Beam Commissioning of J-PARC MR after its high-repetition rate upgrade

Yoichi Sato (KEK/J-PARC)
on behalf of J-PARC MR Accelerator Group

HB2023, 09-October-2023, 11:05 – 11:30

Outline

- **Introduction & MR Upgrade Plan**

- **Keys of Beam Tunings in FX operation**
- **Achievement of FX 750 kW (original design power)**
- **Future Plans**

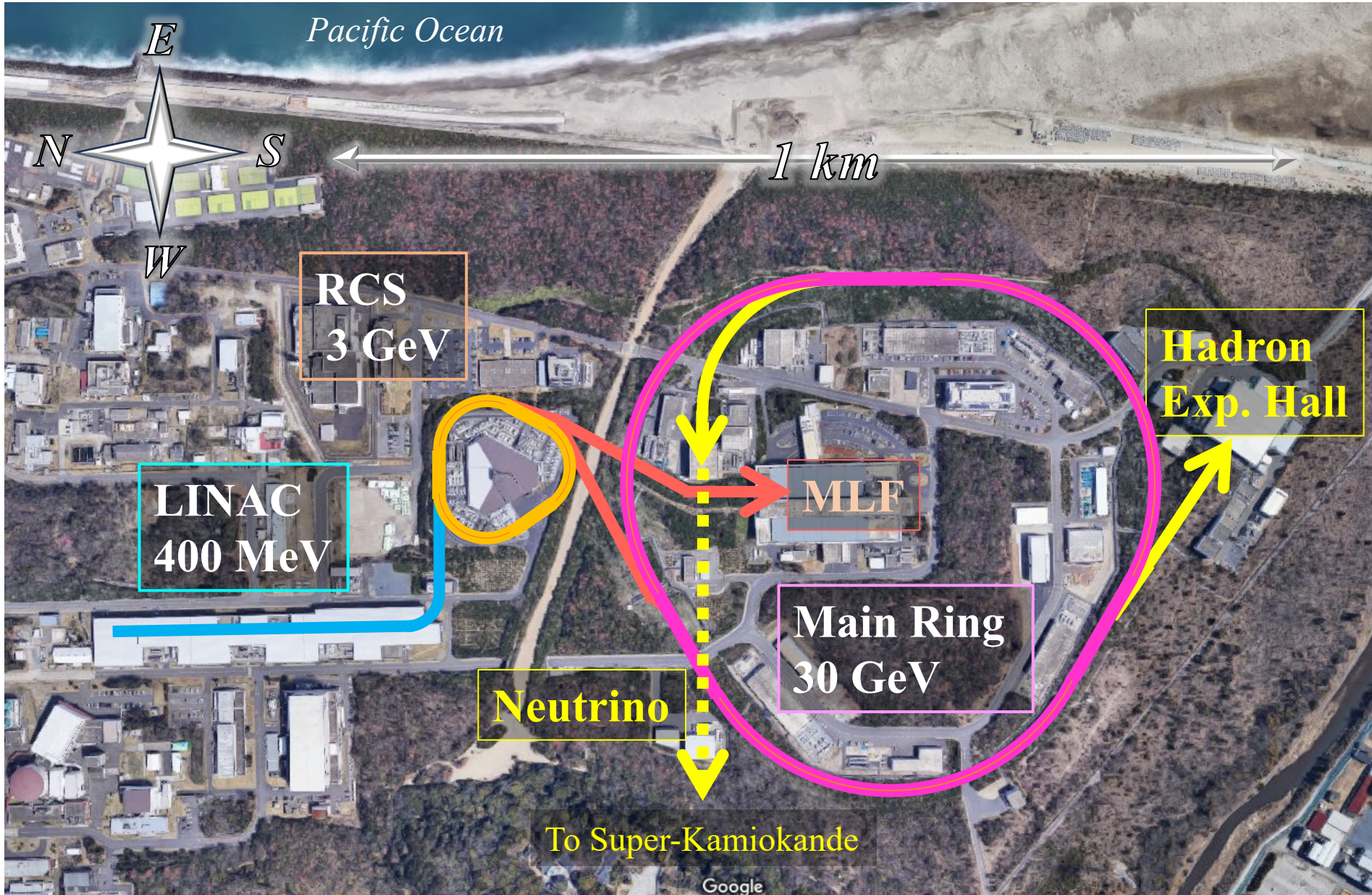
- **SX operation**

- **Summary**

Japan Proton Accelerator Research Complex

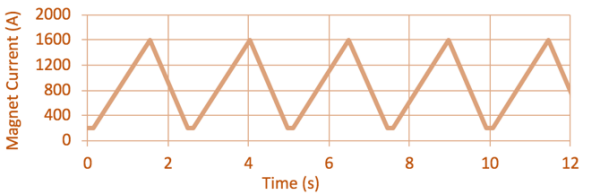
Operated by
Japan Atomic Energy Agency
(JAEA)
and
High Energy Accelerator
Research Organization
(KEK)

- Tokai, Ibaraki, Japan
- High Intensity Proton Accelerators
- Facilities to use the secondary beams

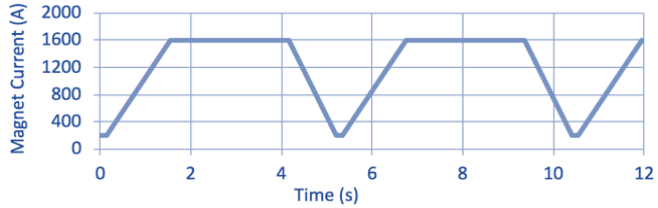


Main Parameters of MR

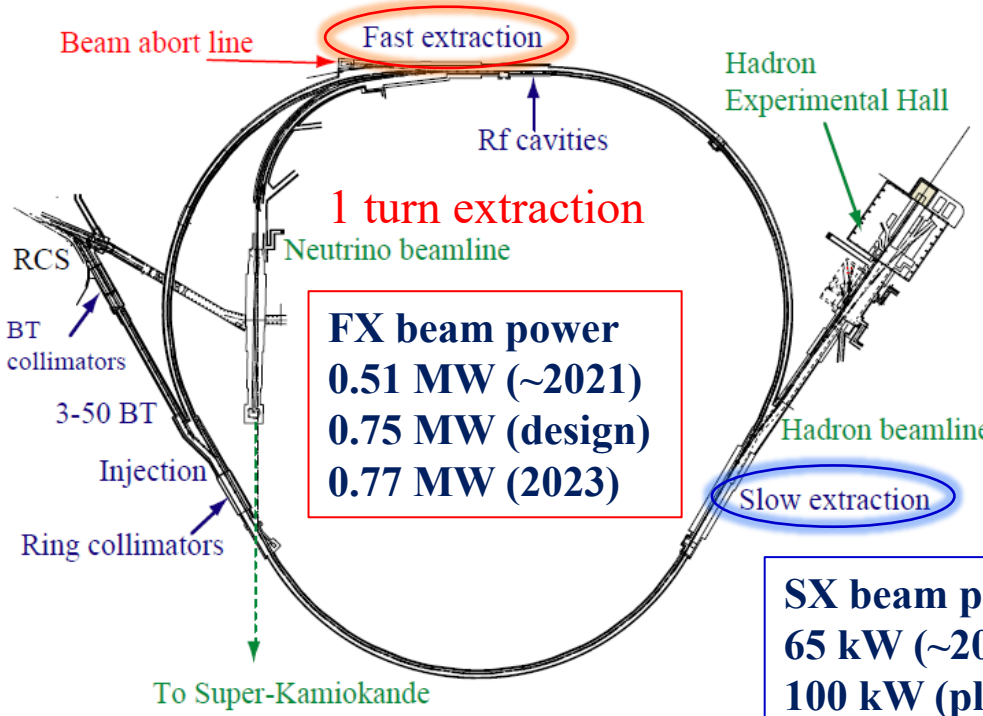
Circumference	1567.5 m
Injection energy	3 GeV
Extraction energy	30 GeV
Super-periodicity	3
harmonic	9
Number of bunches	8
Physical Aperture	81π mm-mrad
Ring Collimator	54-70 π mmmrad
Transverse emittance	
At injection	54π mm-mrad
At extraction	10π mm-mrad (30 GeV)



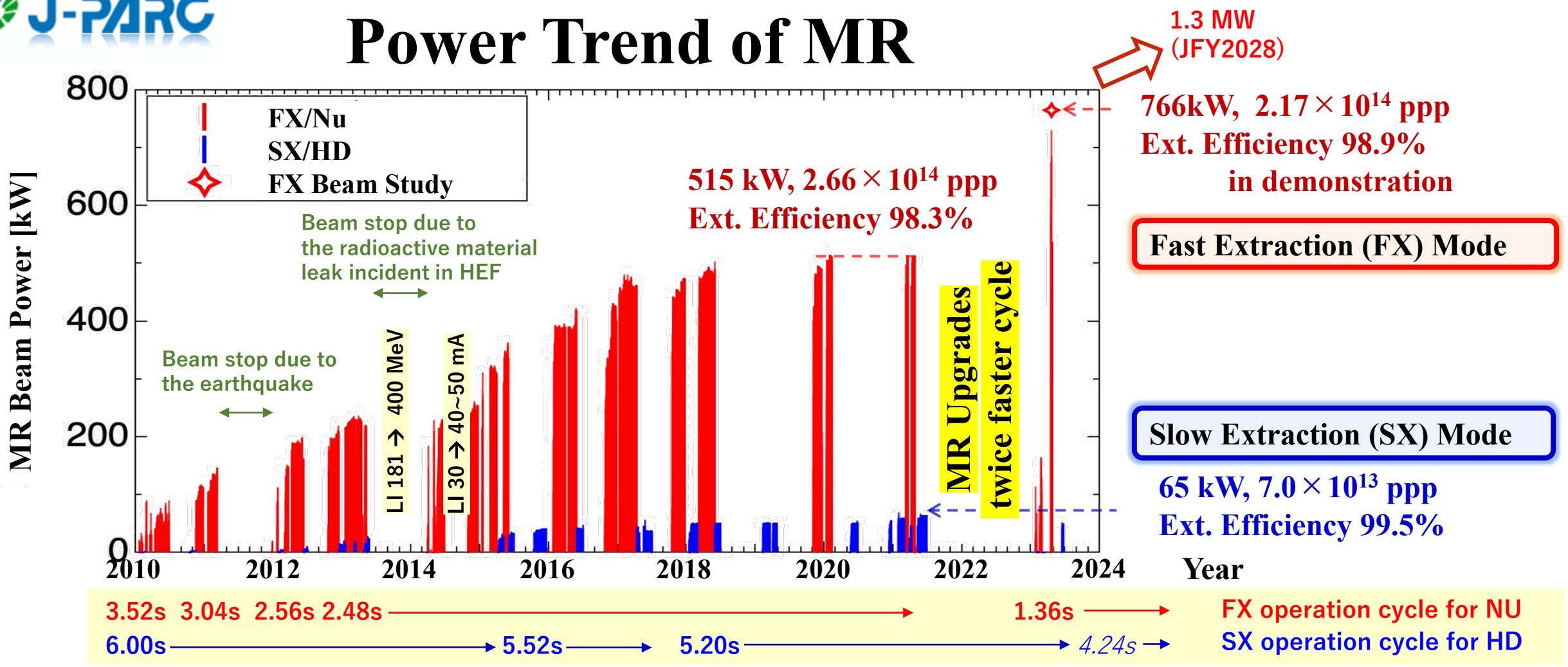
Fast Extraction (FX) mode
in 2.48 s cycle (~2021)
in 1.36 s cycle (2023)



Slow Etraction (SX) mode
in 5.20 s cycle (~2023)
in 4.24 s cycle (2024)



Power Trend of MR

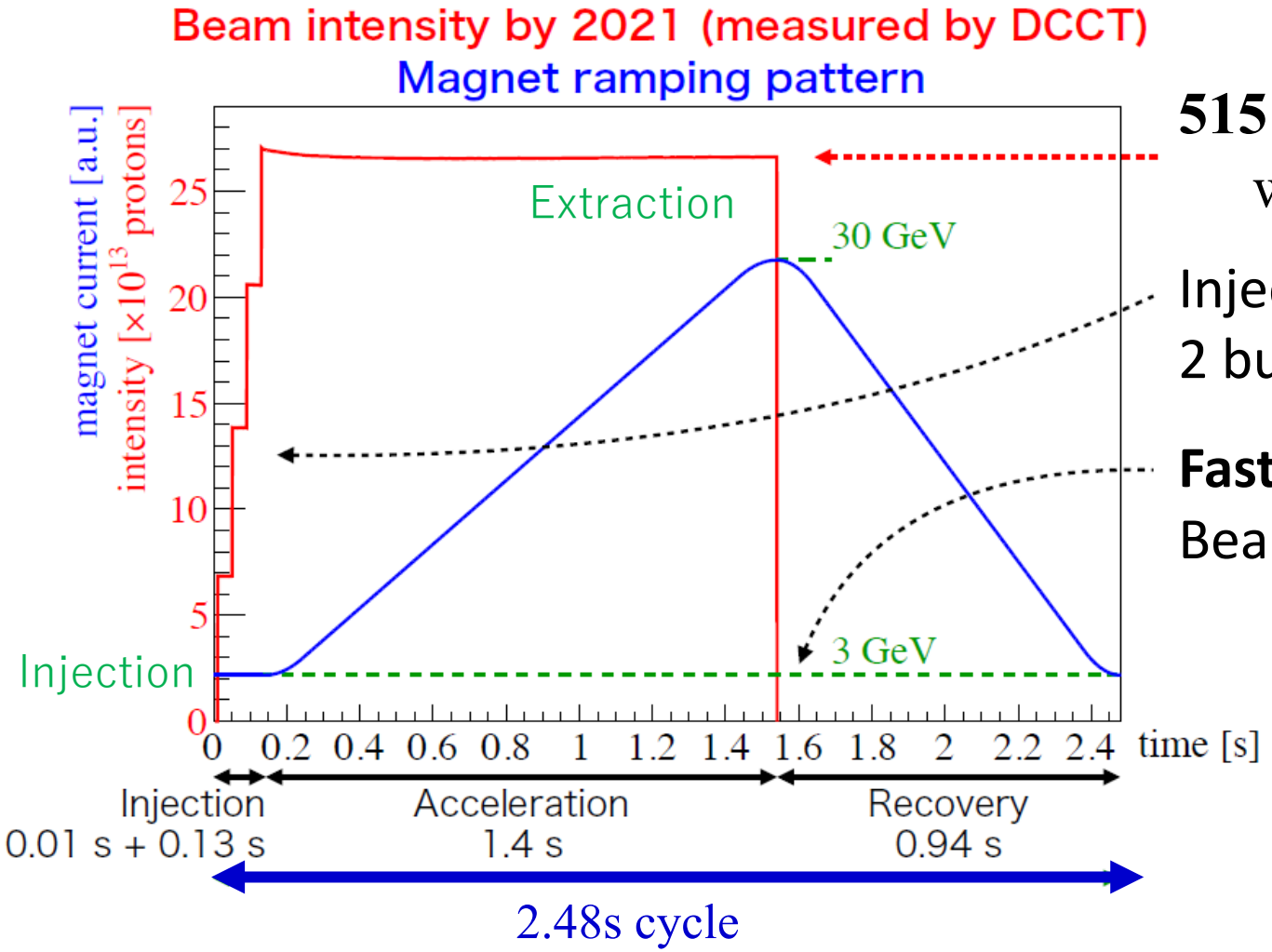


Since 2010, the beam power of MR has been increased by
Faster cycle, Space charge mitigation, Optics improvements,
and Hardware enhancement associated with them.

Typical Operation of MR FX （by 2021）

Beam Power = Energy (30GeV) × 1/T_{rep} (pulse/s) × # of protons (/pulse)

JFY2021	**515 kW**	2.48 s	2.66×10^{14} ppp



515 kW (2.66×10^{14} ppp in 2.48s cycle)
with beam loss ~ 800 W

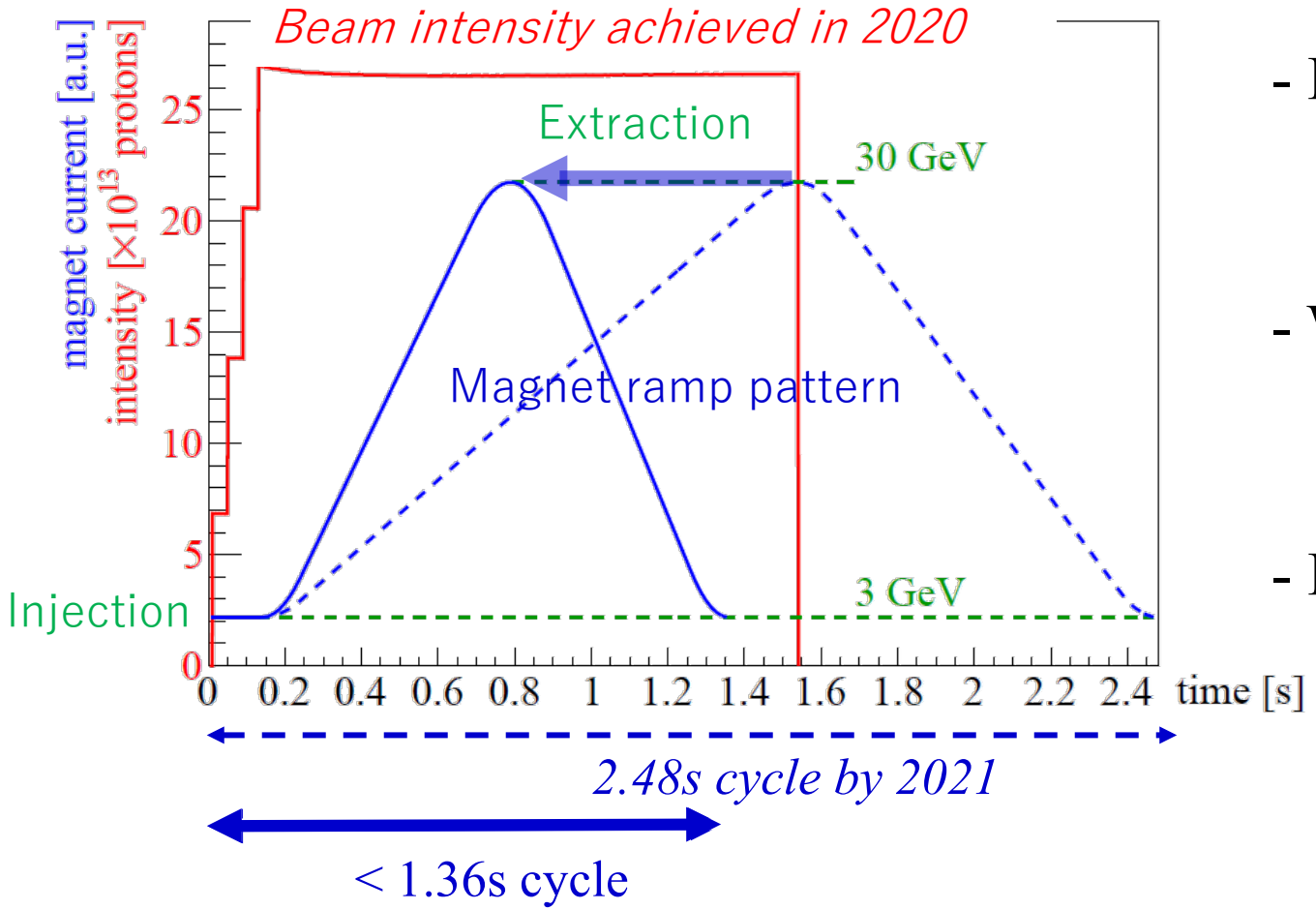
Injection:
2 bunches × 4 times

Fast extraction (FX)
Beams are extracted in one turn

Upgrade plan of MR FX （2023~）

Beam Power = Energy (30GeV) × 1/T_{rep} (pulse/s) × # of protons (/pulse)

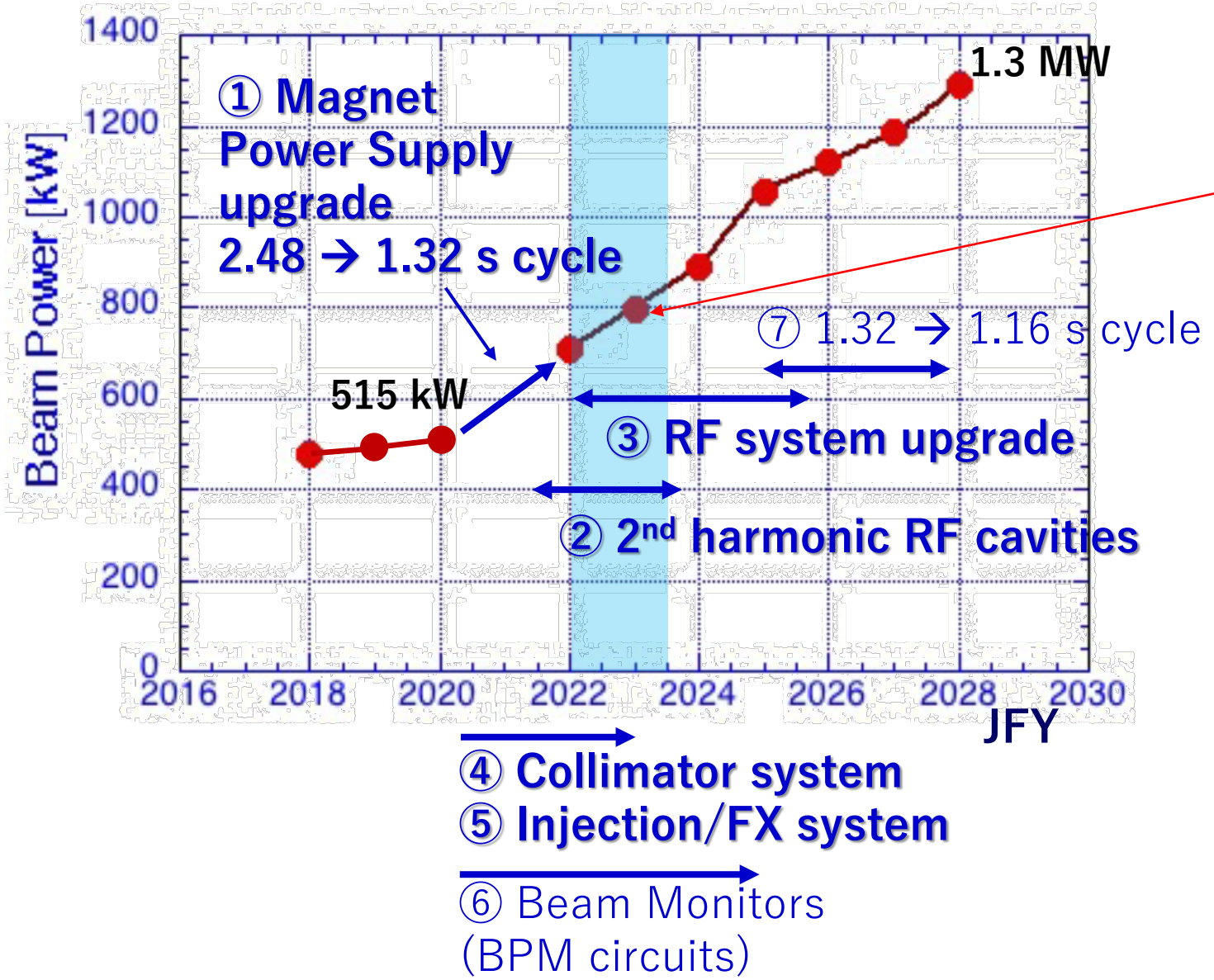
JFY2021	**515 kW**	2.48 s	2.66×10^{14} ppp
*JFY 202**	***> 940 kW***	*<1.36 s*	2.66×10^{14} ppp



- In 2021 -2022, MR major components (RF /Magnet / Injection&FX / …) were upgraded for Twice Faster cycle.
- We are in the way to reproduce *the 2021-Beam-Optics* first, and to make further upgrades.
- In 2023 beam study, we achieved
  FX 766 kW eq.
  2.17×10^{14} protons per pulse
  in 1.36 s cycle

Power Projection in MR Upgrade Plan

S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33



In Spring 2023, beam studies were performed:

- Optics correction
- Tune Tracking
- Collimator balancing

Successful demonstration
MR-FX 30 GeV
766 kW eq. in 1.36 s cycle

Ready for
750 kW in user operation

Keys of Beam Tunings in FX operation
3-fold Symmetry in Optics

- Quadrupole magnets
- Bending magnets
- Leakage field from FX Septum magnets

Magnet Power Supply (PS) Upgrades

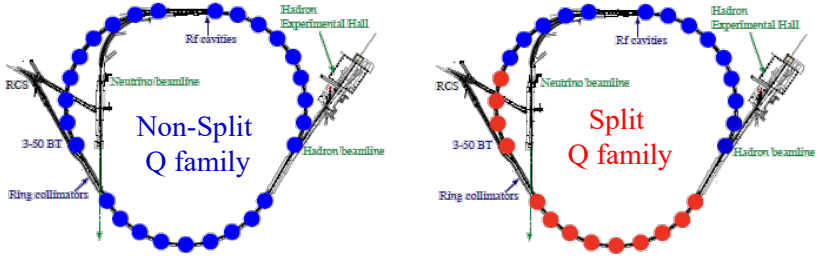
Twice faster cycle ➔ Twice Voltage at Mag PS.

Y. Morita *et. al.*, WEPM082, IPAC'23

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

New BM-PS

- **New Power Supplies**
  - **6 BM-PSs**, 4 QM-PSs, 2 SM-PSs
    - 1 Main-Bending-Magnet-family is operated by 6 BM-PSs (not in series)
- **Reuse Original Power Supplies**
  - Re-cabled Quadrupole Magnet Power Supplies
  - 7 Quadrupole-Magnet-families are operated by 12 QM-PSs :
    - 2 QM-PSs + **Paired-10-QM-PSs (5 "Pairs")**
    - "Pair" = 1 Magnet-family operated by 2 PSs
    - MR has 5-Split-Q-families after the upgrade.



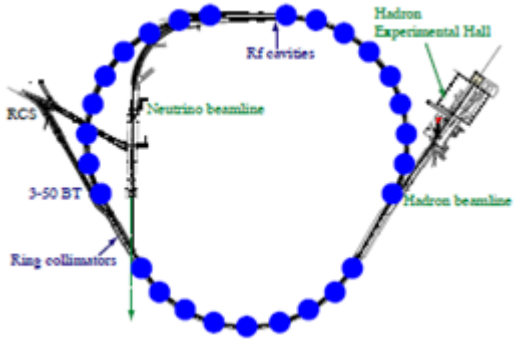
Adjust BM-PSs and Paired-QM-PSs to avoid Broken Symmetry enhancing resonance effects.

To Reproduce 3-fold-symmetry in Optics (I)

T. Yasui, *et. al.*, Nufact 2022
T. Yasui, TUXG1, IPAC'23

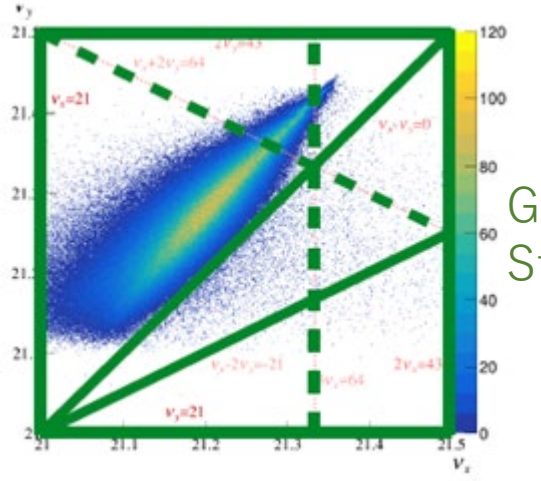
✓ Asymmetric cabling of Split-Quad-Magnet-family to Paired-QM-PSs

Before Upgrade



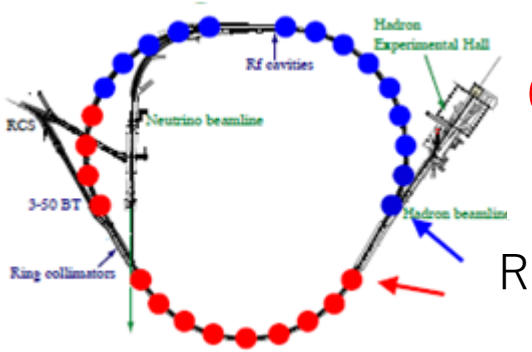
Example of Quadrupole family (QDX)

Every Quadrupole-Magnet-family operated by 1 QM-PSs



Green lines:
Strong resonances

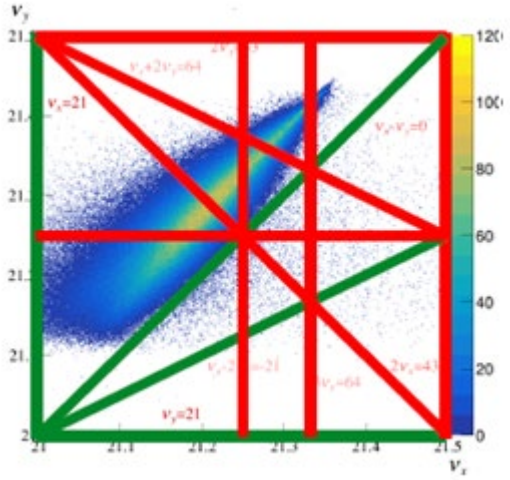
After Upgrade



QDX family was split!

Ramped by different PSs

Need to Adjust the different PSs (paired)



Red lines:
Reinforced or newly appeared resonances

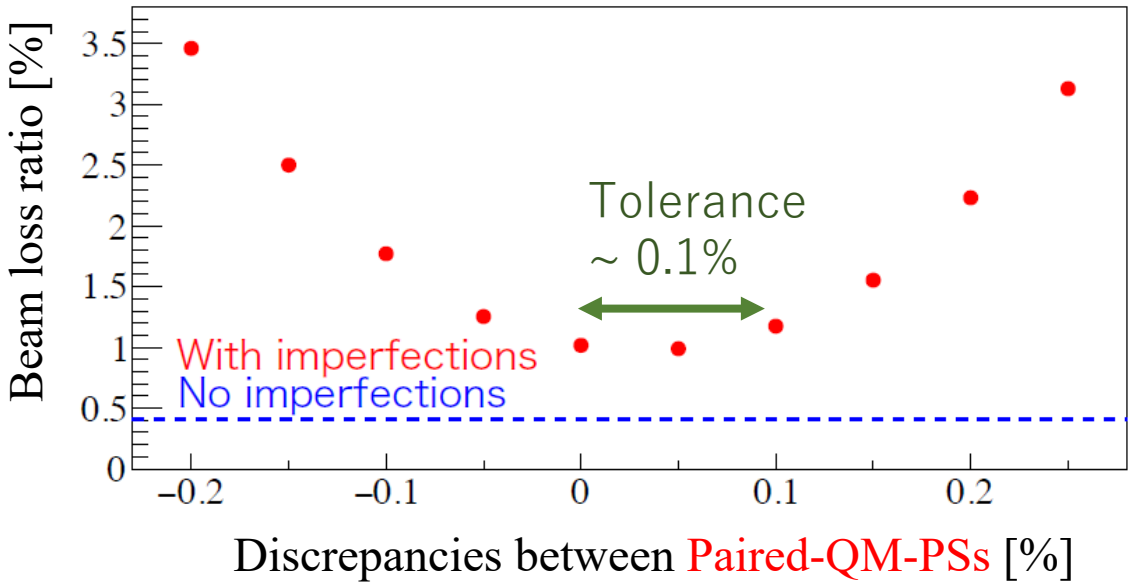
To Reproduce 3-fold-symmetry in Optics (I)

T. Yasui, *et. al.*, Nufact 2022
T. Yasui, TUXG1, IPAC'23

✓ Asymmetric cabling of Split-Quad-Magnet-family to Paired-QM-PSs

Tolerance in Discrepancies

Tracking simulations for beam loss during injection period
- Beam intensity： 3.3 x 10^{13} ppb



Ripple of QM-PSs ~ 0.01%

Discrepancies between
the pair of power supplies for each
Quadrupole family cause serious beam loss.
→ 0.1% Tolerance in discrepancies

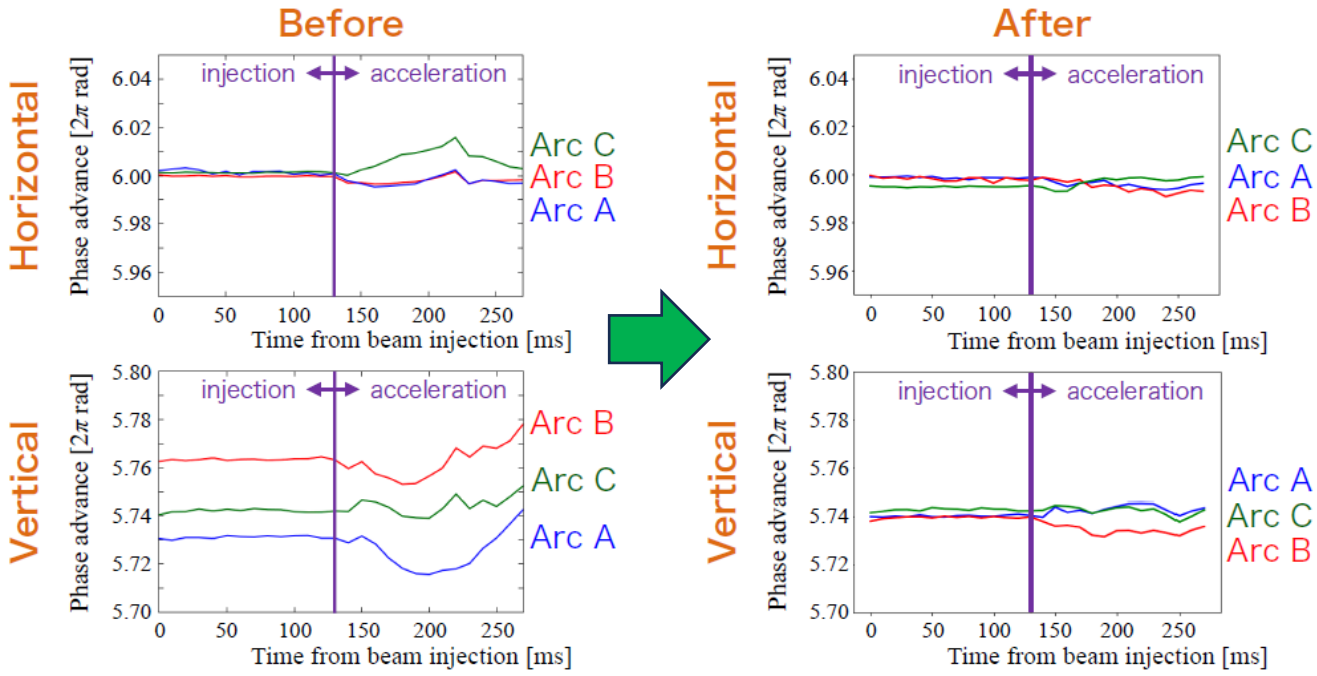
→Remaining sources of beam losses are
expected from
magnet imperfections and
space charge effects

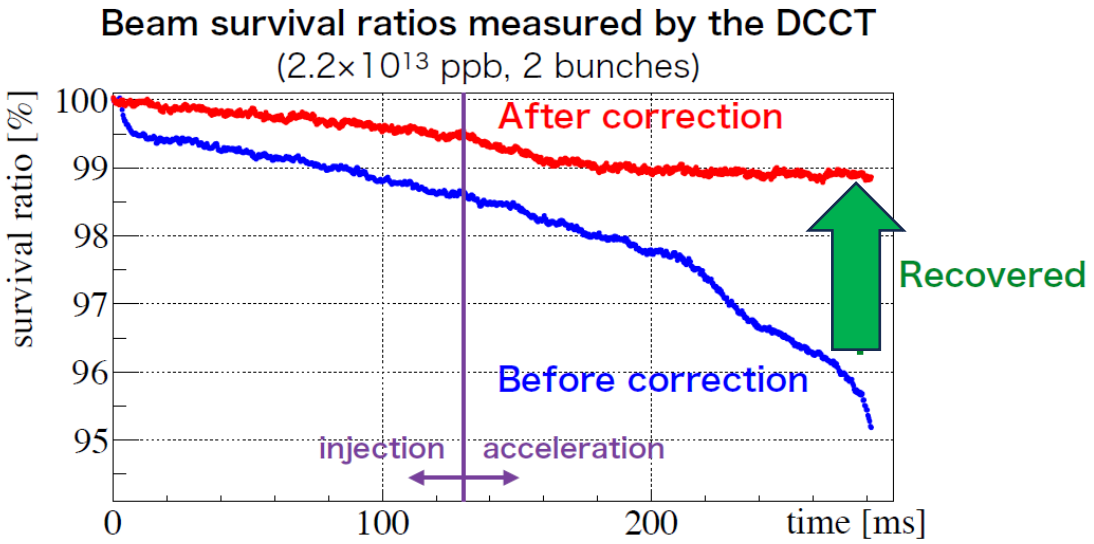
To Reproduce 3-fold-symmetry in Optics (I)

T. Asami, et. al., WEPL074, IPAC'23

✓ Asymmetric cabling of Split-Quad-Magnet-family to Paired-QM-PSs

→ Optics correction for the quadrupoles observing the 3-fold symmetry in phase advances



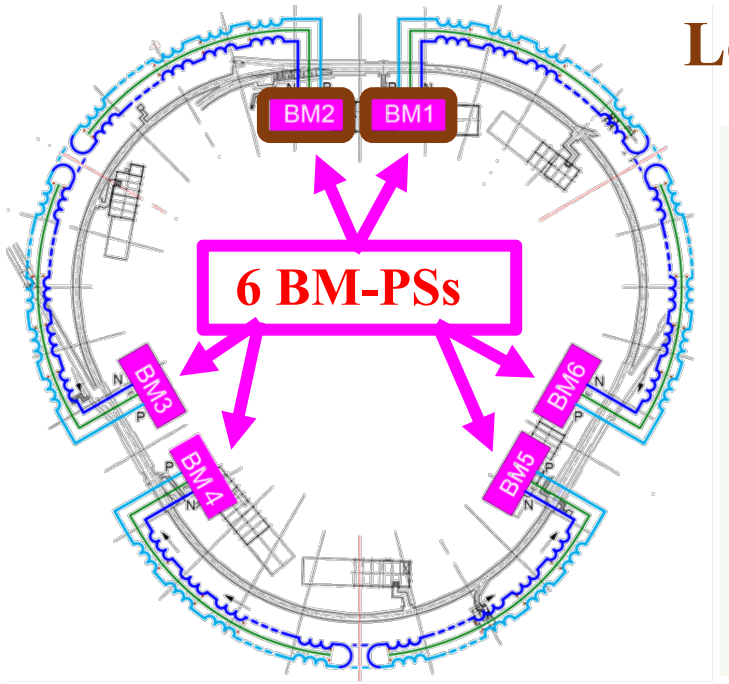


✓Separate cabling of

96 Main Bending Magnets in 6 BM-PSs

We are **on the way of commissioning of the BM-PSs**.

In Spring 2023, we performed beam tunings managing the effect of **Low freq. ripples of 2 BM-PSs**, which harmed Optics Symmetry.



Effects of BM-PSs and QM-PSs in half-Arcs

$(\Delta K_1 \cdot L)_{\mathrm{Half-Arc}}$ $[10^{-4}/\mathrm{m}]$

BM1	BM2	BM3	BM4	BM5	BM6
4.6	4.2	1.3	1.8	1.0	1.7

Quad imperfections	Quad ripples
2.2 (average)	0.6 (average)

How BM-PS Balance affects on Arc Phases

$$\Delta x = \eta_x \frac{\Delta B}{B}, \qquad |\Delta K_1| = |K_2 \Delta x|$$

dispersion — sext. field

In this Fall, we will perform beam tunings with **best parameters of ALL 6 BM-PSs.**

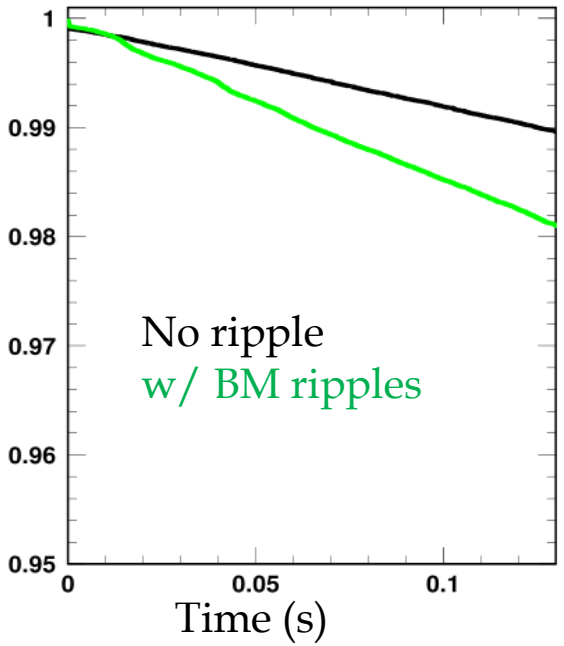
✓Separate cabling of
96 Main Bending Magnets in 6 BM-PSs

Effect of the **Low freq. ripples of 2 BM-PSs**

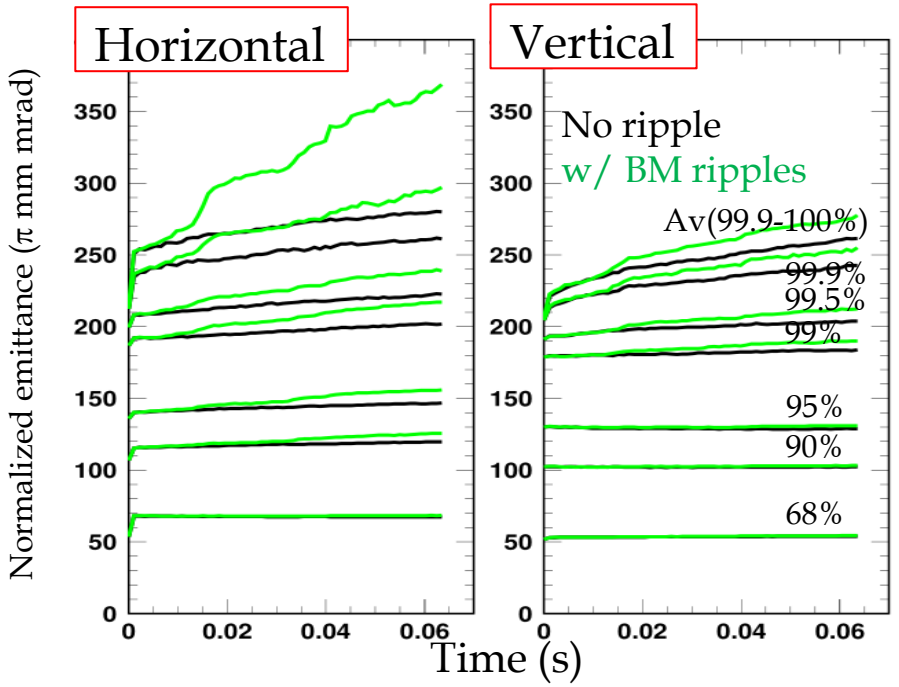
Tracking simulation suggests that these ripples enlarge the horizontal beam halos.

Tracking simulations (Beam intensity： 4.1 x 10^{13} ppb)

Survival



Emittance Growth



H. Hotchi

In Spring 2023,
we handled the effect
by tune tracking.

In this Fall, we will perform
beam tunings with
the best parameters for
ALL 6 BM-PSs.

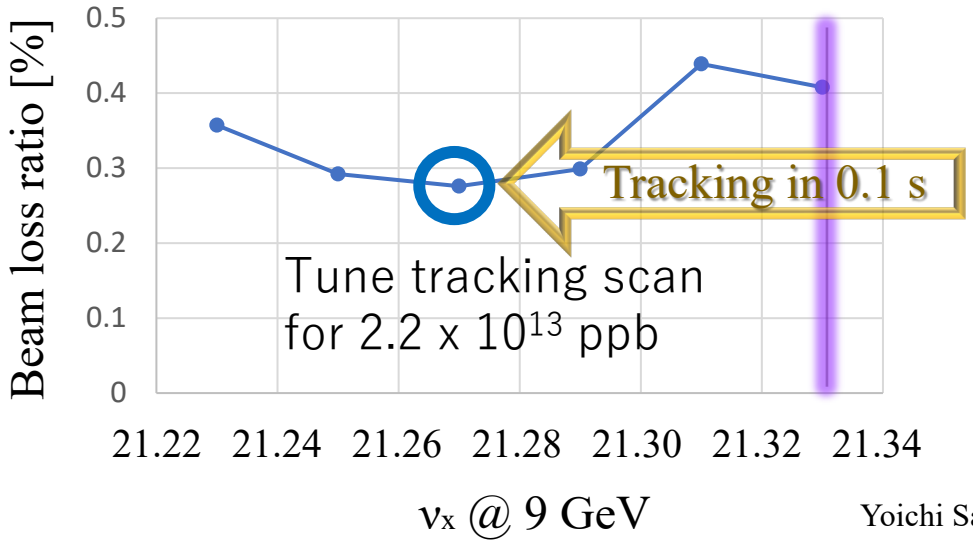
✓Separate cabling of
96 Main Bending Magnets in 6 BM-PSs

Measures to Effect of the **Low freq. ripples of 2 BM-PSs**

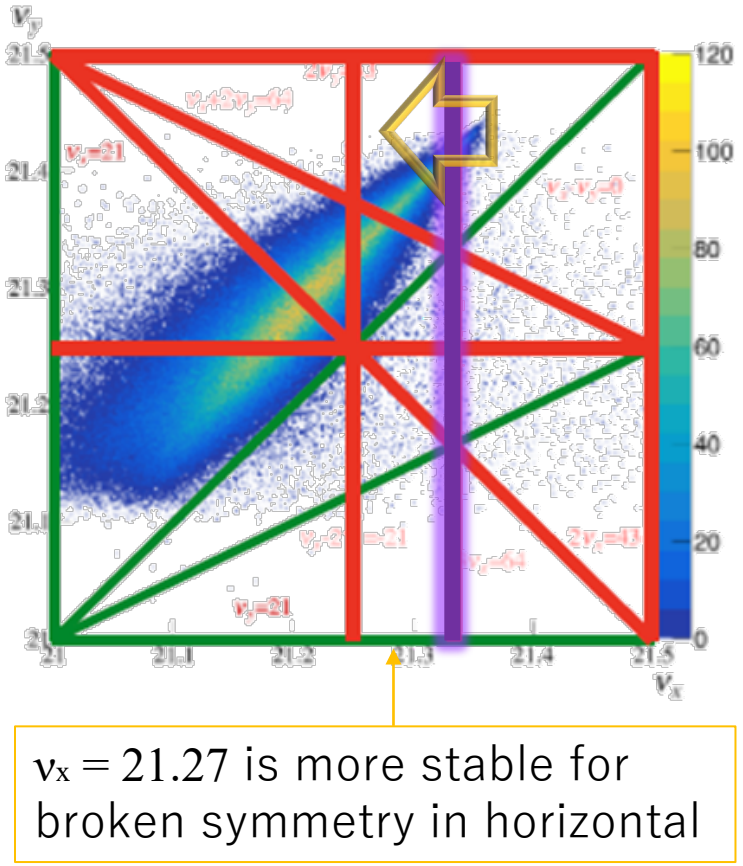
FX best operation point is (ν_x, ν_y) = (21.35, 21.41) at 3 GeV.
The **ν_x = 21.33** is corrected with trim-sextupoles below 6 GeV,
but the resonance effect was severe in Spring 2023.

→ We adopt tune tracking

ν_x = 21.35@ < 4 GeV => 21.27@9 GeV



Cross ν_x = 21.33 quickly
at the beginning of acceleration.



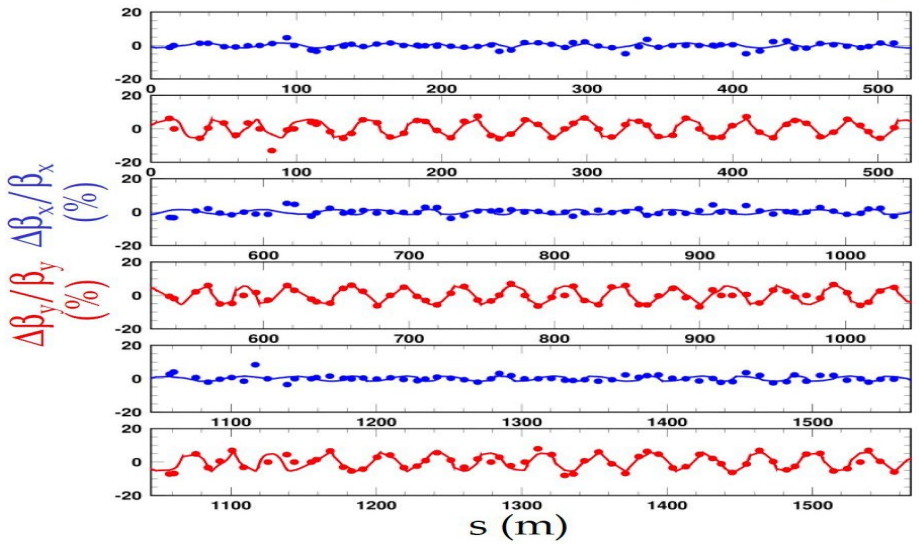
Yoichi Sato, J-PARC MR, MOA2I1, HB2023

✓Leakage field from FX Septum magnets

FX septum magnets were replaced to new magnets in the MR upgrade.

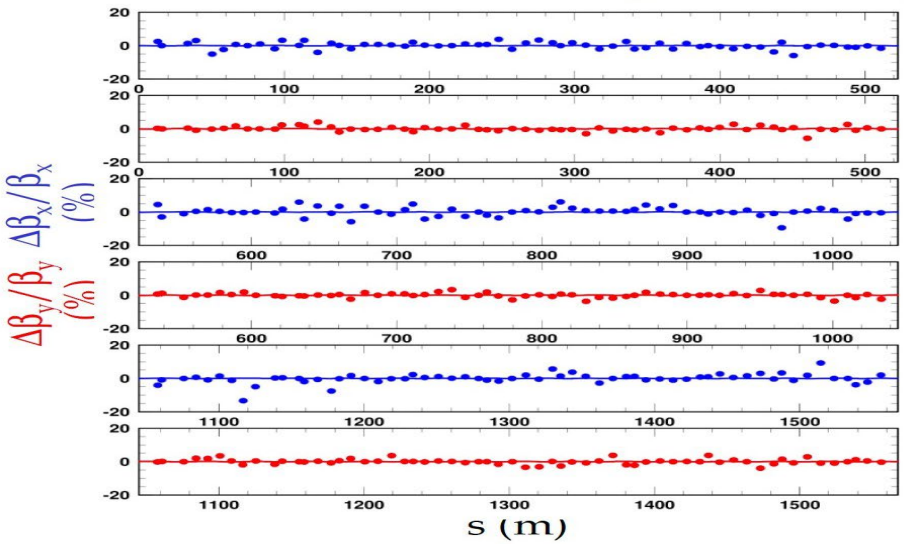
- New features: Less Impedance, Larger Aperture, and **Less Quadrupole Leakage Field.**
- Beta measurements revealed that
  - Previous FX septum magnets had serious leakage field and caused optics modulation.
  - New FX septum magnets have 10 times smaller leakage field.

With Previous FX septum magnets



$|\Sigma(\Delta K_1 L)| = 0.00230\ m^{-1}$

With New FX septum magnets



$|\Sigma(\Delta K_1 L)| < 0.00015\ m^{-1}$

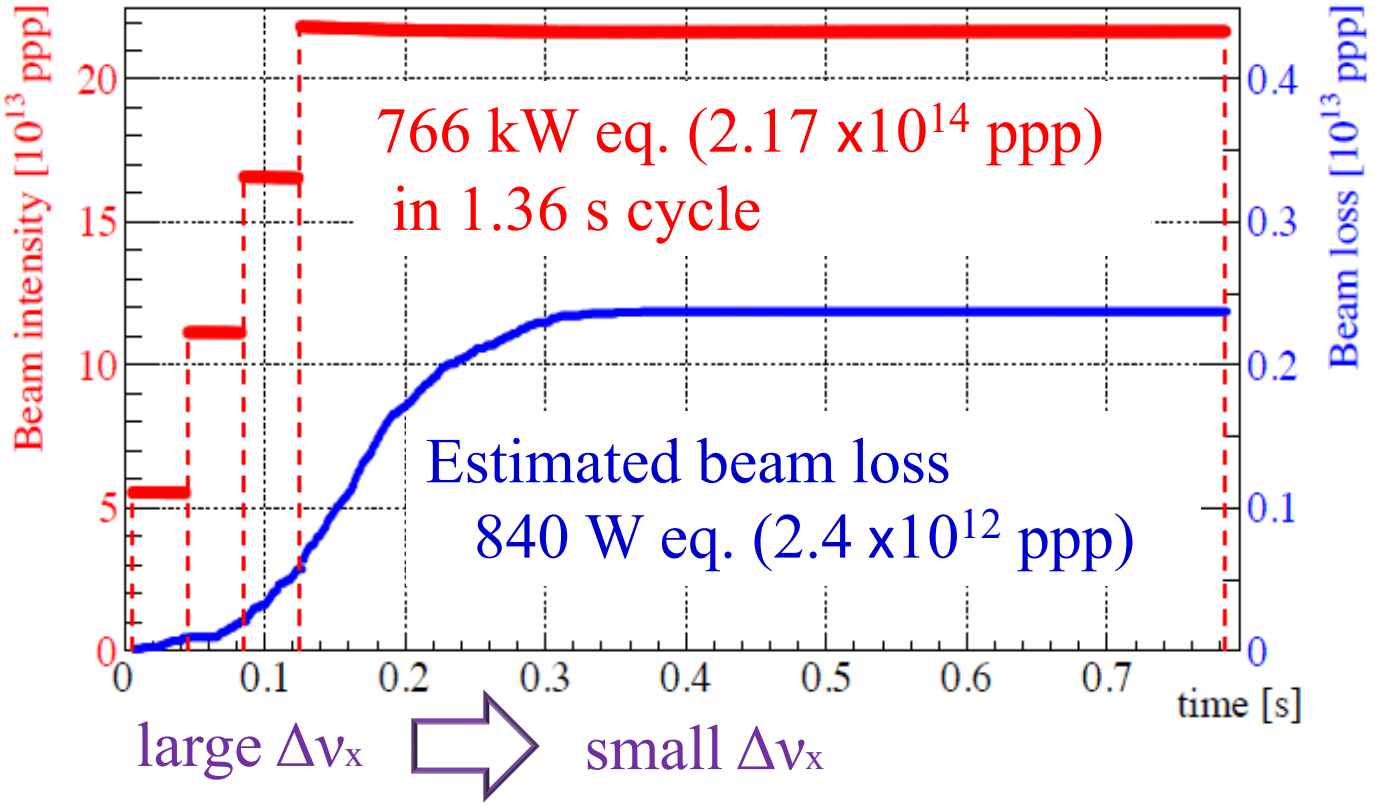
T. Shibata, *et. al.*, TUPM103, IPAC'23

Achievement of FX 750 kW (original design power)

Achievement of MR FX-ABD 750 kW eq.

In April 2023 we demonstrated FX 766 kW in 30GeV successfully

Beam intensity and beam loss estimated by the DCCT



To reduce the effect of the resonance lines, we performed

- ✓ Optics correction to make fine balancing the pair-QM-PSs
- ✓ Tune tracking at the beginning of acceleration to cross $\nu_x = 21.33$ quickly

In this Fall we expect to reduce the beam loss 20%, after completing BM-PS commissioning.
Beam loss distribution is to be optimized for user operation.

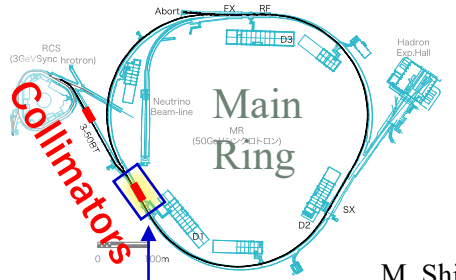
S. Igarashi, *et. al.*,
PTEP vol 2021, Issue.3,p33

Collimator System Upgrades

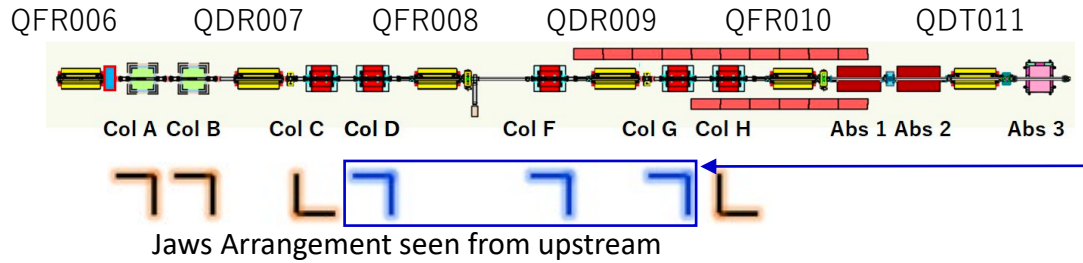
✓ More Collimator Capacity

2021: 2.0 kW → 2023~: 3.5 kW

M. Shirakata *et. al.*,
Proc HB2016, p543



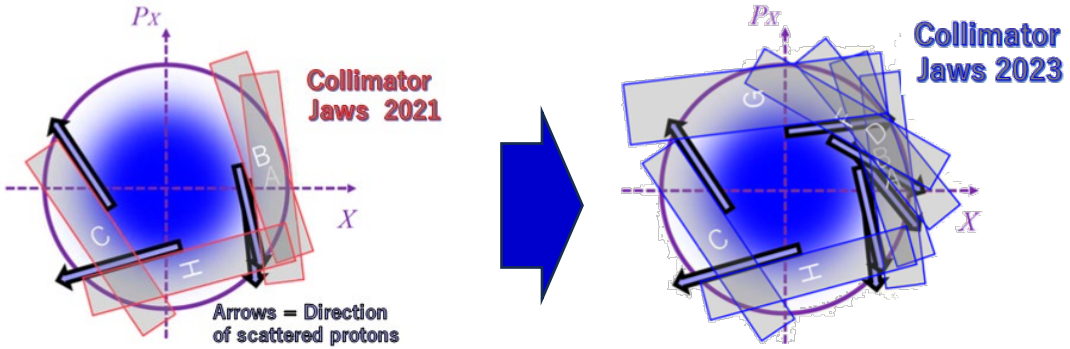
M. Shirakata
M. Uota
K. Kadowaki
T. Sasaki

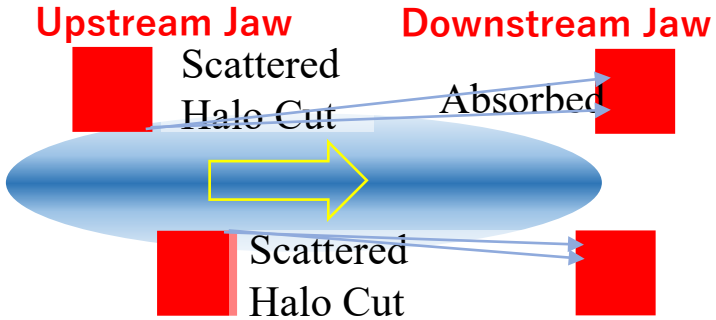


Jaws Arrangement seen from upstream

New Collimators
D: Fall 2022
F: Summer 2023
G: Fall 2022

✓ More Effective Halo Cut



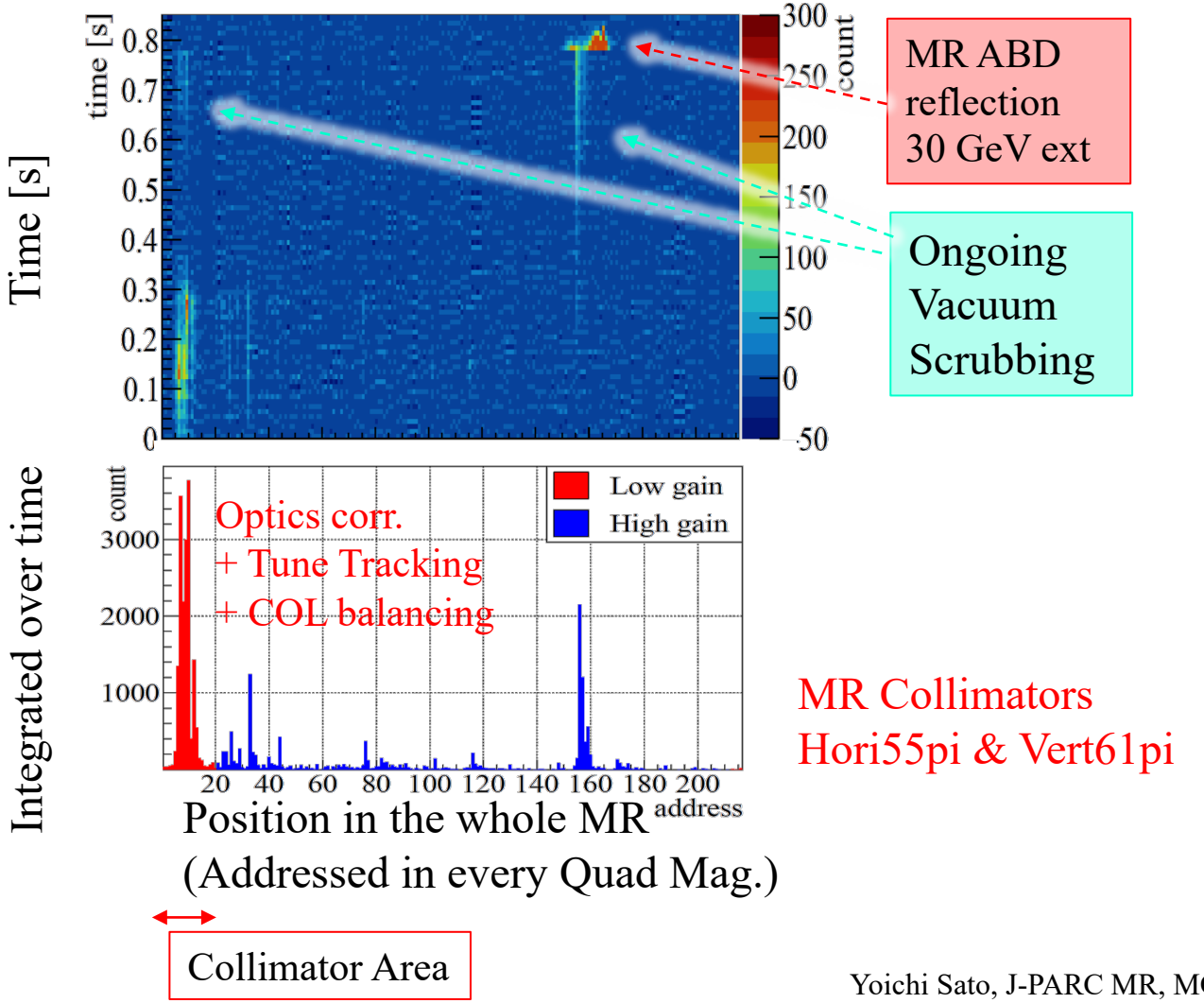


➔Better beam loss localization at collimator area

Yoichi Sato, J-PARC MR, MOA2I1, HB2023

Beam loss localization of FX 766 kW eq.

Beam losses counts for FX 766 kW eq.



Besides
Optics correction,
Tune tracking,
Collimator balancing was also performed.

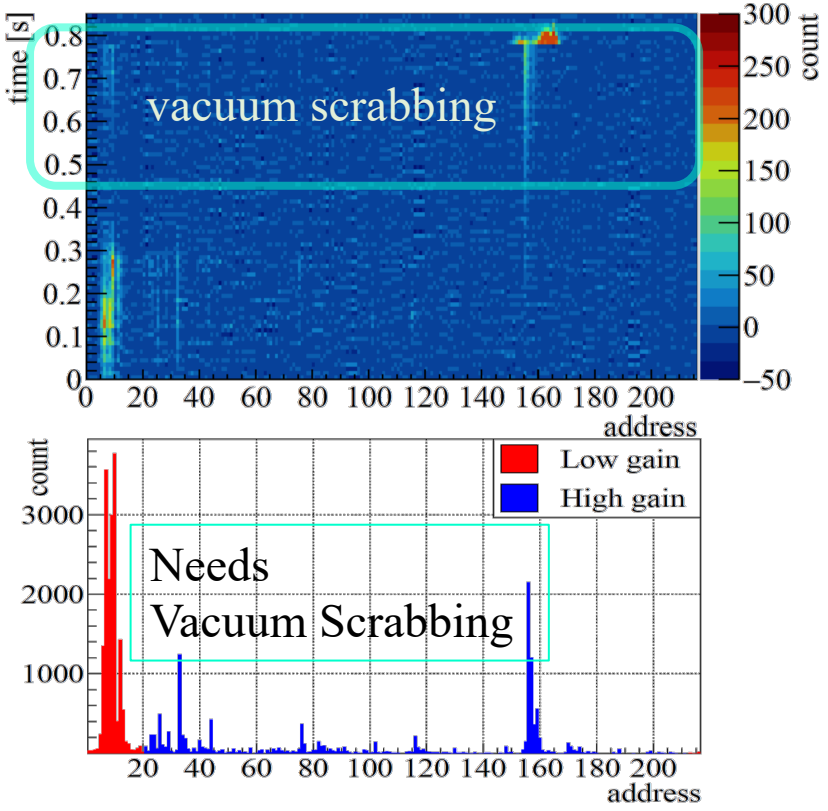
Beam losses are well localized
at collimator area
except for outgassing chambers.

We are on the way of vacuum scrubbing.

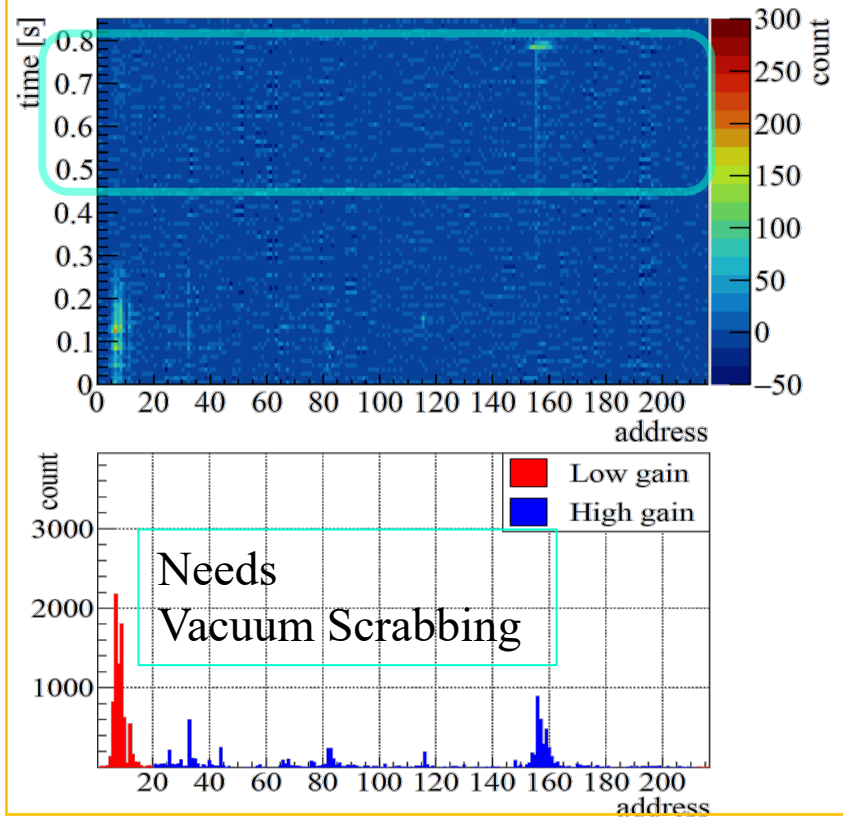
Y. Sato
T. Yasui

Beam loss localization after vacuum scrubbing

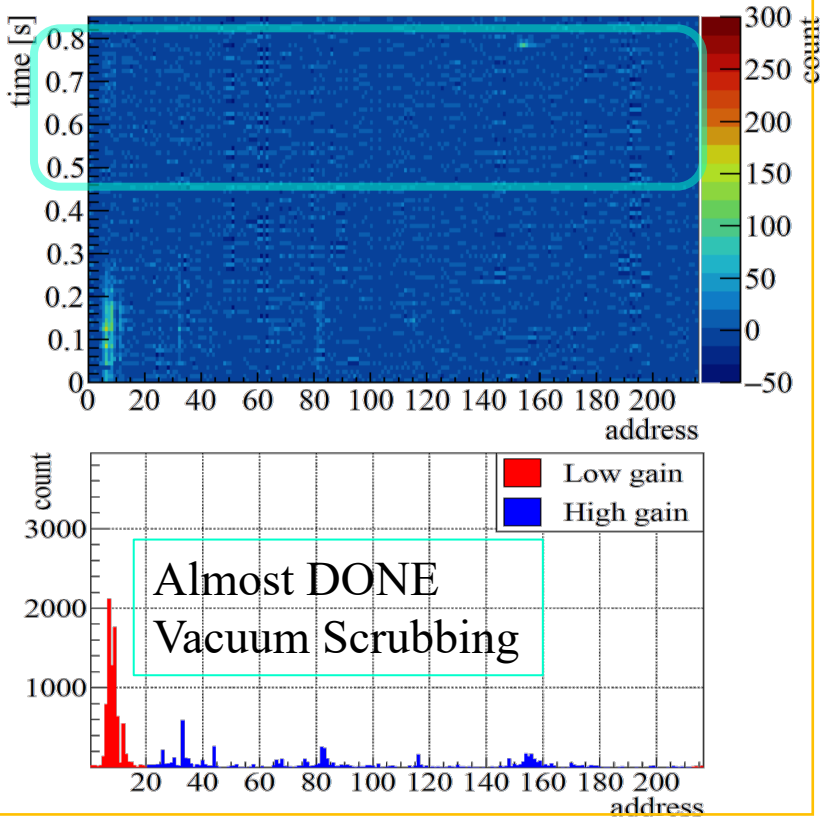
MR766 kW eq. with loss 840 W eq.



Nu 535 kW with loss 400 W
After 1-hour-vacuum-scrubbing



Nu 535 kW with loss 350 W
After 21-hour-vacuum-scrubbing



Beam loss localization was improved after vacuum scrubbing.
We are going to perform vacuum scrubbing for **750 kW in Nu Operation this Fall.**

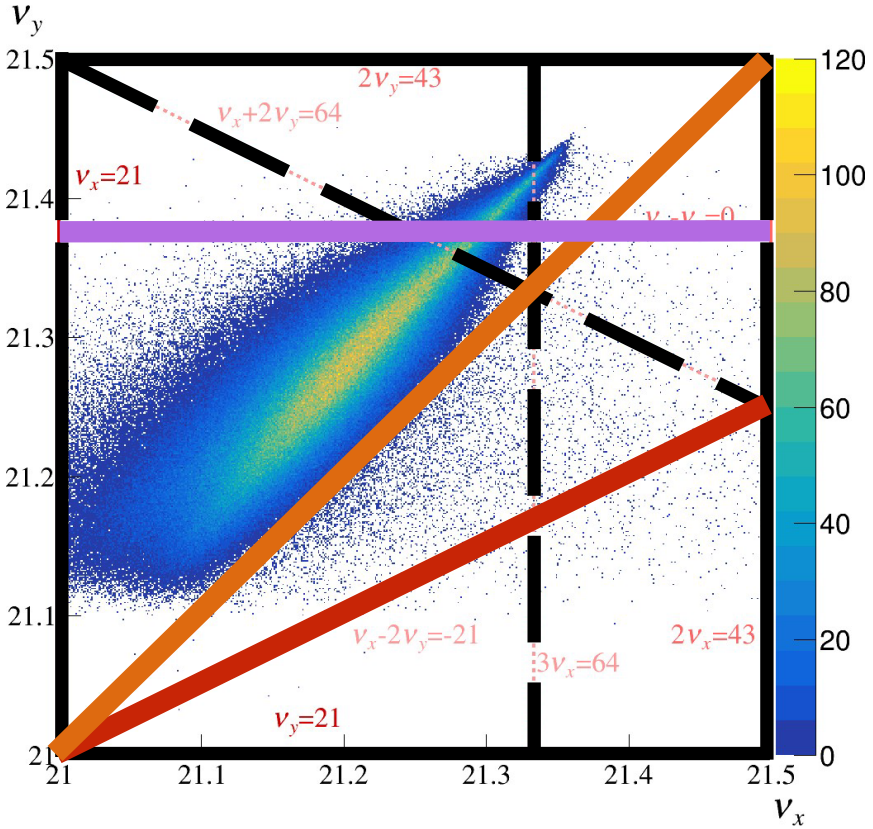
Future Plans

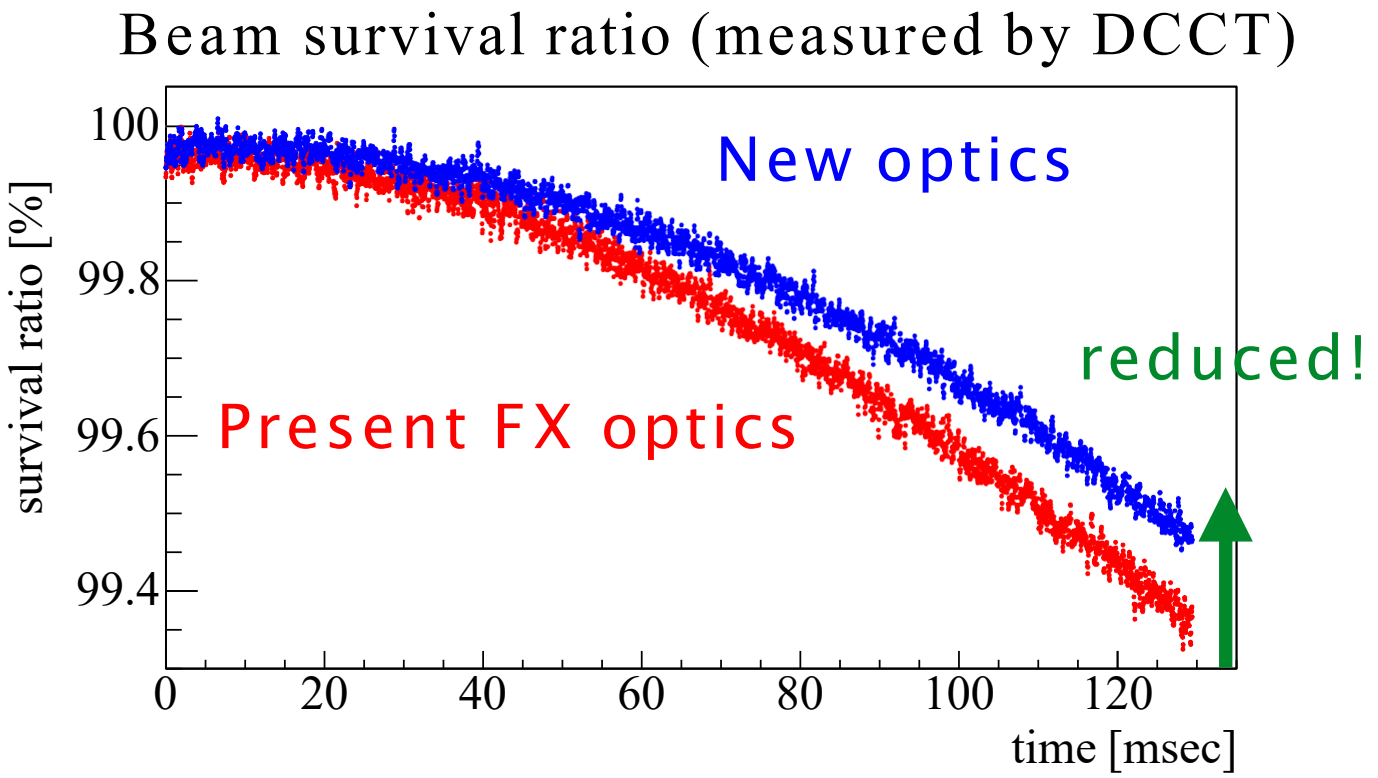
- New Beam Optics for FX operation
- Upgrade Plan of Correction Magnet System

New Beam Optics for FX operation

New beam optics controlling vertical phase advances in Arcs can compensate/weaken some resonances.

T. Yasui et al., PTEP 2022, 013G01 (2022)





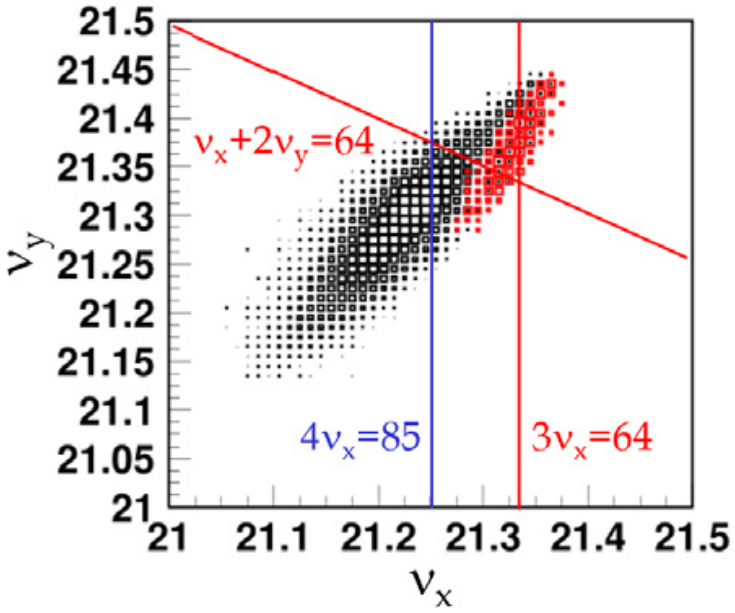
More Details are to be discussed in T. Yasui's talk (on Wednesday)
"Space charge induced resonances and suppression in J-PARC MR"
11 Oct 2023, 11:35 - 11:55, 500/1-001 - Main Auditorium (CERN)

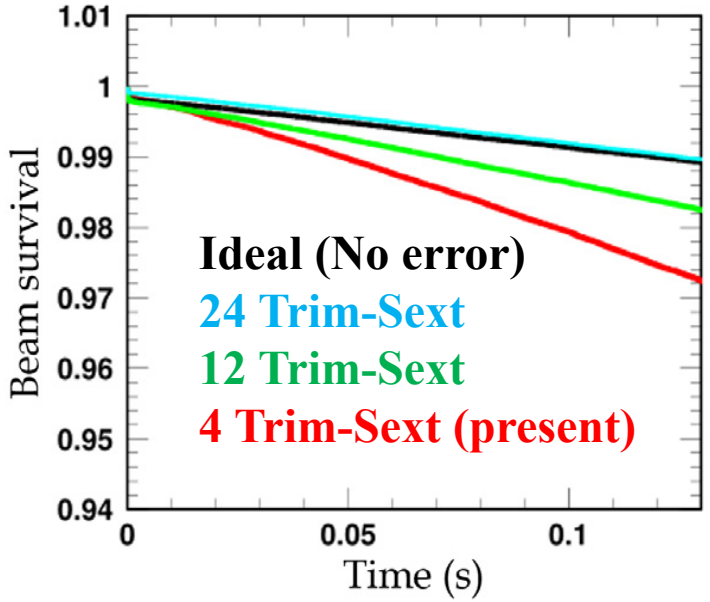
Upgrade Plan of Correction Magnet System

- ✓ Two 3rd resonance lines ($3\nu_x = 64$, $\nu_x + 2\nu_y = 64$) are corrected by 4 Trim-Coils on Sexupoles
- ✓ Tracking simulations suggest that upgrade to 24 Trim-Coils on Sextupoles suppresses the effect of the resonances to off-momentum particles and provides significant beam loss reduction.
- ✓ We are going to increase Trim-Coils on Sextupoles in stages, finally adding up to 24 units

Tracking simulations
(4.1 x 10^{13} ppb)

H. Hotchi, et. al.
TUPM055 IPAC'23





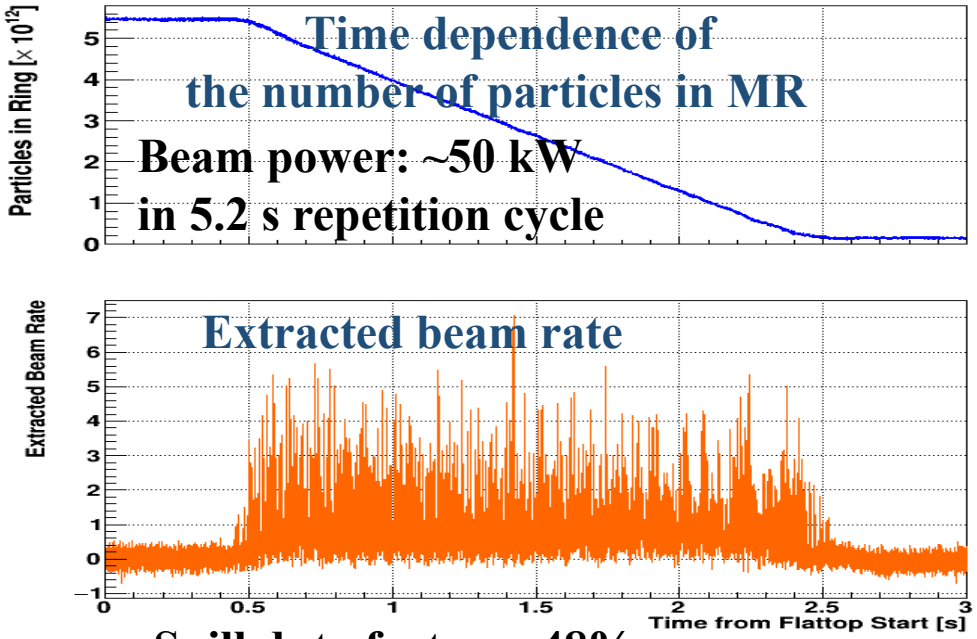
Yoichi Sato, J-PARC MR, MOA2I1, HB2023

Slow Extraction

SX Beam after Mag. PS upgrades

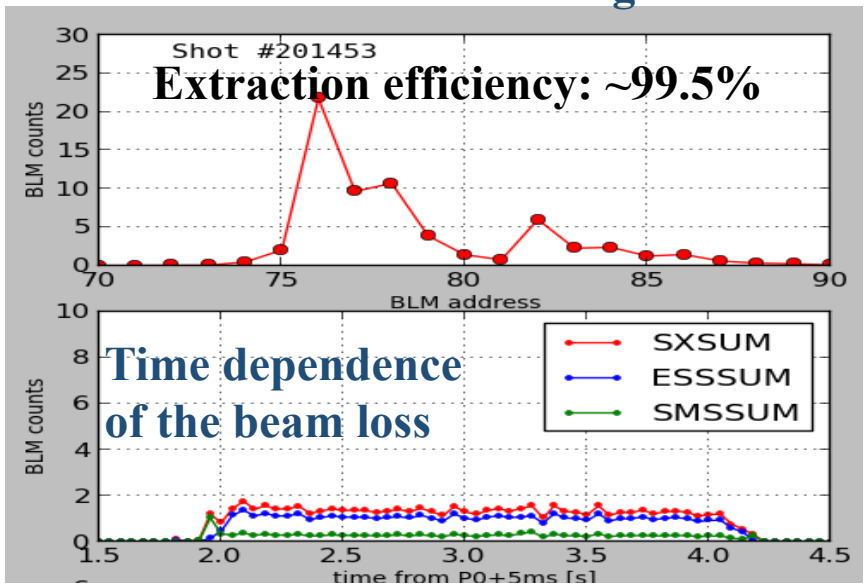
R. Muto

- ✓ SX 8 GeV/COMET phase-α (~240 W in 9.6 cycle) with improved duty factor 76% (62% in 2021)
- ✓ SX 30GeV/HD in 5.2 s cycle upto 50 kW with reproducing 99.5 % extraction efficiency



Spill duty factor: ~48%
(53% in 2021 51kW operation)

Beam loss distribution in SX straight section



The extraction efficiency of 99.5%
was well reproduced as before
the main power supply upgrade

R. Muto
in Friday talk

- ✓ BM-PS commissioning will be completed by Fall 2023.
- ✓ SX/HD 30GeV is going to achieve 80 kW in faster repetition cycle (4.24 s cycle).
- ✓ To aim > 100 kW, diffuser system is under development and demonstrated 99.7% extraction efficiency.

Summary

- ✓ **MR system has been upgraded for higher repetition cycle.**
  Main magnet PSs, RF system, Inj/FX systems, Collimator system
- ✓ **Initial commissioning were performed after 2021-2022 upgrades.**
  FX/NU 30GeV in 1.36s cycle has been performed.
    766 kW eq. beam was demonstrated with reasonable beam losses.
  SX Tunings were performed
    for COMET phase α (8GeV in 4.8s × 2 cycle) with improved duty factor
    for HD (30GeV in 5.2 s cycle) upto 50 kW with reproducing 99.5 % ext. efficiency
- ✓ **In JFY2023, we are aiming Nu 750 kW and HD 65~80 kW**
  BM-PS commissioning will be completed by Fall 2023.
- ✓ **Additional upgrades are planned for > 1 MW beam faster**
  to achieve better beam optics.