High Power Beam Operation of the J-PARC: Present Status and Outlook

Yoichi Sato for J-PARC Accelerator Group

May 8th, 2018

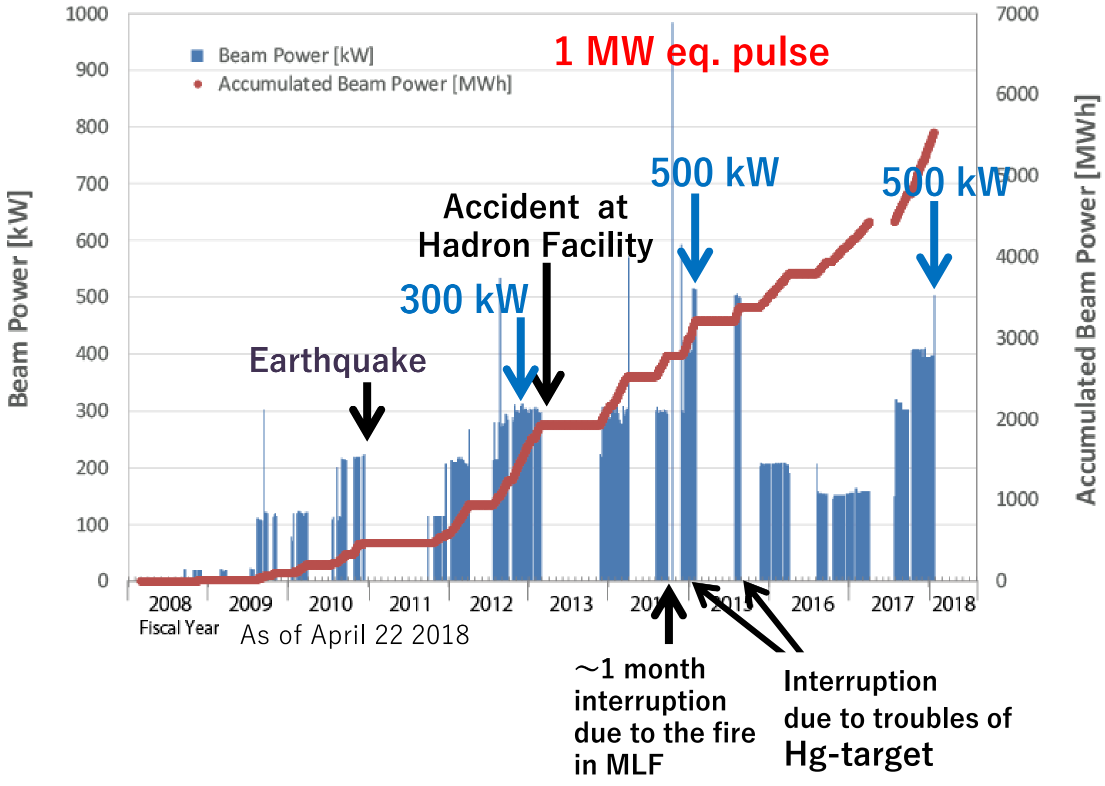
Fermilab workshop on Megawatt Rings & IOTA/FAST Collaboration Meeting

Contents

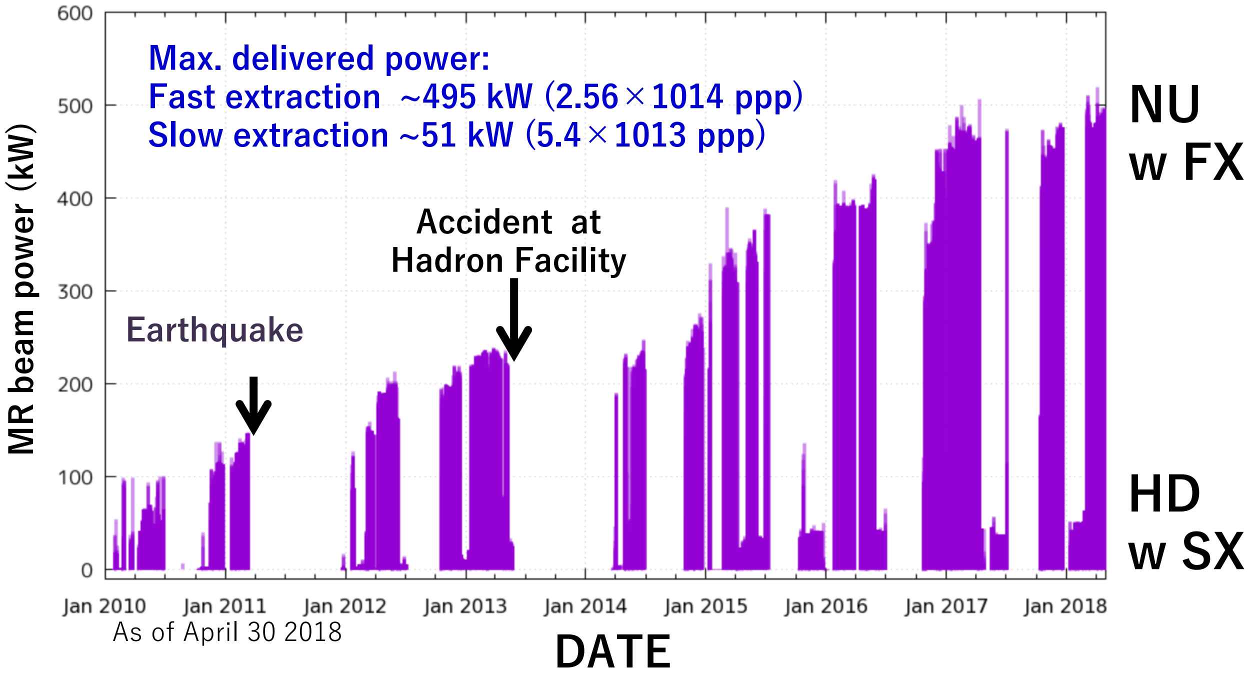
- Overview
- RCS
  - 1 MW beam test
  - Compatibility of both MLF and Main Ring operations
- MR with fast extraction
  - Typical operation
  - High intensity tuning keys
- MR upgrade plan
  - Concept
  - Beam loss localization
- Summary

Japan Proton Accelerator Research Complex (J-PARC)

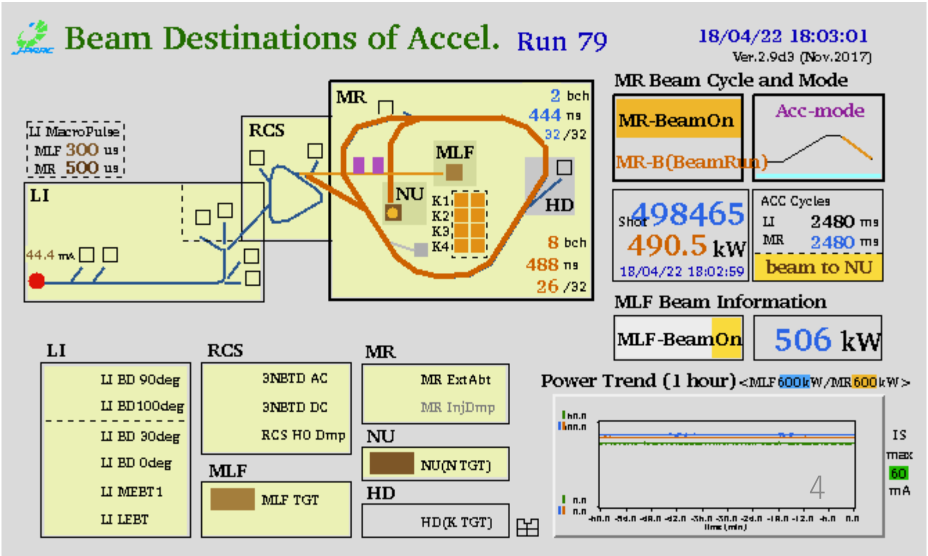
Beam Power History RCS to MLF



Beam Power History MR to NU (FX) / HD (SX)



- Beam power has steadily increased.
- Stable user operation:
  - MLF 500 kW
  - NU 490 kW
  - HD 50 kW



Contents

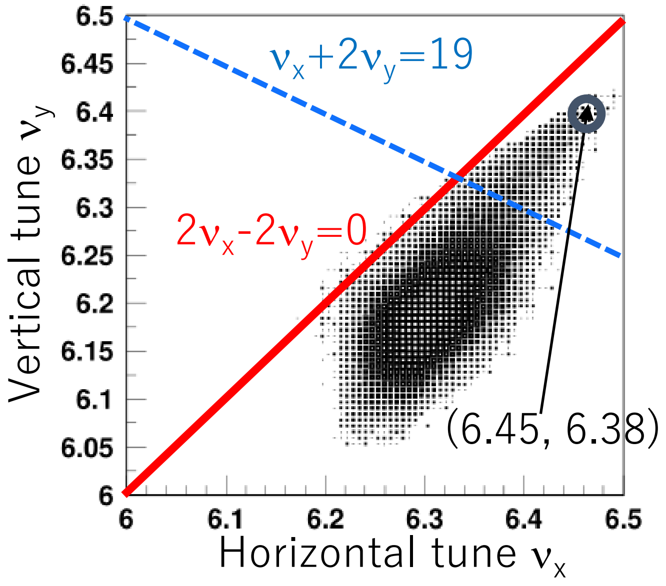
- Overview
- **RCS**
  - **1 MW beam test**
  - **Compatibility of both MLF and Main Ring operations**
- MR with fast extraction
  - MR overview and Typical operation
  - High intensity tuning keys
- MR upgrade plan
  - Concept
  - Beam loss localization
- Summary

See ***Saha-san's talk yesterday*** *for the efforts overcoming the impedance effects*

J-PARC

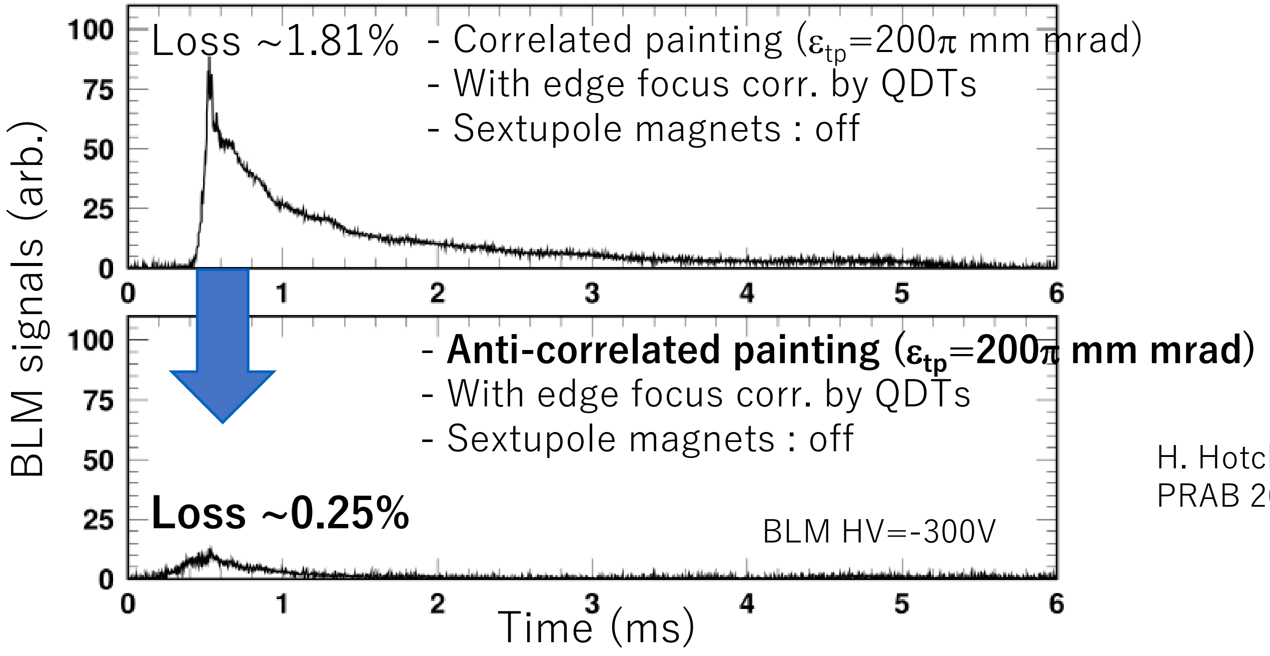
1-MW beam (designed beam power) test in 2016

Tune footprint @ injection



BLM signals @ collimator

Measurement



H. Hotchi et al.,
PRAB 20, 060402 (2017)

- Issues in **realizing a large transverse painting** were $\nu_x+2\nu_y=19$ and $2\nu_x-2\nu_y=0$;
  they cause a shrinkage of the dynamic aperture and make additional beam loss when the transverse painting area is enlarged to $\varepsilon_{tp}>100\pi$ mm mrad.
- By minimizing the effects of $\nu_x+2\nu_y=19$ and $2\nu_x-2\nu_y=0$,
  the transverse painting area was successfully expanded to 200π mm mrad.

H. Hotchi et al., PRSEAB 15, 040402 (2012)
PRAB 19, 010401 (2016)

- **We achieved a 1-MW beam acceleration with a very small beam loss of a couple of 10^{-3}.**

Loss: ~0.25% at ~400 MeV ⇒ 333 W ・・・ Small, but not negligible for machine activations

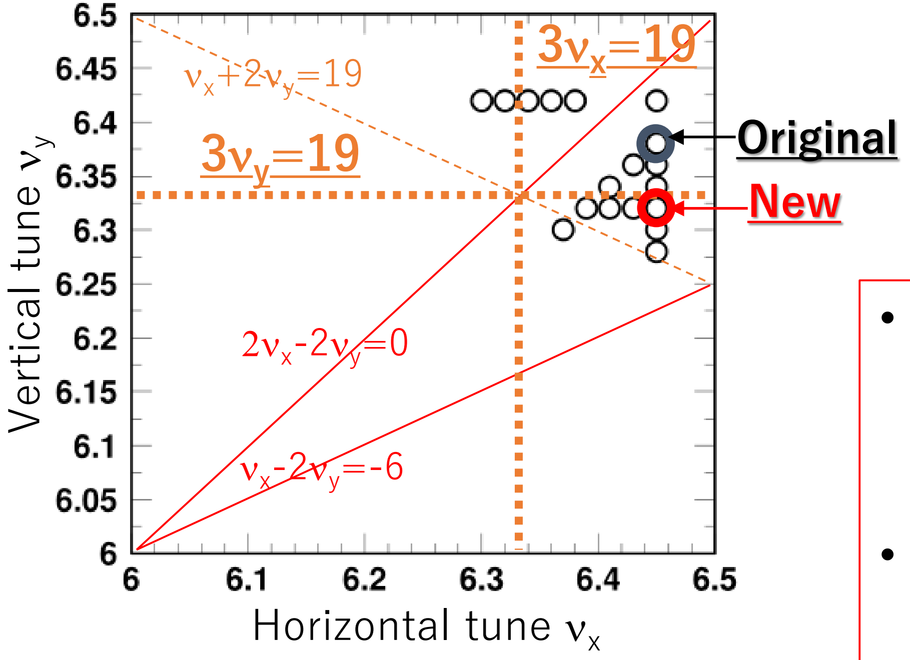
- We tried **further** beam loss mitigation with better operation point

Beam loss : (6.45, 6.38) vs (6.45, 6.32)

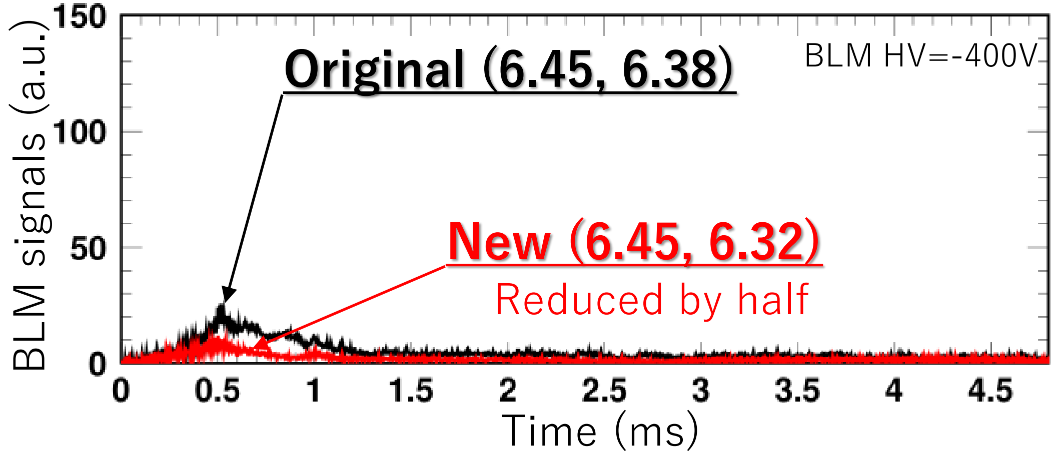
H. Hotchi et al.

- 40 mA, 500 μs, 489 ns, 2 bunches;
  ~7.70 x 10^{13} ppp (~924 kW-eq.)
- Transverse painting;
  $\varepsilon_{tp}=200\pi$ mm mrad
- Full longitudinal painting

Tune survey area



BLM signals @ collimator　Measurement

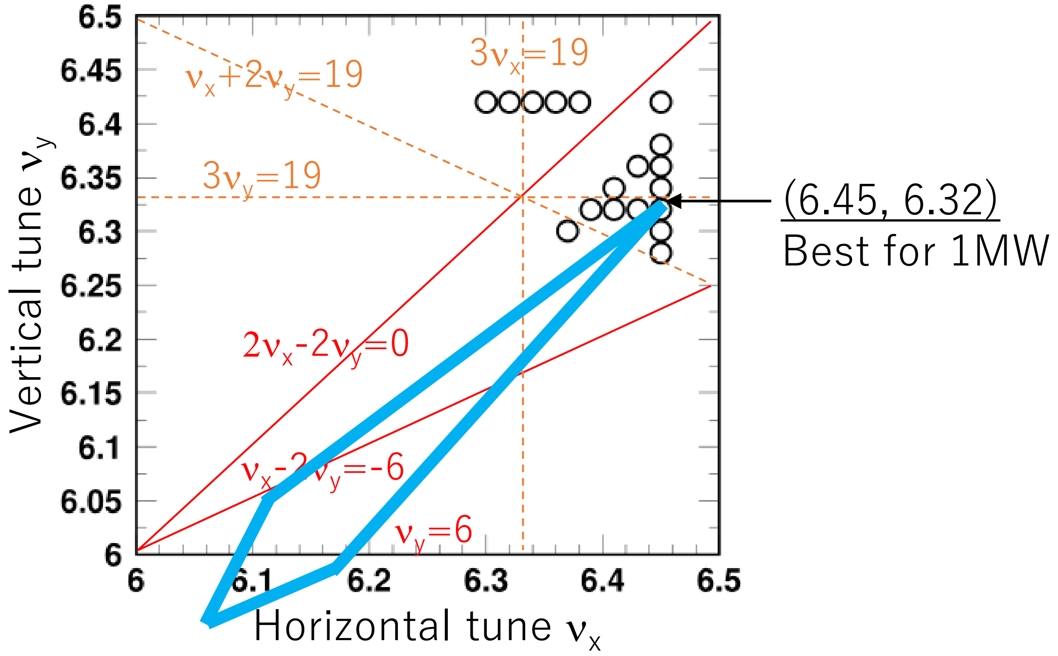


- **Through the experiment and the simulation study, we got a new operating point: more suitable for the beam operation to MLF**, which requires 200π mm mrad painting
- **New operating point (6.45, 6.32),** avoids the effect of $3\nu_y=19$, and also keeps the less effect of $3\nu_x=19$.
- **The beam loss was well reduced 1/2.**

H. Hotchi

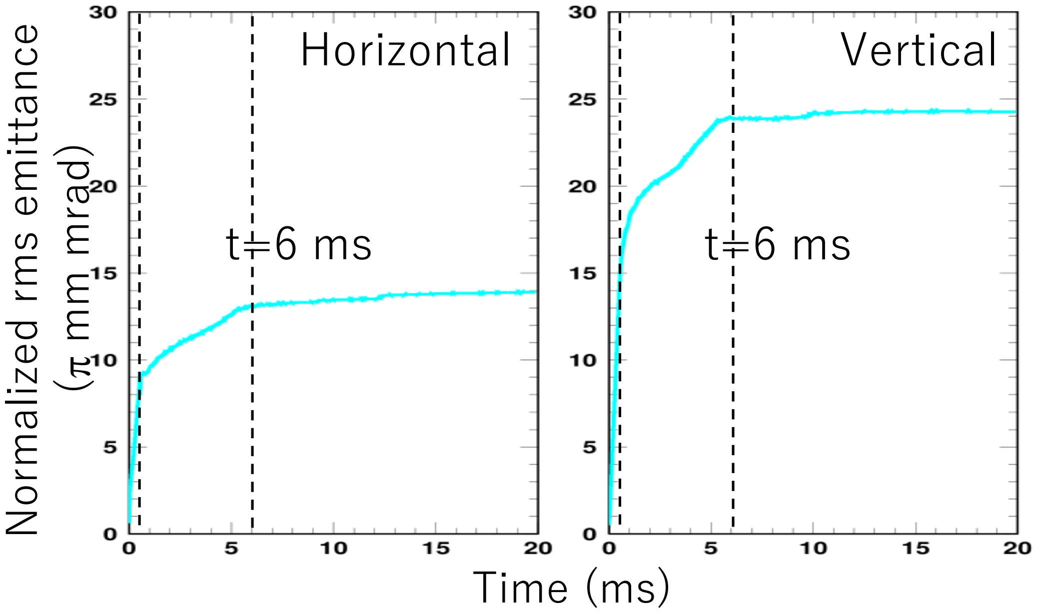
FOR MR: Emittance growth and cause

Tune diagram



Main cause of the emittance growth : ν_y=6

Time dependence of beam emittance simulated



Significant emittance growth occurs for the first 6 ms, especially on the vertical plane.

- **Low emittance beam required in MR**, because its physical aperture is much smaller than the MLF.
- **Small injection painting emittance is adopted: ε_{tp}=50π mm mrad**
  - ⇒ **A large space-charge detuning is generated.**
  - ⇒ **A part of beam particles reaches ν_y=6**: all-order systematic resonance are excited, causing a large emittance growth especially on the vertical plane.
- **This emittance growth can be mitigated by manipulating the tune and the chromaticity so as to separate the beam from the integer.**

Extracted beam emittances, manipulating tune and chromaticity

H. Hotchi, et al., TUPAL018, IPAC2018

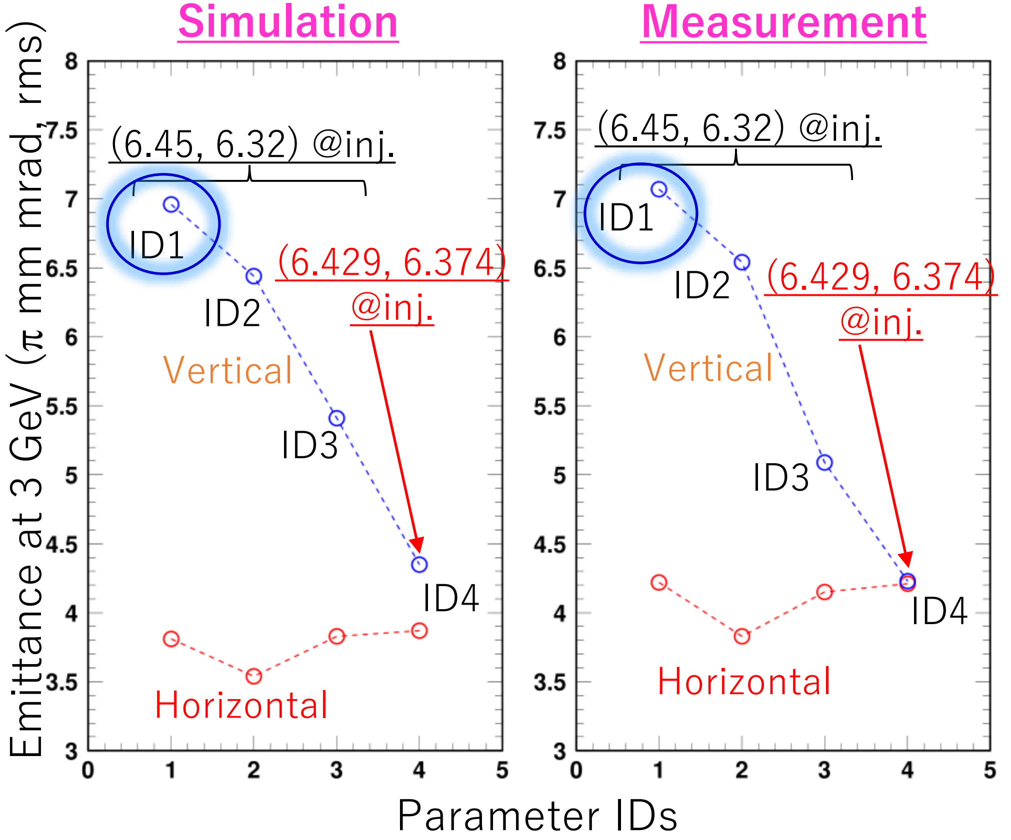
ID1 : - ε_{tp}=50π mm mrad
- No chromatic corr.
- Tune variation: (a)

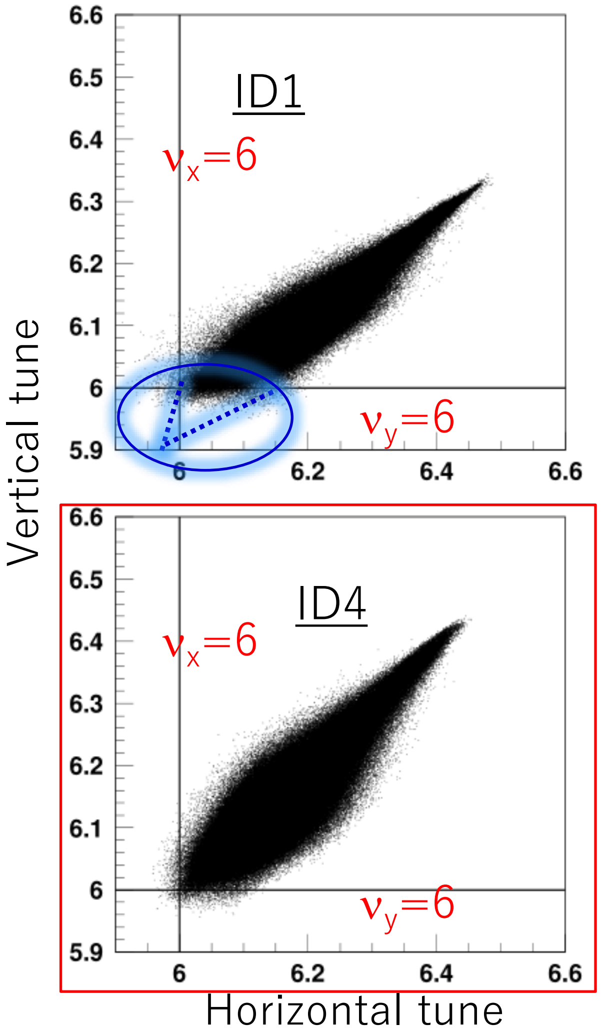
ID2 : - ε_{tp}=50π mm mrad
- With chromaticity corr. (Bipolar excitation)
- Tune variation: (a)

ID3 : - ε_{tp}=50π mm mrad
- With chromaticity corr. (Bipolar excitation)
- Tune variation: (b)

ID4: - ε_{tp}=50π mm mrad
- With chromaticity corr. (Bipolar excitation)
- Tune variation : (c) by adding 6 quadrupole-correctors

Un-normalized rms emittance of the extraction beam





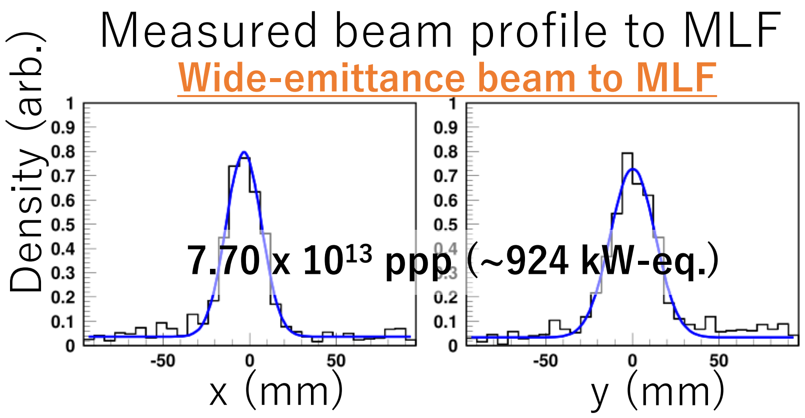
- Manipulating tune and chromaticity, the separation from ν_y=6 was well improved in ID4, and extracted beam emittance was well reduced, as predicted by simulation.
- Pulsed quadrupole correctors (QDTs) enabled additional tune change from ID3 to ID4.
  → we can perform pulse by pulse switching of optimal tunes between MLF and MR

Operational parameters optimized to date considering the compatibility of the beam operations to MLF & MR

H. Hotchi, et al., TUPAL018, IPAC2018

To MLF:

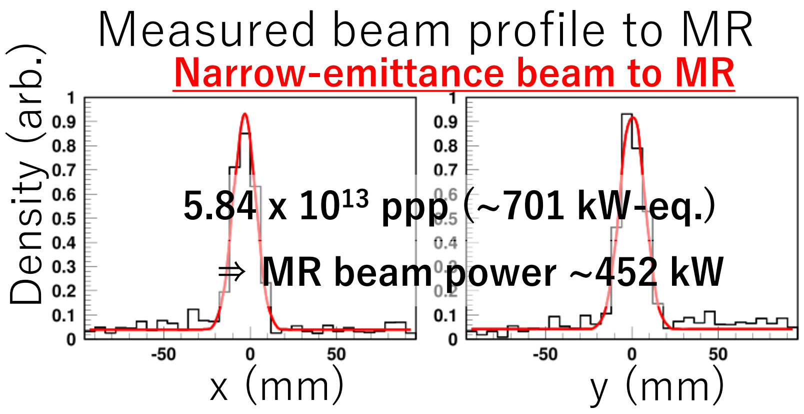
- Tune @ injection: (6.45, 6.32)
- Transverse painting: ε_{tp}=200π mm mrad (anti-correlated/correlated)
- Sextupoles : off
- Full longitudinal painting



Pulse-by-pulse switching

To MR:

- Tune @ injection: (6.429, 6.374), changed by pulsed quadrupole correctors (installed Summer 2017)
- Transverse painting: ε_{tp}=50π mm mrad (correlated)
- Sextupoles : bipolar excitation
- Full longitudinal painting



By introducing a pulse-by-pulse switching of the tune, the painting area and the chromaticity, we successfully met different requirements from MLF and MR while keeping the RCS beam loss within acceptable levels.

Summary of RCS high intensity operation

- RCS has recently initiated a pulse-by-pulse switching of painting emittance, chromaticity and betatron tune. By this effort, we successfully met different requirements from MLF and MR while keeping beam loss within acceptable levels.

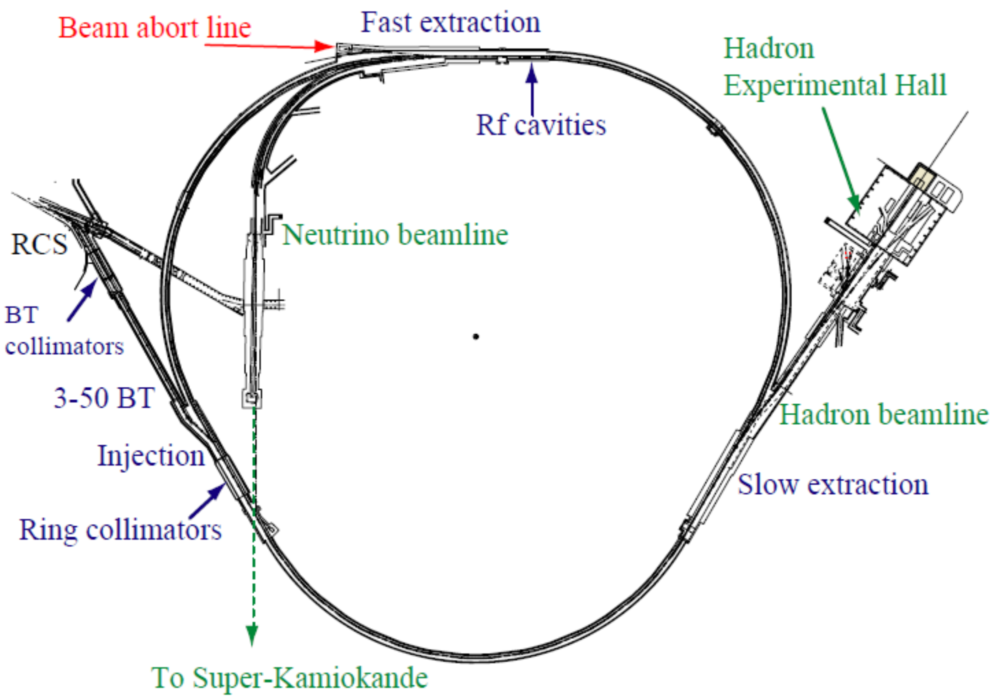
- Before the next summer maintenance, we will conduct a beam test with the design injection beam current of 50 mA, in which the feasibility of the design 1-MW beam operation to MLF and also its compatibility with the beam operation to MR will be inspected again with the new operational parameters optimized this time.

Contents

- Overview
- RCS
  - 1 MW beam test
  - Compatibility of both MLF and Main Ring operations
- **MR with fast extraction**
  - **MR overview and Typical operation**
  - **High intensity tuning keys**
- MR upgrade plan
  - Concept
  - Beam loss localization
- Summary

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	
Rf frequency	1.67 - 1.72 MHz	
Transition γ	j 31.7 (typical)	
Physical Aperture		
3-50 BT Collimator	54-65 π mmmrad	Capacity 2 kW
3-50 BT physical ap.	> 120 π mmmrad	
Ring Collimator	54-70 π mmmrad	Capacity 2 kW (JFY2017)
Ring physical ap.	> 81 π mmmrad	

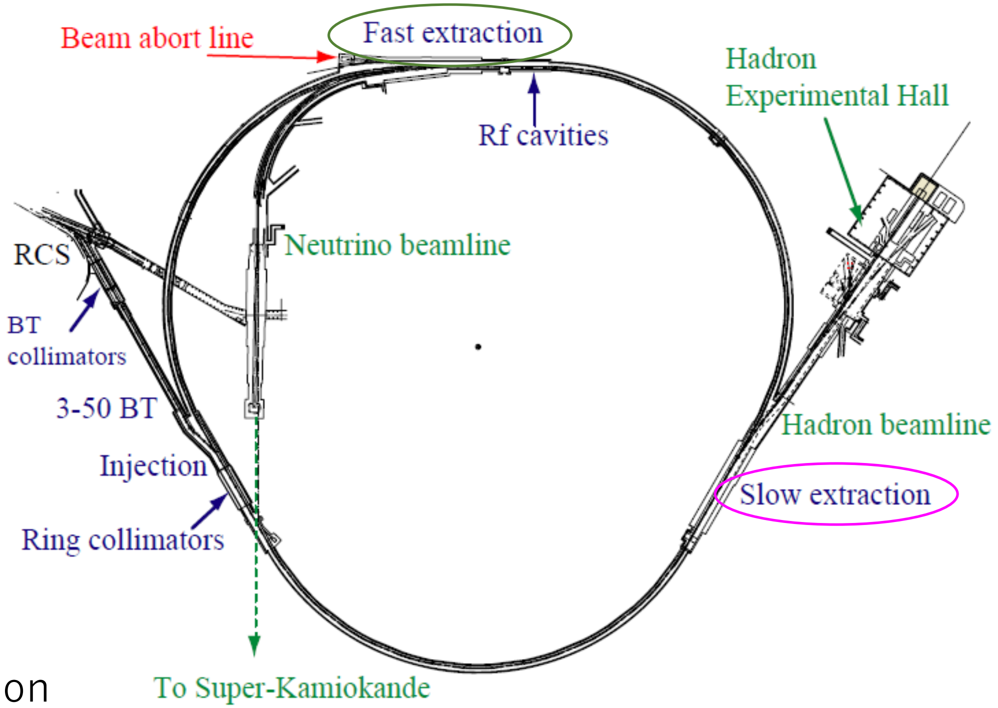


FX beam power
0.75 MW (design)
0.49 MW (present)

Three dispersion free straight sections of 116-m long:
- Injection and collimator systems
- Slow extraction (SX)
  to Hadron experimental Hall
- RF cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)
  outside: Beam abort line
  inside: Neutrino beamline (intense ν beam is send to SK)

Main parameters of MR

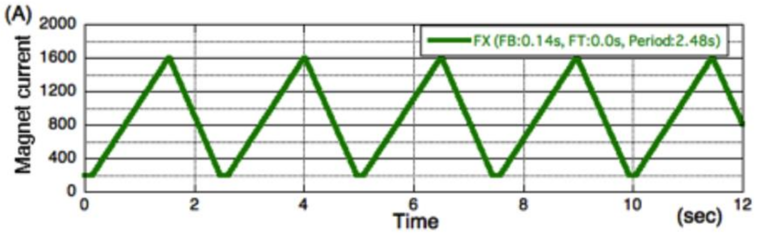
Circumference	1567.5 m
Injection energy	3 GeV
Extraction energy	30 GeV
Super-periodicity	3
harmonic	9
Number of bunches	8
Rf frequency	1.67 - 1.72 MHz



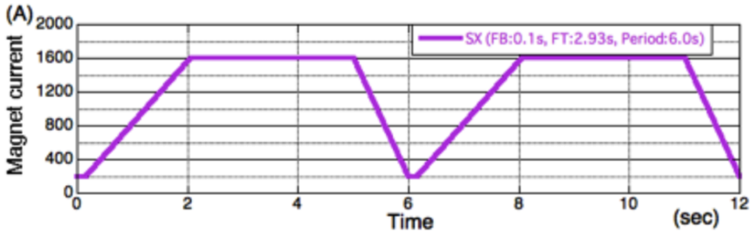
TWO OPERATION MODES:

- **Fast extraction mode (FX)** for the neutrino experiment: 1 turn extraction
- **Slow extraction mode (SX)** for the hadron hall experiments: 2 s extraction

FX beam power
0.75 MW (design)
0.49 MW (present)



FX Cycle time 2.48 s

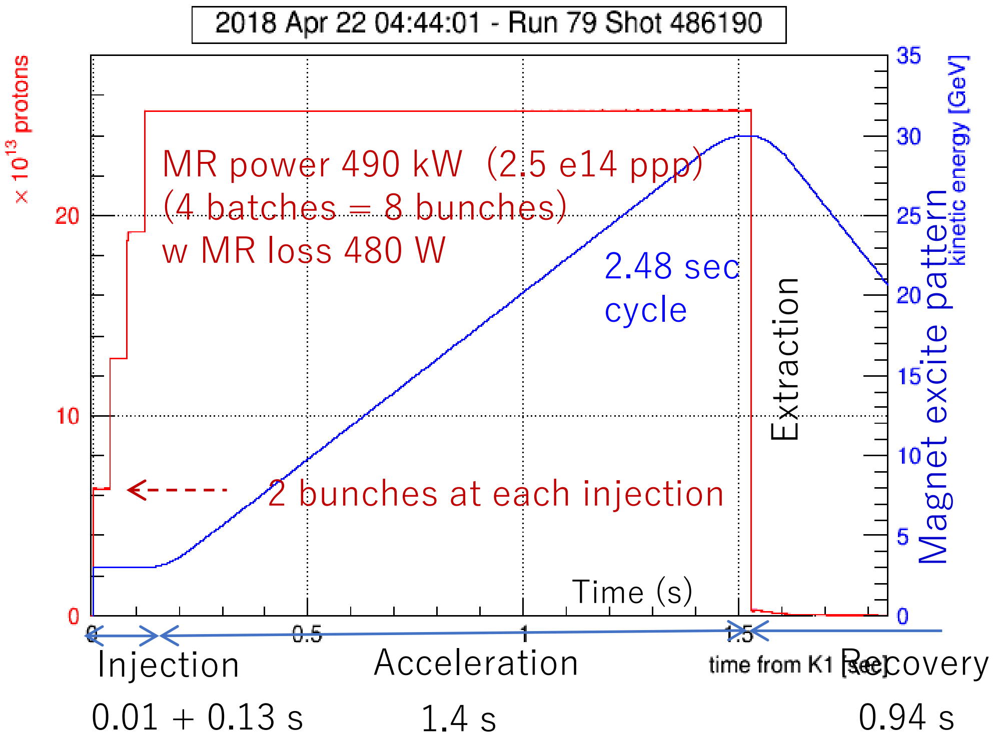


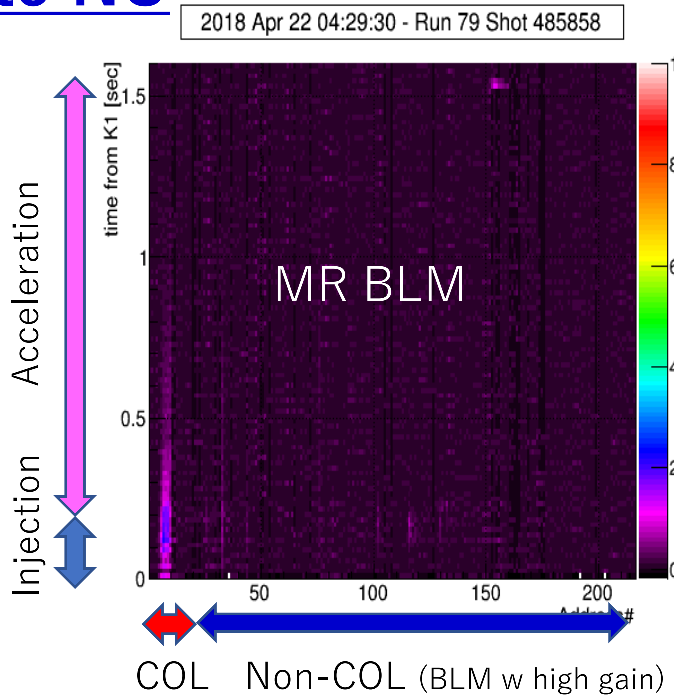
SX Cycle time 5.52 s → 5.20 s

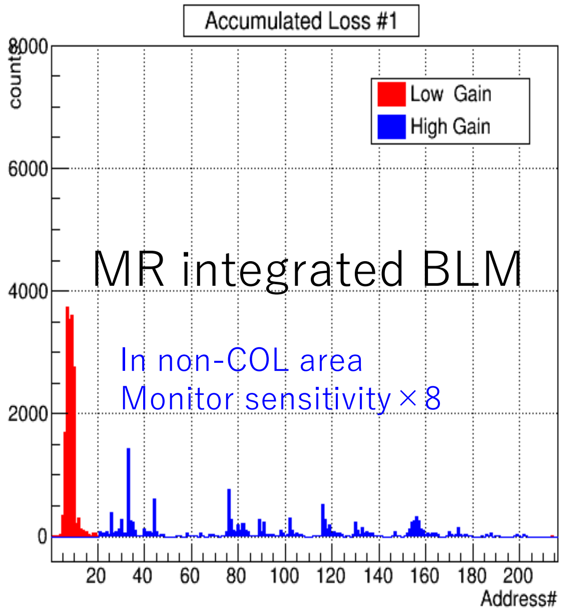
Beam power is the most important parameter for our experiments.
We need more particles and higher repetition.

Beam power [W] = Ave. Beam Current [A=C/s] × Beam Energy [eV]
= **Number of charged particles [C/pulse]** × **Number of pulse [pulse/s]** × Beam Energy [eV]

Typical operation of MR 490 kW to NU







Tuning Items:

- RCS conditions
- Operation point
- Optics corr.
- Resonance line corr.
- Instability damping
- Space charge effect mitigation
- Collimator balancing

MR power	**490 kW**	
3-50BT loss	**50 W**	**< BT COL capacity 2 kW**
MR loss	**480 W** (*1)	**< MR COL capacity 2 kW**
Injection	*230 W*	
Acc 1st 90 ms	*200 W*	
Acc after 90ms	*50 W*	

NOTE *1: Beam loss estimated with DCCT#1.

- **MR total loss, ~ 1%, is well localized in COL section and low energy, and less than the COL capacity**
- **Most of non-COL section: One foot residual doses are < 300 μSv/h (4H after operation)**

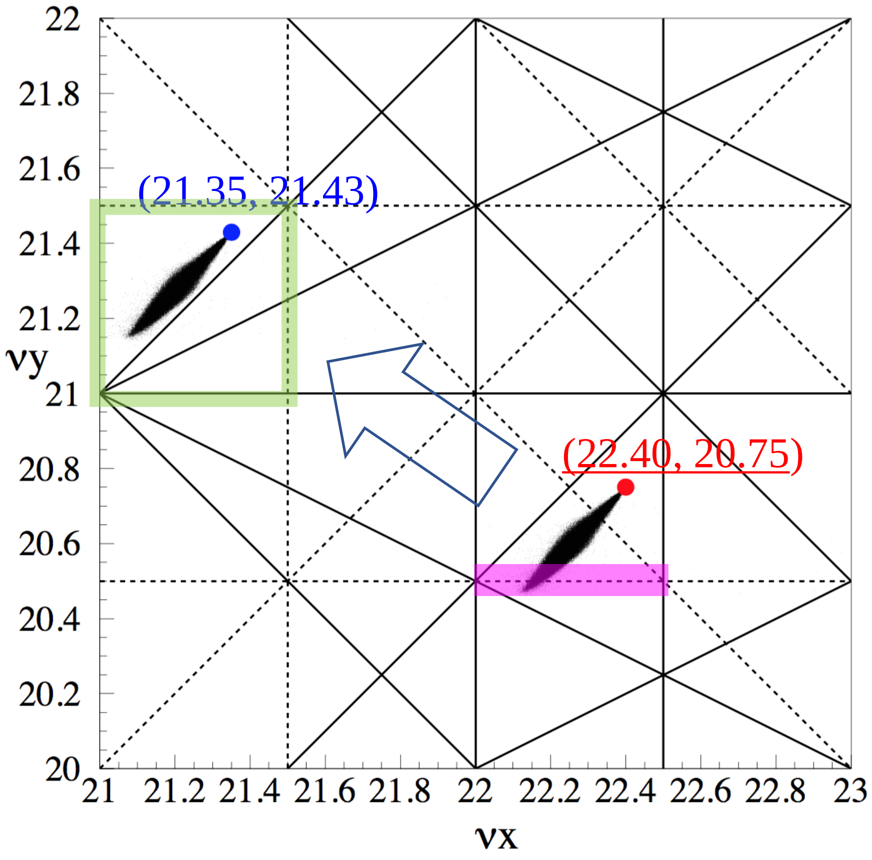
Beam loss sources and tuning items for fast extraction

Beam loss sources in MR

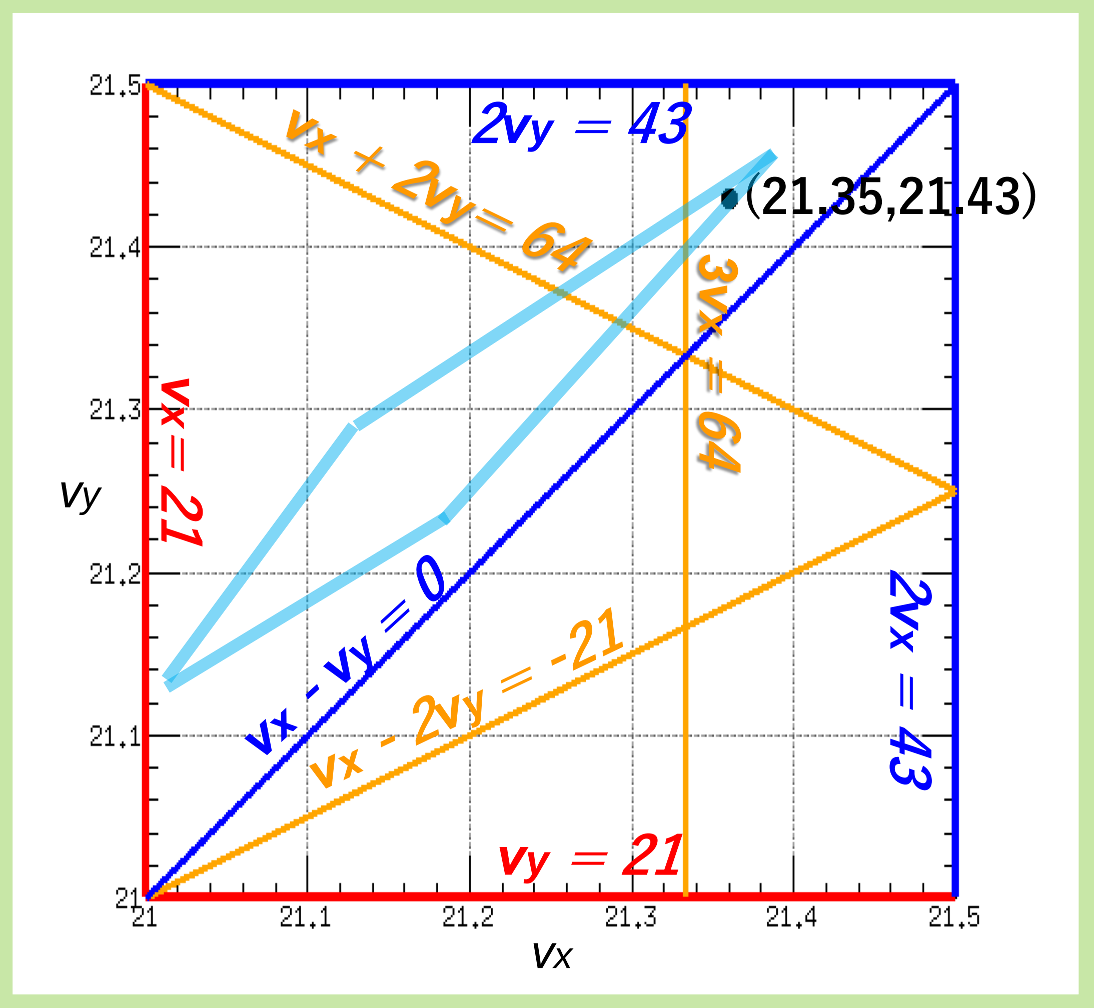
- **Upstream beam quality from RCS:**
  → In Transverse, to choose optimal conditions with 3-50BT OTR monitor
- **Physical aperture**
  → to hold effective aperture with closed orbit correction, optics correction
- **Emittance growth by Betatron resonances**
  → To choose optimal operation point considering
  - Tune spread by space charge
    → to control high bunching factor with higher harmonic RF
  - Tune spread by chromaticity
    → patterned Chromaticity correction with sextupoles
  - Resonance strength
    → to enlarge dynamic aperture by
    leakage field corrections with Trim-quadrupoles
    resonance corrections with Skew-quadrupoles, Trim-Sextupoles
    optics meas. & correction not only injection period but acceleration period
- **Emittance growth by beam instability (impedance from resistive wall)**
  → transverse feedback system (bunch by bunch, intra-bunch)
  → large tune spread (but acceptable level in betatron resonance)
  to suppress instabilities: optimizing bunching factor & chromaticity

Many Items
to be optimized
iteratively

Choice of operation betatron tune (21.35, 21.43)



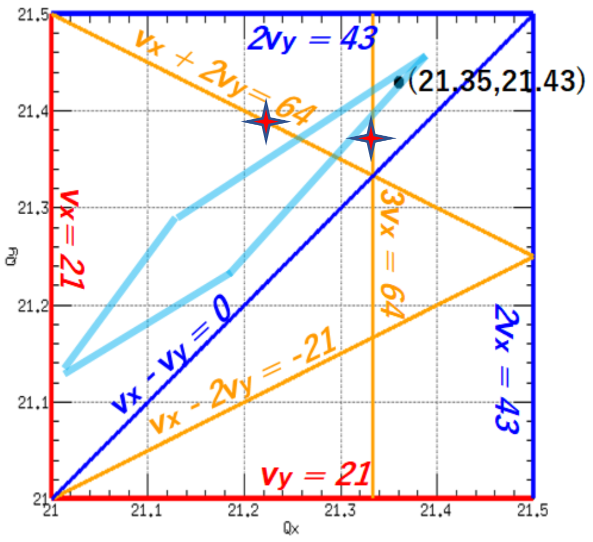
- Structure resonances of up to 3rd order (Solid lines)
- Non-structure resonances of half integer and linear coupling resonances (Dashed lines)

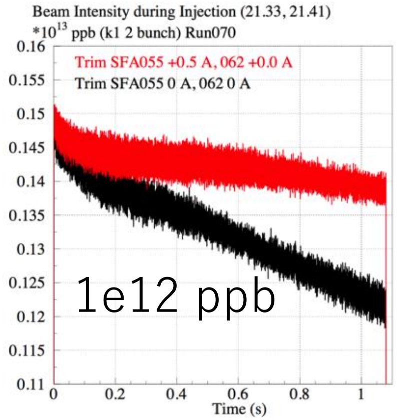


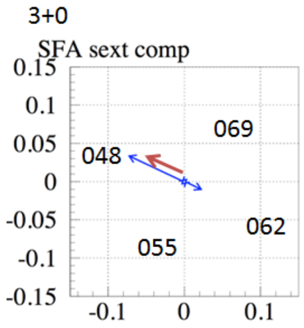
- Tune was shifted from (22.40, 20.75) to (21.35, 21.43) in 2016, to avoid the small tunability by $\nu_y = 20.5$
- At the new tune (21.35, 21.43), to correct $\nu_x + 2\nu_y = 64$ and $3\nu_x = 64$ are important.

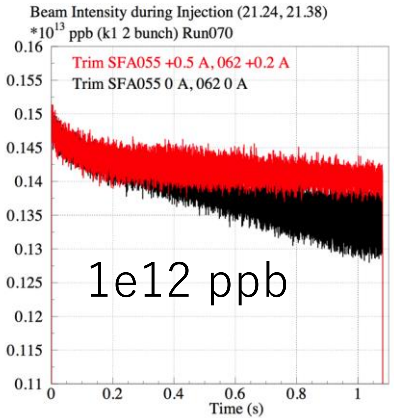
  → Trim coils of 4 sextupoles have been optimized.

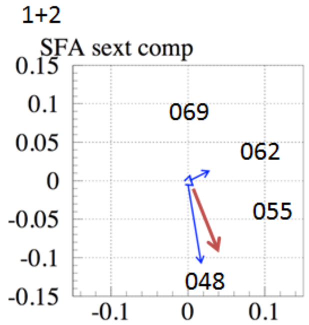
Correction of the 3rd order resonances of both vx+2vy = 64 and 3vx = 64











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

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

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

Activated trim-coils of
4 sextupole magnets
locating independent phase

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

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

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

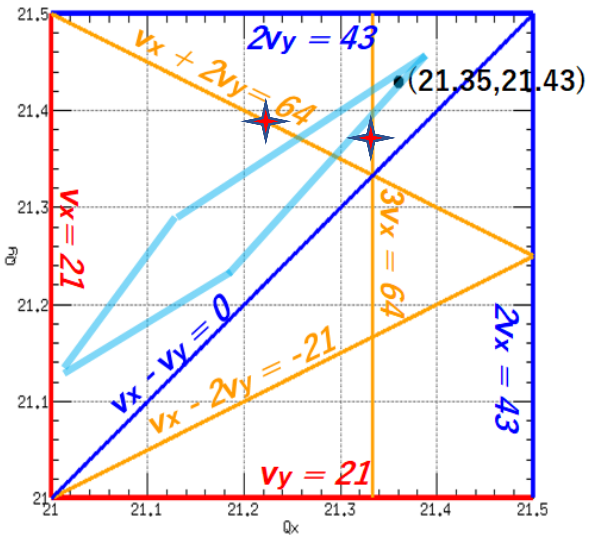
Measured
G 1,2,64
w 2 Trim-Ss

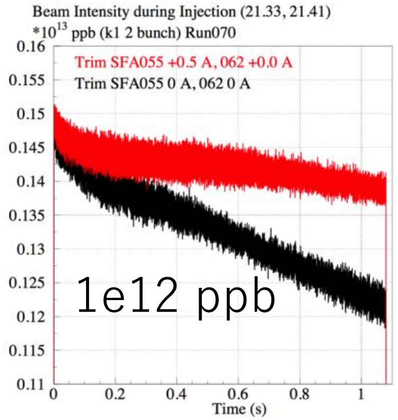
1 = T-SFA048, 2 = T-SFA055, 3 = T-SFA062, 4 = T-SFA069

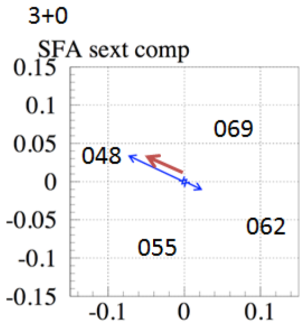
- Scanning 2 trim-sextupoles identify the driven factors of ν x+2 ν y = 64 and 3 ν x = 64
- 4 parallel eqs. provide a solution to correct both lines simultaneously with 4 trim-sextupoles
- Beam losses were reduced with the correction not only injection but acceleration
- We keep investigating the resonance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

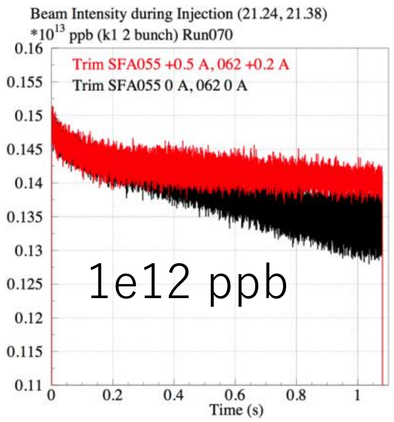
Correction of the 3rd order resonances of both vx+2vy = 64 and 3vx = 64

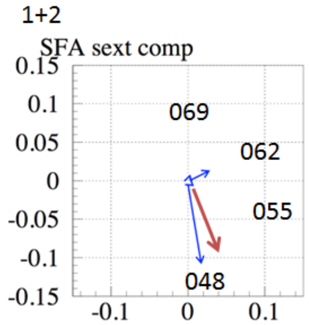
S. Igarashi et al., Proc. HB2016, pp 21-26, 2016











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

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

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

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

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

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

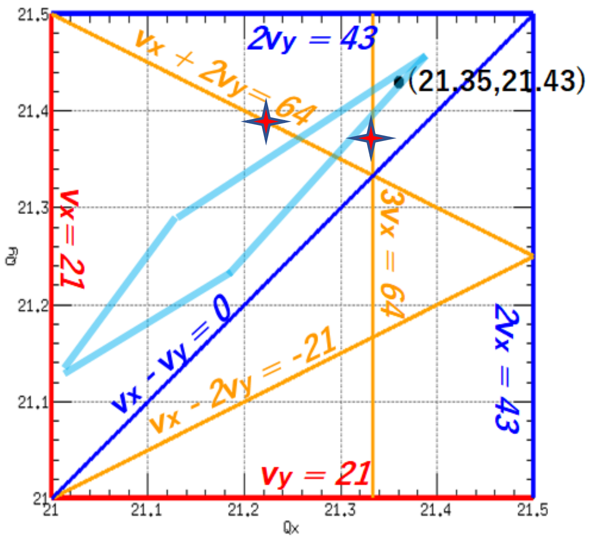
Equations for canceling both resonances, for $k_2(1)$, $k_2(2)$, $k_2(3)$, $k_2(4)$.

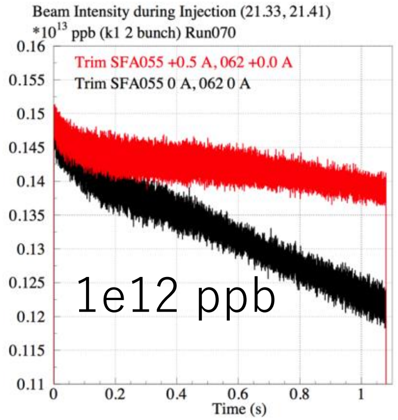
1 = T-SFA048, 2 = T-SFA055, 3 = T-SFA062, 4 = T-SFA069

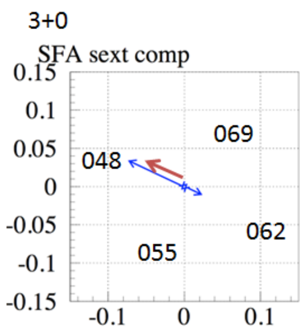
- Scanning 2 trim-sextupoles identify the driven factors of ν x+2 ν y = 64 and 3 ν x = 64
- 4 parallel eqs. provide a solution to correct both lines simultaneously with 4 trim-sextupoles
- Beam losses were reduced with the correction not only injection but acceleration
- We keep investigating the resonance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

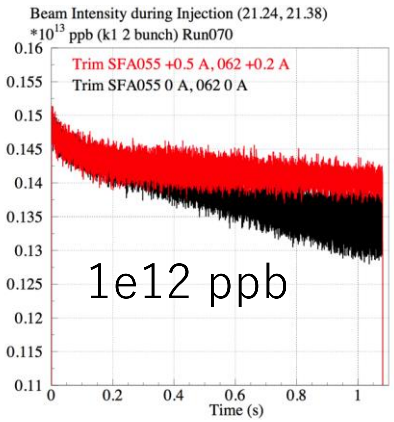
Correction of the 3rd order resonances of both vx+2vy = 64 and 3vx = 64

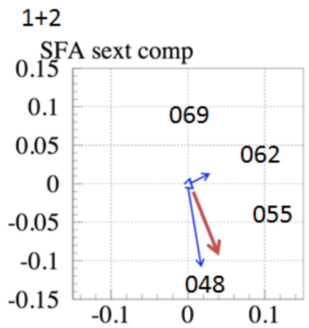
S. Igarashi et al., Proc. HB2016, pp 21-26, 2016











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

$$G_{1,2,64} = \frac{\sqrt{2}}{8\pi}\beta_x^{1/2}\beta_y k_2 \exp[i(\phi_x + 2\phi_y)]$$

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

$$\sum_{j=1}^{4}\frac{\sqrt{2}}{24\pi}\beta_x^{3/2}(j)\, k_2(j) \cos[3\phi_x(j)] = \sum_{j=2}^{3}\frac{\sqrt{2}}{24\pi}\beta_x^{3/2}(j)\, k2(j) \cos[3\phi_x(j)]$$

$$\sum_{j=1}^{4}\frac{\sqrt{2}}{24\pi}\beta_x^{3/2}(j)\, k_2(j) \sin[3\phi_x(j)] = \sum_{j=2}^{3}\frac{\sqrt{2}}{24\pi}\beta_x^{3/2}(j)\, k2(j) \sin[3\phi_x(j)]$$

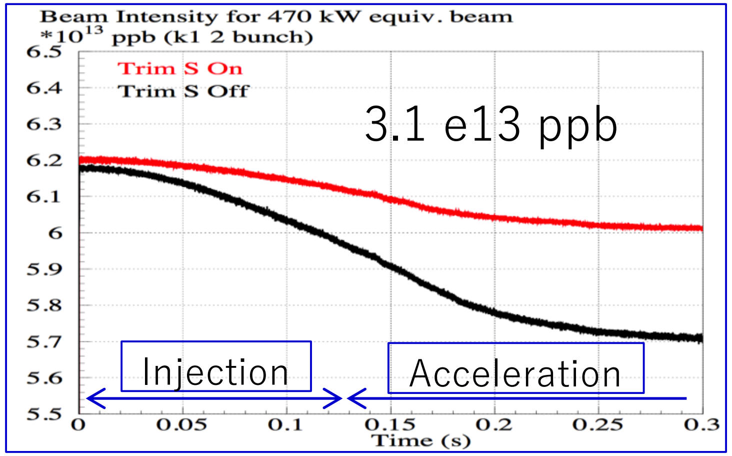
Measured G 3,0,64 w 2 Trim-Ss

$$\sum_{j=1}^{4}\frac{\sqrt{2}}{8\pi}\beta_x^{1/2}(j)\beta_y(j)\, k_2(j) \cos[\phi_x(j)+2\phi_y(j)] = \sum_{j=2}^{3}\frac{\sqrt{2}}{8\pi}\beta_x^{1/2}(j)\beta_y(j)\, k2(j) \cos[\phi_x(j)+2\phi_y(j)]$$

$$\sum_{j=1}^{4}\frac{\sqrt{2}}{8\pi}\beta_x^{1/2}(j)\beta_y(j)\, k_2(j) \sin[\phi_x(j)+2\phi_y(j)] = \sum_{j=2}^{3}\frac{\sqrt{2}}{8\pi}\beta_x^{1/2}(j)\beta_y(j)\, k2(j) \sin[\phi_x(j)+2\phi_y(j)]$$

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

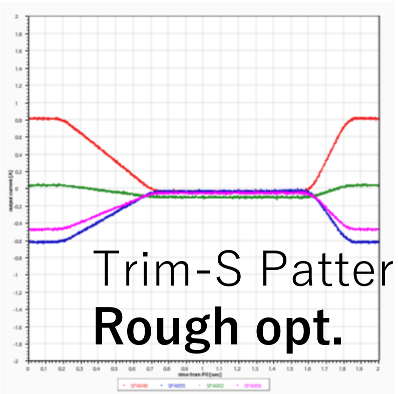
Equations for canceling both resonances, for $k_2(1)$, $k_2(2)$, $k_2(3)$, $k_2(4)$.
1 = T-SFA048, 2 = T-SFA055, 3 = T-SFA062, 4 = T-SFA069



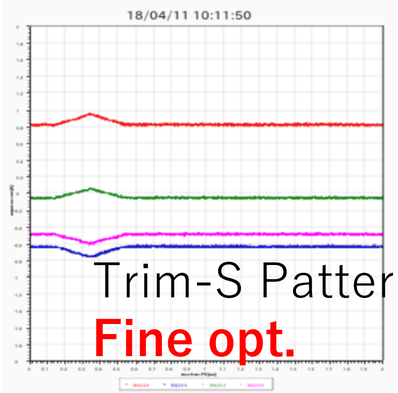
- Scanning 2 trim-sextupoles identify the driven factors of ν x+2 ν y = 64 and 3 ν x = 64
- 4 parallel eqs. provide a solution to correct both lines simultaneously with 4 trim-sextupoles
- Beam losses were reduced with the correction not only injection but acceleration
- We keep investigating the resonance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

Further optimization of 3rd order resonances and higher order

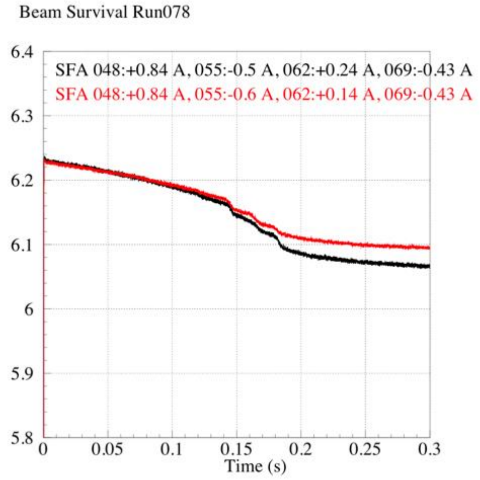
Trim S Optimization
475 kW equiv.,
Rough opt: 0.14 s flat & 0.14 s → 0.76 s ramp down
Fine opt: pattern opt. w observing beam losses



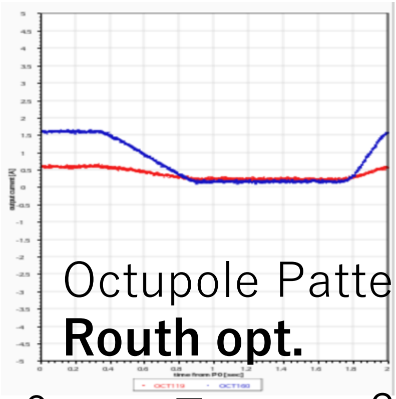
0 s Time 2 s



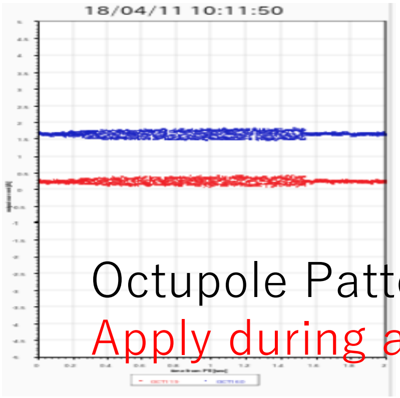
0 s Time 2 s



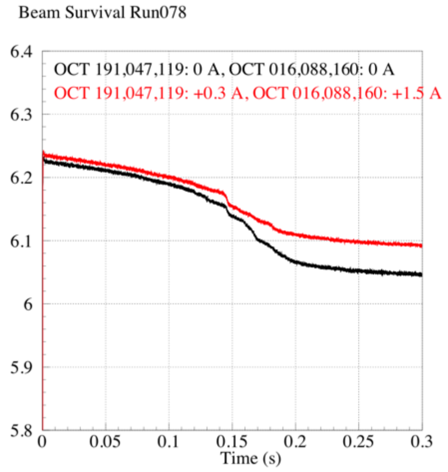
Octupole Optimization
475 kW equiv.,
Rough opt.: 0.14 s flat & 0.14 s → 0.76 s ramp down
Apply during accel: flat pattern (DC)



0 s Time 2 s



0 s Time 2 s

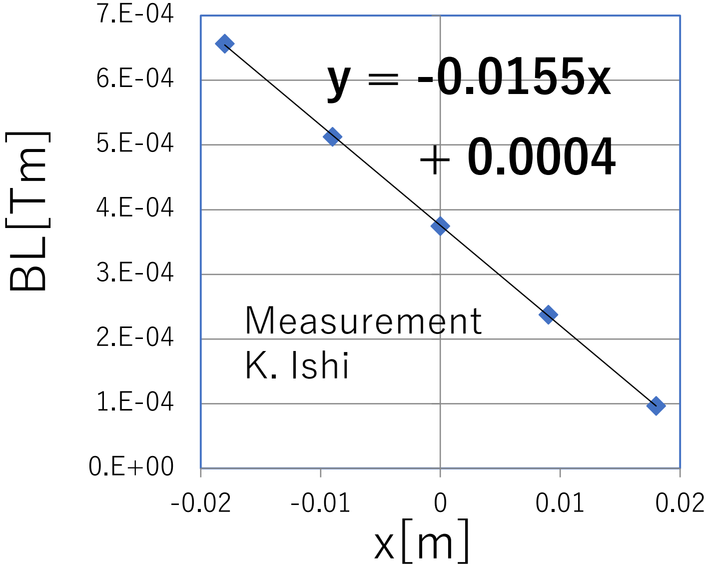


- Parameter scan works well for higher order correction.
- Identifying the sources of these resonances --- under discussion *(higher order of sextupoles?, leakage fields?, …)*

FX Septum Leak field

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

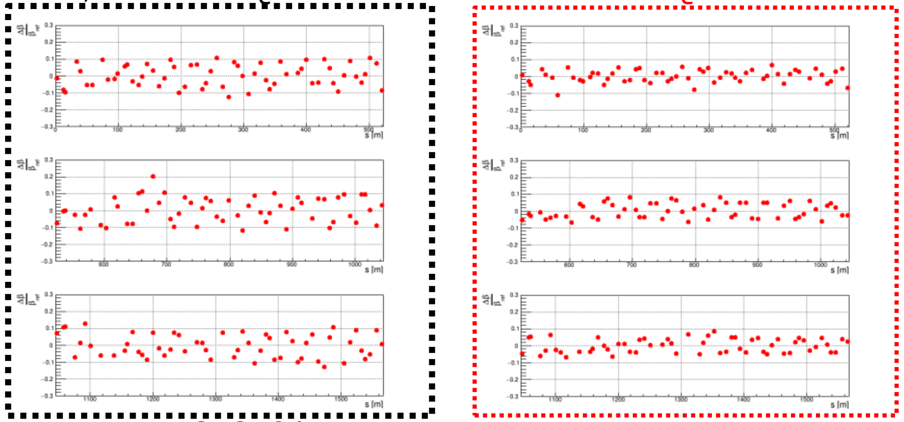
SM30 (336A) with duct



βy modulation

w/o Trim Q corr.

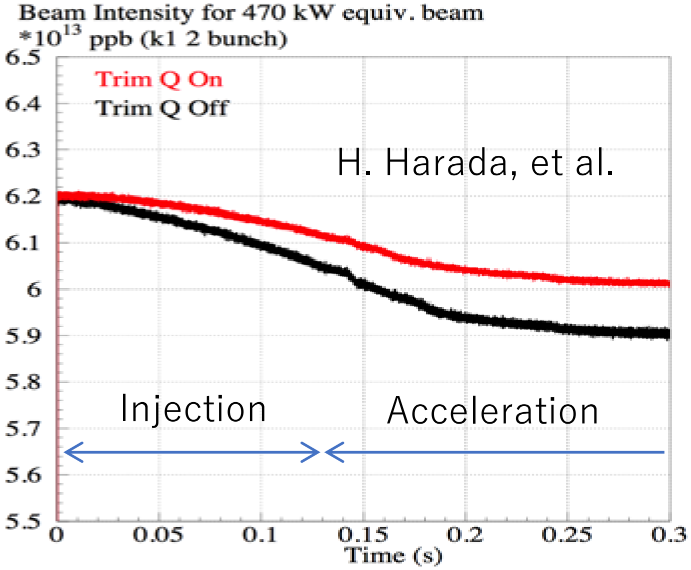
w Trim Q corr.



σ=6.9 %

σ=4.1 %

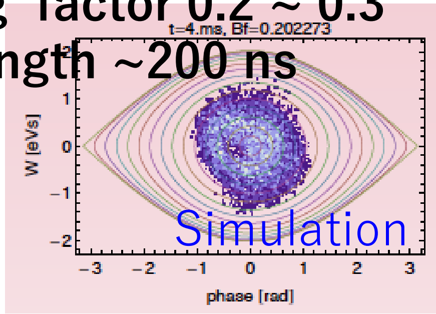
Kurimoto, et al.

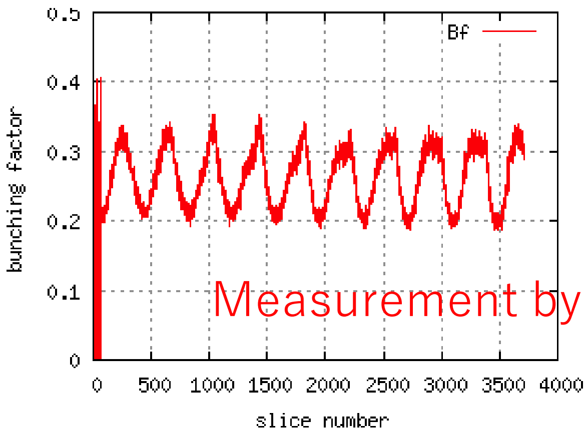


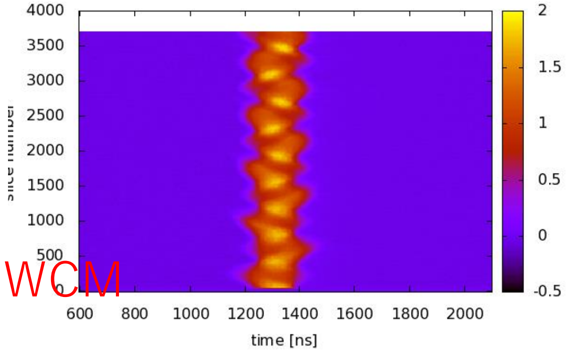
- **Leak field of 8 FX septum magnets corresponds to ~3% of K1 of the main Q magnet.**
  → One of main sources of beam optics modulation and reduce MR physical aperture
- **Trim coils of 3 Q magnets have been used to correct the leak field of FX septum magnets.**
- All main quadrupoles are also adjusted 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.**

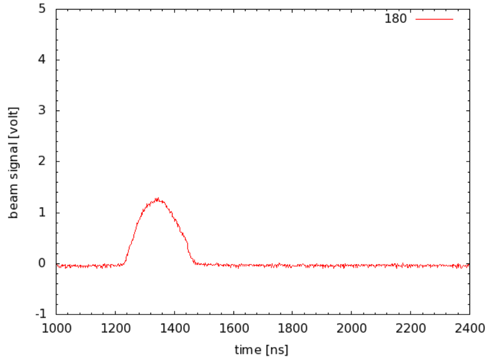
Longitudinal Profiles with high intensity (500 kW eq.)

(100 kV, 0 kV)
Bunching factor 0.2 ~ 0.3
Bunch length ~200 ns

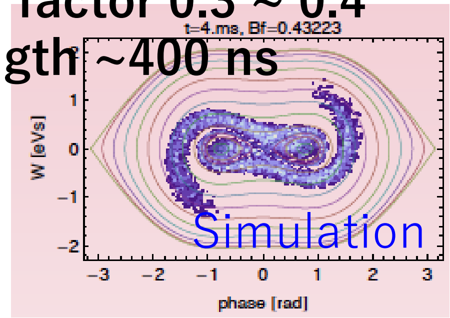


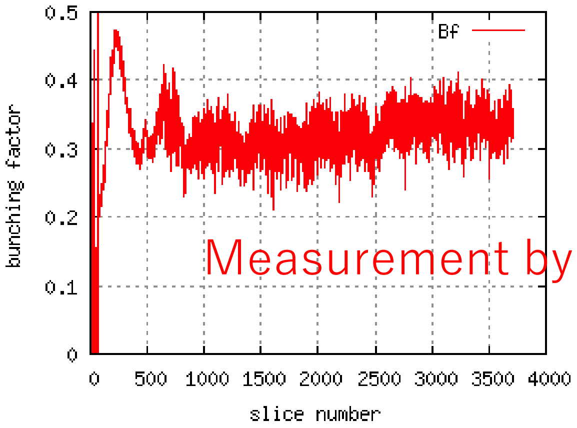


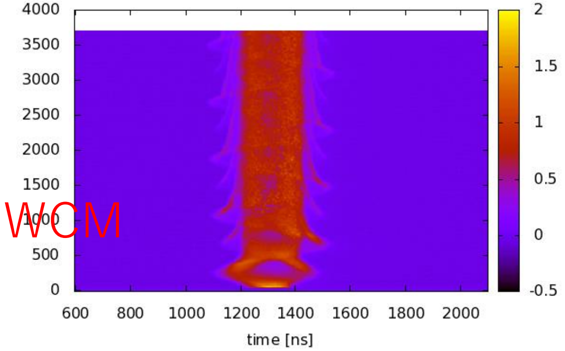


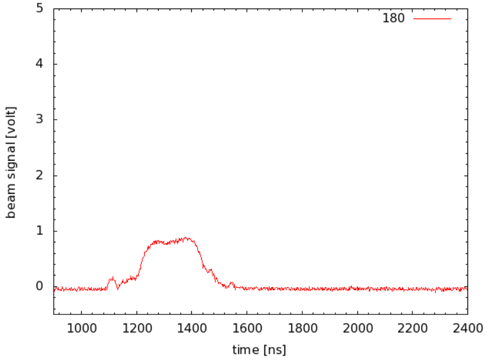


(100 kV, 70 kV)
Bunching factor 0.3 ~ 0.4
Bunch length ~400 ns



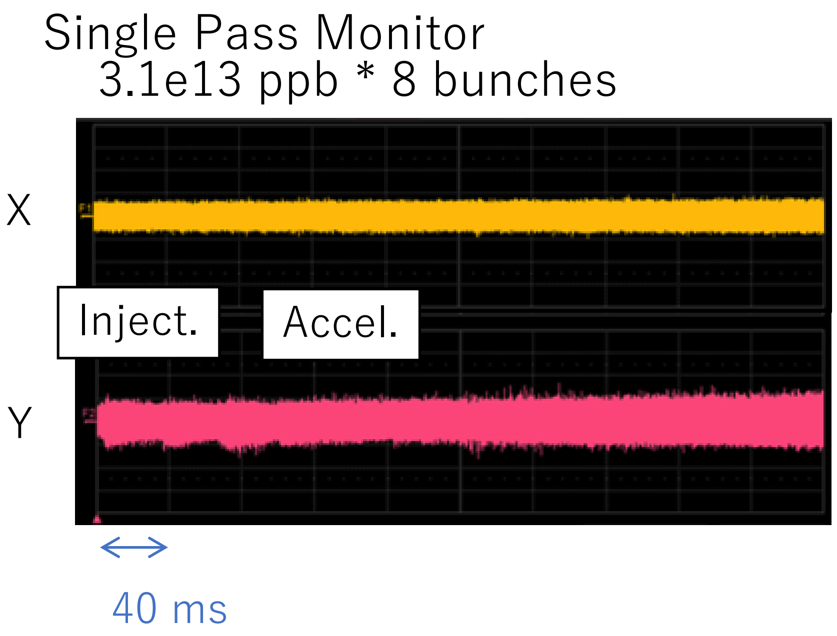


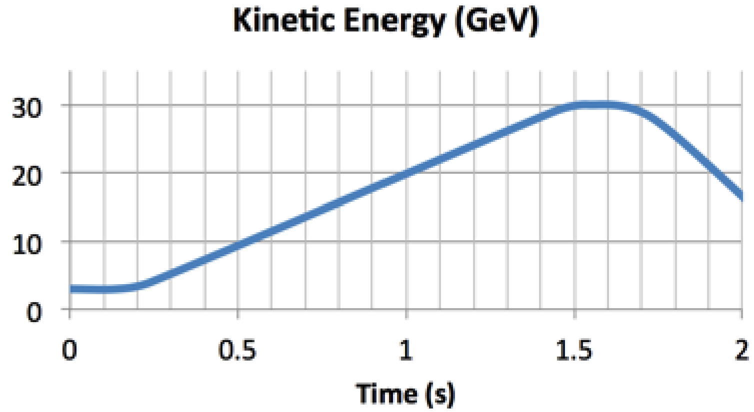


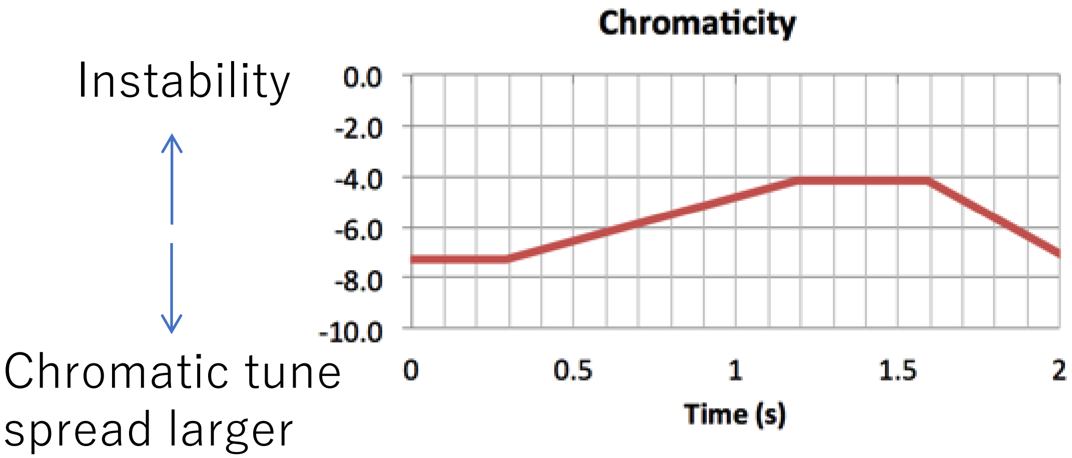


- **Large amplitude voltage of 2nd harmonic RF, over 50% to fundamental harmonic RF, is adopted**
- **Longitudinal mismatch is purposely used to suppress space charge effect promptly**

Instability Suppression (1) Chromatic Pattern



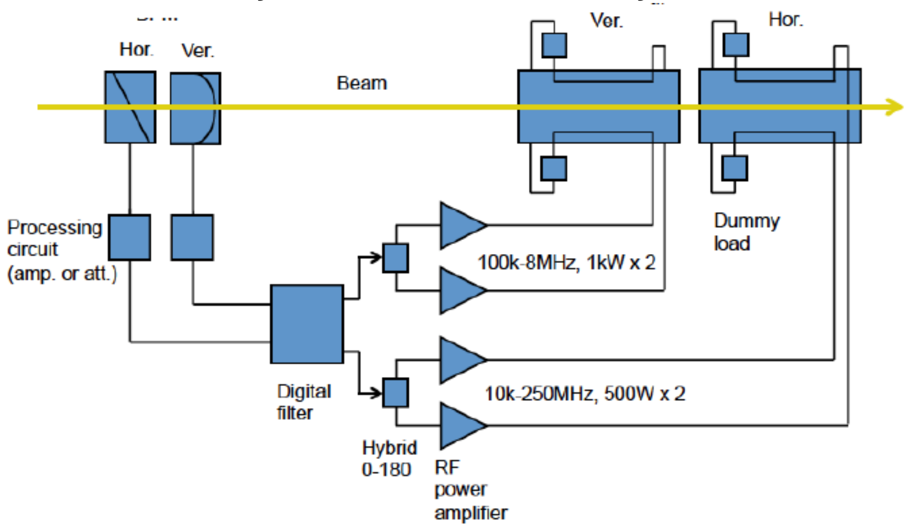




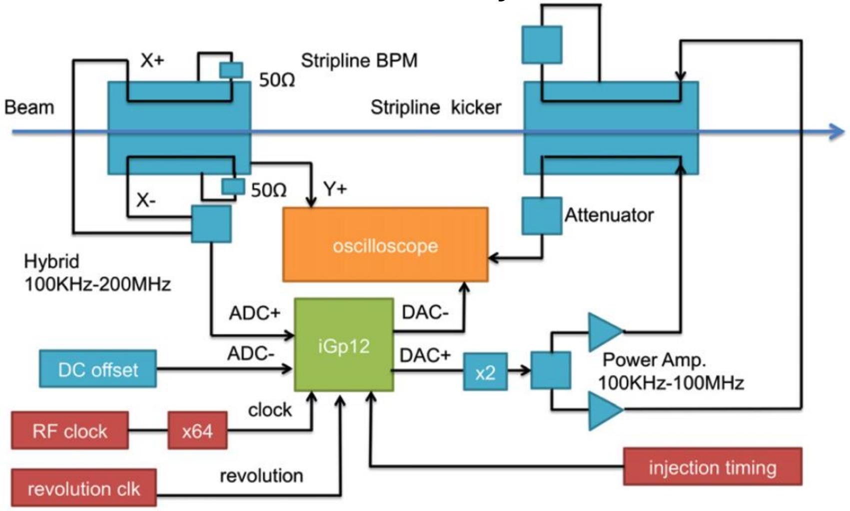
- The chromaticity pattern was set to minimize the beam loss, and kept in negative value
- If the chromaticity is too small, we observe instability
- If the chromaticity is too large, we observe the beam loss due to chromatic tune spread
- This pattern scheme works but is not enough for high intensity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

Instability Suppression (2) Transverse Feedback System

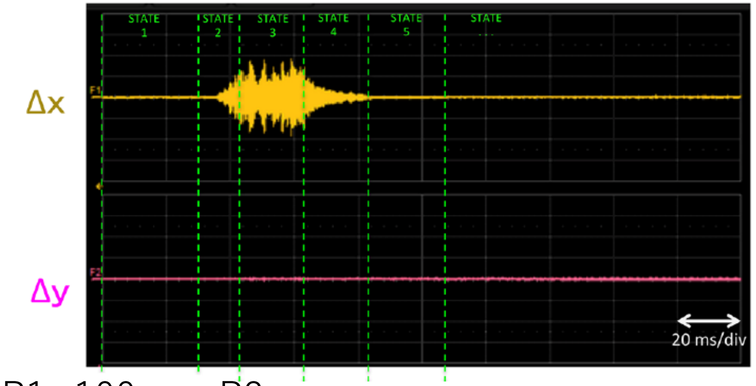
Bunch by bunch feedback system



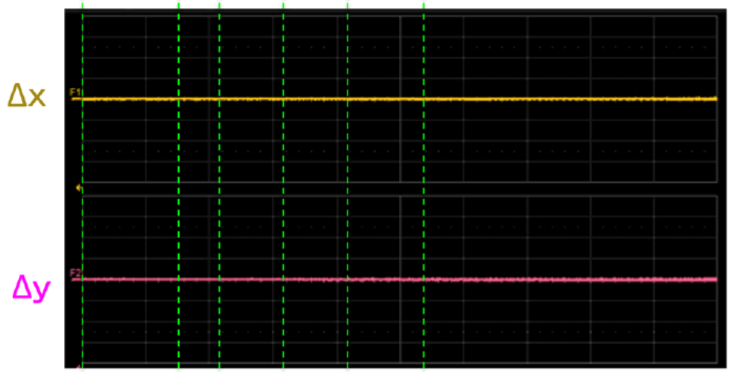
Intra-bunch feedback system (wideband)



Beam Position with Intra-bunch FB off



Beam Position with Intra-bunch FB on



P1+100 ms P2 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

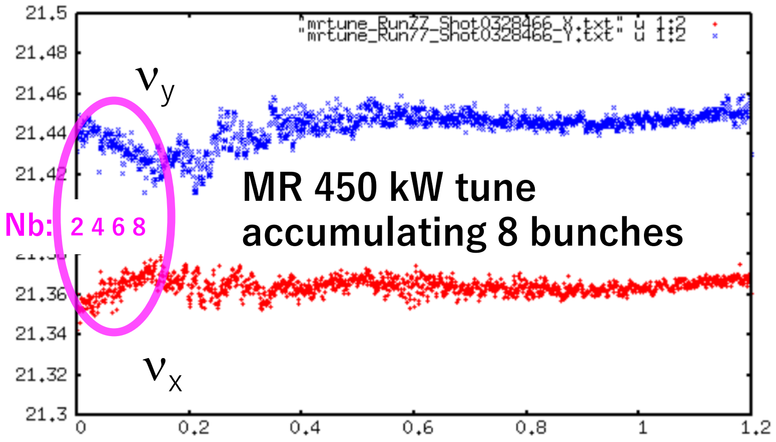
Tune tracking for bunch train tune shift (1)

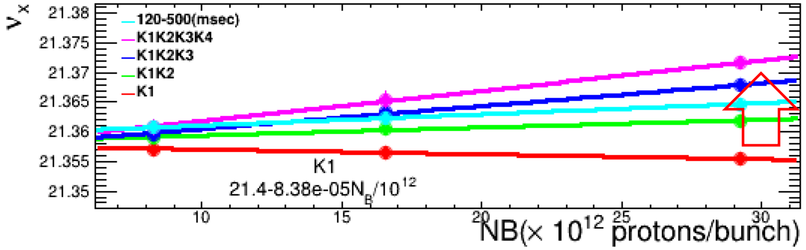
Bunch train tune shift in case of PEP-II octagonal chamber in dipoles (A. Chao *et al.*, PRSTAB, 5, 111001 (2002))

$$\Delta\nu_{x,y} = \pm\frac{\Gamma}{2\omega_0\omega_{x,y}}h \approx \pm\frac{\Gamma}{2\omega_0\omega_{x,y}}\frac{rb}{\delta_0} = \pm\frac{1}{48}\frac{rNr_0L}{\gamma b^2\nu_{x,y}}$$

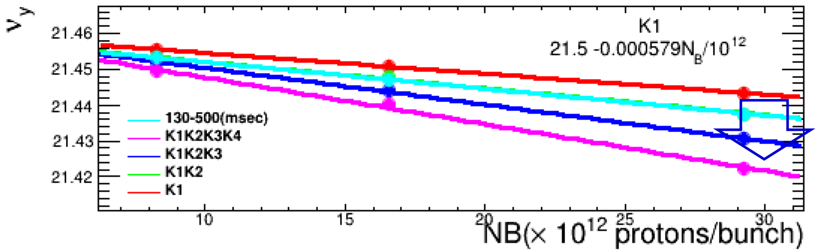
N: total number of particles in beam
L: Length of octagonal chamber
b: half of vertical separation
r: parameter of impedance

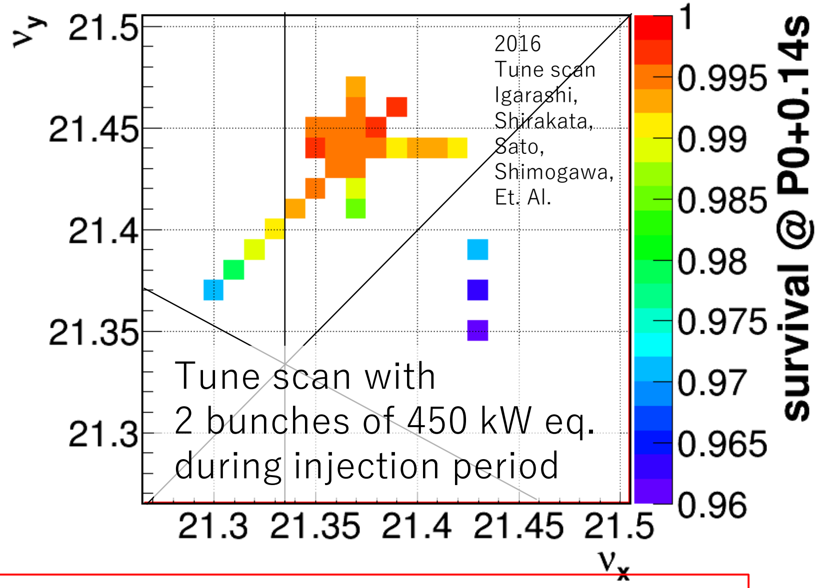
MR tunes are shifted by Quadrupolar Wake of non-circular beam pipe ($d\nu_x = +0.02$, $d\nu_y = -0.02$)





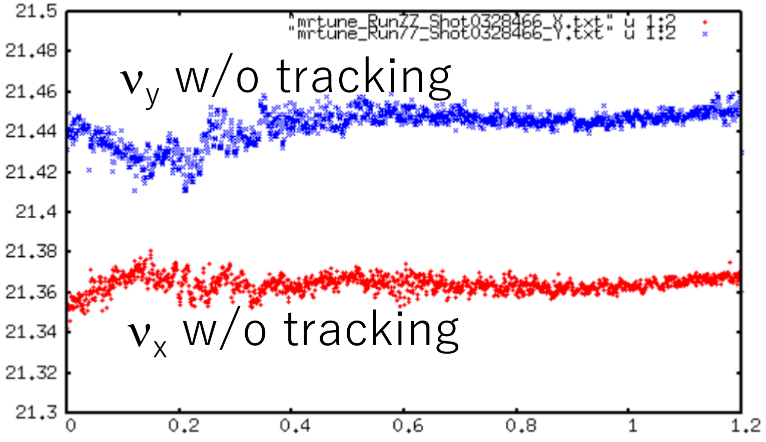
A. Kobayashi, T. Toyama

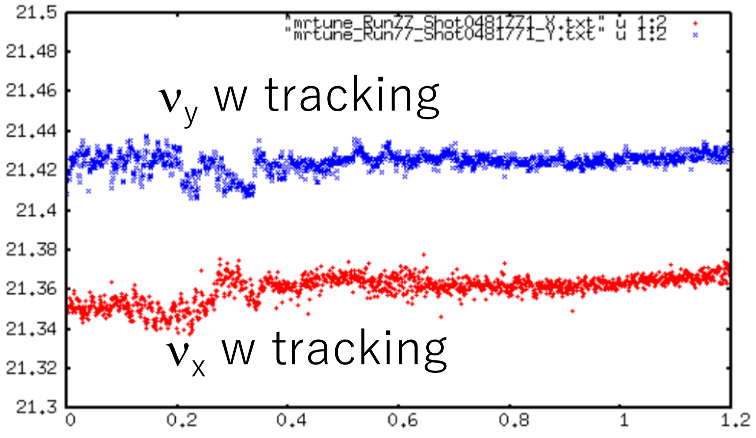


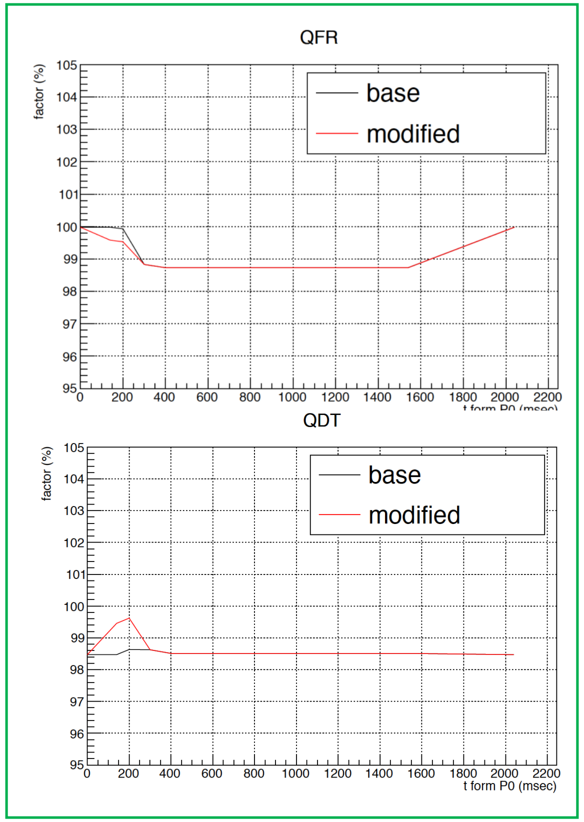


- **Non-circular beam pipe causes bunch train tune shift as a whole ring.**
- **In MR, the bunch train tune shift during injection was observed for high intensity beam > 450 kW, though best survival betatron tune is in limited area**

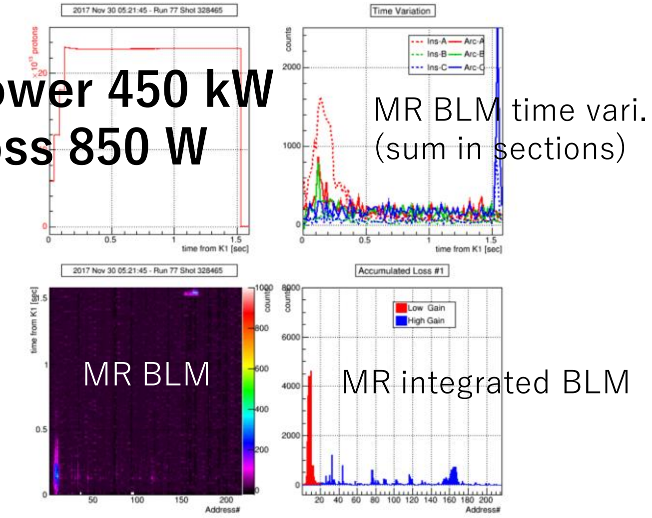
Tune tracking for bunch train tune shift (2)



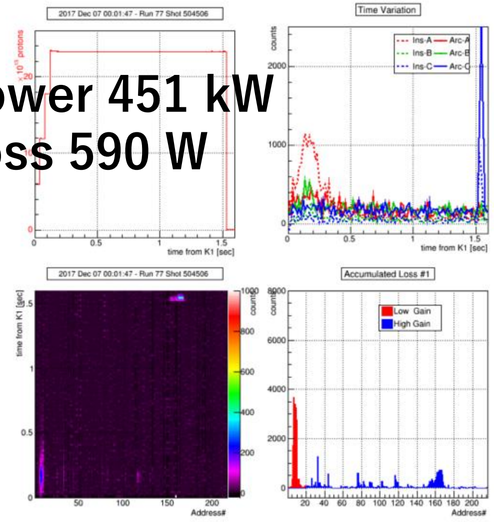




Power 450 kW
Loss 850 W



Power 451 kW
Loss 590 W



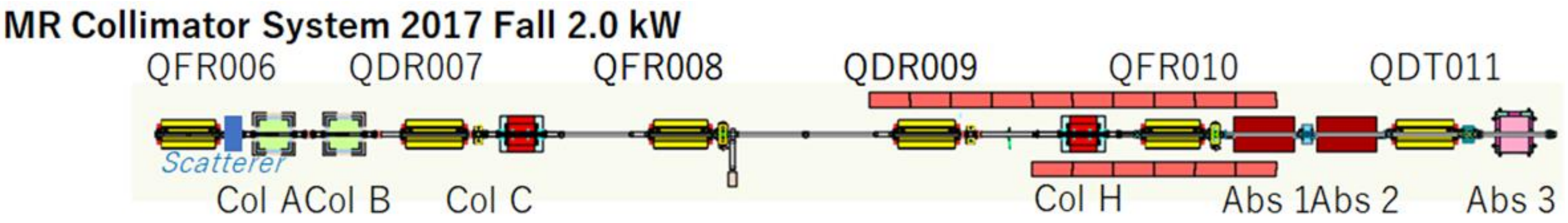
490 kW user operation achieved By this trick.

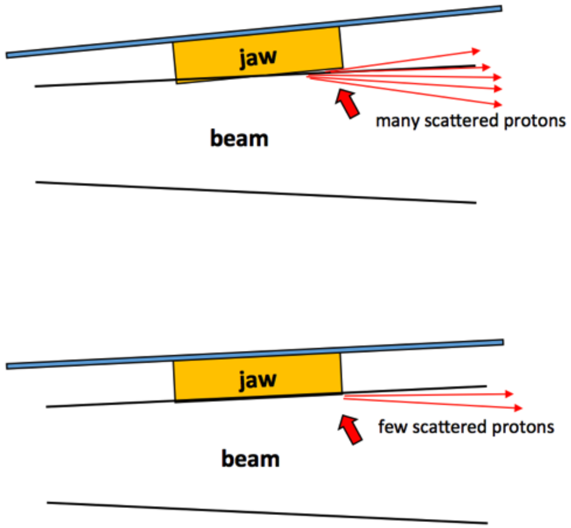
Beam survival was improved with correction of the tune shift.

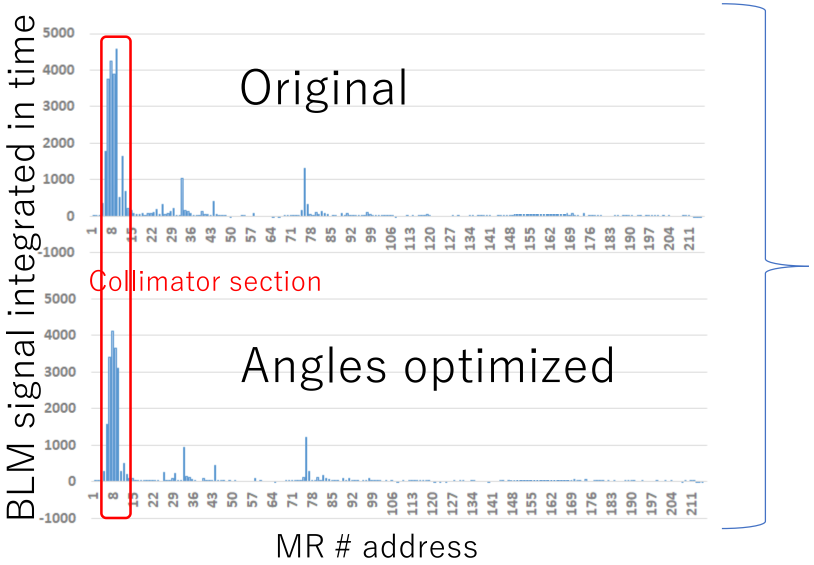
New power supply of QFR (prepared for MR upgrade) enabled this tune tracking.

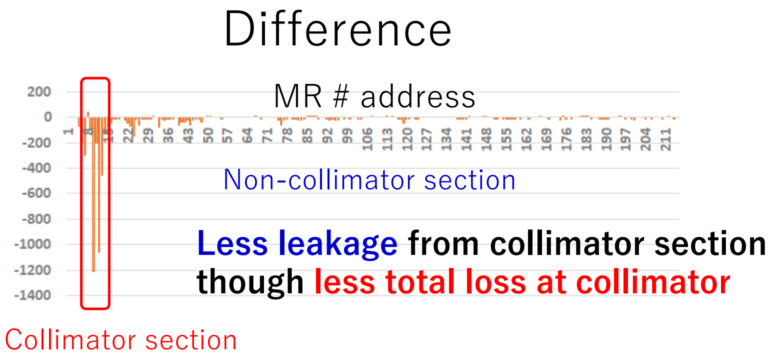
→ Stable 490 kW user operation ***(Trim-Sextupoles/Octupole/MR COL were tuned also)***

Beam loss localization with MR Collimators









M. Shirakata, Y. Sato

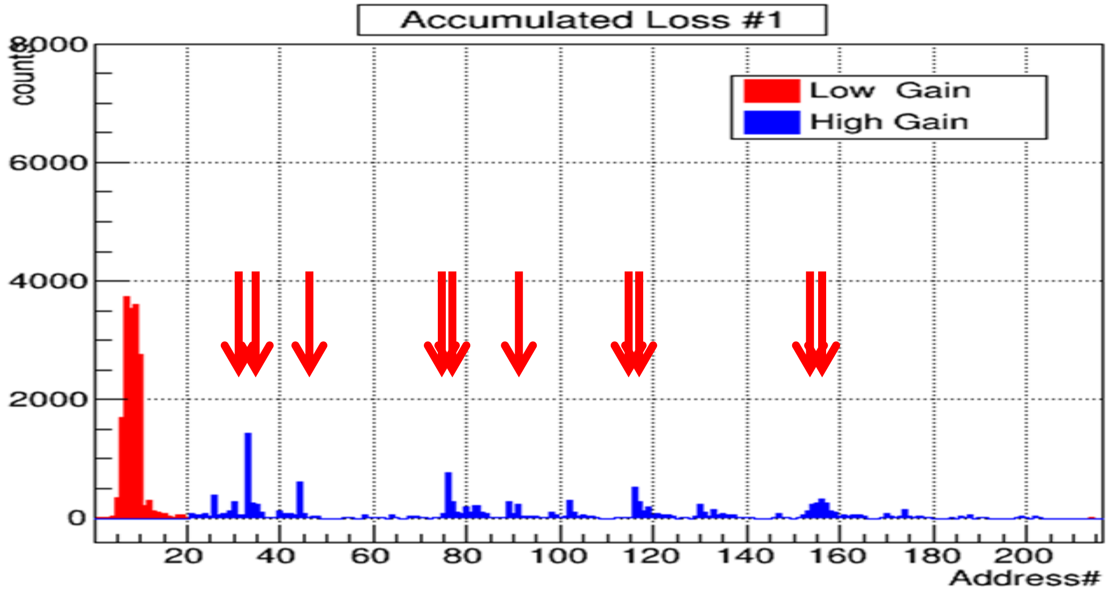
- **Collimators C and D have angle adjustment capability**
- **Fitting the collimator jaws to beam envelopes reduced loss leakage in non-collimator section**
- **Additional rotational collimators are considered to be installed.**

Residual Radiation and Beam Losses during Operation

- Residual radiation is measured 4 hours after the 478 kW operation on 2018/4/12
- One foot < 300 uSv/h in most of non-collimator section
- High-radiated points in non-collimator section are as follows:

One foot [μSv/h]	QFN029	QFX033	BM QDX044	QFT075 ESS	ESS QFP076	QDX089	BM QDX116	QFN117	SM2 QDT155	SM30 QFP156
3/22	100	300	200	400	600	500	200	300	1000	300
3/27	100	300	250	700	600	700	150	350	1000	300
4/2		200	250	350	450	350	180	300	700	300
4/12		250	250	400	400	400	150	500	800	350

- At these places beam losses are observed to be 100 ~ 1500 of Integ-BLM counts during operation



→ Enough eyes to manage them

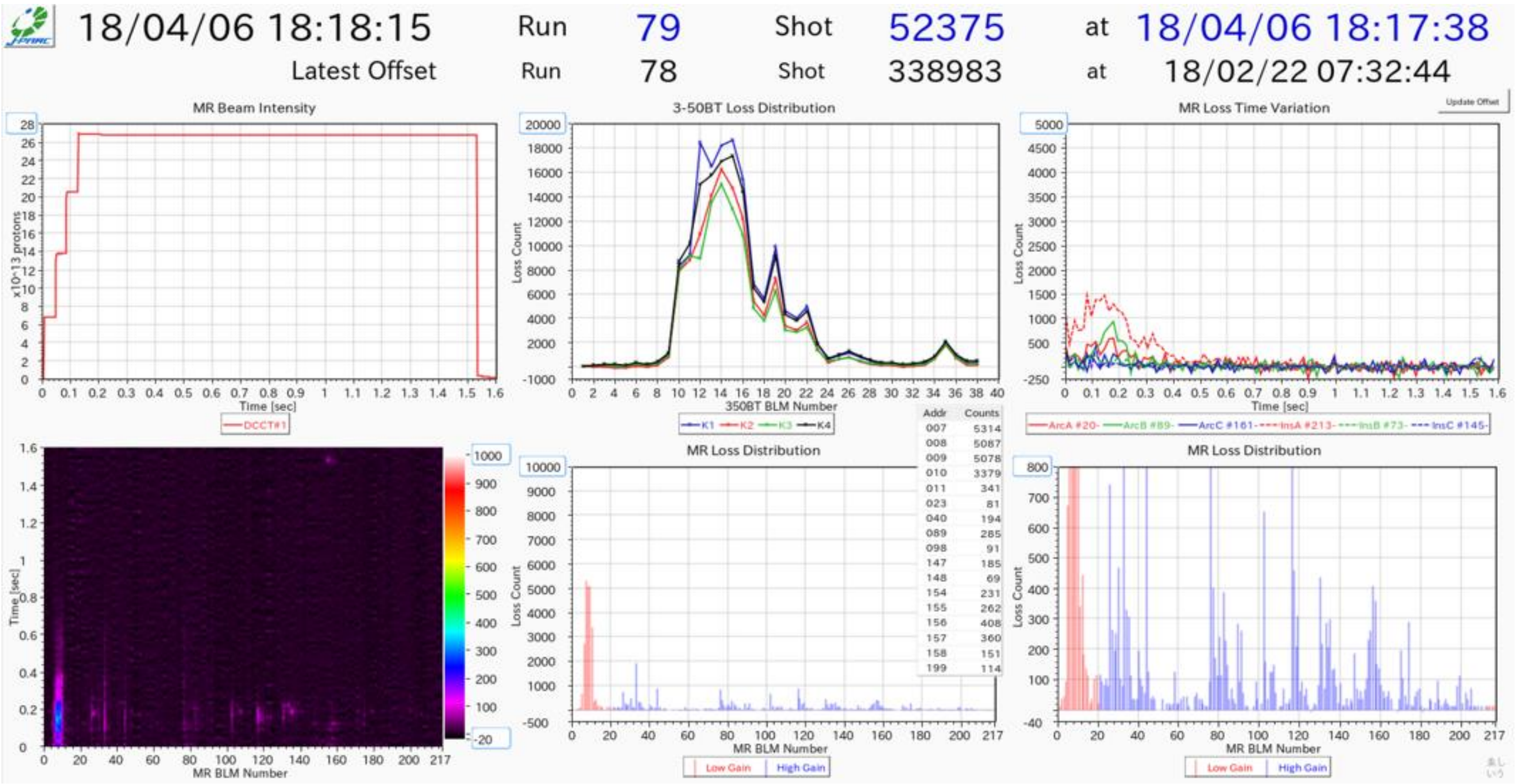
- **Residual activation is well controlled with high power beam operation**
- **Less beam loss and better loss localization are under studied, observing BLM signal**

High Intensity Trial at 520 kW

MR power 520 kW (2.68e14 ppp)
3-50BT loss 200 W
< BT COL capacity 2 kW
MR loss 1 kW (*1)
< MR COL capacity 2 kW

Injection 450 W
Acc 1st 90 ms 460 W
Acc after 90ms 90 W

NOTE *1: Beam loss estimated with DCCT#1.



- Losses at the beginning of the acceleration: ArcB loss (@ high βy)
- V-profile was large @ NU.
- Optimization necessary for loss reduction.
- Longitudinal oscillation enlarged but no leakage from RF bucket
- RF#3 anode current 100 A

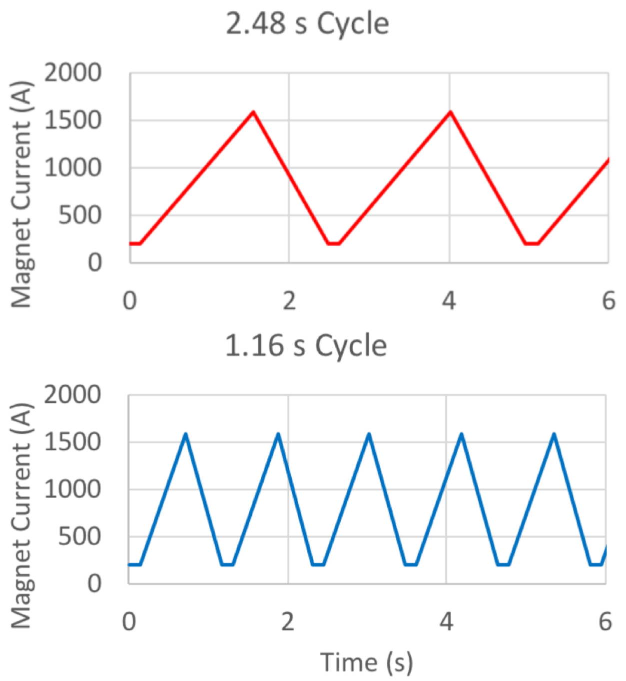
- **520 kW in 2.48 s cycle shows no significant total loss with ~ 2%.**
  → 1.1 MW capability demonstrated in 1.16 s near-future-cycle
- **Beam loss collimation is needed. We can perform iterative tunings of Tune/ IntraBFB/ RF/ Sextupoles/ Trim-S/ Octupoles for less losses and better loss localization in > 520 kW**
- **We are developing longitudinal feedback system newly, also**

Contents

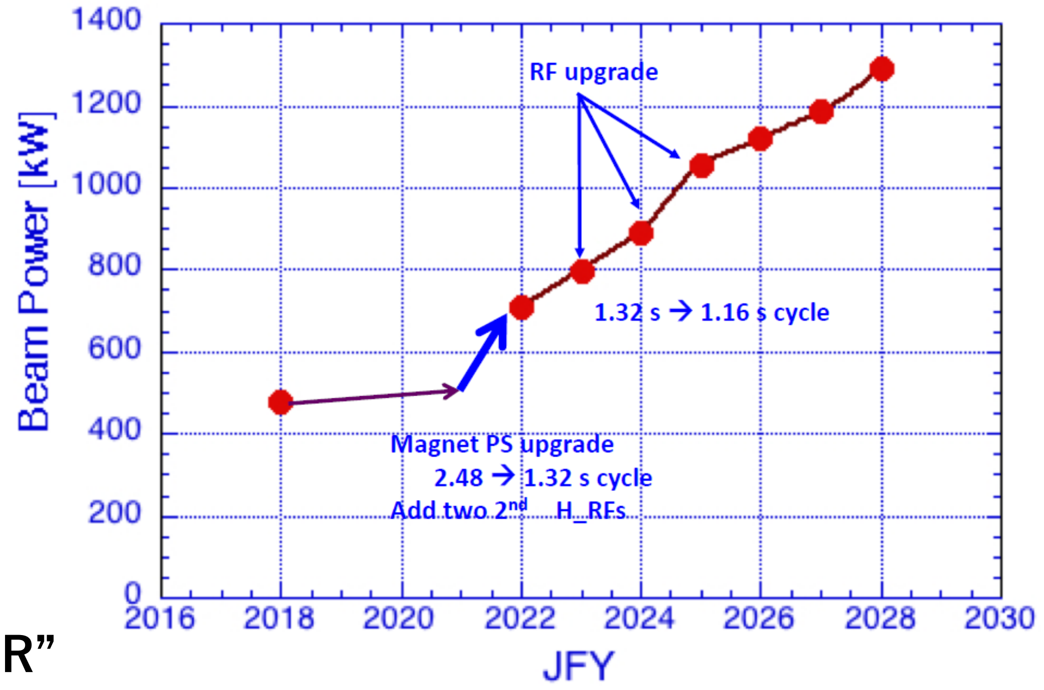
- Overview
- RCS
  - 1 MW beam test
  - Compatibility of both MLF and Main Ring operations
- MR with fast extraction
  - Typical operation
  - High intensity tuning keys
- **MR upgrade plan**
  - **Concept**
  - **Beam loss localization**
- Summary

Beam Power Upgrade Concept

- The operation of 490 kW has been achieved so far with
  the cycle time of 2.48 s and
  the accelerated protons of 2.5e14 ppp.
- The beam power of 1.3 MW is planned with
  the faster cycling of 1.16 s and
  the accelerated protons of 3.3e14 ppp.
- Hardwares (Magnet PS/ RF/ Colli/ Inj&FX/…) are under preparation
- **The most powerful neutrino beam can be realized in several years.**



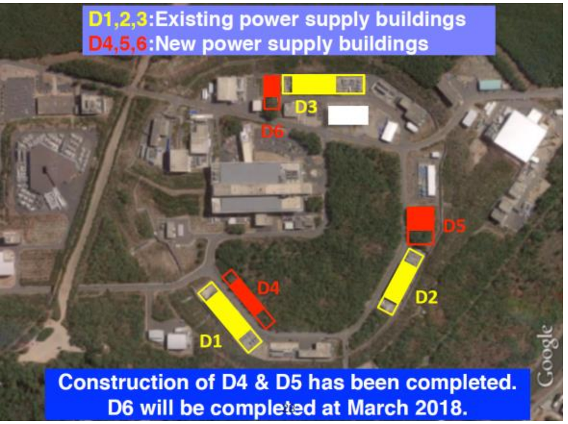
Beam Power	Cycle time	Protons per pulse (ppp)	Protons per bunch (ppb)	Eq. beam power in RCS
490 kW	2.48 s	2.5 e14	3.1 e13	760 kW
520 kW	2.48 s	2.7 e14	3.4 e13	810 kW
750 kW	1.3 s	2.0 e14	2.5 e13	610 kW
1.3 MW	1.16 s	3.3 e14	4 e13	1 MW



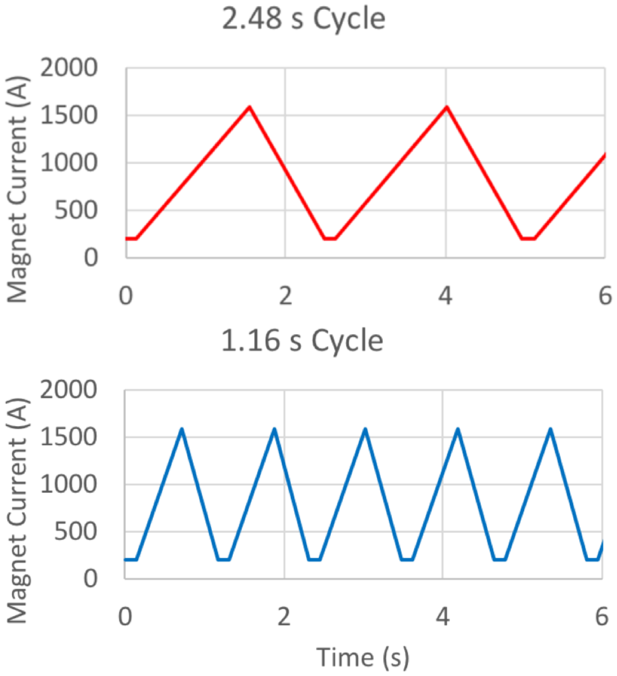
T. Koseki: TUPAK005, IPAC2018, "Upgrade Plan of J-PARC MR"

Hardware preparation

New power supply buildings

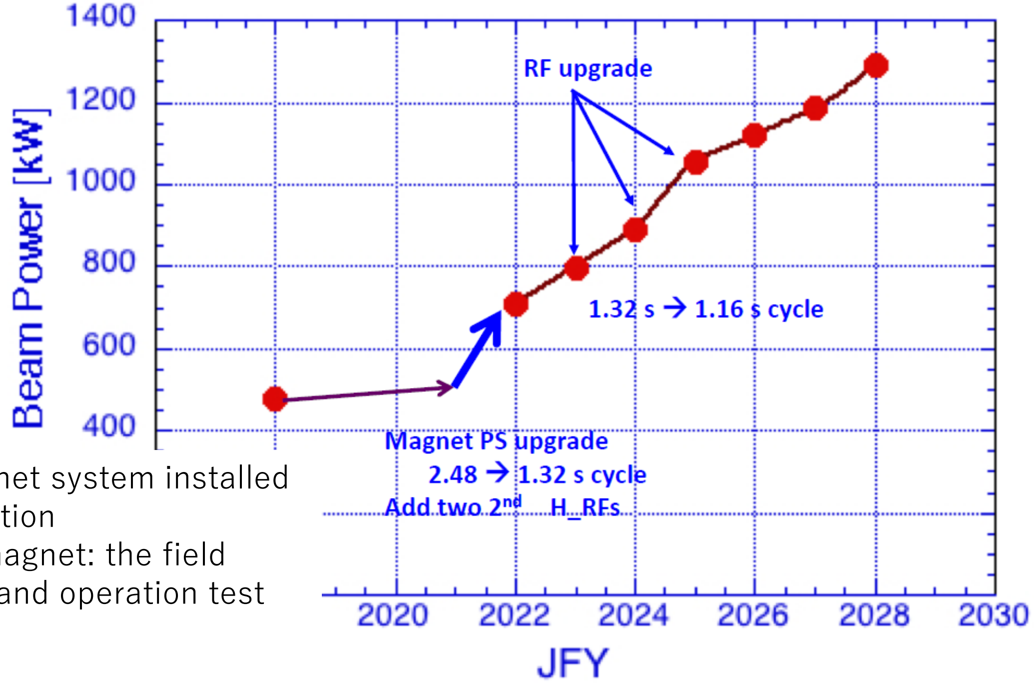


The first manufactured
new PS of dipole magnet
→ Installed In D4
System performance test
Is now in progress

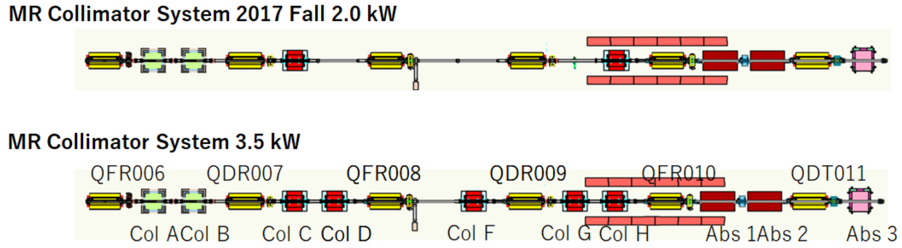


RF system	Present 490 kW	For 750 kW	For 1.3 MW
Rep. time	2.48 s	1.32 s	1.16 s
Accel. time	1,4 s	0.65 s	058 s
Accel. voltage	280 kV	510 kV	600 kV
2nd h. voltage	120 kV	120 kV	120 kV

- Arranged new type of magnetic alloy core for higher gradient.
- Old type MA will be Recycled for 2nd h
- Additional inverter output units
- M. Yoshii *et al.*, TUPAK011, IPAC2018



Collimator
Total capacity of MR COL: 2 kW → 3.5 kW

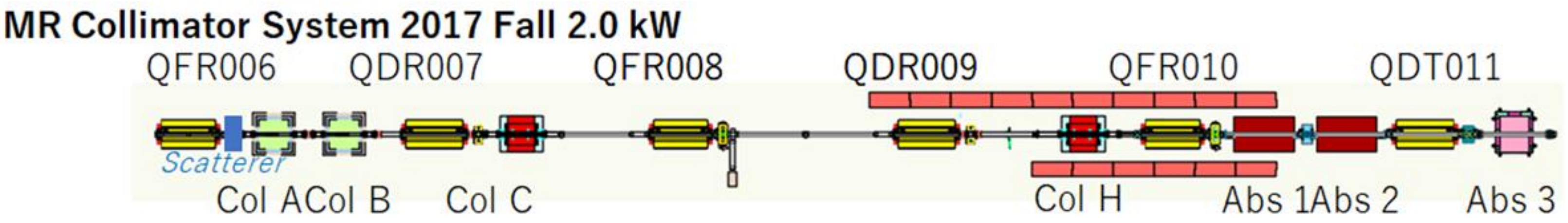


Injection & FX systems

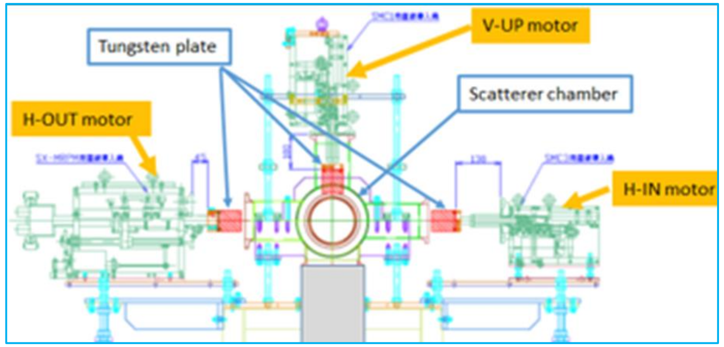
・New injection septum magnet system installed in 2016, and stable 2-y-operation

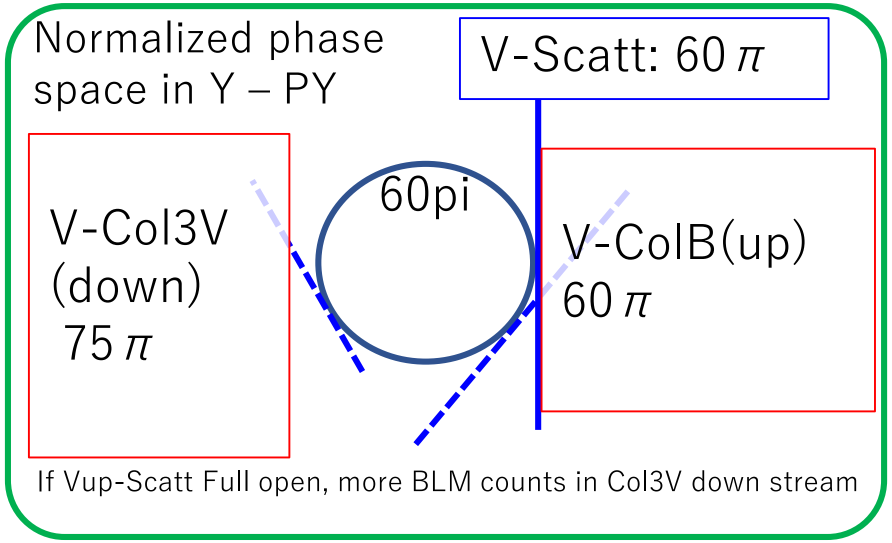
・New low field FX septum magnet: the field measurement of the magnet and operation test of its PS are now in progress

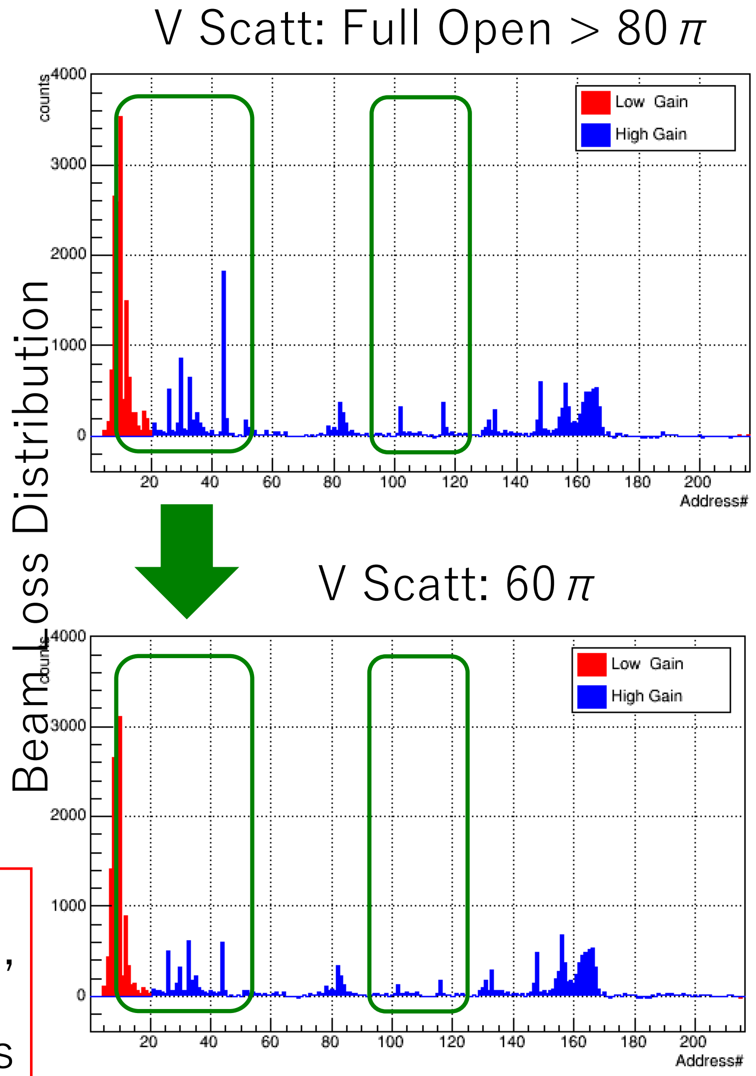
Scatterer Test Device with MR Collimators



Beam test with 450 kW eq. (2 bunches)







Y. Sato, Y. Hashimoto, Y. Kurimoto, M. Shirakata, et. al.

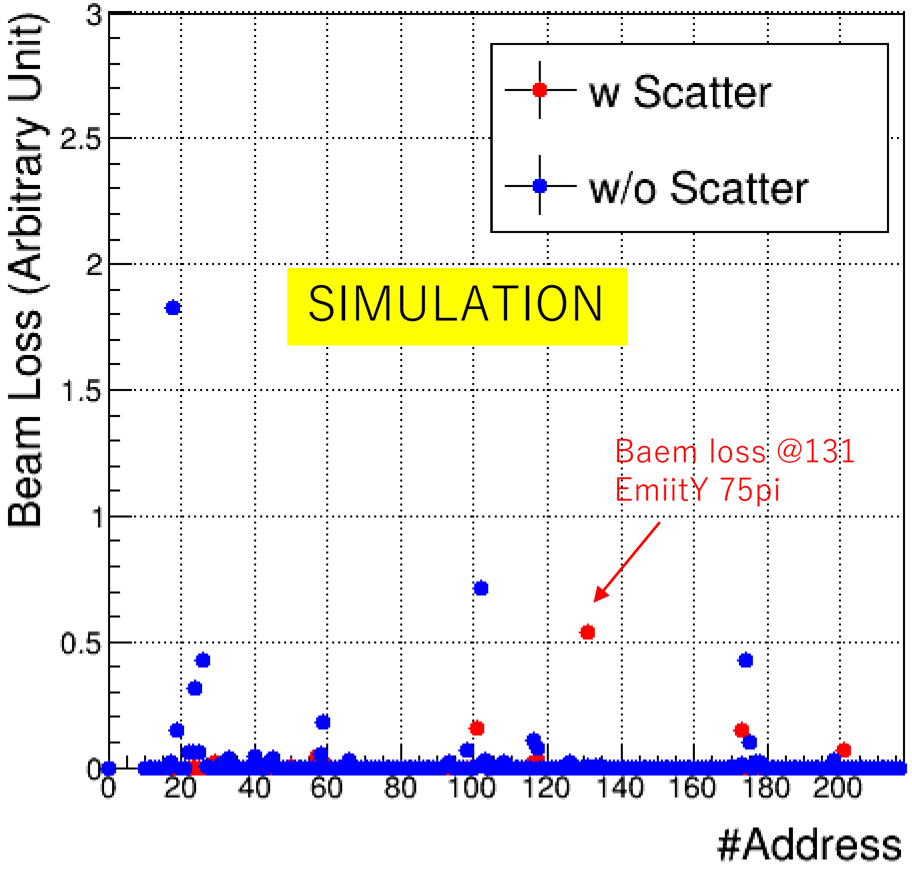
- In the faster cycle itself, beam loss will increase **linearly**.
- In the view of beam operation, loss localization is important
- 2 stage collimator scenario, using thin-plates as scatterer, is under studied, besides adding new collimators having angle adjusted jaws.
- Successful beam test: Less loss leakage without increasing total beam loss

Scatterer Test in Beam Simulation

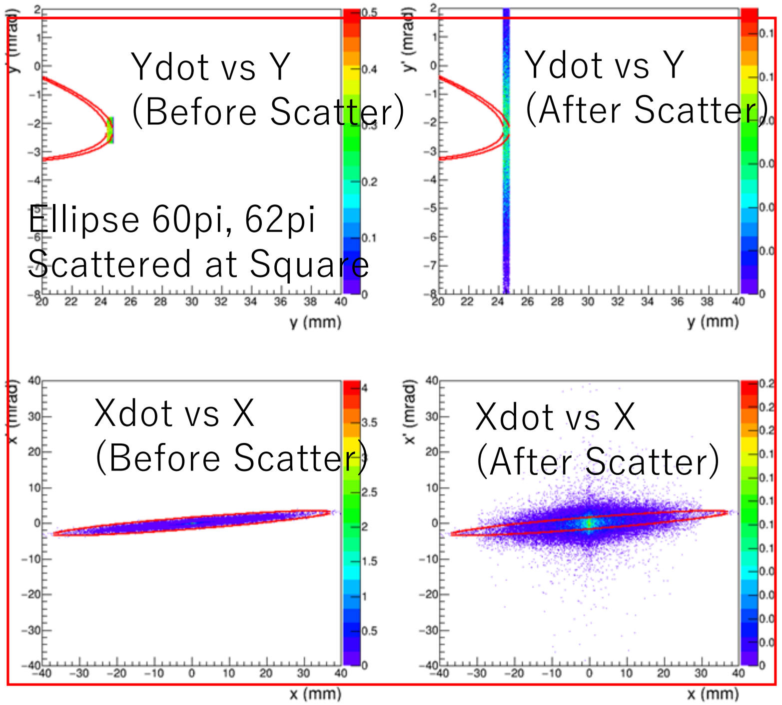
ScatVup >81π COLBV 60π COL3DV 75π

ScatVup 60π COLBV 60π COL3DV 75π

Beam loss distribution in non-COL area

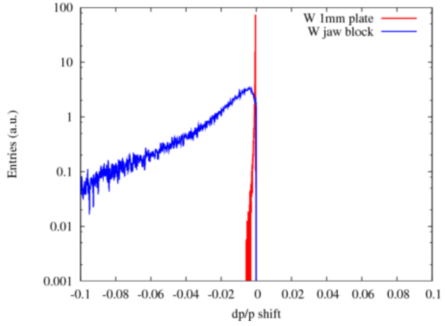


Geant4 for scattering + sad for tracking
- Scatterered at Scatterer Vup /COL B V
  - Independent scattered angles in X-X' and Y-Y'
- COLA,COLC H-Physical aperture 75pi
- Non-collimator physical aperture > 81pi



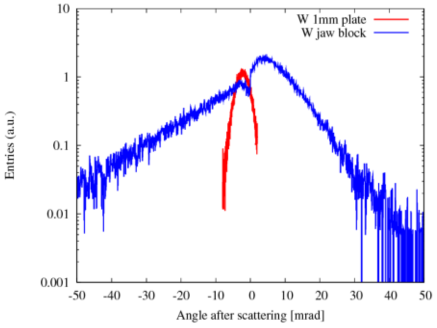
Y. Kurimoto

COL W-Jaw vs. W-1mm-plate Geant4 simulation



Dp/p shift
Scattered at
COLBV 60pi:
0 to 5%
ScatVup 60p:i
0 to 0.2 %

Momentum shift



Scattered angle at
COLBV 60pi or
ScatVup 60pi
10 mrad is sufficient

35

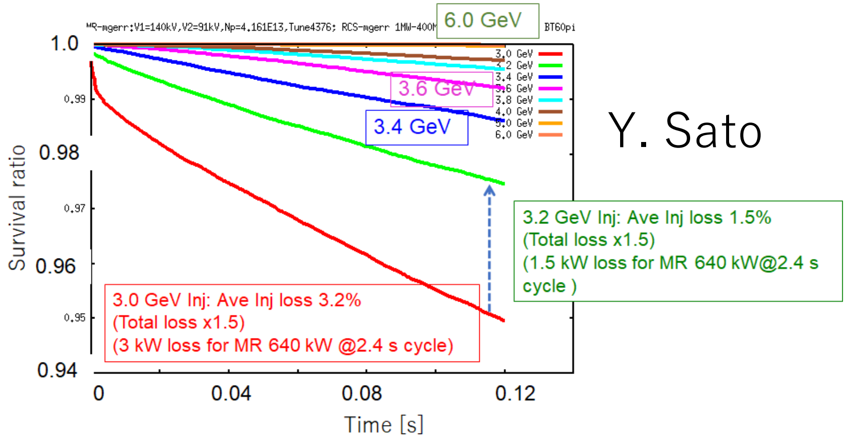
Scattered angle

Scatter effect was well simulated in the beam loss distribution

New 8 GeV booster ring between RCS and MR*

Injection energy and beam loss in the MR

Simulation of beam survival in the injection period of the MR
for the RCS 1MW eq. beam (4e13 ppb)

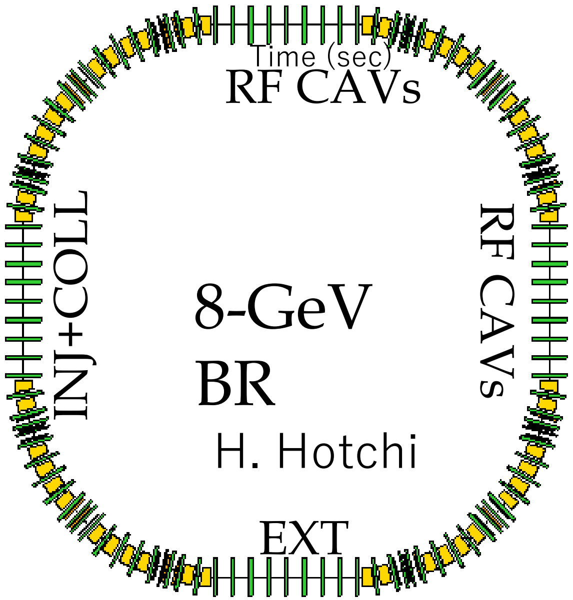


Y. Sato

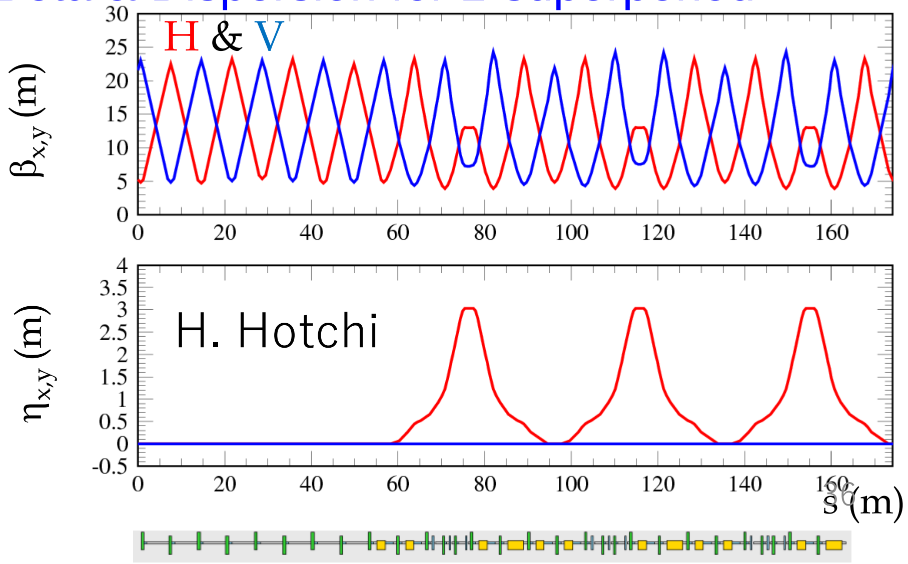
Higher injection energy

- **Reduce space charge effect**
- **Increase physical aperture**
- **Reduce bunch lengh**

8 GeV Booster Ring
→ 3 ~ 5 MW scenario



Beta & Dispersion for 1-superperiod



*: J-PARC Symposium July 15, 2014 S. Igarashi, H. Harada, H. Hotchi, T. Koseki, Y. Sato

Summary

- 1 MW acceleration in the RCS was successfully demonstrated with minimum beam losses. Pulse-by-pulse switching of major parameters for MLF and MR is in operation.
- MR with fast extraction achieved stable 490 kW (2.5 e14 protons per pulse) operation without significant beam loss. Changing operation point was a big key to increase the beam power.
- MR upgrade is planned with preparing faster cycle (from 2.48 s to 1.3 s and 1.16 s) to achieve 1.3 MW. 80% of required protons were accelerated in 2.48 s cycle.

References: Procs of IPAC2018 by H. Hotchi, et al. (TUPAL018), Y. Sato, et al. (THYGBF1), T. Koseki et al., (TUPAK005), ….

Thank you for listening!

J-PARC

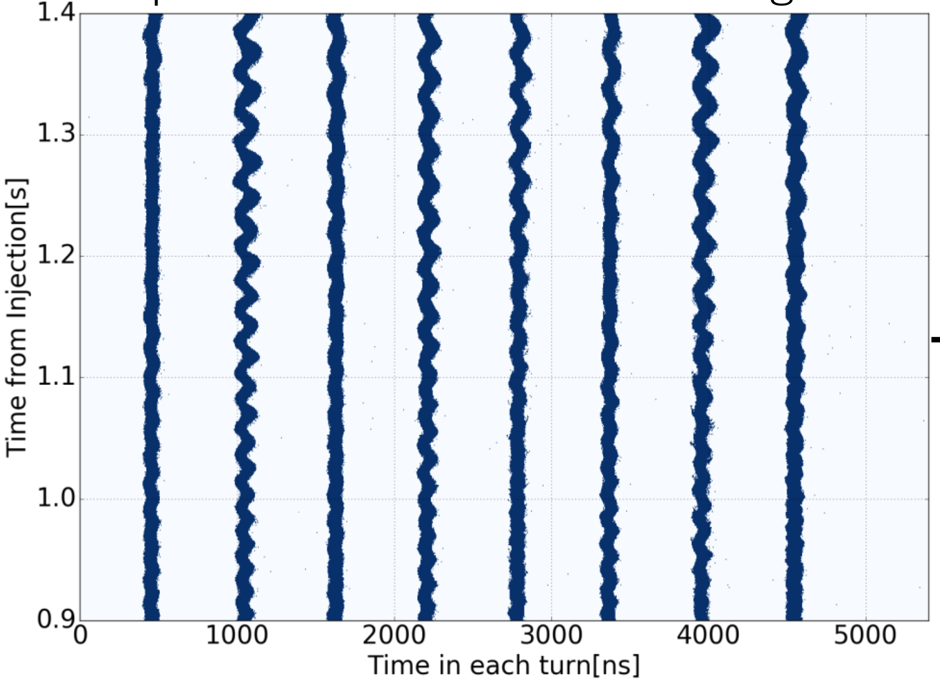
Backups

Longitudinal Coupled Bunch Instability

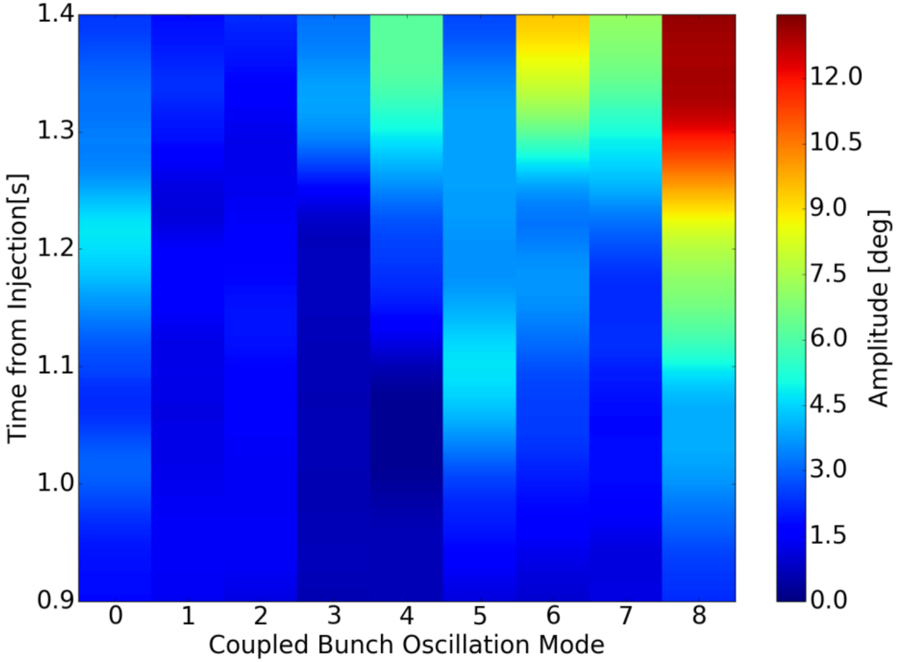
Sugiyama
Tamura et. al.

- Large Longitudinal Dipole Oscillation observed > 480kW
- Significant growth observed in Coupled Bunch Oscillation of mode n=8.
- →Longitudinal Dipole Coupled Bunch Instability in the MR.

Mountain plot for 480kW case with large oscillation



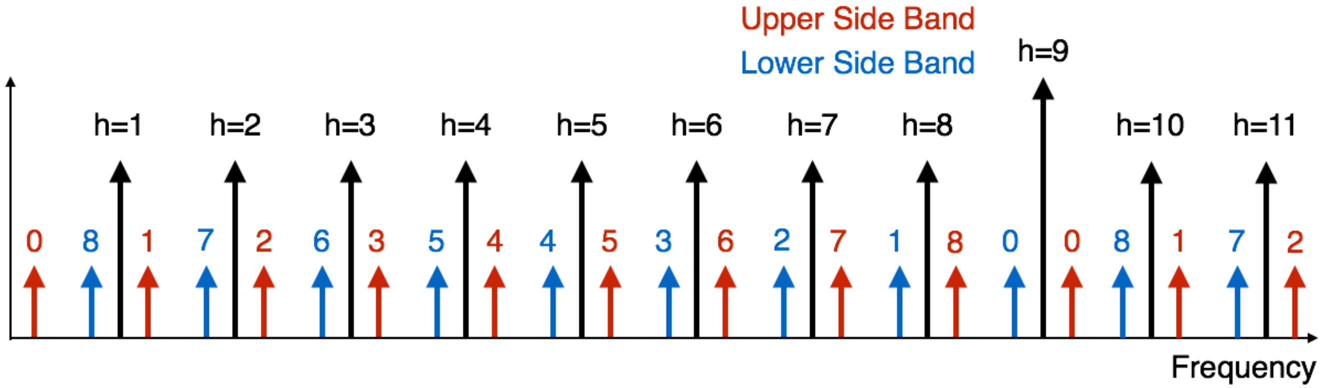
Coupled Bunch Oscillation Analysis



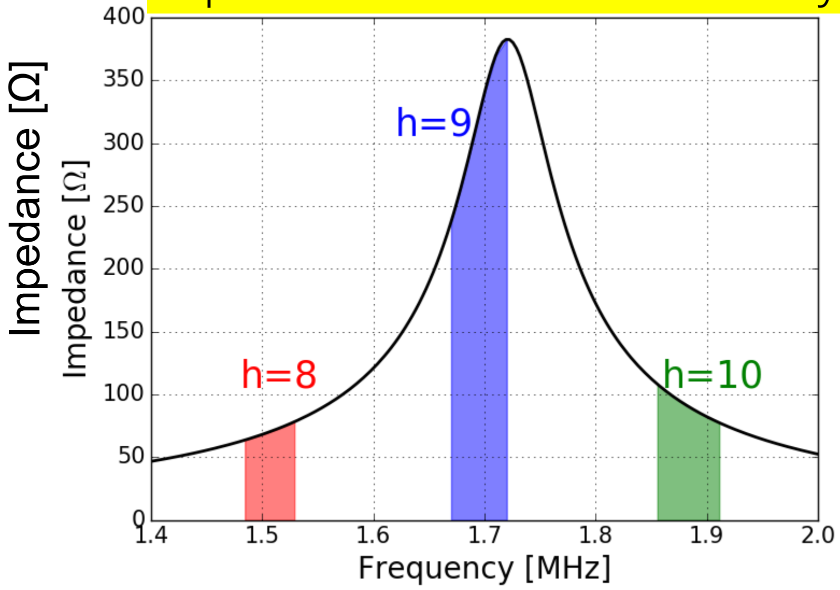
New FB system for the long. C.B. instability

- Longitudinal coupled bunch oscillation of Mode n=8 can be seen in the synchrotron sidebands of h=8,10 component.
- MR RF cavities has enough impedance for the sidebands
  - Feedforward for h=8, 9, 10 beam loading compensation has been used.
  - Present RF cavities can be used as the Feedback kickers.
- Mode-by-Mode longitudinal Bunch FB system is newly developping
  - “Longitudinal Feedback Damper” in a present RF cavity.

Synchrotron sideband around the harmonics of the revolution frequency of the MR.



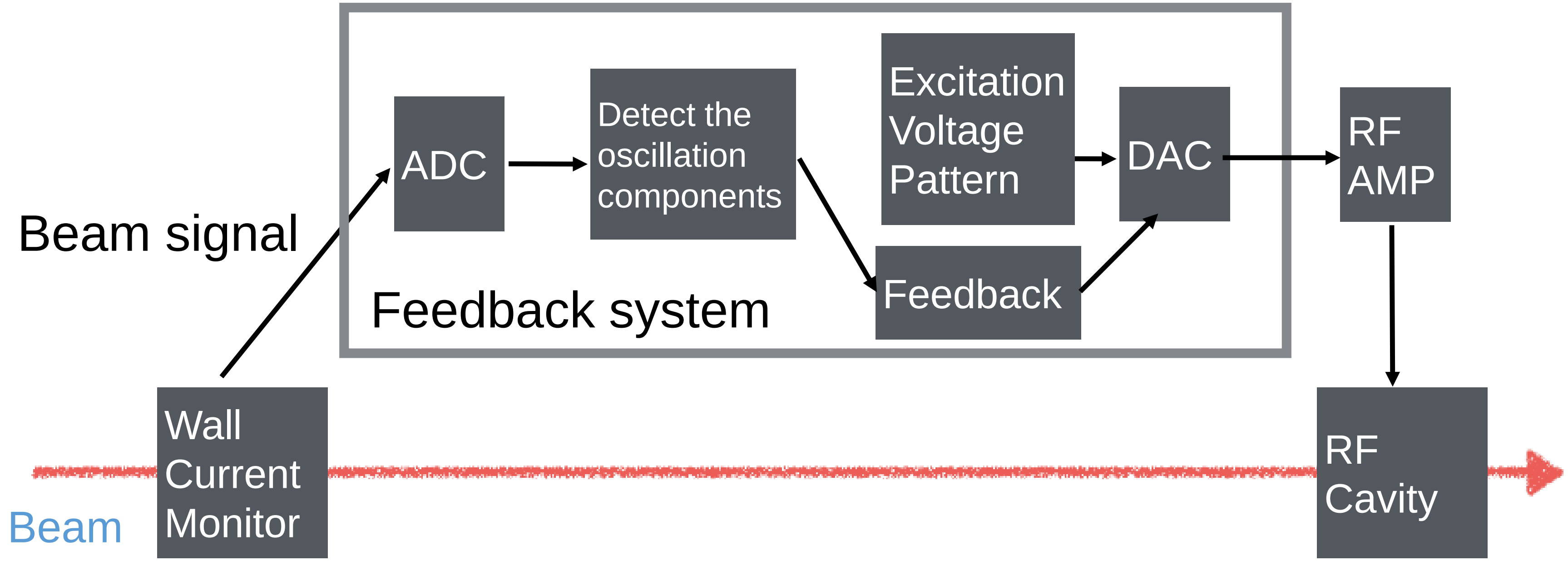
Impedance of the MR RF cavity.



Longitudinal Feedback Damper

Sugiyama
Tamura et. al.

- Feedback system detects the oscillation components of the beam signal and put the feedback signal into the RF cavity. (=Longitudinal FB damper)
  - FB system is designed to separate and detect the synchrotron sidebands including dipole and quadruple oscillation components.
- Tested the function of the Longitudinal FB Damper by exciting, observing, and damping the longitudinal oscillation by FB Damper.

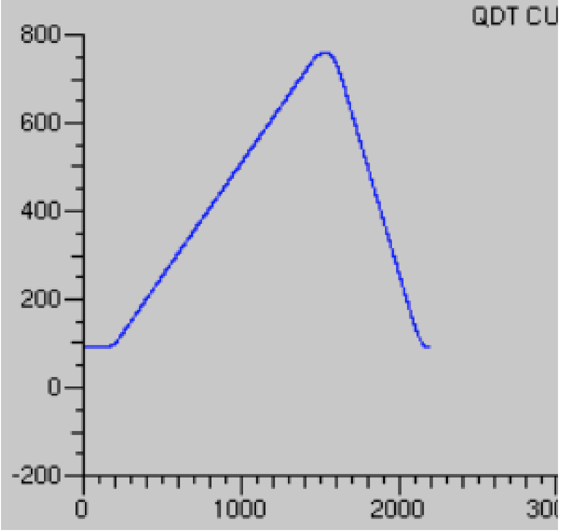


Feedback system

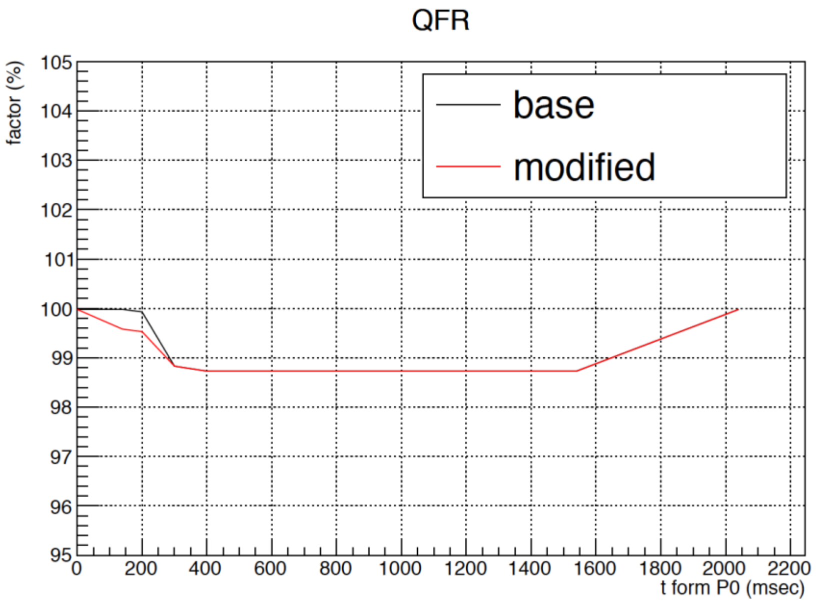
Tune Shift Correction with QFR and QDT

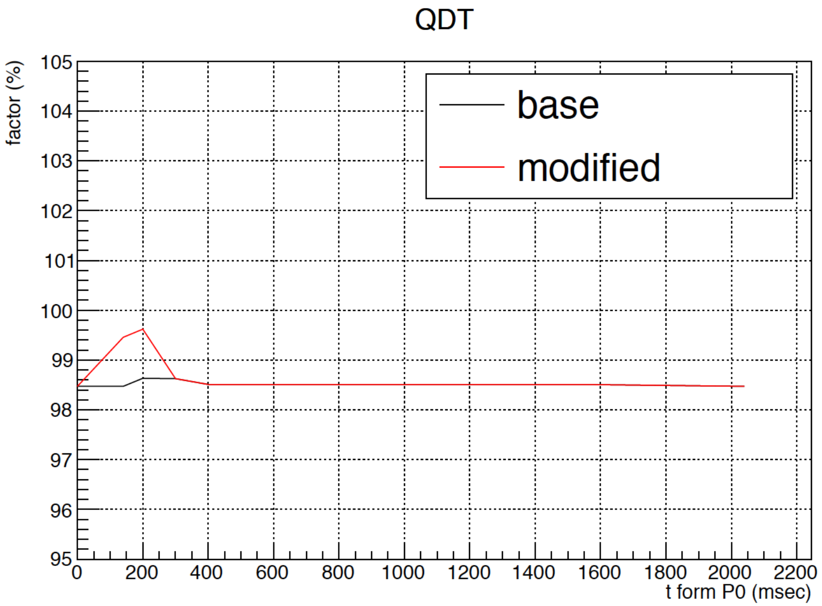
Shimogawa
Igarashi

- For the correction of the tune shift,
  - QFR K1 should be adjusted to −0.4 %.
  - QDT K1 should be adjusted to +1 %.
- The old power supplies have a restriction for adjustment.
- The new power supply of QFR is more adjustable.
- Effect to the betatron function is small.

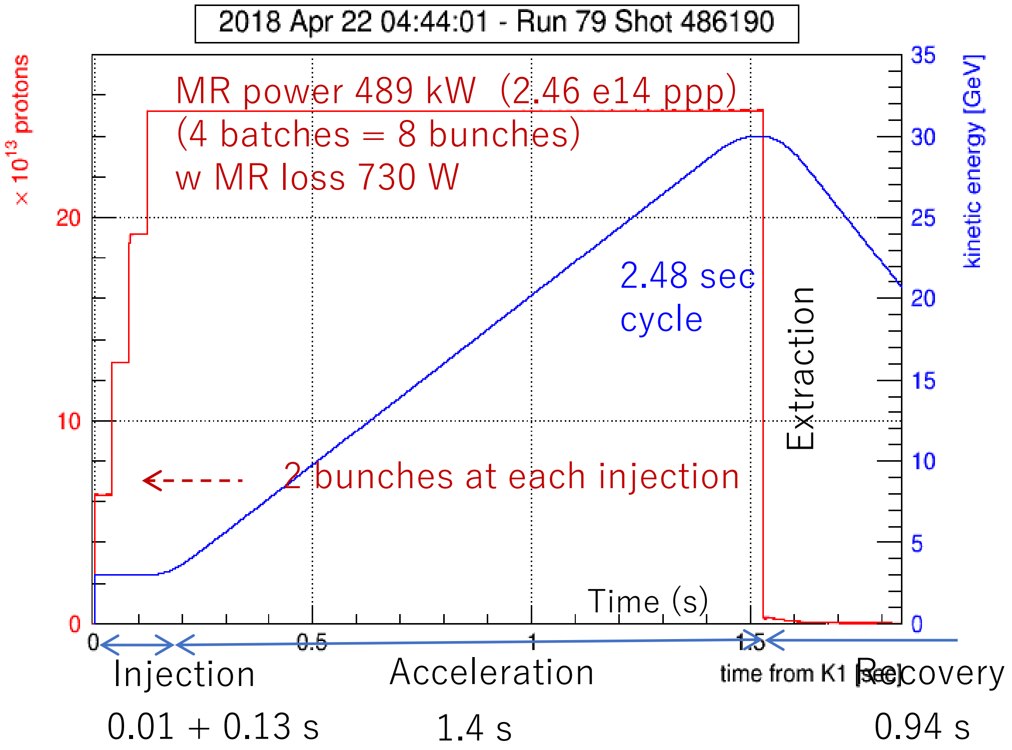


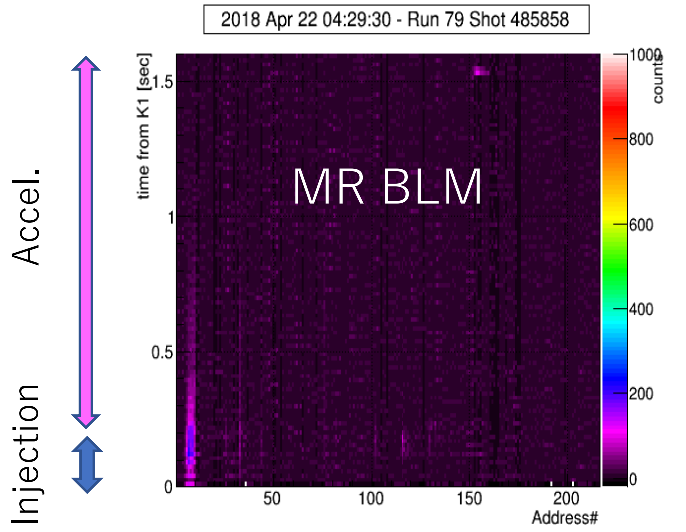
Correction pattern of QFR and QDT

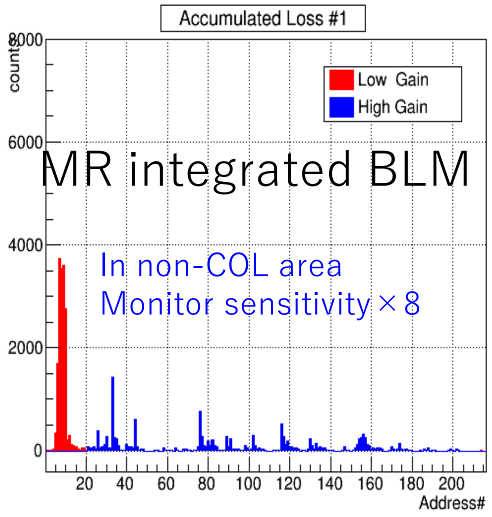


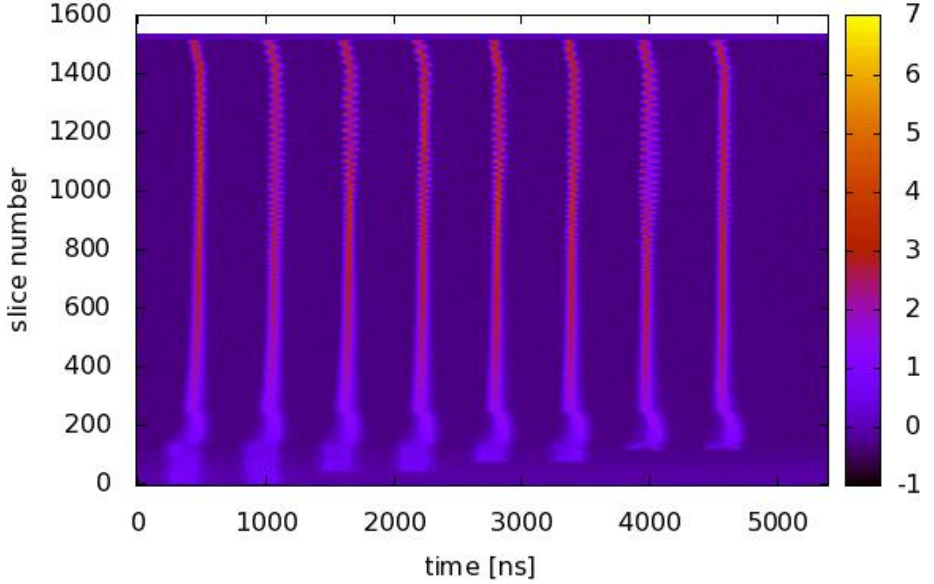


Typical operation of MR 490 kW









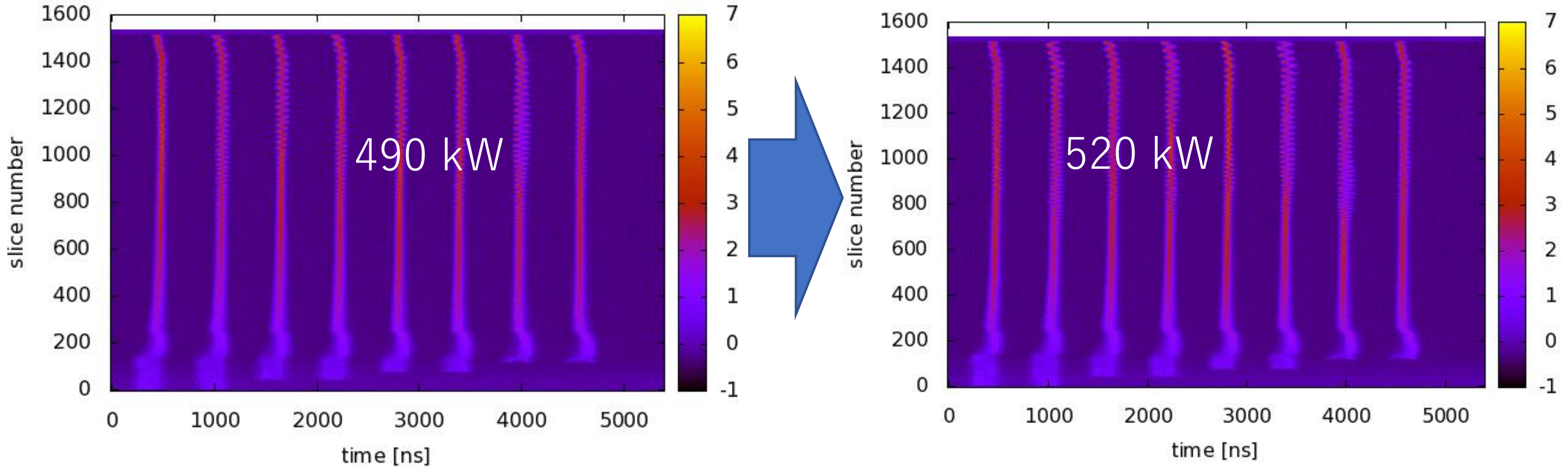
MR power	**490 kW**
3-50BT loss	**50 W** < **BT COL capacity 2 kW**
MR loss	**480 W** (*1) < **MR COL capacity 2 kW**
Injection	***230 W***
Acc 1st 90 ms	***200 W***
Acc after 90ms	***50 W***

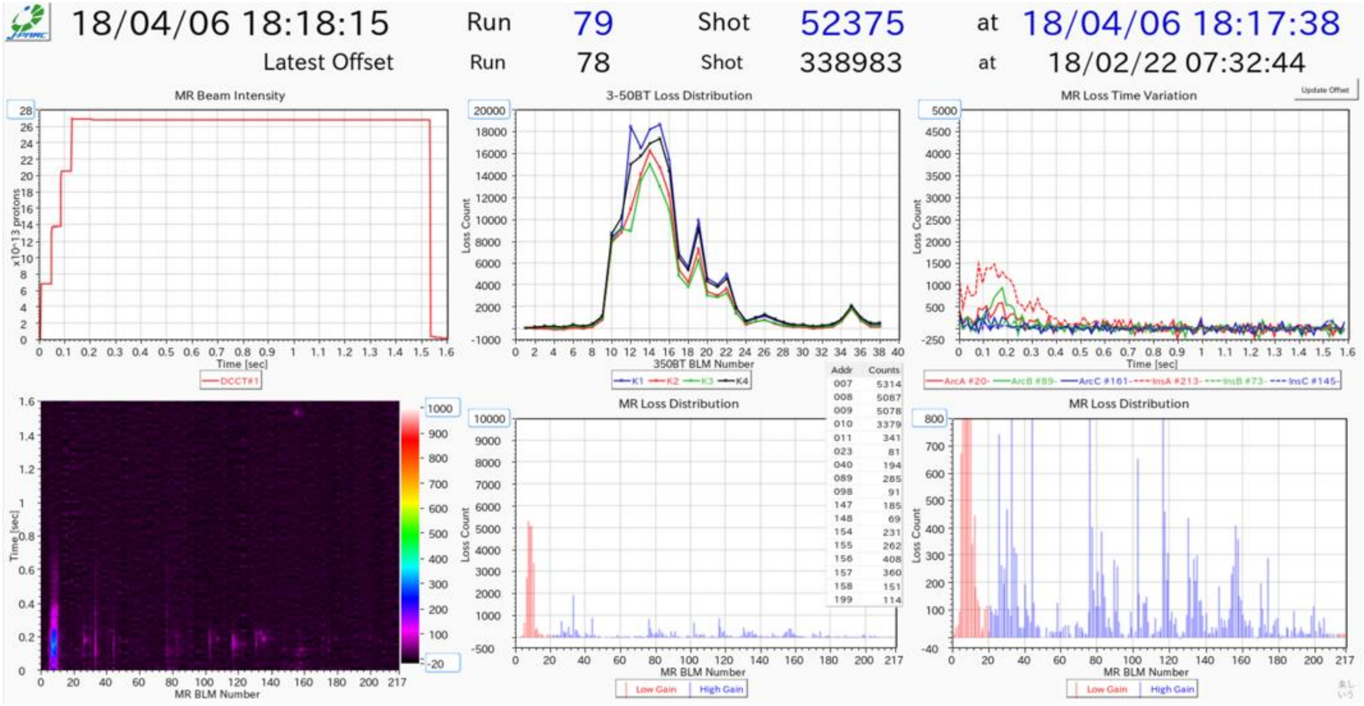
NOTE *1: Beam loss has been estimated with DCCT#1.

RCS conditions have been optimized

High Intensity Trial at 520 kW

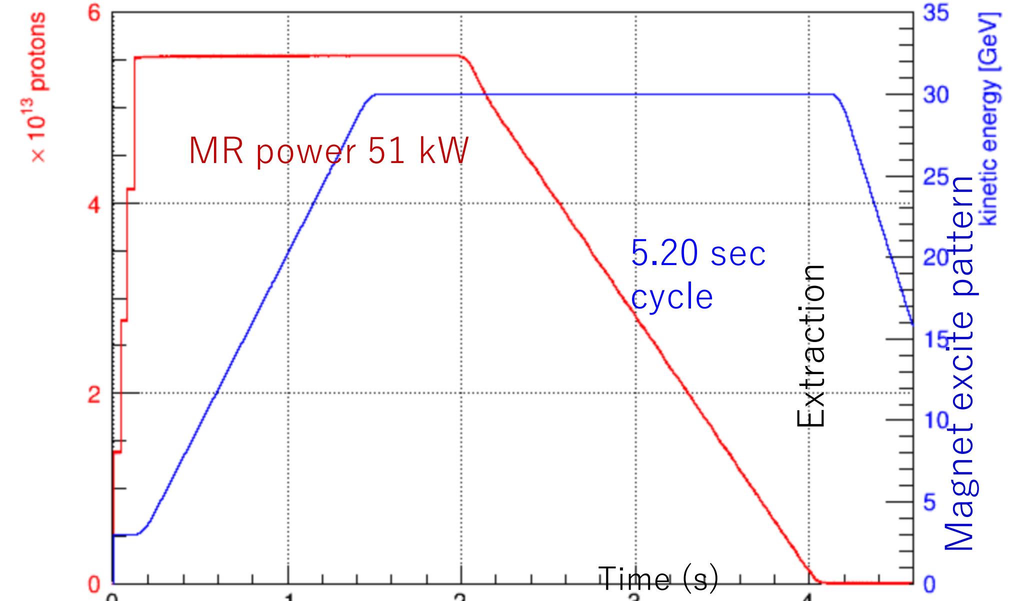
- 519.20 kW, 28/32, 489 ns
- MR Beam Loss: 1 kW @ 520 kW
  - Inj. Loss 391 W
  - P2 Loss 549 W
- Losses at the beginning of the acceleration: ArcB loss (@ high By)
- K4R V-profile was large @ NU.
- Optimization necessary for loss reduction.
- Longitudinal oscill. enlarged
- RF#3 Anode Current: 100 A



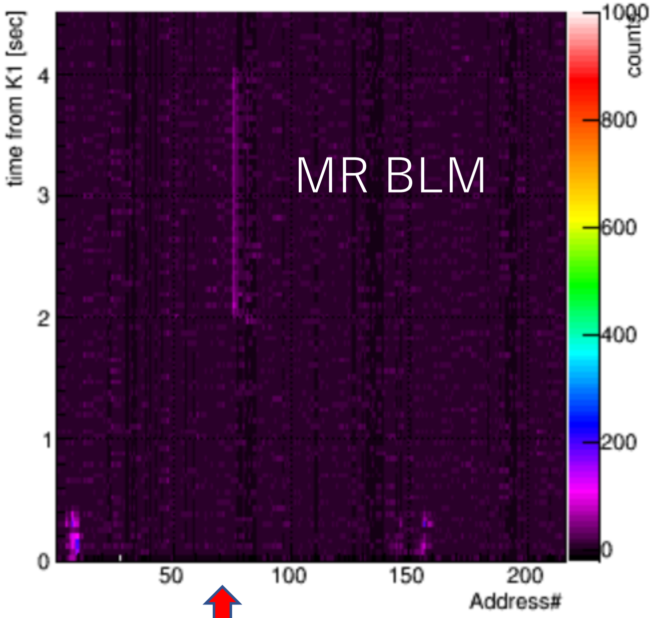


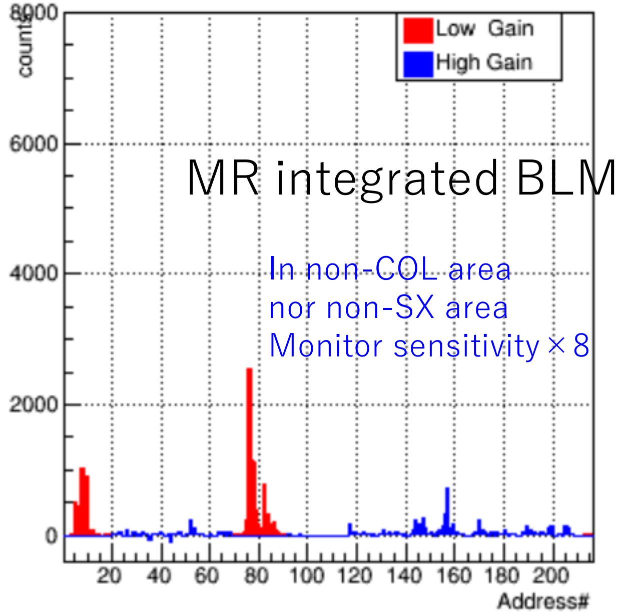
We will perform iterative tunings of IntraBFB/RF/Sextupoles/Trim-S/Octupoles for less losses and better loss localization

Typical operation of MR 50 kW with 30 GeV slow extraction to HD



Injection 0.01 + 0.13 s
Acceleration 1.4 s
Flat top for SX 2.61 s

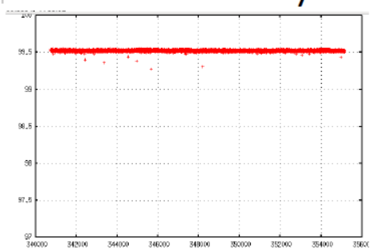


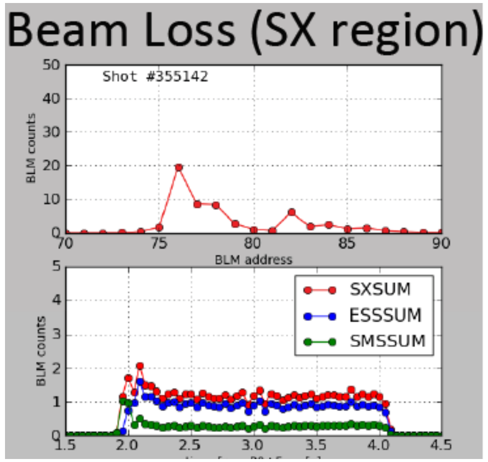


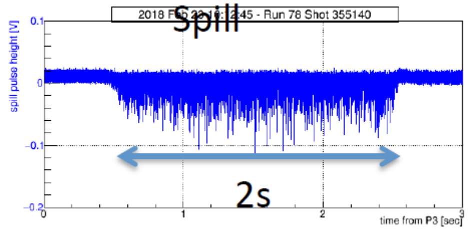
Main loss at SX region (especially at the electrostatic septum)

MR power	**51.1 kW in 5.20 s cycle**
Efficiency	**99.52%**
Spill Duty	**48%**
Spill length	**2.05 s**

Extraction Efficiency Trend





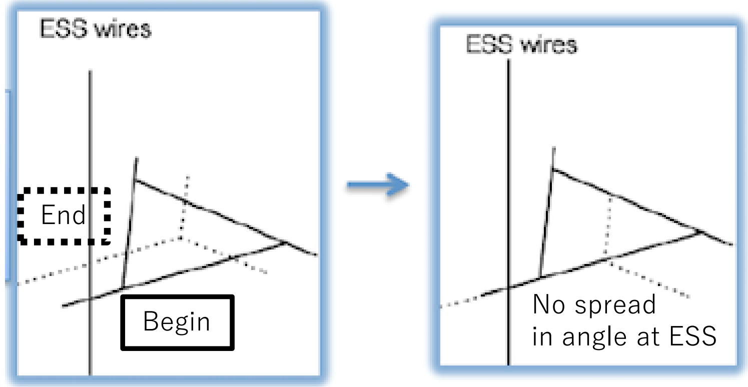


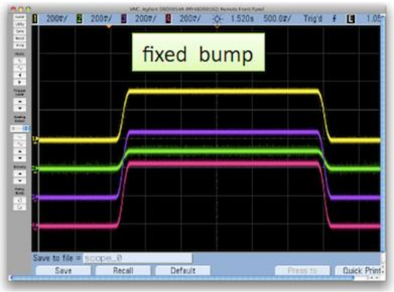
Fine Tunings for Extraction Efficiency

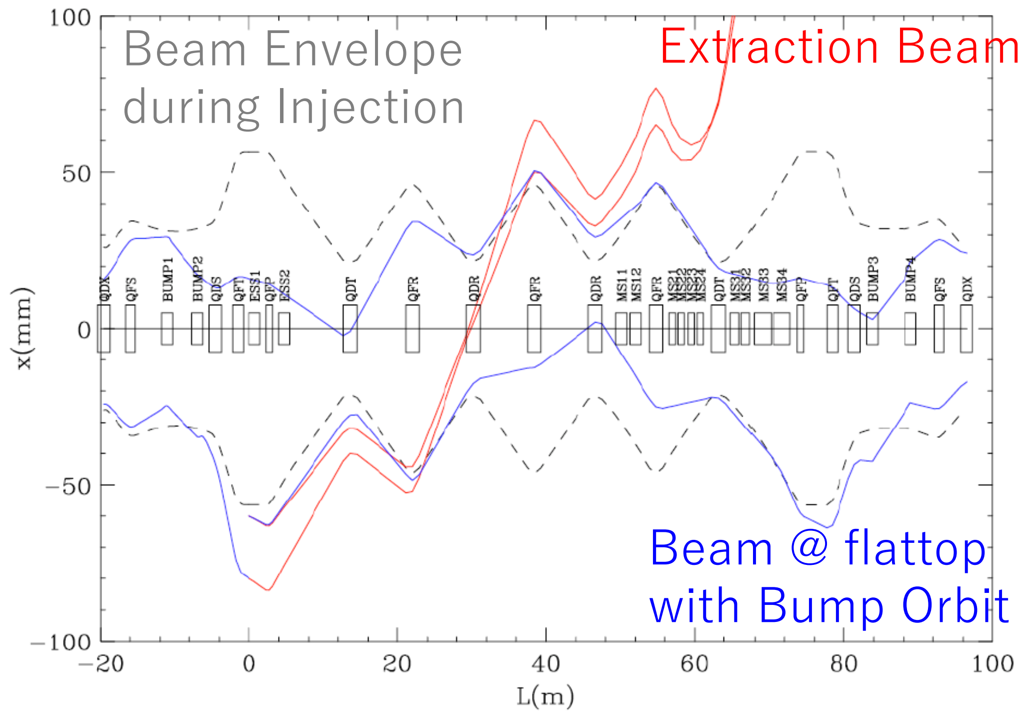
- Besides basic SX tuning,

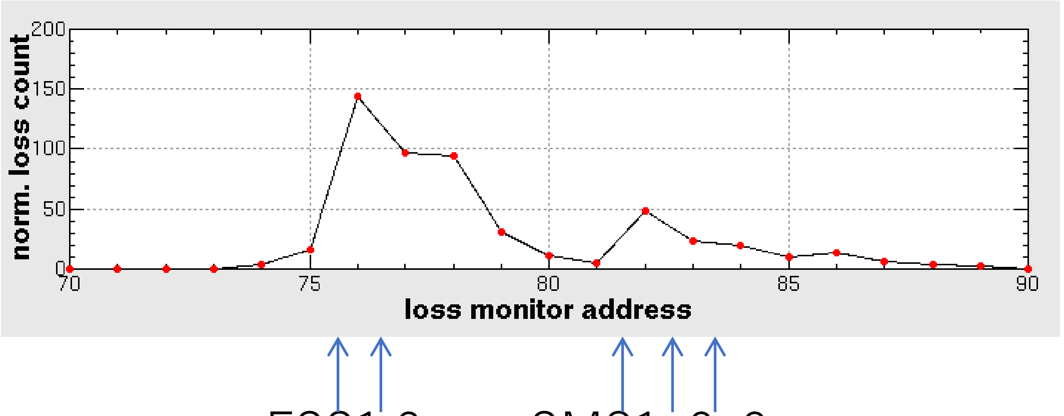
  fine tunings were necessary with
  - ESS1 angle
  - ESS2 position and angle
  - SMS1 position
  - Bump orbit with Dynamic Bump

fixed bump dynamic bump









ESS1 2 SMS1 2 3

To keep same separatrix at ESS is important