WEXB02, IPAC2021
May 26th, 2021

Upgrading J-PARC Accelerator for Hyper-Kamiokande Project

Yoichi Sato* (KEK/J-PARC)
On behalf of the J-PARC Accelerator Group

CONTENTS

- Introduction
- Operation status of MR with fast extraction
- MR upgrade plan
- Summary

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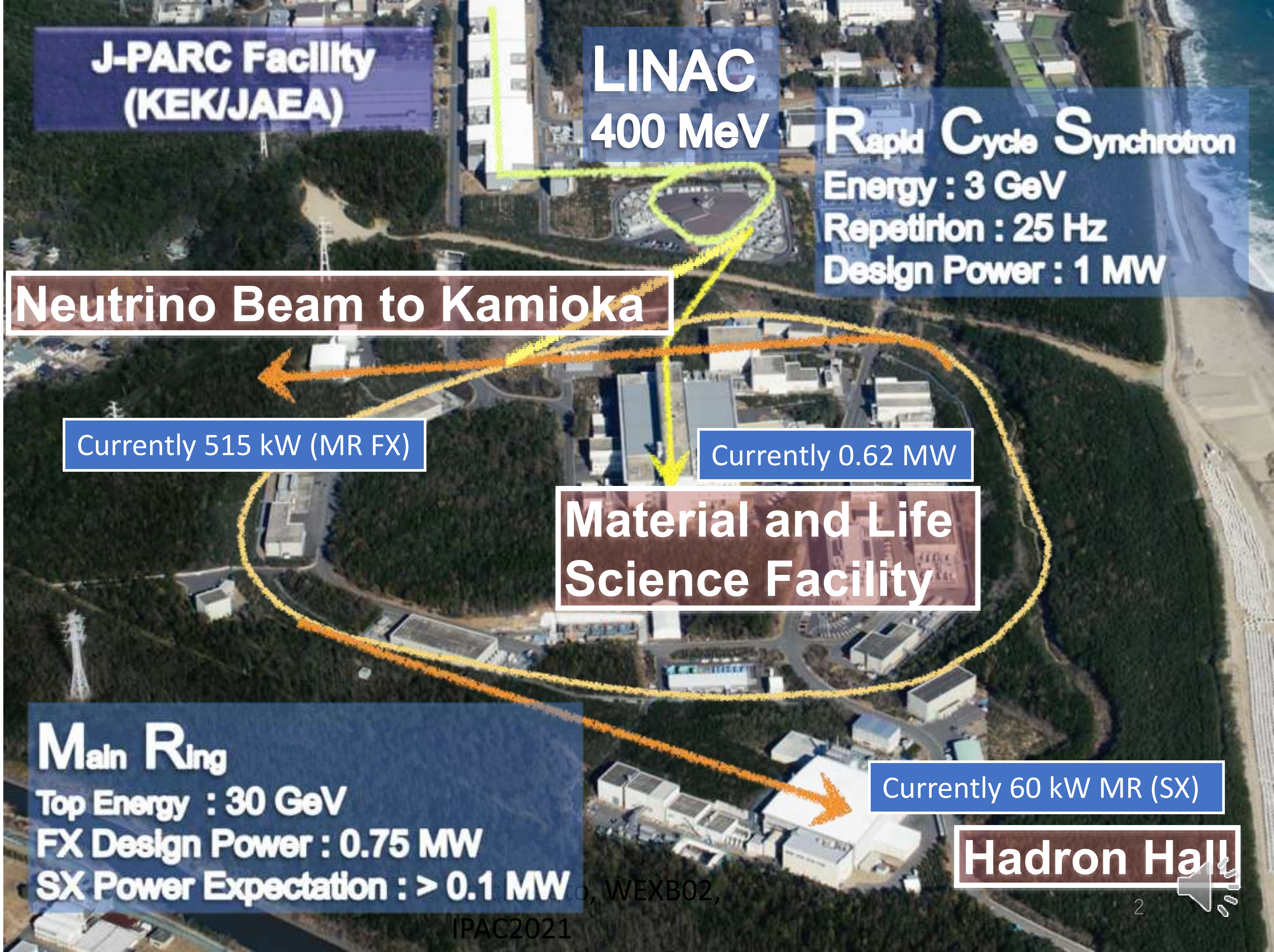
Japan Proton Accelerator Research Complex

High Intensity Proton Accelerators

Facilities to use the secondary beams



Tokai to Hyper-Kamiokande

Neutrino Facility (2009 -) On going experiment

- *Long baseline neutrino oscillation experiment (T2K)*

・Observation of Electron Neutrino Appearance in a Muon Neutrino Beam
Phys. Rev. Lett. 112, 061802 (2014)
・Restrict Possible Values of Neutrino CP Phase
https://www.nature.com/articles/s41586-020-2177-0

515 kW at present
(Design 750 kW)

Upgrade Plan for the Neutrino Experiment

- **Hyper-Kamiokande experiment (HK) (2027 -)**

- **Far Detector**
  Water Cerenkov Detector of **10 times larger fiducial volume** *of Super-Kamiokande*

- **MR Beam Power Upgrade → 1.3 MW**
  Hardware (MR, NU) and Beam dynamics
  - **(anti-)muon neutrino beam produced by 1.3MW proton beam**
  - **New near detector**

HK Main Goal:
Discovery of CPV
Precision measurements, mass hierarchy and exotic searches

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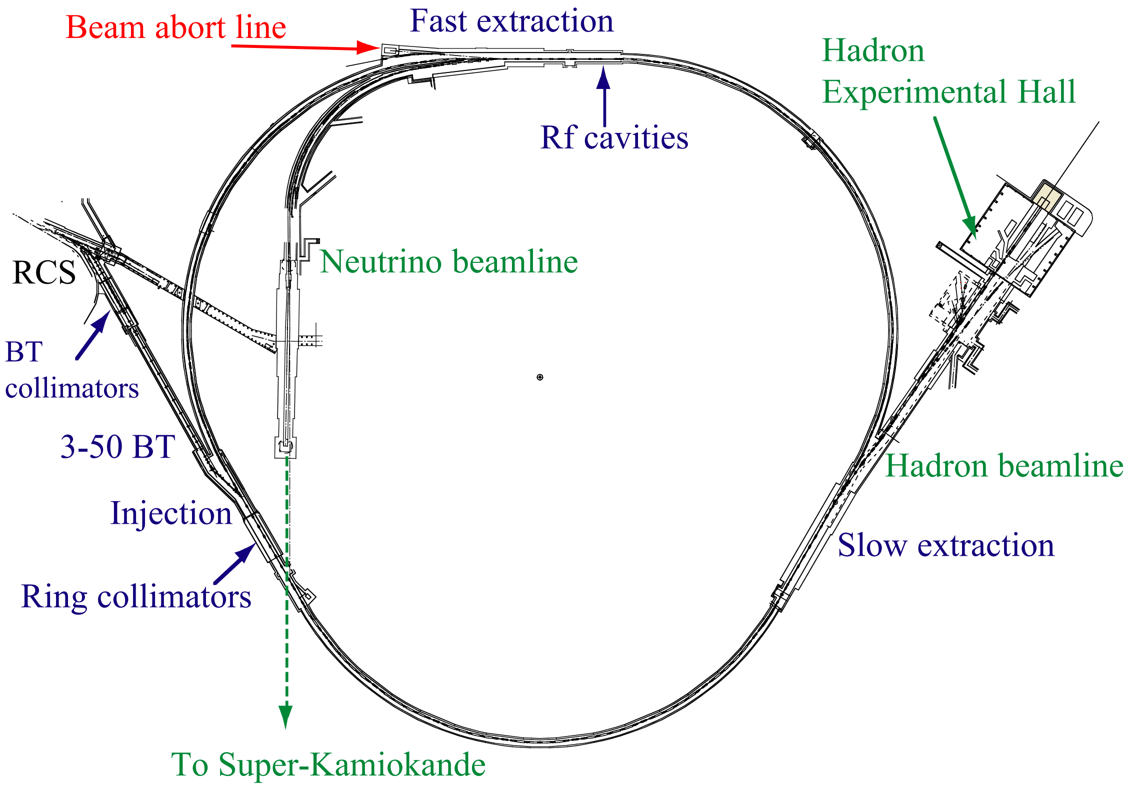
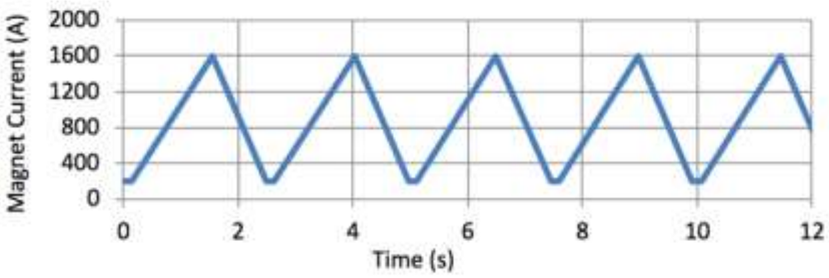
MR Design and Operation Modes

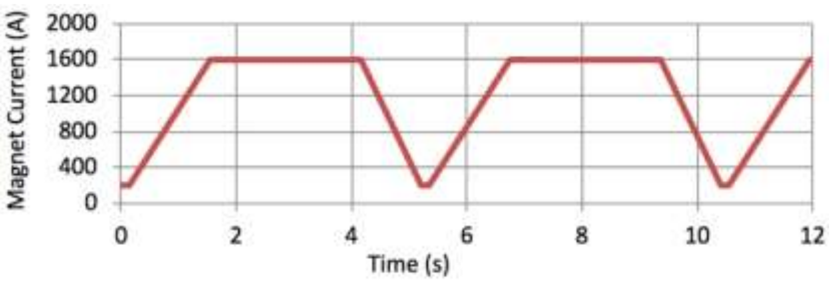
- Circumference 1567.5 m
- Three-fold symmetry
- 3 GeV injection and 30 GeV extraction

- Fast extraction mode (FX) for the neutrino Facility: 1 turn extraction.
- Slow extraction mode (SX) for the hadron hall: 2 s – spill extraction.



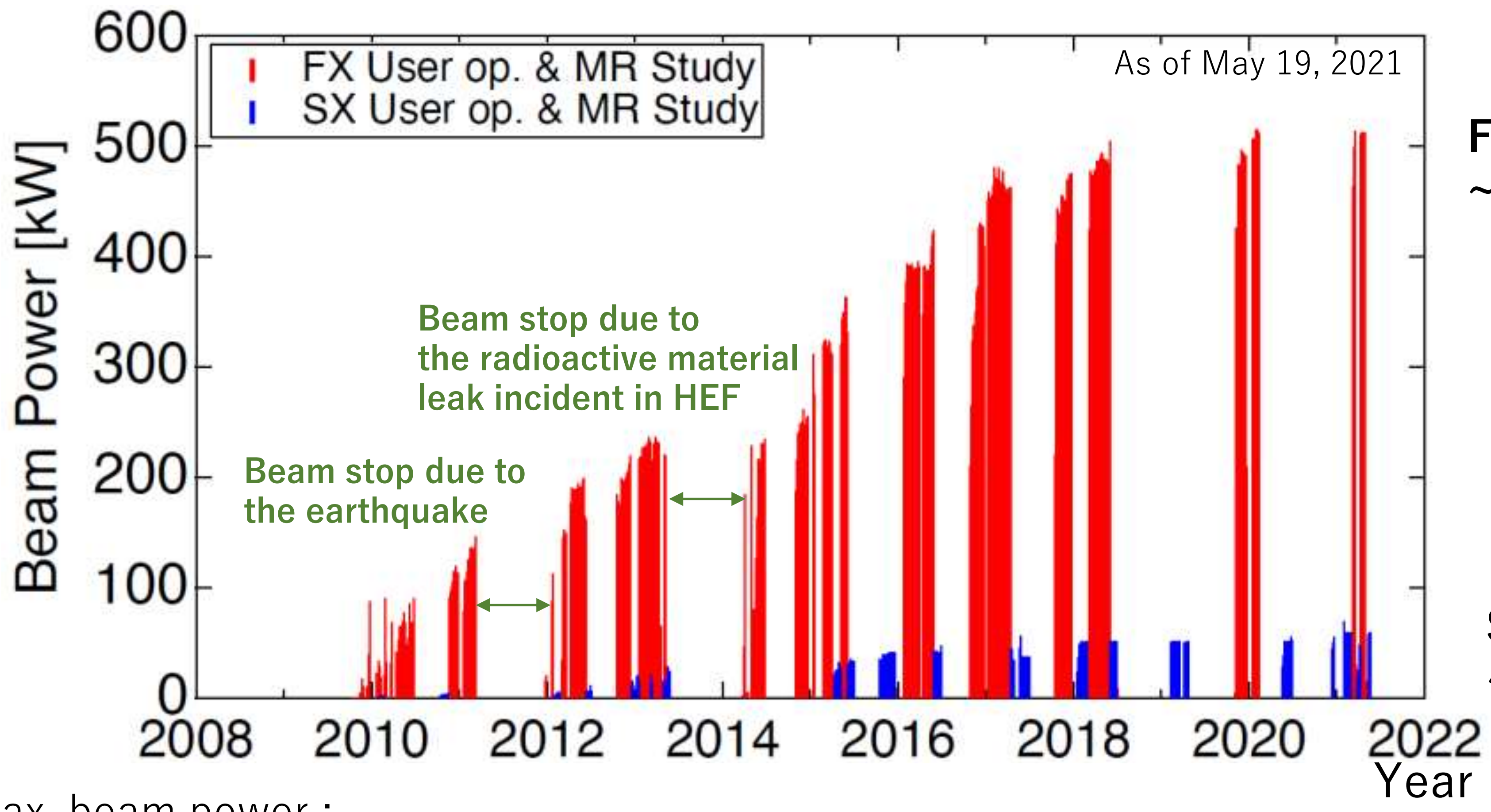


FX (2.48 s)



SX (5.2 s)

Beam power history of MR



Fast extraction
~ 515 kW in 2.48 s cycle

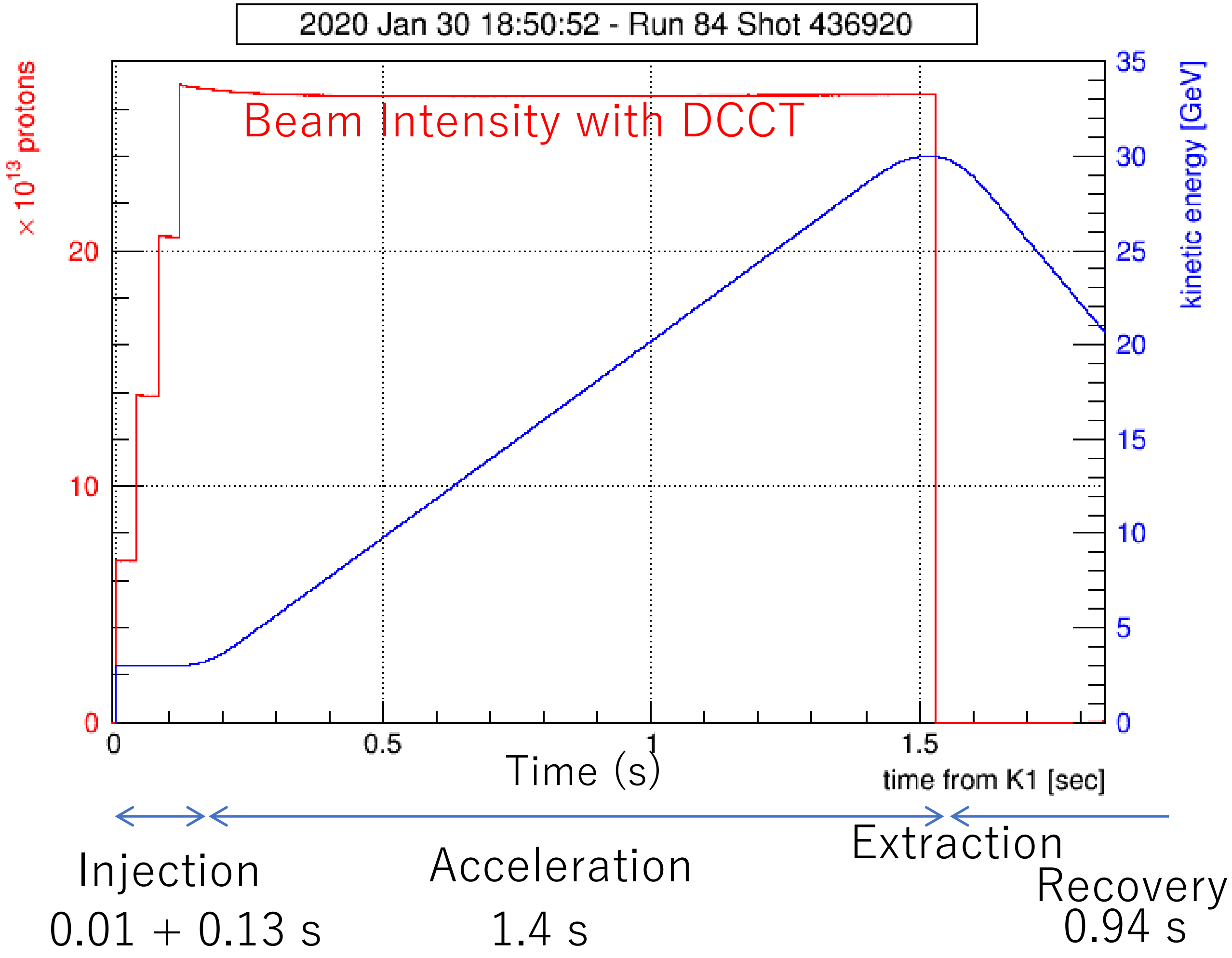
Slow extraction
~ 60 kW in 5.20 s cycle

Max. beam power :
Fast extraction ~ 515 kW (2.66 x10^{14} ppp), the world highest ppp in synchrotrons.
Slow extraction ~ 60 kW (6.5 x10^{13} ppp) in 5.20 s cycle for users with the extraction efficiency of 99.5 %.

Typical Operation Status for FX

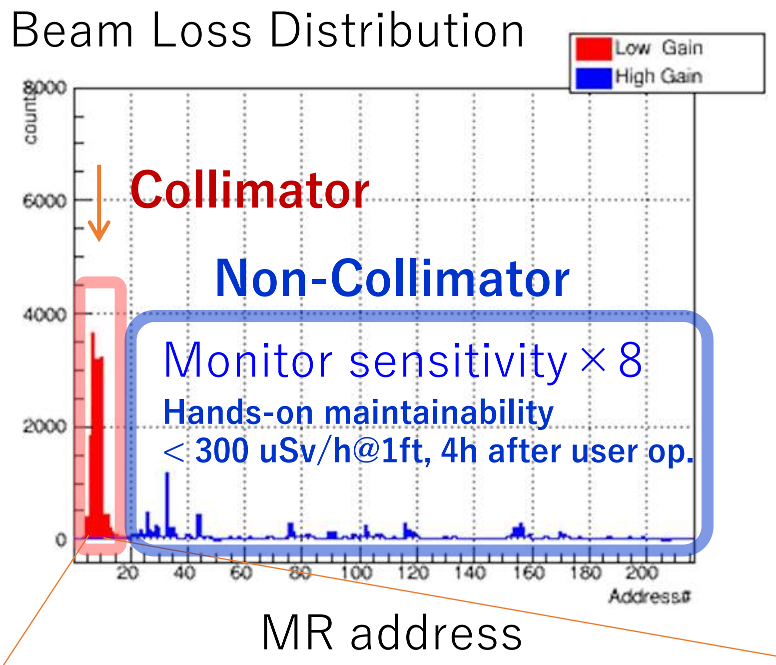
- Power : 515 kW
- Repetition : 2.48 sec
- 4 batch (8 bunch) injection
  during the period of 0.13 s
- 3.4e13 protons per bunch (ppb)
  × 8 @ Injection
- 2.66e14 ppp @ P3 (end of acceleration)
- Beam Loss : 800 W (*)
- Loss power is within
  the MR collimator limit of 2 kW
- Loss at 3-50BT : 100 W,
  < 3-50BT collimator limit of 2 kW

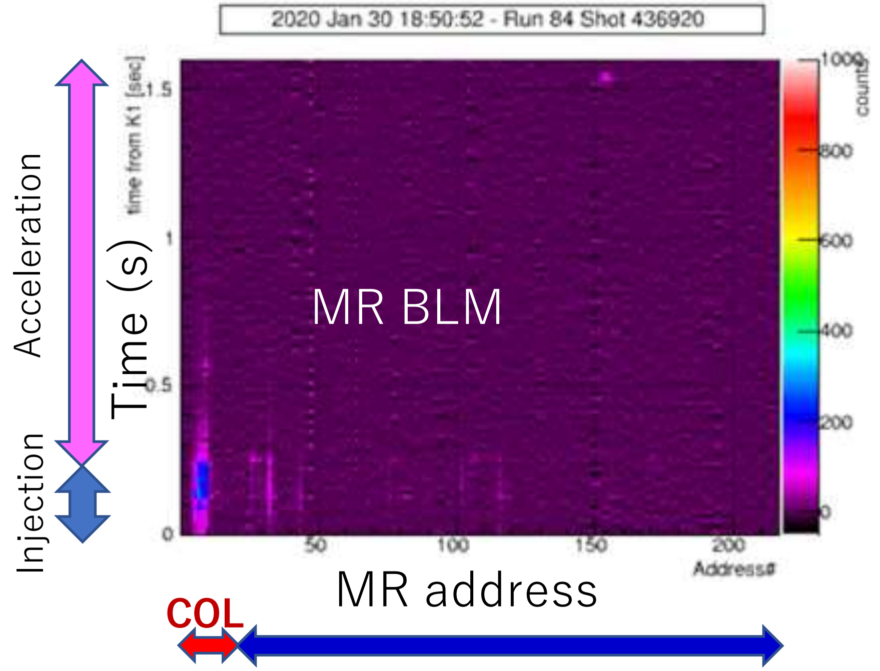
NOTE *: Beam loss estimated with DCCT.

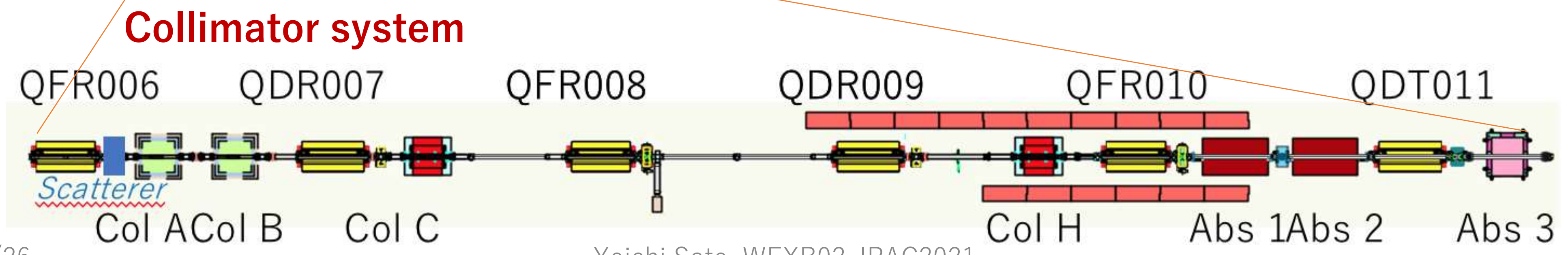


Beam Loss Localization with Collimators

- Four collimators and 3 absorbers are in operation with the total capacity of 2 kW.
- Beam losses are mostly localized at the collimator section.
- **Hands-on maintenance is possible** with minimum exposure of residual radiation.



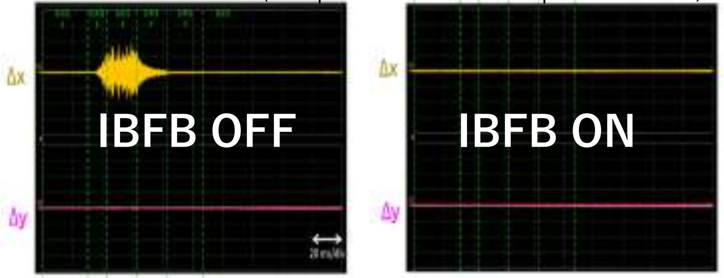




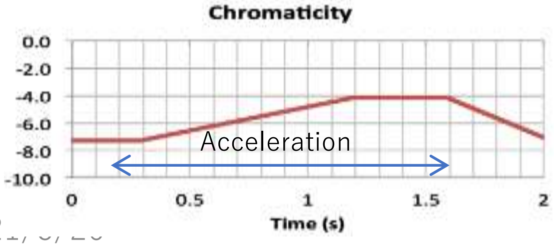
Tuning items for the Beam Loss Reduction
performed till April 2021

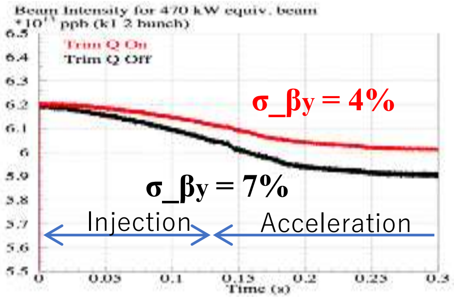
① **Injection beam quality: optimized RCS parameters, verified at 3-50BT monitors**
② **Optics measurements and corrections** needs $\sigma\_\beta_{x,y} < 4\%$
③ **Transverse instability suppression: Intra-BunchFB, controlled chromaticity**
④ **2nd harmonic RF to suppress space charge tune spread**
⑤ **Longitudinal beam loading compensation system**
⑥ **Third order resonance corrections**
⑦ **Tune optimization (injection & acceleration)**
⑧ **…**

Beam Position of 2.1e13 ppb * 2bunches with
Intra-bunch FB (Stripline BPM & Stripline kicker)

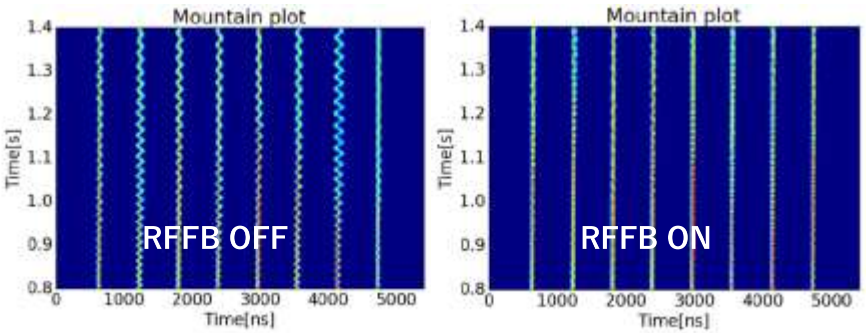


IBFB works well
In first half acc

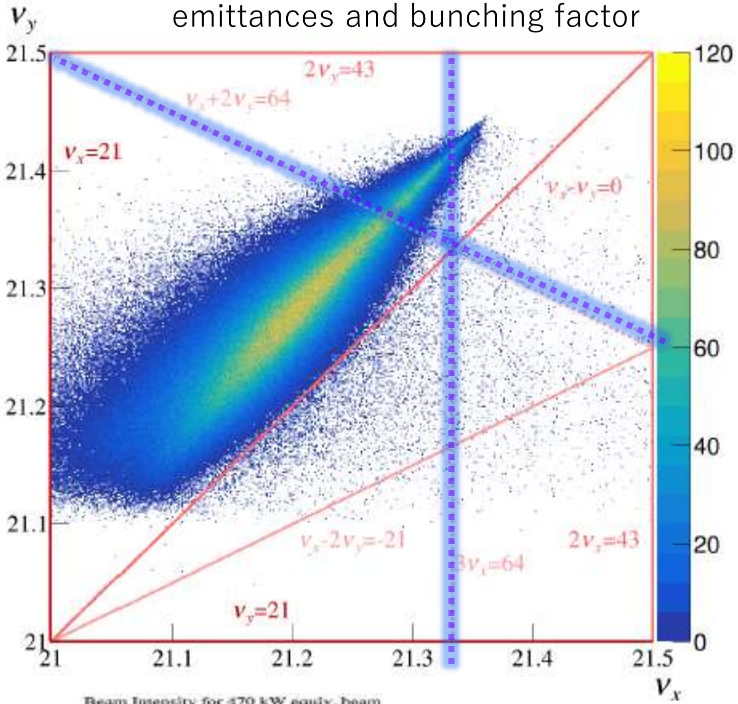


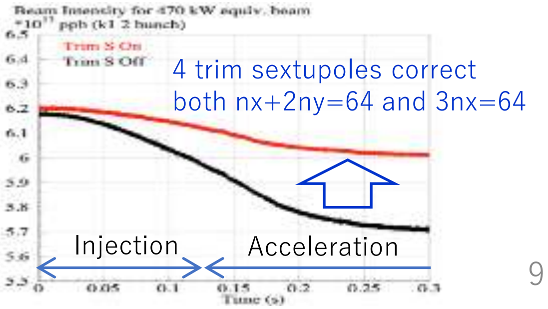


Long. bunch oscillation of 480 kW beam



Simulated tune shift of MR Power 500 kW
(Tune Spread 0.4)
based on the measured transverse
emittances and bunching factor





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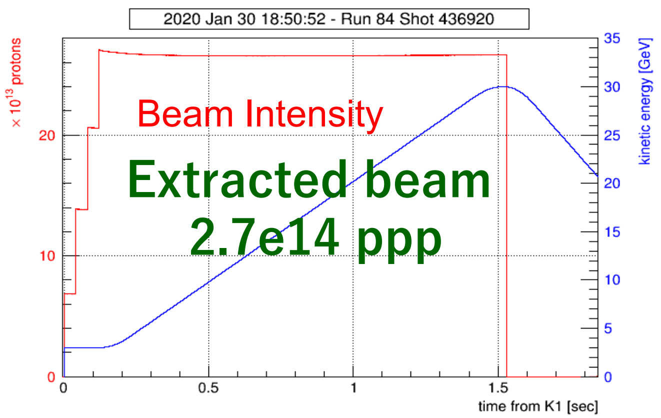
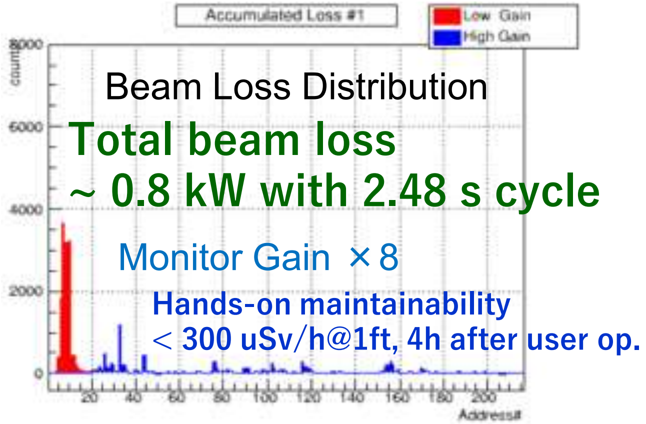
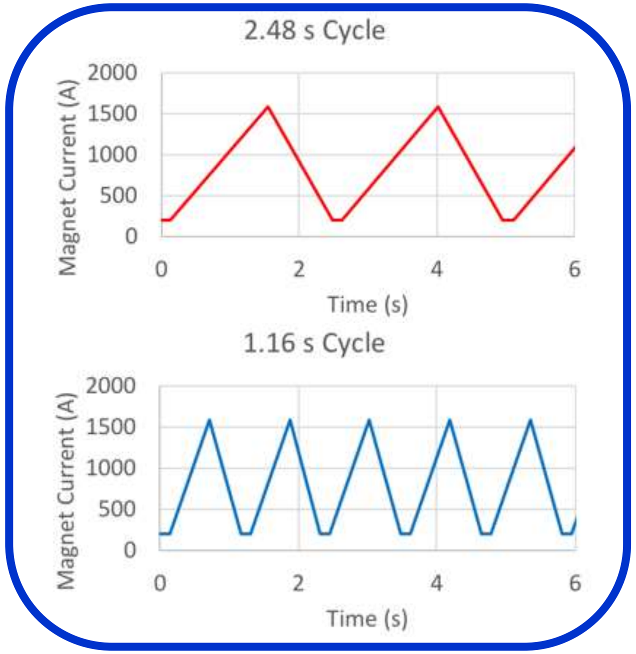
Concept of the Upgrade Plan

- The beam power of 515 kW was achieved by a single shot with the 2.48 s







- The beam power would be 1.1 MW with the beam loss of 1.7 kW if the cycle is 1.16 s.
- Beam study is necessary to reduce the beam loss and further beam loss localization.

	Number of accelerated protons	Bunch number	cycle (s)	Beam power (kW)	Beam loss (kW)	Notes
1	2.7e14 ppp	8	2.48	515	0.8	measurement
2	*2.7e14 ppp*	*8*	*1.32*	*970*	*1.5*	*estimation*
3	*2.7e14 ppp*	*8*	*1.16*	*1100*	*1.7*	*estimation*
4	***3.3e14 ppp***	***8***	***1.16***	***1300***	***?***	

30%gain

Factor 2

Beam Power
∝ 30GeV
× 1/Trep
× # of protons.

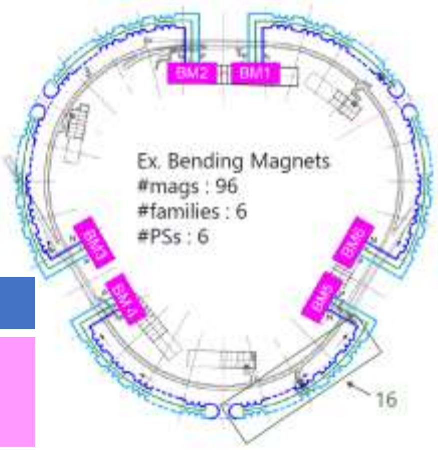
Faster acceleration
→ Mag PS, RF voltage, Transv FB
Faster cycle
→ Mag PS, Inj/FX, Monitors, Collimators, Data taking, …
More protons
→ Beam Dynamics, RF anode PS

New Power Supplies being Constructed

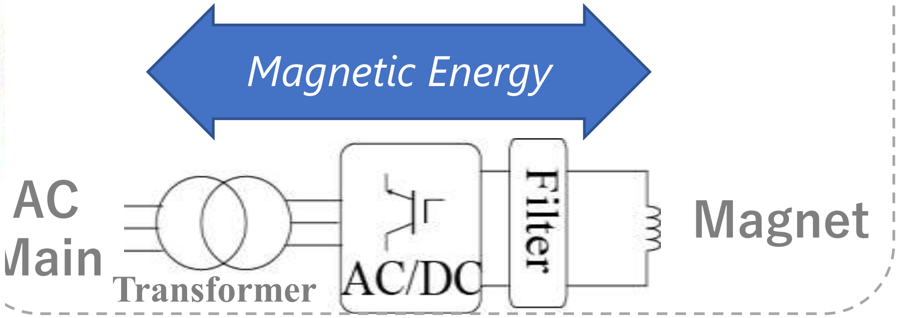
- New power supplies were designed for the faster cycle. -> higher output voltage
- The electric power supplier did not allow us a large power variation by the faster cycle.
- We decided to have capacitor banks for the energy recovery.

Kurimoto

$$V = L_{mag}\frac{dI_{mag}}{dt} + R_{mag}I_{mag}$$



Present PS: All magnetic energy are returned to the AC main grid

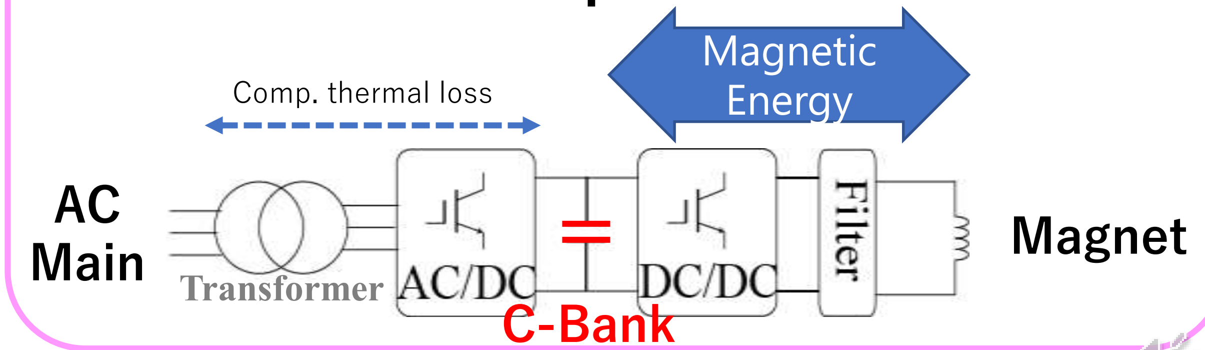


Mag. Family (*)	Type	#mags/PS	PS	Upgrade
BM1 ~ 6	**Bending**	**16**	**Large**	**New PS w C-Bank**
QFN, QDN,	**Quadrupole**	**48**	**Large**	
QFX	Quadrupole	48 → 24	Large	Reuse Present PS w divided budget
QDX	Quadrupole	27 → 14&13	Large	
QDS, QFS, QFT	Quadrupole	6 → 3	Small	
QFP, QFR	Quadrupole	6, 9	Small	Reuse Present PS
QDR, QDT	**Quadrupole**	**6**	**Small**	**New PS w/o C-Bank**
SFA, SDA, SDB	**Sextupole**	**24 → 24, 48**	**Small**	

Large PS: 6000 V, 800-1500 A
Small PS : 1500 V, 800 A-1000 A

* One PS drives several magnets connected in series.
These several magnets are collectively called "a Family"

New PS with capacitor bank: All magnetic energy are recovered to the capacitor bank



New Power Supplies being Constructed

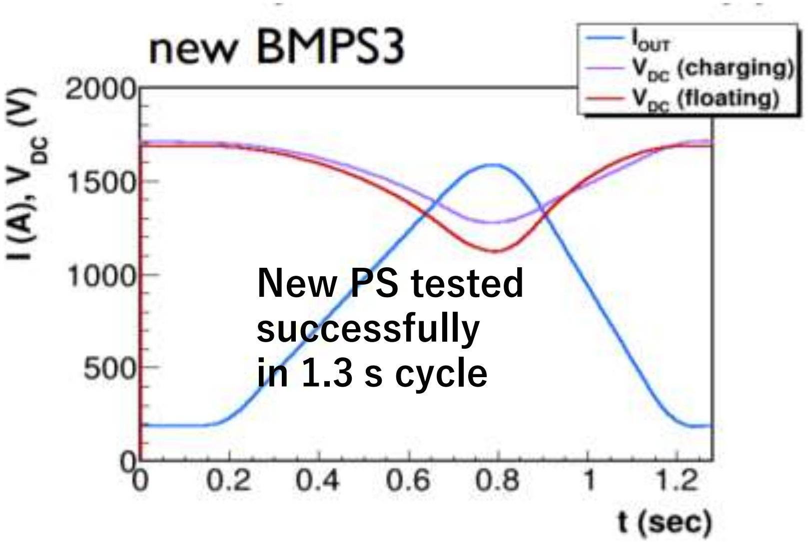
New 3 buildings for the PSs were constructed (complete).
Mass production of the PSs is in progress.

- All 6 bending magnet (BM) PS families were constructed and installed.

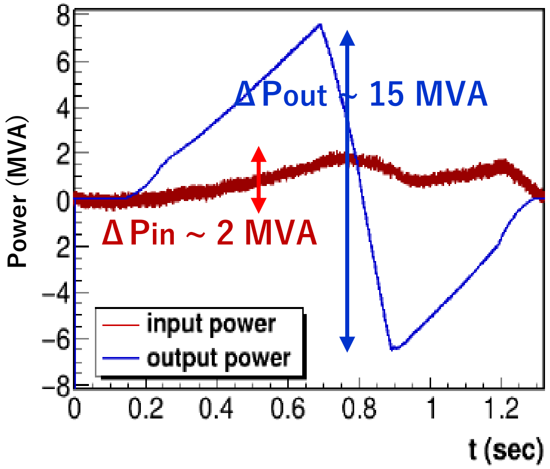
2 BMPSs were successfully tested in 1.3 s cycle, and stably operated over 50-hour.

- Power variation reduced from input to output.
  Total input power estimation = half of present FX op.
- Current ripple at flat top was improved factor 10 in low freq.

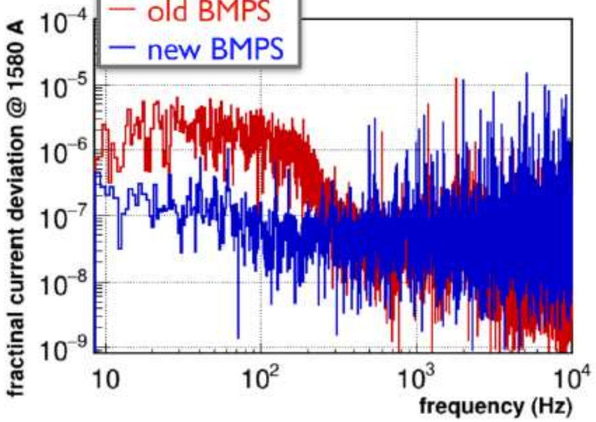
T. Shimogawa et. al., IPAC2019



new BMPS3's Input/output power



ΔI / I @flat top

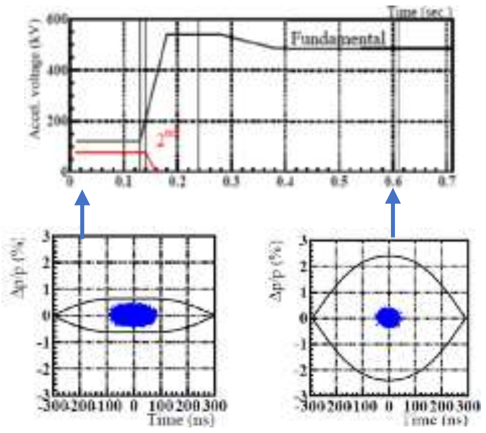


- **Installation of remaining power supplies in 2021.**
- **All processes are on schedule for beam test in Jun 2022.**

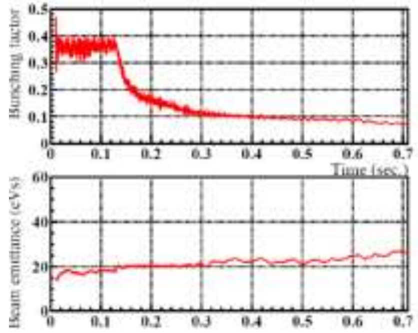
Installation Plan for RF Cavities

- **Higher RF voltages are necessary for the faster cycling.**
- **The following numbers of RF cavities are necessary for the operation of 1.32 s and 1.16 s.**

	2020	2022	202X
MR Cycle	2.48 s	1.32 s	1.16 s
FT3L 4GAP Cavities	7	9	11
2nd Harmonic Cavities	2	2	2
Accelerating Voltage	300 kV	510 kV	600 kV
2nd Harmonic Voltage	110 kV	110 kV	110 kV



Simulated longitudinal motion for 1.16 s cycle (including beam loading & long-SC)



M. Yamamoto

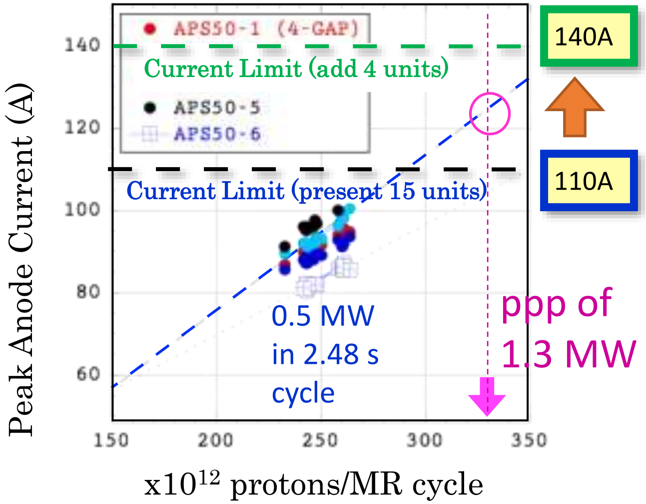
Cavities at MR Ins C

Ins A: **2 2nd harmonic cavities** in Fall 2022

Ins B: **2 fundamental** cavities in 202X

- **Upgrade of the anode power supplies are planned for the beam loading compensation.**

Yoshii

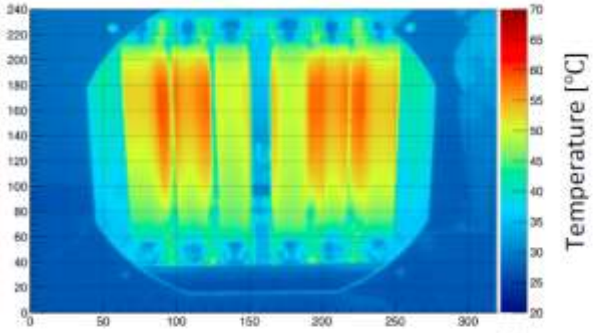


RCS RF Anode power supply

- **New LLRF system, having vector voltage FB**

Injection and Extraction Systems

Injection	
Kicker * (Inj. and Comp.)	Design work is in progress for the cooling of the matching box.
Septum**	Magnet and power supply were replaced and ready for 1 Hz operation.
Fast Extraction	
Kicker	HV charger was upgraded and ready for 1 Hz operation.
Low Field Septum**	Magnets and PS constructed. Testing. Installation in 2021.
High Field Septum**	Magnets constructed. Testing. Installation in 2021.

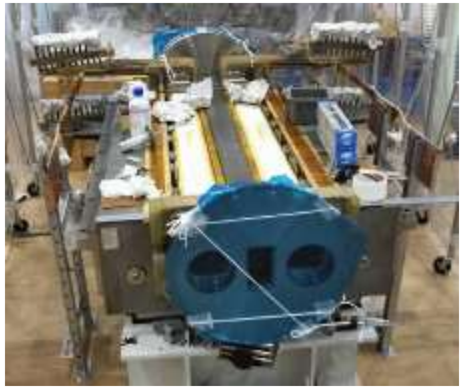


Vcharge=47.5kV, Ipeak=2580A, P=5.20W

* Inj Kickers need to manage beam induced current. Newly designed system demonstrated the surface temperature of their resisters below their threshold 150 °C for high voltage impulses (eq. 1.3 MW op.)

** Septum magnets are to be “EDDY” type by JFY 2022, having Less leakage field by the induced Eddy current and Large aperture (no septum coil). Countermeasure to reduce impedance is planned.

Relating [WEPAB204] S. Iwata



MR beam diagnostics monitors & intra-bunch feedback

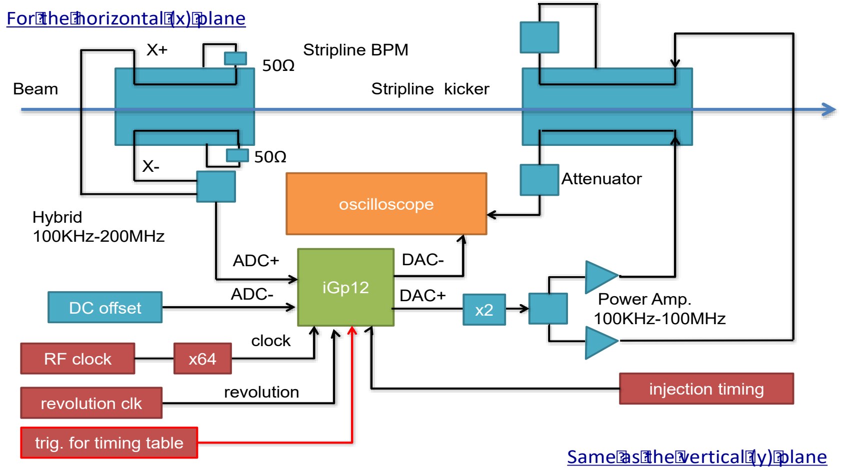
Mission: Provide the diagnostics for realization of 750 kW – 1.3 MW beam operation in the J-PARC MR

Progress in 2017 – 2020:

New BLM signal processing circuit, Abort profile monitor and 16-electrodes monitor have newly started operation. DCCT covers 2.7 e14 ppp with factor 2 margin. All diagnostics devices contributed to beam power upgrade from 450 to 510 kW.

Task(1) Upgrade of the intra-bunch feedback

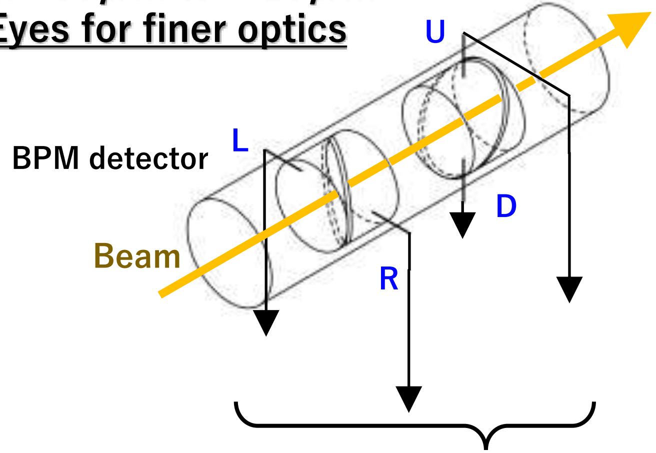
Shorten the damping time（>30%）



Task (2) Upgrade of the BPM circuits

Improve the position accuracy from ~30 μm to < 10 μm

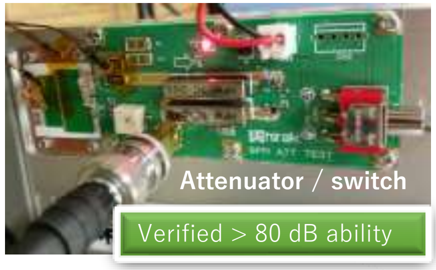
-> Eyes for finer optics



Develop New Signal Acquisition System

Signal processing circuit

- Noise filter
- Attenuator/switch
- ADC
- FPGA + Memory
- CPU + Network



Large Data Storage is needed also

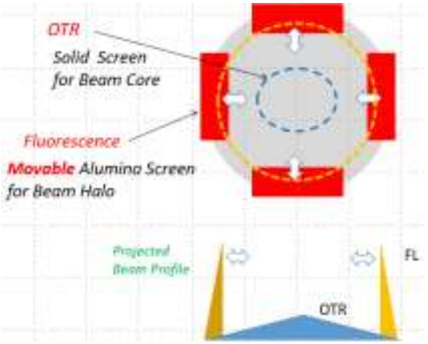
Task(3) OTR profile monitor in the MR

Measure the 2D profile and halo of the injected beam into the MR

-> Eye for Halo collimation by COLs

-> Eye for Halo reduction by optics

Motion mechanism for the target
Ti-foil for the OTR & fluorescent plate



Same type monitor (3-50BT-OTR/FL) realized dynamic range 10^{-6}

New MR-OTR/FL needs high radiated durability and much less impedance.

3-50BT/MR Collimators, Halo monitors and Beam Dump

- BT/MR collimators

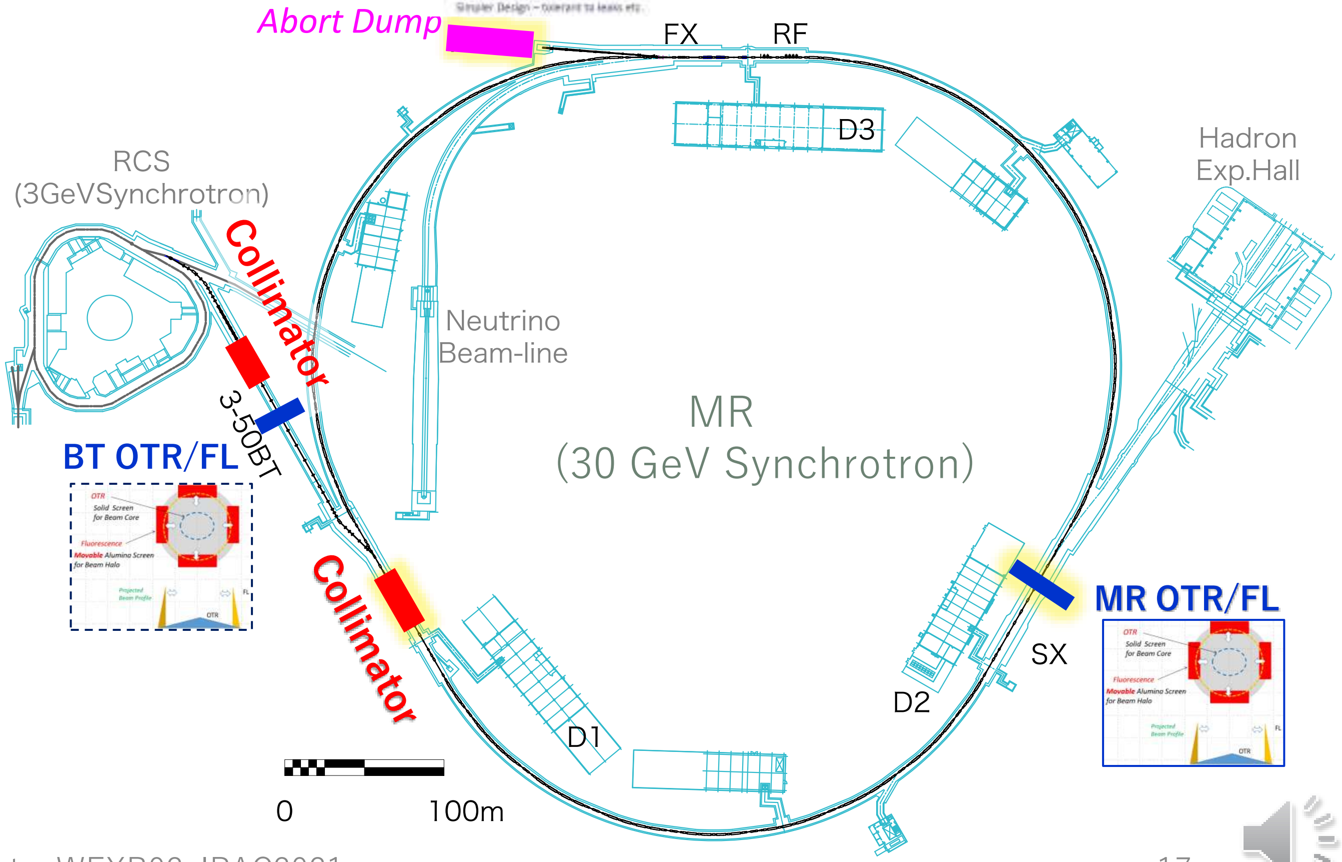
Devices locate outside of MR physical aperture 81 π mmmrad
→ Halo should be absorbed in
3-50BT collimators : 2 kW capacity.
MR collimators: 2 kW → 3.5 kW capacity upgrade in JFY2022.

- Beam halo monitors

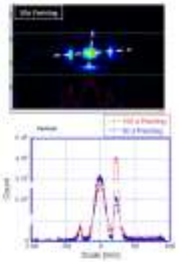
  BT-OTR/FL (in use)
  MR-OTR/FL (to be installed in JFY2022)
  → Halo measurement in diff. phase
  provide halo distribution in phase space and will help efficient halo cut by multiple jaws of the BT/MR collimators

To increase # of high intensity shots and perform efficient beam study, upgrade of beam abort dump is planned : 7.5 kW → 30 kW in near future.

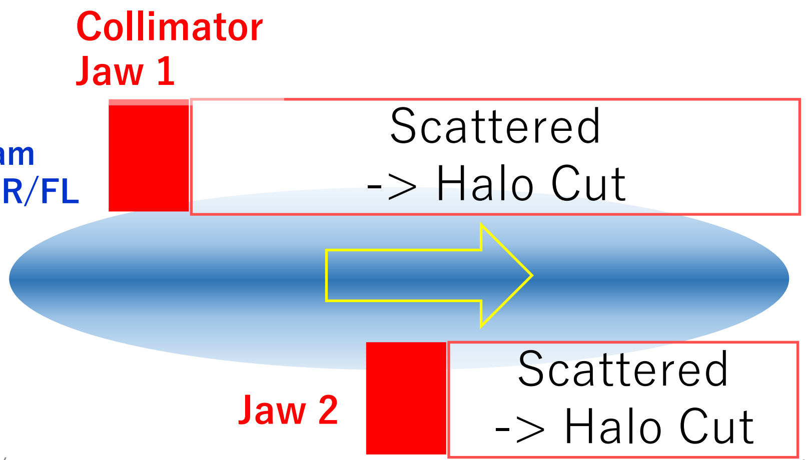
Conceptual Design by STFC RAL - KEK collaboration.: Graphite – Cu core with gas-cooling



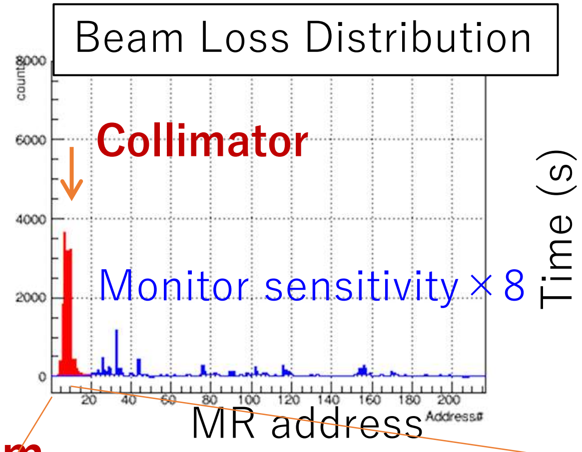
Hashimoto

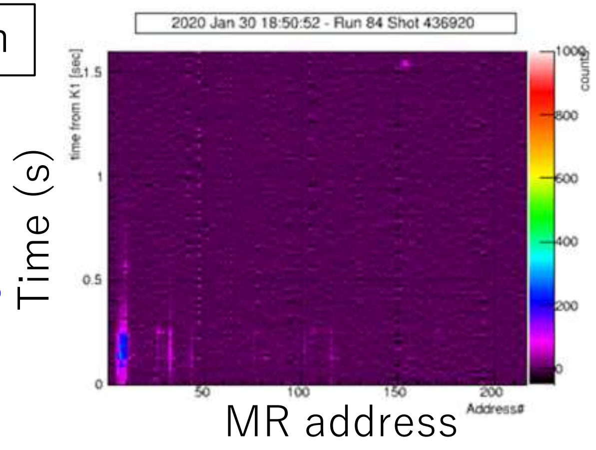


RCS beam
@BT OTR/FL
BT-Col
fullopen



Beam Loss Localization with Collimators





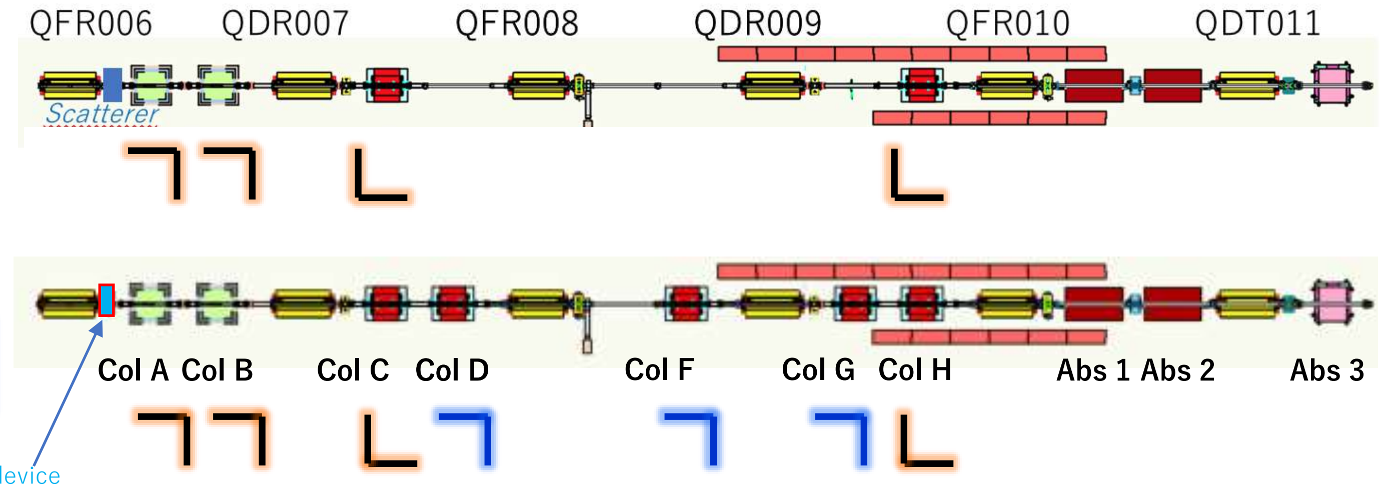
At present
510 kW op. w 0.8 kW loss in 2.48 s cycle

- 4 collimators and 3 absorbers are in operation with the total capacity of 2 kW.
- Beam losses are mostly localized at the collimator section.
- Hands-on maintenance is possible with minimum exposure of residual radiation.

Collimator system

2.0 kW at present

3.5 kW after JFY2022



Scatter test device for 2-stage collimation

Jaws Arrangement seen from upstream

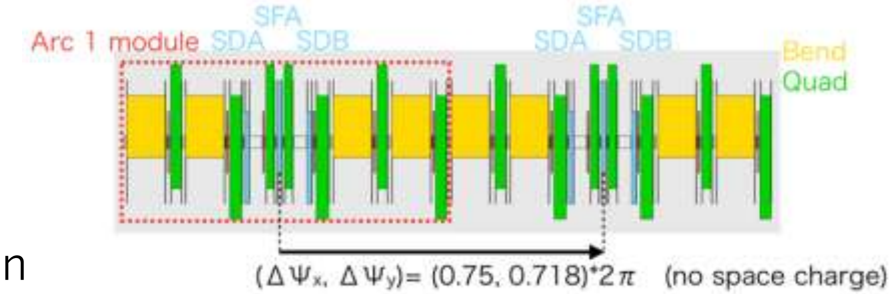
After JFY2022

- **Higher repetition (< 1.32 s cycle)** requires not only COL capacity increment but better loss localization to keep the present level of hands-on maintenance.
- **Add new MR Collimators cover whole halo area of phase space, and initial halo will be cut in a single turn.**
- *2-stage collimation will be studied for further beam loss localization*

Further items to reduce beam loss in FX

Detail in
T. Yasui [MOPPB229]
- Doctoral dissertation

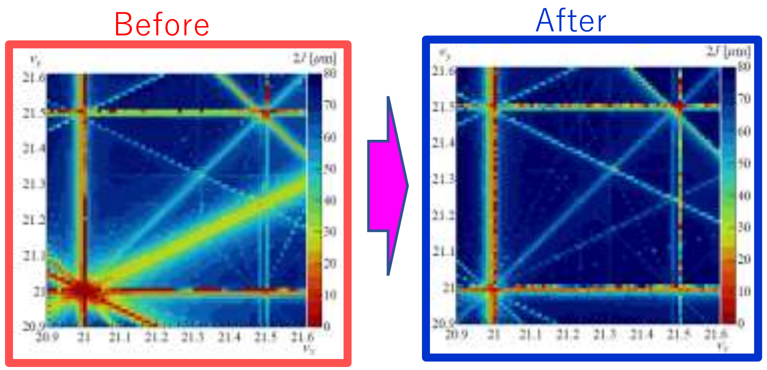
- ✓ New scheme has been studied to correct the structure resonances (nx – ny, nx – 2ny).
- ✓ Enables to explore better operation point far from (21.35, 21.45), and further reduction of the beam loss



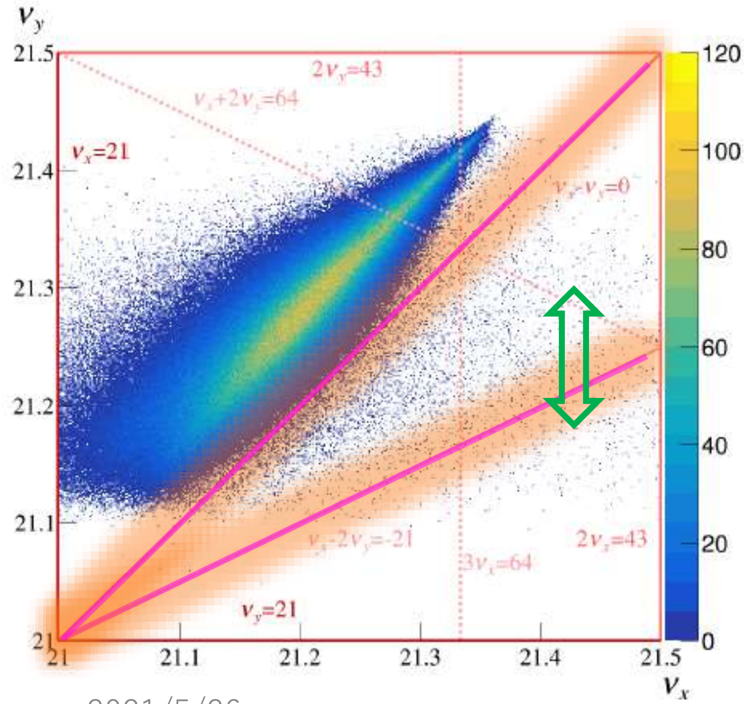
$$G_{1,-2,-21} = \frac{\sqrt{2}}{8\pi}\sum \beta_x^{1/2}\beta_y K_2 \exp[i(\phi_x - 2\phi_y)]$$

Control Φy only w/o breaking the horizontal dispersion function

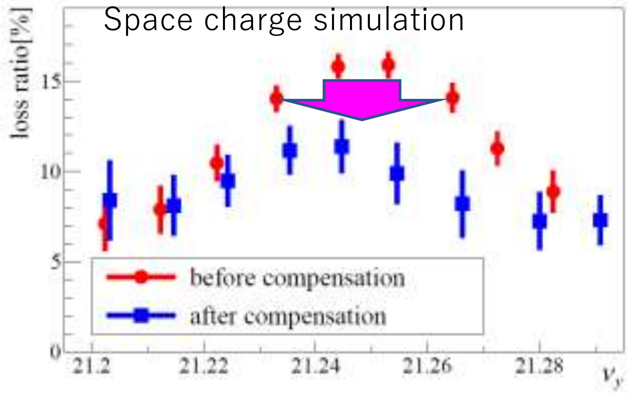
ϕy optimization

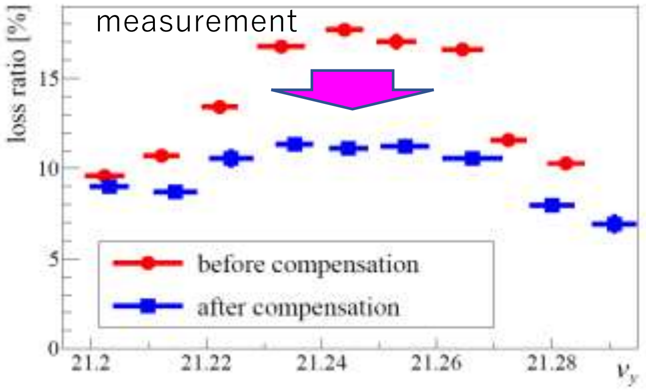


Dynamic aperture survey of single particle (SAD)



Tune scan near nx-2ny line





- ✓ Further beam study is necessary to apply the merit of wider tunability in high intensity operation.

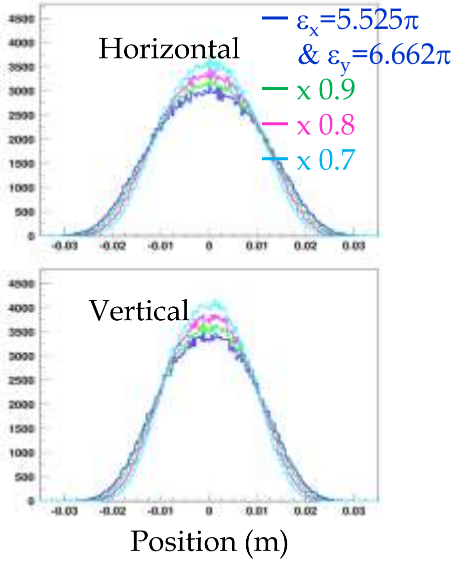
Expected effect of controlling injection emittance
(Optimizing RCS for MR)

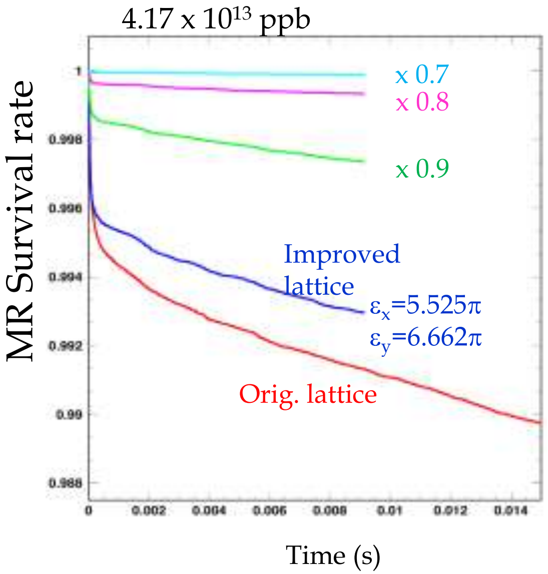
H. Hotchi

Space charge beam simulation suggests reducing injection emittance will increase MR survival rate, in the case of ideal MR lattice. Based on this strategy, we have explored RCS optimization, and studied the error sources in MR lattice.

SC simulation: Effect of injection emittances on the beam survival of MR

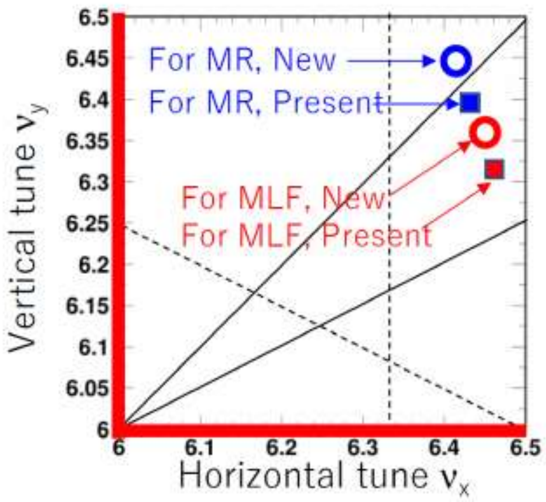
Ideal MR lattice is adopted, as no error and optimized ϕy minimizing the SC induced resonance of 8 νy=171 (improved lattice).
Beam survival is further improved with the small emittance beam from RCS (x 0.9, x 0.8, x 0.7)





In JFY2020, RCS optimization has been done for MR beam for 1.3 MW eq. protons per bunch. Beam emittance was reduced with the new tune setting in RCS.

- εx : 4% smaller
- εy : 13% smaller



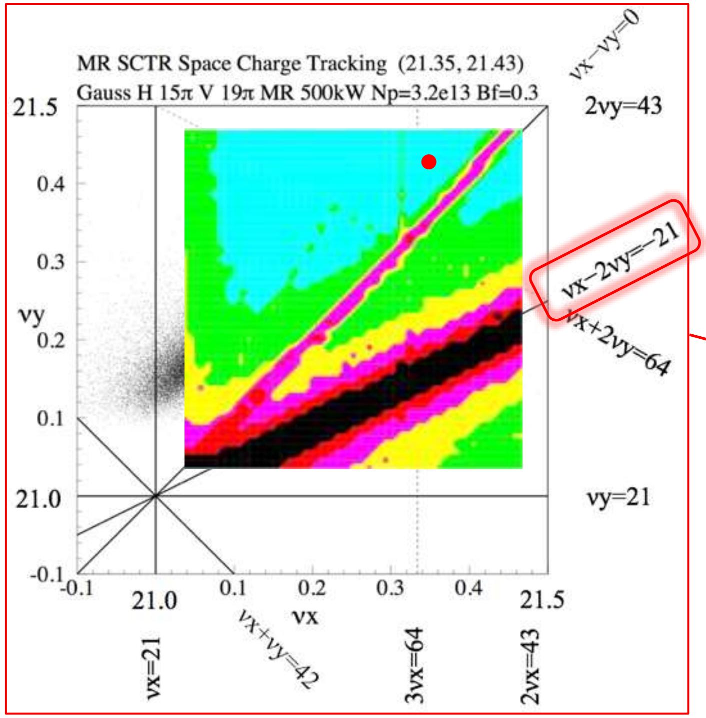
RCS operation point

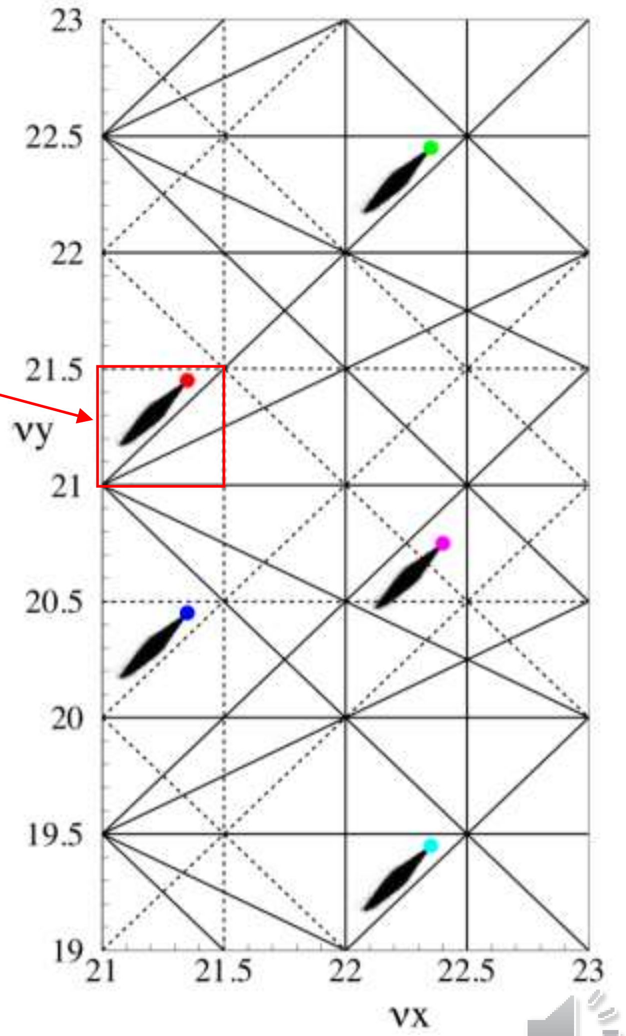
Possibility of new operation point

- ✓ Further reduction of the beam loss is needed.
- ✓ High intensity operation near the present operation tune (21.35, 21.45), is restricted by the structure resonances nx – 2ny=-21, nx – ny = 0.
- ✓ Φy optimization is under discussed.

- New operation working points have been searched for 4 $\times 10^{13}$ ppb.
- ✓ Beam survivals are simulated at (21.40, 20.45), (22.20, 19.40), (22.18, 22.40) for better survival than (21.35, 21.45).
- ✓ Beam study is necessary.

S. Igarashi



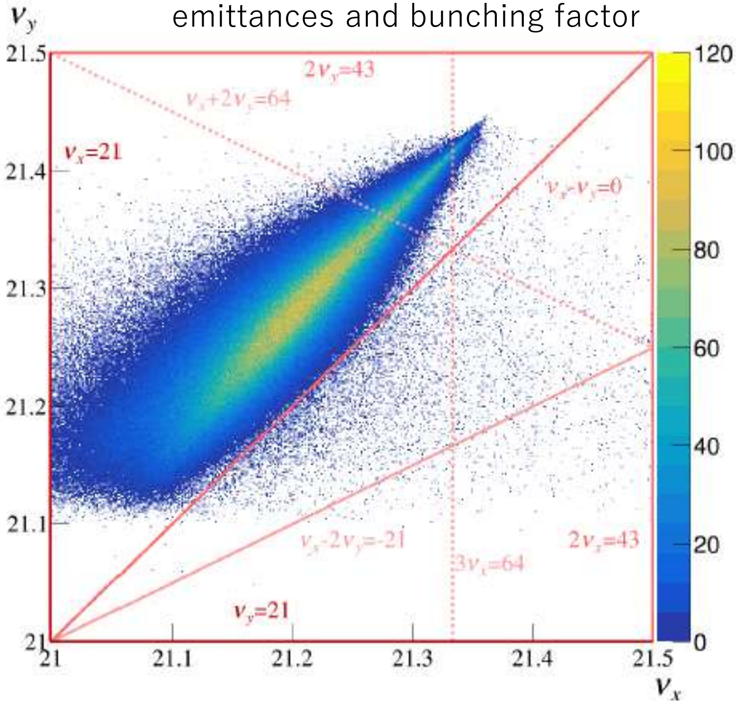


J-PARC Tuning items for the Beam Loss Reduction

till April 2021 → after JFY2022

① *Injection beam quality: optimized RCS parameters, verified at 3-50BT monitors*
② *Optics measurements and corrections* *needs $\sigma\_\beta_{x,y} < 4\%$*
③ *Transverse instability suppression: IntraBunchFB, controled chromaticity*
④ *2nd harmonic RF to suppress space charge tune spread*
⑤ *Longitudinal beam loading compensation system*
⑥ *Third order resonance corrections*
⑦ *Tune optimization (injection & acceleration)*
⑧ …

Simulated tune shift of MR Power 500 kW
(Tune Spread 0.4)
based on the measured transverse emittances and bunching factor



T. Yasui [MOPPB229]

<u>Beam Tunings after JUNE 2022 for the Upgrade 2.48 s → 1.32 s cycle</u>

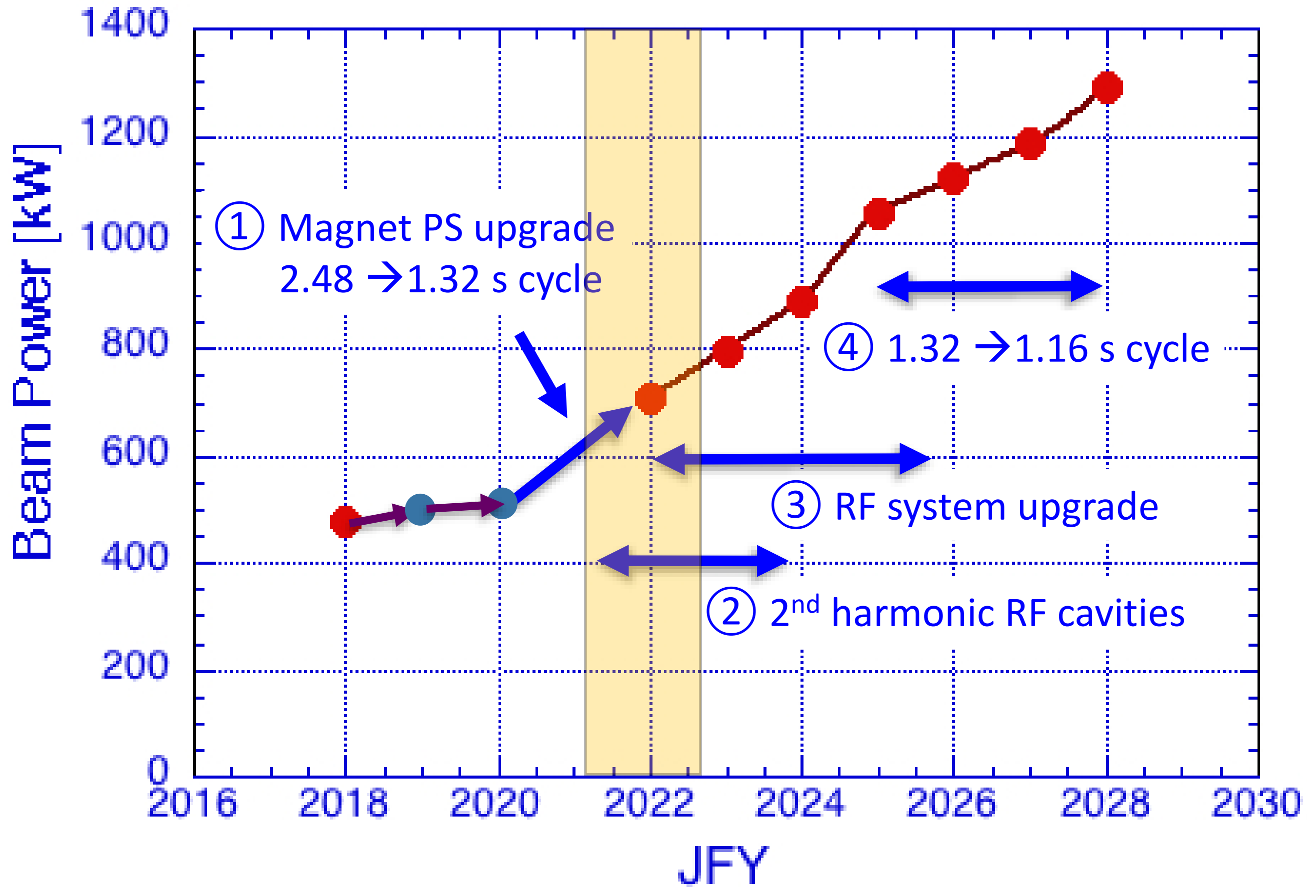
- ***Re-tune ALL existing ITEMs ① ~ ⑦*** **with NEW HARDWARES**
  NOTE: Diff. points (ramping pattern, impedance, leakage field, …) T. Asami [THPAB245]
- **Achieve better beam loss localization** at collimator area
  twice efficiency to keep hands-on maintainability with
  MR-new-collimator-system and Halo Monitors (BT & MR-OTR)
- **Find error sources in optics and make countermeasures**
- **Explore new beam dynamics to increase 30% more protons per bunch**

Mid-term Plan of MR

FX: The higher repetition rate scheme : Period 2.48 s → 1.32 s for 750 kW.
(= shorter repetition period) → 1.16 s for 1.3 MW
SX: Mitigation of the residual activity for the beam power upgrade

JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		Long Shutdown ↔							
FX power [kW] SX power [kW]	515 55	- 60−70	>700 >80	800 >80	900 >80	>1000 >80	>1100 ~100	>1200 ~100	1300 ~100
Cycle time for Fast Extraction New Magnet PS	2.48s Mass Production Installation/Test →		1.32s	1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
RF system upgrade 2nd RF system upgrade									
Collimator system		Add.colli. (3.5kW)							
Injection system FX system	Kicker PS improvement Septa manufacture Test →								
Beam Monitors (BPM circuits)									
SX: Diffuser/Bent crystal/VHF Local shield									

MR FX Beam Power Projection



JUL. 2021 – MAR. 2022
New Magnet Power Supply, New 2nd harmonic RF systems, New FX devices, Collimator upgrades, …

APR. – MAY 2022
High power test for new devices w/o beam

JUN 2022
FX beam tuning for 1.32 s cycle

FALL 2022
Start user operation in 1.32 s cycle

Summary

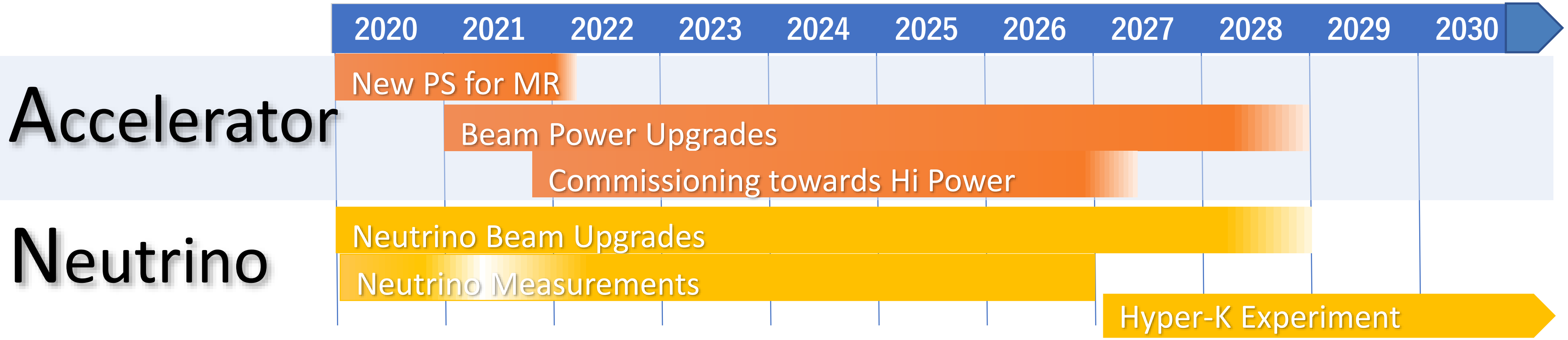
Accelerator upgrade steps

[by JFY2022] To the original target of 750 kW with the 1.32 s cycle.

- Magnet power supply, RF, Injection and extraction devices, Collimators, Monitors, Control

[by JFY2028] To the beam power of 1.3 MW.

- RF, BPM upgrade
- Further beam study for beam loss reduction, localization, instability damping.



Upgrade for 1.3 MW, necessary for HK, was launched as in schedule

- The faster cycling : 2.48 s (present for T2K) → 1.16 s
- The accelerated protons : 2.7E14 ppp (present for T2K) → 3.3E14 ppp.

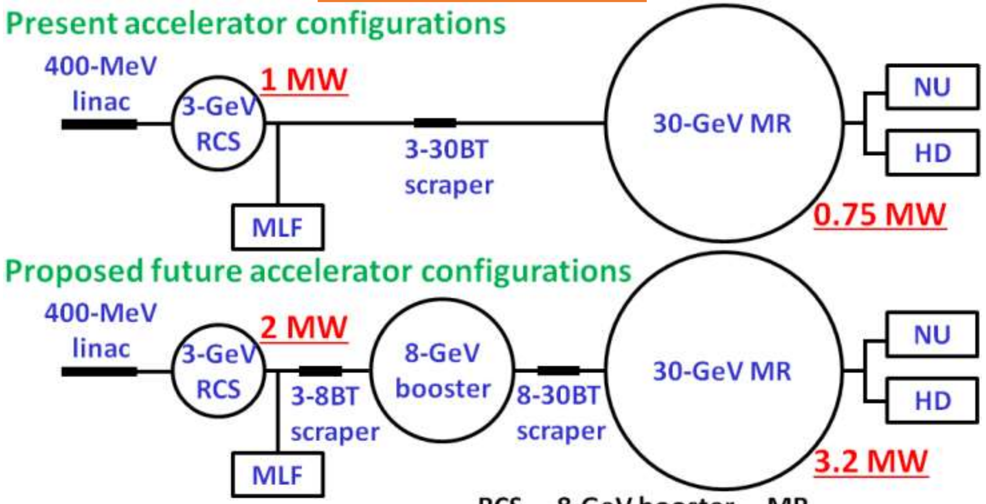
Supplementary slides

- Long-term plan for Multi-MW
- Presentations of J-PARC in IPAC2021

Long term plan for Multi-MW

- 3.2 MW with a new 8-GeV Booster in J-PARC
- 9 MW with a 9-GeV proton driver in the KEKB Tunnel after the B-factory project.

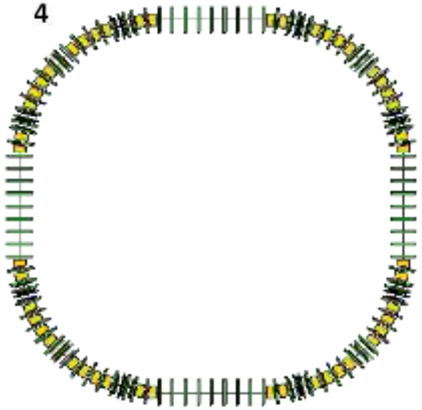
J-PARC Tokai site



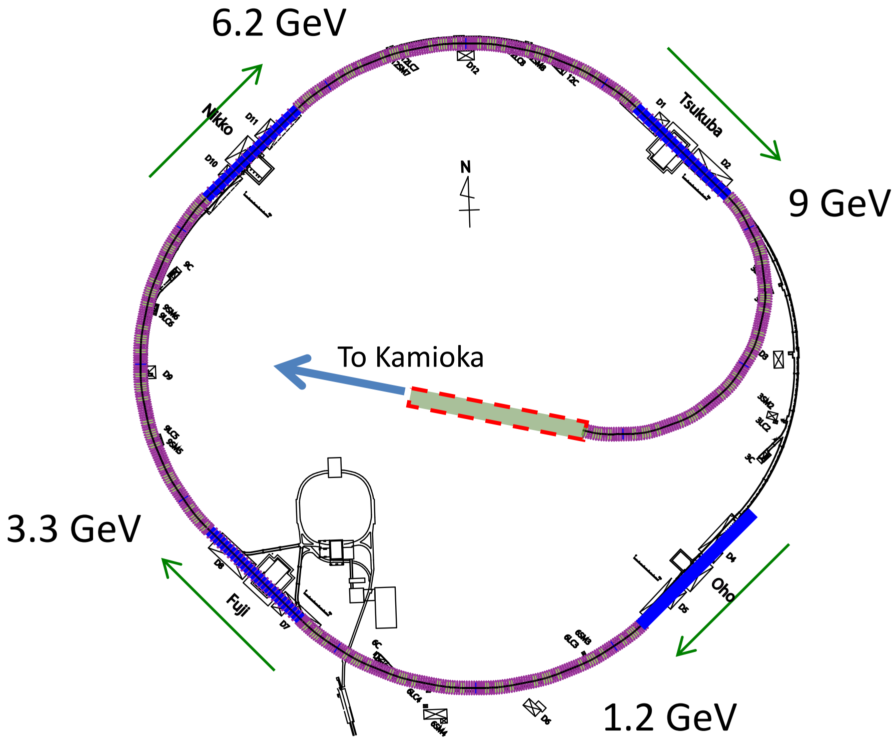
	RCS	8-GeV booster	MR
Physical aperture (mm mrad):	486π	189π	81π
Collimator aperture (mm mrad):	324π	126π	54-60π
Collimator capability (kW):	4	4	4

	3-8BT	8-30BT
Scraper aperture (mm mrad):	126π	54-60π
Scraper capability (kW):	2	2

Conceptional Design of 8 GeV Ring
Circumference 696.666 m
Super-periodicity 4
Transition gamma ~15 GeV



KEK Tsukuba site



For the acceleration in the 2nd to 4th straight section, the ILC cavity is adopted.
- Peak current : 100 mA (pulse)
- Beam duty : 1 %
- Beam power : 9 GeV x 0.1 A x 1 % = **9 MW**

R&Ds : High duty horn, higher gradient SC cavity, high power target...

Relating presentations in IPAC2021

Main Ring
[MOPAB229] Takaaki Yasui, Compensations of Third-Order Resonances in J-PARC MR
[TUPAB315] Ishii Koji, Development of Disaster Prevention System for Accelerator Tunnel
[WEXB02] Yoichi Sato, Upgrading J-PARC Accelerator for Hyper Kamiokande Project
[WEPAB178] Fumihiko Tamura, Non-adiabatic longitudinal bunch manipulation at flattop of the J-PARC MR
[WEPAB192] Ryotaro Muto, Simulation Study on Double Diffuser for Loss Reduction in Slow Extraction at J-PARC Main Ring
[WEPAB201] Kyohei Noguchi, 8 Gev Proton Beam Commissioning and Extinction Measurement for the COMET Experiment at J-PARC Main Ring
[WEPAB204] Soma Iwata, Layout of the new septum magnets for fast extraction in J-PARC Main Ring
[THPAB245] Takashi Asami, A simulation study of beam pipe eddy current effects on beam optics

RCS
[MOPAB174] Pranab Saha, Foil hits reduction by minimizing injection beam size at the foil in J-PARC RCS
[TUPAB201] Masanobu Yamamoto, Vacuum Tube Operation Tuning for a High Intensity Beam Acceleration in J-PARC RCS
[TUPAB207] Lucas Schaper, J-PARC RCS: Recent Efforts Towards a Higher Beam Power Beyond 1 MW
[WEPAB177] Hidefumi Okita, Consideration of triple-harmonic operation for the J-PARC RCS
[WEPAB179] Kazami Yamamoto, Recent status of J-PARC Rapid Cycling Synchrotron
[WEPAB245] Yoshihoro Shobuda, A Possible Modification of Ceramic Chambers in the Injection Area at the RCS in J-PARC
[WEPAB337] Junichiro Kamiya, Some methods of making titanium vacuum chamber act as getter pump for UHV/XHV

LINAC
[WEPAB297] Ersin Cicek, A Recent Upgrade on Phase Drift Compensation System for a Stable Beam Injection at J-PARC Linac