J-PARC Main Ring Optics, Space Charge, Alignment

2013/12/3

Beam Dynamics meets Magnets

Igarashi (KEK)

Contents

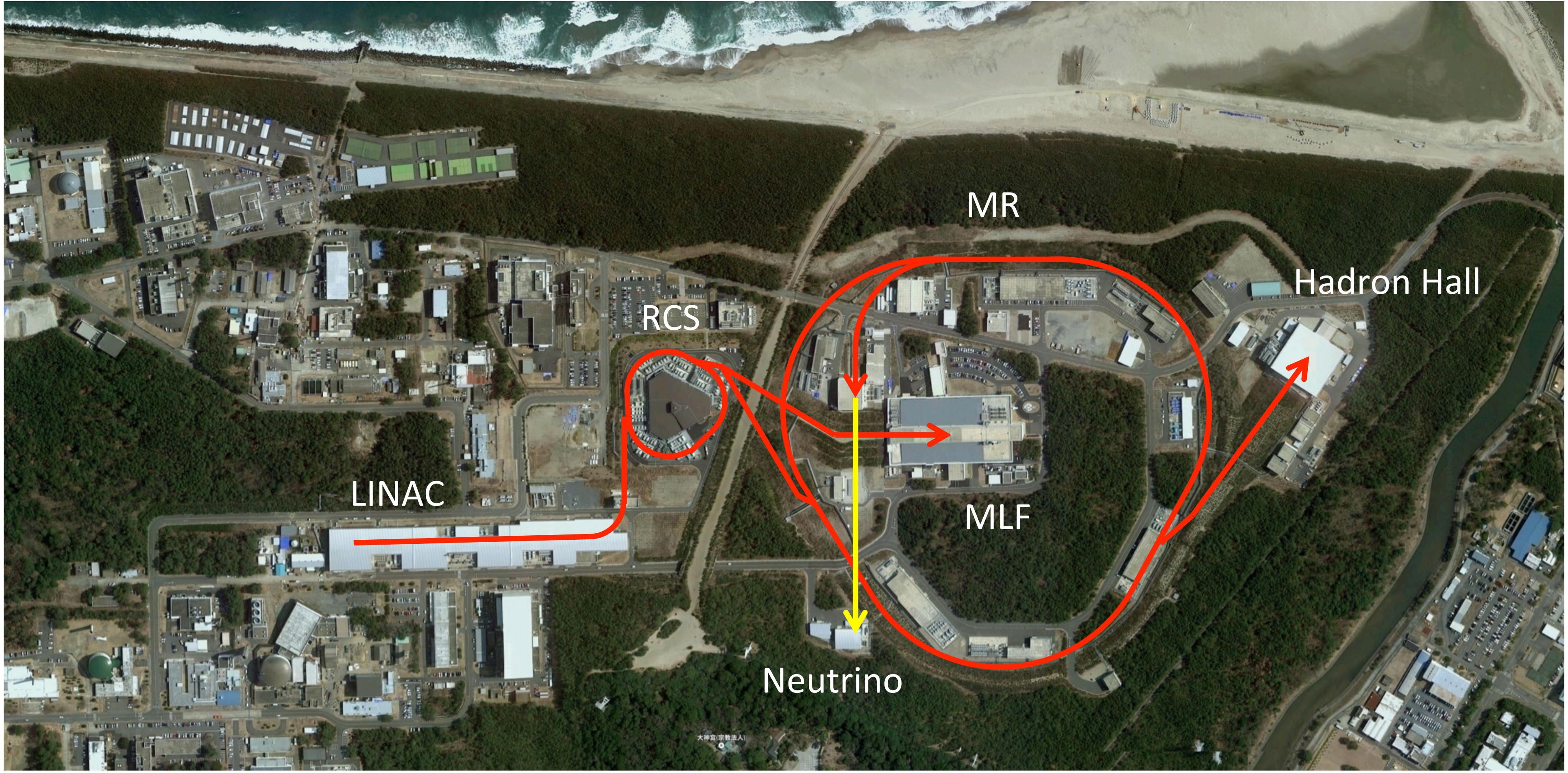
- Overview of J-PARC Main Ring
- Magnetic field measurements
- Alignment
- Implementation to the beam tracking simulation
- Comparison between the beam measurement and simulation
- Coherent oscillation and damping with the octupole magnets

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

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

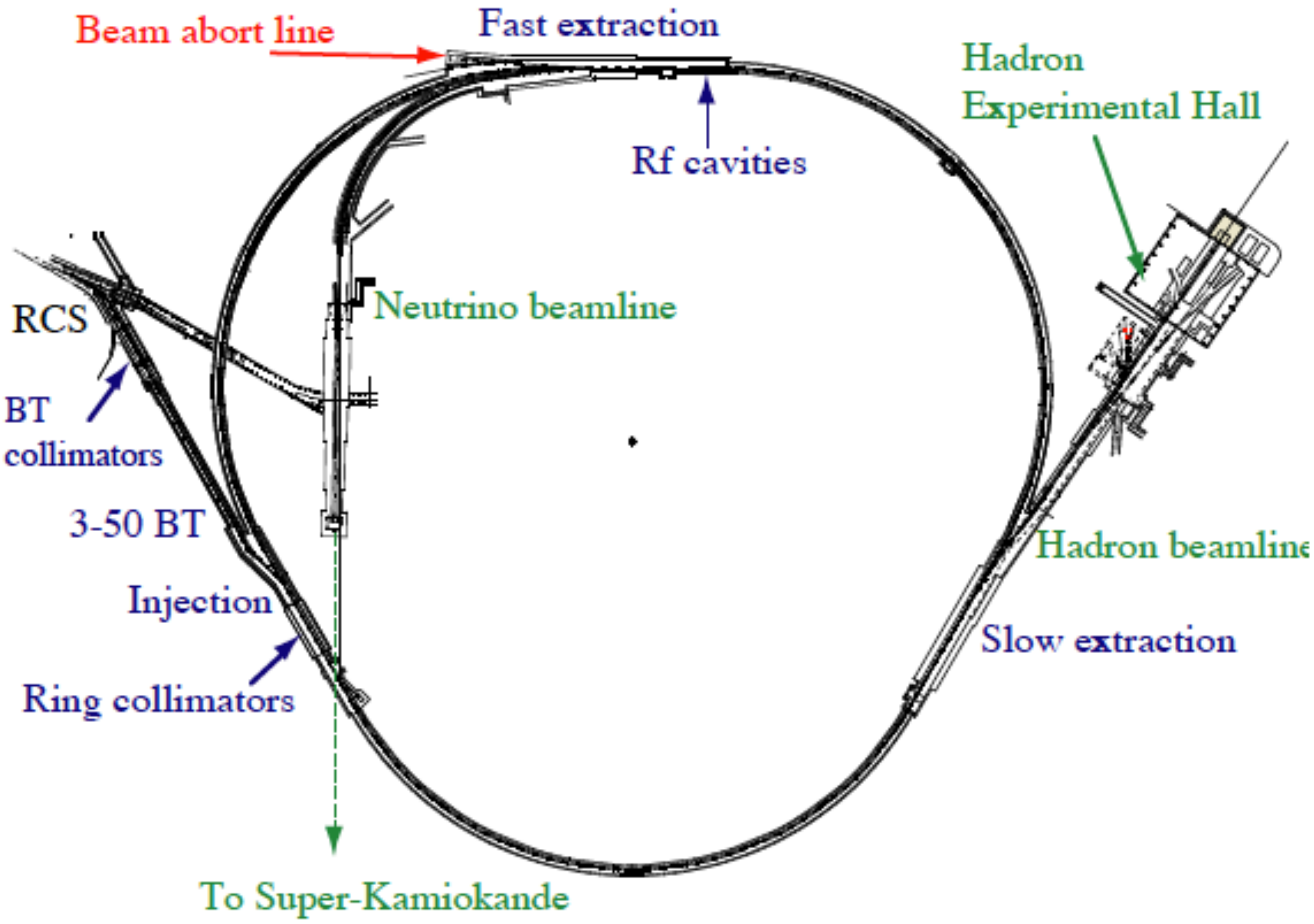


MR Design Features

- To achieve the beam power of 750 kW
- Large Aperture
- Beam Loss Localization
- Imaginary Transition γ lattice

- The first beam in MR
  - Injection 2008 May
  - Acceleration and extraction 2008 Dec.

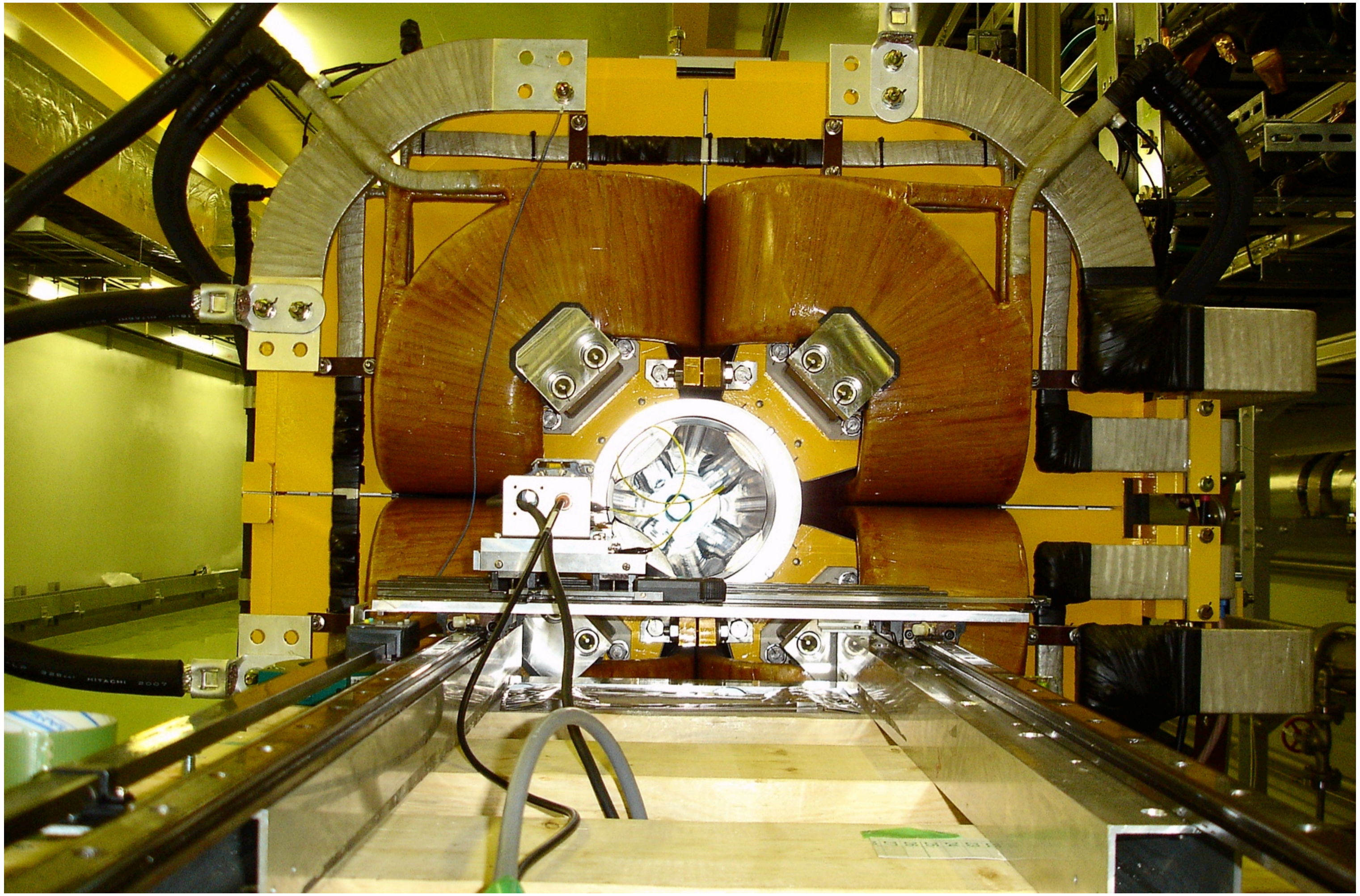
- Circumference 1567.5 m
- Three-fold symmetry
- Injection Energy 3GeV
- Extraction Energy 30 GeV (50 GeV)
- Power achieved so far 240 kW



Large Aperture

- Aperture ≥ 81π mmmrad
- Quadrupole magnet bore diameter ≥ 130 mm

Main Magnets :
96 Bending Magnets
216 Quadrupole Mangets
72 Sextupole Magnets



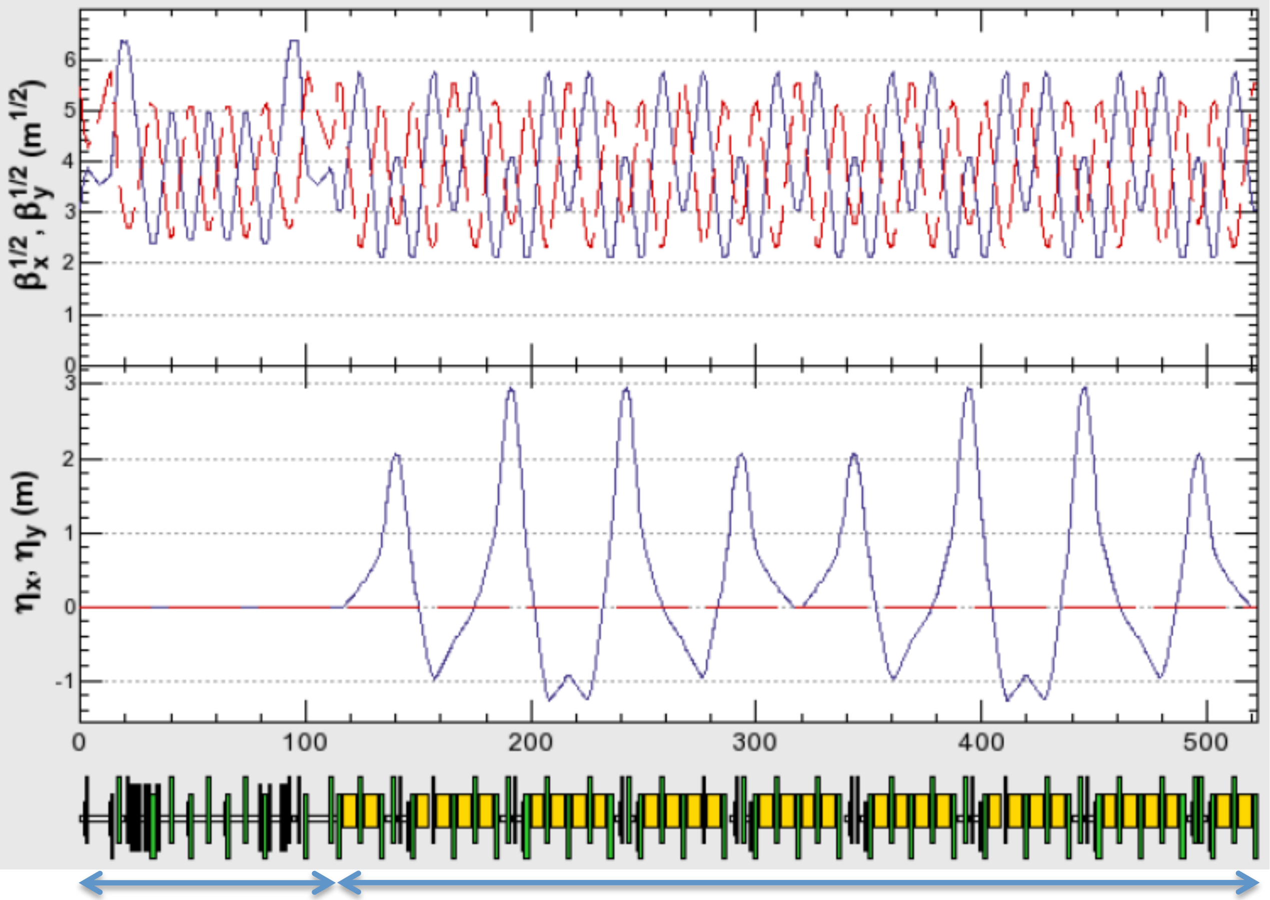
Beam Loss Localization

- Collimator system is being upgraded in 2011 ~ 2013.
- Power capacity: 0.45 kW → 3.5 kW.

MR Optics

- Imaginary Transition γ lattice designed by Machida-san
  - for phase stability of RF acceleration

MR Beta and Dispersion, 1/3 of MR

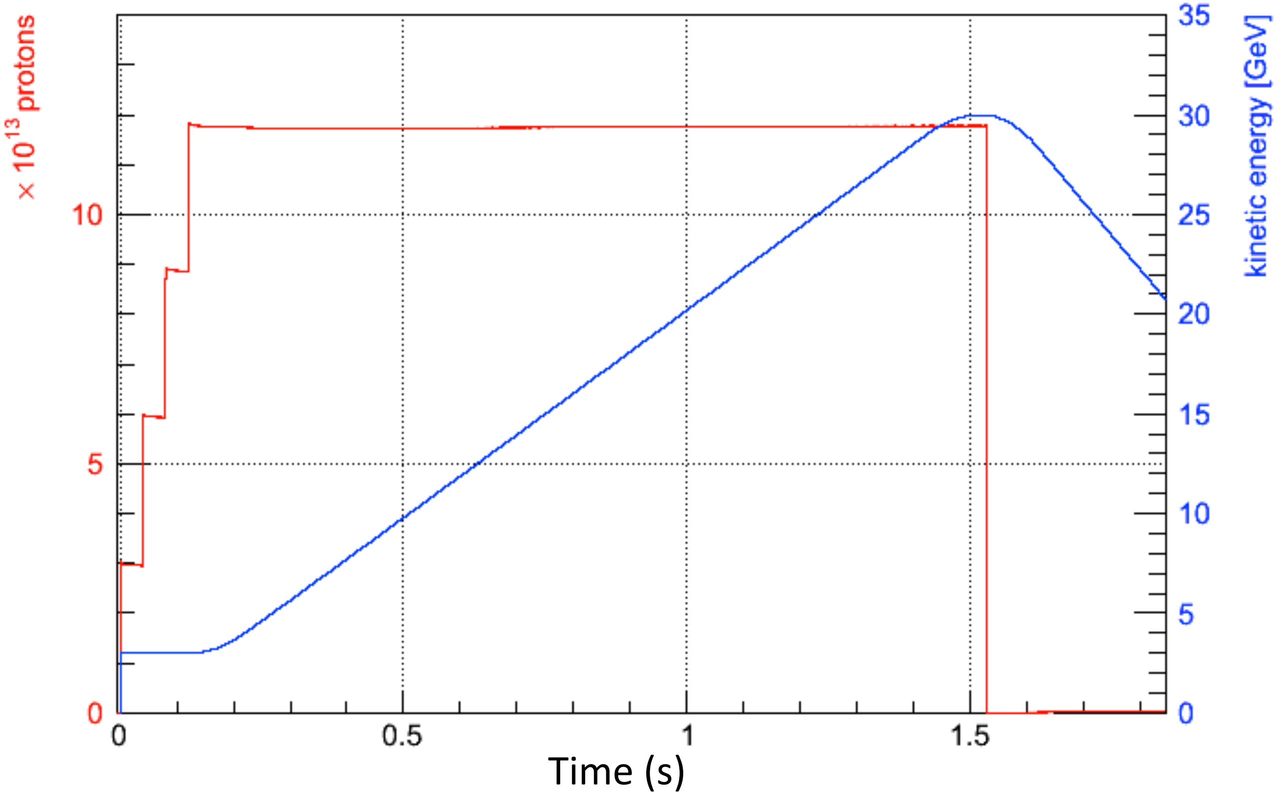


Straight section

Arc section

Typical Operation Status for Fast Extraction

- Power : 225 kW
- Repetition : 2.48 sec
- 4 batch (8 bunch) injection during the period of 0.13 s
- 1.5e13 protons per bunch (ppb) × 8 @ Injection
- 1.17e14 ppp @ P3 (end of acceleration)
- Loss during the injection period :   400 W
- Loss in the beginning of acceleration (0.12 s) : 150 W
- Loss power is within the MR collimator limit of 2 kW.
- Loss at 3-50BT : 70 W,   < 3-50BT collimator limit of 2 kW



Injection

0.01 + 0.13 s

Acceleration

1.4 s

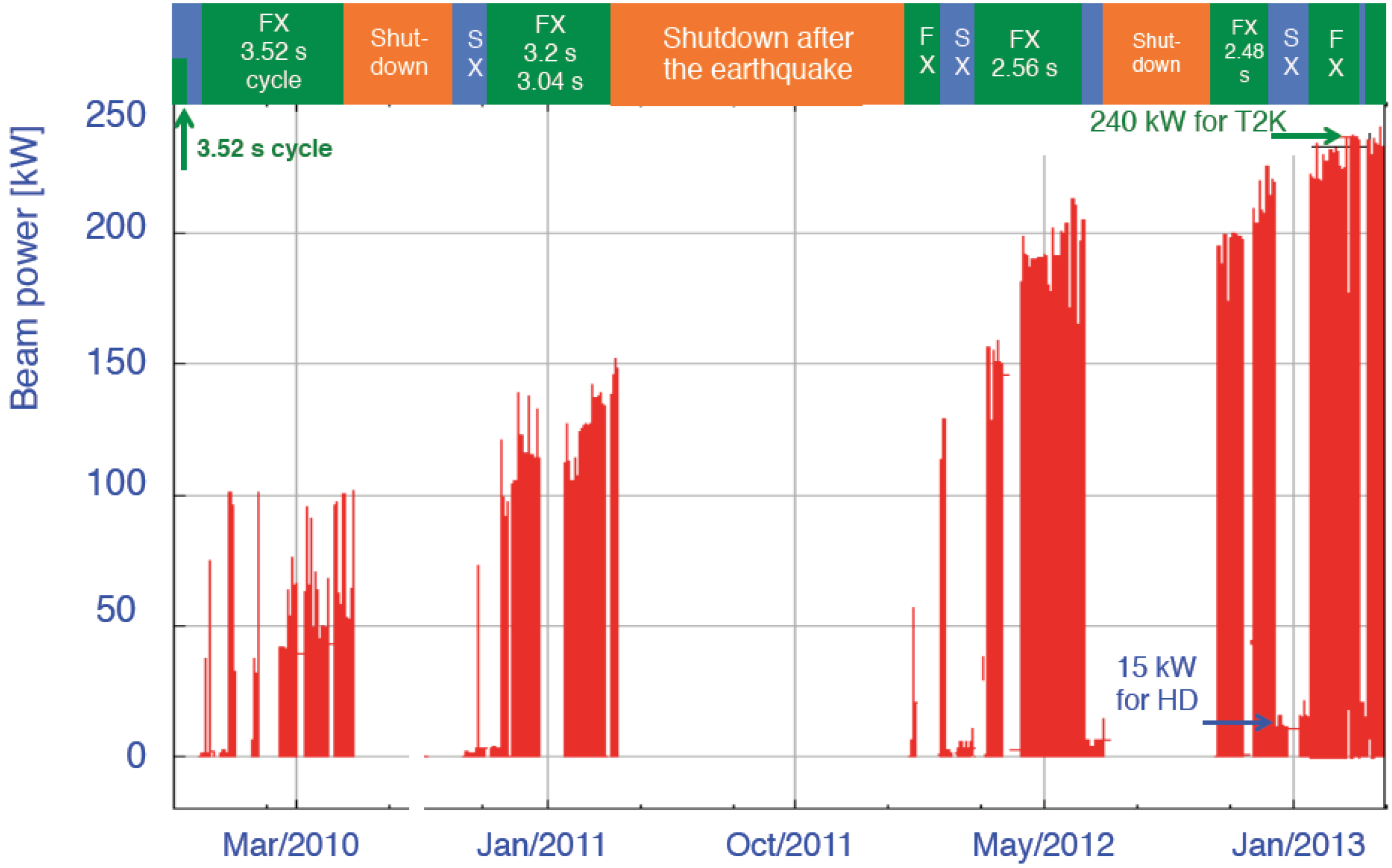
Extraction

Recovery

0.94 s

MR Operation History
from January 2010 to March 2013

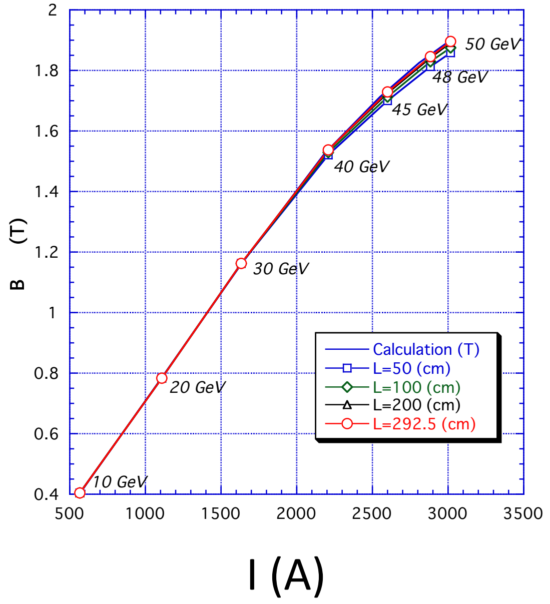
- The Beam power of 240 kW has been achieved for the neutrino oscillation experiment T2K.
- The Target power is 750 kW.



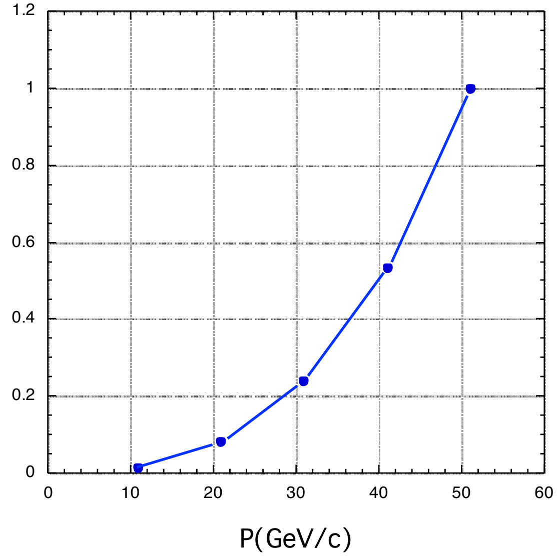
MR Top Energy 30 GeV

- Original Plan was to achieve 750 kW with 50 GeV operation.
  - The number of protons should be twice.
- 50 GeV Operation has disadvantage.
  - Magnet Saturation > 30 GeV
  - Power Consumption
    - P(50 GeV) = 2 P(40 GeV) = 4 P(30 GeV)

Bending Magnet
Magnetic Field B(T)

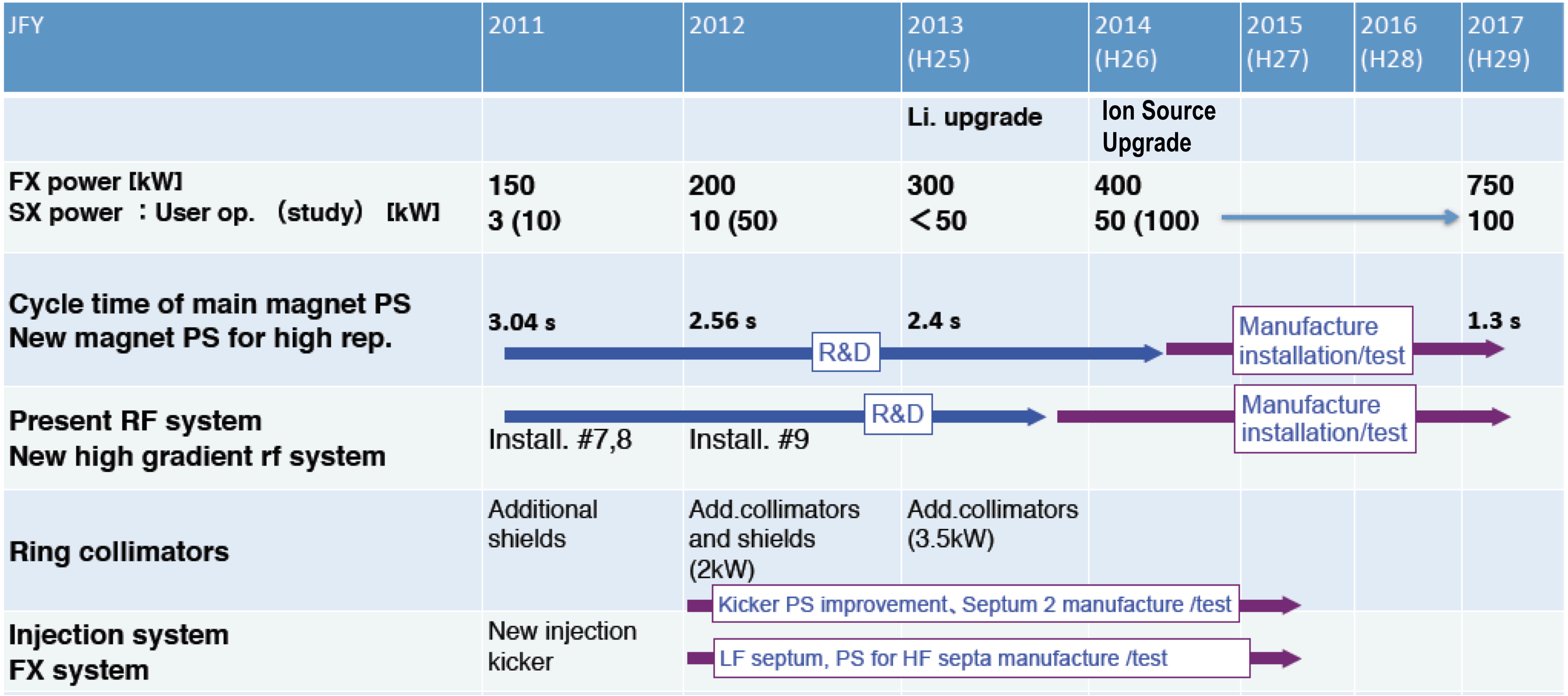


Magnet Power Consumption
(relative to 50 GeV)



Mid Term Plan

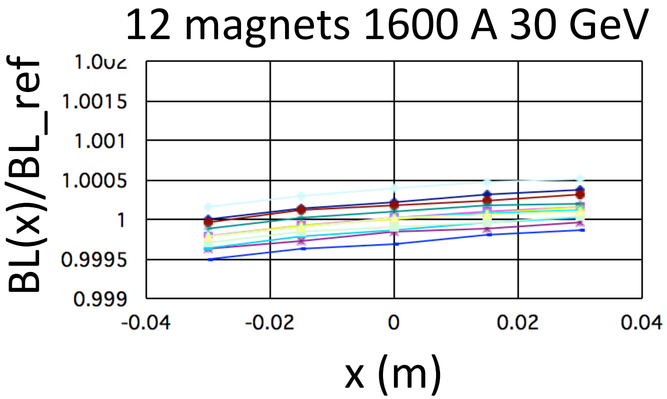
- High repetition rate scheme is been chosen to achieve 750 kW.
- Repetition cycle will be 1.3 s.
- Magnet Power Supplies and RF cavities will be replaced.
- Collimators have been updated from 2 kW to 3.5 kW in this JFY.
- Injection kicker power supplies are being improved and septum will be replaced for high repetition rate.



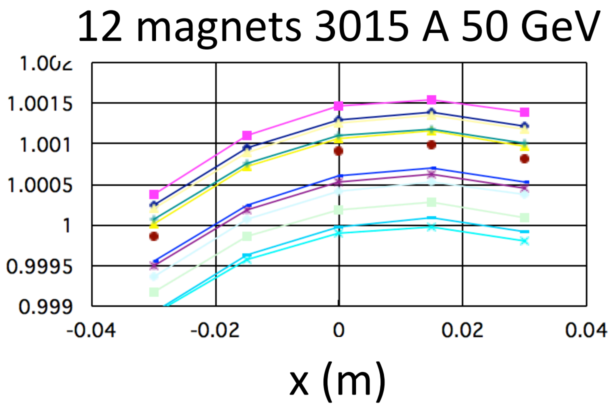
JFY	2011	2012	2013 (H25)	2014 (H26)	2015 (H27)	2016 (H28)	2017 (H29)
			Li. upgrade	**Ion Source Upgrade**			
FX power [kW] **SX power ：User op. （study） [kW]**	**150** **3 (10)**	**200** **10 (50)**	**300** **＜50**	**400** **50 (100)**			**750** **100**
Cycle time of main magnet PS **New magnet PS for high rep.**	**3.04 s**	**2.56 s** R&D	**2.4 s**		Manufacture installation/test		**1.3 s**
Present RF system **New high gradient rf system**	Install. #7,8	Install. #9	R&D		Manufacture installation/test		
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system **FX system**	New injection kicker	Kicker PS improvement、Septum 2 manufacture /test LF septum, PS for HF septa manufacture /test					

Bending Magnet Multipole Measurements

- Bending Magnet
- 96 Magnets
- Field Uniformity Target < 5e-4
- Flip coil Measurement
  - Radius 19.09 mm
  - Length 7 m
  - x: -30 mm, -15 mm, 0 mm, +15 mm, + 30 mm
- Parameters included in the tracking simulation SAD and SCTR
  - Variation of dipole component
  - Quadrupole component
  - Sextupole component
- Installation positions were decided to minimize COD.



12 magnets 1600 A 30 GeV



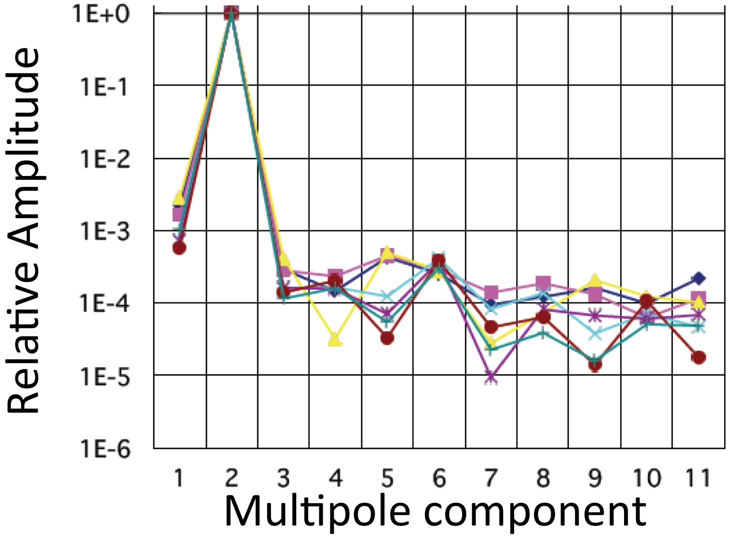
12 magnets 3015 A 50 GeV

BM 96 magnets K0=(1/Bρ)(ByL)	RMS of dipole component (30 GeV)	Average amplitude of quadrupole (30 GeV)	Average amplitude of sextupole (30 GeV)
0.0654 radian	1.2e-5 radian	-3.5e-4 m^{-1}	-7.5e-3 m^{-2}

QM SM Multipole Measurements

- QM: 11 families, 216 magnets
- SM: 3 families, 72 magnets
- Field Uniformity Target < 1e-3
- Harmonic Coil
  - Radial coil: Radius 59.5 mm, Length 2 m
  - Tangential coil: Opening angle 90°, Radius 59.8 mm, Length 3 m
- Parameters included in the tracking simulation SAD and SCTR
  - Variation of main component
  - The first allowed multipole component
- Installation positions were decided to minimize the related resonance amplitudes.

QM Reference mag. 7 time measurements

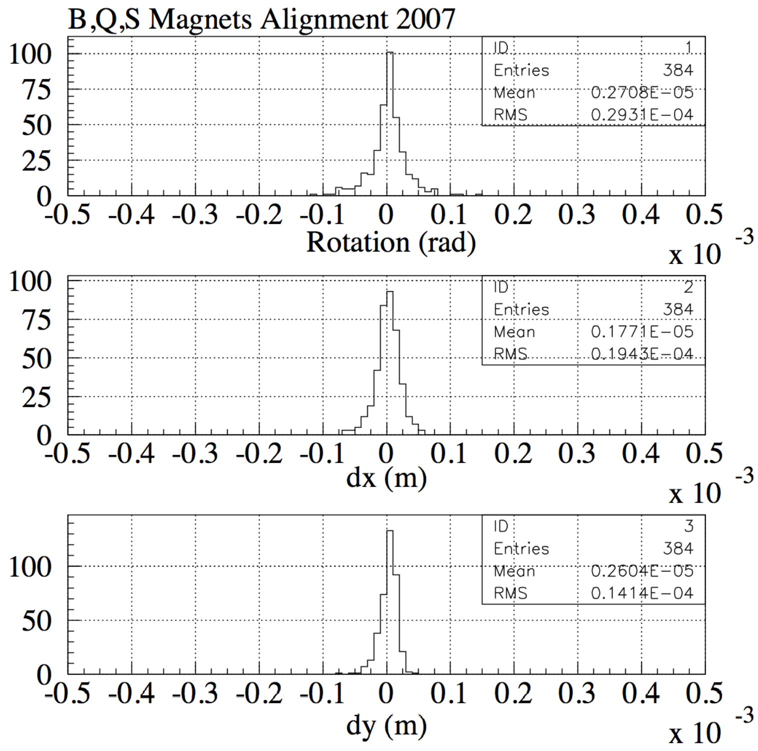


RMS of the K1 (K2) distribution

Q family	Number of magnets	σ30GeV
QFP	6	1.1E-4
QFS,QFX	6+48	3.8E-4
QFT	6	2.1E-4
QFN	48	2.2E-4
QDX	27	1.5E-4
QDS	6	1.1E-4
QFR	9	2.8E-4
QDN,QDR	48+6	2.8E-4
QDT	6	1.5E-4
Sextupole	72	8.9e-4

Magnet Alignment

- Magnet alignment has been done in
  - 2007
  - 2011 (realigned after the earthquake of March 11 2011)
  - 2012 (survey)
  - 2013 (survey)
- Alignment Target
  - Rotation < 0.1 mrad
  - Dx < 0.1 mm
  - Dy < 0.1 mm
- The target has mostly been achieved.
- Alignment data were compiled for the 2007 results for the tracking simulation SAD and SCTR.
- Data generated with random number of Gaussian distribution with certain deviations have also been tried for the tracking simulation.

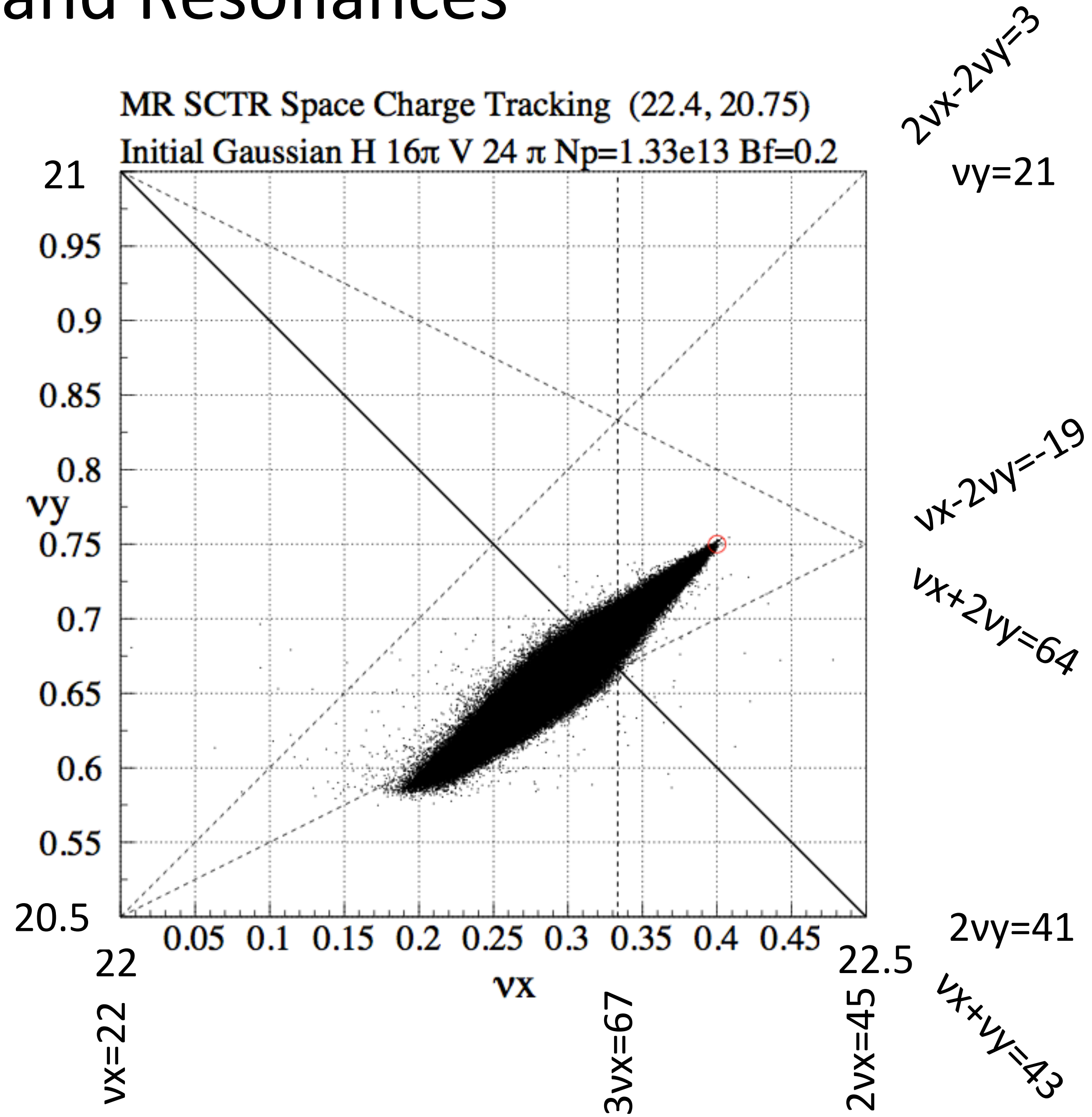


Incoherent Tune Shift for MR Power ~200 kW and Resonances

- 1.33e13 ppb
- Ex 16 πmmmrad (2σ) (from the profile measurement)
- Ey 24 πmmmrad (2σ) (from the measurement with the intensity of 1.18e13 ppb)
- Bunching Factor 0.2
- Tune Shift = 0.2

Resonances

- Linear Coupling
  - νx+νy=43
  - Rotation of Q magnets and Vertical orbit at sextupole magnets
- 3rd order
  - 3νx=67
  - νx+2νy=64
  - νx-2νy=-19
  - Variation of sextupole magnets
- 4th order
  - 2νx-2νy=3
  - Octupole magnets



Sum Resonance Correction with Skew Q's

MR tune: (νx, νy) = (22.275, 20.685)

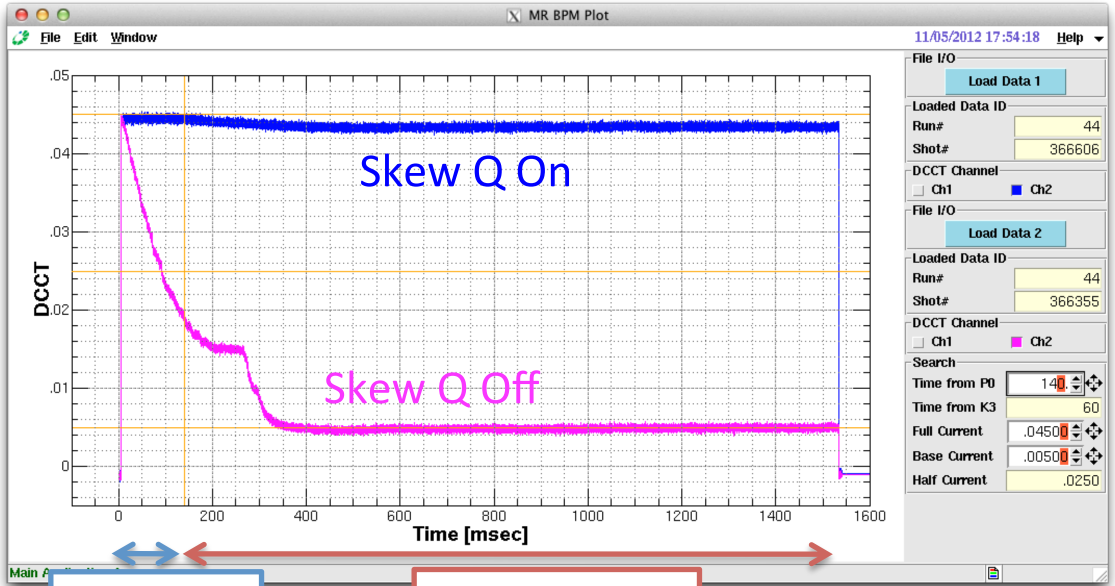
νx + νy ≅ 43

Beam Intensity 4e11 ppb

Chromaticity: ξx = ξy = -6

MR mode: Accl (Abort)

Beam Intensity



11/05/2012 17:54:18

File I/O

Loaded Data ID
Run# 44
Shot# 366606

DCCT Channel
☐ Ch1 ■ Ch2

File I/O

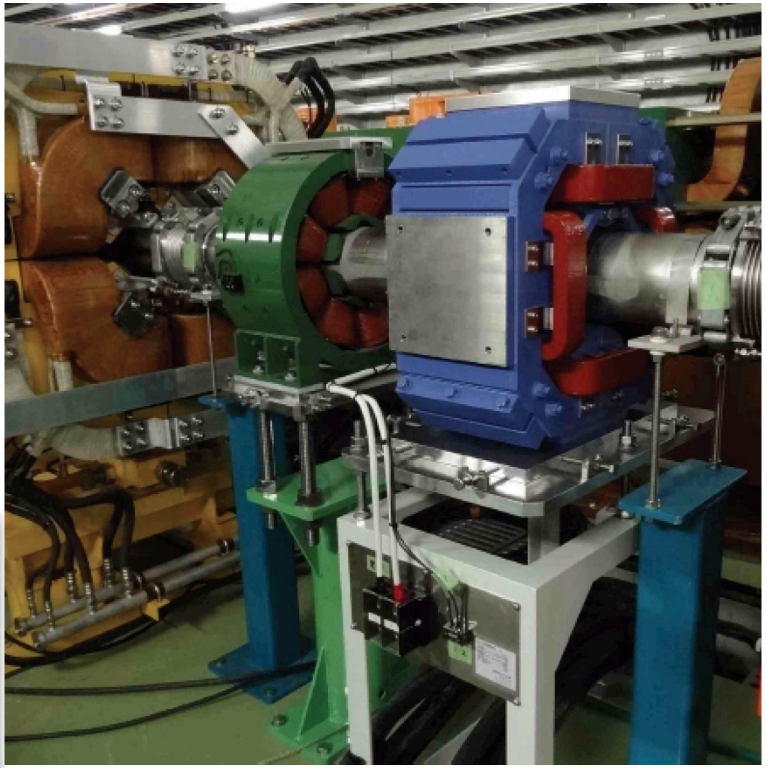
Loaded Data ID
Run# 44
Shot# 366355

DCCT Channel
☐ Ch1 ■ Ch2

Search
Time from P0 140.
Time from K3 60
Full Current .04500
Base Current .00500
Half Current .0250

Injection

Acceleration



SQ address	Injection	Flat Top
001, 016	+1.25A	+6.79A
145, 160	+0.20A	+4.70A

Sum Resonance νx+νy=43

Beam Measurement

- The following skew Q settings improve the beam survival.
  - SQ001, 016: sk1 = 7.11e-4 m-1
  - SQ145, 160: sk1 = 1.14e-4 m-1
- The sum resonance amplitude is then
  - G1,+1,43=1.6e-3

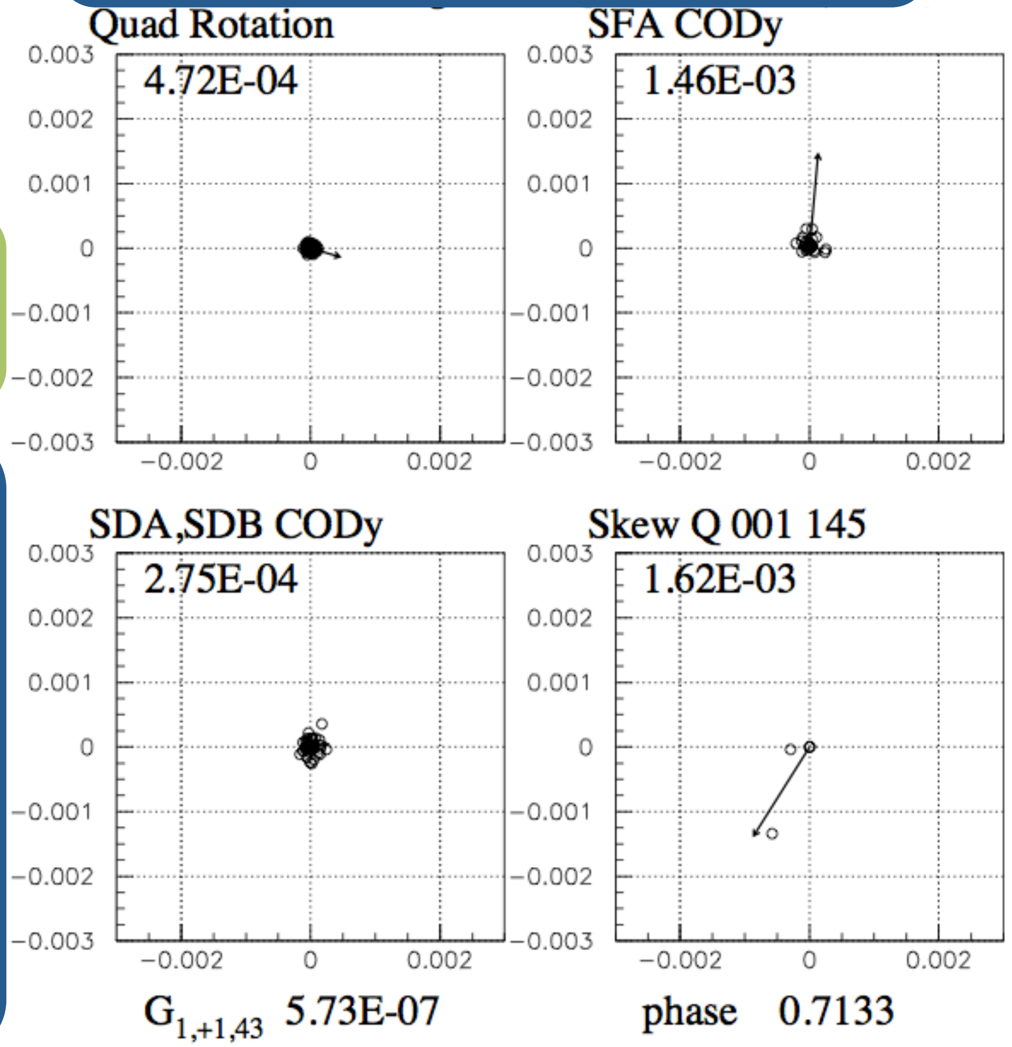
Calculation with Survey and Field Measurements

- The resonance amplitude is estimated to be smaller with the alignment results.
  - G1,+1,43=3.6e-4

Calculation to reproduce the Beam Measurement

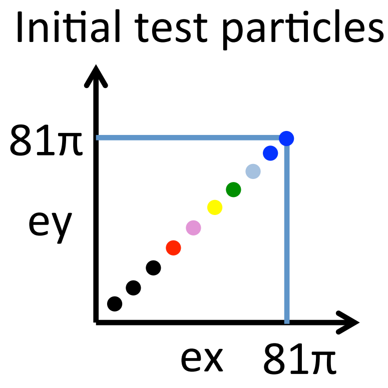
- The resonance amplitude was reproduced with SAD simulation,
  - Magnet position offsets : random Gaussian of σ = 0.14 mm
  - Magnet rotation errors : random Gaussian of σ = 0.14 mmmrad.
- The following skew Q settings cancels the resonance in SAD simulation,
  - SQ001: sk1 = -1.08e-4 m-1
  - SQ145: sk1 = 5.4e-4 m-1
- The resonance amplitude is less than 1e-6 after the correction.

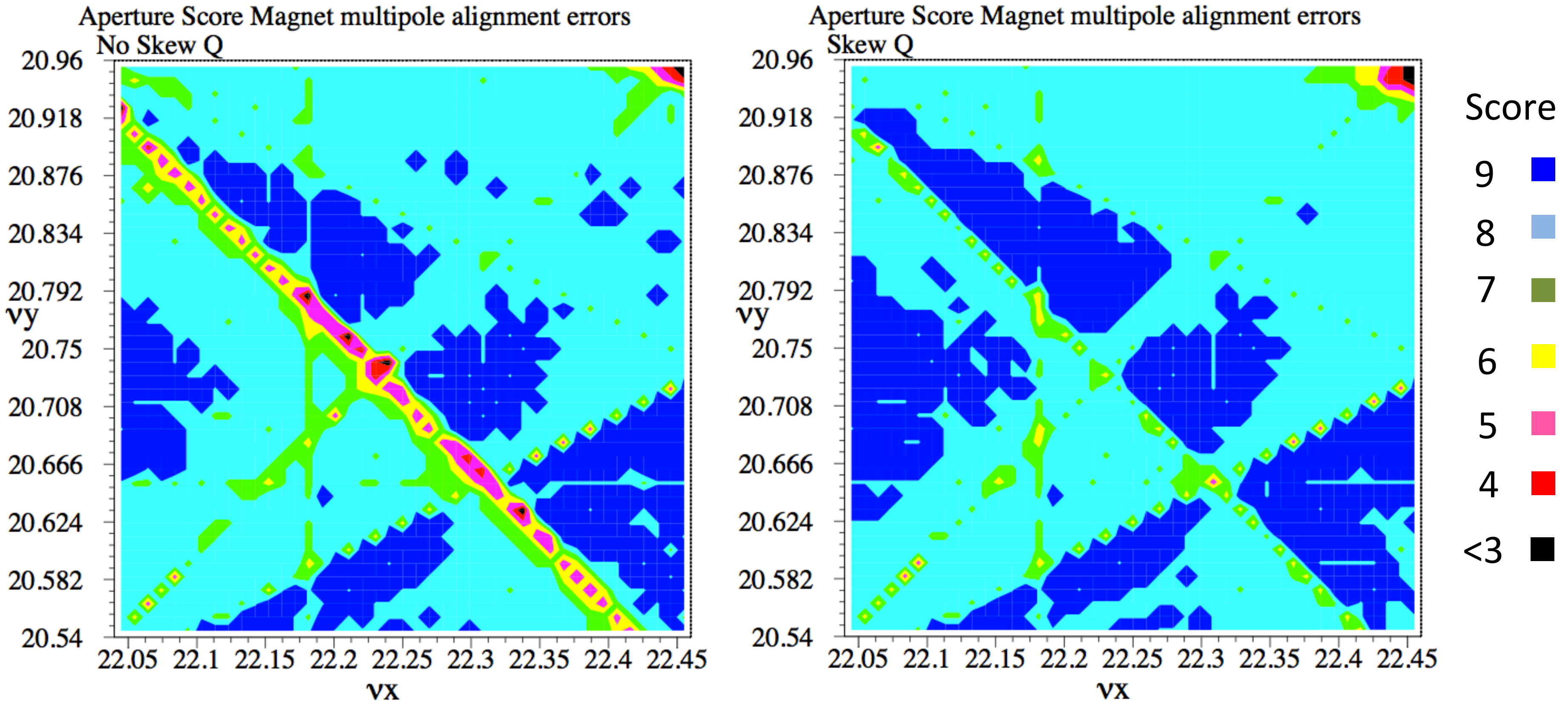
Sum Resonance Amplitude to reproduce the Beam Meausrement at (22.31, 20.69)



Aperture Survey in Tune Space

- Aperture was studied using SAD simulation with errors.
- 10 particles with ex = ey = 8.1π, 16.2π, … , 81π mmmrad
- After 1000 turns the number of survived particles with 81π cut was calculated as the score.
- The score was plotted In the horizontal tune range of 22.04 ~ 22.46 and vertical tune range of 20.54 ~ 20.96.





Space Charge Tracking Simulation SCTR

- Program with the Particle in Cell method developed by Ohmi-san
- The potential solver is based on FACR (Fourier Analysis and Cyclic Reduction) algorithm.
- Typically ~200,000 macro particles and 128 × 128 of 1 mm grid.
- The boundary is square perfect conducting wall.
- Potential is assumed to be proportional to the line density of the beam.
- Transverse potential is given by solving two-dimensional Poisson equation.

$$\Phi = \frac{N_p r_p}{\beta^2 \gamma^3} \lambda(z) \phi(x, y : s) \qquad \Delta_\perp \phi = \rho$$

- Space charge is grad of the potential.

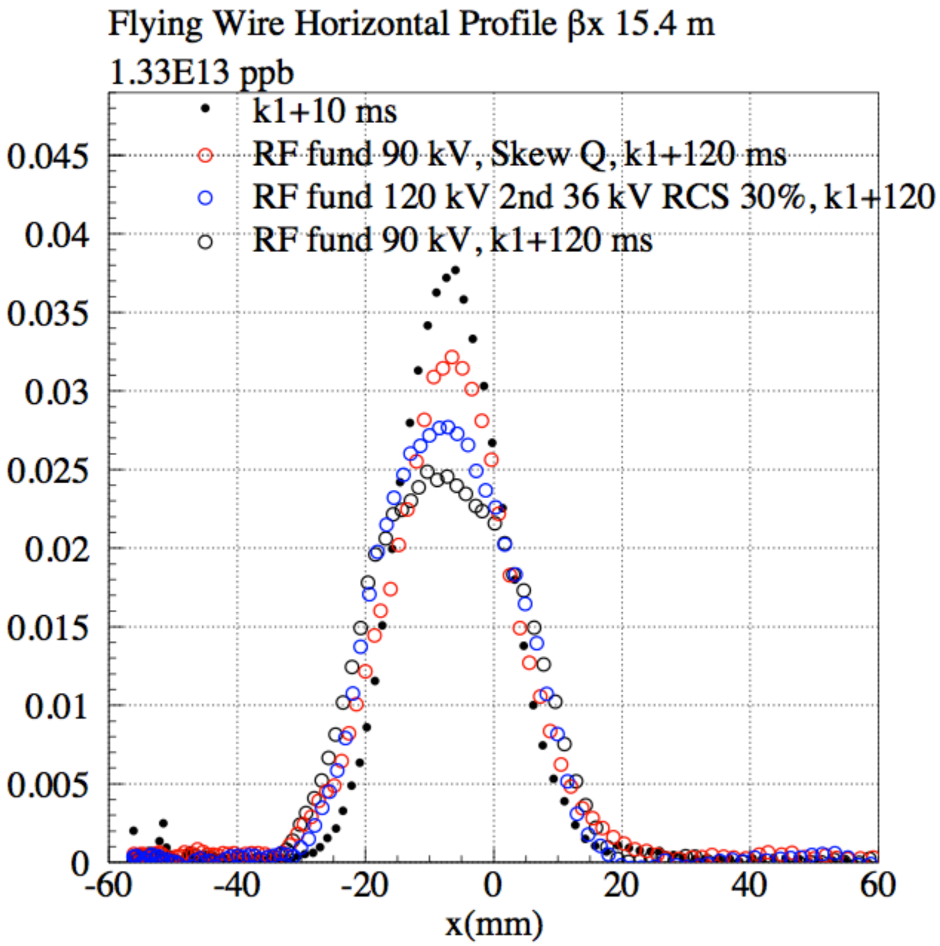
$$\frac{\Delta p_x}{\Delta s} = -\frac{\partial \Phi}{\partial x}, \quad \frac{\Delta p_y}{\Delta s} = -\frac{\partial \Phi}{\partial y}, \quad \frac{\Delta p_z}{\Delta s} = -\frac{\partial \Phi}{\partial z}$$

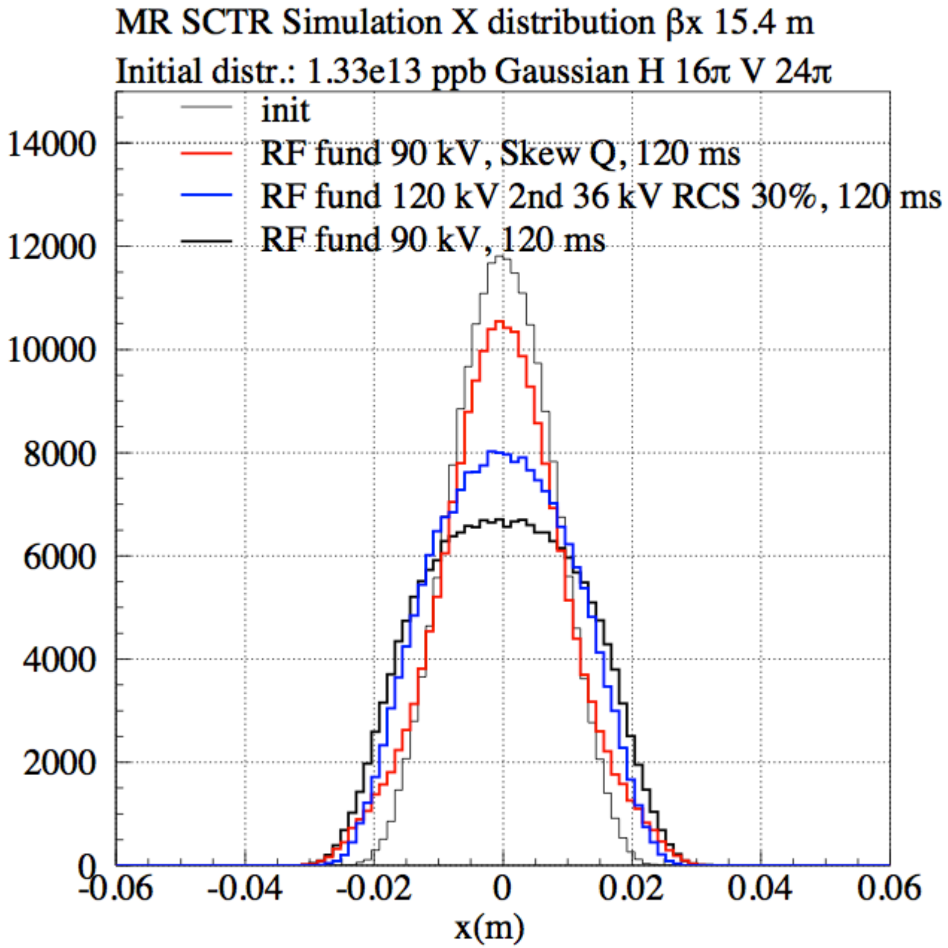
- Δs < β(s) =4~30 m for J-PARC MR → Δs ~ 1.5 m.
- Ring Lattice and optics come from SAD.

REF: K. Ohmi et al., proceedings of PAC07, 3318 (2007).
K. Ohmi et. al., Proceedings HB2010, 425.

Horizontal Beam Profiles (Measurement and Simulation)

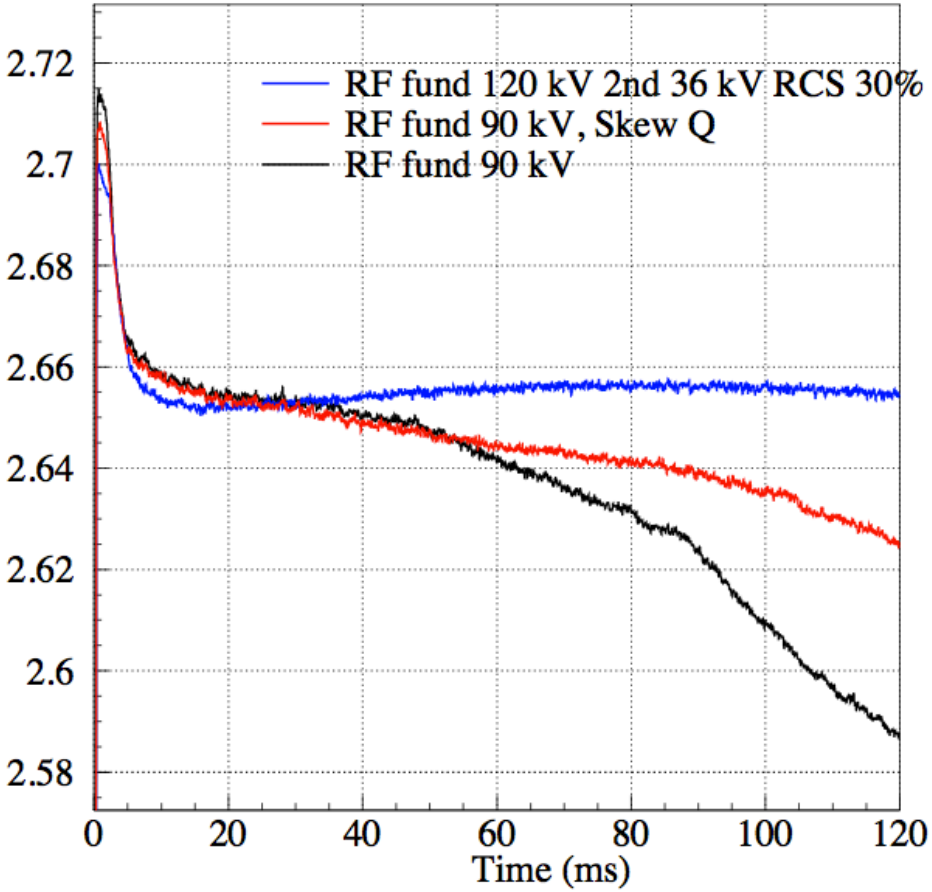
- 2.7e13 ppp (2 bunch injection)
- Flying Wire measurements at K1+10 ms and K1+120 ms.
- SCTR simulation with initial distribution of 16π mmmrad of Horizontal 2σ emittance and 24π for Vertical 2σ emittance.



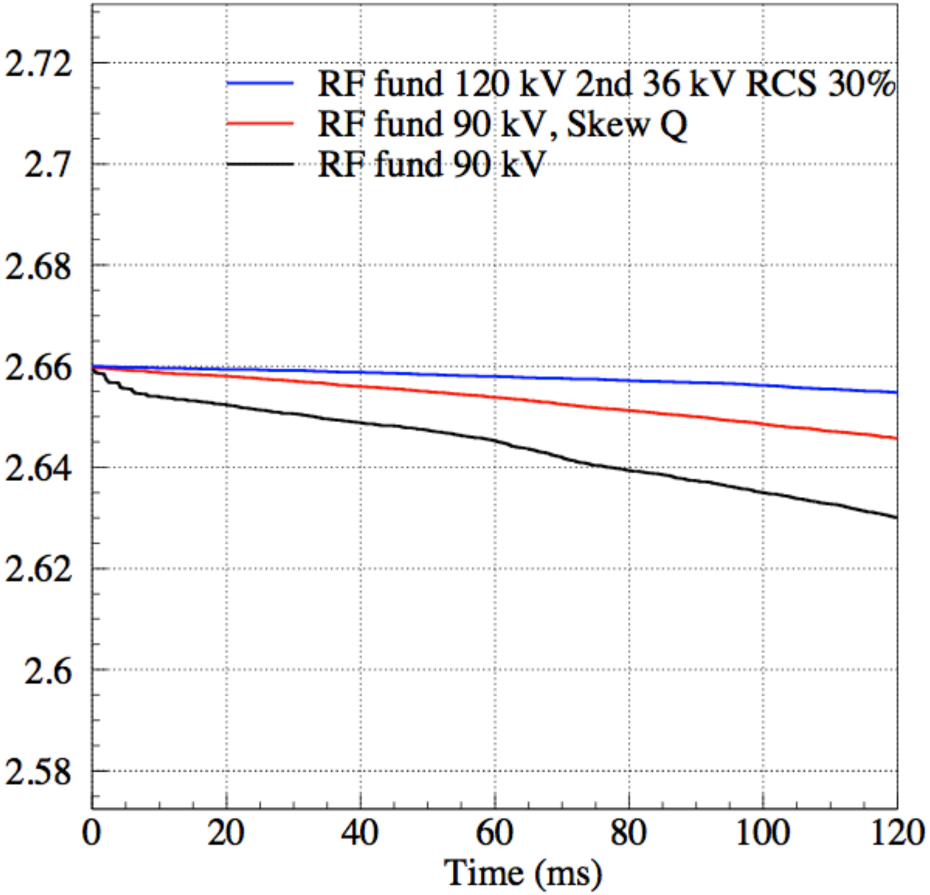


Beam Intensity (Measurement and Simulation)

- DCCT measurement during the injection period of 130 ms
- 2 bunch injection
- SCTR simulation with initial distribution of 16π mmmrad of Horizontal 2σ emittance and 24π for Vertical 2σ emittance.



Beam Intensity during Injection
$*10^{13}$ ppp (2 bunches)

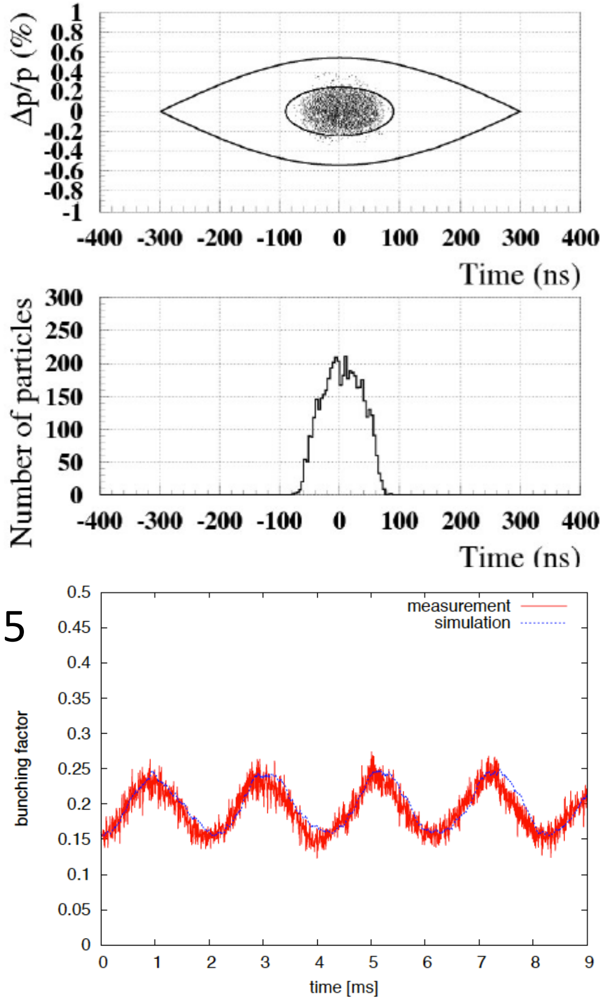


SCTR MR, Gaussian H 16π V 24π Np=1.33e13 ppb
($*10^{13}$ ppp) Survived particles with 70 π MR collimator

Longitudinal Distribution Measurement

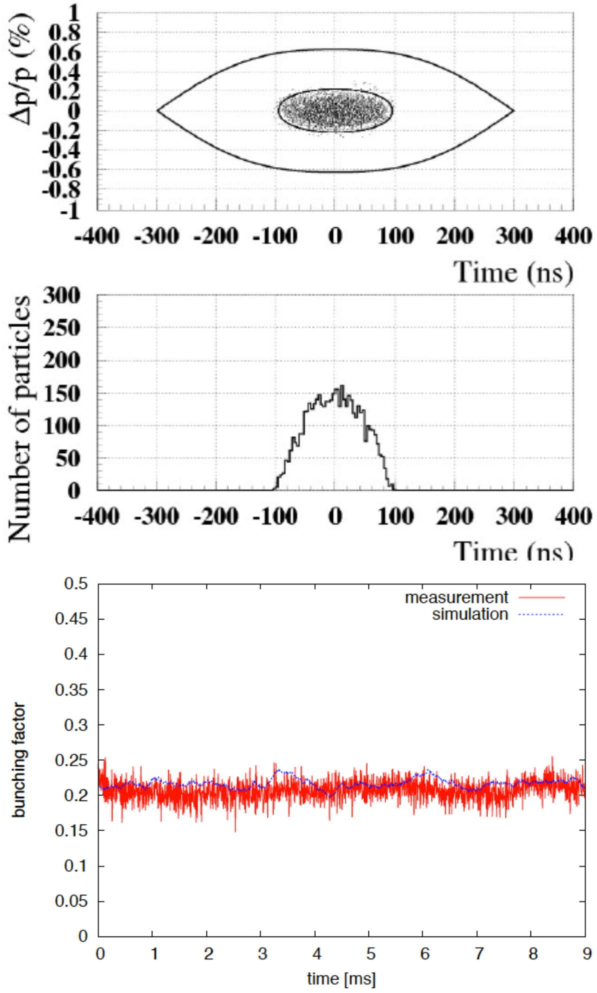
- Bunching Factor have been improved with the 2nd harmonic RF.
  - MR fundamental 90 kV; RCS fund. only
  - MR fund. 120 kV, 2nd 36 kV; RCS fund. & 2nd (30 %)

RF fund. 90 kV



BF = 0.15 ~ 0.25

RF fund. 120 kV, 2nd 36 kV



BF ~ 0.2

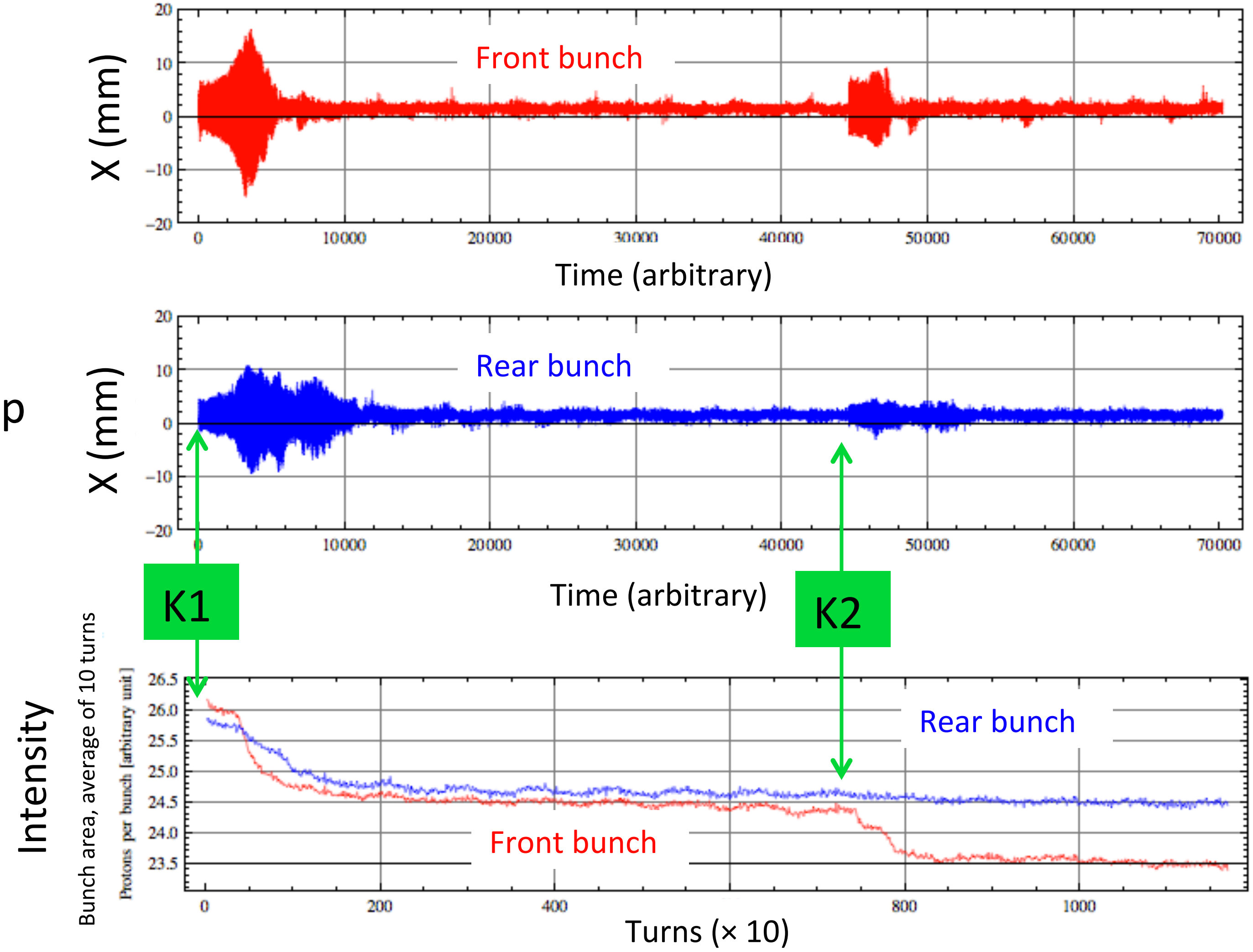
Beam Loss right after the Injection

- Coherent Oscillation was observed right after the injection.
- It is initiated by the injection error.
- The impedance source may be resistive wall.

X
by Position
Monitor

N_B~ $1.67\text{x}10^{13}$ ppp
2 bunches
ξ_x~-7.5
ξ_y~-7.0 (-25%)

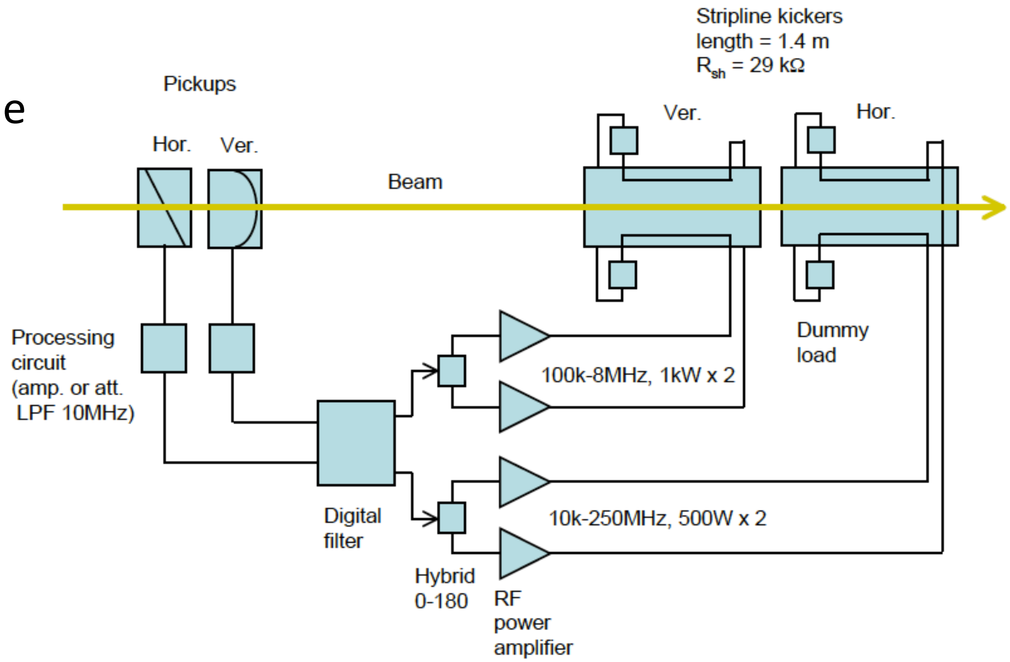
Beam Intensity
by Fast Current
Transformer

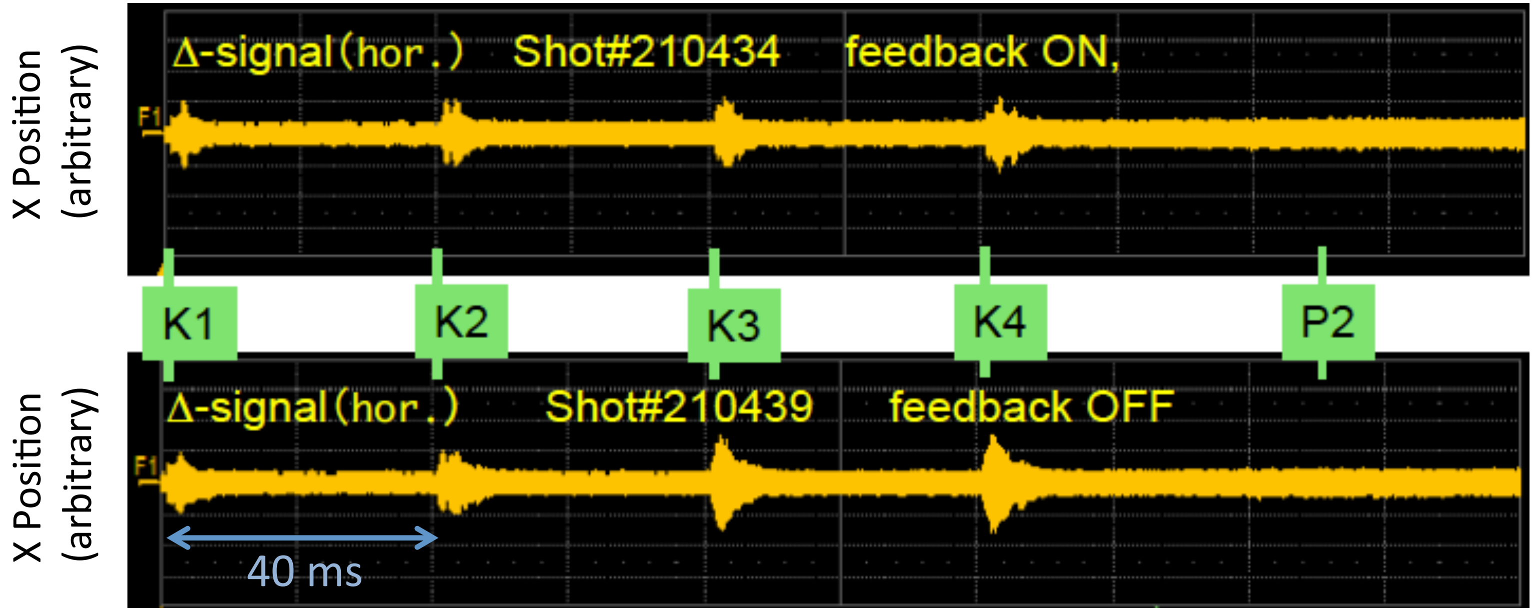


Bunch by Bunch Feedback

- Coherent Oscillation is damped with the bunch by bunch feedback system.
- Beam loss is reduced to be half.
- NB ~ 7.3e13 ppb
- 8 bunches
- Power ~ 115 kW

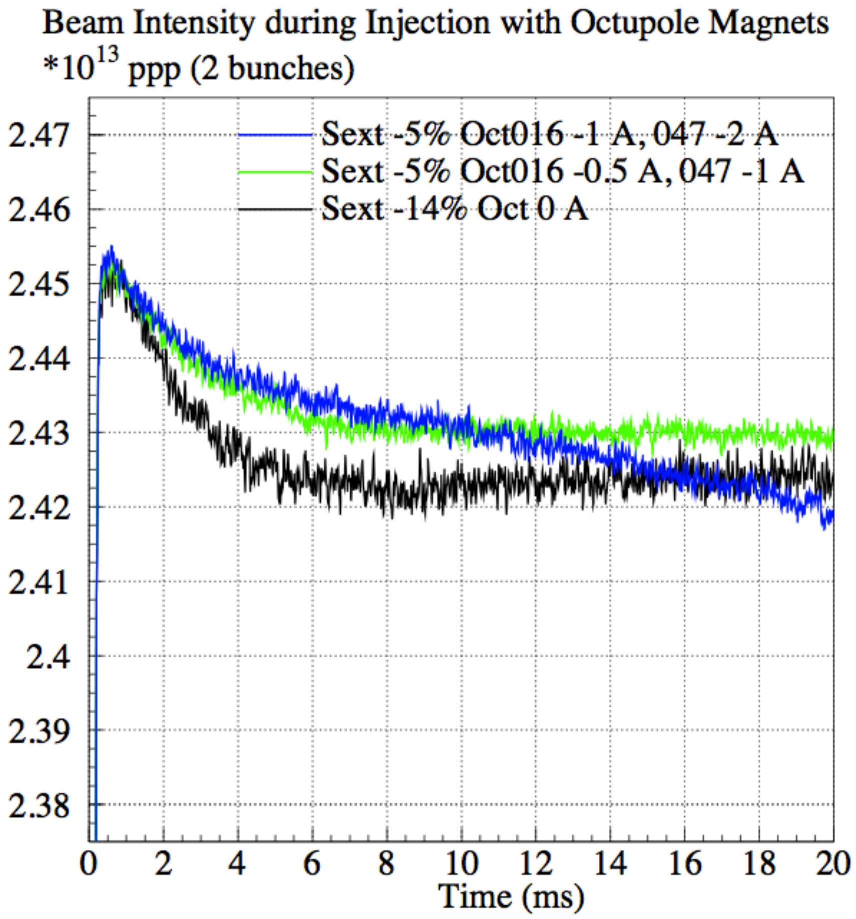
- Intra bunch feedback will be implemented.

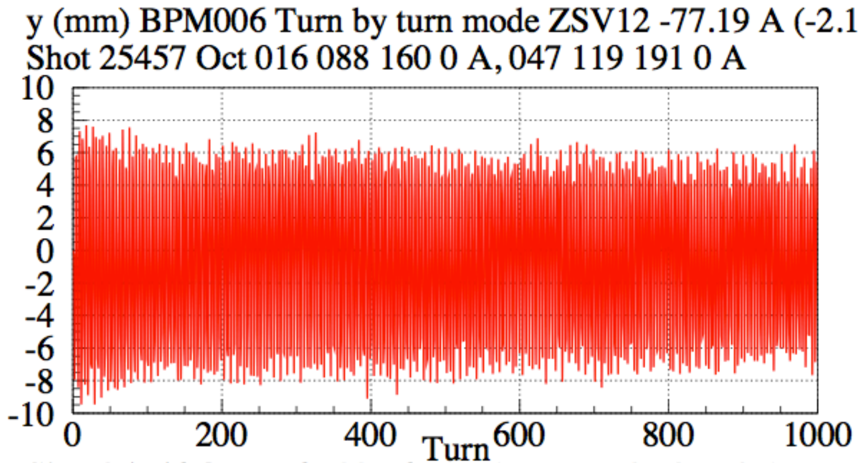




Octupole Mangets for Coherent Oscillation Damping

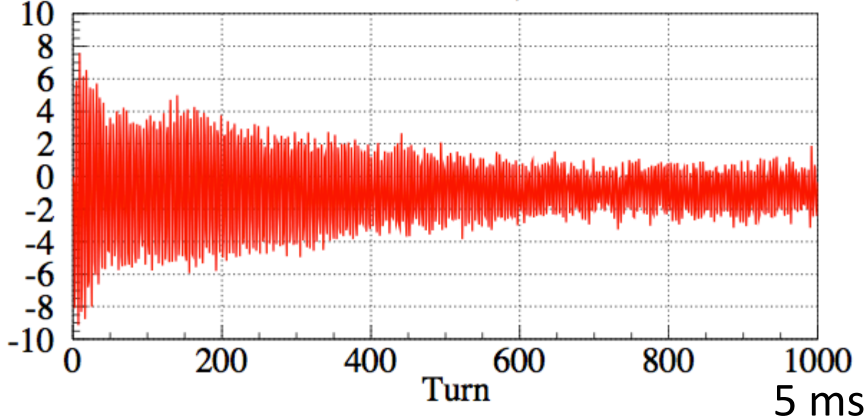
- Coherent oscillation damping was observed with octupole magnets.
- Beam loss right after the beam injection (~ 5 ms) was improved.
- Dynamic aperture was reduced and beam loss during the injection period was increased.
- Careful current adjustment may recover the dynamic aperture.


Beam Intensity during Injection with Octupole Magnets


y (mm) BPM006 Turn by turn mode ZSV12 -77.19 A (-2.1

Shot 25457 Oct 016 088 160 0 A, 047 119 191 0 A

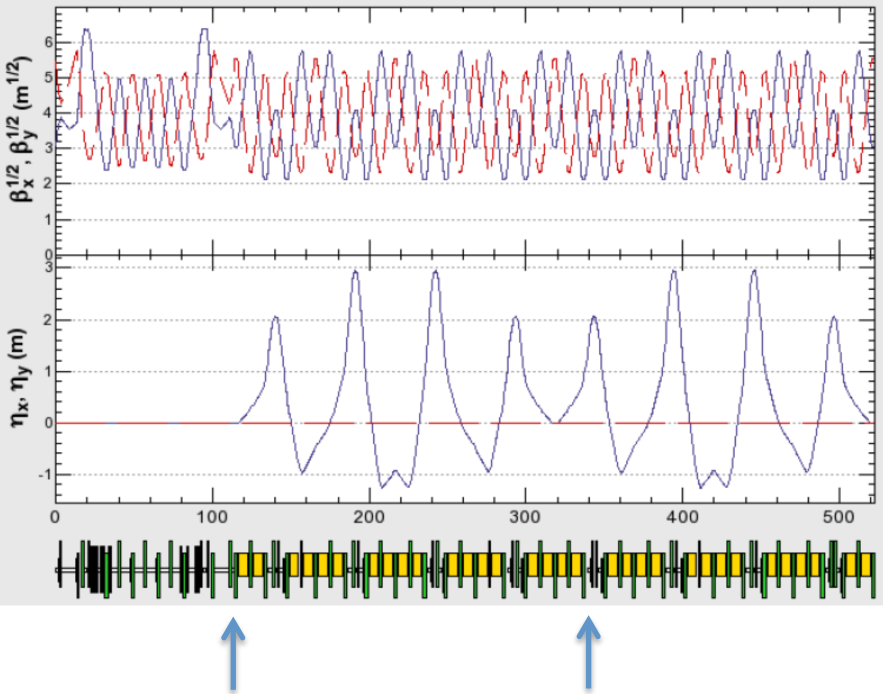
Shot 25456 Oct 016 088 160 +1 A, 047 119 191 +2 A



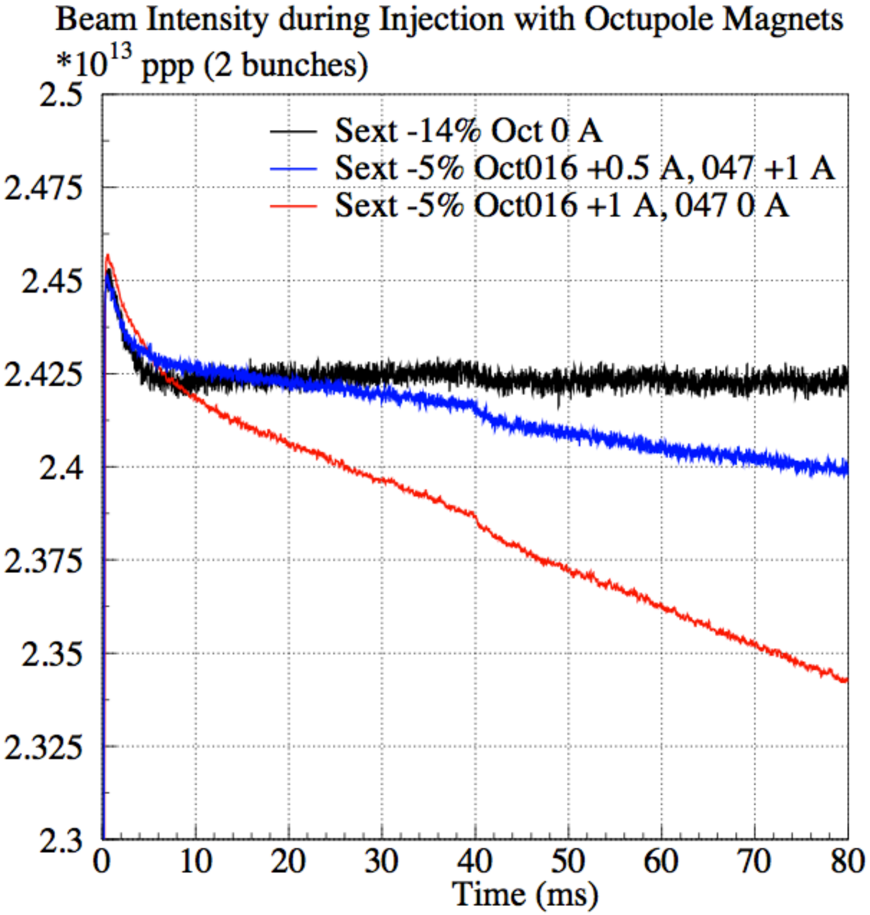
5 ms

Octupole Magnets for Coherent Oscillation Damping (Side Effect)

- Three octupole magnets were installed in 2011.
- Three other magnets have been installed in 2012 to cancel the structure resonance of 2vx-2vy=3, 4vx=90.
- Improvement of beam loss was observed with 6 magnets.
- We have a plan to make octupole magnets for pulse excitation (~ 5 ms) to minimize the aperture reduction effect.



016, 088, 160 (2011) 047, 119, 191 (2012)



Summary

- The beam power of 240 kW has been achieved in J-PARC MR with the scheme of
  - large aperture,
  - beam collimator and
  - imaginary transition γ lattice.
- The beam profile and beam loss measurement during the injection period (after 5 ms from the injection) are reproduced with the space charge tracking program SCTR.
- The Beam loss right after the injection (~ 5 ms) is caused by the horizontal coherent oscillation triggered by the injection error.
  - Suppression with the bunch by bunch feedback
  - Octupole magnets
- The target beam power of 750 kW is to be achieved with the high repetition rate scenario.