MOA2I1

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**

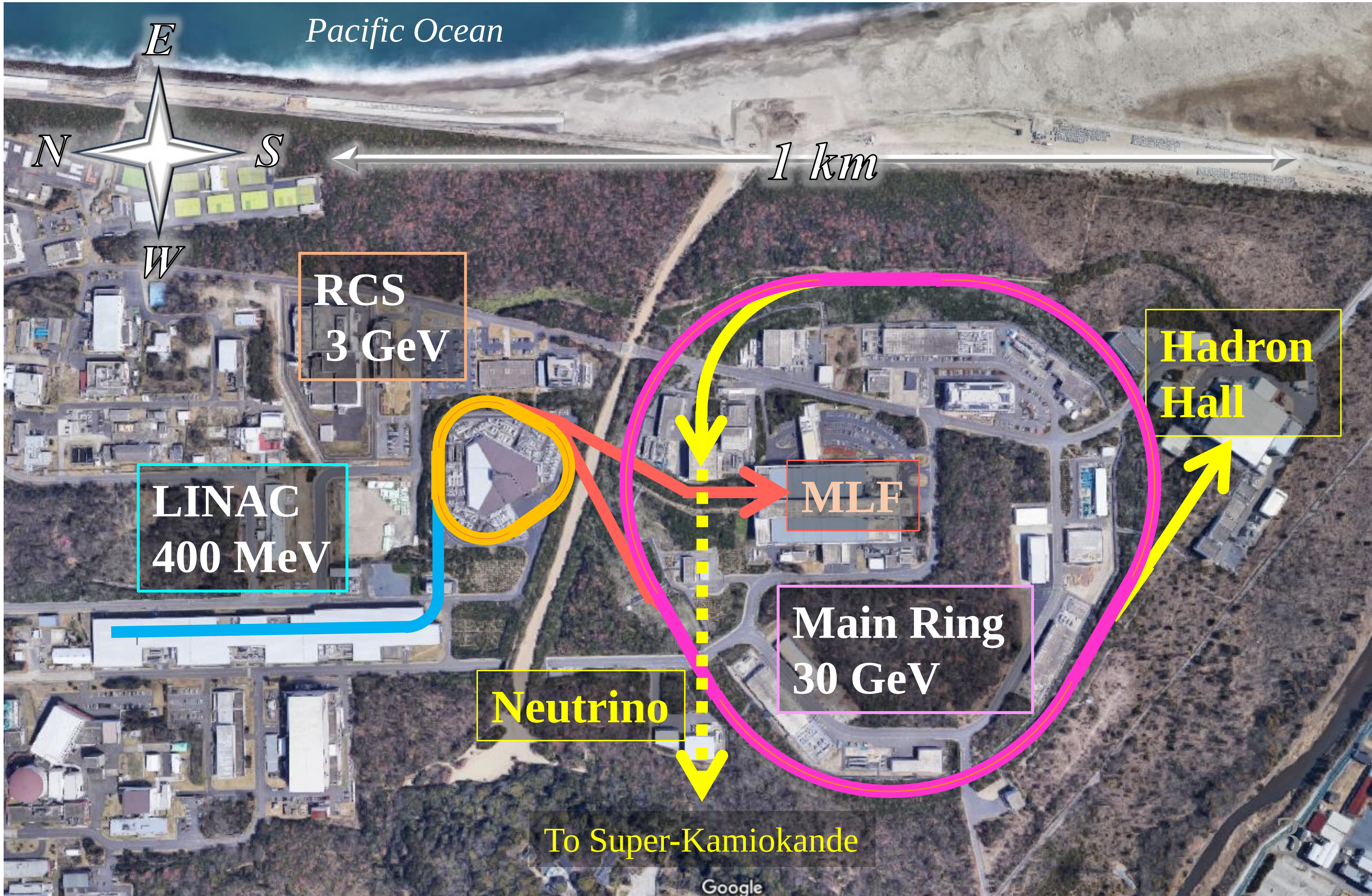
- **SX operation**

- **Summary**

Japan Proton Accelerator Research Complex

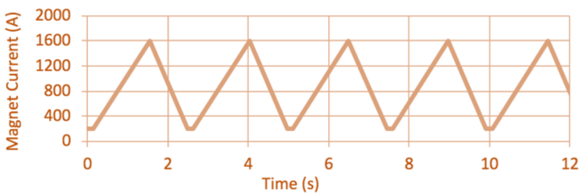
Operated by
Japan Atomic Energy Agency (JAEA)
and
High Energy Accelerator Research Organization (KEK)

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

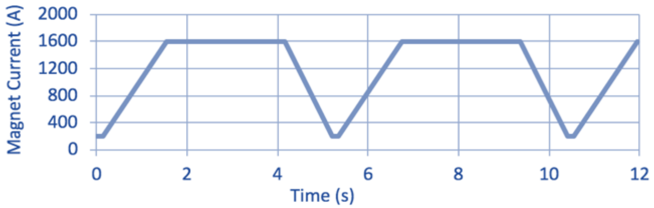


Main Parameters of MR

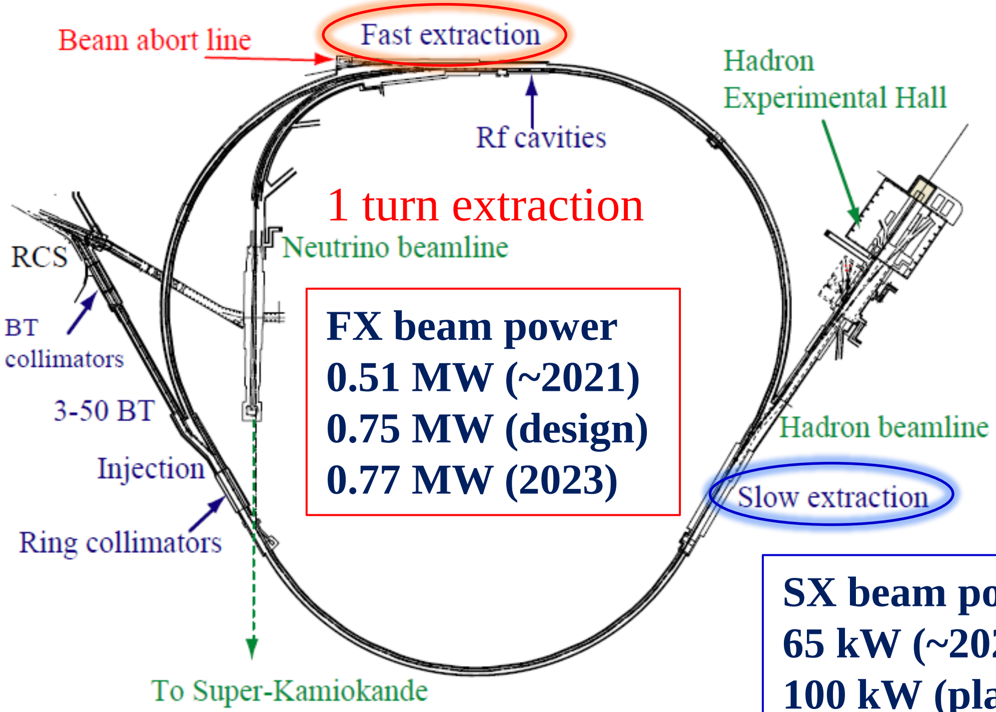
Circumference	1567.5 m
Injection energy	3 GeV
Extraction energy	30 GeV
Super-periodicity	3
harmonic	9
Number of bunches	8
Physical Aperture	81π mm-mrad
Ring Collimator	54-70 π mmmrad
Transverse emittance	
At injection	54π mm-mrad
At extraction	10π mm-mrad (30 GeV)



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)

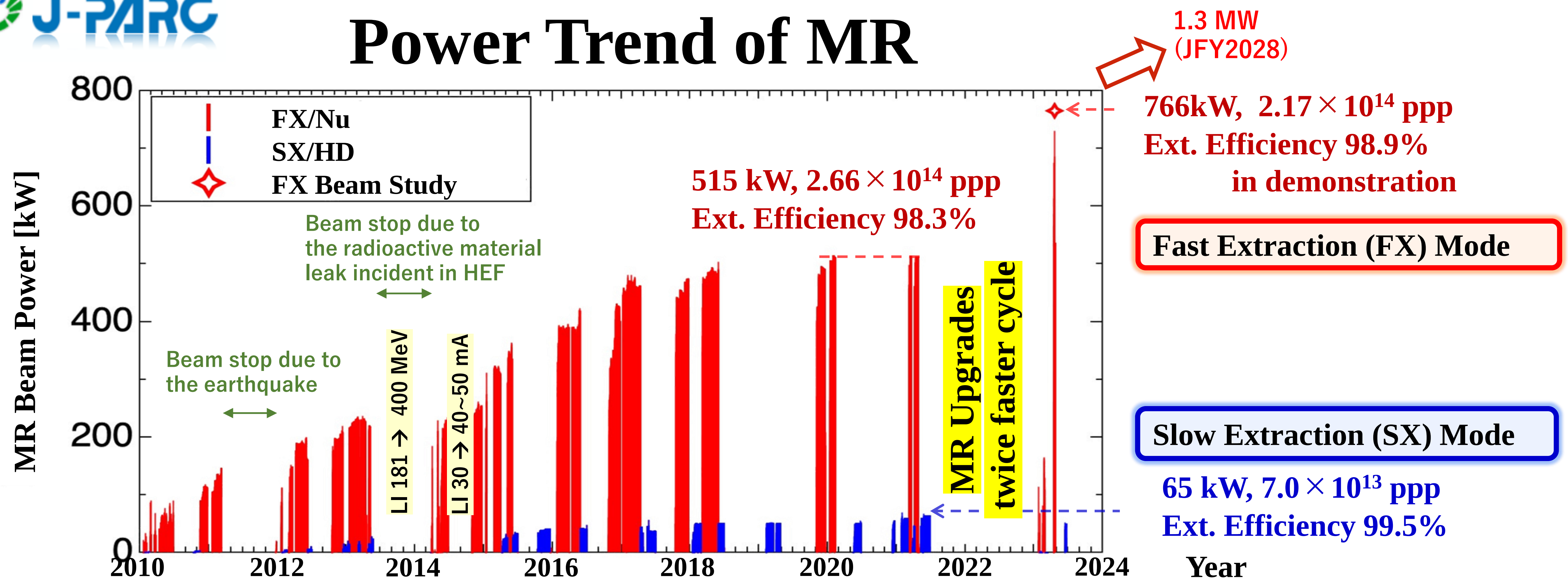


FX beam power
0.51 MW (~2021)
0.75 MW (design)
0.77 MW (2023)

2 second
extraction

SX beam power
65 kW (~2021)
100 kW (plan)

Power Trend of MR



3.52s 3.04s 2.56s 2.48s → 1.36s → FX operation cycle for NU

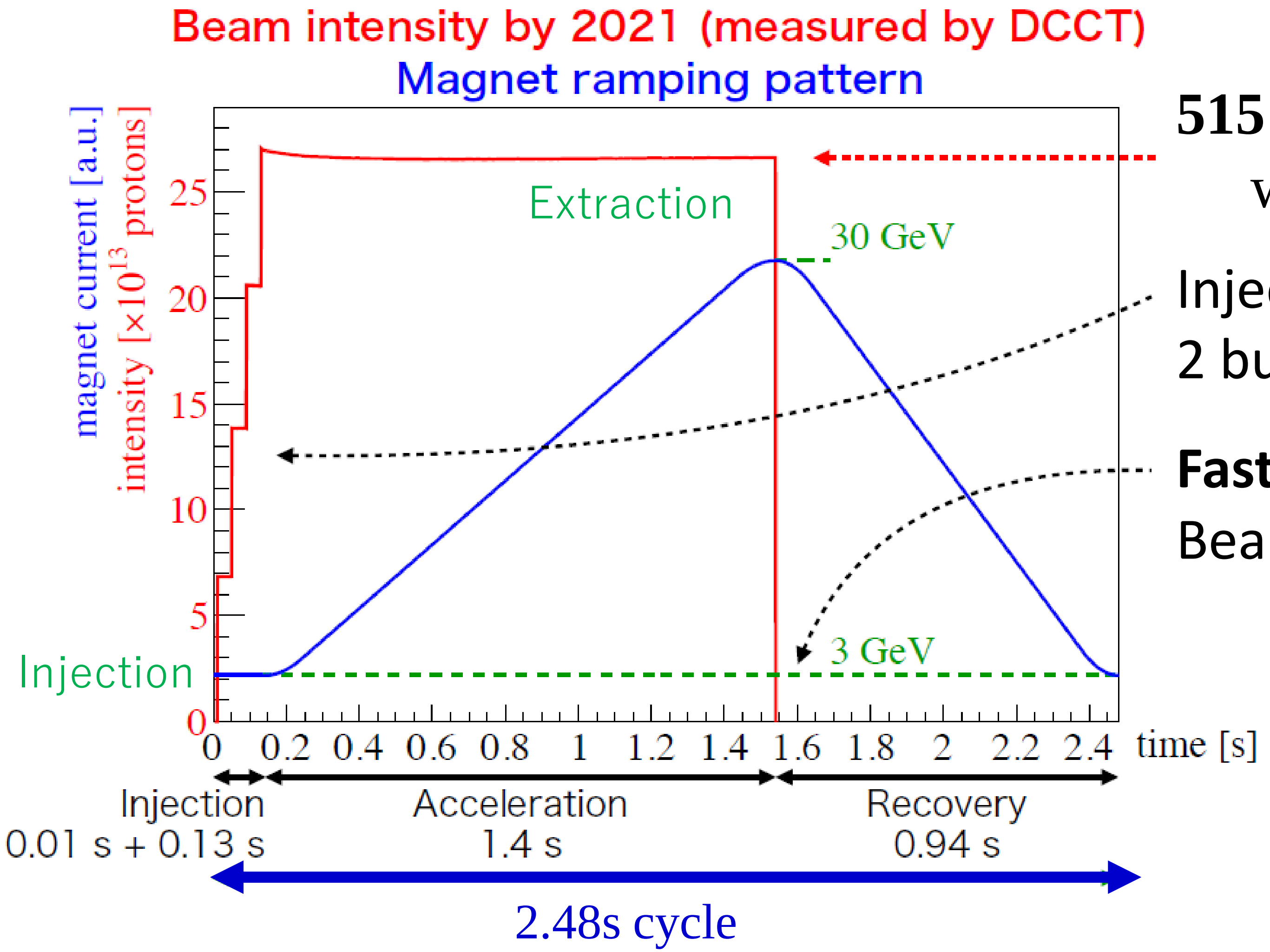
6.00s → 5.52s → 5.20s → *4.24s* → SX operation cycle for HD

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

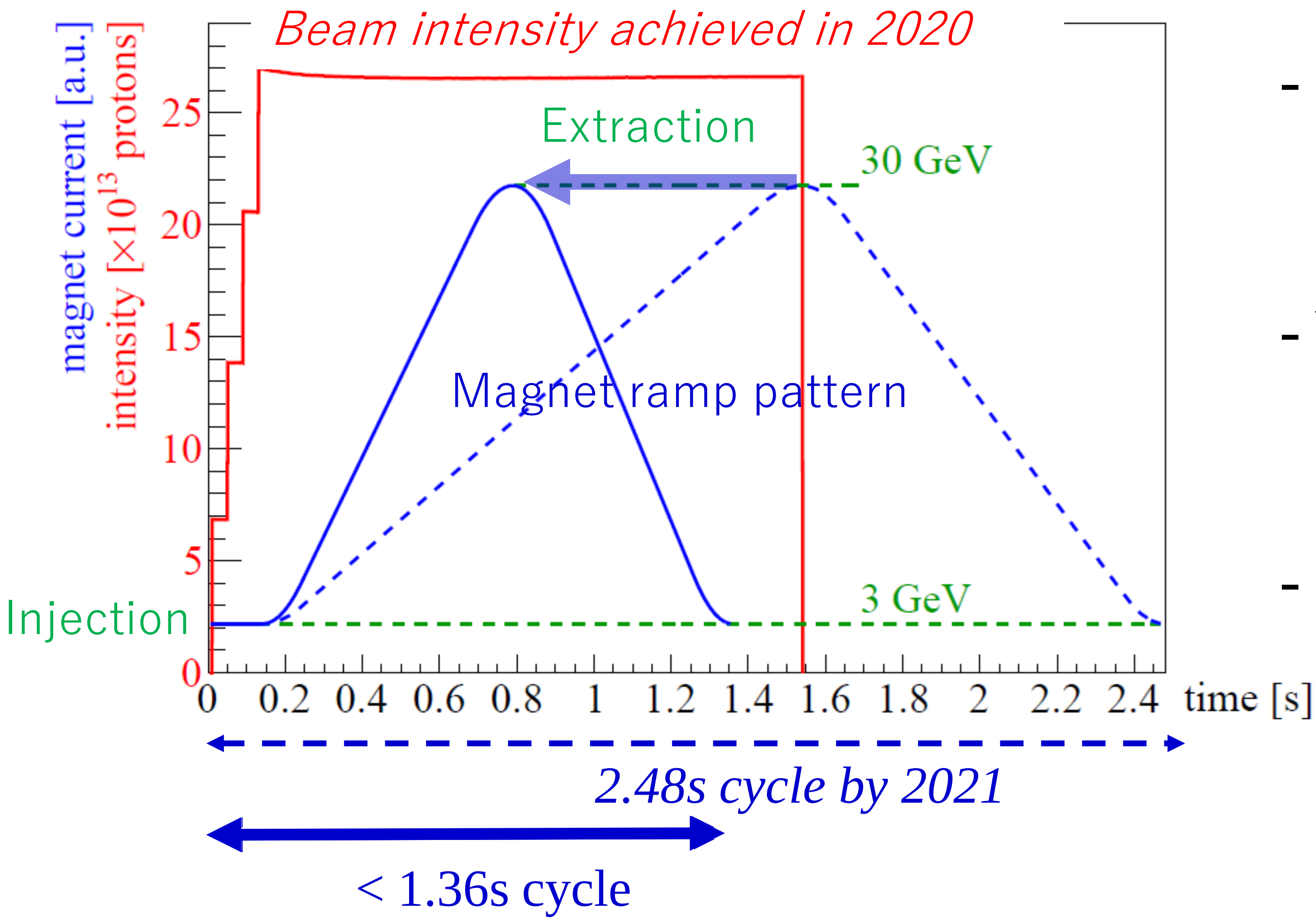
Injection:
2 bunches × 4 times

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)

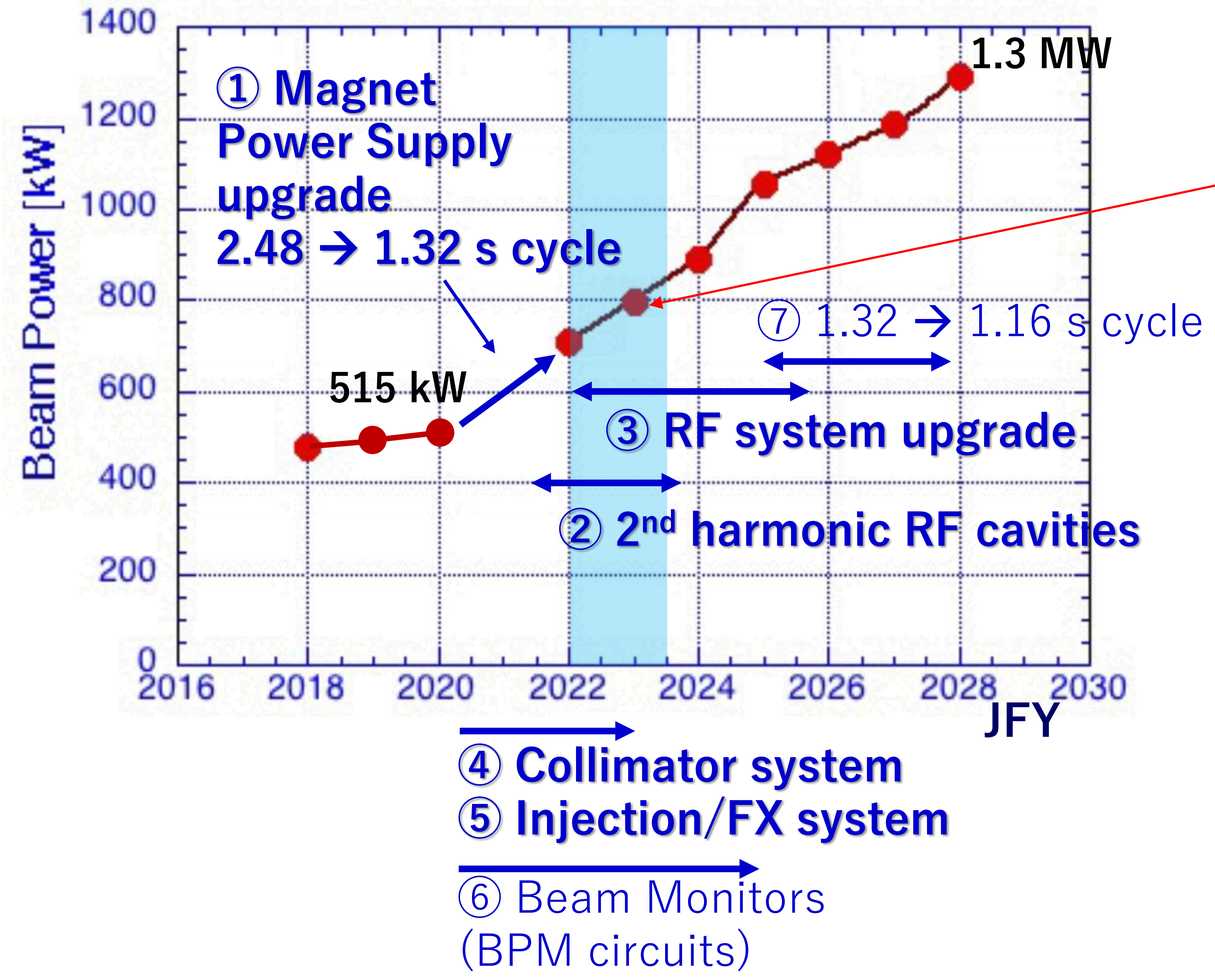
JFY2021	**515 kW**	2.48 s	2.66×10^{14} ppp
*JFY 202**	***> 940 kW***	*<1.36 s*	2.66×10^{14} ppp



- In 2021 -2022, MR major properties (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

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

<u>**Twice faster cycle ➔ Twice Voltage at Mag PS.**</u>

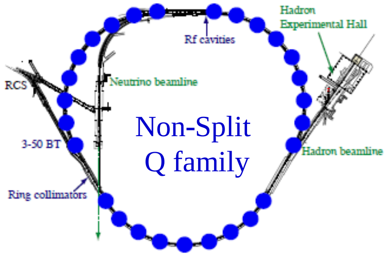
Y. Morita *et. al.*, WEPM082, IPAC'23

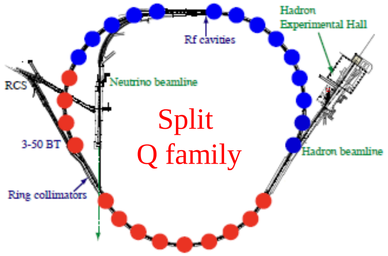
New BM-PS

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

- **New Power Supplies**
  6 BM-PSs, 4 QM-PSs, 2 SM-PSs
  1 Main-Bending-Magnet-family is operated by 6 BM-PSs

- **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.



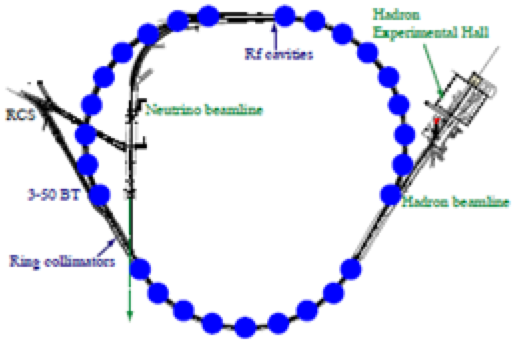


Adjust BM-PSs and Paired-QM-PSs to avoid Broken Symmetry enhancing resonance effects.

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

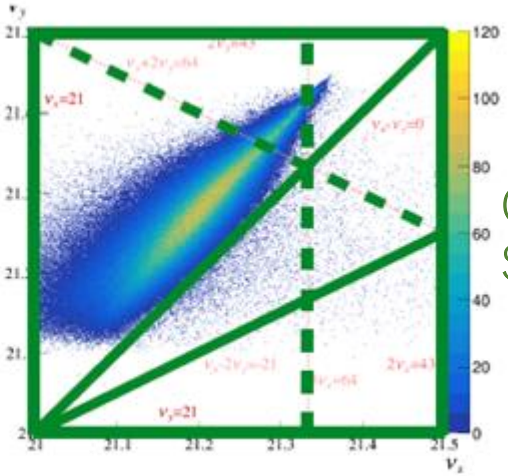
✓Asymmetric cabling of Split-Quad-Magnet-family to Paired-QM-PSs

Before Upgrade



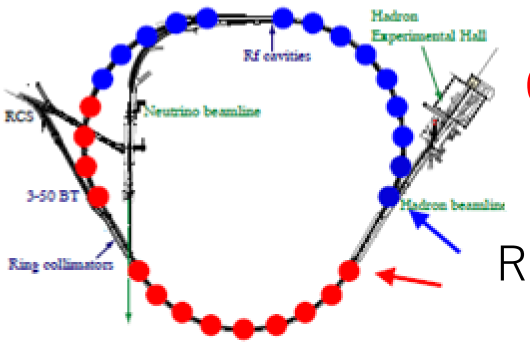
Example of Quadrupole family (QDX)

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



Green lines:
Strong resonances

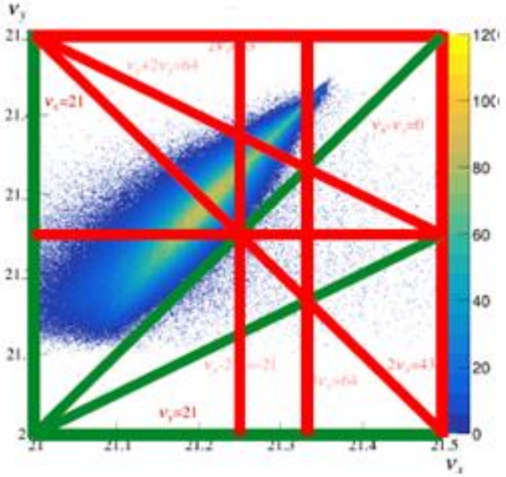
After Upgrade



QDX family was split!

Ramped by different PSs

Need to Adjust the different PSs (paired)



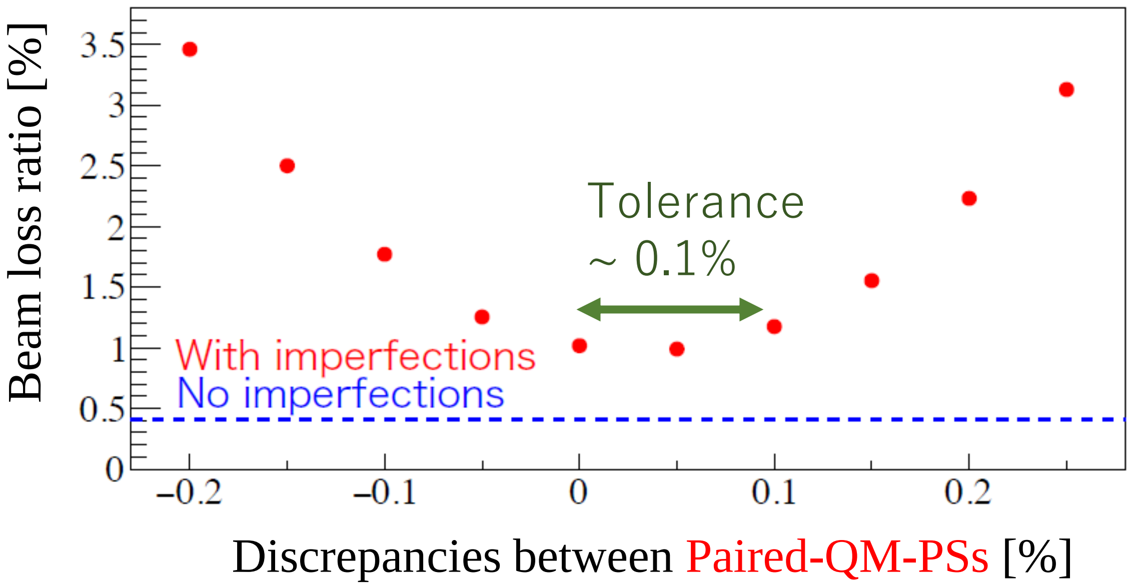
Red lines:
Reinforced or newly appeared resonances

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%

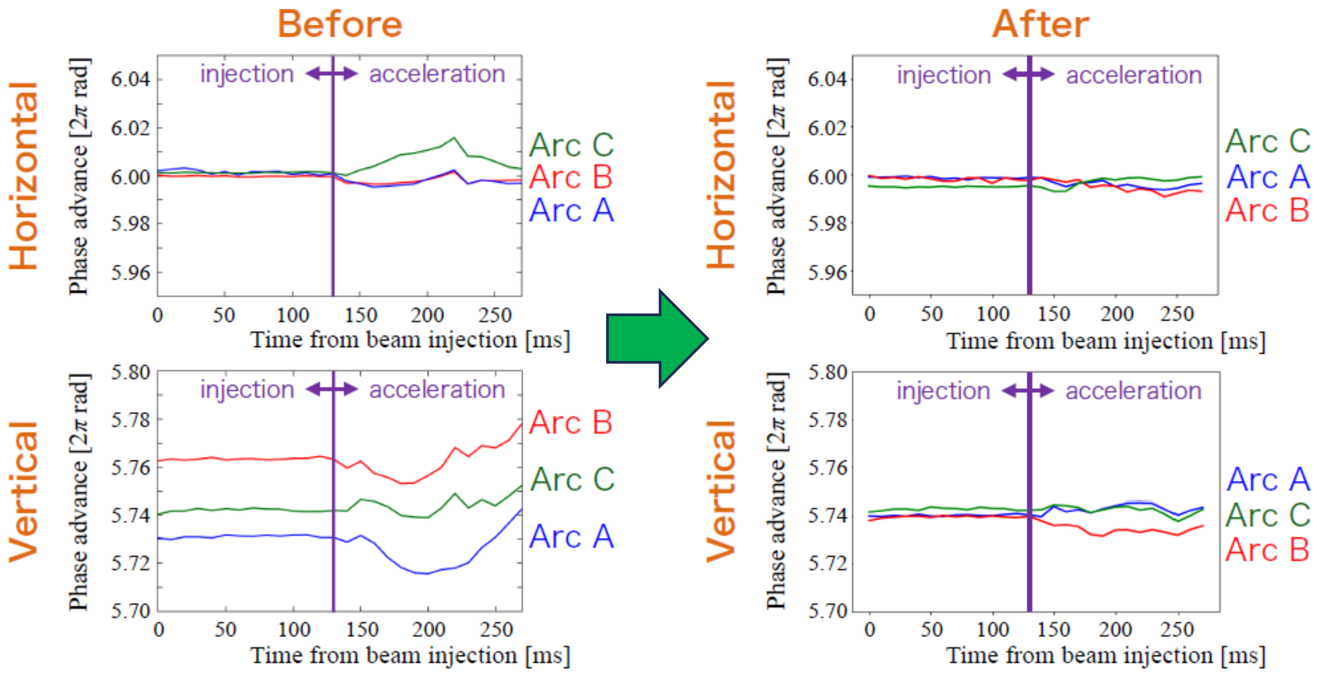
Discrepancies between the pair of power supplies for each Quadrupole family cause serious beam loss.
→ 0.1% Tolerance in discrepancies

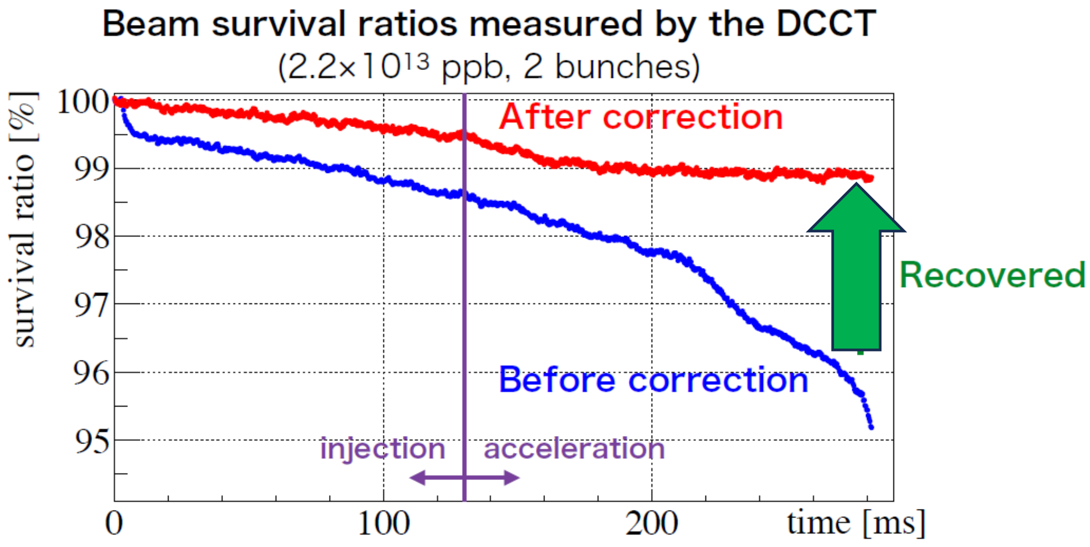
→Remaining sources of beam losses are expected from
magnet imperfections and
space charge effects

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

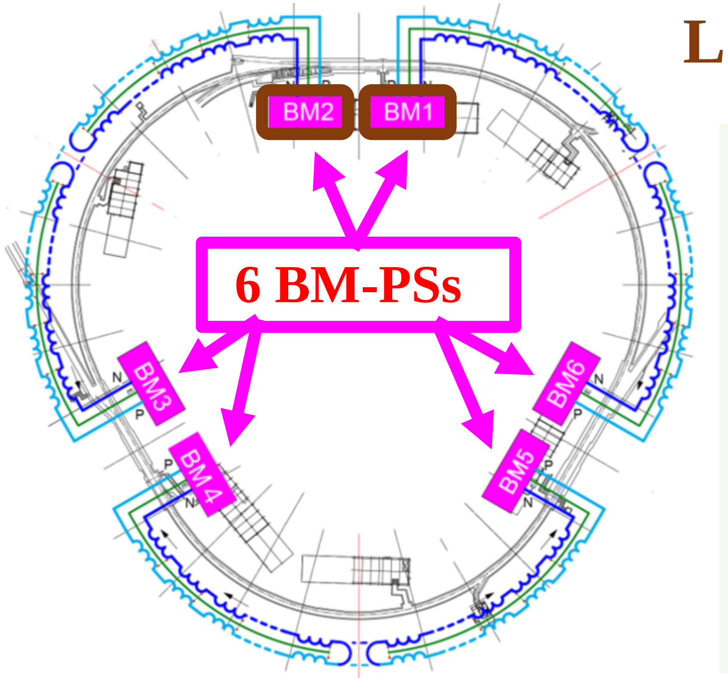




✓Separate cabling of 96 Main Bending Magnets in 6 BM-PSs

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 tortured 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
2.2 (average)

Quad ripples
0.6 (average)

How BM-PS Balance affects on Arc Phases

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

dispersion   sext. field

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

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

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

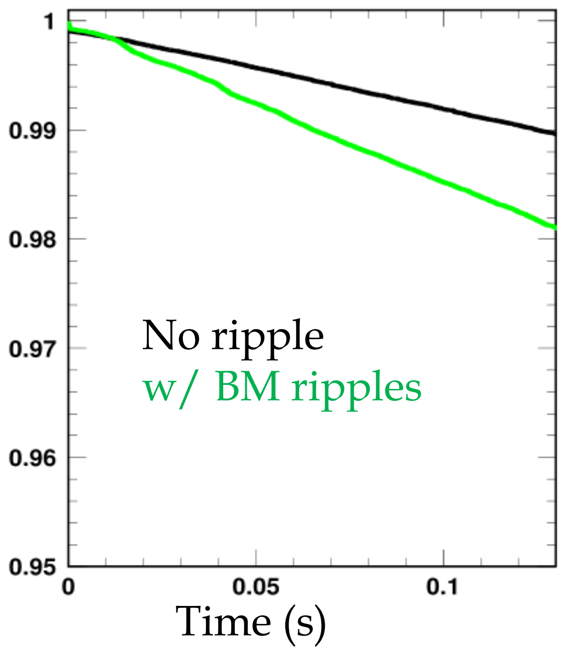
Effect of the Low freq. ripples of 2 BM-PSs

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

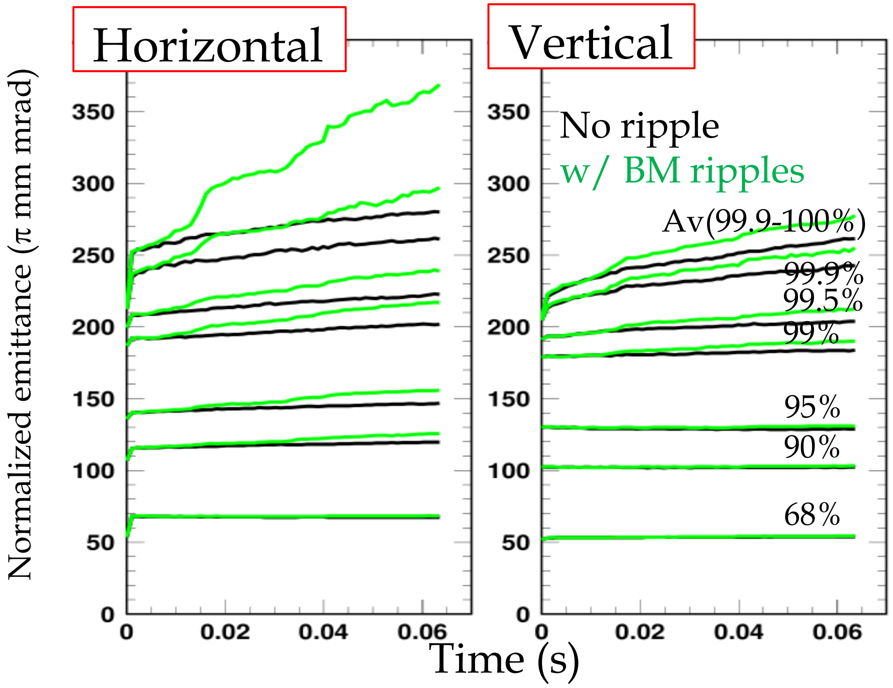
Tracking simulations（Beam intensity： 4.1 x 10^{13} ppb)

H. Hotchi

Survival



Emittance Growth



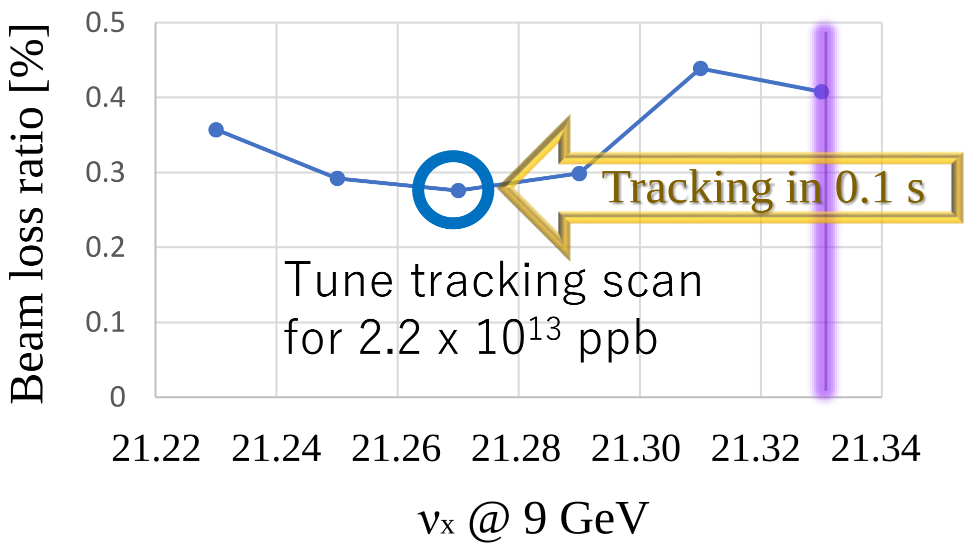
In this Fall, we can perform beam tunings with **best sets of ALL 6 BM-PSs.**

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

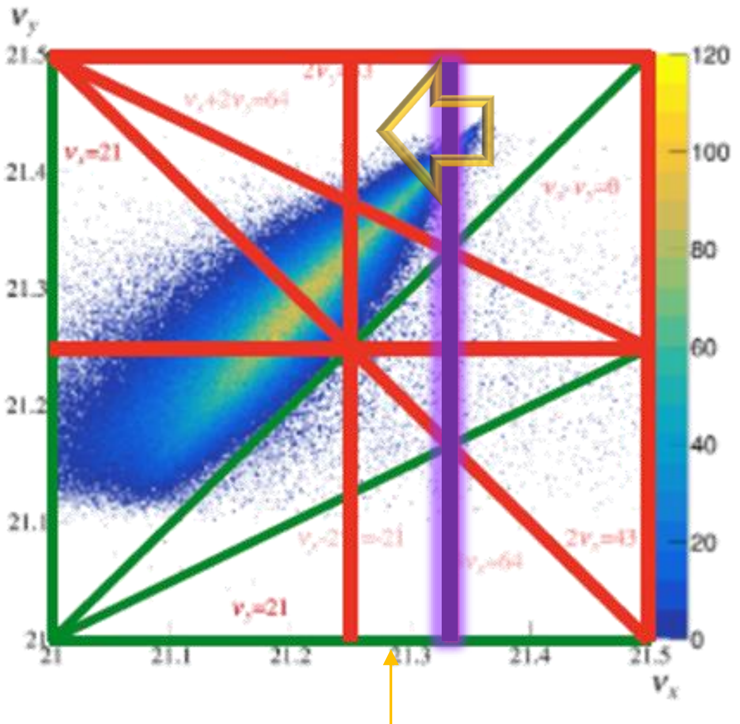
Measures to Effect of the Low freq. ripples of 2 BM-PSs

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.



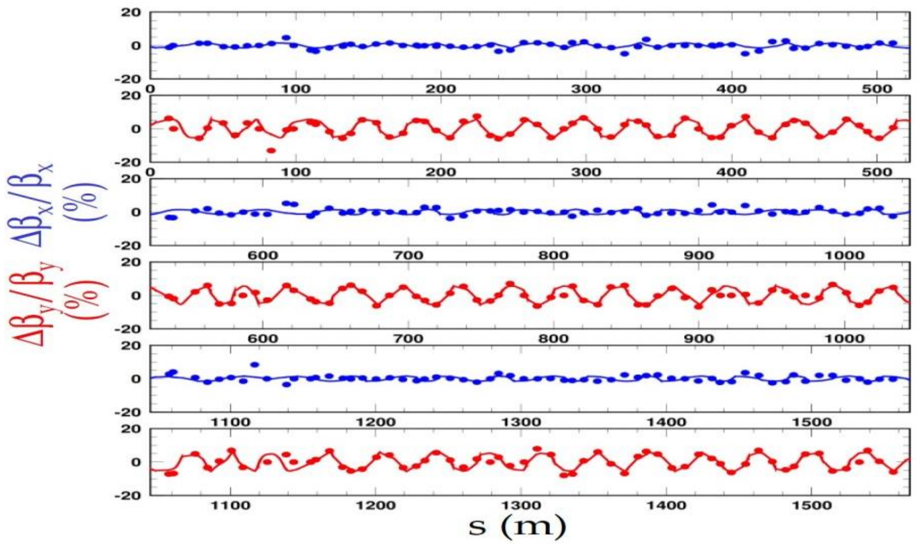
ν_x = 21.27 is more tough for broken symmetry in horizontal

✓Leakage field from FX Septum magnets

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

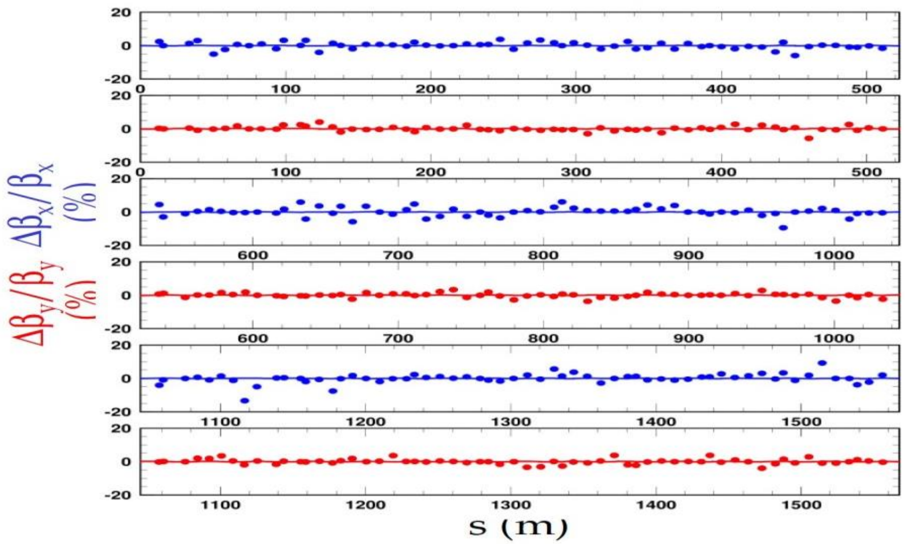
- New features: Less Impedance, Larger Aperture, and **Less Quadrupolar Leakage Field.**
- Beta measurements revealed that
  - Previous FX septum magnets had serious leakage field and caused optics modulation.
  - New FX septum magnets have 10 times smaller leakage field.

With Previous FX septum magnets



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

With New FX septum magnets



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

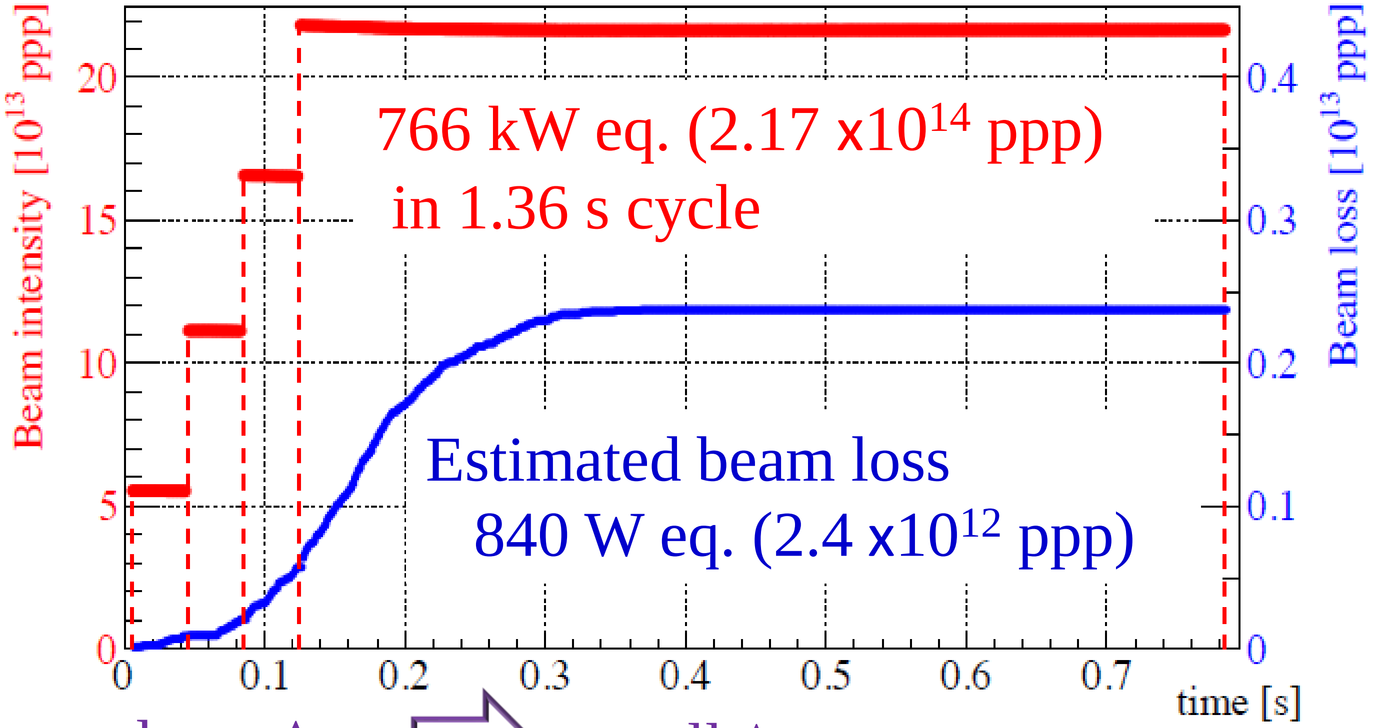
T. Shibata, *et. al.*, TUPM103, IPAC'23

Achievement of FX 750 kW
(original design power)

Achievement of MR FX-ABD 750 kW eq.

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

Beam intensity and beam loss estimated by the DCCT



large $\Delta\nu_x$ ⇒ small $\Delta\nu_x$

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 ν_x = 21.33 quickly

In this Fall we expect to reduce the beam loss 20%, after completing BM-PS commissioning.

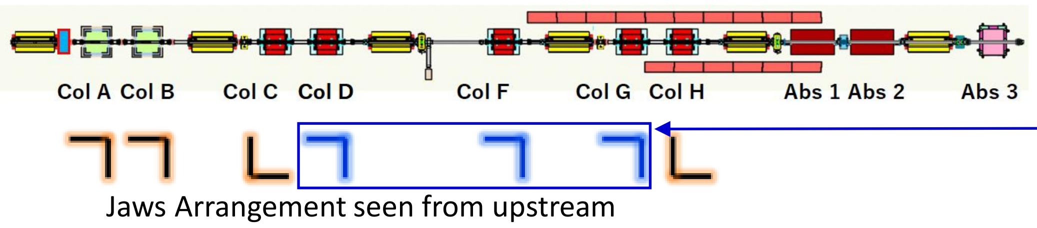
S. Igarashi, *et. al.*,
PTEP vol 2021, Issue.3,p33

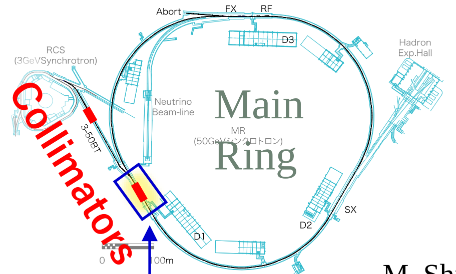
Collimator System Upgrades

✓ More Collimator Capacity

2021: 2.0 kW → 2023~: 3.5 kW

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

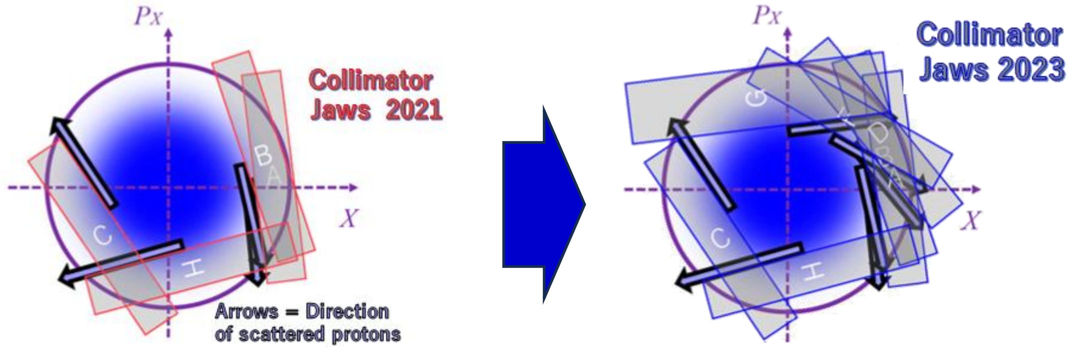


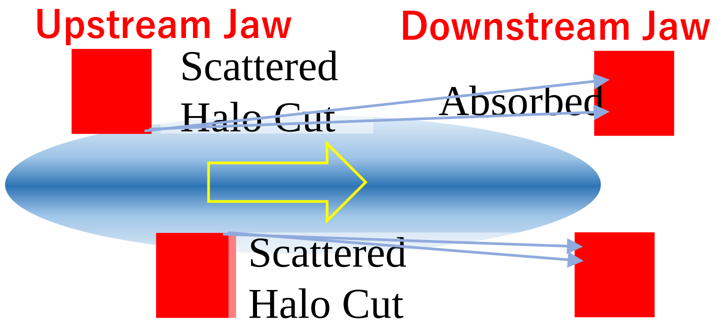


M. Shirakata
M. Uota
K. Kadowaki
T. Sasaki

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

✓ More Effective Halo Cut

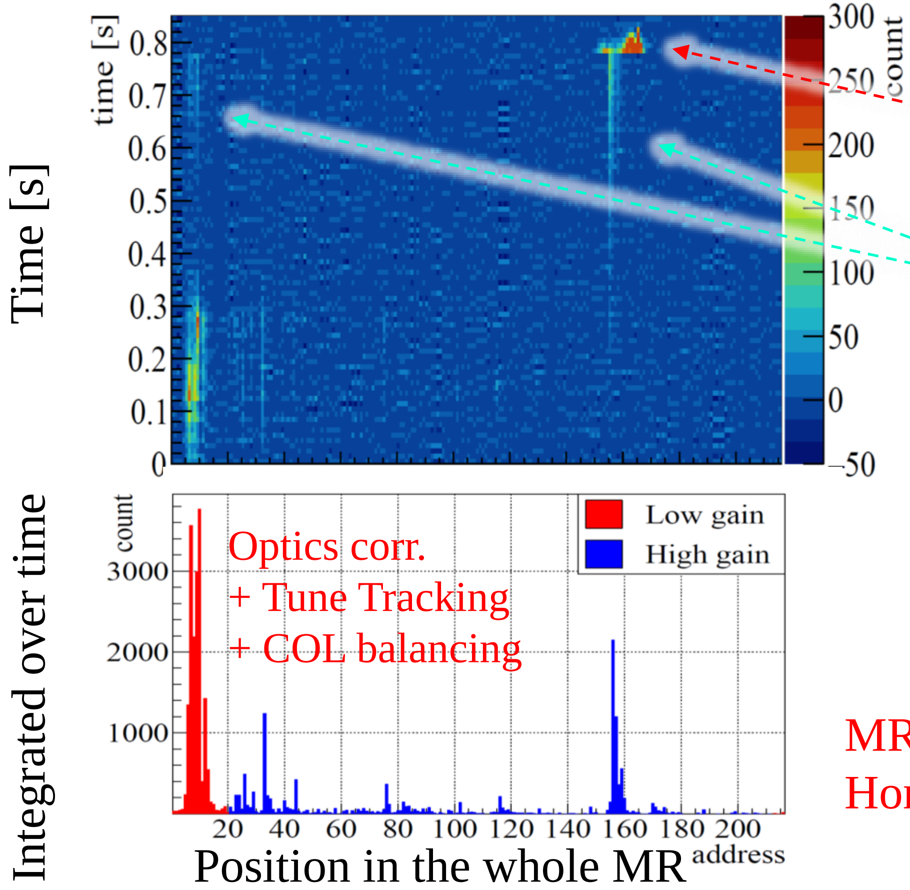




→Better beam loss localization at collimator area

Beam loss localization of FX 766 kW eq.

Beam losses counts for FX 766 kW eq.



MR ABD
reflection
30 GeV ext

Ongoing
Vacuum
Scrubbing

MR Collimators
Hori55pi & Vert61pi

Position in the whole MR
(Addressed in every Quad Mag.)

Collimator Area

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

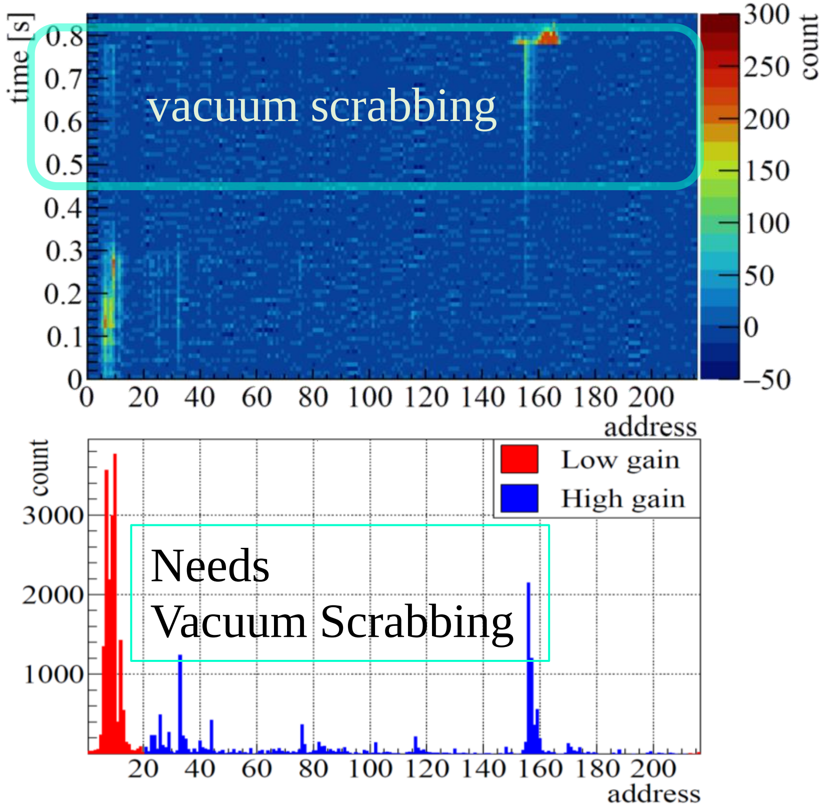
Beam losses are well localized
at collimator area
except for outgassing chambers.

We are on the way of vacuum scrubbing.

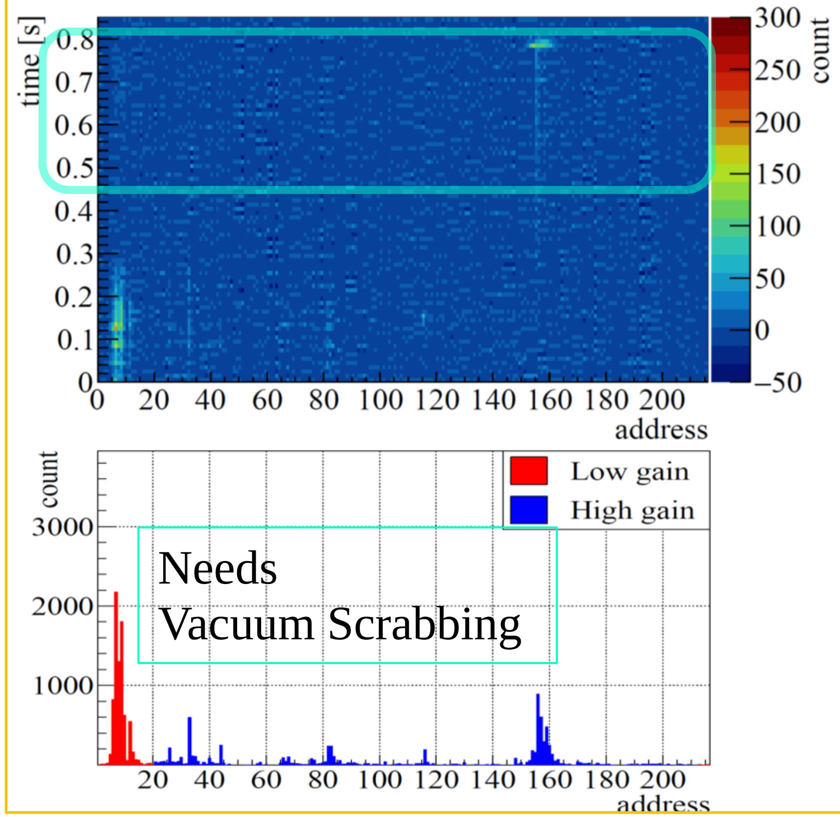
Y. Sato
T. Yasui

Beam loss localization after vacuum scrubbing

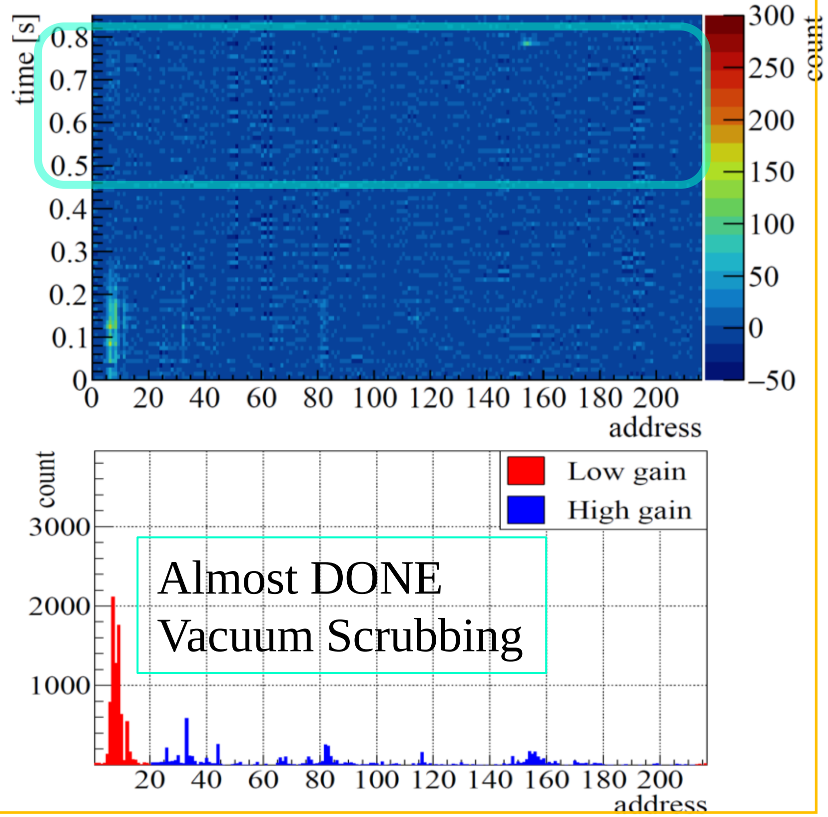
MR766 kW eq. with loss 840 W eq.



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.**

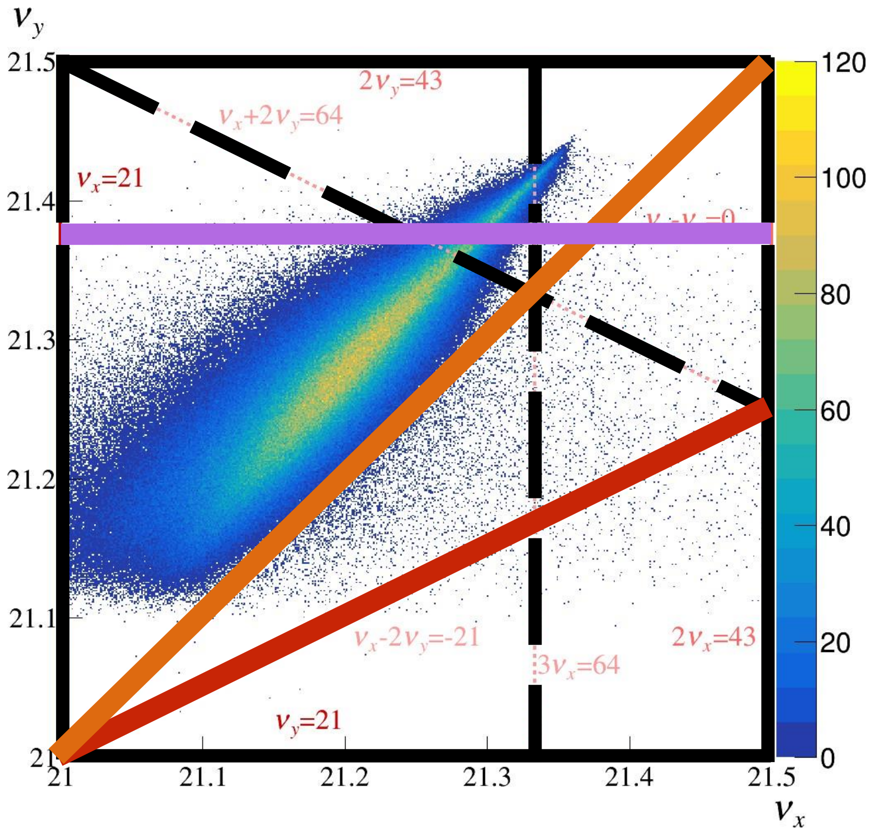
Future Plans

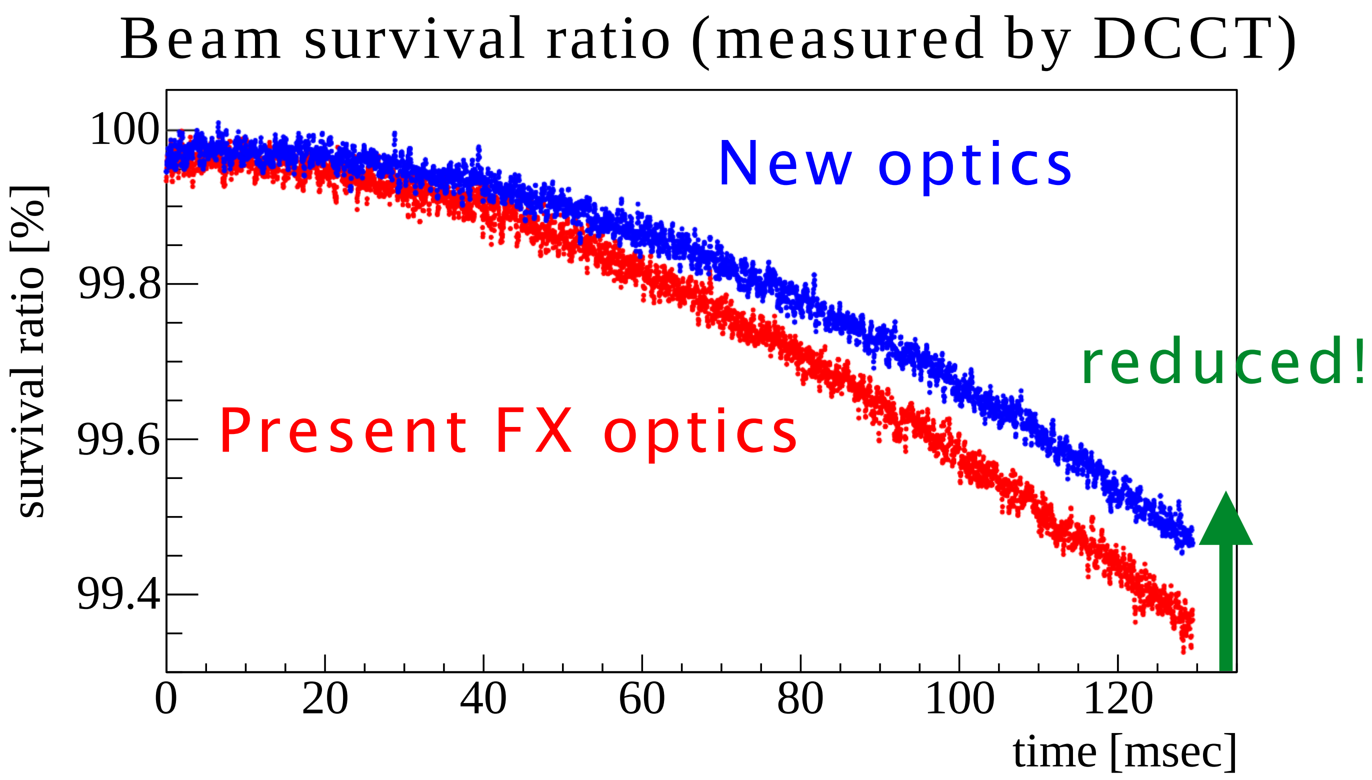
- New Beam Optics for FX operation
- Upgrade Plan of Correction Magnet System

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)





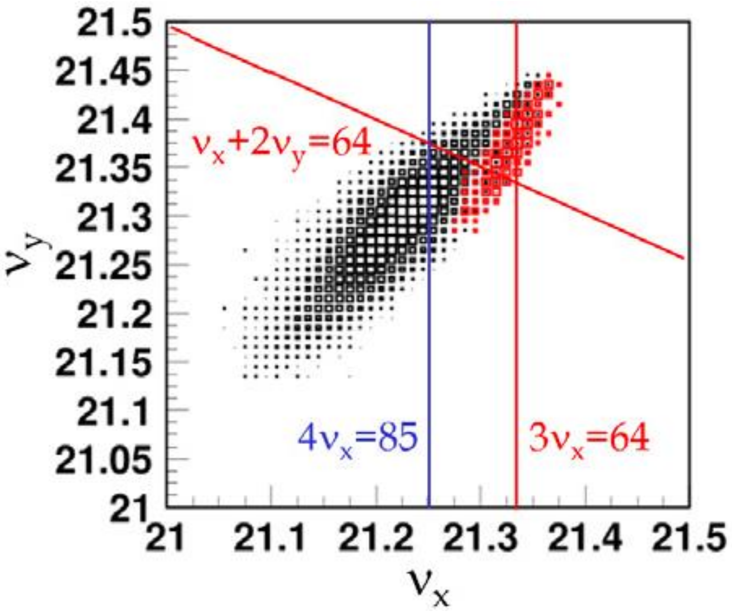
More Details are to be discussed in T. Yasui's talk (on Wednesday)
"Space charge induced resonances and suppression in J-PARC MR"
11 Oct 2023, 11:35 - 11:55, 500/1-001 - Main Auditorium (CERN)

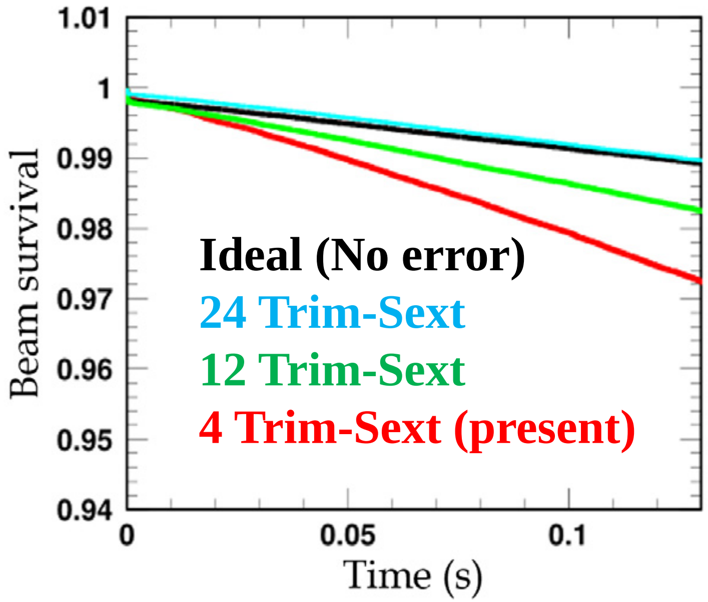
Upgrade Plan of Correction Magnet System

- ✓ 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
(4.1×10^{13} ppb)

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



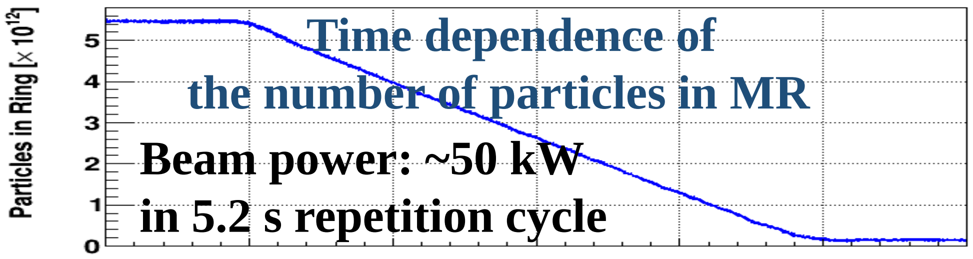


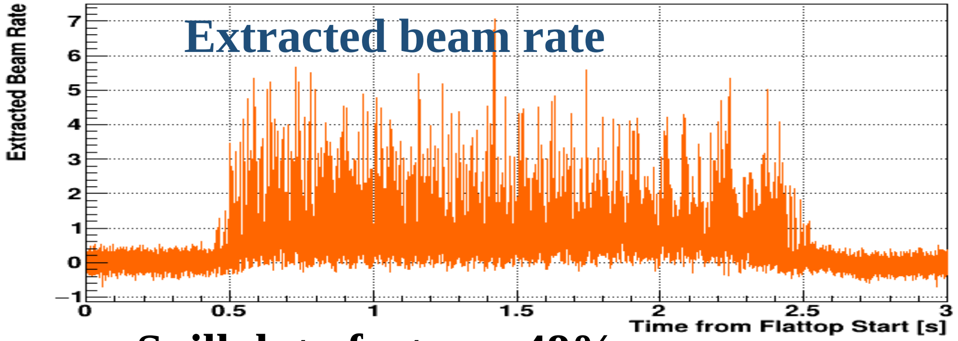
Slow Extraction

SX Beam after Mag. PS upgrades

R. Muto

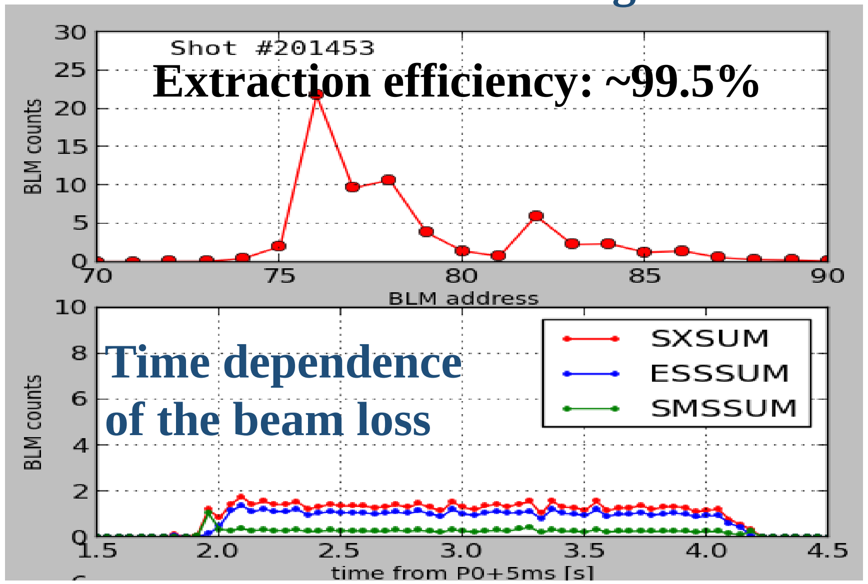
- ✓ SX 8 GeV/COMET phase-α (~240 W in 9.6 cycle) with improved duty factor 76% (62% in 2021)
- ✓ SX 30GeV/HD in 5.2 s cycle upto 50 kW with reproducing 99.5 % extraction efficiency





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

- ✓ 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.

Backups

Main Magnet Power Supplies (PSs)

Upgrade of Main Magnet Power Supplies

Kurimoto, Morita, Shimogawa, Miura

- **The Power Supplies (PSs) of main magnets were upgraded for faster cycling.**
- Present power supplies are reused for the other Q families.
- There are some changes in power supply and/or cabling for all the families.
- We have checked the polarity of magnets, so the beam operation was successful from 1st shot.

	Family Label	Magnet	Number of Family	Number of magnets	Inductance (H)	Current @ 30 GeV (A)	Upgrade strategy
Arc	BM	Bend	6	16 each	1.47	1600	New PSs with capacitor bank
Arc	QFN, QDN	Quad	1 each	48 each	2.93, 3.46	750	New PSs with capacitor bank
Arc	QFX	Quad	1→2	48→24 each	2.39	750	Reuse of Present PSs with divided budget (Family divided)
Arc	QDX	Quad	1→2	27→14(13)each	1.75	750	Reuse of Present PSs with divided budget (Family divided)
Ins	QDS	Quad	1→2	6→3 each	0.35	900	Reuse of Present PSs with divided budget (Family divided)
Ins	QFS, QFT	Quad	1→2 each	6→3 each	0.3, 0.32	900	Reuse of Present PSs with divided budget (Family divided)
Ins	QFP	Quad	1	6	0.2	900	Reuse of Present PSs
Ins	QFR	Quad	1	9	0.57	850	Reuse of Present PSs
Ins	QDR, QDT	Quad	1 each	6 each	0.44, 0.37	900	New PSs w/o capacitor bank
Arc	SFA	Sext	1	24	0.41	200	New PSs w/o capacitor bank
Arc	SDA, SDB	Sext	2 →1	24+24 → 48	0.82	200	New PSs w/o capacitor bank

New Power Supplies

- 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.

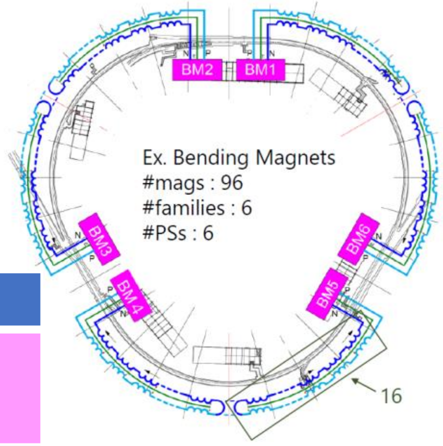
Kurimoto

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

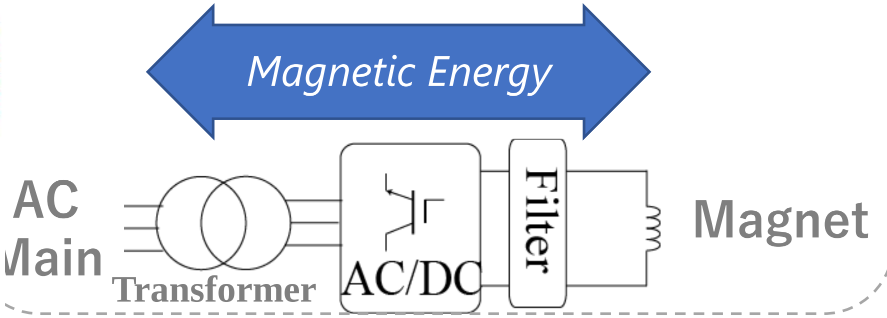
Mag. Family (*)	Type	#mags/PS	PS	Upgrade
BM1 ~ 6	**Bending**	**16**	**Large**	**New PS w C-Bank**
QFN, QDN,	**Quadrupole**	**48**	**Large**	
QFX	Quadrupole	48 → 24	Large	Reuse Present PS w divided budget
QDX	Quadrupole	27 → 14&13	Large	
QDS, QFS, QFT	Quadrupole	6 → 3	Small	
QFP, QFR	Quadrupole	6, 9	Small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

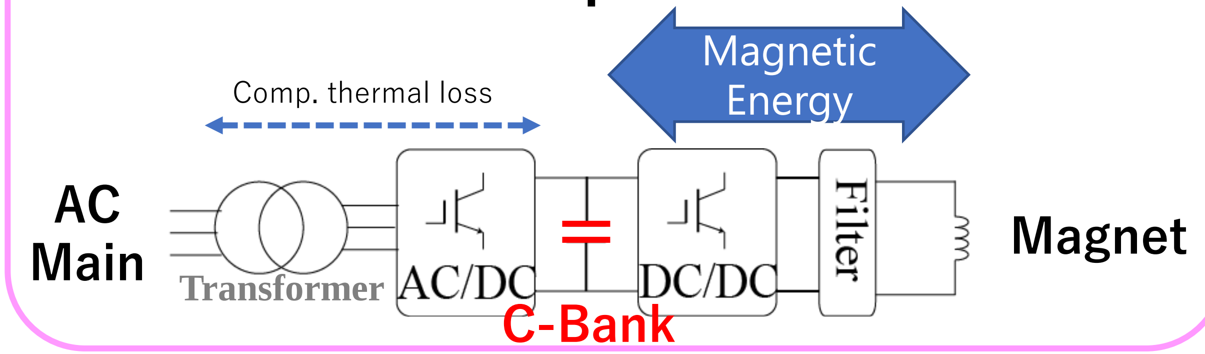
* One PS drives several magnets connected in series.
These several magnets are collectively called "a Family"



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



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



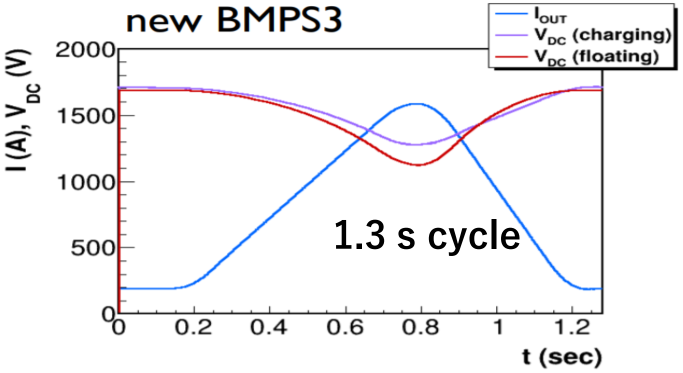
New Power Supplies

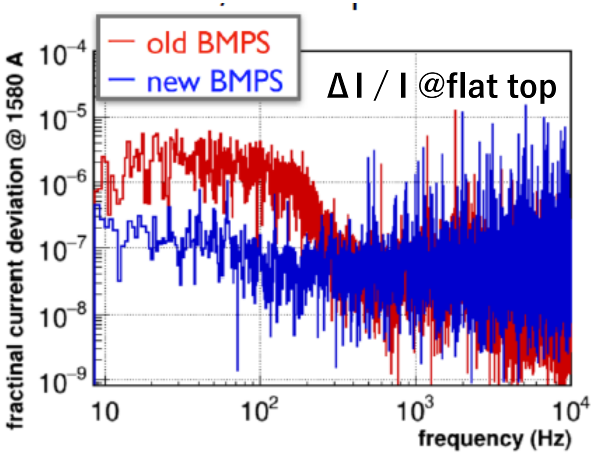
New 3 buildings for the PSs were constructed (complete).
Mass production of the PSs is in progress.

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

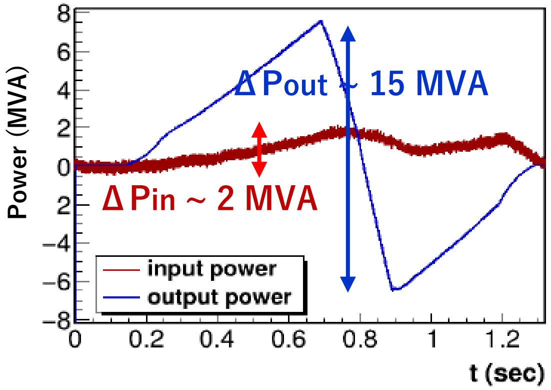
2 BMPSs were successfully tested in 1.3 s cycle,
and stably operated over 50-hour.

- 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.

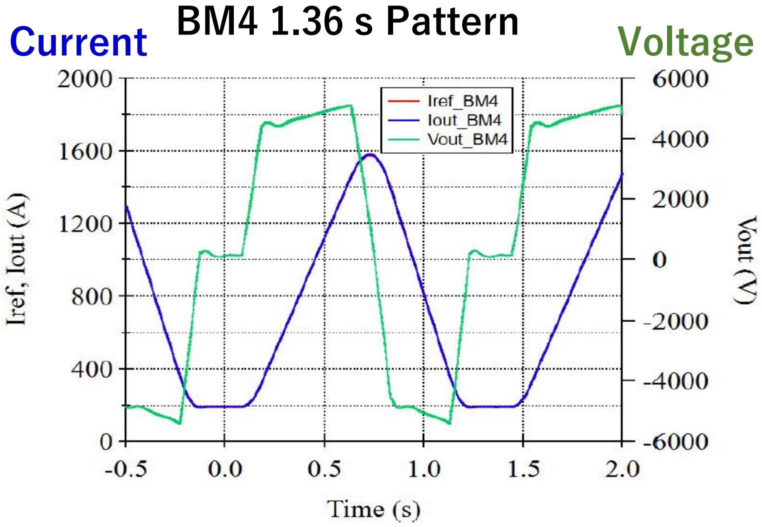




new BMPS3's Input/output power



T. Shimogawa *et al.*,
in *Proc. IPAC'19*, pp. 1266-1268.



Morita et. al, WEPM082, IPAC'23

Effect of Current Ripple in Spring 2023

- Status of Current Ripple of Main Magnet PSs
- COD modulation
- Effects on beam survival
- Relation with Upgrade plan of Trim-S system
- Review of 3rd resonance correction with 4 Trim-S coils

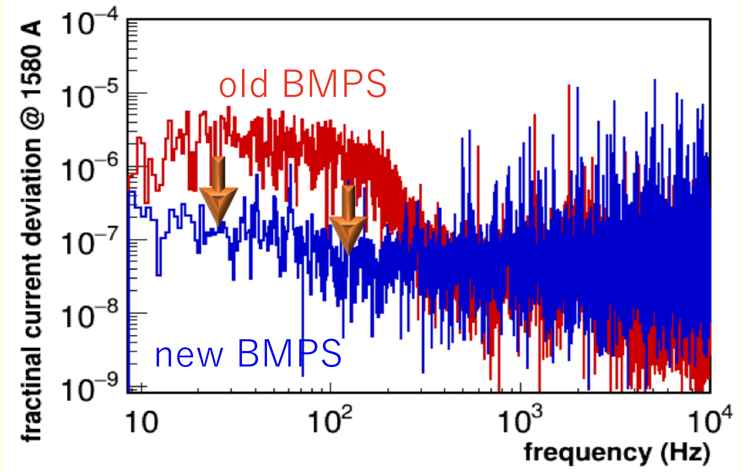
To REPRODUCE 3-fold-symmetry (BM-PSs)

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

We were **on the way to best commissioning of all BM-PSs**, and complete by this Fall.

In Spring 2023, we performed beam tunings with **Low freq. ripples of 2 BM-PSs**.

Ripple of current of a BM-PS (**BEST tuning**)

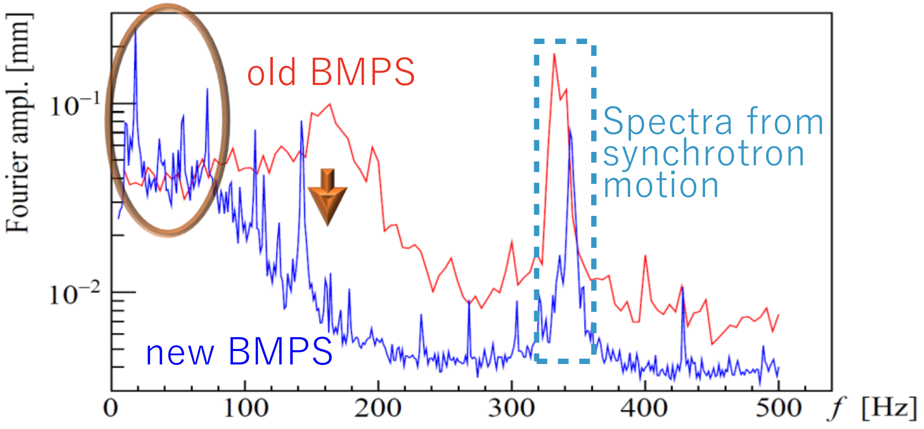


T. Shimogawa *et al.*, in *Proc. IPAC'19*, pp. 1266-1268.

Morita et. al, WEPM082, IPAC'23

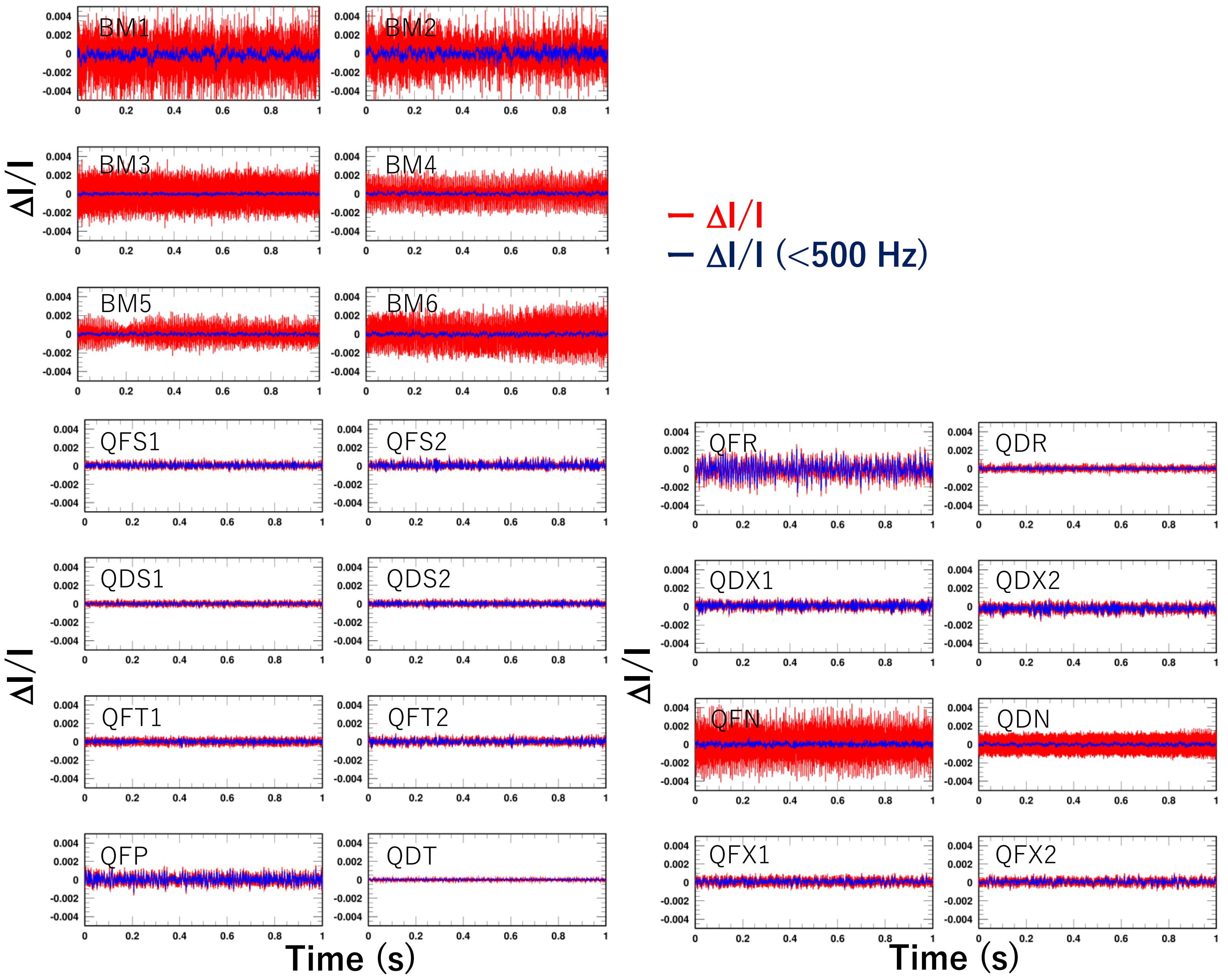
Ripple observed in beam orbit (Spring 2023)

(effect of all Bend PSs)

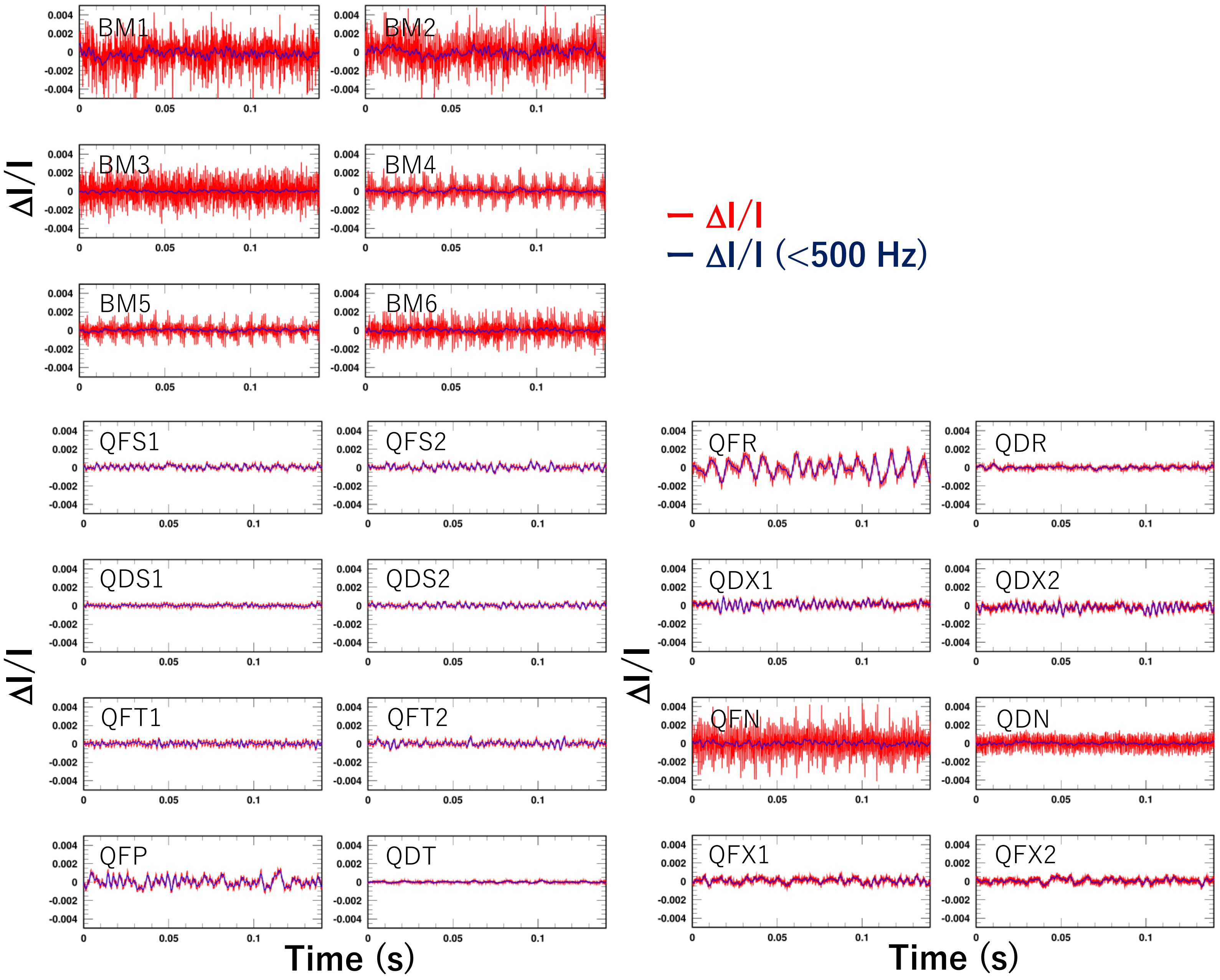


In this Fall, we can perform beam tunings with **best sets of ALL 6 BM-PSs.**

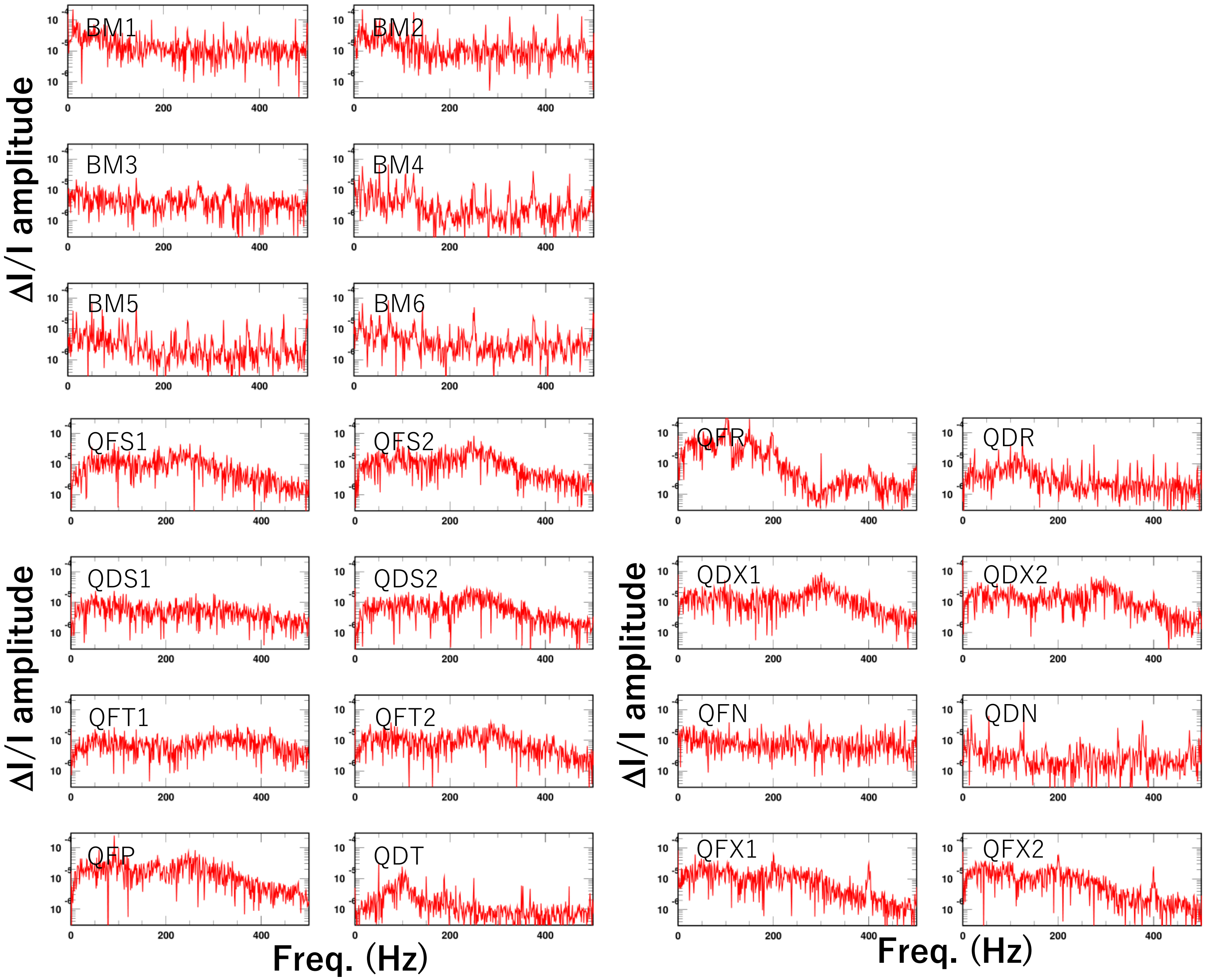
Current ripples in Spring 2023



Current ripples in Spring 2023



Frequency spectra of current ripples

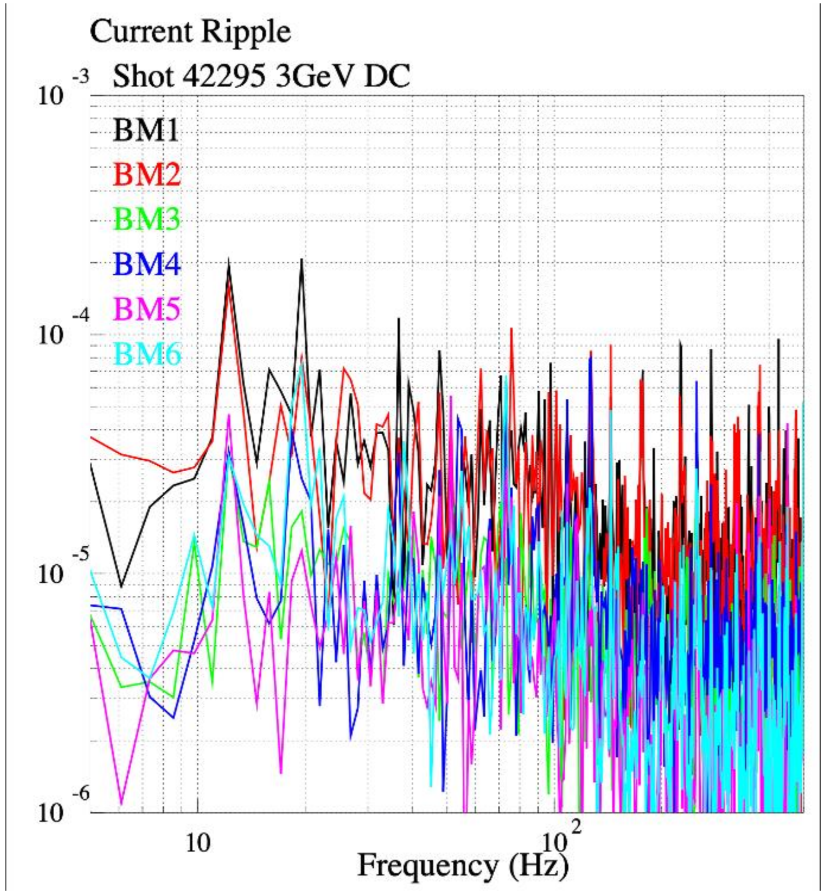


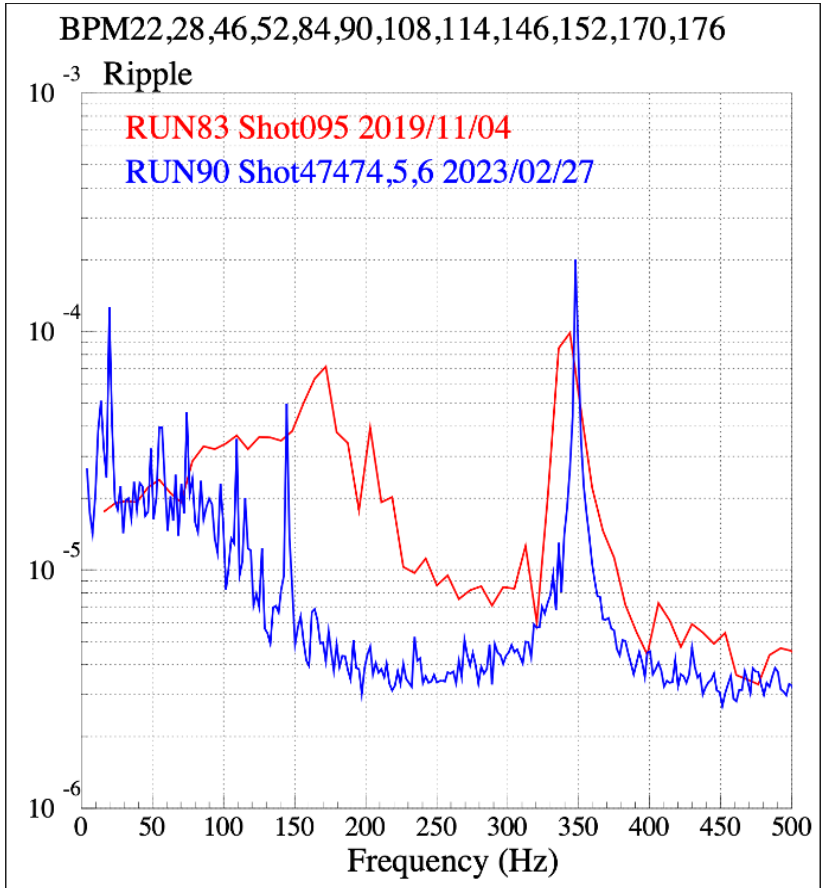
各偏向電磁石の電流リップル

S. Igarashi

高ディスパージョン位置でのビームのx方向振動をフーリエ解析し、 ビームベースで偏向電磁石リップルを測定した 20 Hz付近にピークが見える

ビームで測定したリップル





磁場リップルの導出

T. Yasui

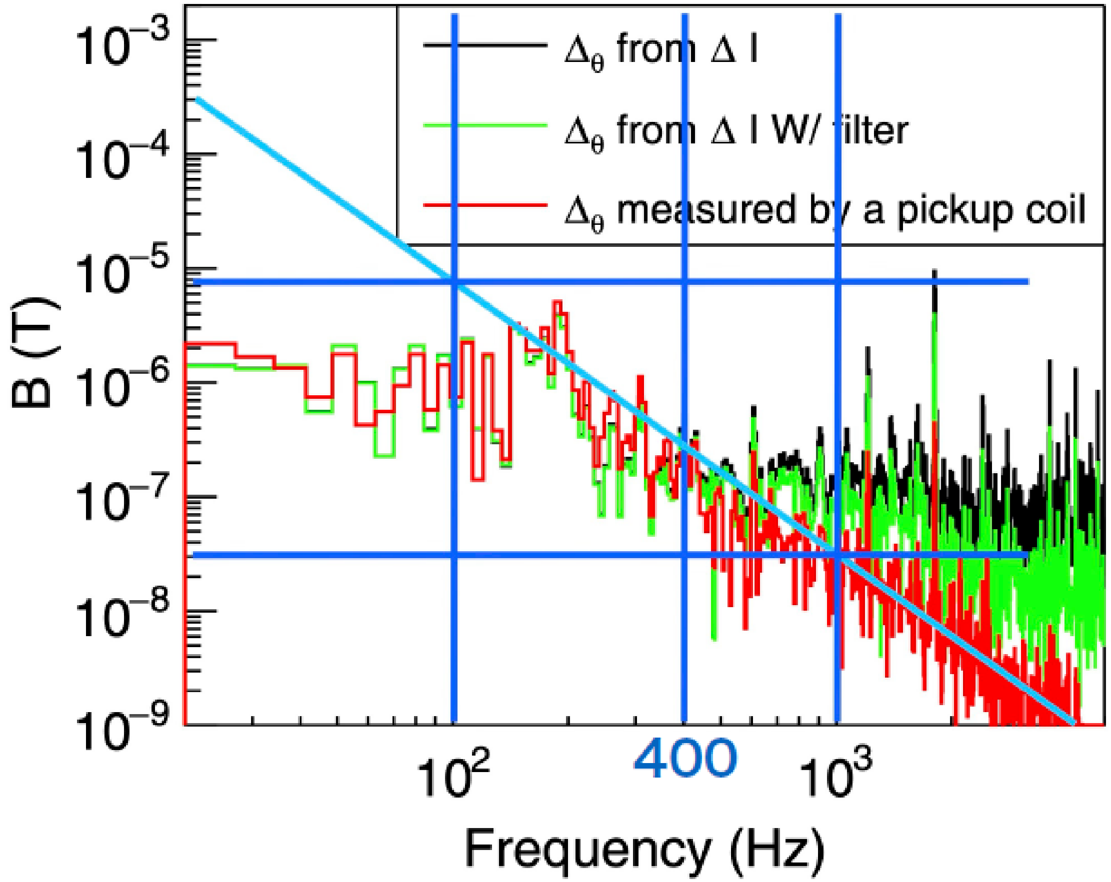
右図は電流リップルと
磁場リップルの比較例

電流リップルは
高周波も残っているが、
磁場リップル(赤線)の
高周波成分は小さくなっている

400 Hz以上について、
磁場リップルを目の子Fitした

電流の各周波数成分に
以下の係数gをかけた

$$g = \begin{cases} 1 & (f < 400\ \mathrm{Hz}) \\ \left(\frac{f}{400\ \mathrm{Hz}}\right)^{2\log_{10}2-3} & (f > 400\ \mathrm{Hz}) \end{cases}$$



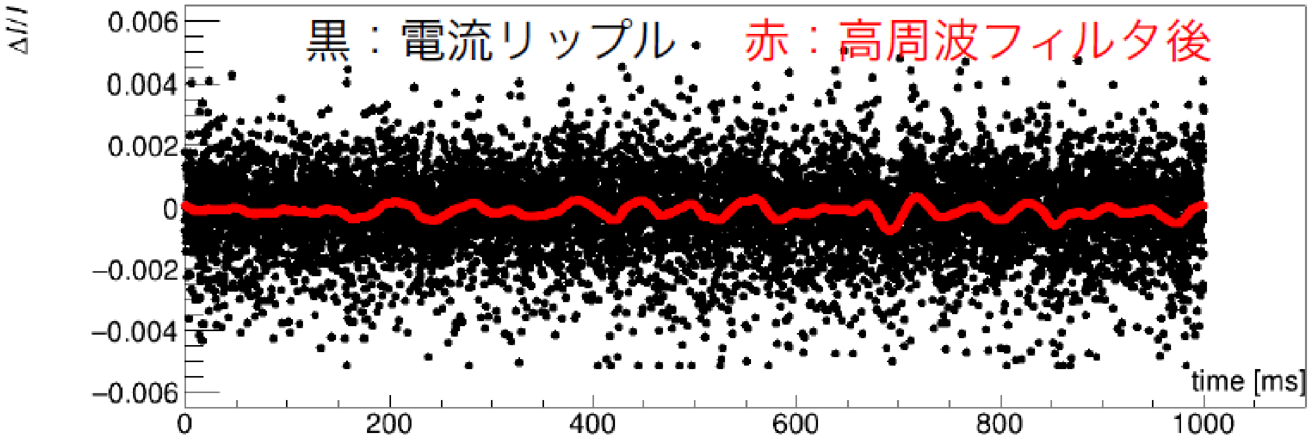
D. Naito *et al.*, PRAB **22**, 072802 (2019).

磁場リップルの値

T. Yasui

電流リップルの高周波成分をフィルタして標準偏差を求めた

BM1の例

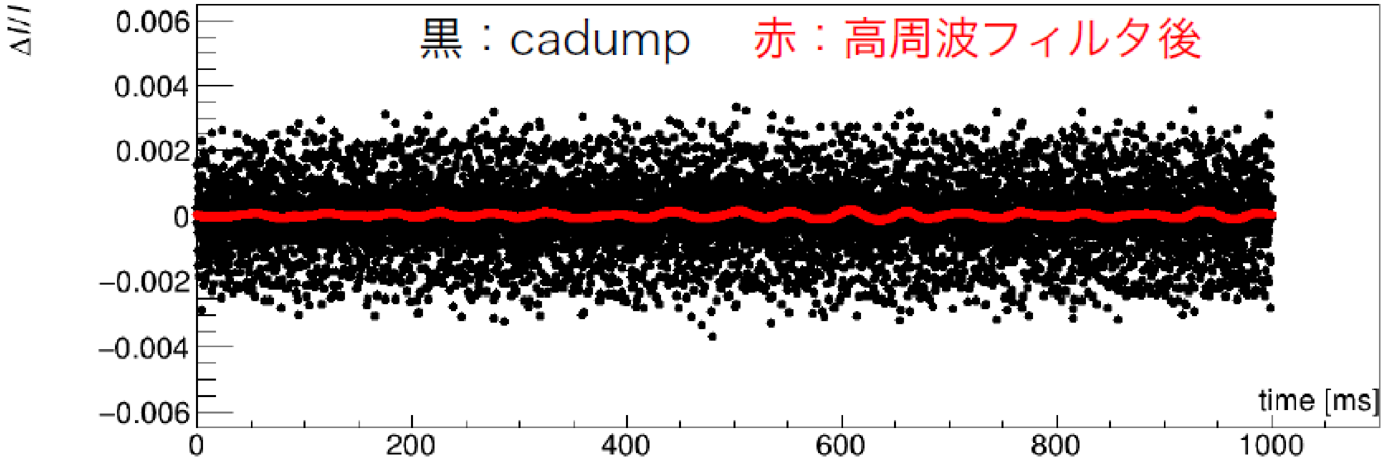


BM1	BM2	BM3	BM4	BM5	BM6
0.0191%	0.0176%	0.0055%	0.0077%	0.0042%	0.0071%
QFS1	QFS2	QDS1	QDS2	QFT1	QFT2
0.0026%	0.0034%	0.0020%	0.0017%	0.0025%	0.0028%
QFP	QDT	QFR	QDR	QFN	QDN
0.0069%	0.0006%	0.0153%	0.0022%	0.0081%	0.0075%
QFX1	QFX2	QDX1	QDX2	SD	SFA
0.0057%	0.0057%	0.0051%	0.0057%	0.0015%	0.0010%

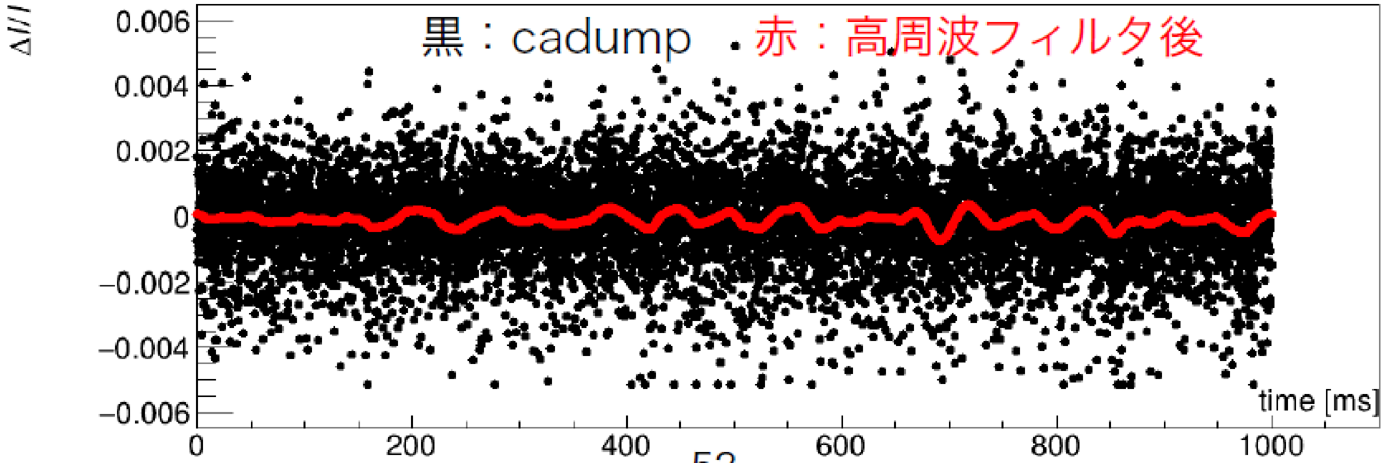
T. Yasui

解析にはトリガOFF時のデータを用いた

BM3の例



BM1の例



磁場リップルによるΔK_1

T. Yasui

偏向電磁石以外にも四極磁場誤差ΔK_1のソースとして、
四極電磁石のリップル、四極電磁石の個体差がある

各ΔK_1ソースごとに、半Arc単位で以下を評価した

$$\Delta K_{1,\mathrm{sum}} \equiv \sqrt{\sum_{\text{half Arc}} (\Delta K_1)^2}$$

	Bend ripple由来	Quad ripple由来	Quad個体差
Arc A1 (BM4)	0.000184	0.000061	0.000197
Arc A2 (BM5)	0.000101	0.000061	0.000208
Arc B1 (BM6)	0.000170	0.000062	0.000254
Arc B2 (BM1)	0.000459	0.000062	0.000197
Arc C1 (BM2)	0.000423	0.000062	0.000271
Arc C2 (BM3)	0.000133	0.000061	0.000206

分割四極ファミリーのリップル

T. Yasui

QFS1	QDS1	QFT1	QFX1	QDX1
0.0026%	0.0020%	0.0025%	0.0057%	0.0051%
QFS2	**QDS2**	**QFT2**	**QFX2**	**QDX2**
0.0034%	0.0017%	0.0028%	0.0057%	0.0057%

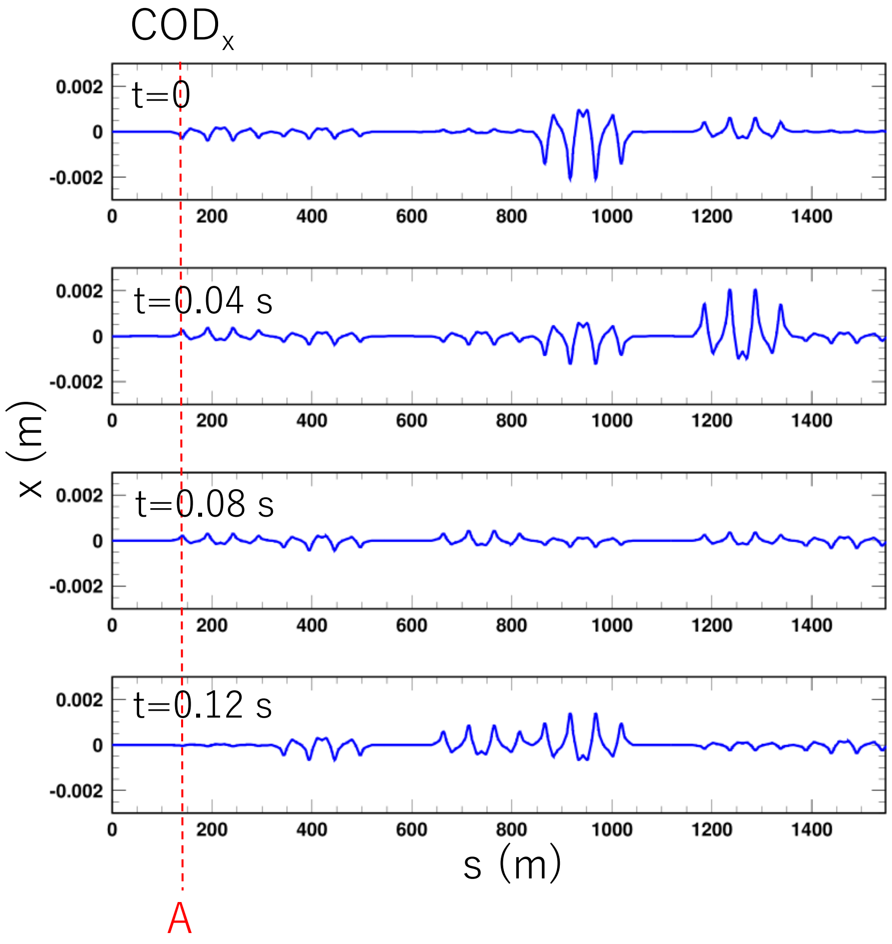
※全てdI/Iの高周波成分をフィルタして標準偏差を求めたもの

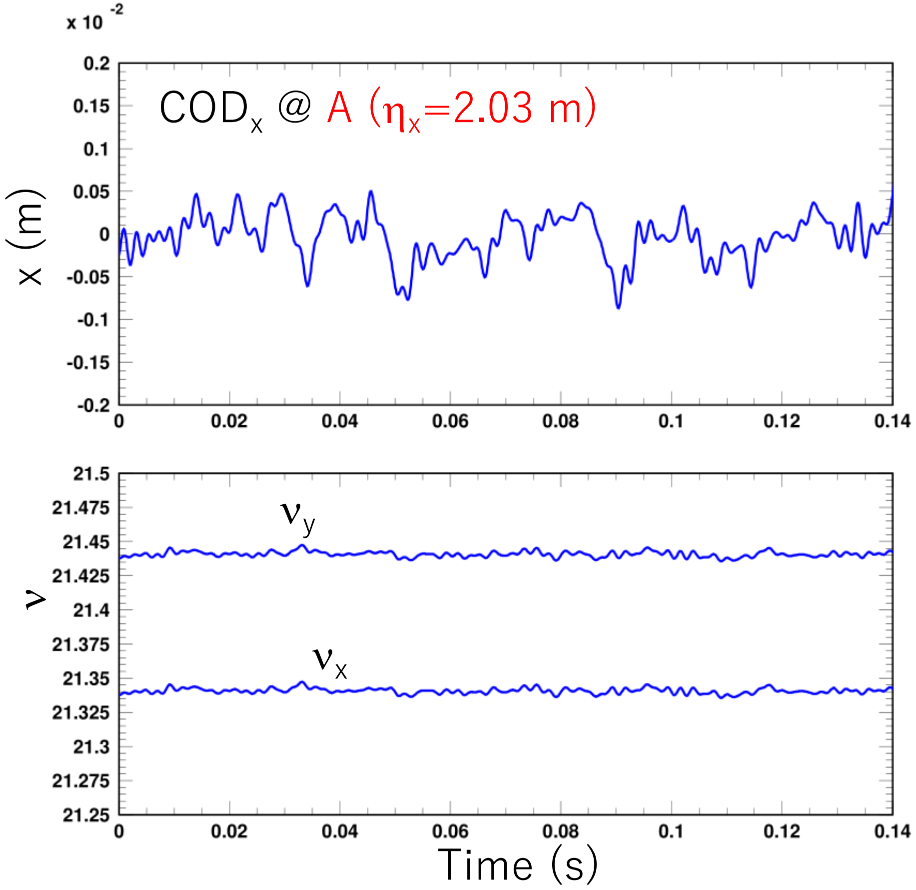
どれも0.1%より十分に小さいため、
分割四極ファミリーリップルがビームロスを悪化させるとは考えにくい

中央値を合わせ込みさえすればよい

Effects of BM ripples (<500 Hz) on COD

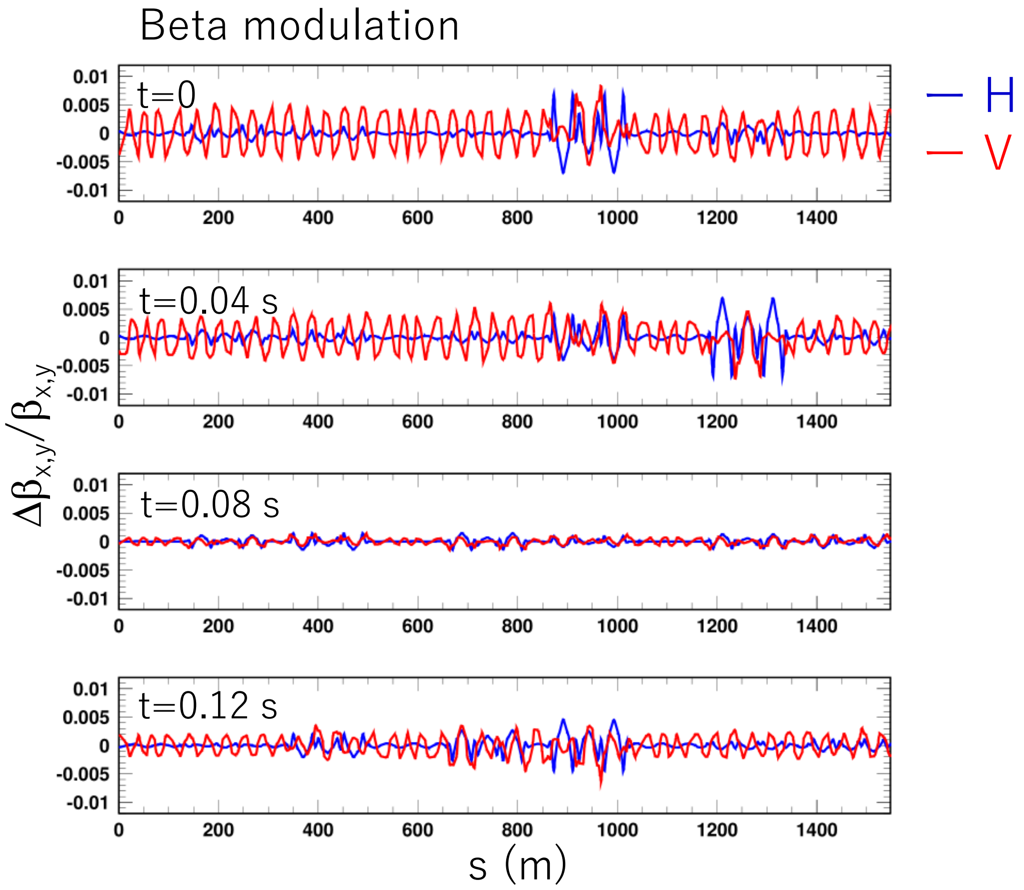
H. Hotchi





Effects of BM ripples (<500 Hz) on COD

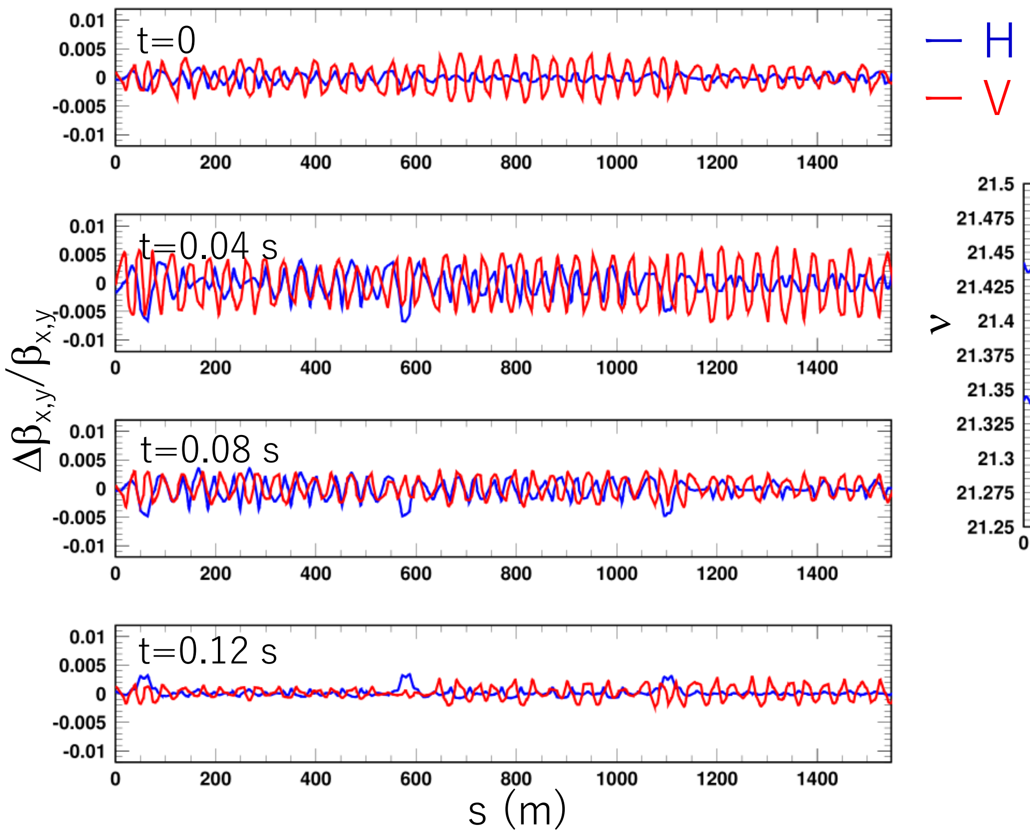
H. Hotchi

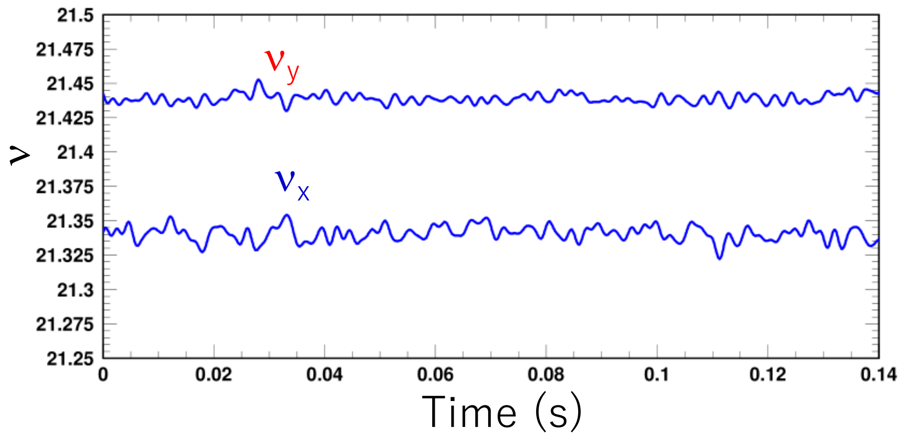


Effects of QM ripples (<500 Hz) on COD

H. Hotchi

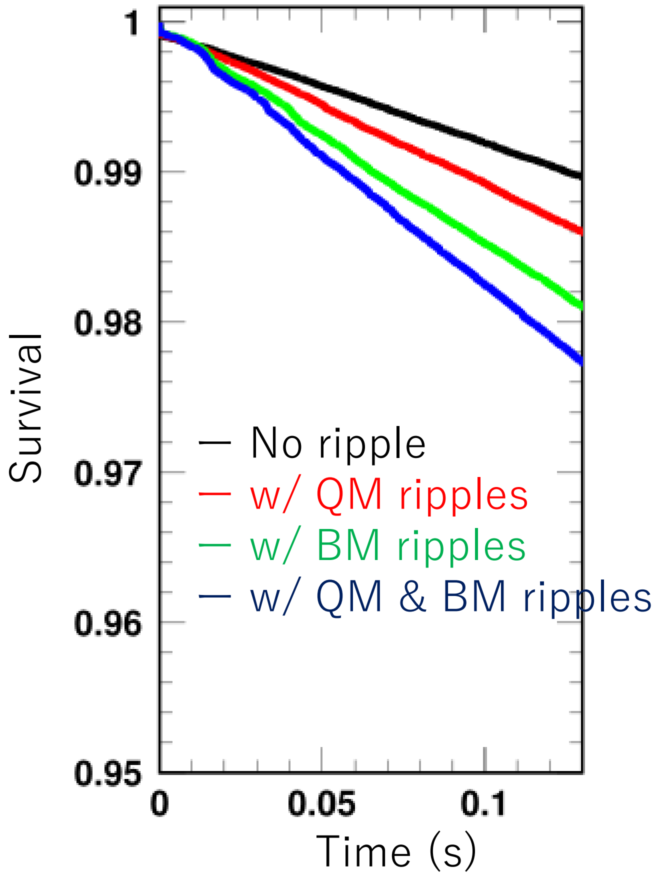
Beta modulation





Beam loss Simulations 1

Effects of Magnet Ripples



Survival ratio in Tracking Simulations (SIMPSONS)
1.3 MW-eq intensity (4.1 x 10^{13} ppb)

H. Hotchi

- ✓ Ripplesを導入することでロスが増加した
- ✓ 特にBM ripplesが有意なロス増加を引き起こしている
  - → Arc部にCODが非対称に発生
  - → CODとK_2成分（六極電磁石&BM中の六極成分）がカップルしてK_1誤差が発生
  - → 3回対称性が悪化
  - → エミッタンス増大

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

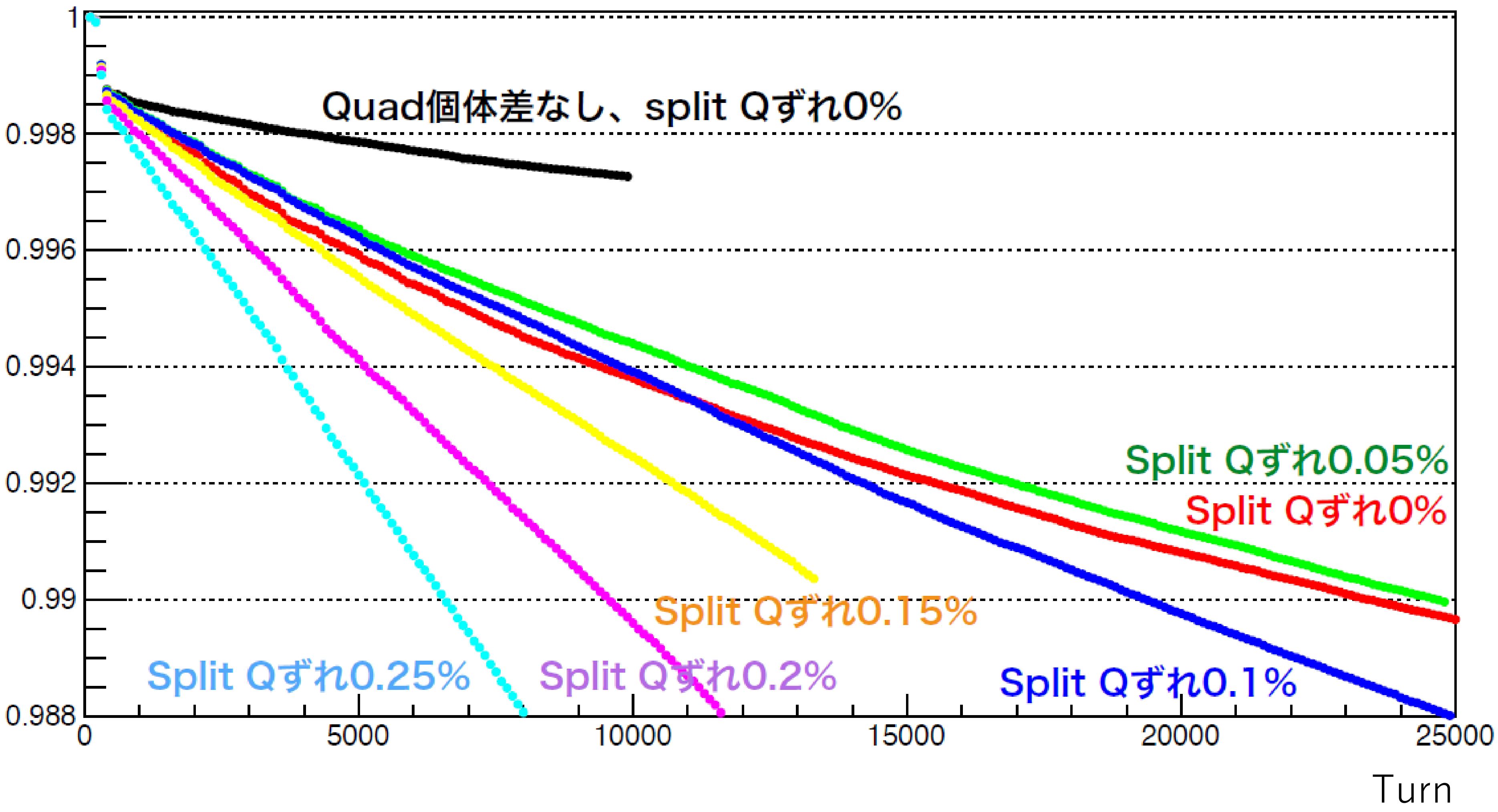
η_x: dispersion　　K_2: sext. field

Beam loss Simulations 2

Effects of Q imperfection
& Split Q discrepancy

Survival ratio in Tracking Simulations (SCTR)
0.9 MW-eq intensity (3.3 x 10^{13} ppb)

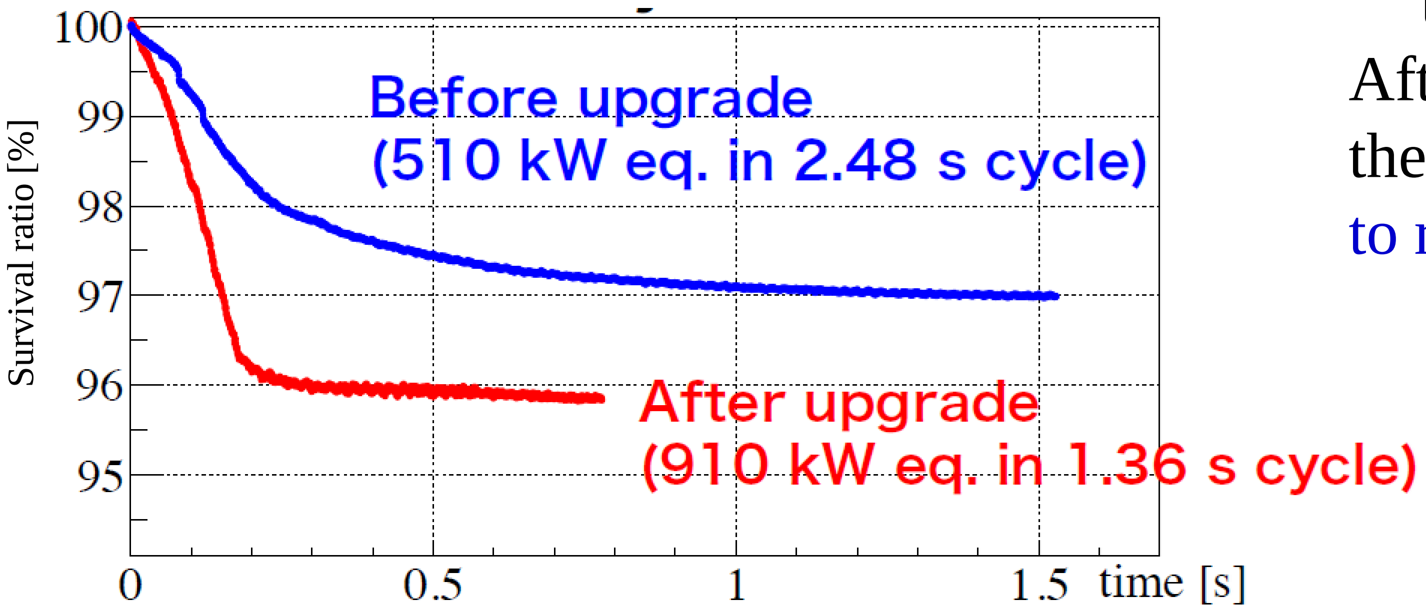
T. Yasui



Demonstration for 900 kW eq. (only with 2 bunches)

We tried higher intensity with 2 bunch of 3.3 x10^{13} ppb,
which were the same ppb for 510 kW in 2.48 s cycle by 2021.

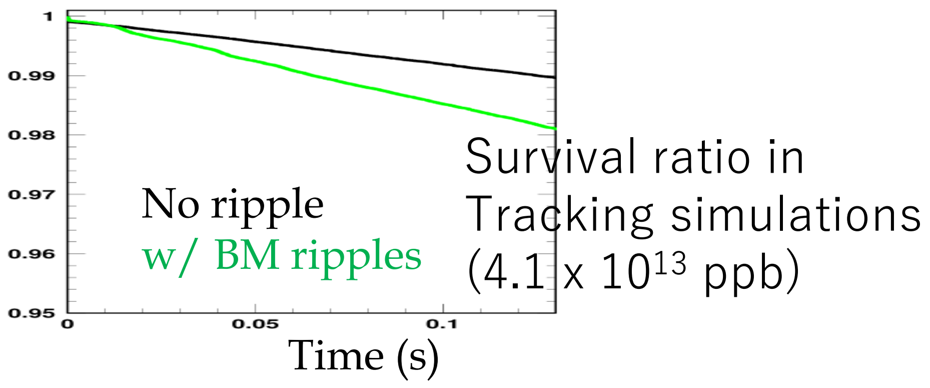
Survival ratio of 3.3 x10^{13} ppb (DCCT meas.)



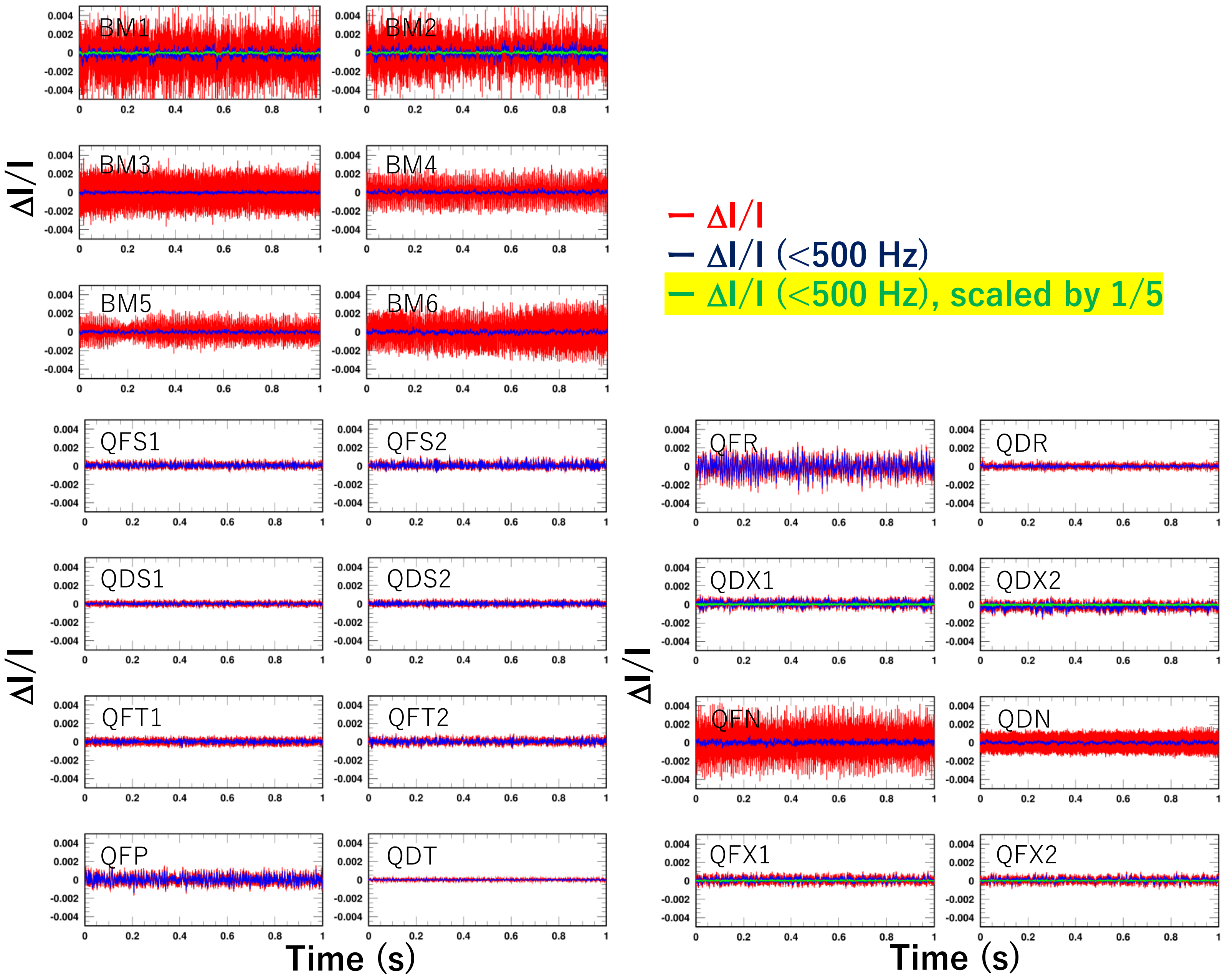
A major difference came from

- ✓ The **Low freq. ripples of 2 BM-PSs** tortured Optics Symmetry.

After completing commissioning of the 2 BM-PSs this Fall, we can expect to reproduce 2021-survival ratio.



Current ripples

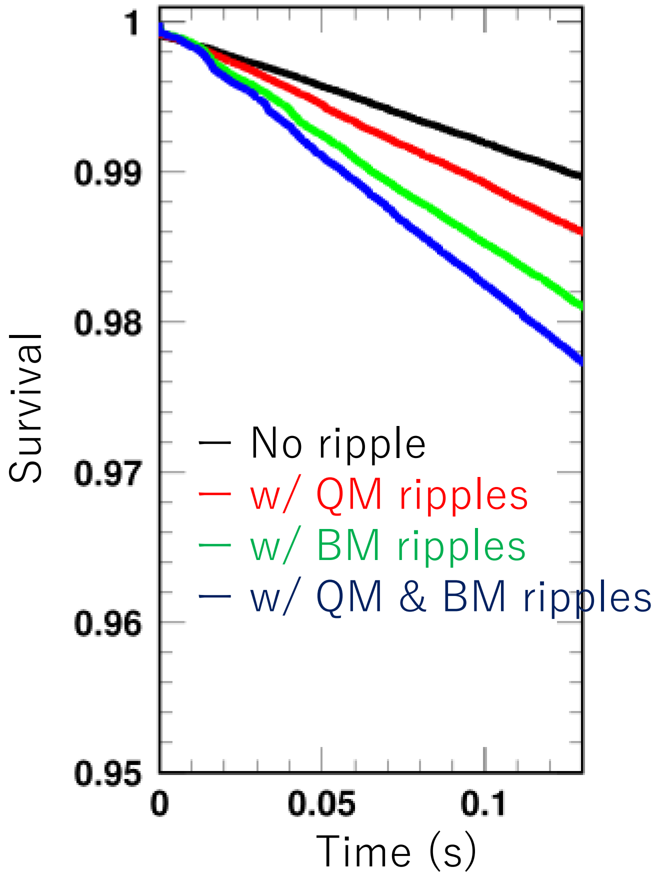


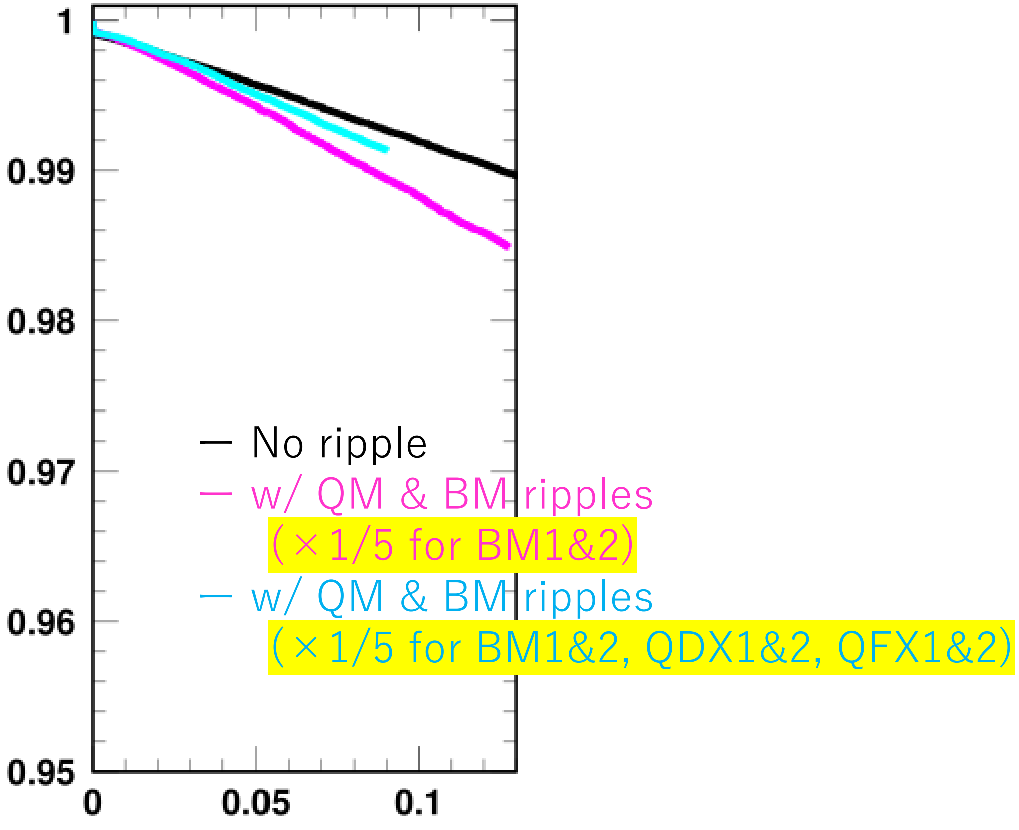
Beam loss Simulations 1+

Effects of Magnet Ripples

Survival ratio in Tracking Simulations
1.3 MW-eq intensity (4.1 x 10^{13} ppb)

H. Hotchi

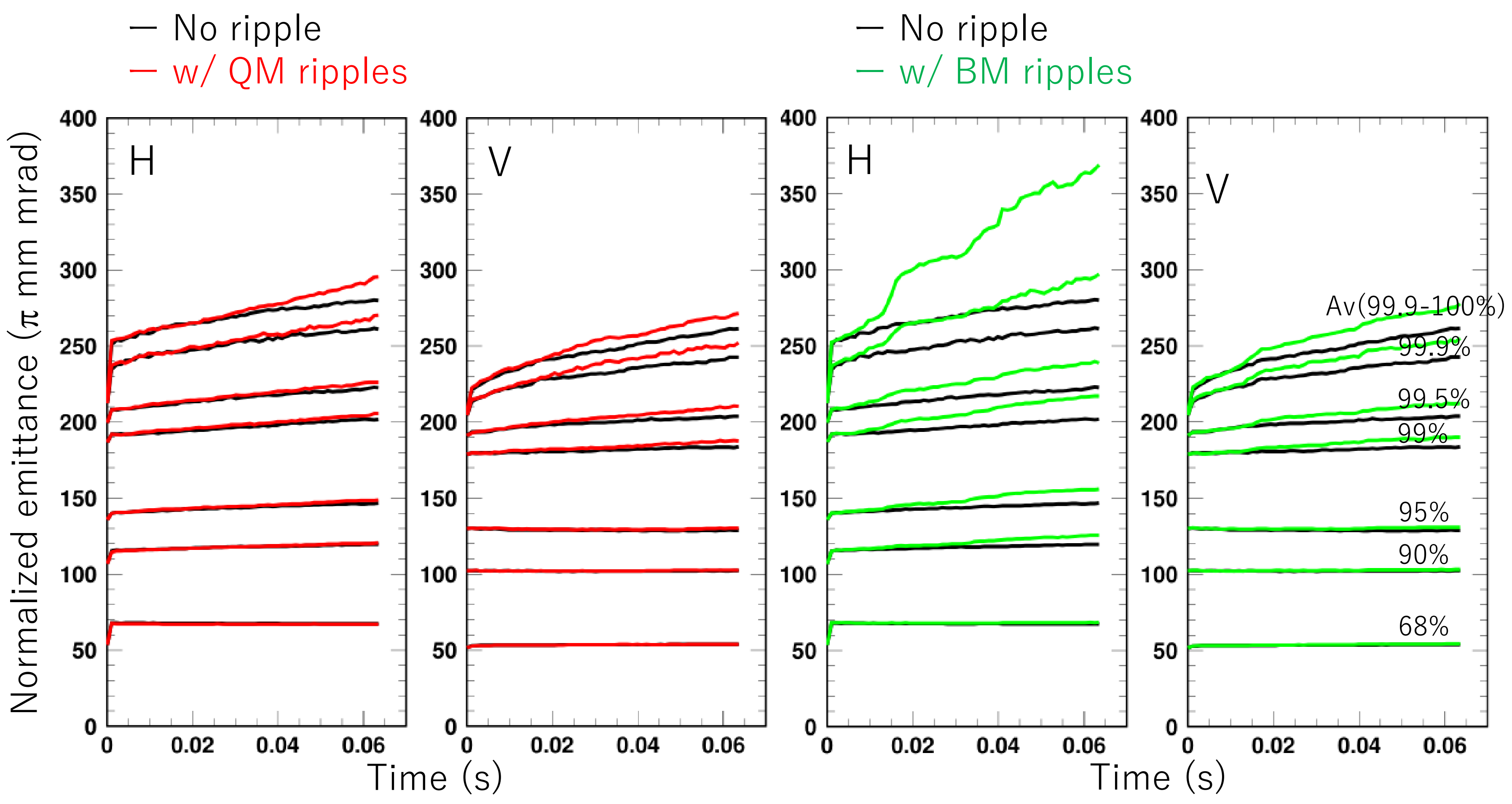




- ✓ ロスに大きく寄与しているのはBM1&2、次はQDX1&2とQFX1&2
- ✓ QFP, QFR→rippleは大きいがロスへの寄与はほとんどない
（ラティスの対称性は崩れない）

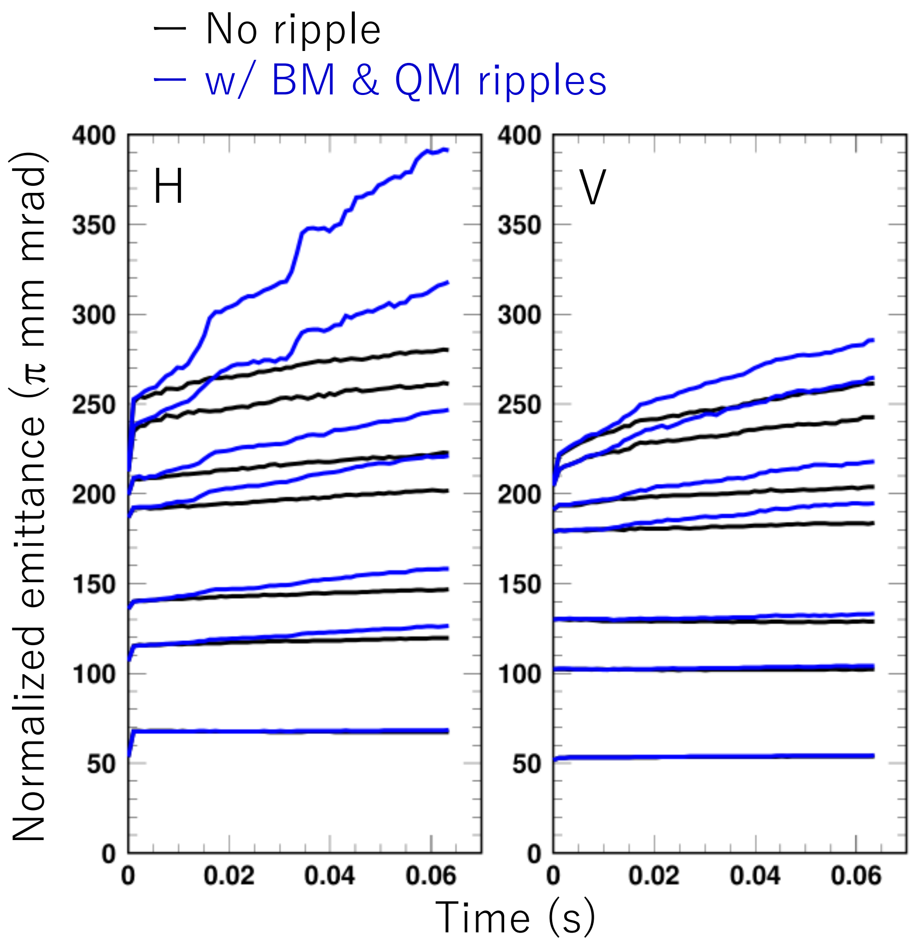
H. Hotchi

Emittance growth



H. Hotchi

Emittance growth

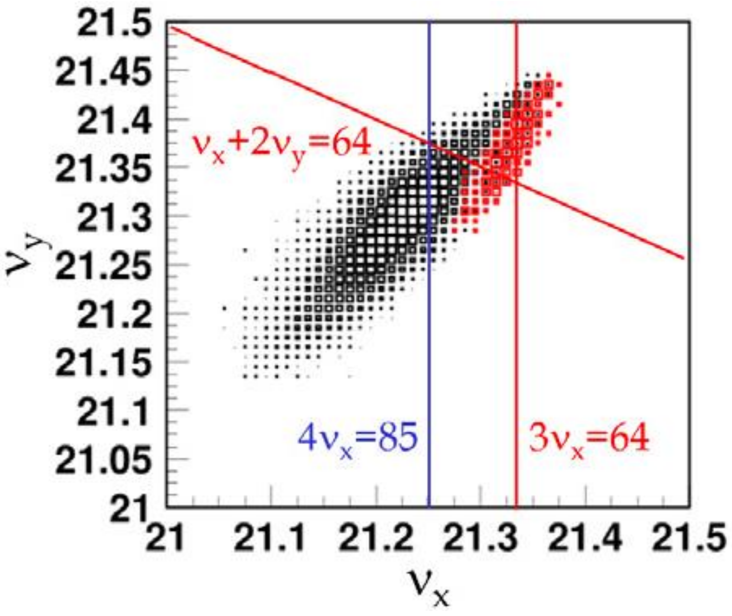


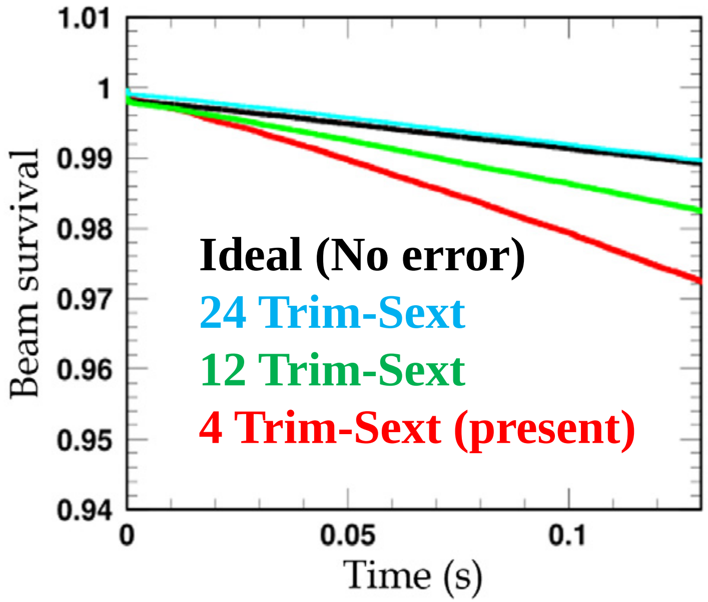
Upgrade Plan of Correction Magnet System

- ✓ 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
(4.1×10^{13} ppb)

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





With 24 Trim-Sext System

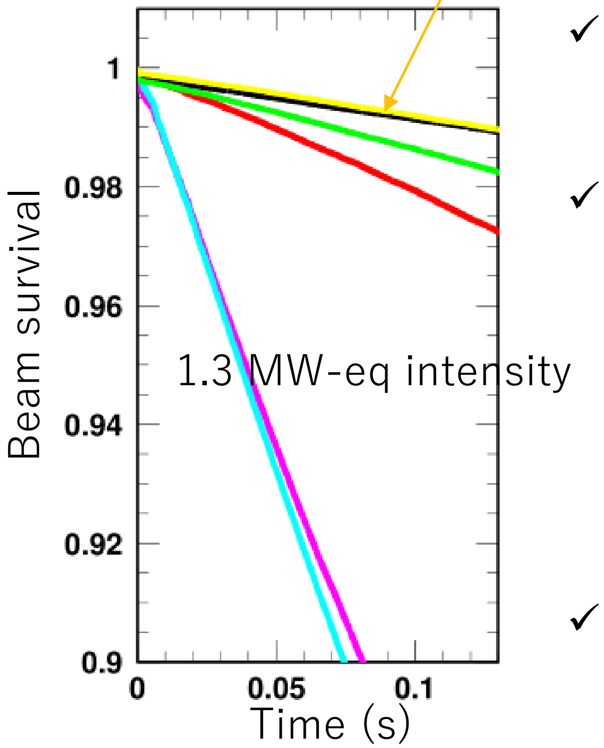
Simulations

Effects of Magnet Ripples on Upgrade Plan of Trim Coil Corr. System

H. Hotchi

✓ ATACで発表した1.3 MWシミュレーションにBM & QM ripples（<500 Hz）を追加
→エミッタンス増大やロスがどう応答するかを確認した

— Ideal lattice (no lattice error)
— Trim-Q on, Trim-S on (4 sets)
— Trim-Q on, Trim-S on (12 sets)
— Trim-Q on, Trim-S on (24 sets) ←BM & QM ripplesを追加



✓ Updated lattice errors
 - Measured beta functions
 - Measured resonance driving terms

✓ Actual experimental conditions
 - Beam intensity： 4.1 x 10^{13} ppb (1.3-MW eq.)
 - Betatron tunes: （21.34, 21.44）
 - Collimators：
  COL-A: H65π,V61π
  COL-B,C: H75π,V75π, COL-H: H67π,V67π
 - Input beam distribution
  reconstructed from the measurements

✓ Measured BM & QM ripples (<500 Hz) ←追加

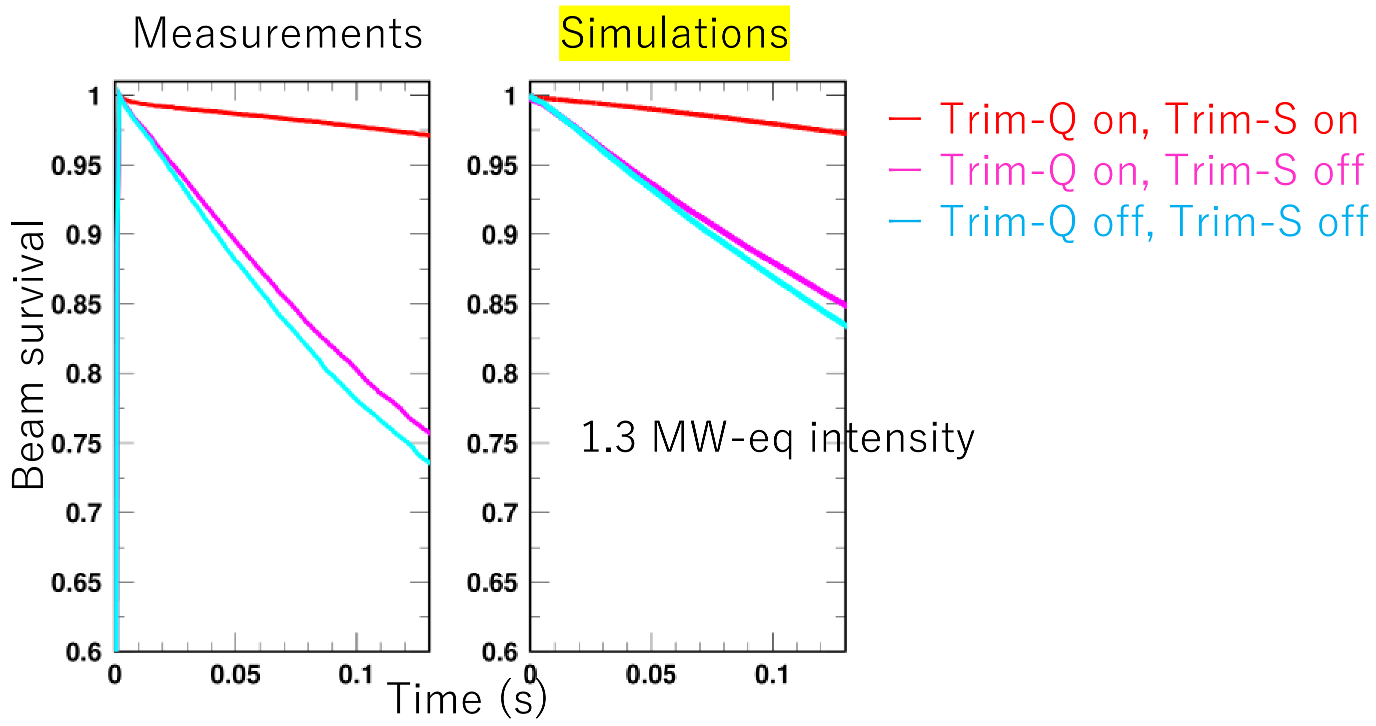
Set of “Trim-Q on, Trim-S on (24 sets)“ is tough for BM/QM ripples

With 4 Trim-Sext (present) System

Measurements vs simulations

H. Hotchi

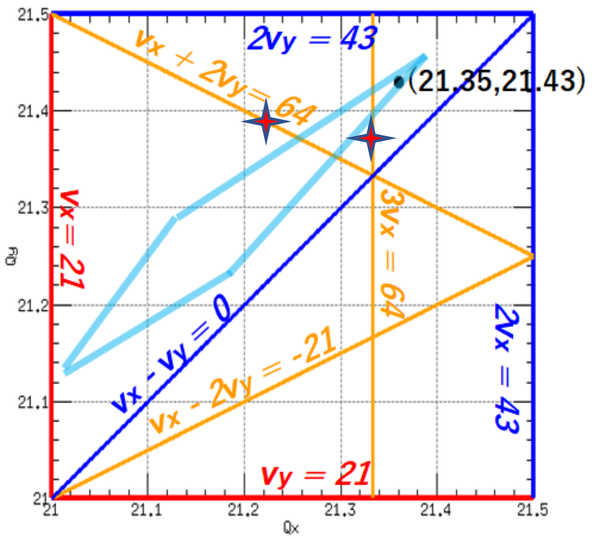
Effects of Trim Coil Corr. System

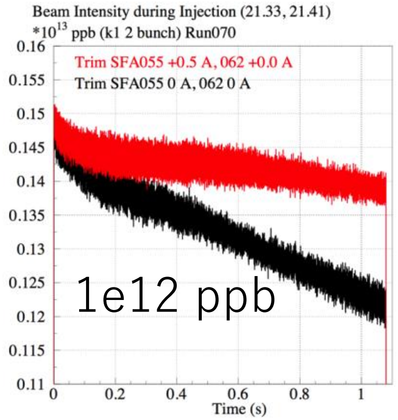


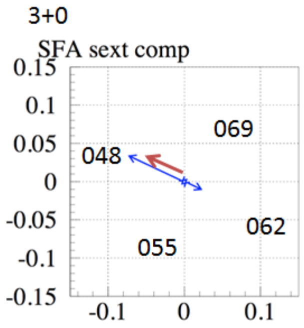
With 4 Trim-Sext (present) System

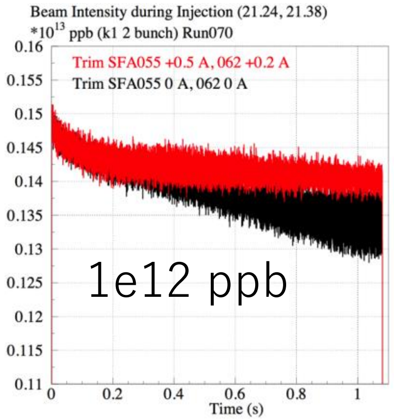
Correction of the 3rd order resonances of both νx+2νy = 64 and 3νx = 64

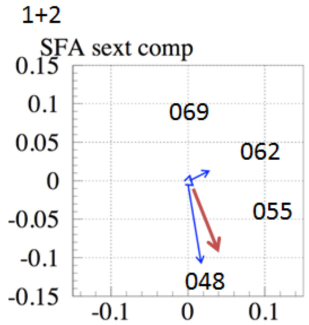
S. Igarashi et al., Proc. HB2016, pp 21-26, 2016











$$G_{3,0,64} = \frac{\sqrt{2}}{24\pi} b_x^{3/2} k_2 \exp[i(3f_x)]$$

$$G_{1,2,64} = \frac{\sqrt{2}}{8\pi} b_x^{1/2} b_y k_2 \exp[i(f_x + 2f_y)]$$

Activated trim-coils of 4 sextupole magnets locating independent phase

$$\sum_{j=2}^{3} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\, k2(j) \cos[3\phi_x(j)]$$
$$\sum_{j=2}^{3} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\, k2(j) \sin[3\phi_x(j)]$$

Measured G 3,0,64 w 2 Trim-Ss

$$\sum_{j=2}^{3} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\, k2(j) \cos[\phi_x(j)+2\phi_y(j)]$$
$$\sum_{j=2}^{3} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\, k2(j) \sin[\phi_x(j)+2\phi_y(j)]$$

Measured G 1,2,64 w 2 Trim-Ss

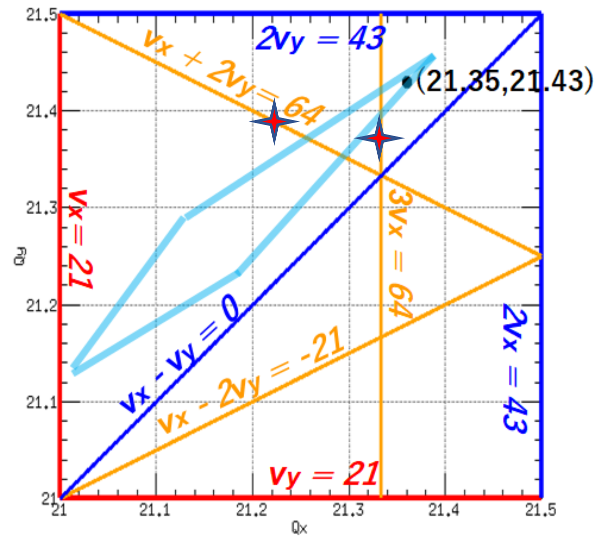
1 = T-SFA048, 2 = T-SFA055, 3 = T-SFA062, 4 = T-SFA069

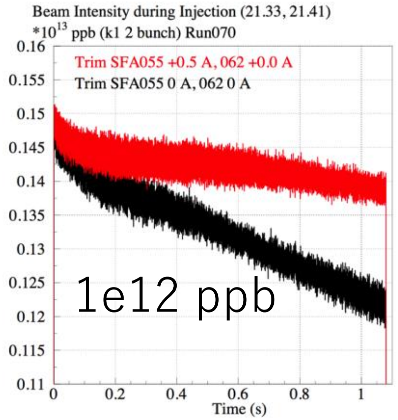
- Scanning 2 trim-sextupoles identify the driven factors of νx+2νy = 64 and 3νx = 64
- 4 parallel eqs. provide a solution to correct both lines simultaneously with 4 trim-sextupoles
- Beam losses were reduced with the correction not only injection but acceleration
- We keep investigating the resonance sources.
  Residual magnetism of the resonance sextupoles (RSX) for SX → degaussed in FX operation.

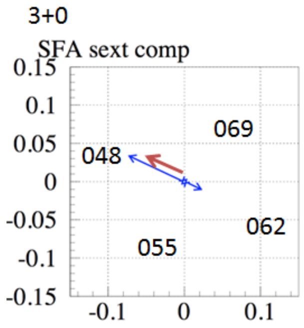
With 4 Trim-Sext (present) System

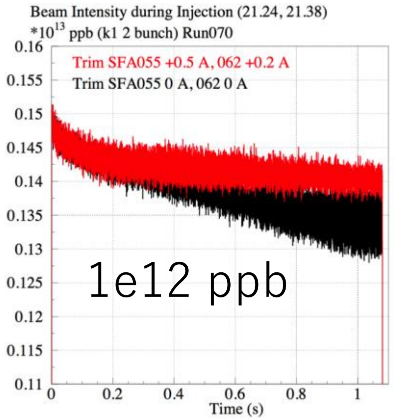
Correction of the 3rd order resonances of both νx+2νy = 64 and 3νx = 64

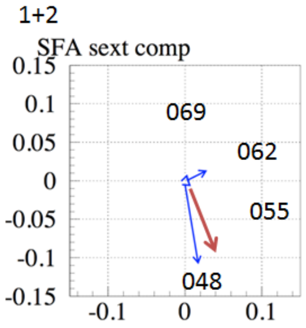
S. Igarashi et al., Proc. HB2016, pp 21-26, 2016











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Calc. k2 of 4 Trim-Ss for both G 3,0,64 G 1,2,64

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\, k_2(j) \cos[3\phi_x(j)] = \sum_{j=2}^{3} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\, k_2(j) \cos[3\phi_x(j)]$$

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\, k_2(j) \sin[3\phi_x(j)] = \sum_{j=2}^{3} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\, k_2(j) \sin[3\phi_x(j)]$$

Measured G 3,0,64 w 2 Trim-Ss

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\, k_2(j) \cos[\phi_x(j)+2\phi_y(j)] = \sum_{j=2}^{3} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\, k_2(j) \cos[\phi_x(j)+2\phi_y(j)]$$

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Measured G 1,2,64 w 2 Trim-Ss

Equations for canceling both resonances, for $k_2(1)$, $k_2(2)$, $k_2(3)$, $k_2(4)$.
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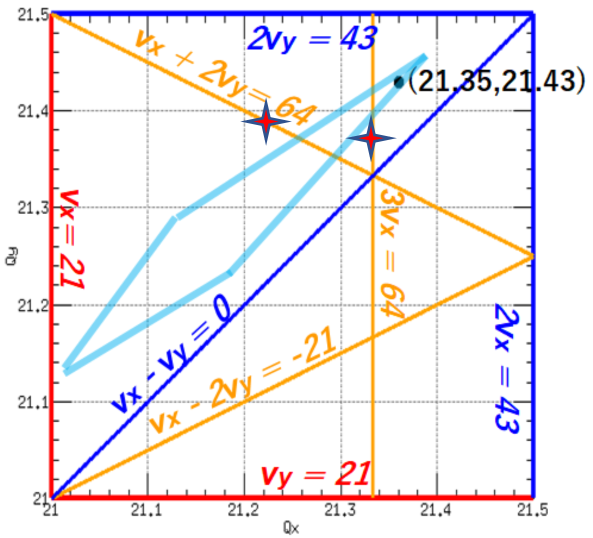

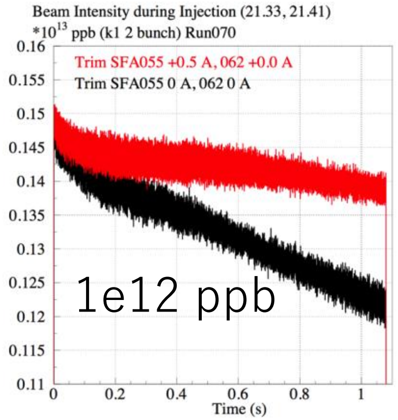

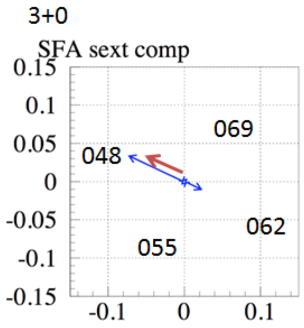

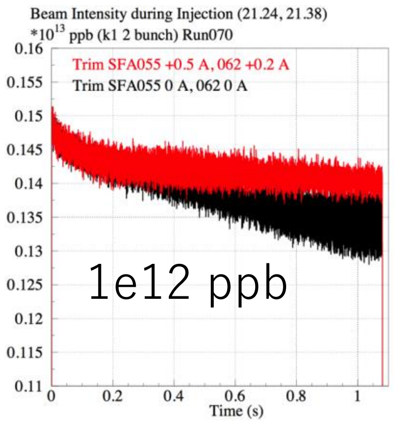

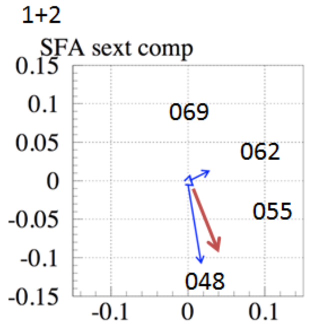

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Measured G 3,0,64 w 2 Trim-Ss

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\, k_2(j) \cos[\phi_x(j)+2\phi_y(j)] = \sum_{j=2}^{3} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\, k_2(j) \cos[\phi_x(j)+2\phi_y(j)]$$

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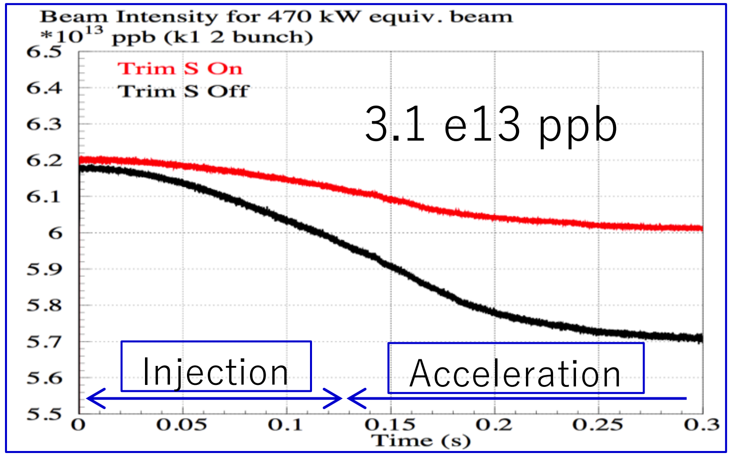

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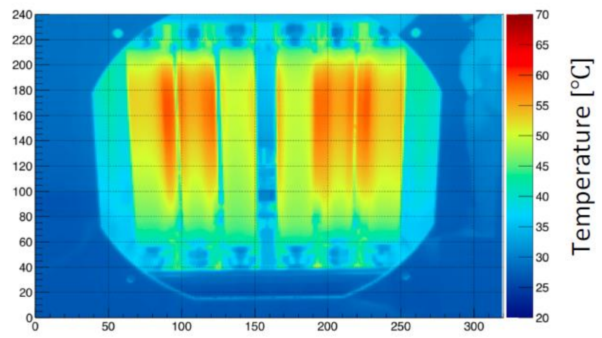
Effect of Hardware Upgrades

- Injection/FX systems
- RF systems
- Monitors

Injection / FX system Upgrades

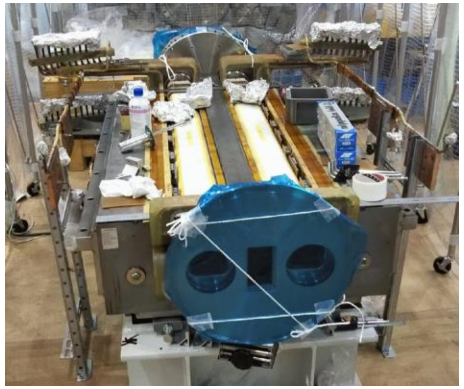
Injection	
Kicker * (Inj. and Comp.)	Design work is in progress for the cooling of the matching box.
Septum**	Magnet and power supply were replaced and ready for 1 Hz operation.
Fast Extraction	
Kicker	HV charger was upgraded and ready for 1 Hz operation.
Low Field Septum**	Magnets and PS constructed.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

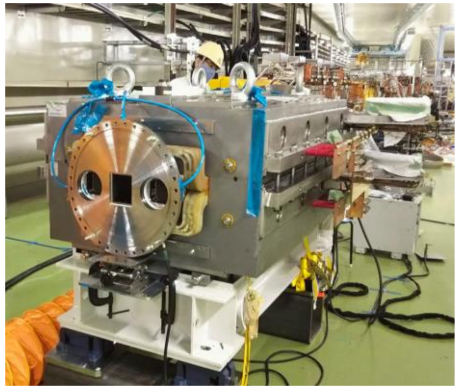


Vcharge=47.5kV, Ipeak=2580A, P=5.20W

* 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.



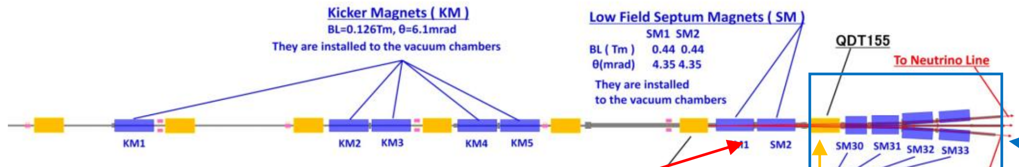


FX system Upgrades

K. Fan *et. al.*, in Proc IPAC'14 p821

- *Upgraded and ready for 1 Hz operation and high intensity operation.*
- *New FX septum magnets (2 for low field, 3 of 4 for high field)*
- *New FX septum magnets have Less Impedance, Larger Aperture, and* **Less Leakage Field**

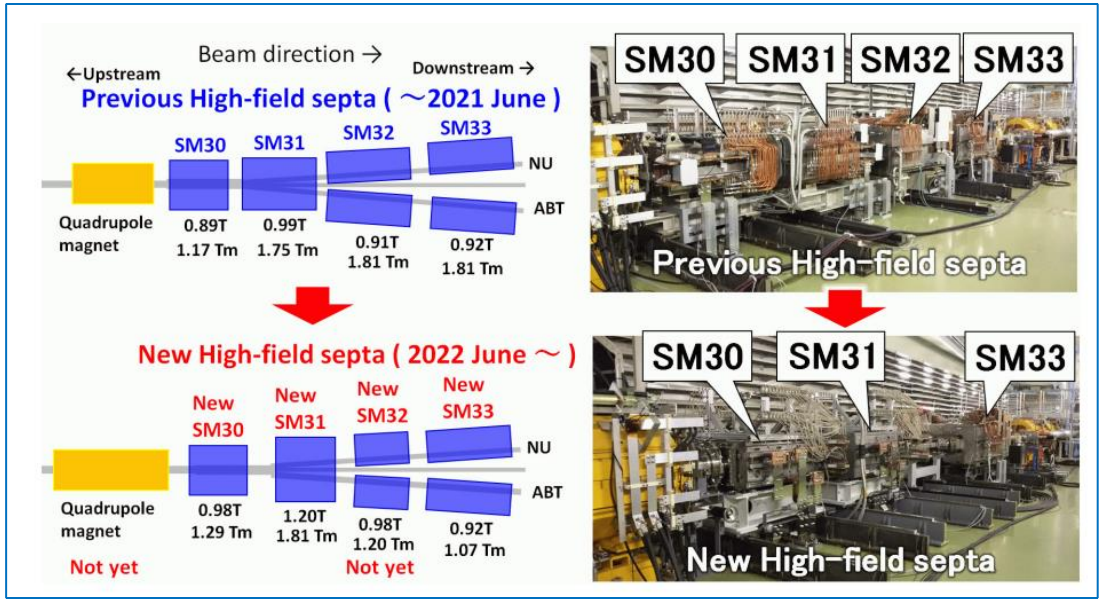
A. Kobayashi, *et. al.*, NIMA1031 (2022) 166515



New eddy current septum magnet

QDT155

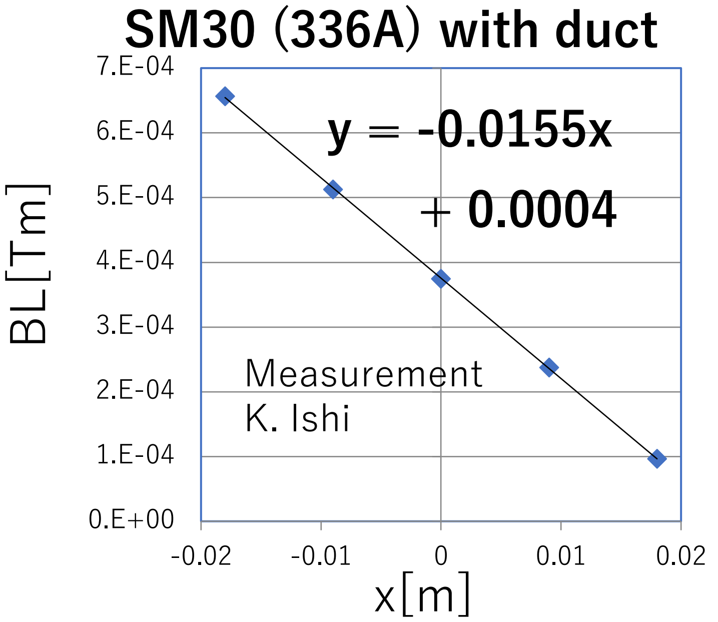
T. Shibata *et. al.*, TUPM103, IPAC'23



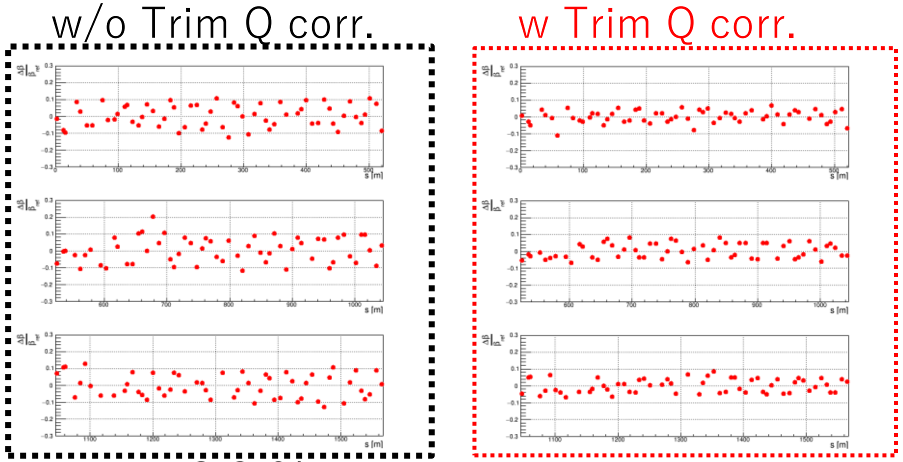
New pure iron duct-type magnetic shields
in the circulating ducts of the two high-field FX-septa in 2022

FX Septum Leak field from Previous System and Adopted Measures by JFY2021

QFR 154 | SM11-22 | QDT 155 | SM30-33 | QFP 156

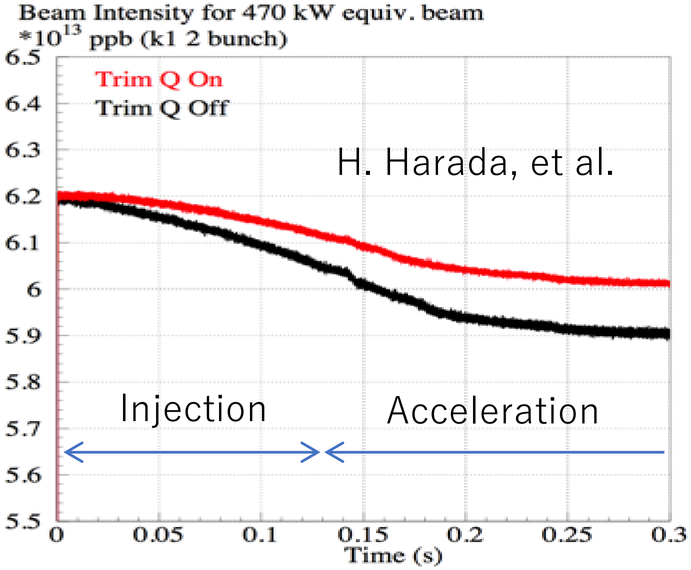


βy modulation



σ=6.9 % σ=4.1 %

Kurimoto, et al.

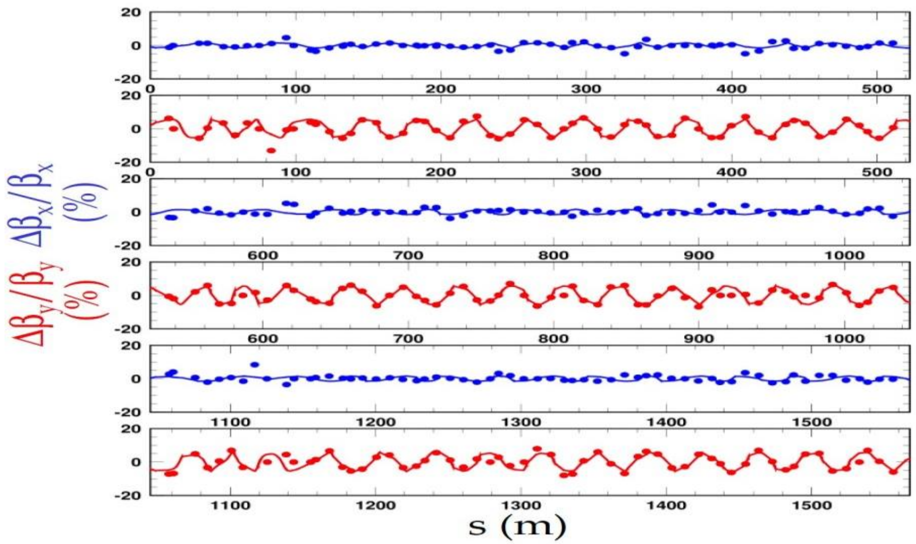


- **Leak field of 8 FX septum magnets corresponds to ~3% of K1 of the main Q magnet.**
  → One of main sources of beam optics modulation and reduce MR physical aperture
- **Trim coils of 3 Q magnets have been used to correct the leak field of FX septum magnets.**
- All main quadrupoles are also adjusted to correct beam optics (tune, beta, phase advance, dispersion, chromaticity) in not only injection but also acceleration.
- **The beam loss was reduced with these adjustments.**

Less FX Septum Leak field in New System and No-need of ΔK1 correction

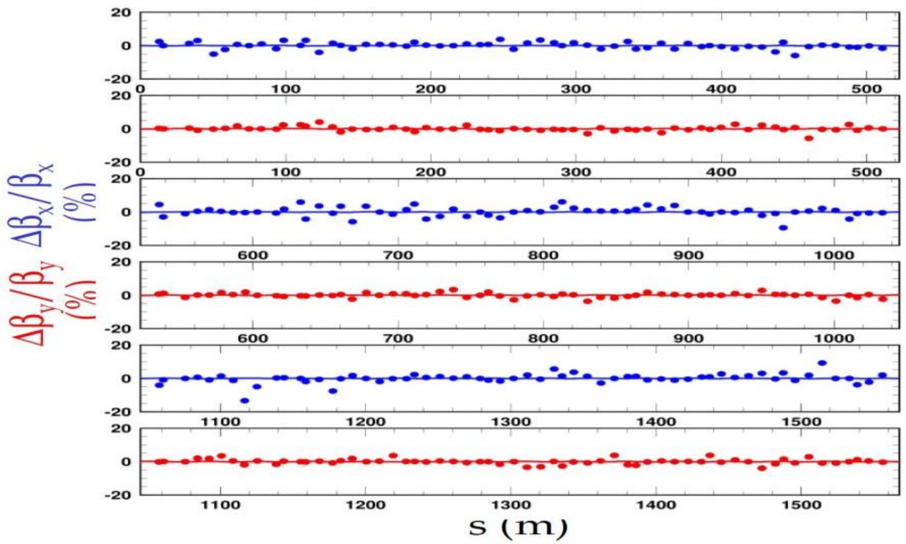
- ✓ **FX septum magnets were replaced to new magnets in the upgrade.** They have features of Less Impedance, Larger Aperture, and **Less Quadrupolar Leakage Field.**
- ✓ Beta measurements revealed that
  - Previous FX septum magnets had serious leakage field and caused optics modulation.
  - New FX septum 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



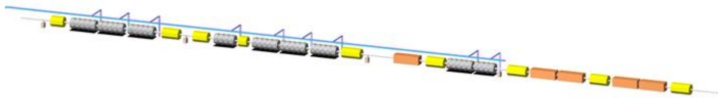
$|\Sigma(\Delta K_1 L)| < 0.00015\ m^{-1}$

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

RF system Upgrades

- 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.

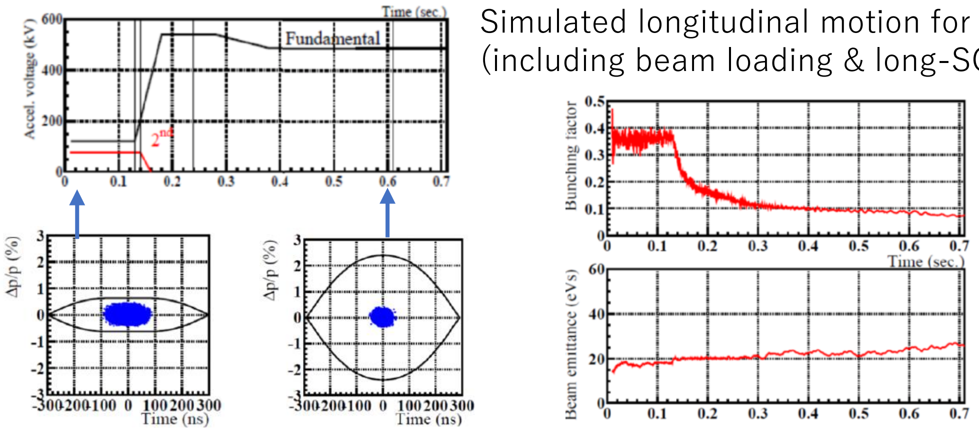
	2020	2023	2026
MR Cycle	2.48 s	1.32 s	1.16 s
FT3L 4GAP Cavities	7	9	11
2nd Harmonic Cavities	2	2	2
Accelerating Voltage	300 kV	510 kV	600 kV
2nd Harmonic Voltage	110 kV	110 kV	110 kV



Cavities at MR Ins C

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

Ins B: **2 fundamental** cavities in 2026

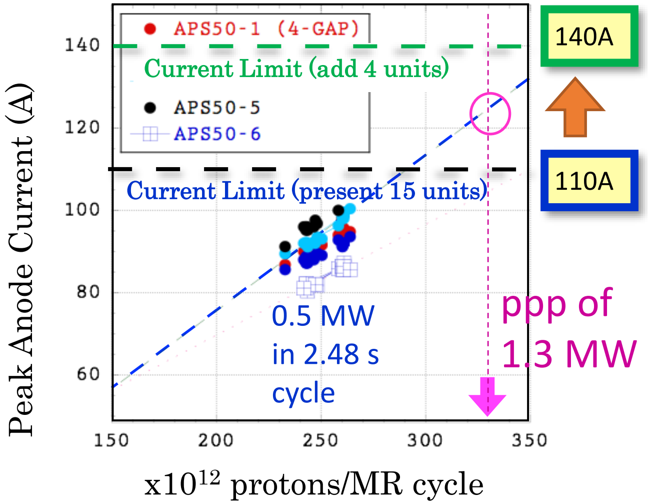


Simulated longitudinal motion for 1.16 s cycle (including beam loading & long-SC)

M. Yamamoto

- 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

Status of RF system Upgrades in 2023

RF cavity increment

M. Yoshii *et. al.*, in Proc IPAC'18 p984
K. Hasegaea *et. al.*, in Proc IPAC'22 p2031

Faster acceleration to 30 GeV: 1.4 s (2.48 s cycle) → 0.65 s (1.36 s cycle)

✓ Enough V_RF

✓ Enough anode PSs

RCS RF Anode power supply

	2021	2023	2026
MR Cycle	2.48 s	1.36 s	1.16 s
FT3L 4GAP Cavities	7	9	11
2^{nd} Harmonic Cavities	2	2	2
Accelerating Voltage	300 kV	510 kV	600 kV
2^{nd} Harmonic Voltage	110 kV	110 kV	110 kV

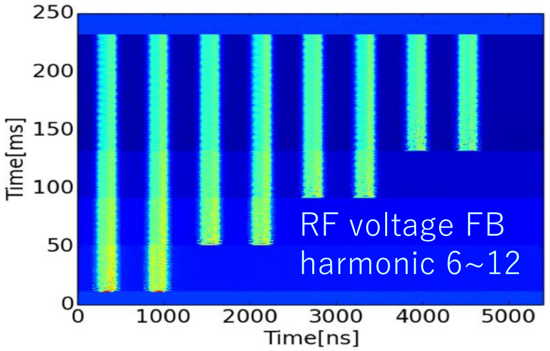
Complete the upgrade in 5 years

RF system upgrade

Y. Sugiyama *et. al.*, TUPM056, IPAC'23

✓ Compression of new LLRF feedback system having vector voltage FB

Longitudinal oscillation WCM for 2.5×10^{14} ppp



- **Longitudinal tuning processes are almost the same as in 2021.**
- **LLRF FB works for stable acceleration for high intensity beam**
- **Anode PSs is to be ready for 800 kW within JFY2023.**

MR beam diagnostics monitors & intra-bunch feedback

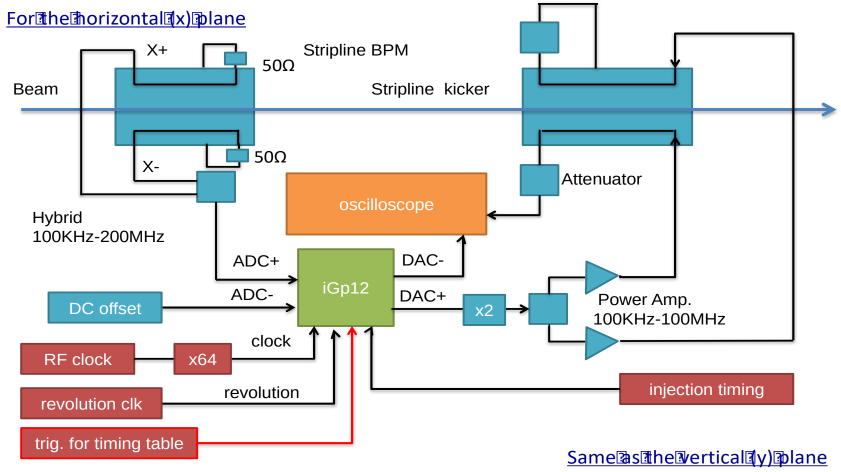
Mission: Provide the diagnostics for realization of 750 kW – 1.3 MW beam operation in the J-PARC MR

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

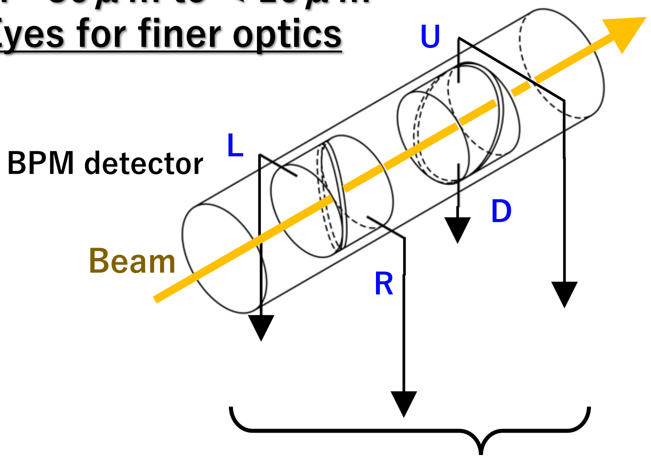
Shorten the damping time (>30%)



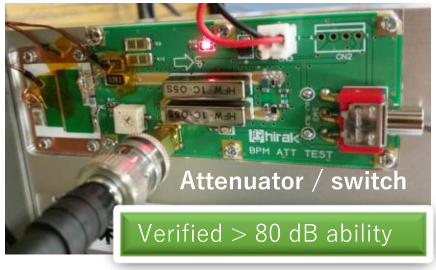
Task (2) Upgrade of the BPM circuits

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

-> Eyes for finer optics



Develop New Signal Acquisition System



Large Data Storage is needed also

Signal processing circuit

Noise filter

Attenuator/switch

ADC

FPGA + Memory

CPU + Network

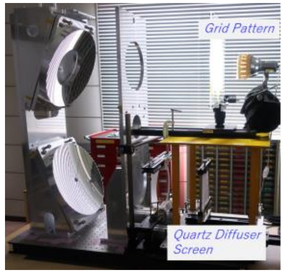
Task(3) OTR profile monitor in the MR

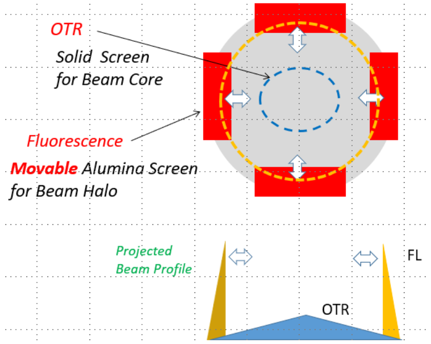
Measure the 2D profile and halo of the injected beam into the MR

-> Eye for Halo collimation by COLs

-> Eye for Halo reduction by optics

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



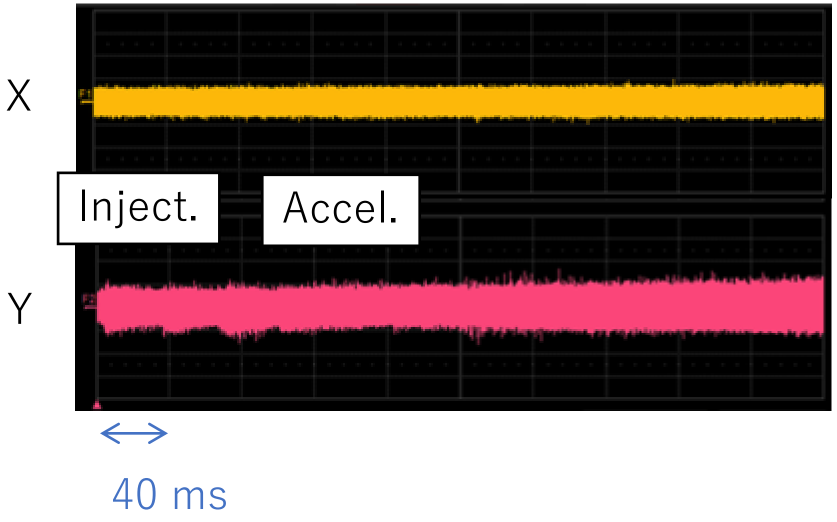


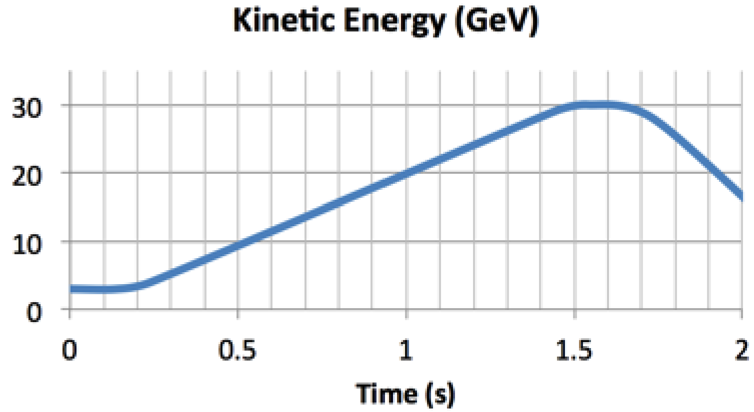
Same type monitor (3-50BT-OTR/FL) realized dynamic range 10^{-6}

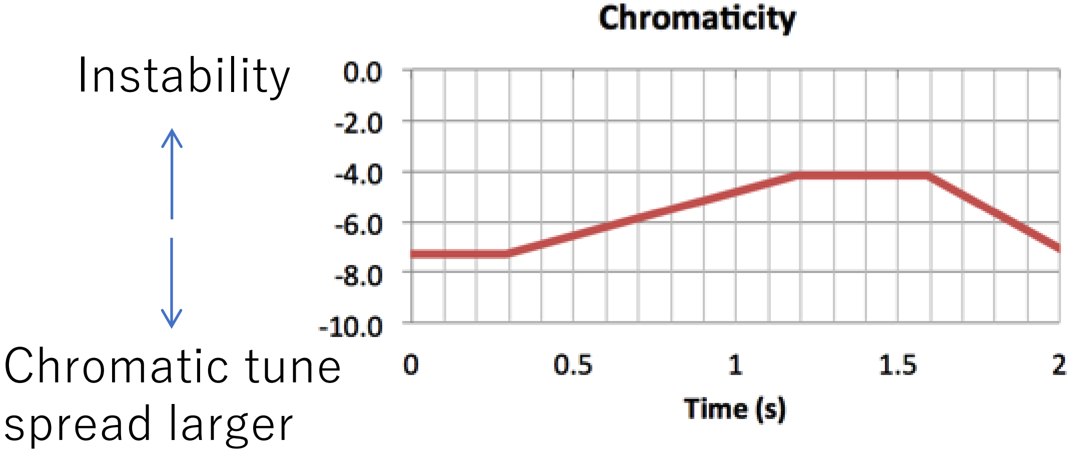
New MR-OTR/FL needs high radiated durability and much less impedance.

Instability Suppression (1) Chromatic Pattern

Single Pass Monitor
3.1e13 ppb * 8 bunches



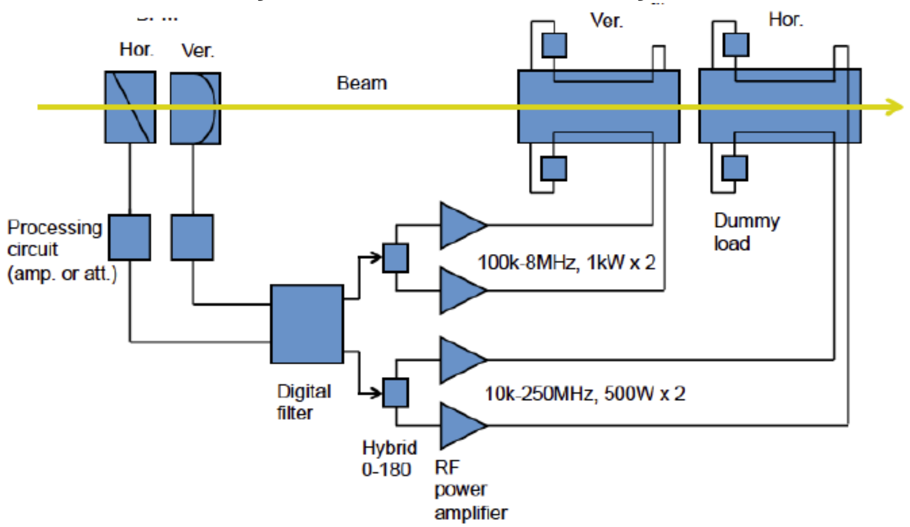




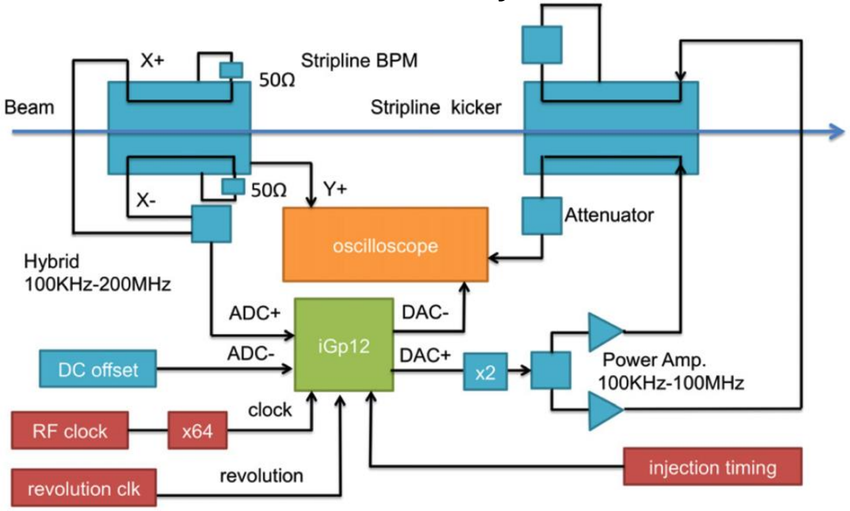
- **The chromaticity pattern was set to minimize the beam loss, and kept in negative value**
- **If the chromaticity is too small, we observe instability**
- **If the chromaticity is too large, we observe the beam loss due to chromatic tune spread**
- **This pattern scheme works but is not enough for high intensity operation**

Instability Suppression (2) Transverse Feedback System

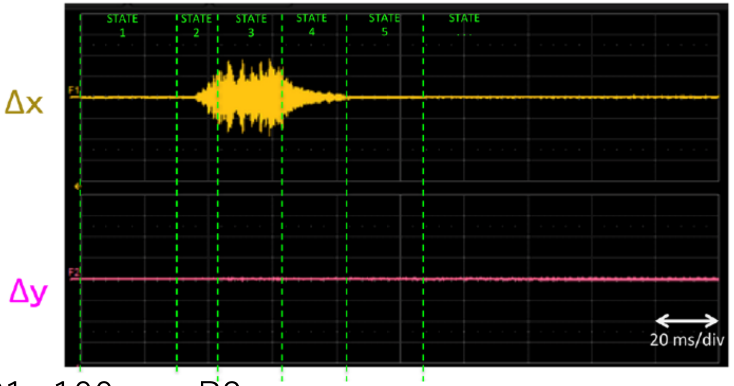
Bunch by bunch feedback system



Intra-bunch feedback system (wideband)

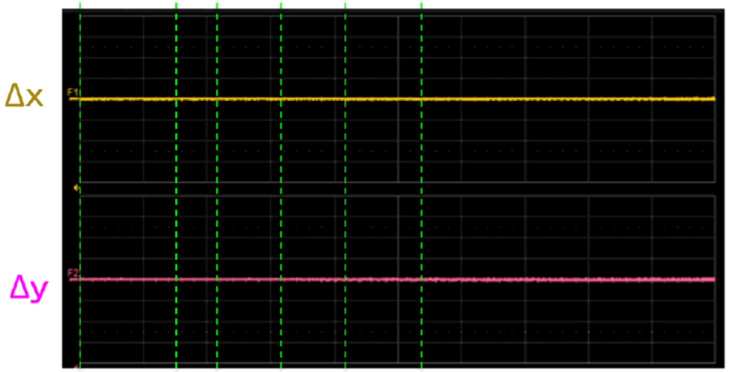


Beam Position with Intra-bunch FB off



P1+100 ms P2

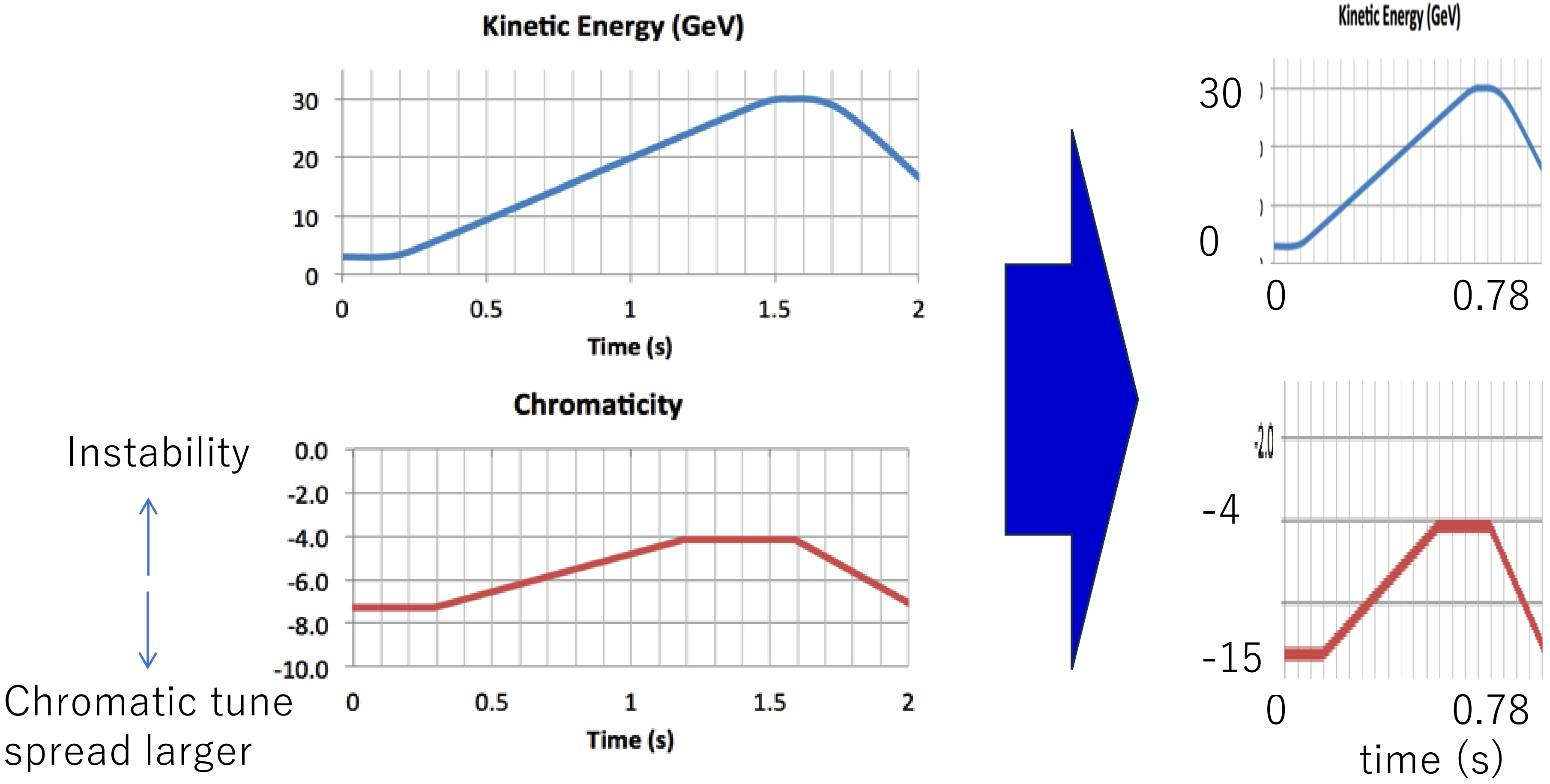
Beam Position with Intra-bunch FB on



P1+100 ms P2

- **The bunch by bunch and intra-bunch feedback system were developed to suppress coherent oscillation. It is damped well during injection and the beginning of acceleration**
- **The feedback system is indispensable for high intensity operation**

Instability Suppression in 2023



- **In faster cycle, IntraBFB system needs to be re-optimized to match with several beam properties including tune tracking pattern.**
- **In the first beam commissioning after the upgrade requires to optimize tune-tracking under no-instability conditions. Thus, in 2021-2022, we renewed the sextupole magnet PSs which enable wider and faster ramping pattern in patterned chromaticity.**

Beam Halo Collimation

- Vacuum Scrubbing
- Beam loss distribution / residual dose estimation

Effective Beam Halo Cut at Collimators

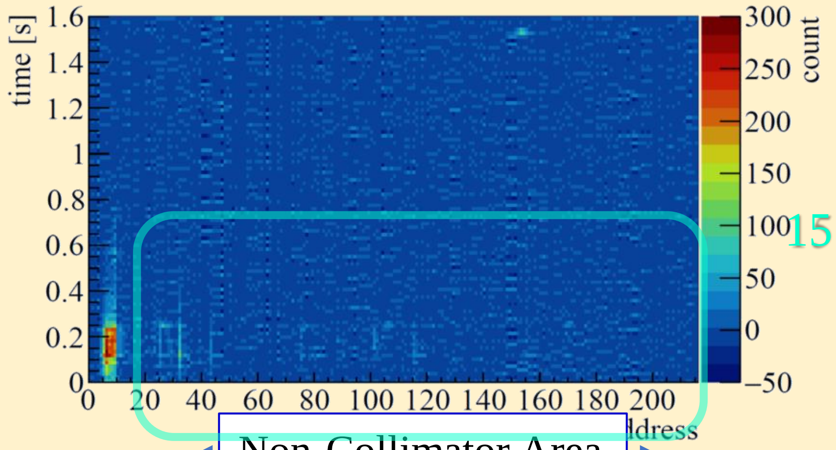
Jan 30, 2020

Nu User Operation in 2.48 s cycle:

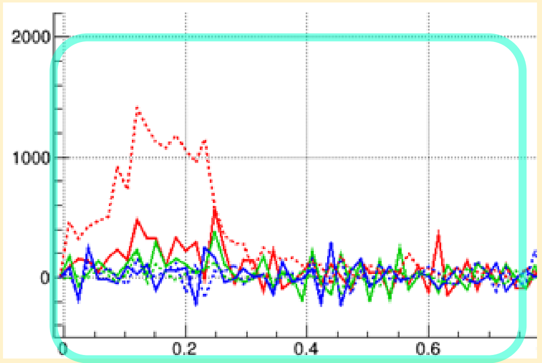
515 kW eq. (2.66e14 ppp)

loss 800~900 W eq. (4.1e12 ppp)

MR Col: Hori64pi e-6 & Vert61pi e-6



Non-Collimator Area



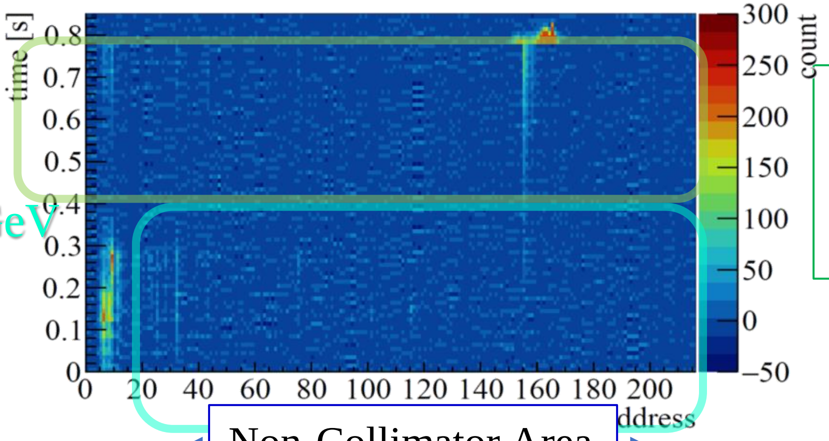
Apr. 20, 2023

FX-ABD study in 1.36 s cycle:

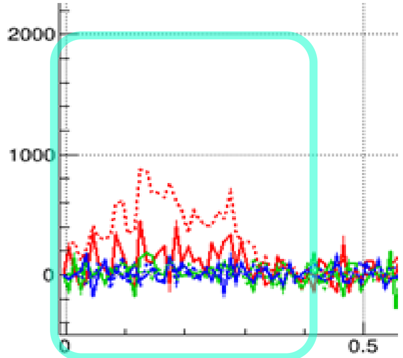
766 kW eq. (2.17e14 ppp)

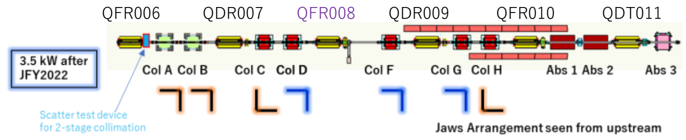
loss ~840 W eq. (2.4e12 ppp)

MRCol: Hori55pi e-6 & Vert61pi e-6



Non-Collimator Area





MR Collimators

4 sets (-2021) → 6 (2022) → *7 (2024)*

MR Col area (007-010) are set in smaller aperture to save the FX area from radiation. We will optimize the collimator balance again after completing the vacuum scrubbing.

In latter acceleration, We observe the effects of vacuum scrabbing as results of beam halo enlargement.
MR Cols are balanced by observing beam loss distribution during the injection period and low energy period.

We are expecting less radiation in Non-Collimator Area for FX 766 kW operation, comparing with the 2021 operation of 515 kW

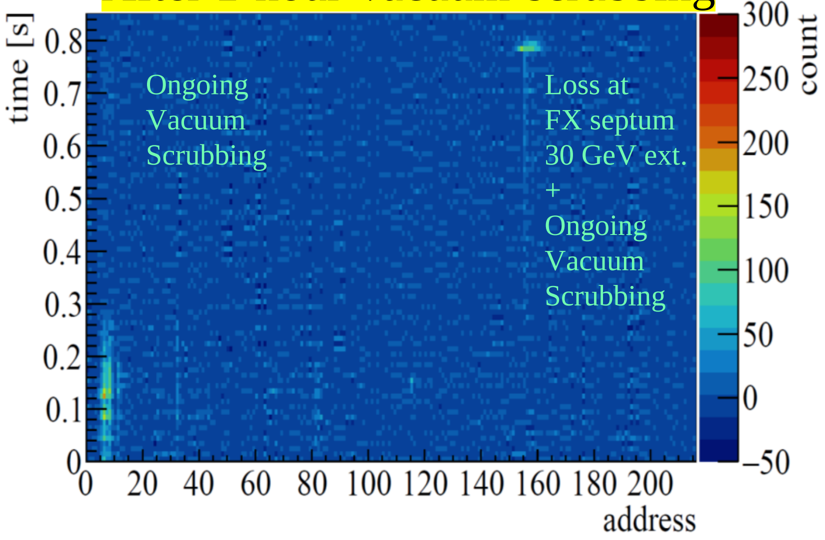
FX調整シナリオ（2023.11.19 ~）

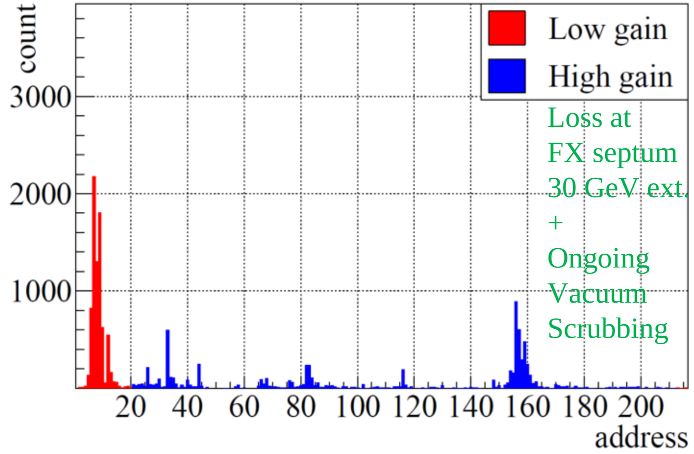
主調整： 真空焼き出し運転はまだまだ必要

April 24, 2023

Nu 535 kW with loss 400 W

After 1-hour-vacuum-scrubbing

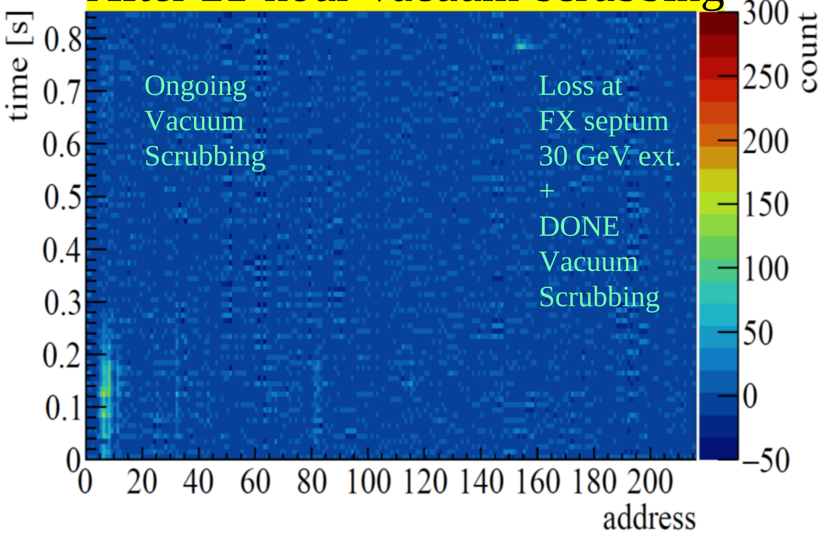


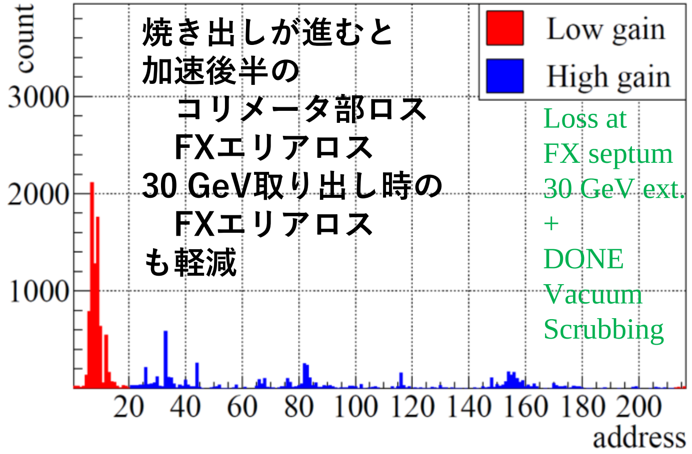


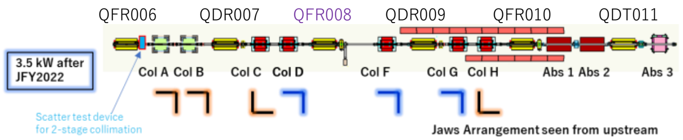
April 25, 2023

Nu 535 kW with loss 350 W

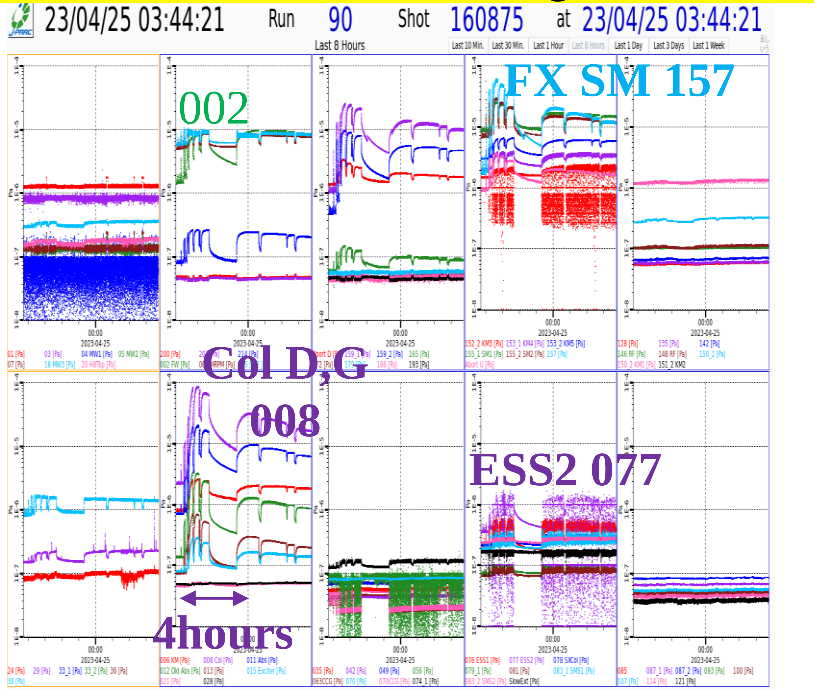
After 21-hour-vacuum-scrubbing







Nu 535 kW Vacuum scrubbing first 8 hours



- 真空履歴の少ない/大気暴露エリア（InsA,InsC）は強度上げ毎に1~2晩の焼き出し運転が必要
- 残留線量評価は十分な焼き出し後

Effective Beam Halo Cut at Collimators

Apr. 20, 2023

FX-ABD study in 1.36 s cycle:

766 kW eq. (2.17e14 ppp)

April 25, 2023

Nu 535 kW

After 21-hour-vacuum-scrubbing

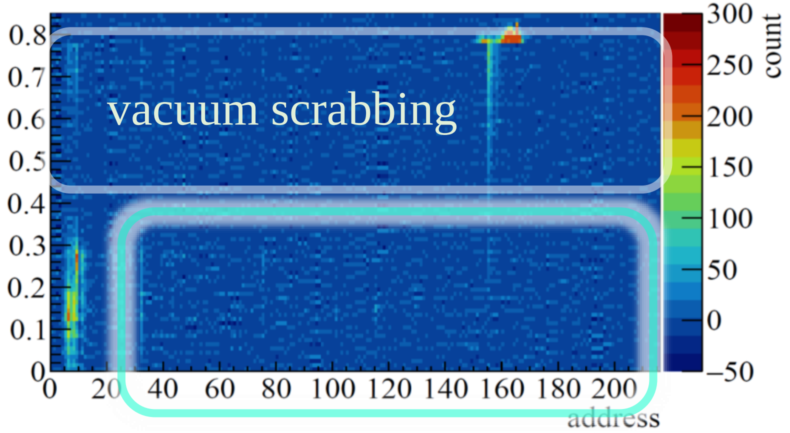
MRCol: Hori55pi e-6 & Vert61pi e-6

Jan 30, 2020

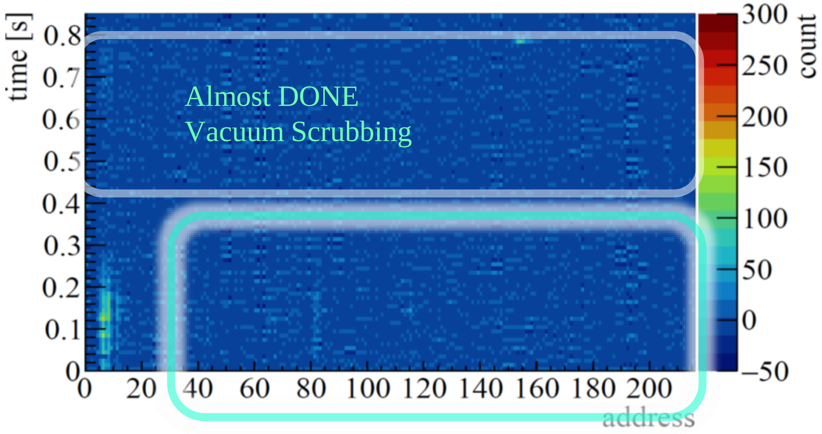
Nu User Operation in 2.48 s cycle:

515 kW eq. (2.66e14 ppp)

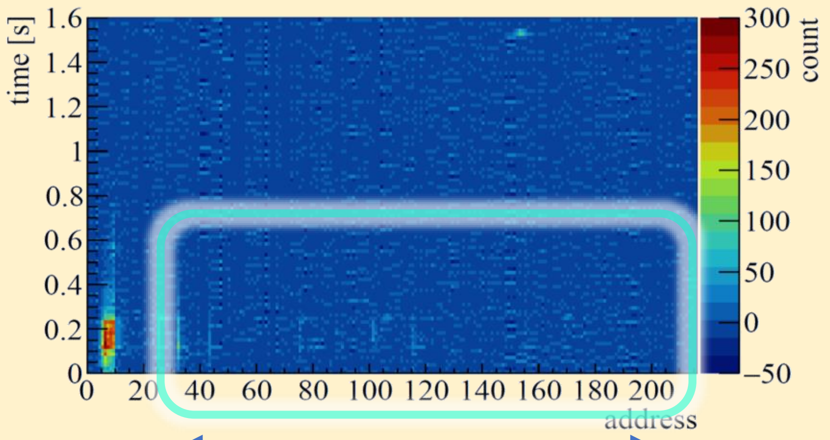
MR Col: Hori64pi e-6 & Vert61pi e-6



Non-Collimator Area



Non-Collimator Area



Non-Collimator Area

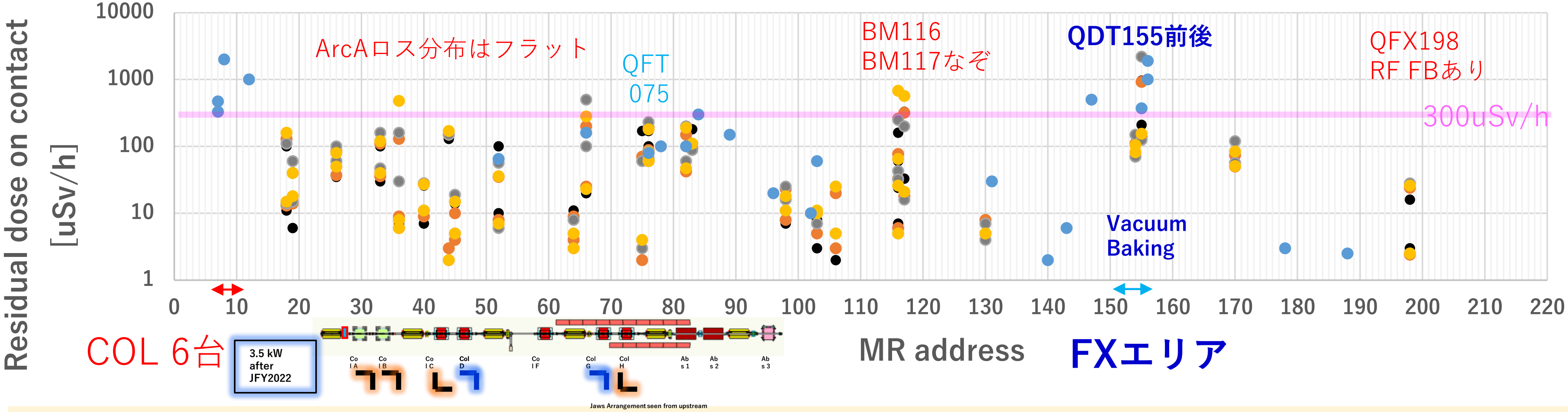
Less beam loss in Non-Collimator Area

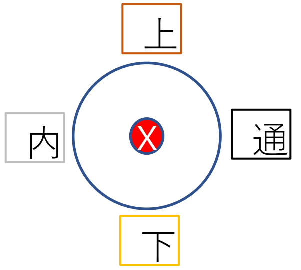
We had kept hands-on-maintenance-capability in Non-Collimator Area by JFY2021.
After completing vacuum-scrubbing, we are ready for 750 kW in Nu User Operation.

Nu 535 kW in 1.36s cycle 利用運転停止後24H残留線量 (20230426 16:30 - 18:00)

w ~400 W loss Tune (21.35, 21.41) @ for selected B & Q

BLM高めもしくは過去線量高め箇所をOn-Contact測定



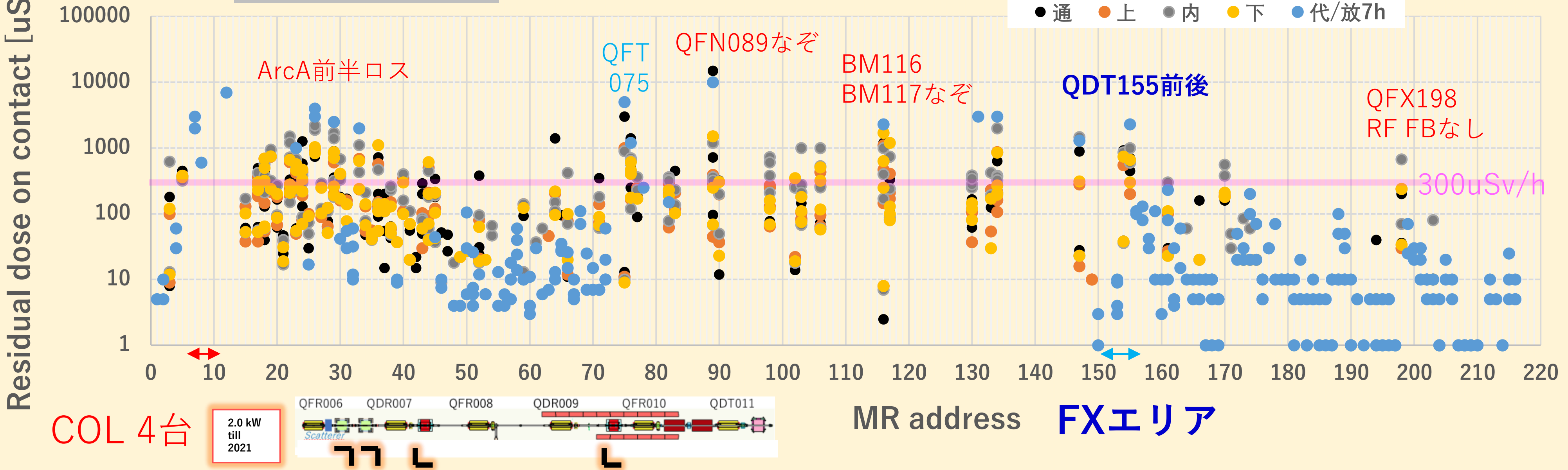


On-Contact測定
上下流磁極近傍
ダクト周り４点
もしくは
線量ピーク点

Nu 430 kW in 2.48s cycle 利用運転停止後12H残留線量 (20161214 18:30 - 20:30)

w ~700 W loss Tune (21.35, 21.43) @ all Bend & Quad (except for Address #006-014)

COL部を除く全BQ線量をOn-Contact測定し高め箇所を記録

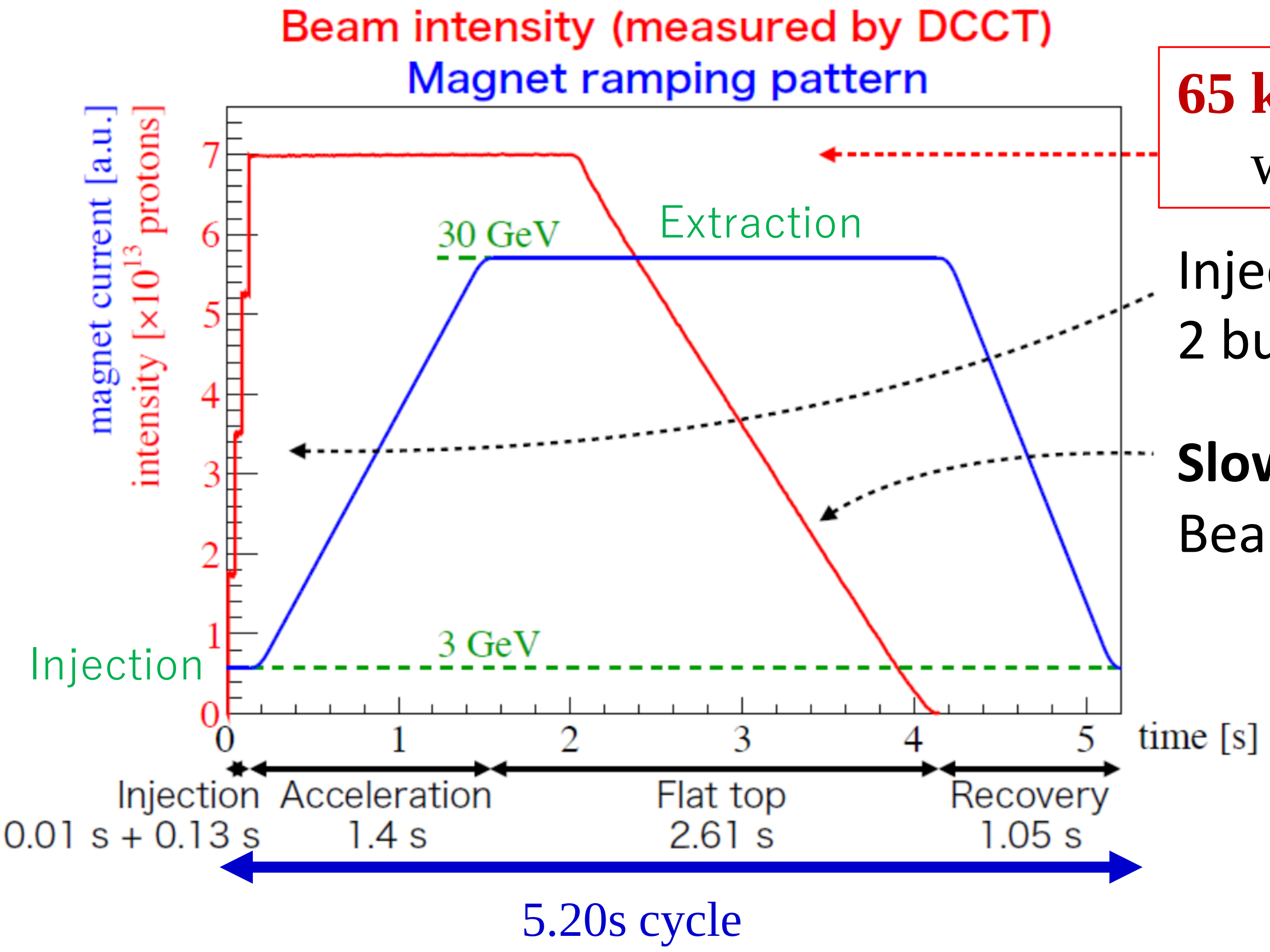


過去のNU利用運転と比べ、真空焼き出し影響の大きいFXエリアを除き、概ね低線量

Slow extraction

BK Typical Operation of MR SX（by 2021）

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



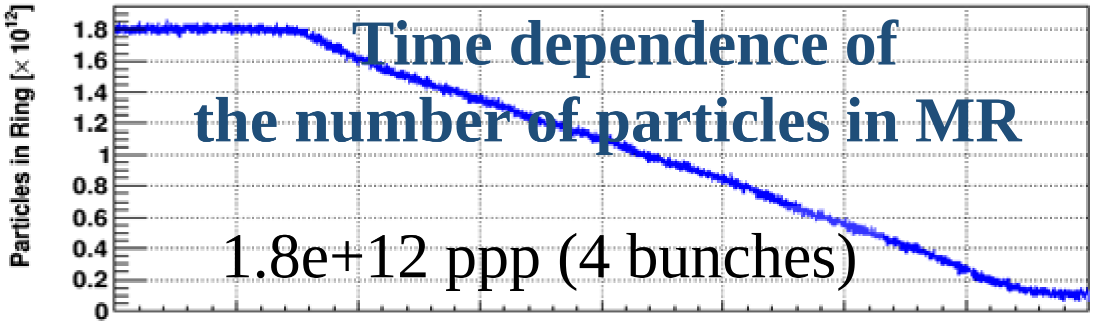
65 kW (7.0E13 ppp in 5.20s cycle)
with extraction efficiency 99.5%

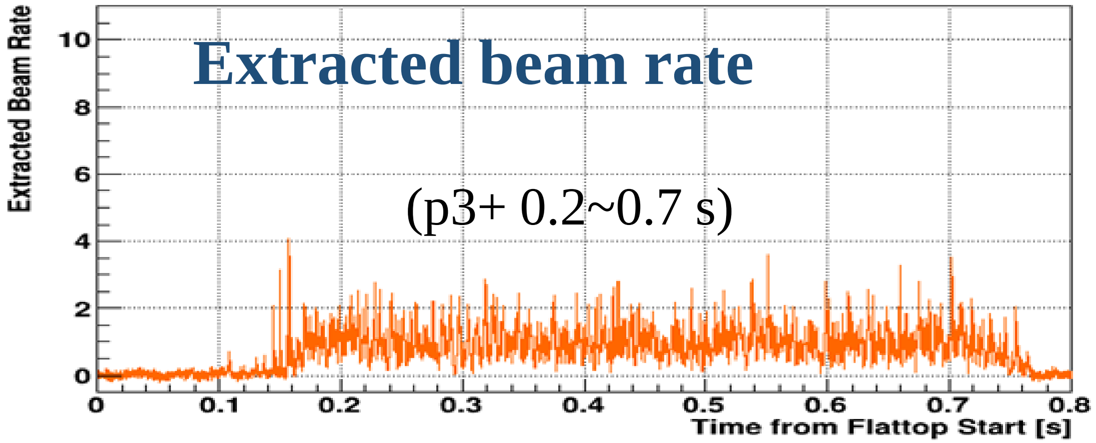
Injection:
2 bunches ×4 times

Slow extraction (SX)
Beams are extracted during 2 second

R. Muto

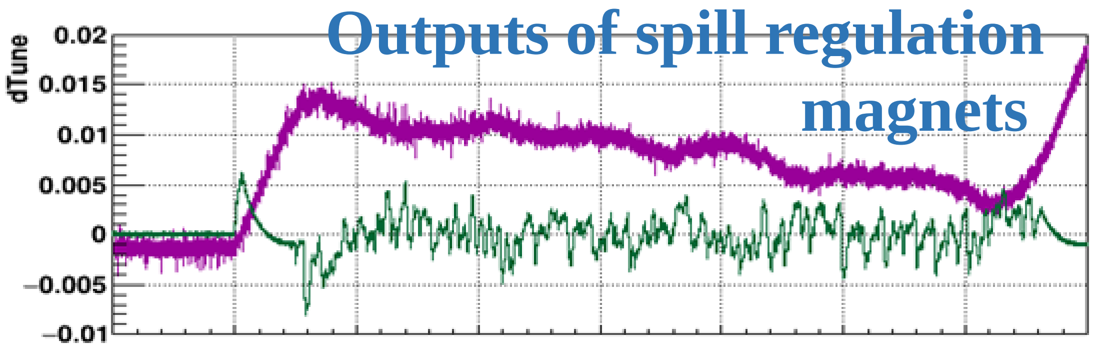
First 8 GeV SX Beam after Mag. PS upgrades Feb. – Mar. 2023





Spill duty factor: 76%
(Improved from ~62% in 2021)

by newly applying the transverse RF (not used in 2021)



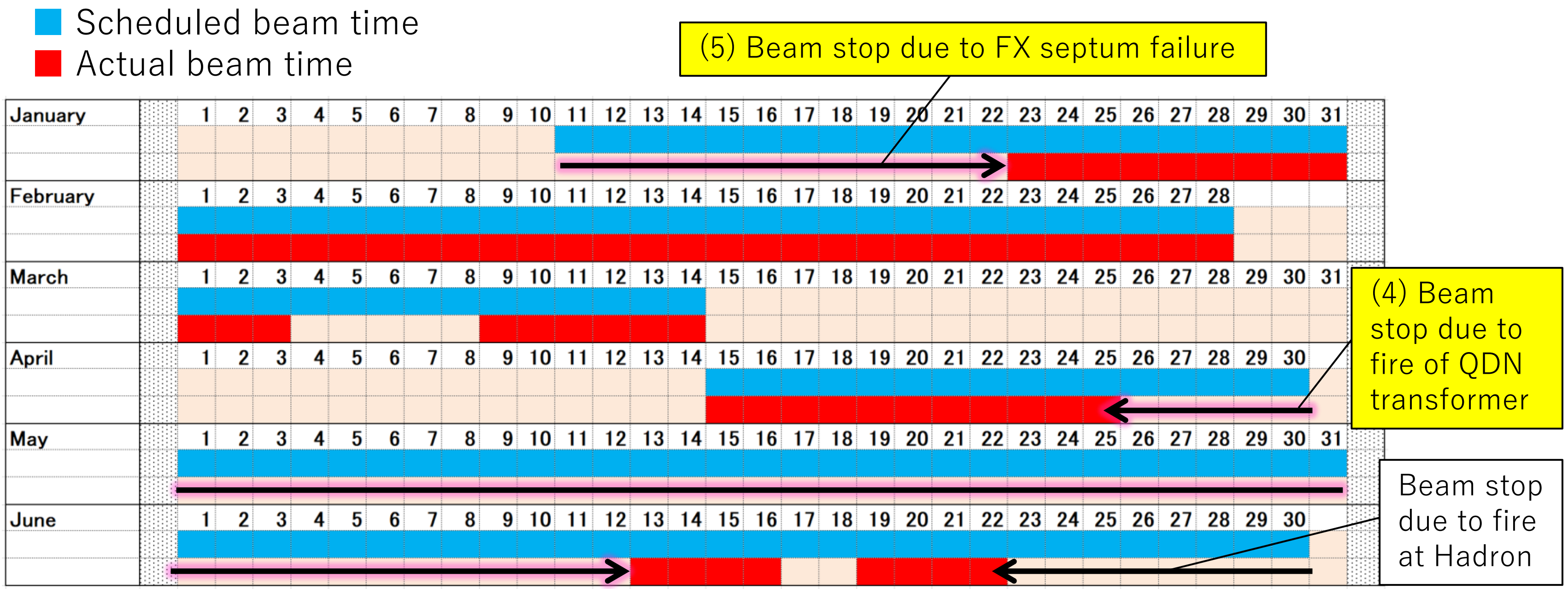
- Protons are accelerated up to **8 GeV for COMET phase-α** (~240 W)
- Bunched beam extraction in every 9.6 s, but Same magnet pattern (2.38 s pattern) as in 2021

The extraction efficiency of ~99% was well reproduced as before the main power supply upgrade

MR Operation Status

MR Operation Status (January – June 2023)

During the initial operation after the hardware upgrades, various machine troubles occurred with the updated devices.



Main magnet power supplies

(1) Failure of a contactor

(2) Blowout of fuses

(3) Breakage of IGBT unit

(4) Burnout of transformer

Apr.25, 2023

High-field FX septum magnets

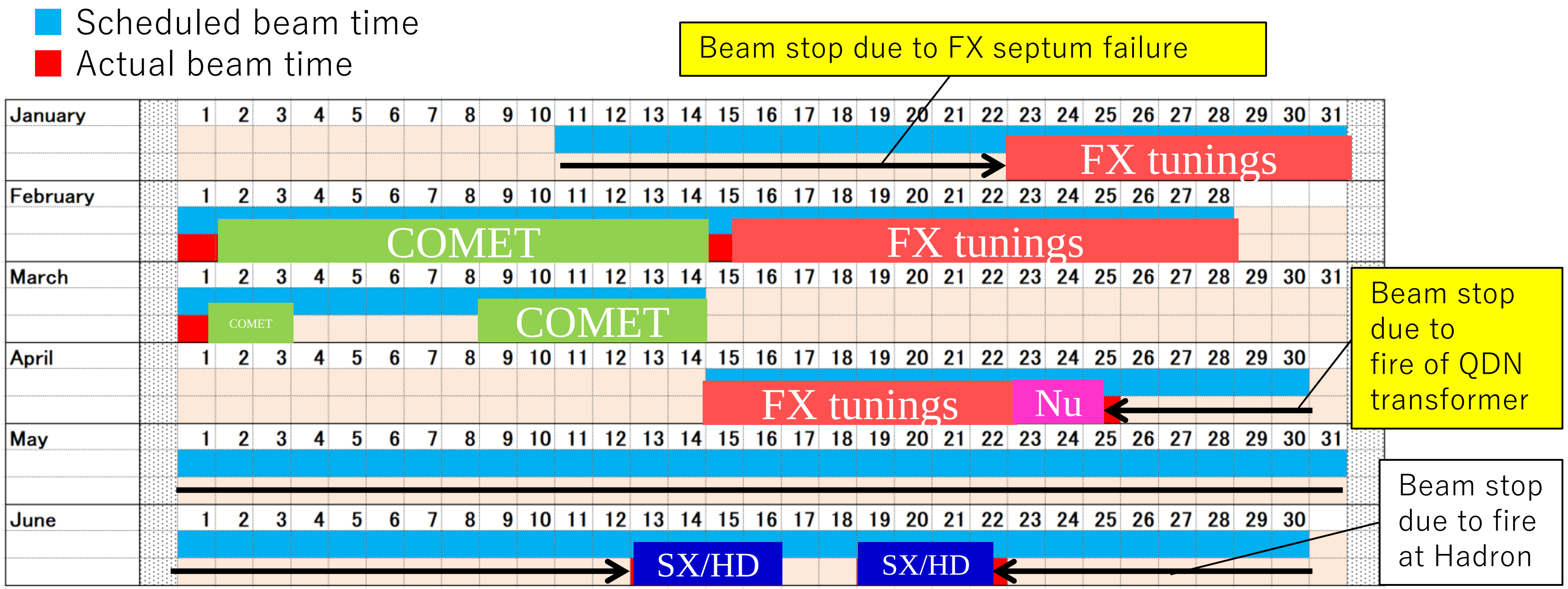
(5) Breakage of coils

Jul. 28, 2021, Dec. 23, 2022

Major impact on the beam operation schedule after January 2023.

MR Operation Status (January – June 2023)

During the initial operation after the hardware upgrades, various machine troubles occurred with the updated devices.
However, most of required beam qualities were confirmed successfully.



- FX tunings (30 GeV 1.36 s cycle pattern with 8 GeV & 30 GeV ext.)
  → Successful demonstration of **766 kW eq. with reasonable loss in MR-30GeV-FX.**
- Nu operation & vacuum scrubbing in late April. → **535 kW in 1.36 s cycle**
- SX/HD 8GeV tunings & COMET experiment → **Improved spill duty ~76% .**
- **SX/HD 30 GeV tunings and operation in 5.2 s cycle** were performed for a week
  → Achieved 50 kW in 5.2 s cycle **after the upgrades with extraction efficiency 99.5%.**