Recent Progress of J-PARC MR Beam Commissioning and Operation

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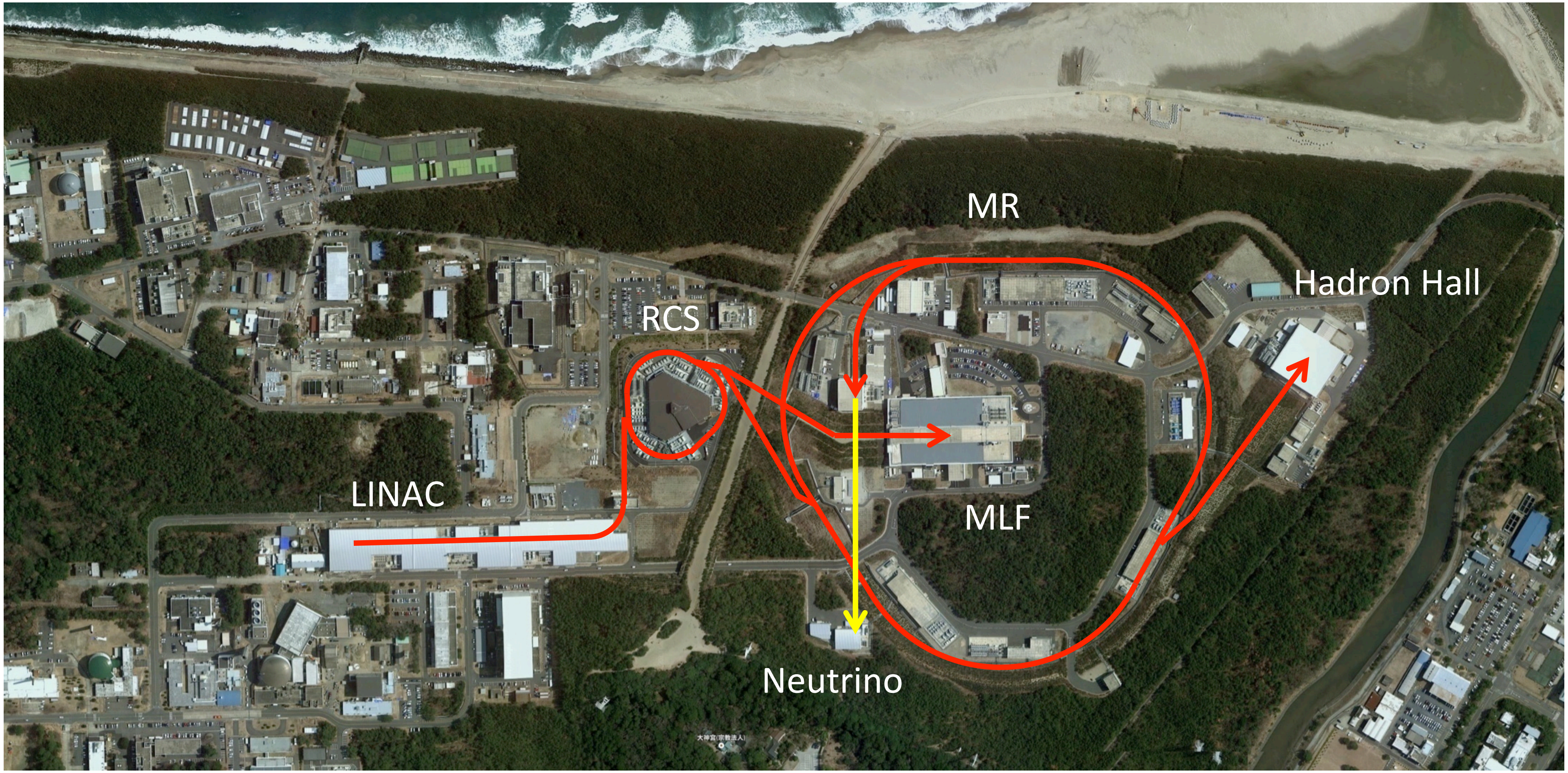
- Upgrade plan to the beam power of 750 kW and more
- Summary

Japan Proton Accelerator Research Complex (J-PARC)

- High Intensity Proton Accelerators
- Facilities to use the secondary beams
- Operated by Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK)

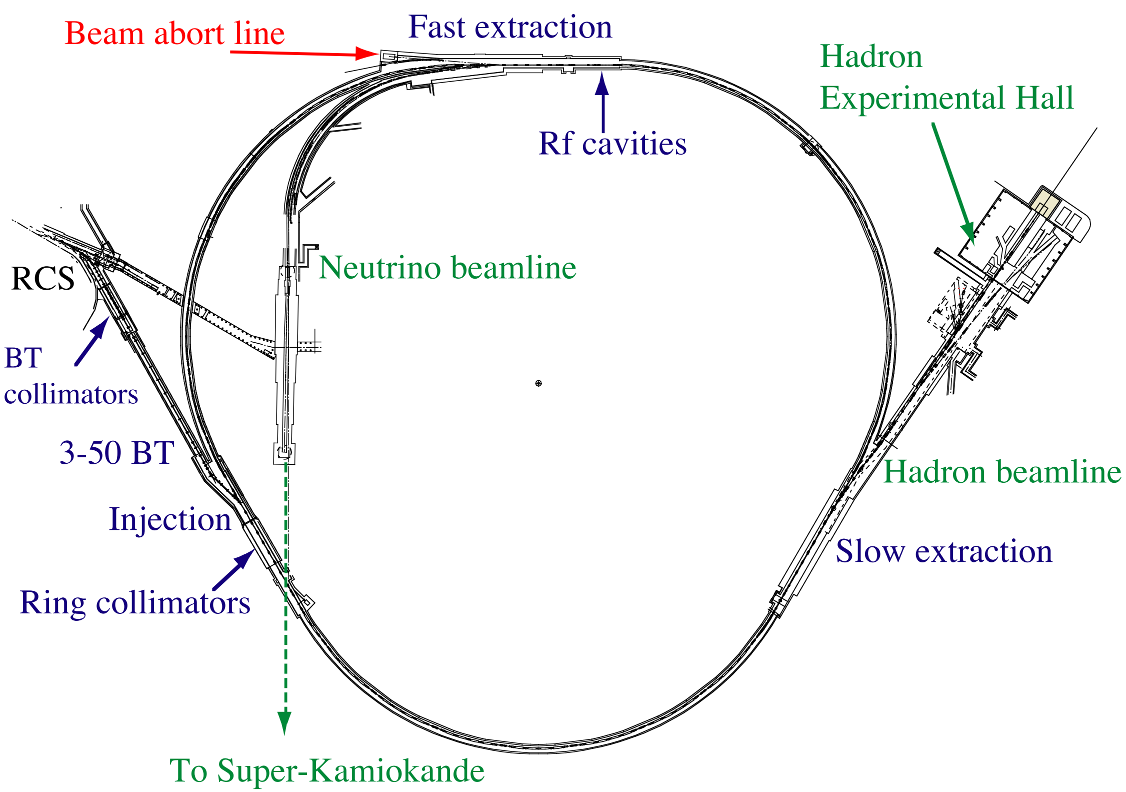
- LINAC (400 MeV)
- Rapid Cycling Synchrotron (RCS) (3 GeV)
  – Material and Life science Facility (MLF)

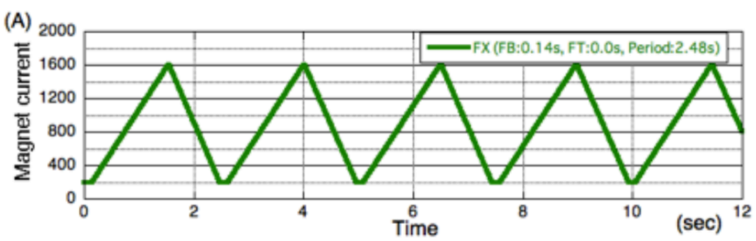
- Main Ring (MR) (30 GeV)
  – Neutrino Facility
  – Hadron Hall



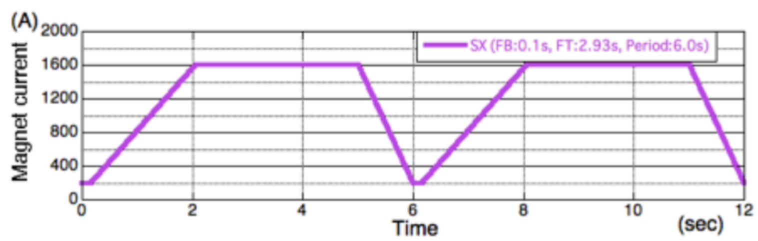
MR Design and Operation Modes

- Circumference 1567.5 m
- Three-fold symmetry
- Injection Energy 3GeV
- Extraction Energy 30 GeV
- Design Beam Power: 750 kW
- The first beam in MR
  - Injection 2008 May
  - Acceleration and extraction 2008 Dec.
- Fast extraction mode (FX) for the neutrino oscillation experiment: 1 turn extraction.
- Slow extraction mode (SX) for the hadron hall experiments: 2 s extraction.





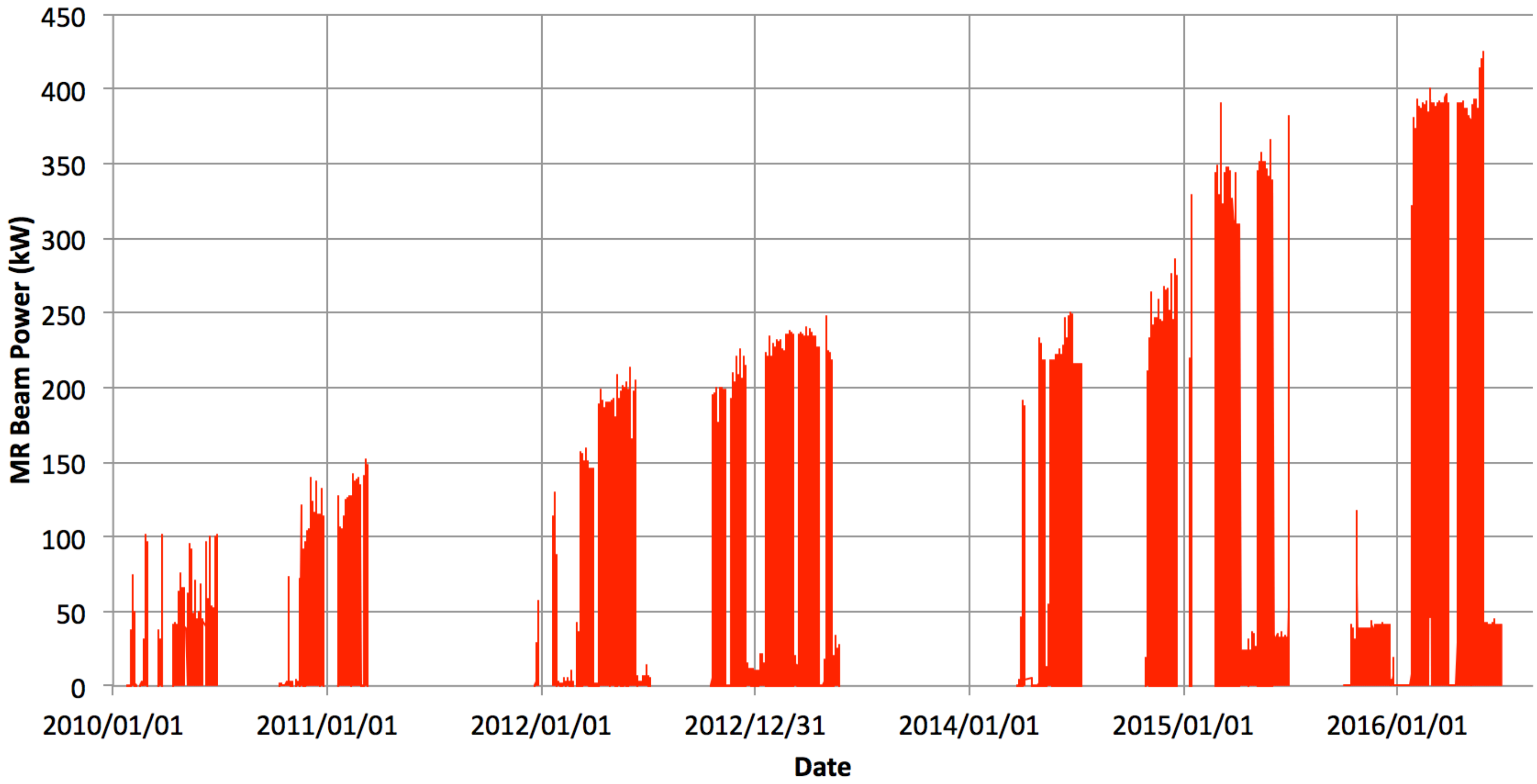
FX (2.48 s)



SX (6.0 s → 5.52 s)

MR Beam Power History

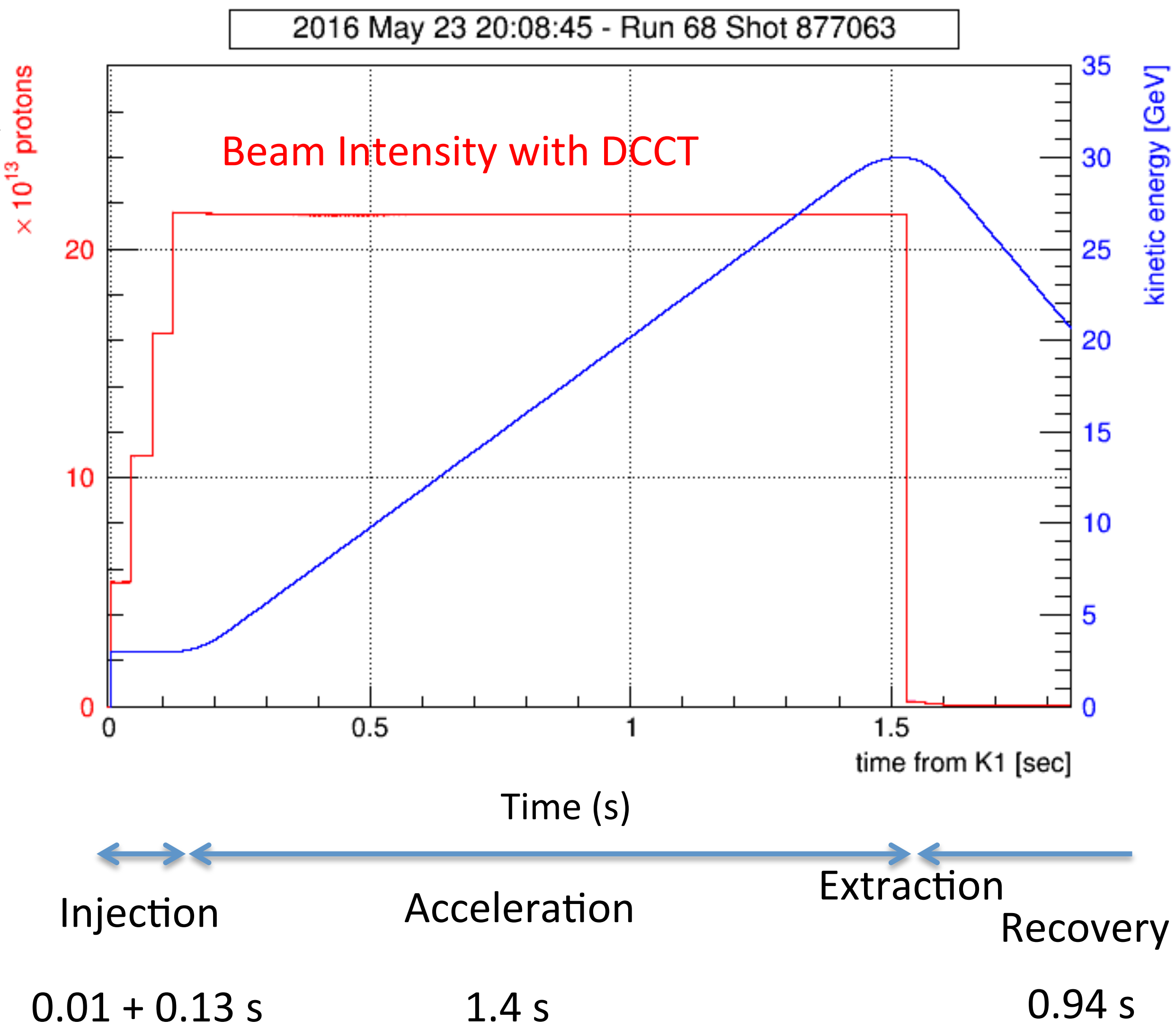
- MR beam power has been increasing since Dec. 23 2008 (30 GeV Acceleration).
- In the operation of Jan ~ May 2016, the beam power was mostly about 390 kW with 2×10^{14} protons per pulse.
- The target beam power is 750 kW and is planned to be achieved with the faster cycling 2.48 s to 1.3 s.
- The operation of 415 kW was successful for the last three days.



Operation Status for the Fast Extraction

Typical Operation Status for Fast Extraction

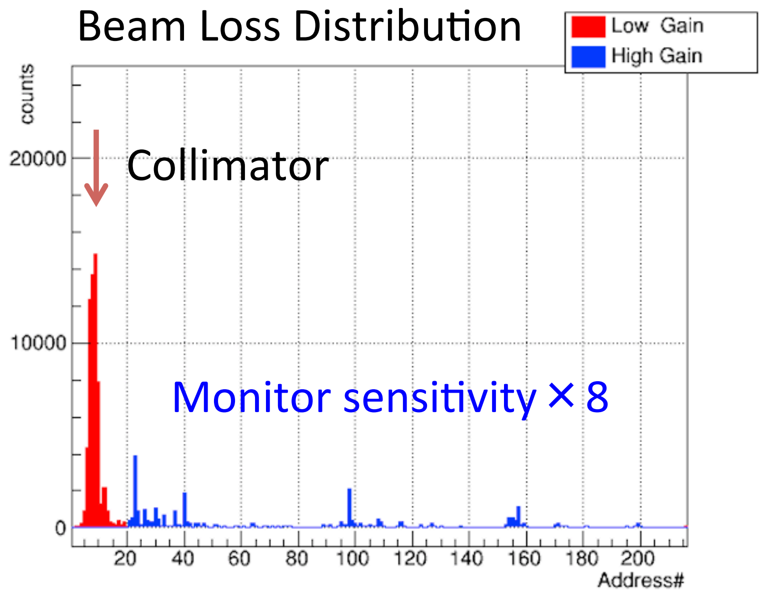
- Power : 416 kW
- Repetition : 2.48 sec
- 4 batch (8 bunch) injection during the period of 0.13 s
- 2.7e13 protons per bunch (ppb) × 8 @ Injection
- 2.15e14 ppp @ P3 (end of acceleration)
- Loss during the injection period : 170 W
- Loss in the beginning of acceleration (0.12 s) : 417 W
- Loss power is within the MR collimator limit of 2 kW.
- Loss at 3-50BT : <100 W, < 3-50BT collimator limit of 2 kW

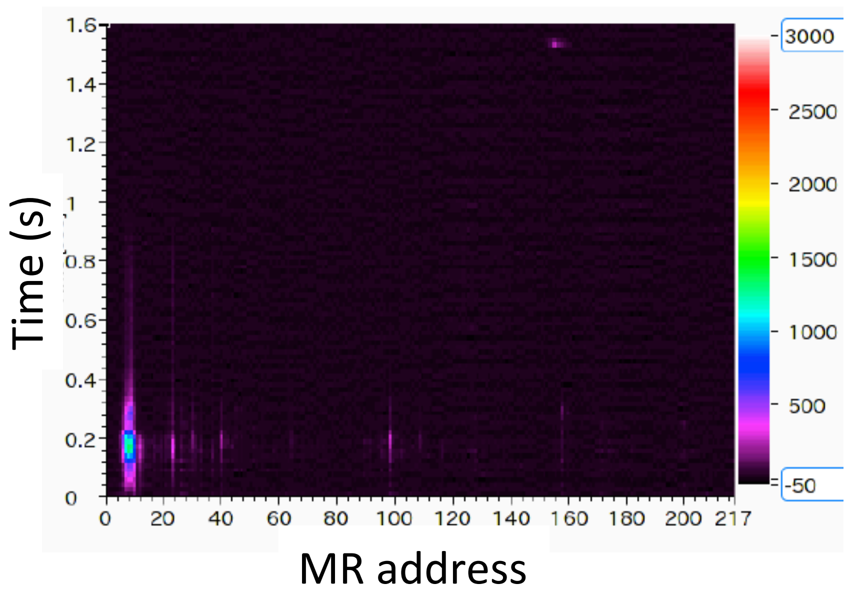


Tuning Items for Fast Extraction

To minimize the beam losses

- Reduction of Space Charge Effects
  - Bunching factor improvement with 2nd harmonic rf operation
- Improvement of the effective physical aperture
  - Correction of closed orbit distortion
  - Optics measurements and corrections
- Improvement of dynamic aperture
  - Correction of the linear coupling sum resonance.
  - Correction of the half integer resonance
  - Correction of the third order reonances
- Beam loss localization with collimators.
  - ➢ "New Arrangement of Collimators of J-PARC Main Ring", M. Shirakata, THAM4Y01, in this conference.

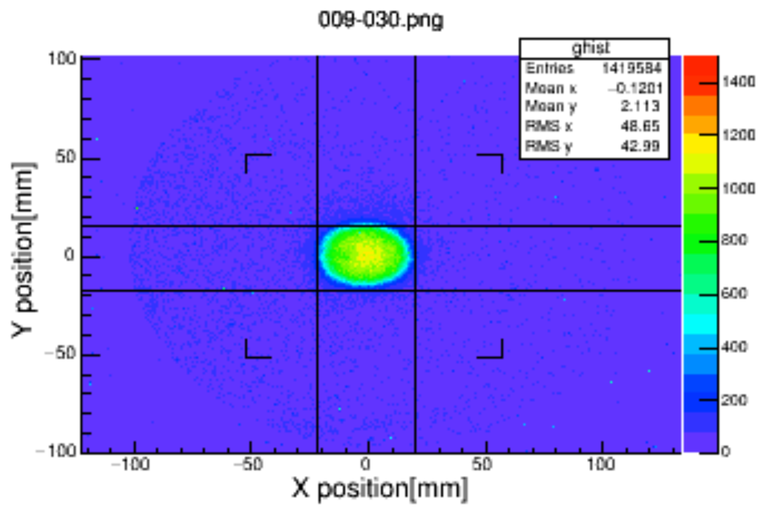




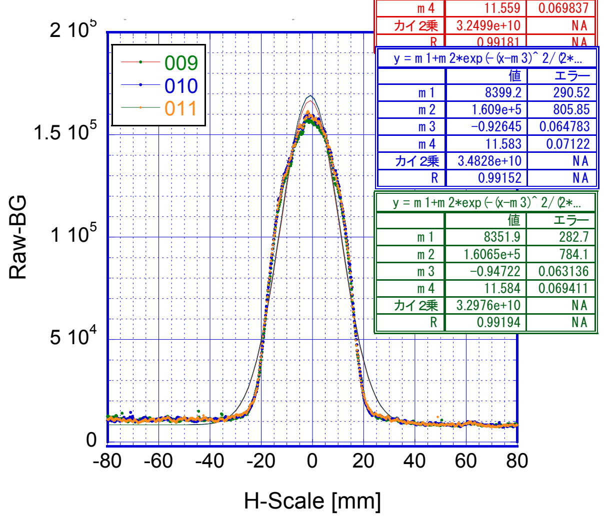
Recent Improvements

Injection Beam Distribution

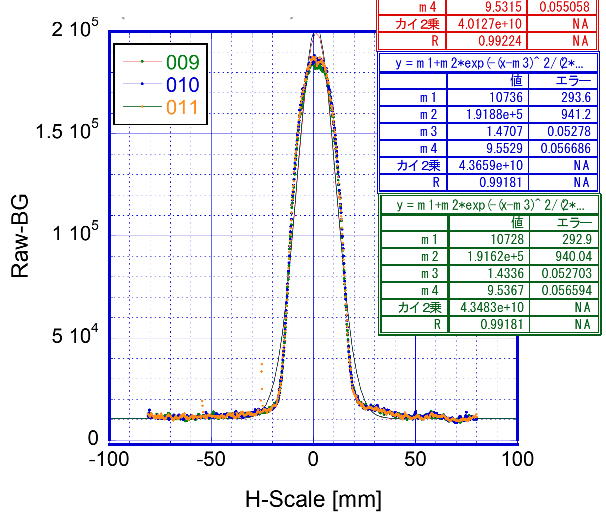
- One of the RCS study itmes is to optimize the parameters such as painting and operation tune for high intensity MR operation.
- Transverse beam profiles were measured with optical transition radiation monitor (OTR) at 3-50BT.
- Beam Intensity 3.48e13 ppb
- RCS 830 kW equiv., MR 540 kW equiv.
- RCS 50π correlated paint
- Full emittances were measured to be 26.8π mmmrad and 24.6π mmmrad for horizontal and vertical, respectively, assuming the beta's at OTR are βx = 27.2 m and βy = 17.9 m from the design values.



Hori. emit. (full)
26.8π mmmrad

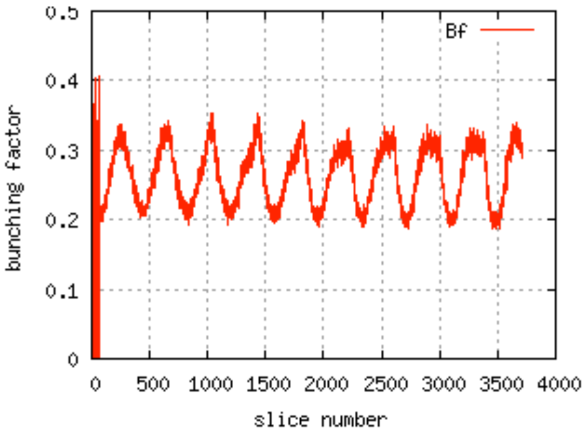


Vert. emit. (full)
24.6 mmmrad

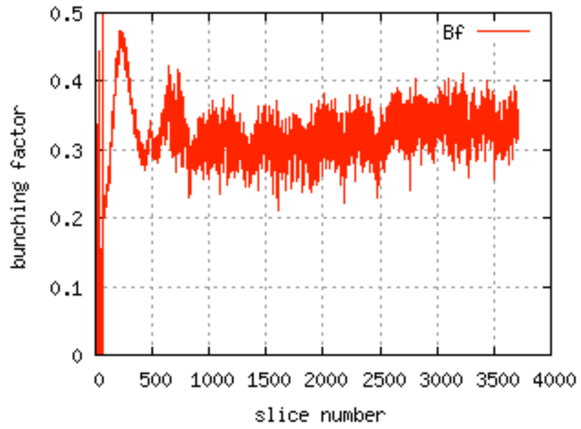


Longitudinal Profiles with High Intensity Beam of 500 kW equivalent

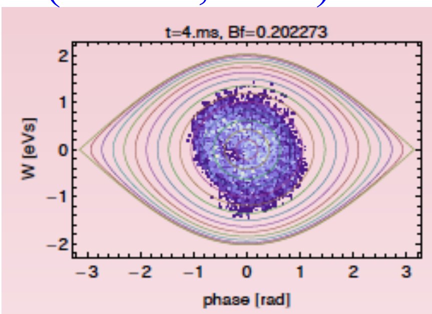
(100 kV, 0 kV)
Bunching factor
0.2 ~ 0.3
Bunch length
~200 ns

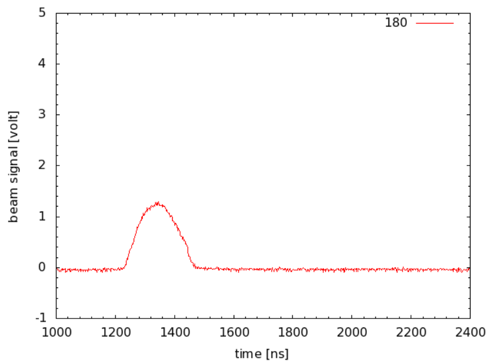


(100 kV, 70 kV)
Bunching factor
0.3 ~ 0.4
Bunch length
~400 ns

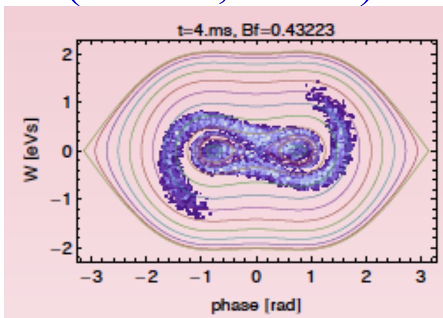


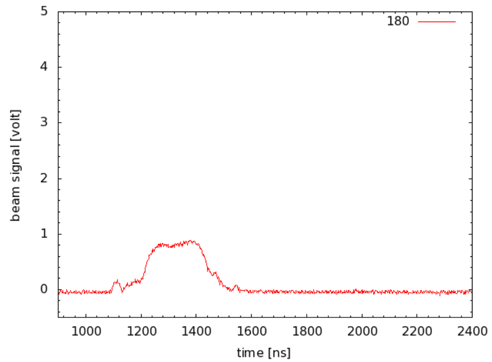
Simulation
(100 kV, 0 kV)

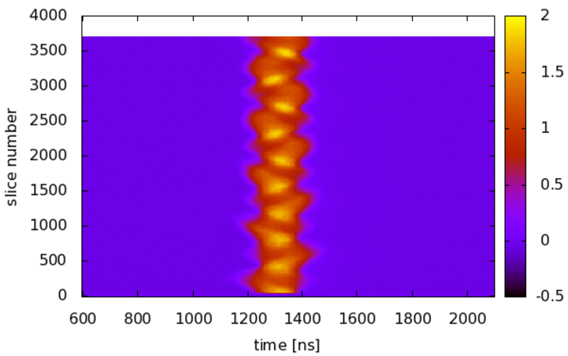


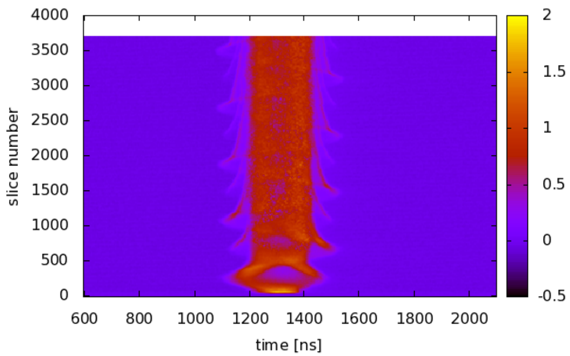


Simulation
(100 kV, 70 kV)





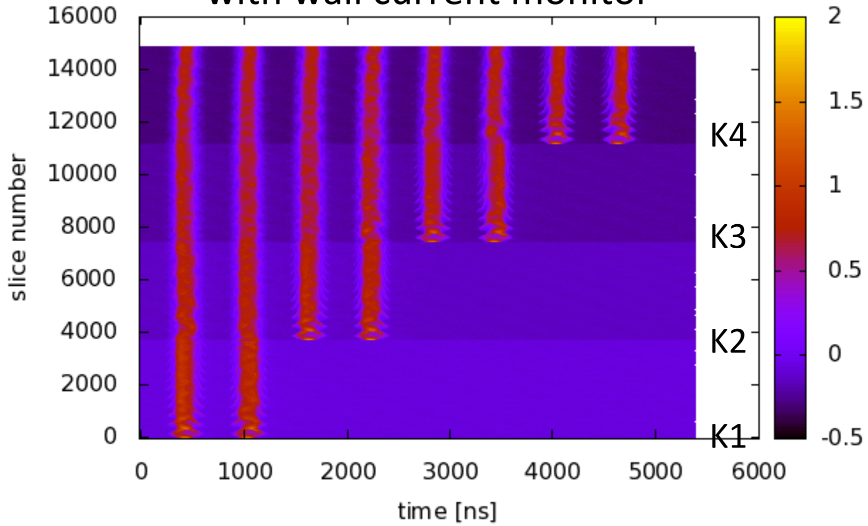


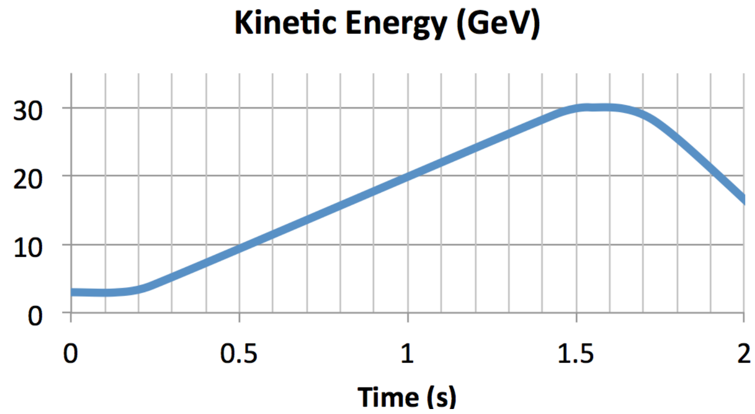


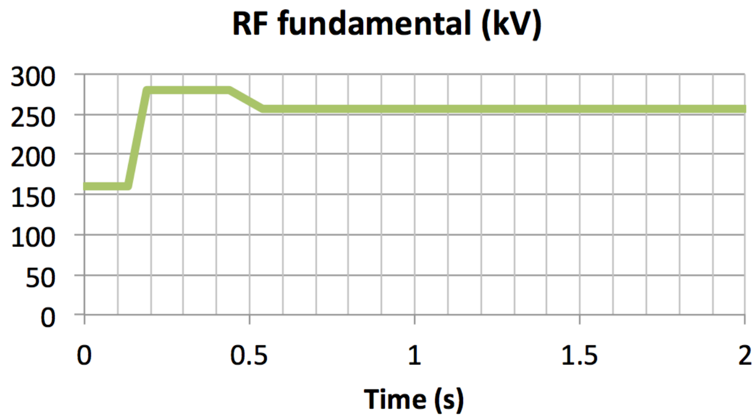
RF Pattern

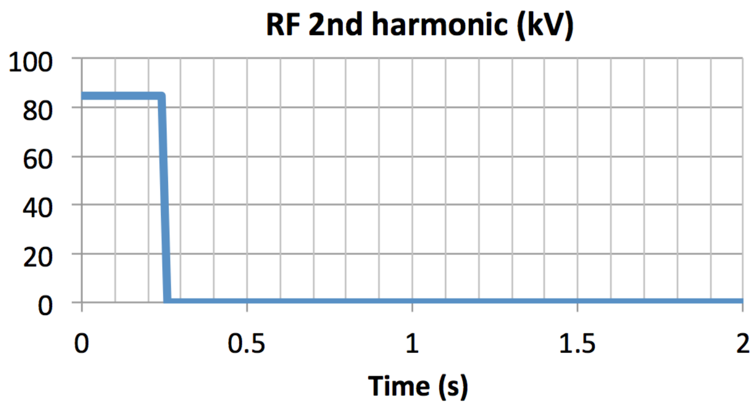
- RF pattern :
  - Injection : 160 kV (fundamental), 85 kV (2nd harmonic)
  - Acceleration : 280 kV → 256 kV (fundamental)
- Beam loading compensation effectively works to reduce longitudinal oscillations.
- Bunching factor was measured to be 0.3 during injection.

Longitudinal wave forms during injection with wall current monitor

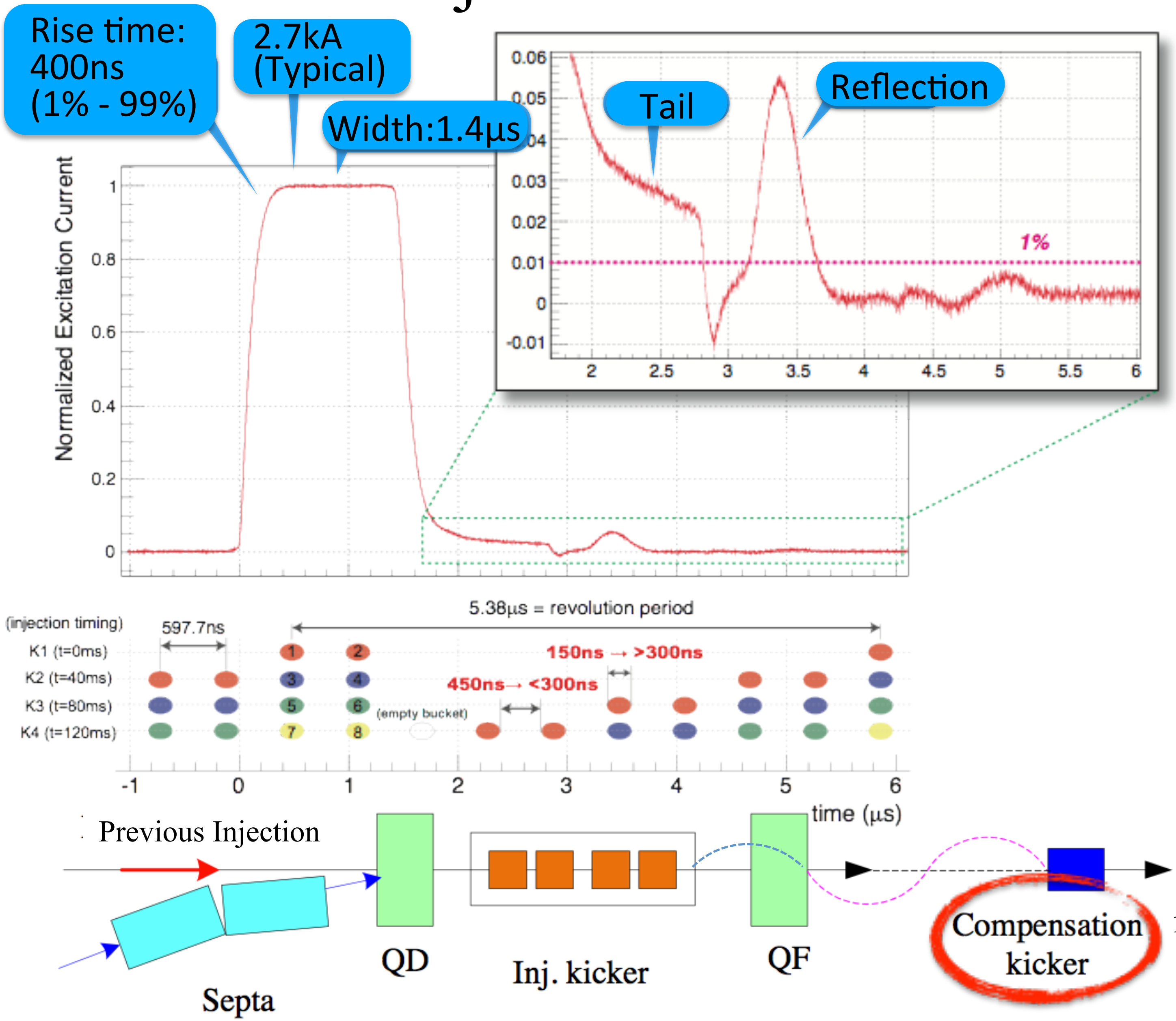








Injection Kicker Waveform

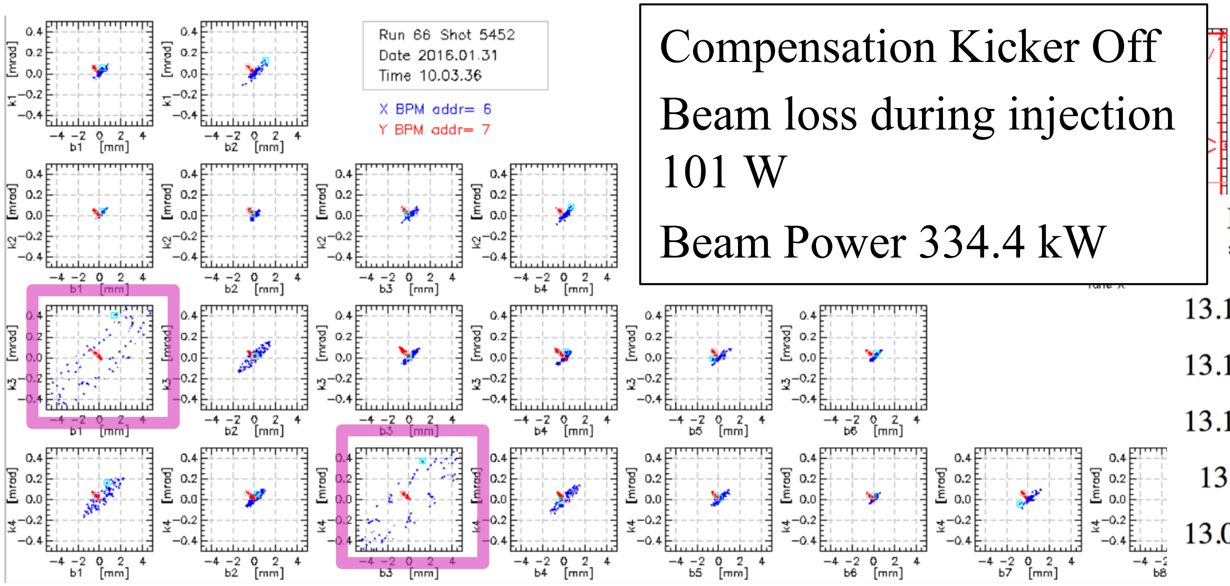


- Rise time is improved with speed up circuit.
- Tail is suppressed with tail matching circuit.
- Reflection kicks circulating beam.

Compensation kicker is to kick the bunch back on the original orbit.

Compensation Kicker

- $V_1 = 0$ kV
- $V_2 = 27$ kV
- Δt (1-2) = 600 ns



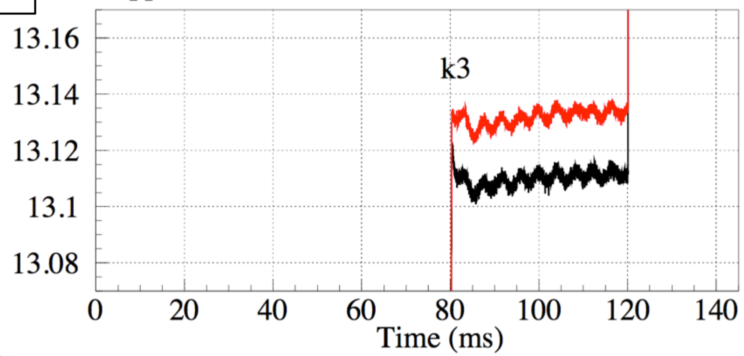
Compensation Kicker Off

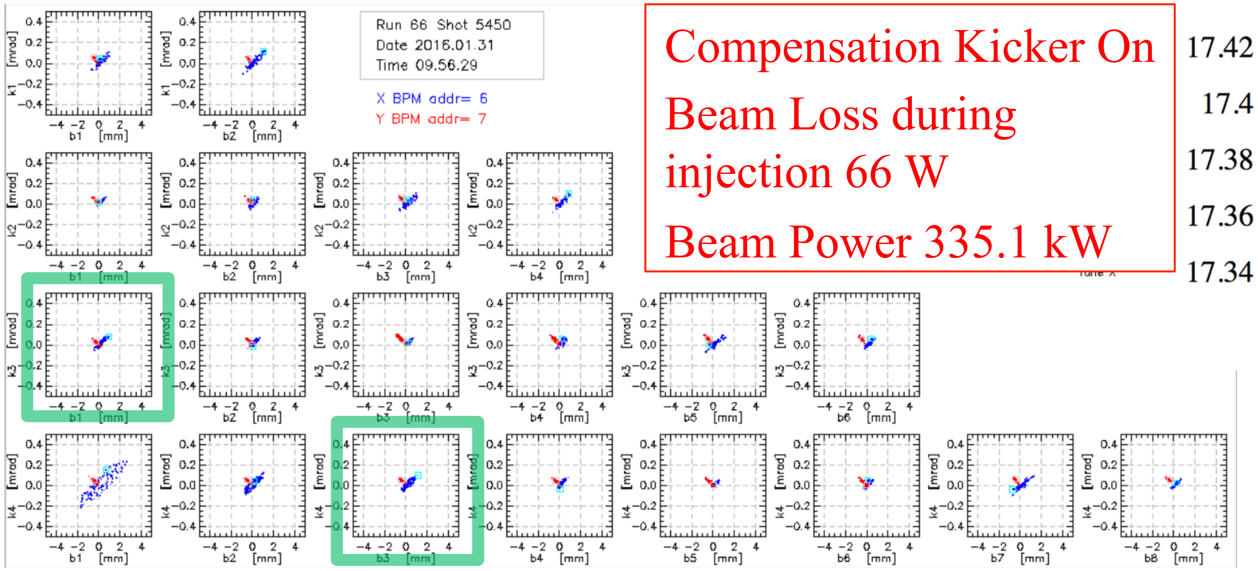
Beam loss during injection 101 W

Beam Power 334.4 kW

Beam Intensity Compensation Kicker On /Off

$*10^{13}$ ppb (k1 1 bunch) Run066

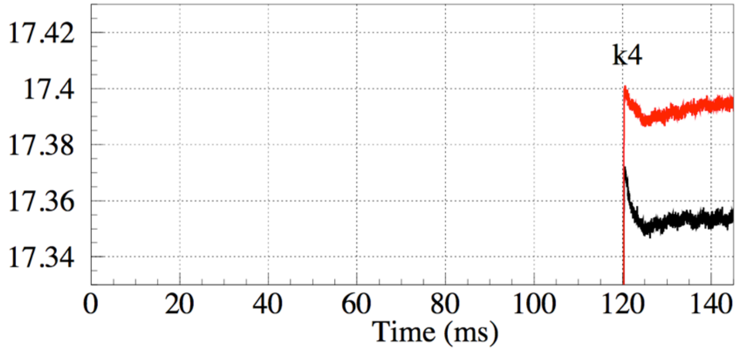




Compensation Kicker On

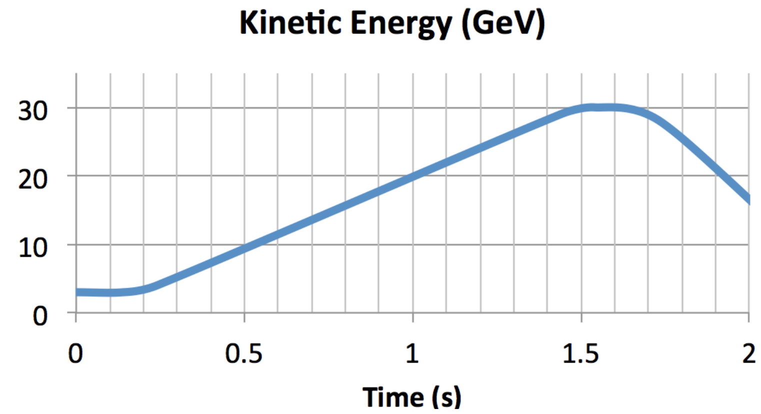
Beam Loss during injection 66 W

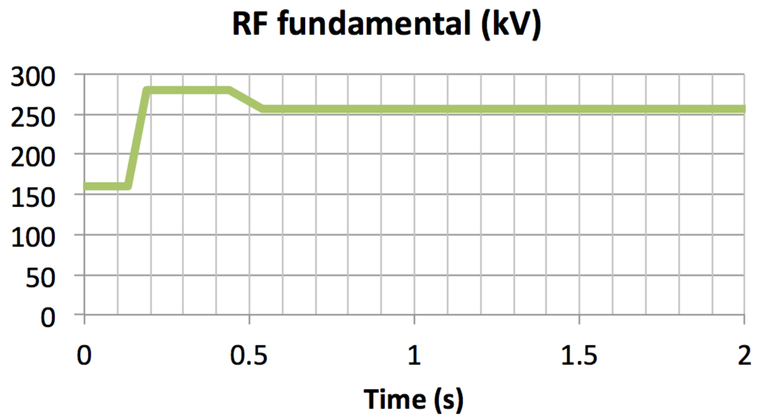
Beam Power 335.1 kW



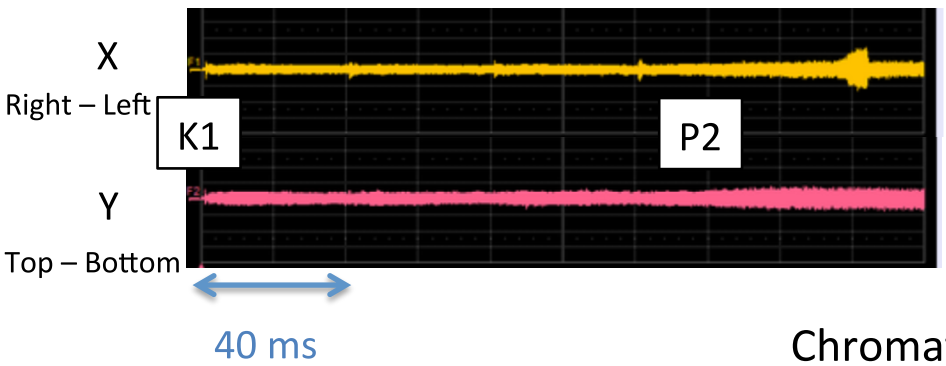
Chromaticity Pattern for Instability Suppression

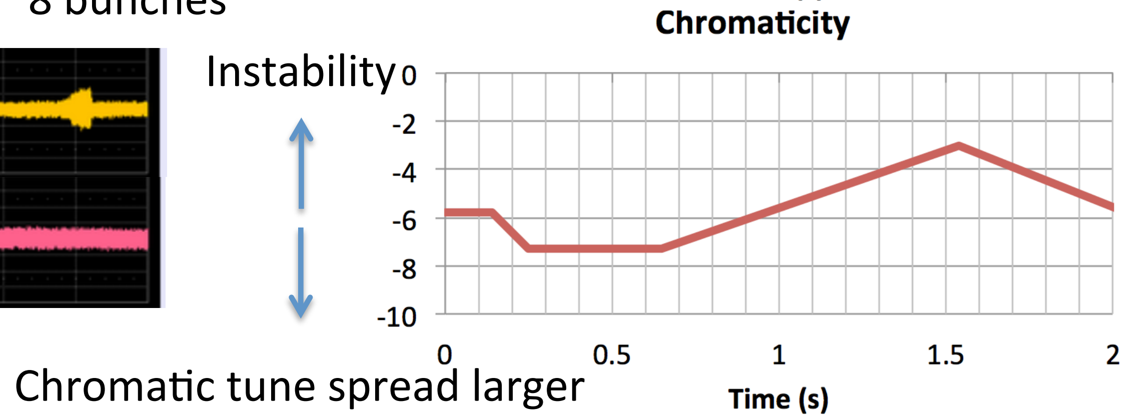
- The chromaticity pattern was optimized to minimize the beam loss.
- To suppress instabilities the chromaticity is kept to be negative, typically −6 during injection.
- If the chromaticity is too small in negative value, we observe instability.
- If the chromaticity is too large in negative value, we observe beam losses those are probably due to chromatic tune spread.
- Instabilities are suppressed with bunch by bunch feedback and intra-bunch feedback system.
- The optimization is iterated after the change of parameters feedback systems.





Single Pass Monitor 2.53e13 ppb * 8 bunches

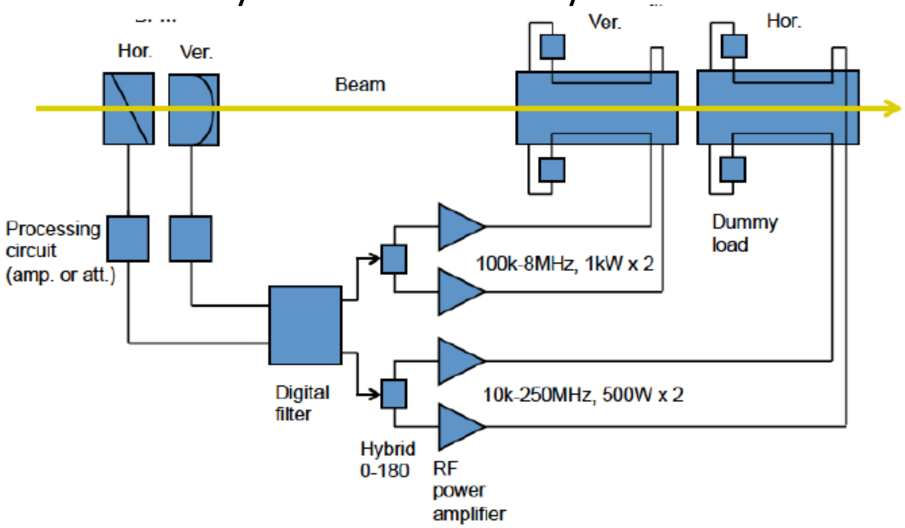




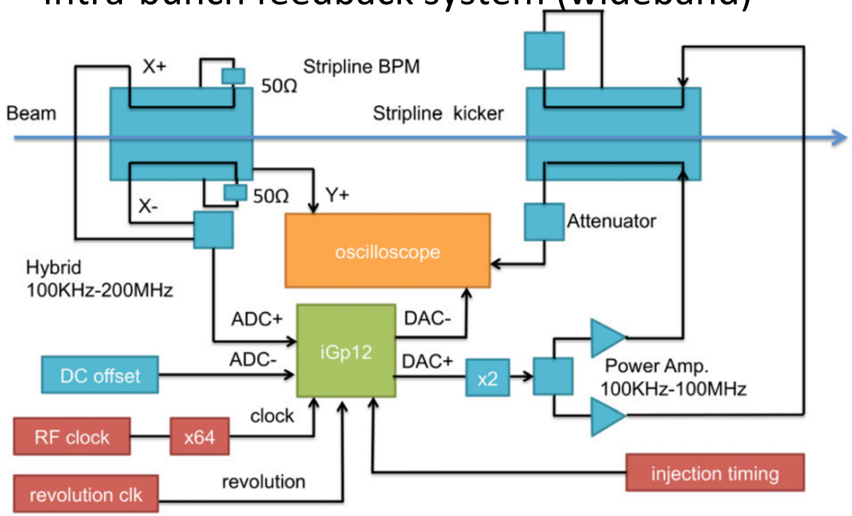
Bunch by Bunch and Intra-bunch Feedback

- Coherent Oscillation is damped with the bunch by bunch and intra-bunch feedback system during injection and in the beginning of acceleration.
- Intra-bunch FB has been applied during injection and up to 0.2 s after acceleration start.

Bunch by bunch feedback system

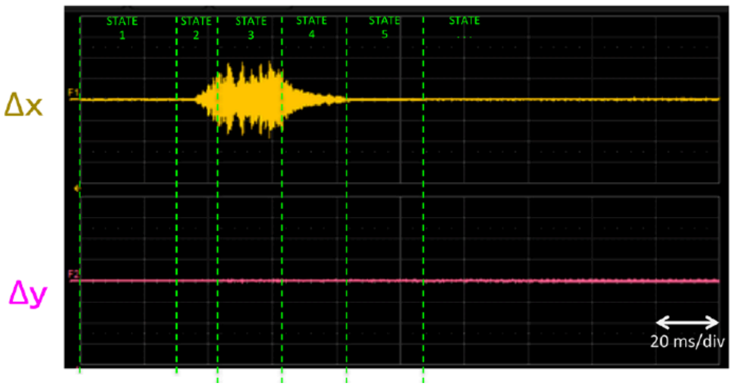


Intra-bunch feedback system (wideband)



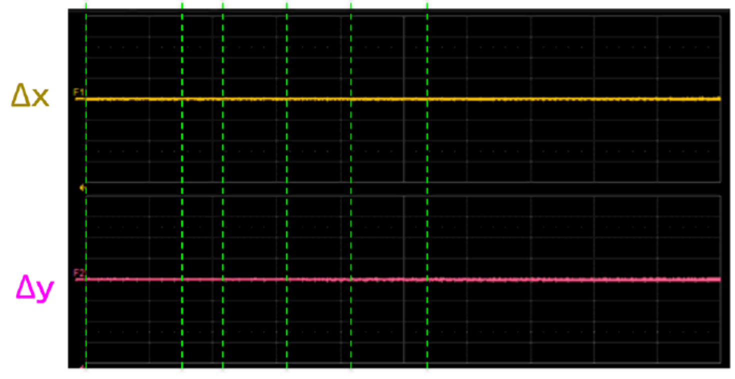
Beam Position with Intra-bunch FB off

2.1e13 ppb
× 2 bunches



P1+100 ms P2

Beam Position with Intra-bunch FB on

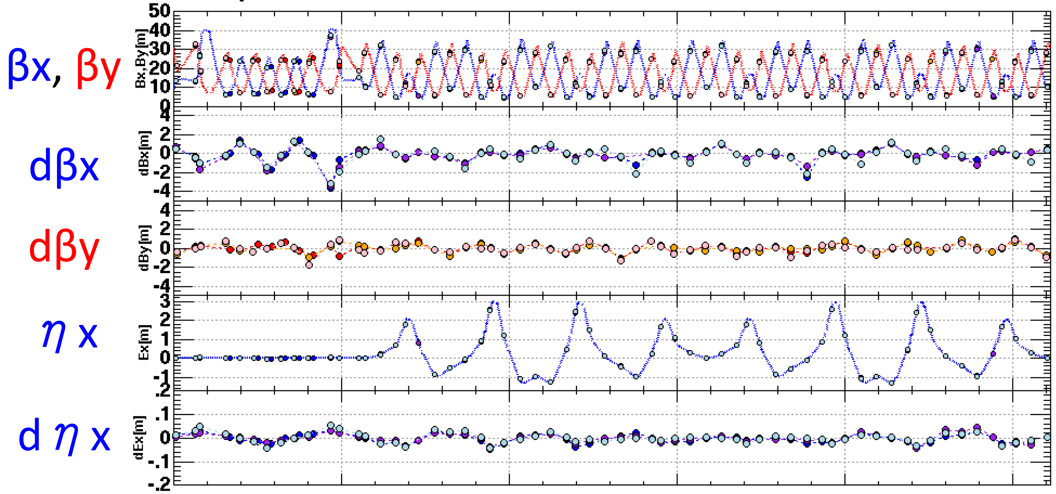


P1+100 ms P2

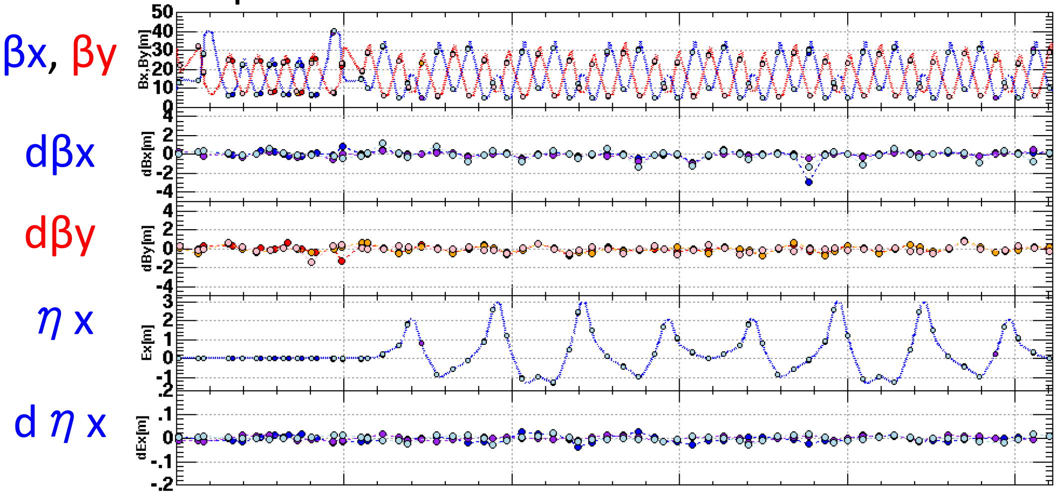
Optics Measurement and Correction

- The stripline kickers and power amplifiers of the intra-bunch feedback system are used for optics measurement during injection and in the beginning of acceleration up to P2 + 0.37 s.
- The kicker is to excite the betatron oscillation and the amplitude at each BPM is measured.

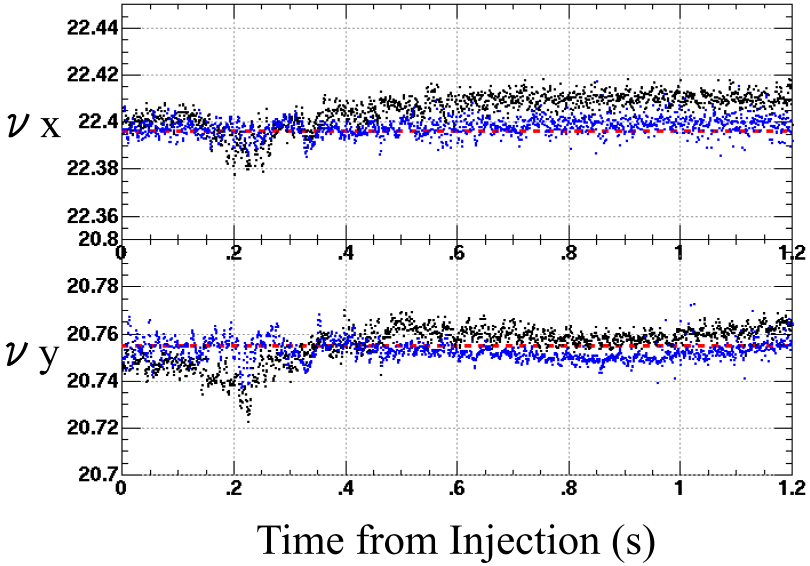
Optics before Correction at P1+300 ms



Optics after Correction at P1+300 ms



Tune before and after Correction

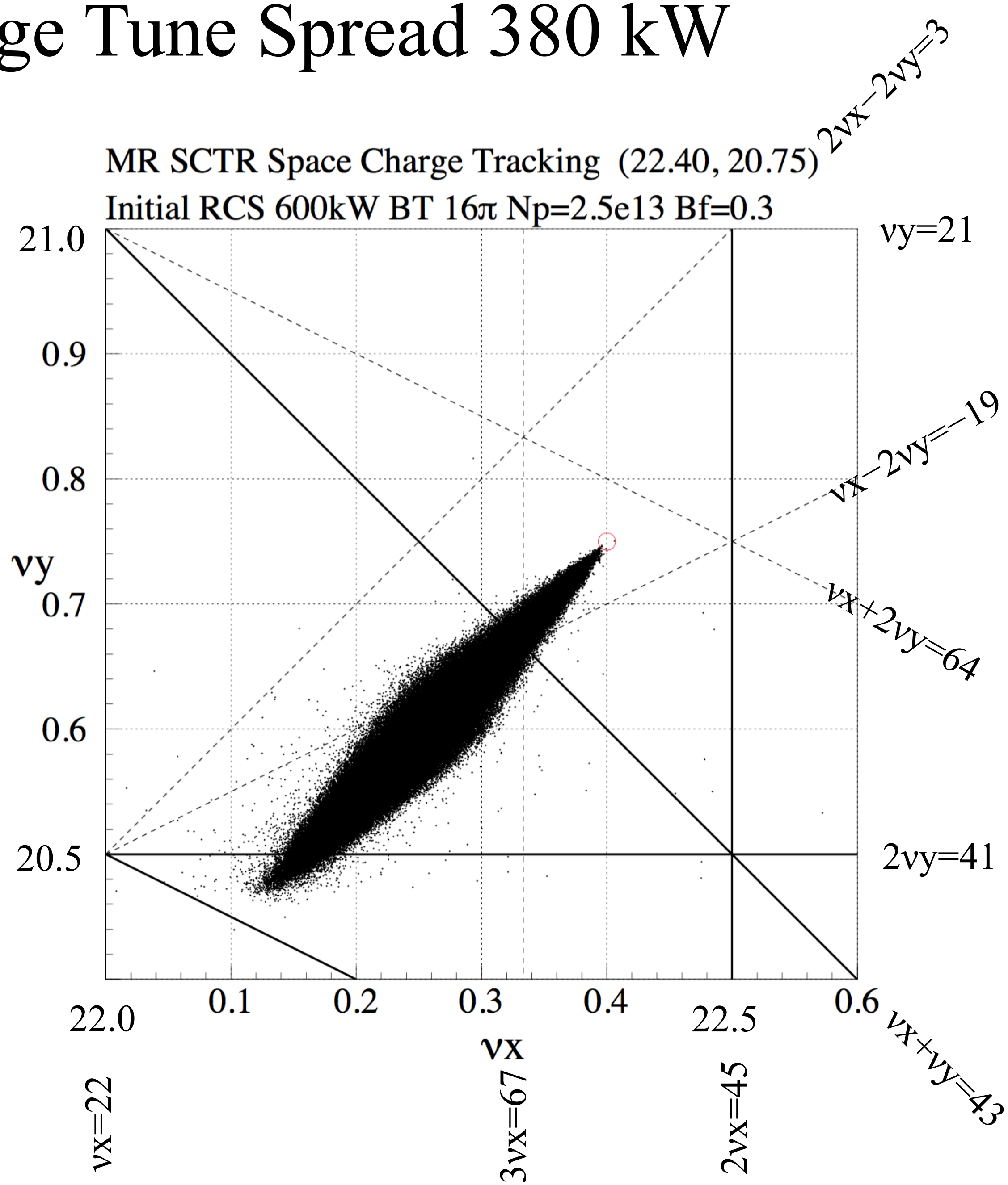


Space Charge Tune Spread 380 kW

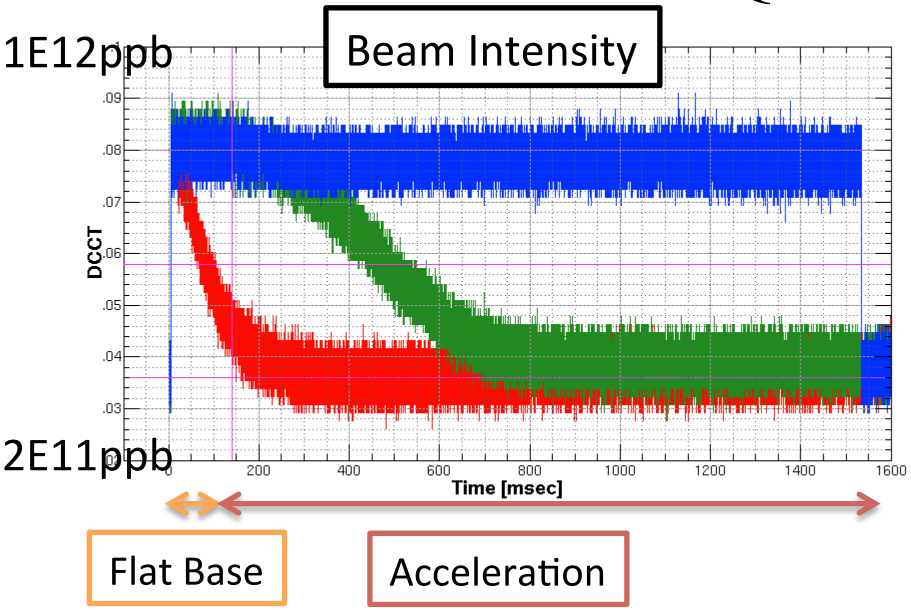
- MR Power 380 kW
- MR Cycle: 2.48 s
- Number of protons: 2.5e13 ppb
- Transverse Emittance: 16π mmmrad
- Bunching Factor: 0.3
- Space Charge Tune Shift: 0.33

$$\Delta\nu = \frac{2\pi R N r_0}{4\pi\sigma^2 / \beta (v/c)^2 \gamma^3 B_f} = 0.33$$

- E = 3 GeV
- $(v/c)^2\gamma^3$=69.751
- $2\pi RN = 2.5\times10^{13}\times9$: Intensity
- $4\pi\sigma^2/\beta$ = 16π mmmrad : Emittance
- B_f = 0.3 : Bunching factor



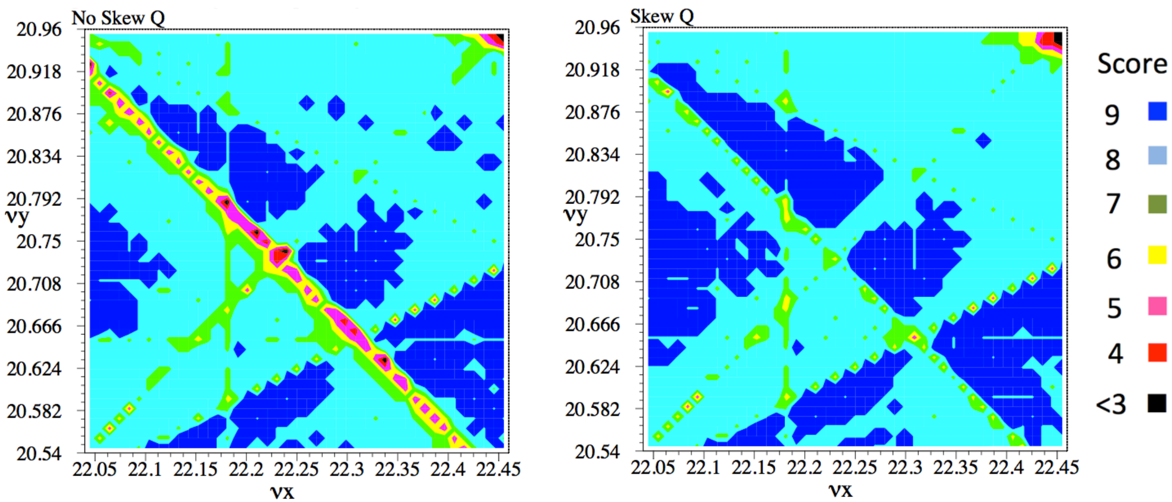
Linear Coupling Resonance Correction with Skew Quadrupole Magnets



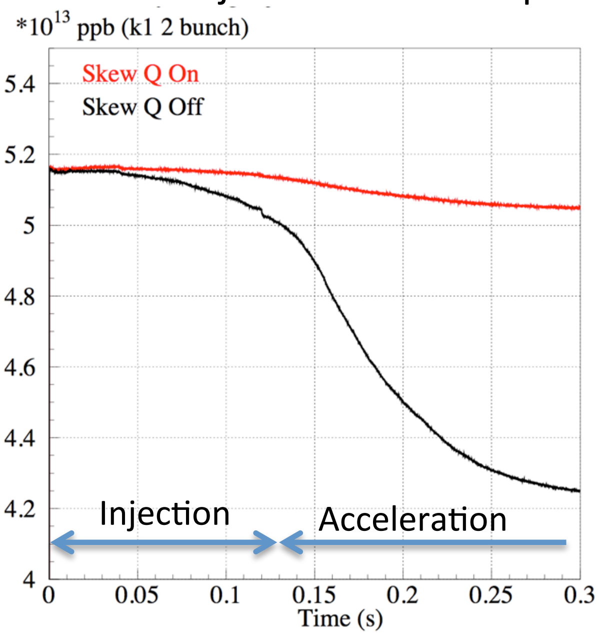
Measured beam survival
on LCR (22.28, 20.71)
w changing Skew Q
No correction
Corrected with 3 GeV DC
Corrected from 3 to 30 GeV

Skew Q setting reduces beam loss in high intensity operation and is used for the user operation.

Simulation for tune survey for aperture w/o Skew Q, with Skew Q

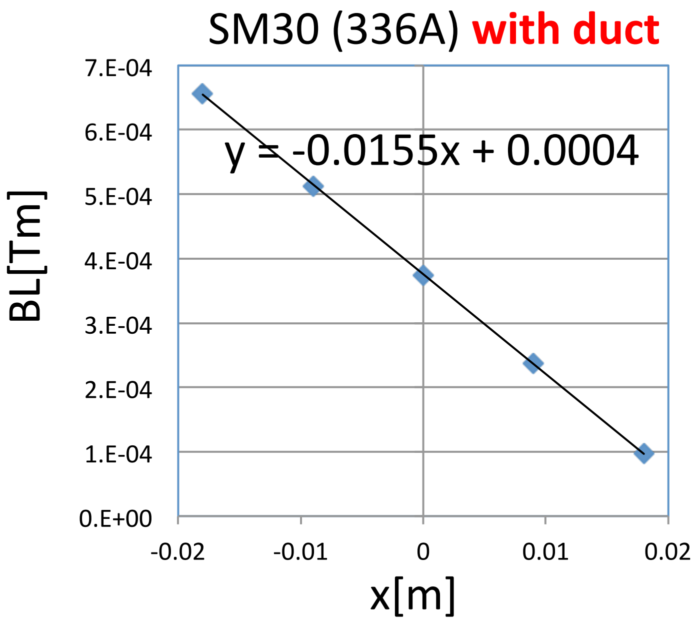


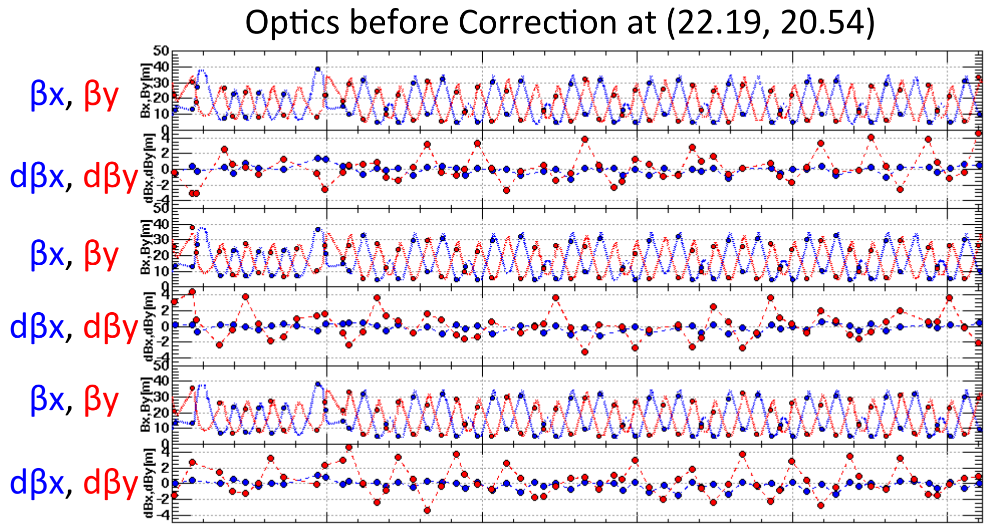
2 bunch injection 380 kW equiv.

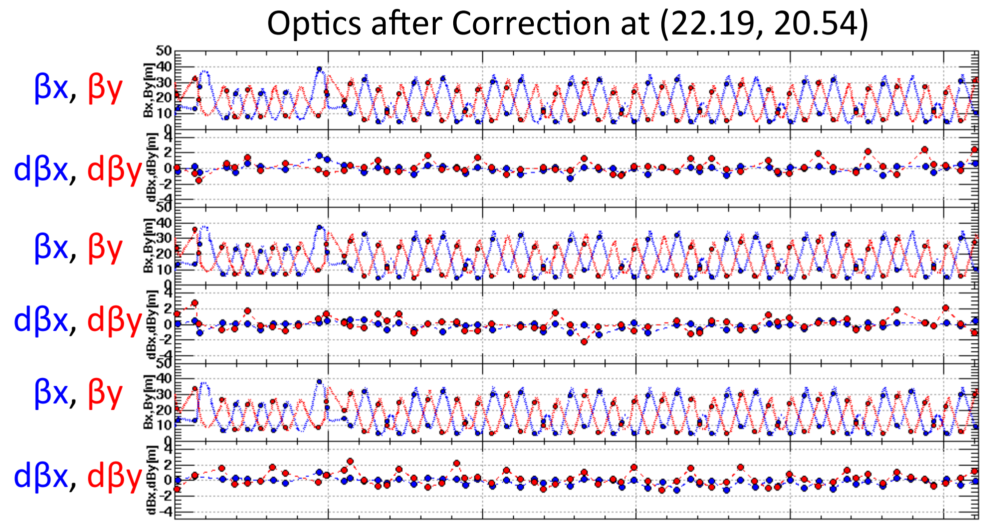


FX Septum Leak Field

- FX septum magnets makes undesirable Q fields for circulating beam with the leak fields.
- Leak field of 8 FX septum magnets corresponds to ~3% of K1 of the main Q magnet.
- Trim coils of 3 Q magnets have been used to correct the leak field of FX septum magnets.

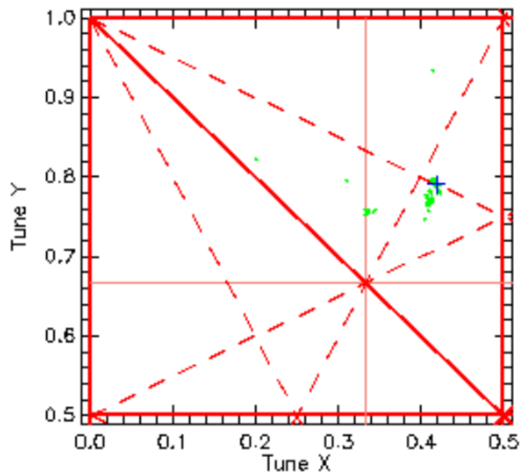


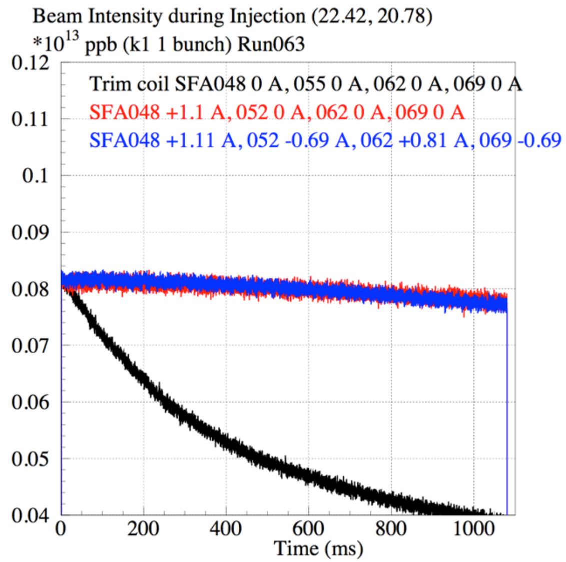




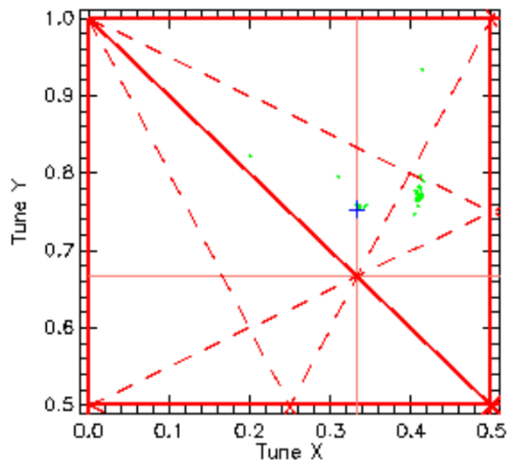
3^{rd} Order Resonance Corrections with Trim Coils of Sextupole Magnets

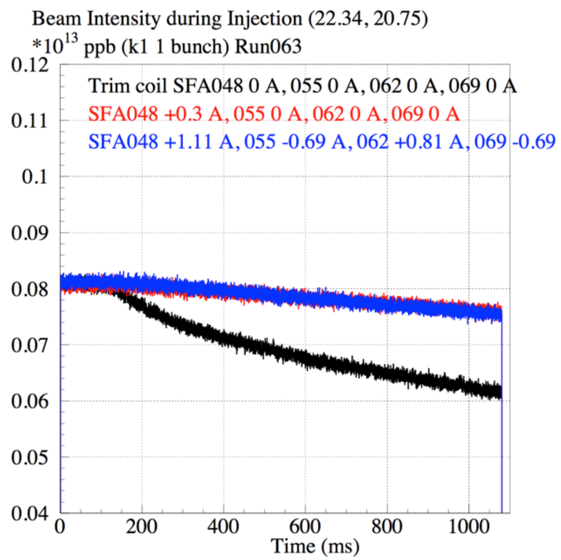
- $\nu_x+2\nu_x=64$
- 8e11ppb, 1 bunch injection at k1
- 3 GeV DC
- Search the resonance with worse beam survival around (22.42, 20.78).
- Beam survival recovers with SFA048: +1.1 A, SFA055: 0 A.





- $3\nu_x=67$
- Search the resonance with worse beam survival around (22.34, 20.75).
- Beam survival recovers with SFA048 −0.3 A, SFA055 −0.0 A.
- Both resonances of νx+2νy = 64 and $3\nu_x=67$ were corrected with SFA048 +0.86 A, 055 −1.15 A, 062 +1.26 A, 069 −0.85 A.





Correction of the 3rd Order Resonances of both νx+2νy = 64 and 3νx = 67

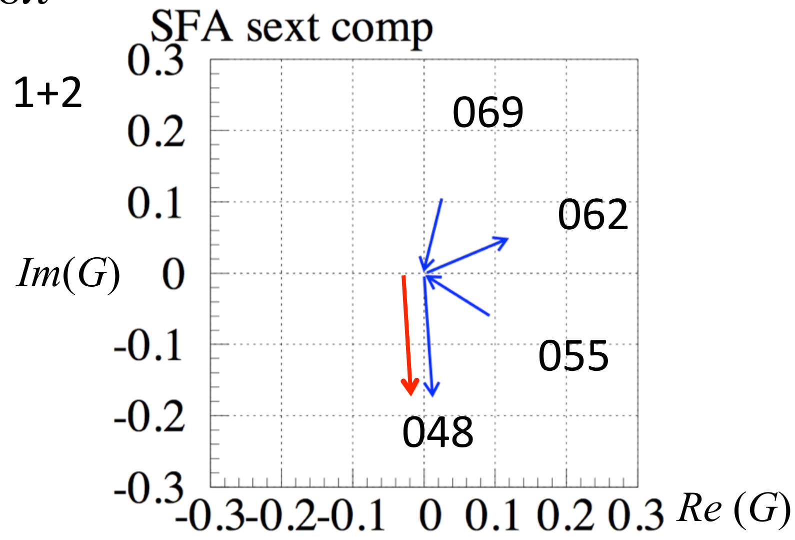
- Equations for canceling both resonances, for $k_2(1)$, $k_2(2)$, $k_2(3)$, $k_2(4)$.
- 1 = SFA048, 2 = SFA055, 3 = SFA062, 4 = SFA069

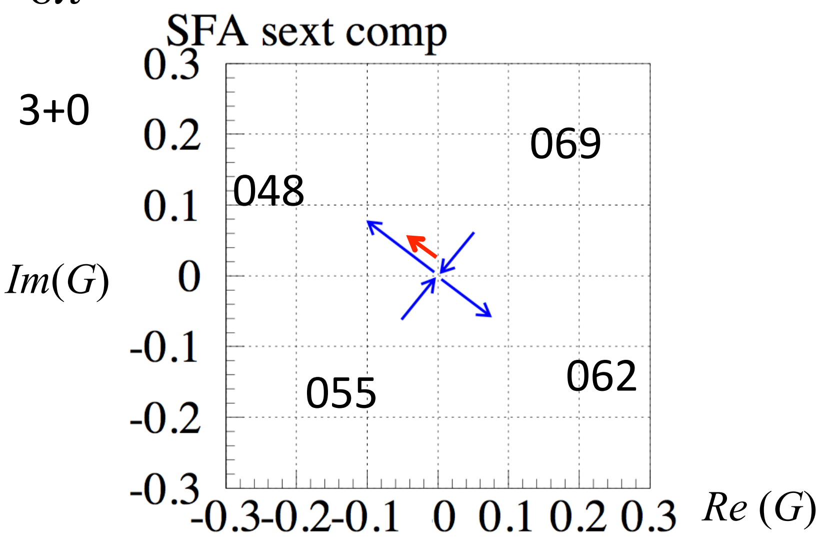
$$\sum_{j=1}^{4} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\ k_2(j) \cos[3\phi_x(j)] = \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(1)\ k_2(1) \cos[3\phi_x(1)]$$

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

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

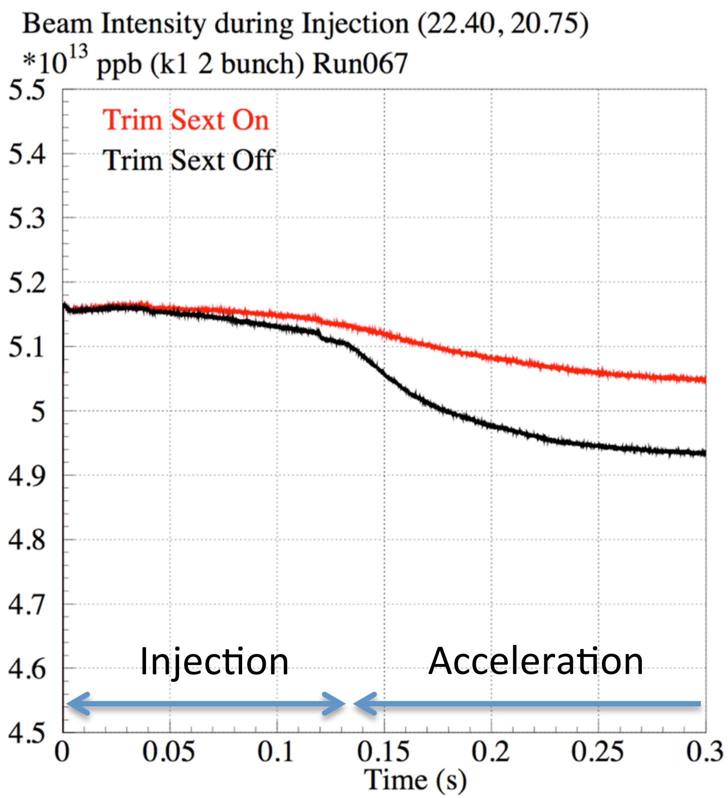
$$\sum_{j=1}^{4} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\ k_2(j) \sin[\phi_x(j)+2\phi_y(j)] = \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(1)\beta_y(1)\ k_2(1) \sin[\phi_x(1)+2\phi_y(1)]$$

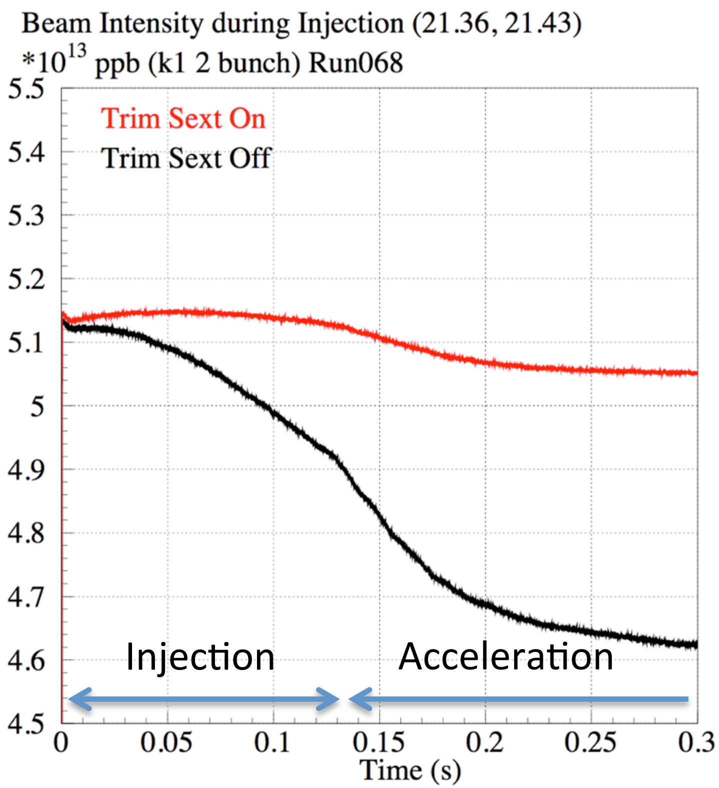




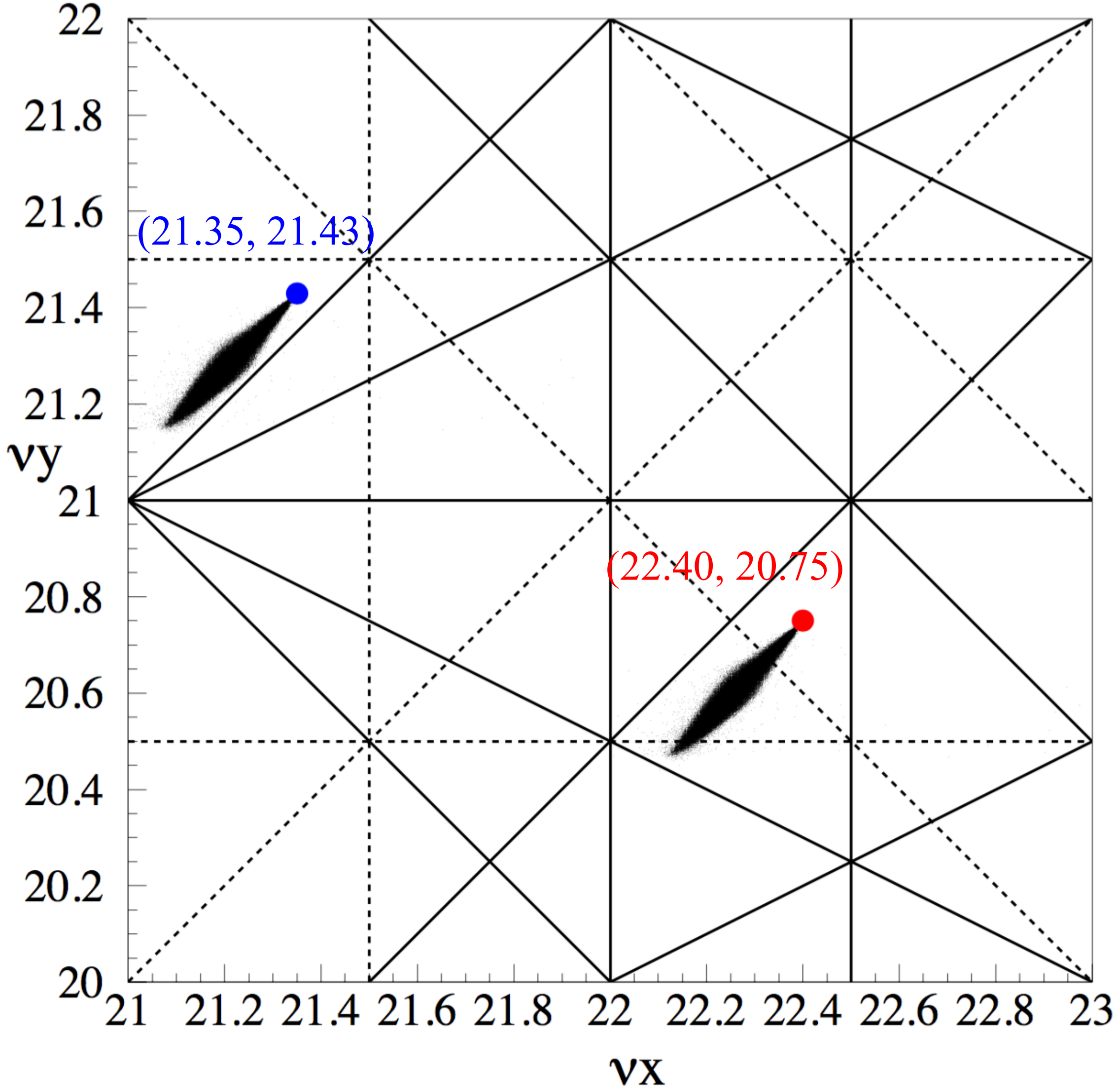
Correction of the 3rd Order Resonances of both νx+2νy = 64 and 3νx = 67 (or 64)

- Beam losses were reduced with the correction during injection and the beginning of acceleration for high intensity beam of 380 kW equivalent.
- Correction of both $\nu_x+2\nu_x=64$ and $3\nu_x=67$ for tune of (22.40, 20.75)
- Correction of both $\nu_x+2\nu_x=64$ and $3\nu_x=64$ for tune of (21.36, 21.43)





Operation with the Betatron Tune of (21.35, 21.43)

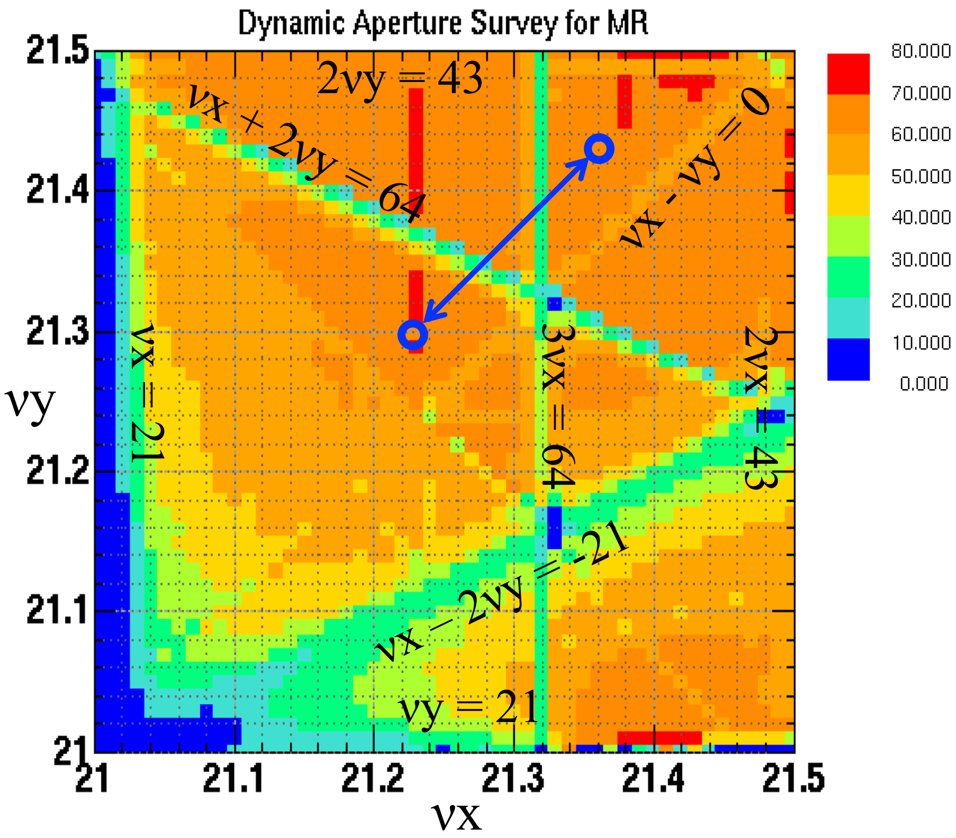


Structure resonances of up to 3rd order (Solid lines)

Non-structure resonances of half integer and linear coupling resonances (Dashed lines)

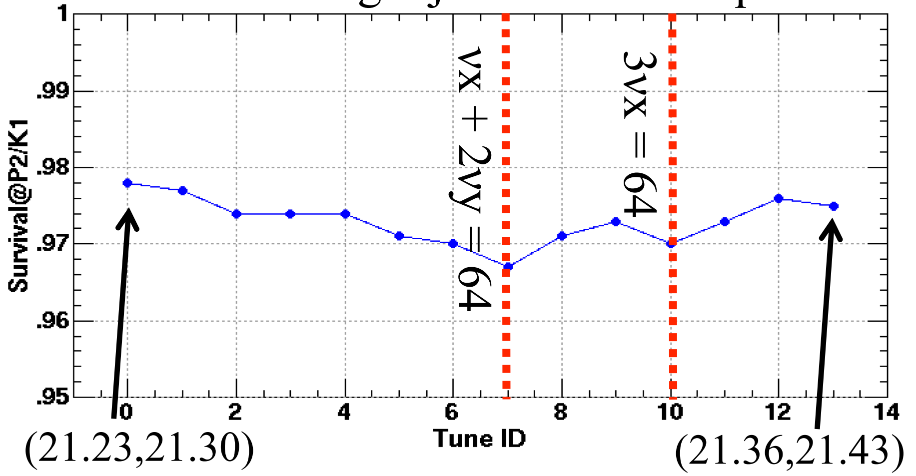
Optimization for (21.x, 21.x)

Dynamic Aperture Survey Simulation
B,Q,S field errors : ON
Alignment errors : ON
$dp/p_0 = 0.0\%$
FX septum leakage : OFF
3rd resonance corr. (Trim-S) : OFF
Emittance : 80π (2π step), Turn : 2000



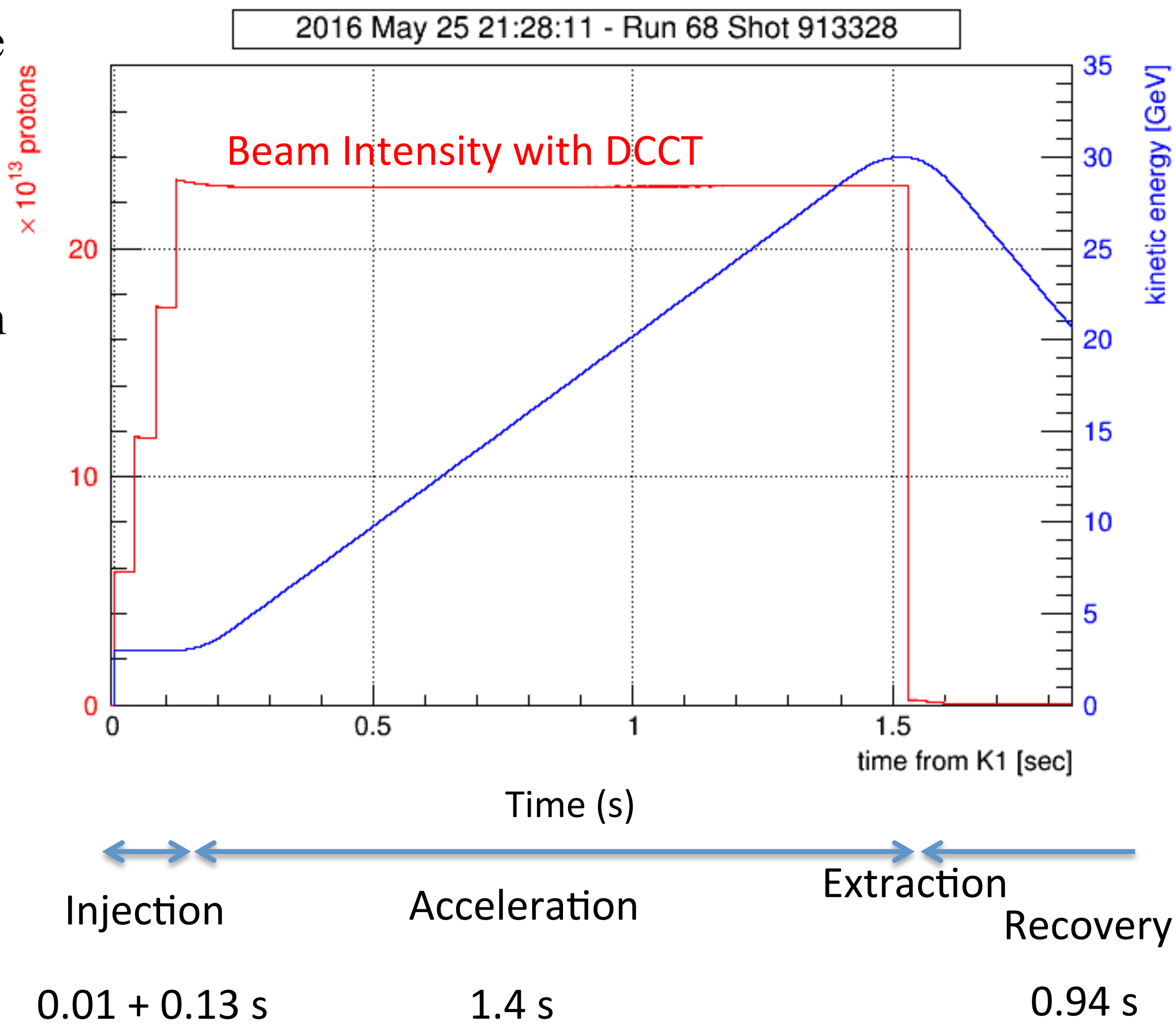
- Optics correction
- Tune scan
- 2nd rf operation
- Trim Q correction for FX septum mag.
- Trim S correction for 3rd order res.
- Skew Q correction for $\nu x - \nu y = 0$
- Octupole correction
- Instability suppression
  - Chromaticity: −7
  - Bunch by bunch and intra-bunch FB
- Extraction orbit for neutrino beamline
- Compensation kicker is not optimized yet.

Survival during inj. for 390 kW equiv. beam



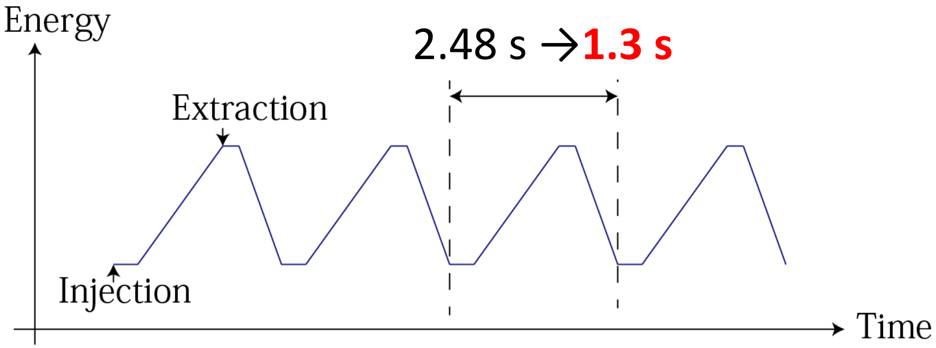
440 kW Trial with (21.35, 21.43)

- 2016/5/25 21:28: Trial shots to MR-abort with the betatron tune of (21.35, 21.43)
- Power : 440 kW
- Repetition : 2.48 sec
- 4 batch (8 bunch) injection during the period of 0.13 s
- 2.9e13 protons per bunch (ppb) × 8 @ Injection
- 2.27e14 ppp @ P3 (end of acceleration)
- Loss during the injection period : 443 W
- Loss in the beginning of acceleration (0.12 s) : 795 W
- Loss power is within the MR collimator limit of 2 kW.



Upgrade Plan for the Beam Power of 750 kW and more

Faster Cycling 2.48 s → 1.3 s or Faster

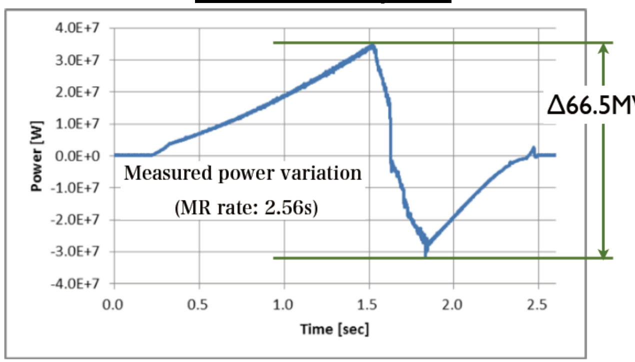


- Magnet Power Supply
- RF
- Injection and Extraction Devices

Requirement to the magnet power supplies

Issue : Large power variation @ AC main grid

2.56sec cycle



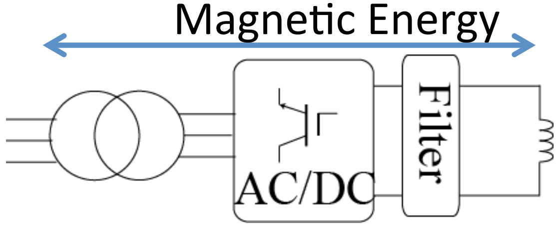
~~1.3 sec cycle~~

~~~Δ140MW~~

Not allowed by Tokyo Electric Power Company

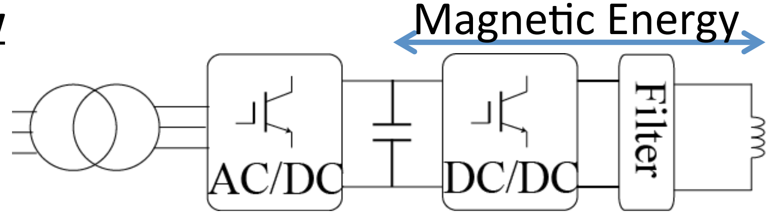
Energy Recovery with Bank Capacitor

Present



All magnetic energy recover to AC main.

New



All magnetic energy recover to capacitor bank
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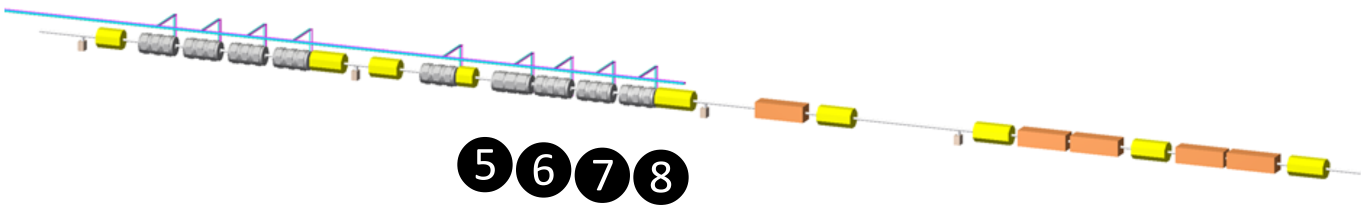
RF Cavities

INS-C FY2012 — FT3M 9 × 3-cell cavity: 315 kV

Required voltage for 2.48 s cycle: 280 kV



Four cavities ⑤～⑧ will be installed in this summer.

FT3L (for High Gradient Cavity)

7 × 5-cell cavity + 2 × 4-cell cavity: 602 kV

Required voltage for 1.3 s cycle: 540 kV

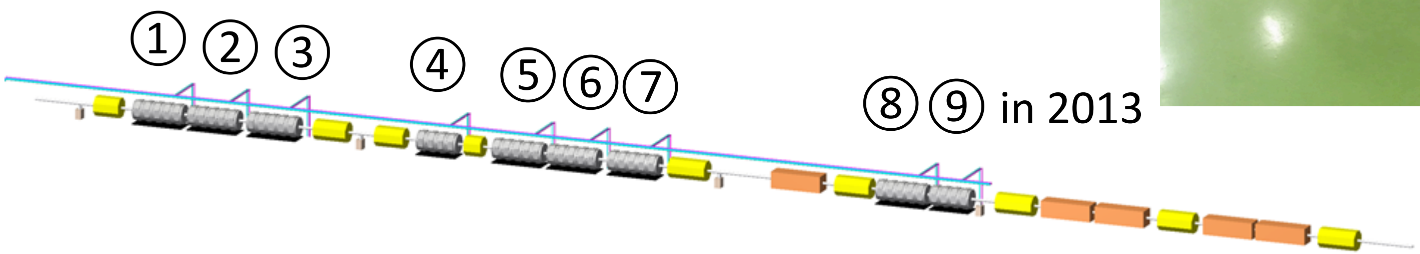


Photo of ①～③ cavities installation in 2015

Plan FY2016

& 2nd Harmonic Cavity in Ins.-A

Mid-term Plan of MR

For the design beam intensity of 750 kW the repetition period will be from 2.48 s to 1.3 s with new magnet power supplies and rf cavities.

JFY	2014	2015	2016	2017	2018	2019	2020
Event	Li. Current 30 → 50 mA		New PS Buildings				
Beam Power (kW)	240-320	350	400	450	700	800	900
Repetition	2.48 s	2.48 s	2.48 s	2.48 s	1.3 s	1.3 s	1.25 s
New Magnet Power Supply	R&D	Prototype	Mass Production				
High Grad. Rf System		Mass Production					
2nd Harmonic Rf							
Collimators		Col C, D			Col E, F		
Injection System	Kicker Improvement and Septa manufac.						
Extraction Syst.	Kicker Improvement and Septa manufac.						

Summary

- Beam power of 415 kW has been achieved for FX user operation with
  - Injection beam distribution by RCS tuning
  - Rf pattern optimization for fundamental and 2nd harmonic
  - Injection kicker improvements
  - Bunch by bunch feedback and intra-bunch feedback
  - Optics correction
  - Correction of $\nu x + \nu y = 43$ with skew Q's
  - Correction of $2\nu y = 41$ with trim coils of Q magnets
  - Correction of 3rd order resonances with trim coils of S magnets
- Operation with the betatron tune of (21.35, 21.43) has been started.
  - There is more free space without serious resonances.
- We plan to achieve the target beam power of 750 kW and more with the faster cycling 2.48 s to 1.3 s. We are upgrading the following hardware by JFY 2018.
  - Main magnet power supplies
  - Rf
  - Injection and extraction devices
  - Collimators