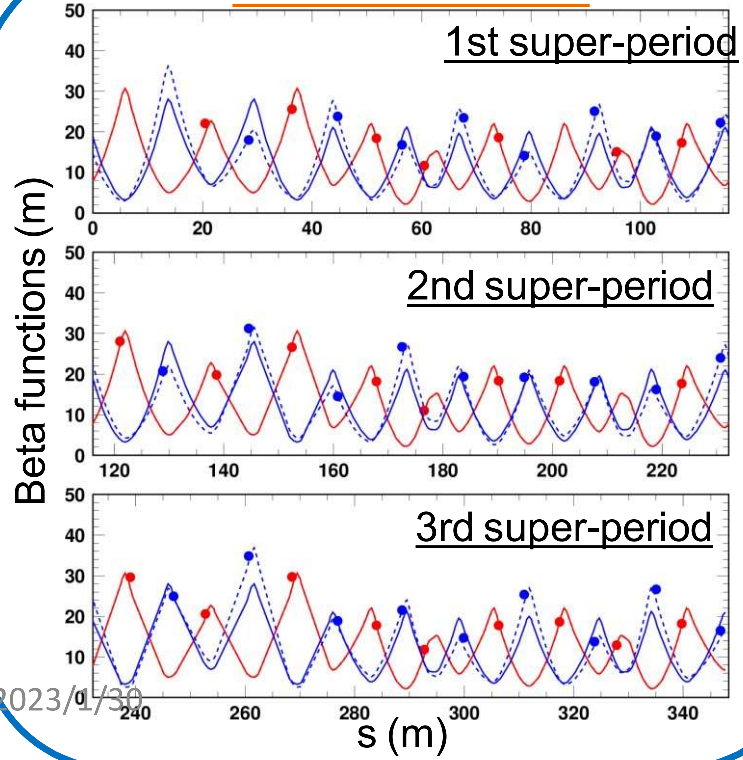
- The painting injection is key issue to achieve low-loss acceleration.
- However, Wide-ranging transverse injection painting with >100π mmmrad had not been realized in an early stage due to much beam loss. (design : 216π)
- Numerical simulations and experiments revealed this was because of the modulation of the beta function caused by the edge effect of injection bump magnets.
- Additional QDT1-6 were prepared to compensate the edge focus and collect the beta modulation.
- This system enabled large transverse painting for MLF.

Installed 2014 summer

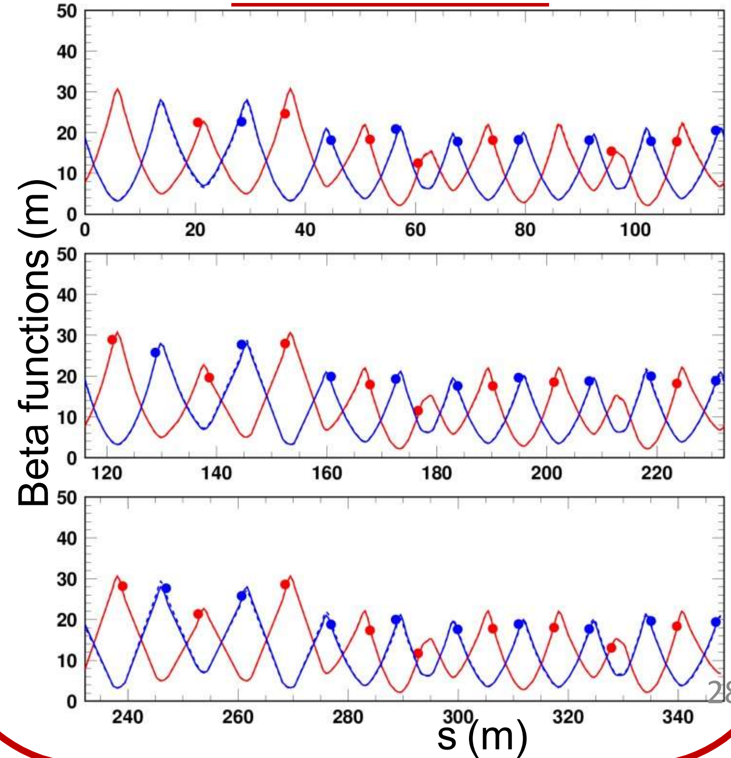
Correction QDT system



Before correction

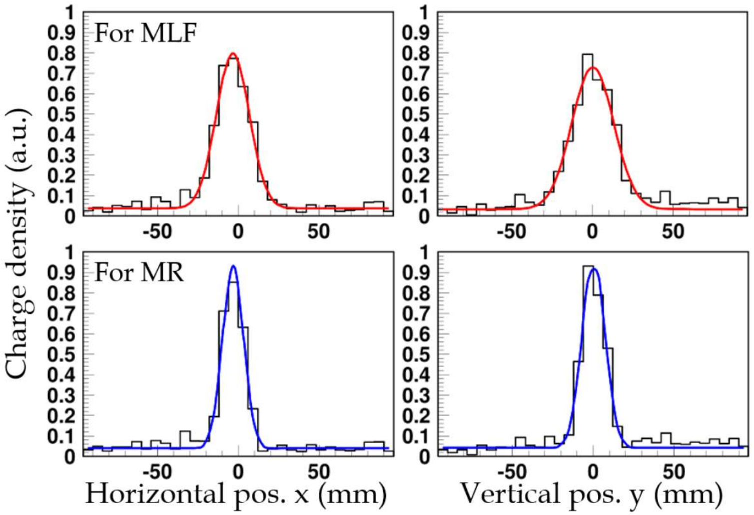


After correction

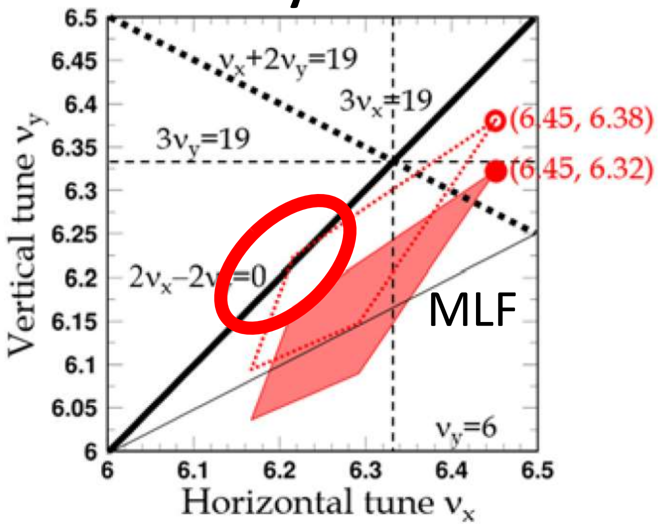


MLF and MR parameter optimization

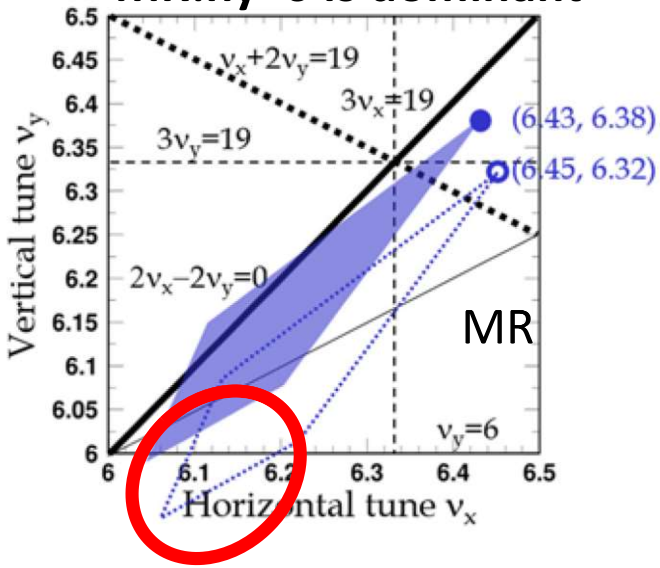
- MLF want to extend the beam profile and reduce the peak density to protect the neutron target. On contrast, MR desired narrower beam to mitigate the beam loss in MR. In order to supply beams with such contradictory condition during simultaneous operation of MLF and MR, the operating parameters have to be switched between the 20 msec from the end of beam acceleration to MLF to the injection of the next beam to MR, and vice versa.
- RCS had originally been able to switch some operating parameters; the painting pattern, the RF excitation pattern, COD correction, and the sextupole magnet excitation pattern.
- To choose the painting pattern, we can change the profiles.



MLF:2nx-2ny=0 is dominant



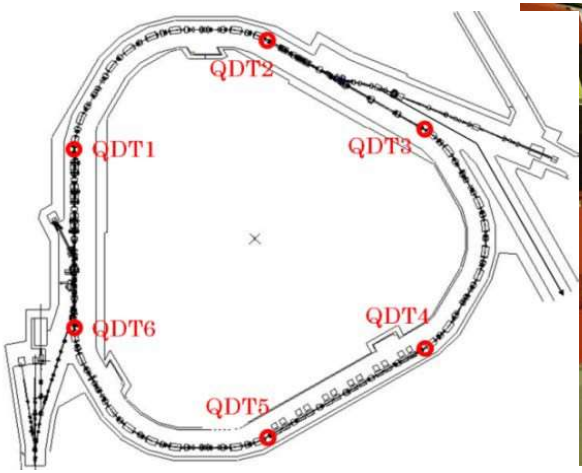
MR:ny=6 is dominant

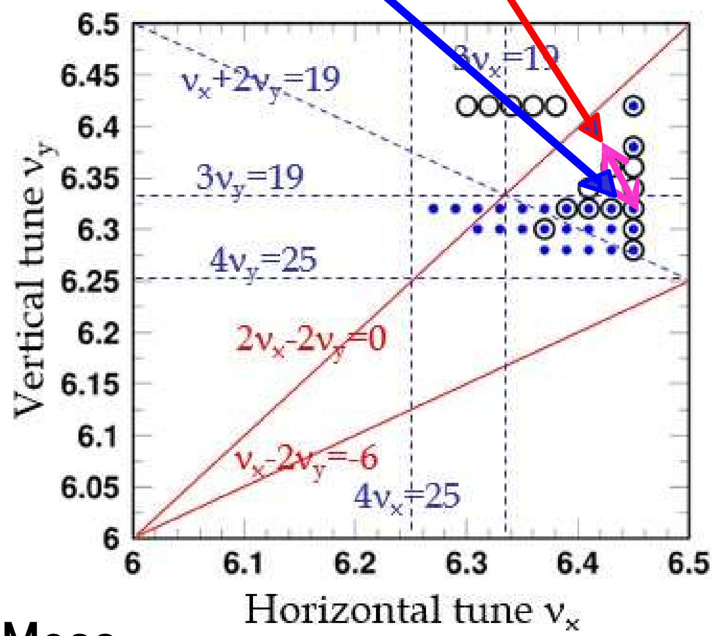


MLF : tune (6.45,6.32) is better
MR : tune (6.45,6.38) is better

However, we had been not able to change the betatron tunes between MLF and MR.

Tune variation in the study of tune switch

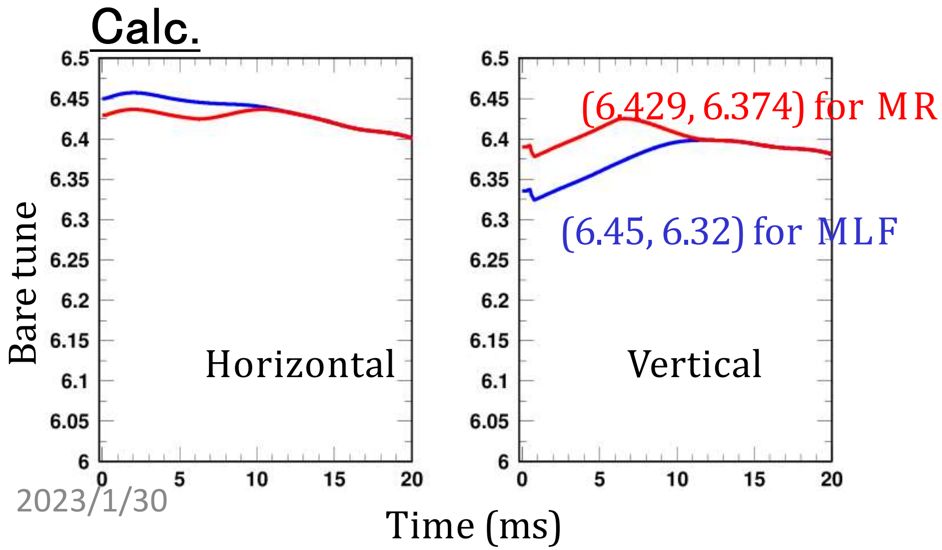


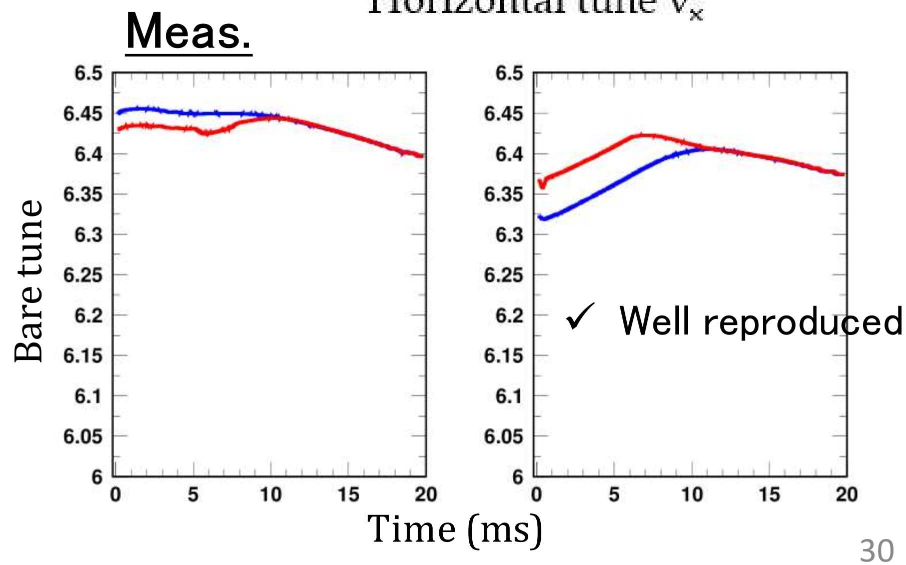


We considered to use additional QDTs not only the beta function correction but the tune variation between the MLF and MR.

→Make two excitation patterns and switch both.

<u>Tune variation during acceleration</u>





Parameter optimization

Latest operational parameters optimized for MLF & MR

Operational parameters	For MLF	For MR
Transverse injection painting	ε_{tp}=200π mm mrad	ε_{tp}=50π mm mrad
Longitudinal injection painting	Momentum offset: -0.1% V_2/V_1: 70% V_2 duration: 6 ms Phase sweep of V_2: -100 to 0°	Momentum offset: -0.2% V_2/V_1: 70% V_2 duration: 6 ms Phase sweep of V_2: -100 to 0°
Bare betatron tune	(6.46, 6.32) at injection (6.37, 6.35) at extraction	(6.43, 6.40) at injection (6.37, 6.35) at extraction
Sextupole fields	3^{rd} order resonance corr.	Chromaticity manipulation

Pulse-by-pulse switching

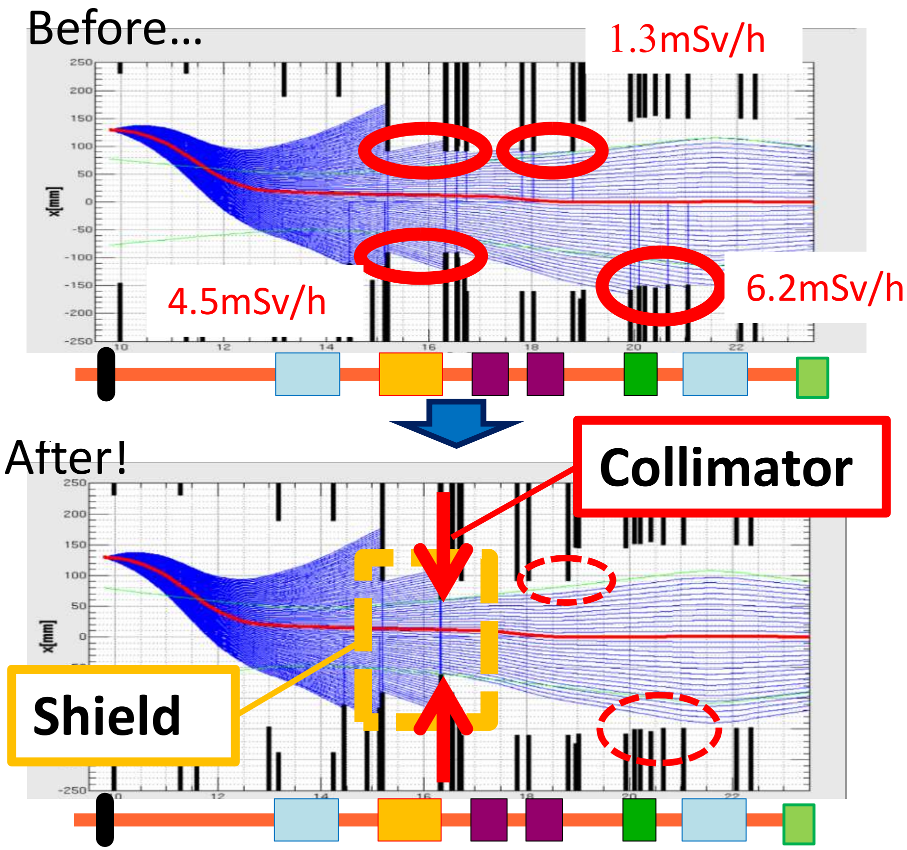
500 kW, 600 kW・・・1 MW

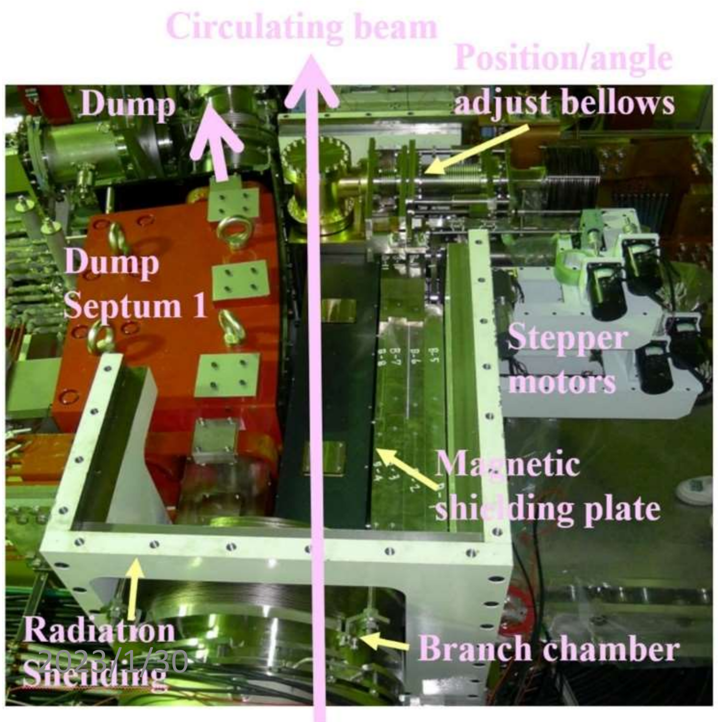
FX: 500 kW, HD

✓ The user operations with these operational parameter sets will continue for the time being.

Additional shielding and collimator

- It remains the foil scattering loss. The foil scattering phenomenon is inevitable as long as it is used to the foil for the charge exchange injection.
- Measurement result of the residual dose distribution and numerical simulation indicated that the scattered protons are lost at the branch of injection dump and down stream BPM.

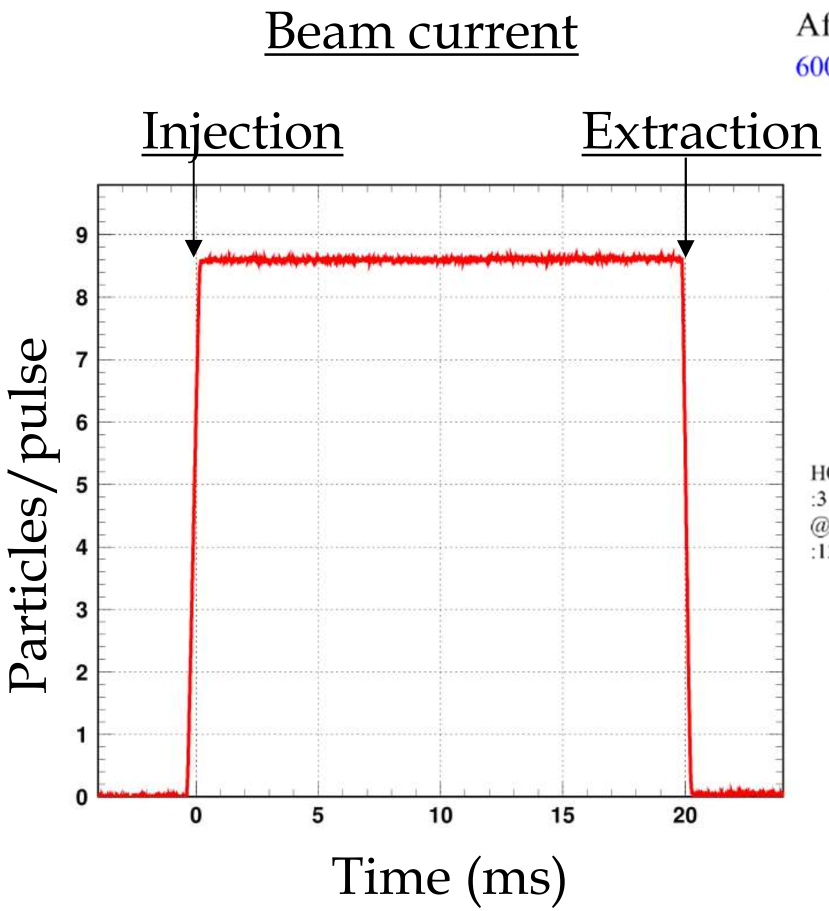




- To mitigate its impact, we replaced the branch chamber with new one, which has the radiation shielding and collimator.

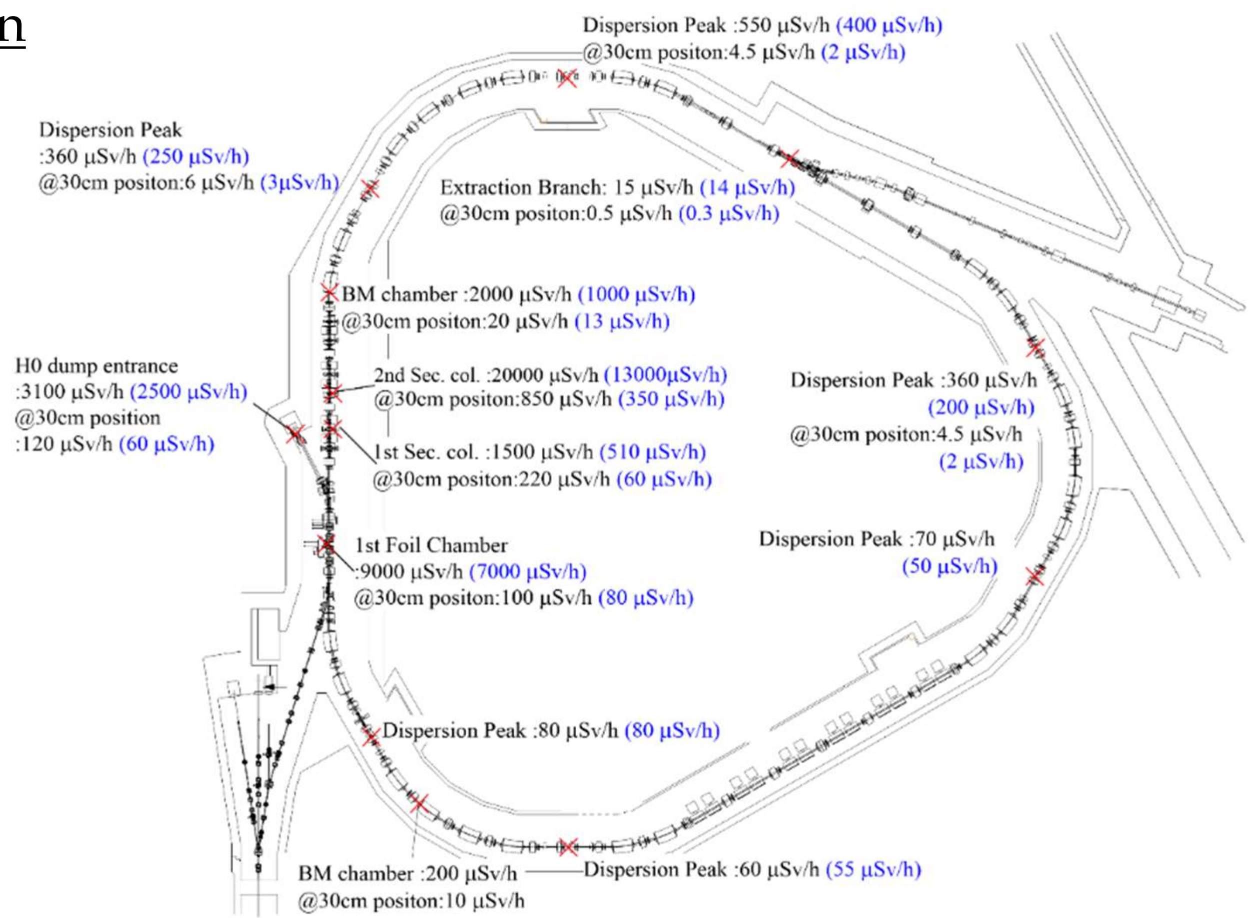
->residual dose reduced to ~1/10!

Result of improvement



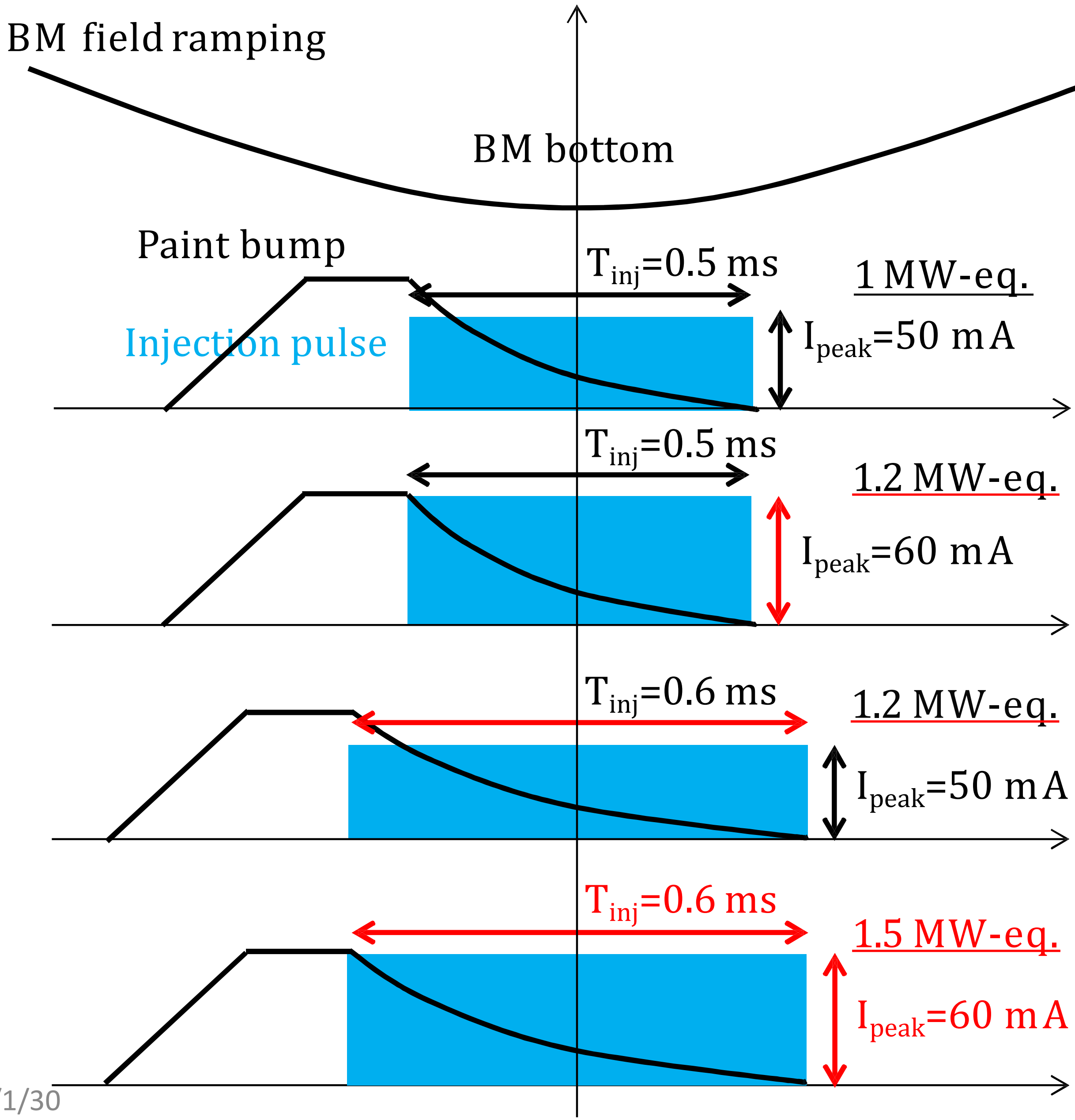
✓ No significant loss

After 1 MW, 40 hr trial for MLF (27th Jun. 2020), Measurement after 5 hours from beam stop
600 kW user operation (24th Jun. 2020) , Measurement after 4 hours from beam stop



- We established extremely small loss operation.
- There is no significant loss even 1-MW beam acceleration.
- The remaining beam loss is < 0.05%. Mostly caused by the foil scattering.

Trial beyond 1-MW



Original 1 MW acceleration scheme

✓ 1 GeV acceleration achieved on Dec. 2018 (Last ATAC)

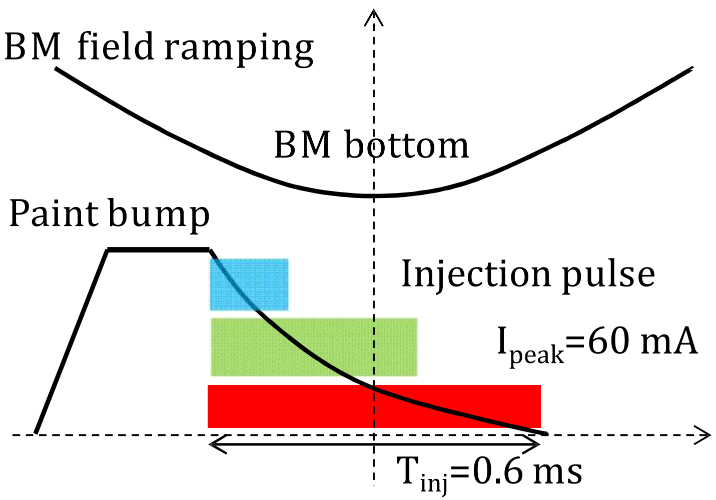
✓ 1 GeV acceleration achieved on Oct. 2018 (Last ATAC)

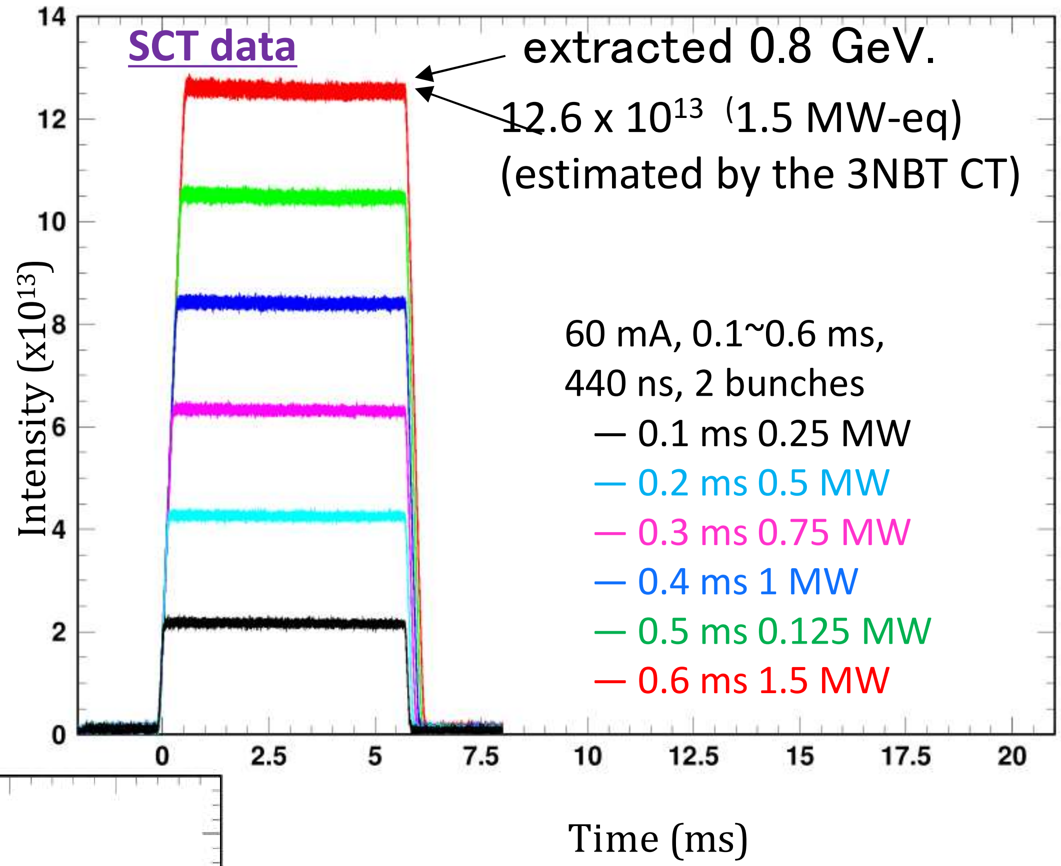
✓ 0.8 GeV acceleration achieved on Dec. 2019

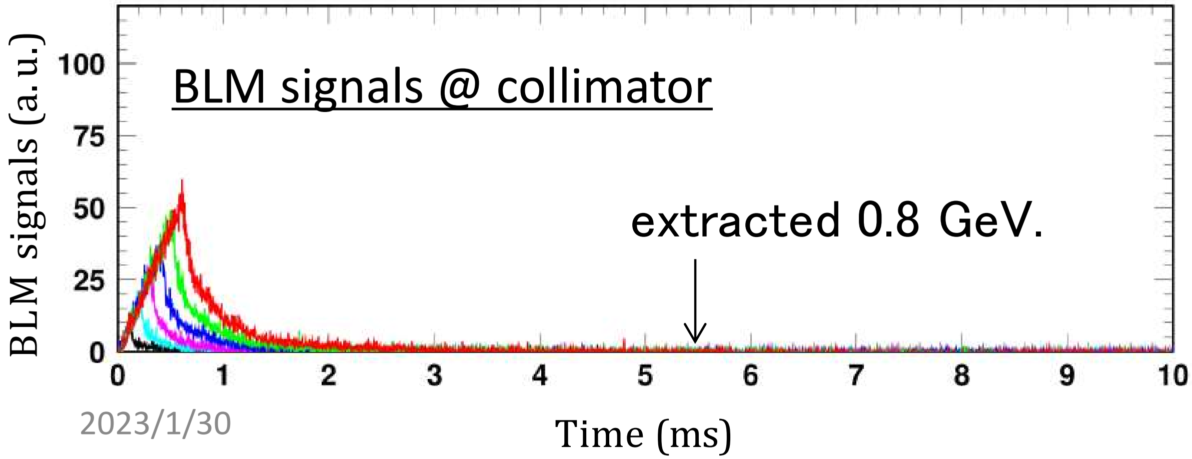
Trial beyond 1 MW (Cont'd)

◆ So far, our RF system cannot accelerate more than 1-MW beam.
->We only accelerate bema as 0.8 GeV.

✓ Injection pulse length were changed to investigate the beam loss as a function of the injection beam current.





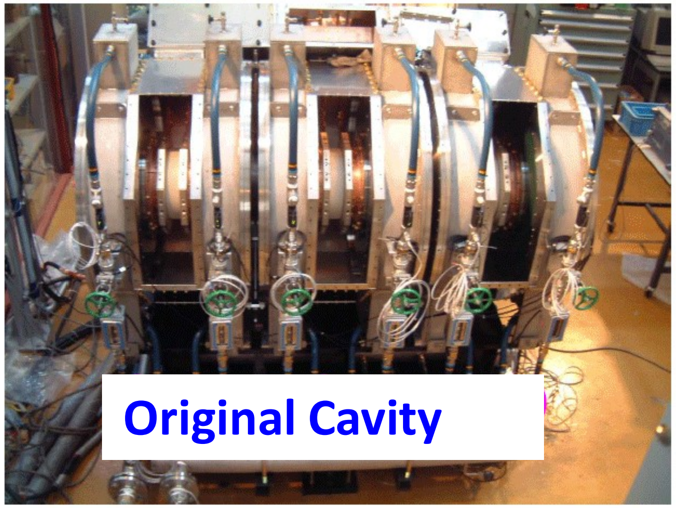


✓ Beam loss were proportional to the beam current.

→well controlled!

New RF cavity beyond 1-MW

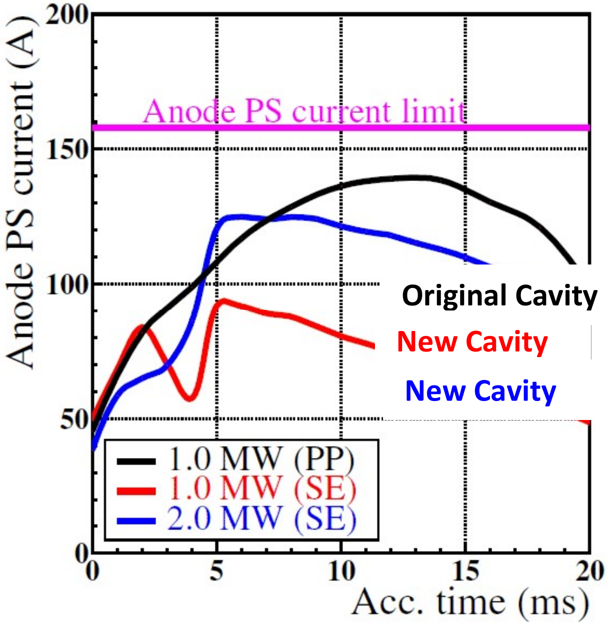
To accelerate > 1-MW beam, we have to reduce required anode current.
->We developed new RF cavities that can reduce the anode current!

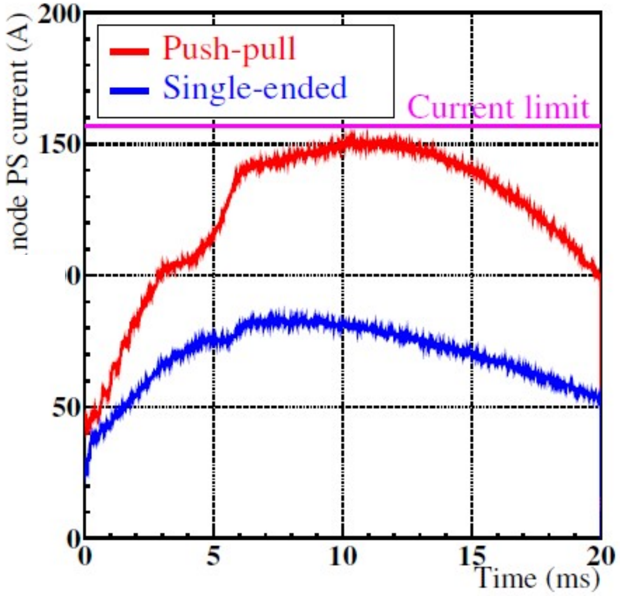


We replaced 1 of 12 cavities with new one.

Original Cavity

New Cavity





(left)Simulation (right)actual result
Anode current during the acceleration

Reduced to 60% !

We started mass-production and will complete in 2027.

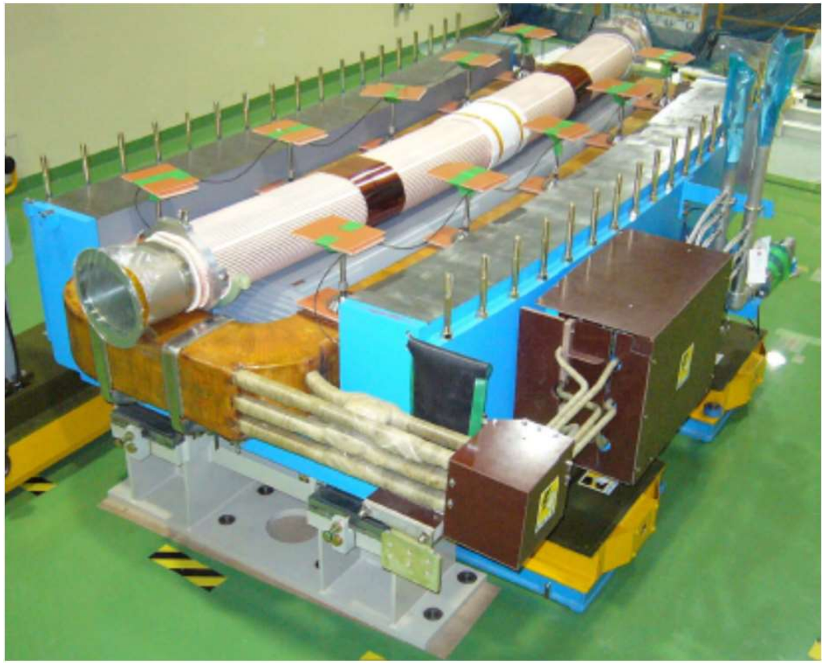
Summary

- RCS is designed to achieve 1-MW beam acceleration.
  - We have continued hardware improvement and now achieved enough stable 1-MW demonstration.
  - RCS is almost continuing stable user operation.
  - At present, ***4.4e13 ppp (800-kW)*** beam delivers to the MLF and ***6.5e13 ppp (780-kW equivalent in RCS)*** beam to the MR.
- Now we try to accelerate more than 1-MW beam.
  - So far, it seems that RCS has a potential to accelerate 1.5-MW beam or more.
  - We will continue the beam study and improvements to achieve more high power beam with less beam loss.

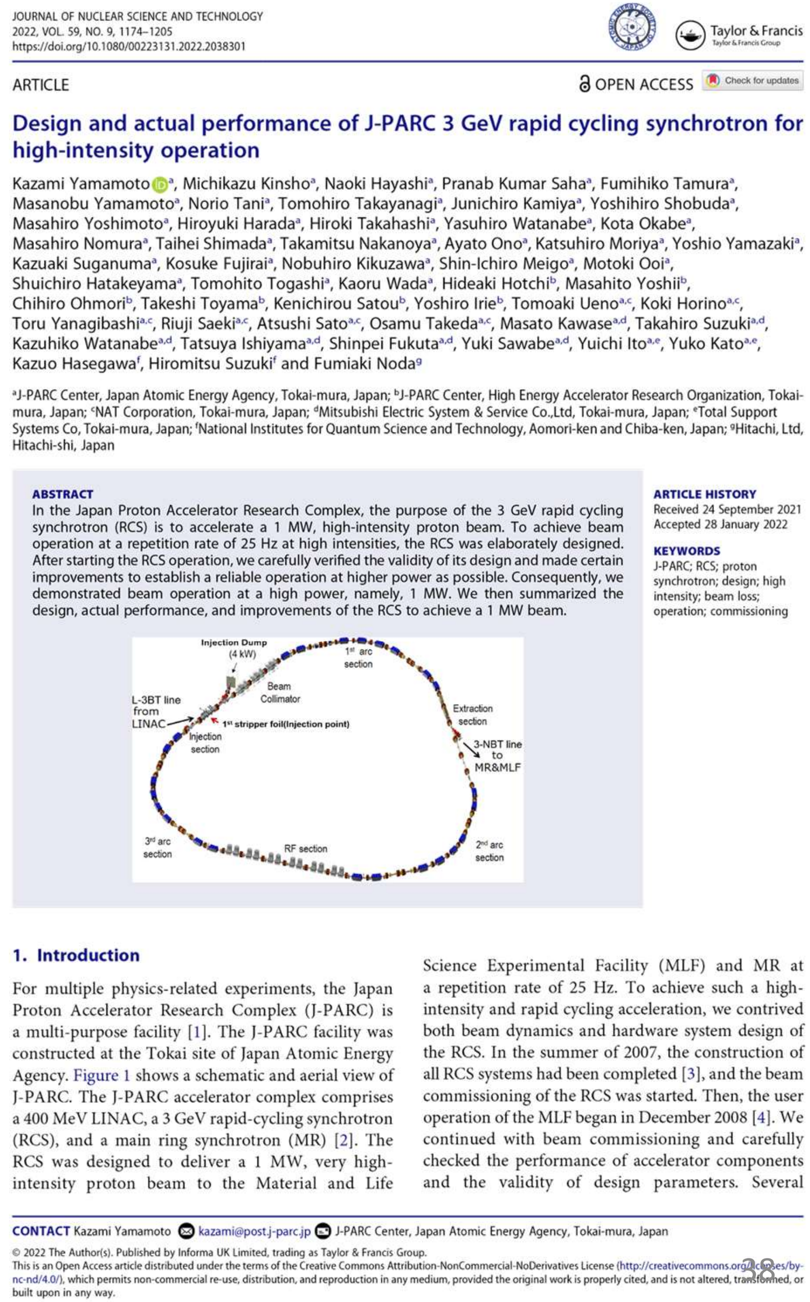
Summary of J-PARC RCS design

J-PARC side summarized the design concept and improvement work of RCS in an article.

https://doi.org/10.1080/00223131.2022.2038301



Dipole magnet and Ceramic duct in J-PARC RCS



JOURNAL OF NUCLEAR SCIENCE AND TECHNOLOGY
2022, VOL. 59, NO. 9, 1174–1205
https://doi.org/10.1080/00223131.2022.2038301

ARTICLE

OPEN ACCESS Check for updates

Design and actual performance of J-PARC 3 GeV rapid cycling synchrotron for high-intensity operation

Kazami Yamamoto[a], Michikazu Kinsho[a], Naoki Hayashi[a], Pranab Kumar Saha[a], Fumihiko Tamura[a], Masanobu Yamamoto[a], Norio Tani[a], Tomohiro Takayanagi[a], Junichiro Kamiya[a], Yoshihiro Shobuda[a], Masahiro Yoshimoto[a], Hiroyuki Harada[a], Hiroki Takahashi[a], Yasuhiro Watanabe[a], Kota Okabe[a], Masahiro Nomura[a], Taihei Shimada[a], Takamitsu Nakanoya[a], Ayato Ono[a], Katsuhiro Moriya[a], Yoshio Yamazaki[a], Kazuaki Suganuma[a], Kosuke Fujirai[a], Nobuhiro Kikuzawa[a], Shin-Ichiro Meigo[a], Motoki Ooi[a], Shuichiro Hatakeyama[a], Tomohito Togashi[a], Kaoru Wada[a], Hideaki Hotchi[b], Masahito Yoshii[b], Chihiro Ohmori[b], Takeshi Toyama[b], Kenichirou Satou[b], Yoshiro Irie[b], Tomoaki Ueno[a,c], Koki Horino[a,c], Toru Yanagibashi[a,c], Riuji Saeki[a,c], Atsushi Sato[a,c], Osamu Takeda[a,c], Masato Kawase[a,d], Takahiro Suzuki[a,d], Kazuhiko Watanabe[a,d], Tatsuya Ishiyama[a,d], Shinpei Fukuta[a,d], Yuki Sawabe[a,d], Yuichi Ito[a,e], Yuko Kato[a,e], Kazuo Hasegawa[f], Hiromitsu Suzuki[f] and Fumiaki Noda[g]

[a]J-PARC Center, Japan Atomic Energy Agency, Tokai-mura, Japan; [b]J-PARC Center, High Energy Accelerator Research Organization, Tokai-mura, Japan; [c]NAT Corporation, Tokai-mura, Japan; [d]Mitsubishi Electric System & Service Co.,Ltd, Tokai-mura, Japan; [e]Total Support Systems Co, Tokai-mura, Japan; [f]National Institutes for Quantum Science and Technology, Aomori-ken and Chiba-ken, Japan; [g]Hitachi, Ltd, Hitachi-shi, Japan

ABSTRACT
In the Japan Proton Accelerator Research Complex, the purpose of the 3 GeV rapid cycling synchrotron (RCS) is to accelerate a 1 MW, high-intensity proton beam. To achieve beam operation at a repetition rate of 25 Hz at high intensities, the RCS was elaborately designed. After starting the RCS operation, we carefully verified the validity of its design and made certain improvements to establish a reliable operation at higher power as possible. Consequently, we demonstrated beam operation at a high power, namely, 1 MW. We then summarized the design, actual performance, and improvements of the RCS to achieve a 1 MW beam.

ARTICLE HISTORY
Received 24 September 2021
Accepted 28 January 2022

KEYWORDS
J-PARC; RCS; proton synchrotron; design; high intensity; beam loss; operation; commissioning

1. Introduction

For multiple physics-related experiments, the Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose facility [1]. The J-PARC facility was constructed at the Tokai site of Japan Atomic Energy Agency. Figure 1 shows a schematic and aerial view of J-PARC. The J-PARC accelerator complex comprises a 400 MeV LINAC, a 3 GeV rapid-cycling synchrotron (RCS), and a main ring synchrotron (MR) [2]. The RCS was designed to deliver a 1 MW, very high-intensity proton beam to the Material and Life Science Experimental Facility (MLF) and MR at a repetition rate of 25 Hz. To achieve such a high-intensity and rapid cycling acceleration, we contrived both beam dynamics and hardware system design of the RCS. In the summer of 2007, the construction of all RCS systems had been completed [3], and the beam commissioning of the RCS was started. Then, the user operation of the MLF began in December 2008 [4]. We continued with beam commissioning and carefully checked the performance of accelerator components and the validity of design parameters. Several

CONTACT Kazami Yamamoto kazami@post.j-parc.jp J-PARC Center, Japan Atomic Energy Agency, Tokai-mura, Japan

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.