Recent Commissioning of High-Intensity Proton Beams in J-PARC Main Ring

Yoichi Sato

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J-PARC KEK/JAEA

HB2012 THO1C06 2012/09/20

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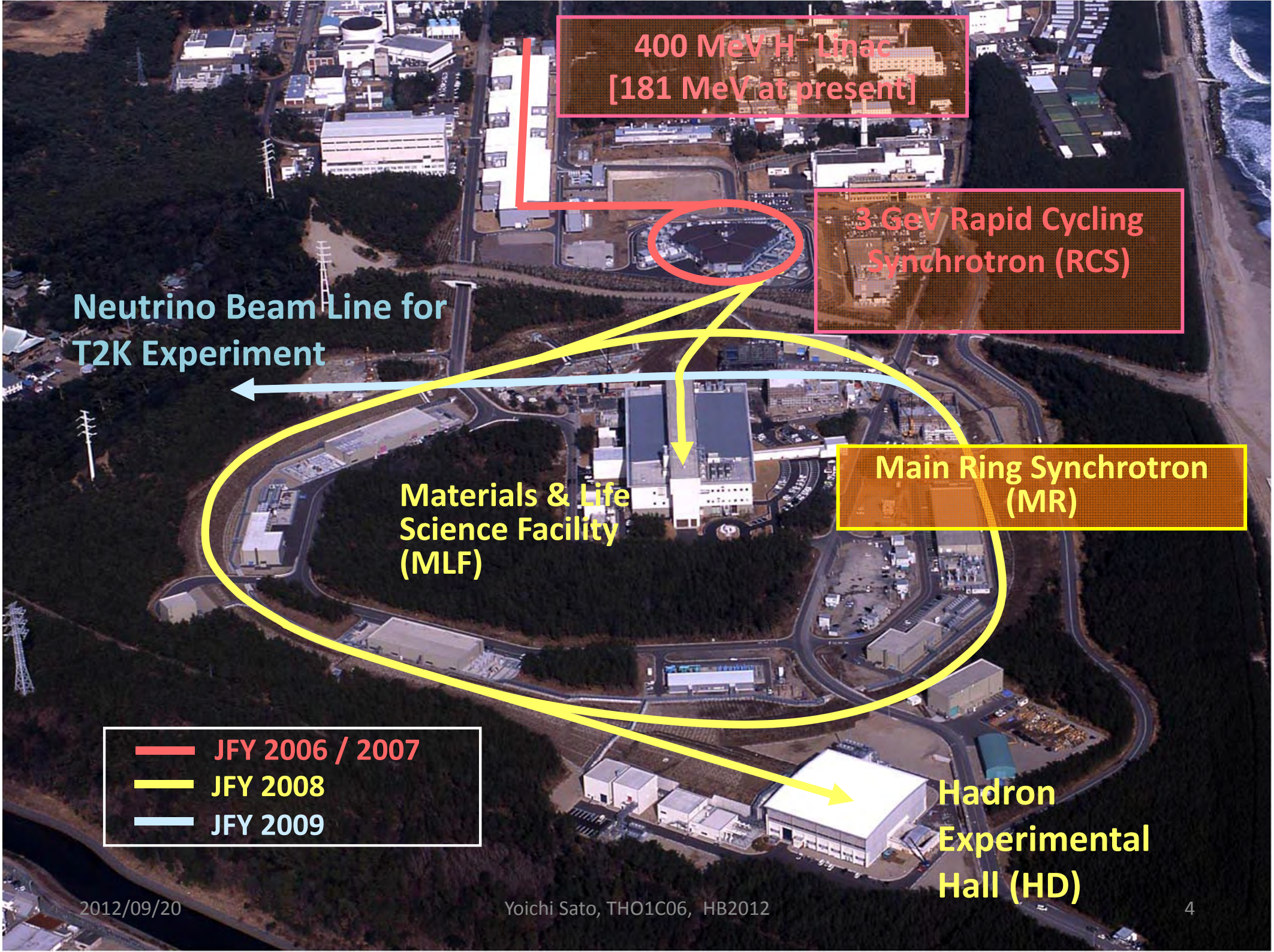
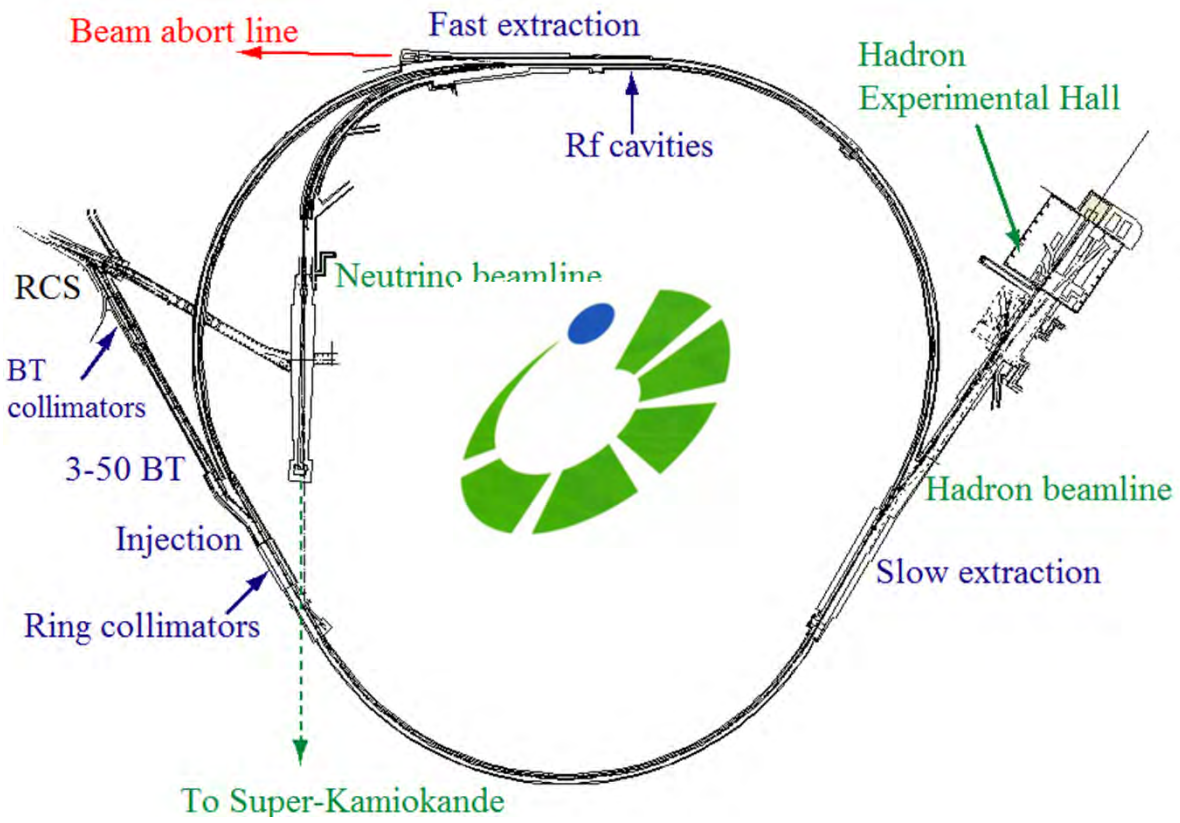
Introduction and achievement of the MR fast extraction operation from December 2011 to June 2012


400 MeV H⁻ Linac
[181 MeV at present]
3 GeV Rapid Cycling Synchrotron (RCS)
Neutrino Beam Line for T2K Experiment
Materials & Life Science Facility (MLF)
Main Ring Synchrotron (MR)
JFY 2006 / 2007
JFY 2008
JFY 2009
Hadron Experimental Hall (HD)

J-PARC MR Parameters

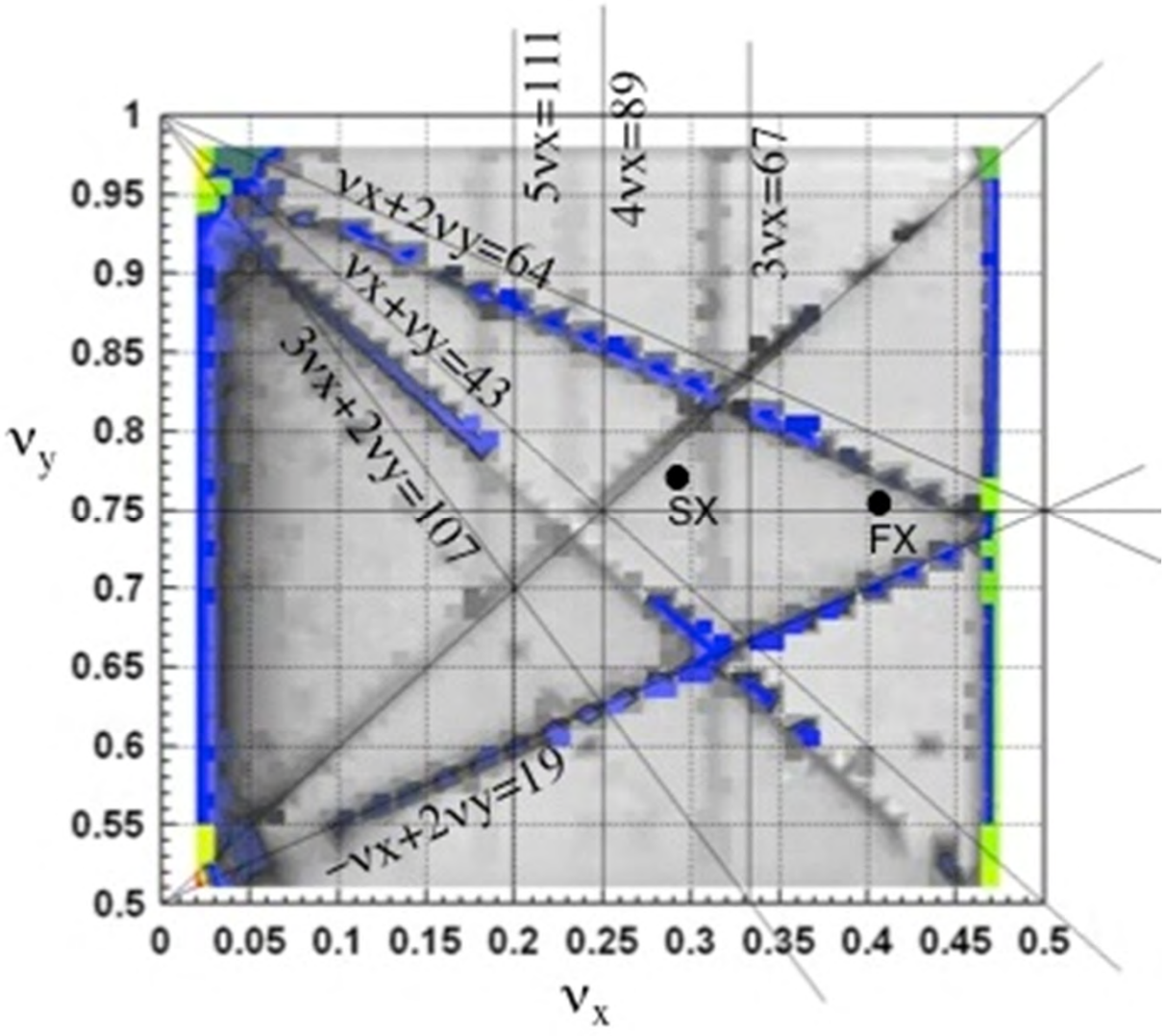
Circumference	**1567.5 m**
Superperiodicity	**3**
Injection energy	**3 GeV**
Extraction energy	**30 GeV (1st phase)**
Harmonic number	**9**
Number of bunches	**8**
Transition γ	**j 31.7**
Typical tune	**22.40, 20.76 (FX)**
	22.30, 20.78 (SX)
Repetition rate	**~0.3 Hz**
Physical aperture	**81π mm-mrad**
Transverse emittance	
At injection	**54π mm-mrad**
At extraction	**10π mm-mrad (30 GeV)**
Collimator capacity	**450 W → 2 kW**
Beam power	**0.75 MW**



3 dispersion free straight sections (116 m)
- Ins A: Injection, Collimator
- Ins B: **Slow Extraction** to Hadron Exp Hall
- Ins C: **Fast Extraction** to Neutrino Beamline

<u>Fast extraction mode:</u>
Whole bunches are extracted in a single turn (~5 us), and are guided to the neutrino beam line.

Operating point



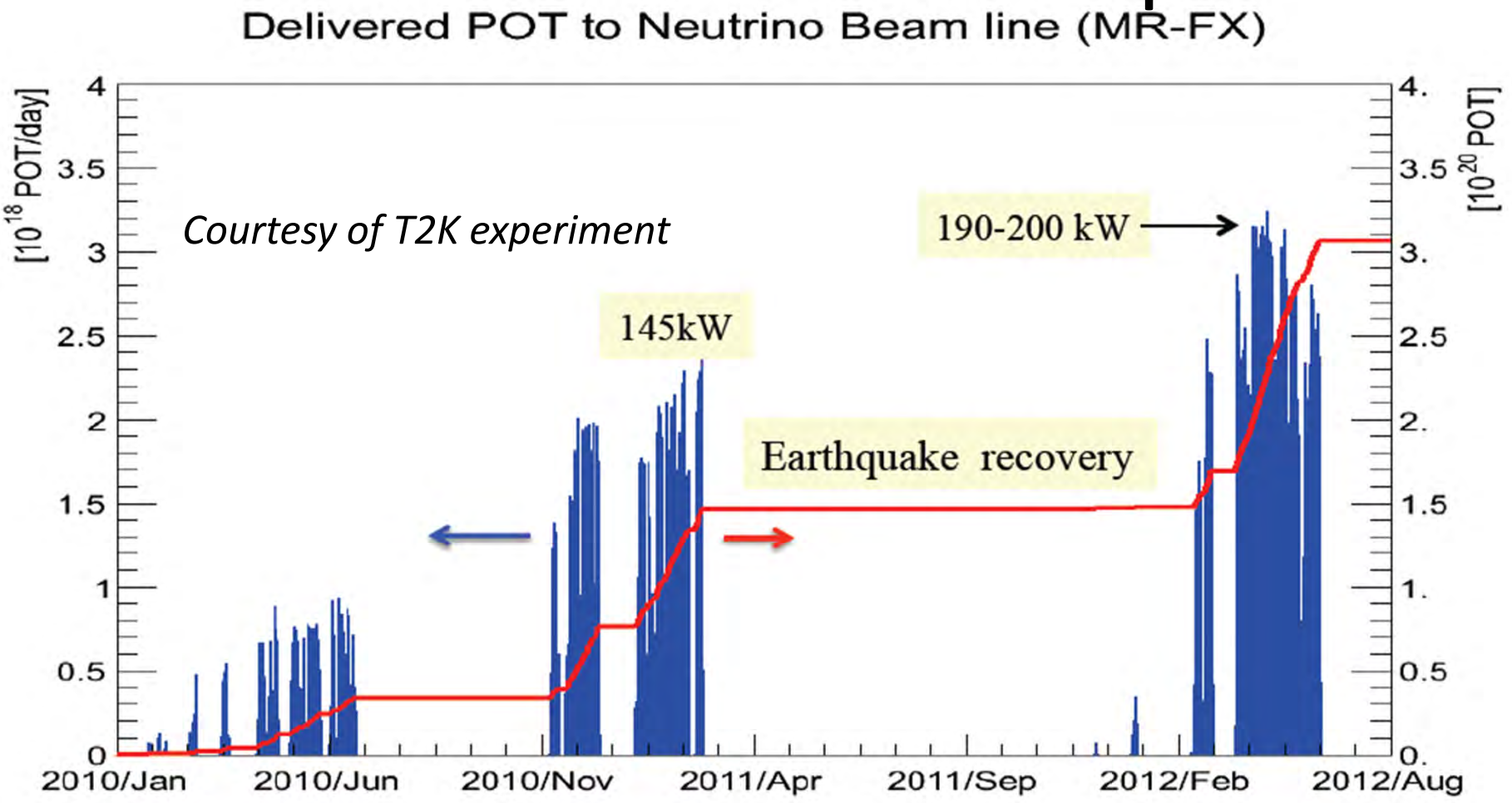
MR aperture survey w
dp/p=0 single particle tracking
including

- Magnetic field error
- Multi-harmonics
- Alignment errors
- Fringing field of Quadrupoles

Operating point (present)
FX 22.40, 20.76
SX 22.30, 20.78

Δνx ~ 0.13, Δνx ~ 0.11 (SC=0.76E13ppb)

Delivered Protons to T2K experiment



MR Fast Extraction Operation (2010/01 – 2012/06/09) ~3E20 POT to T2K experiment
The T2K experiment has observed 11 candidate events,
where muon neutrino appeared to be transformed into electron neutrino.

Beam Commissioning in fast extraction operation of the MR

- Improvements during the shutdown in 2011 and the corresponding beam commissioning

- Operation and troubles

- Beam loss control --- tools to reduce beam losses

Improvements during the shutdown in 2011 and the corresponding beam commissioning

- Re-alignment of main magnets

  - Optics parameters were re-measured

- Replacement of the injection kicker system from transmission-line type to lumped inductance type

  - Injection timing was tuned with observing injection errors and prompt beam losses.

- Two additional RF cavities

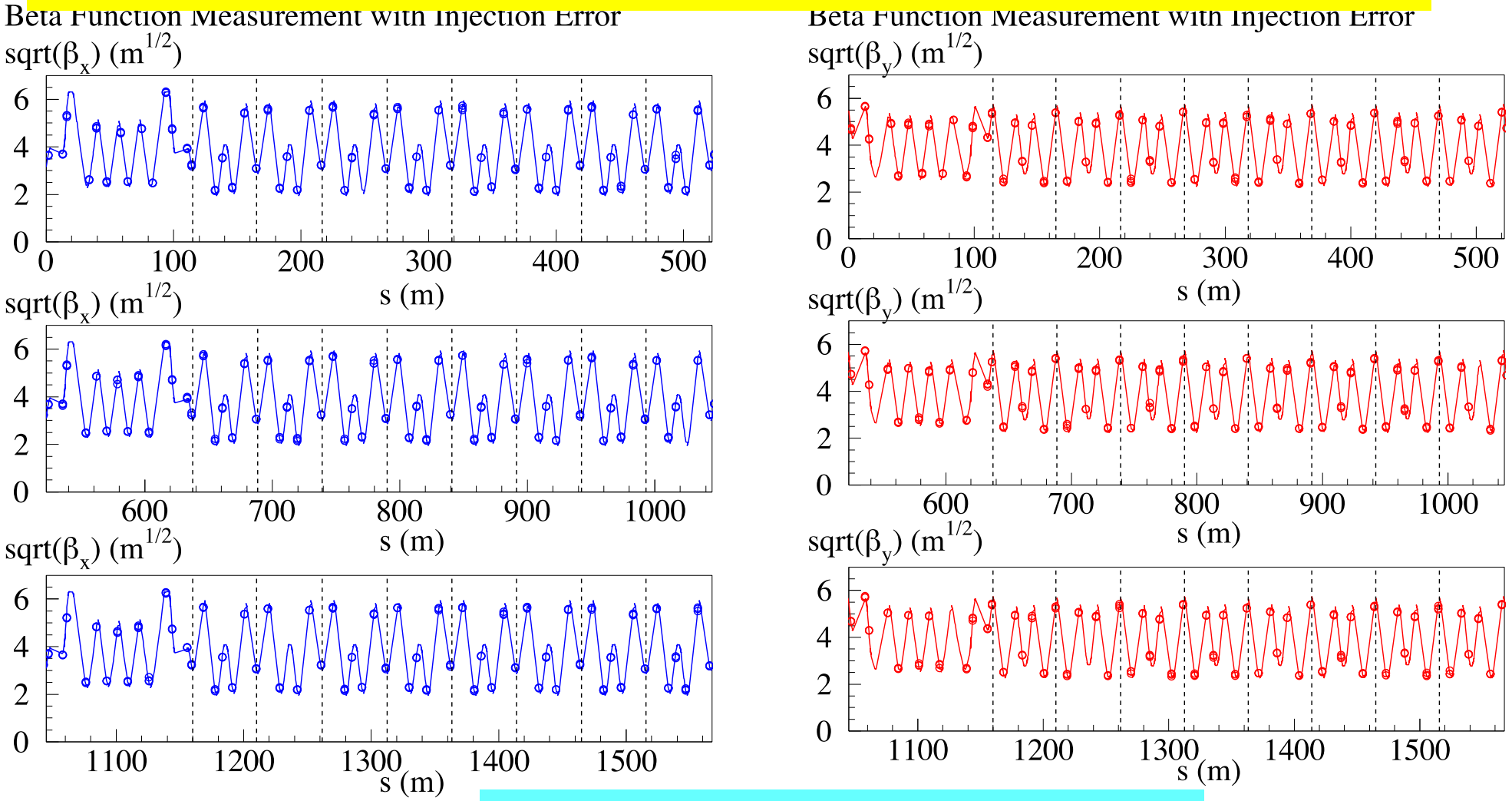
  - Acceleration time 1.9 s → 1.4 s.

- Four skew quadrupoles: *effects to correct the sum resonance*
- Three octupoles: *effects to suppress beam instabilities*

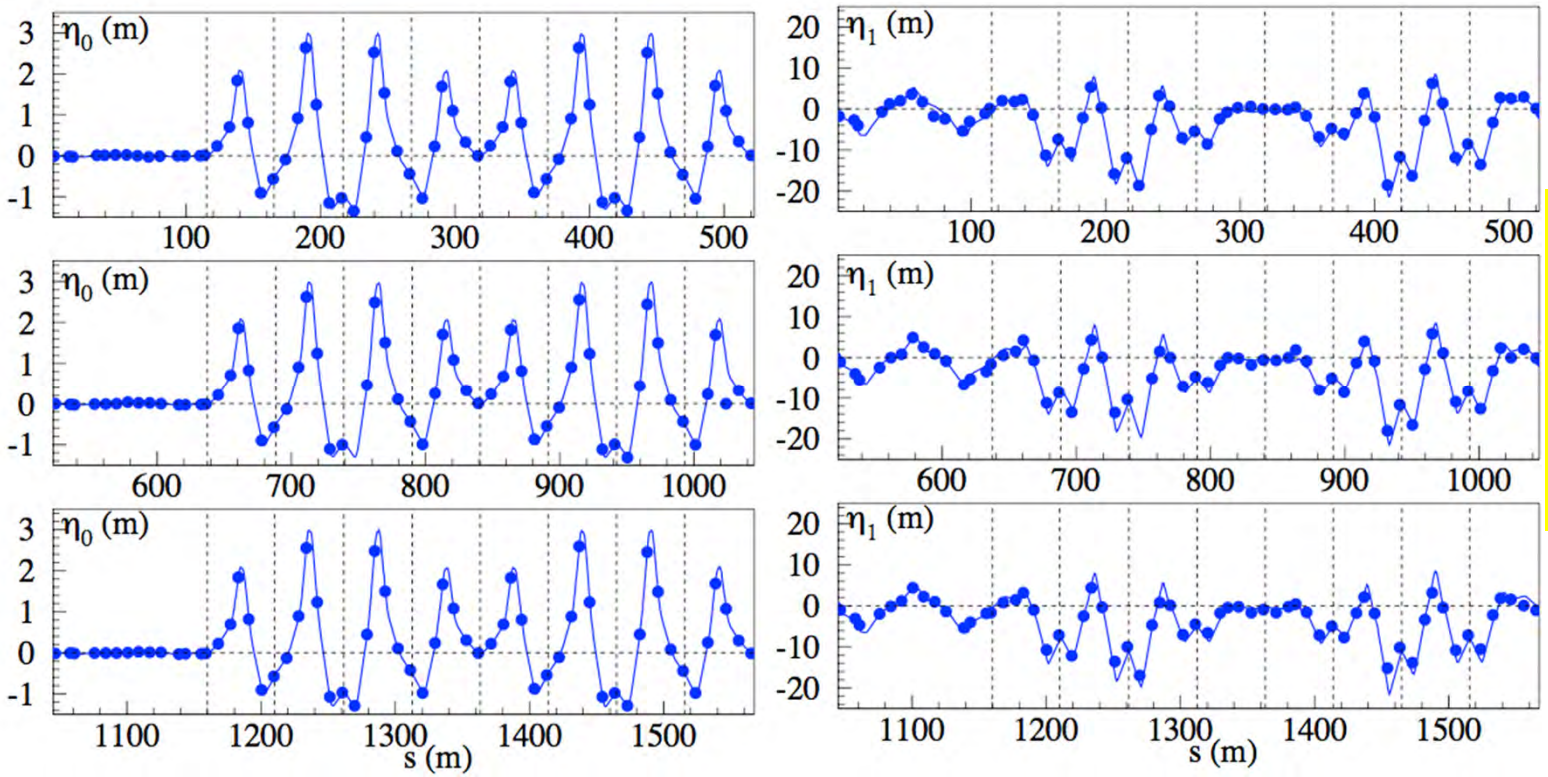
These effects were successfully observed.
They will be used in the beam commissioning this fall

Re-measured optics parameters

After the realignment in the last summer、beta, dispersion, corrected chromaticity were re-measured with low intensity beam (4E11 ppb) to dump collective effect
Operating point was for the FX mode.



Design (solid line) and measurement（〇）

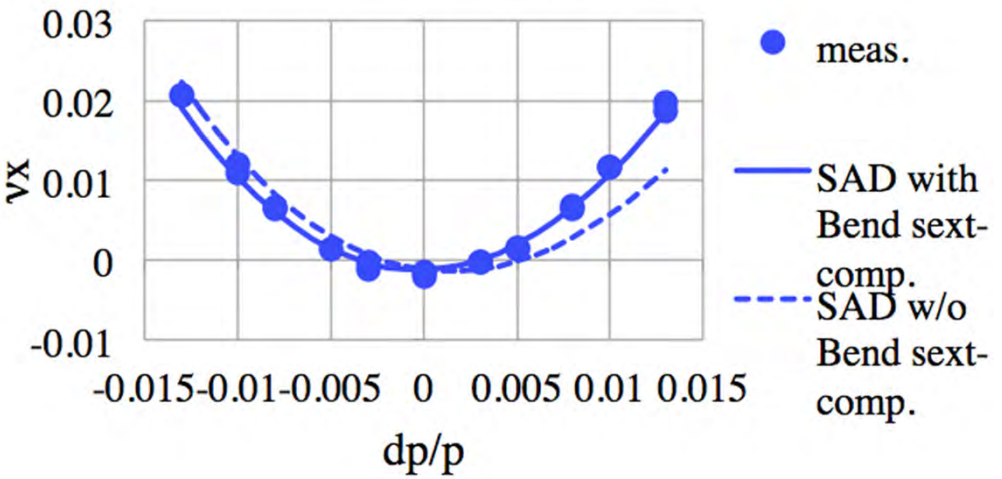


- H- V- beta
- Linear dispersion
- Non-linear dispersion (1st order)

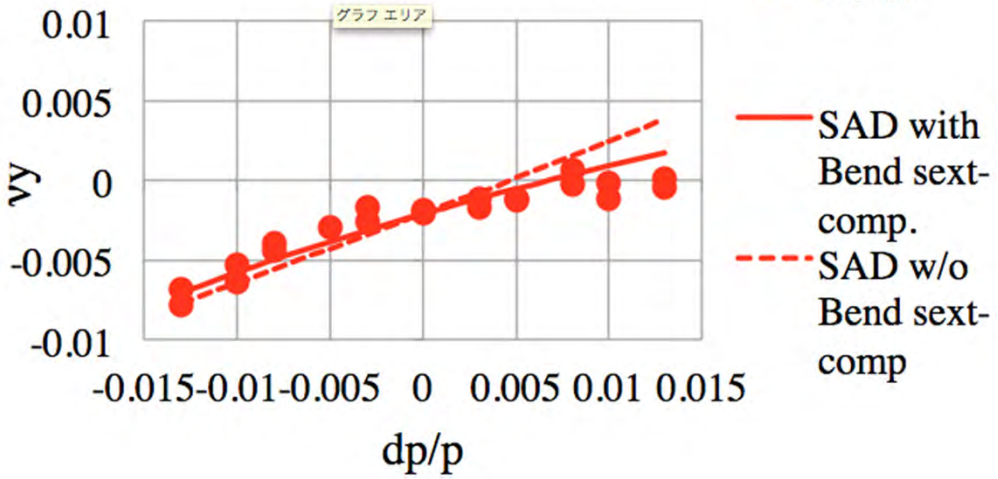
were well matched

Design (solid line)
measurement（〇）

Corrected chromaticity X



Corrected chromaticity Y



Chromaticity was corrected well w the sextupoles

Igarashi, et. al.

Beam Commissioning in fast extraction operation of the MR

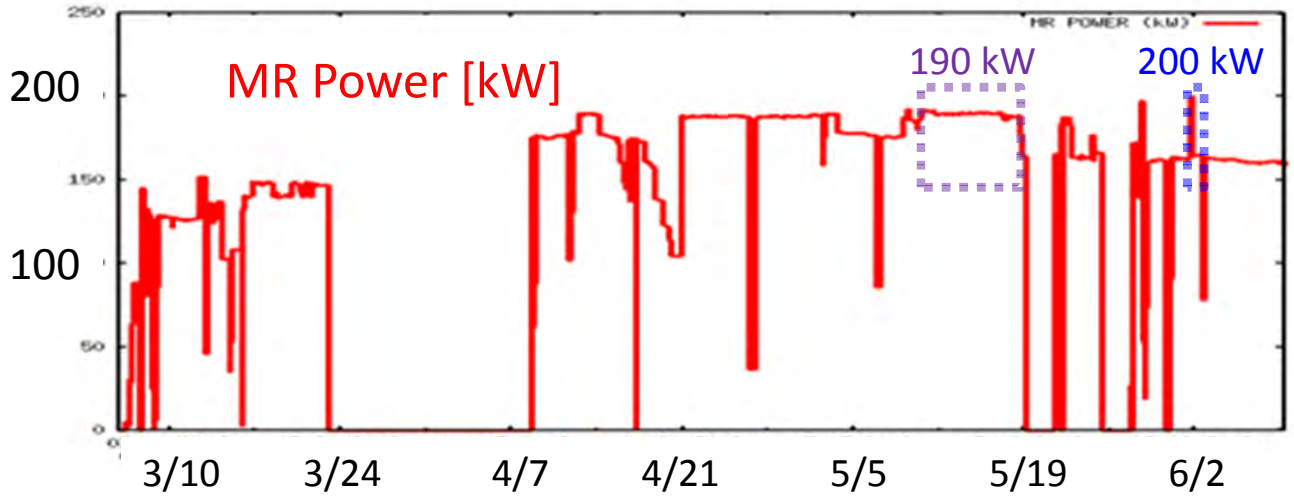
- Improvements during the shutdown in 2011 and the corresponding beam commissioning

- Operation and Troubles

- Beam loss control --- tools to reduce beam losses

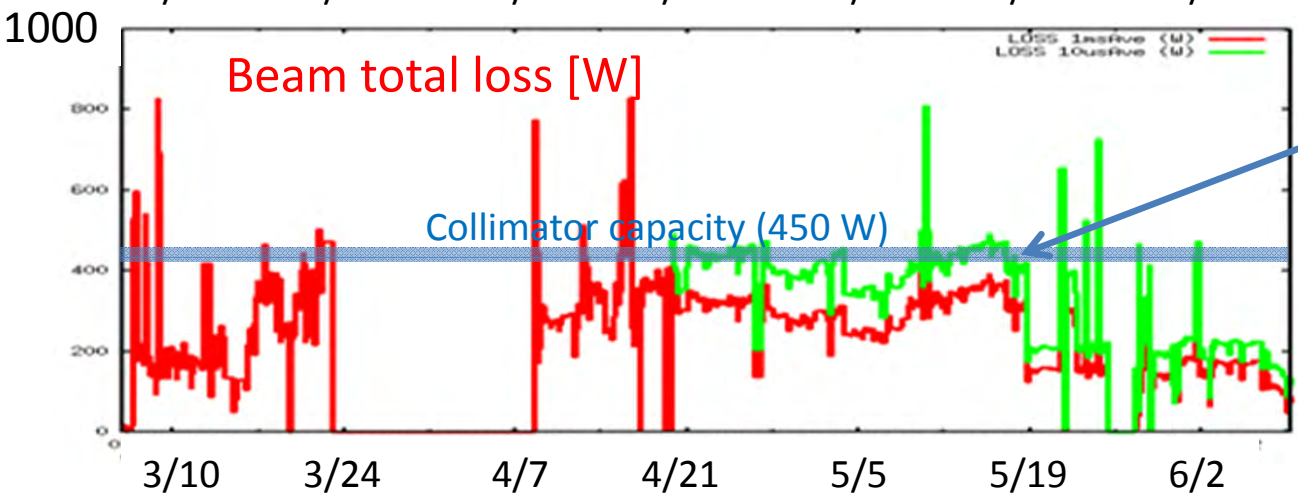
High-Intensity operation MR (2012/3/5 – 6/9)

Delivered beam power to the T2K experiment ; 160 - 200 kW
MR cycle time is 2.56 s, Bunch by bunch feedback ON,
Chromaticity is set to ~ -3
The number of extracted protons is 100 Tppp for 188 kW.



5/10~5/18
MR 190 kW op
Total loss ~450W
No RF_FF

6/1 12:00-17:45
MR 200 kW op
Total loss ~450W
W RF_FF

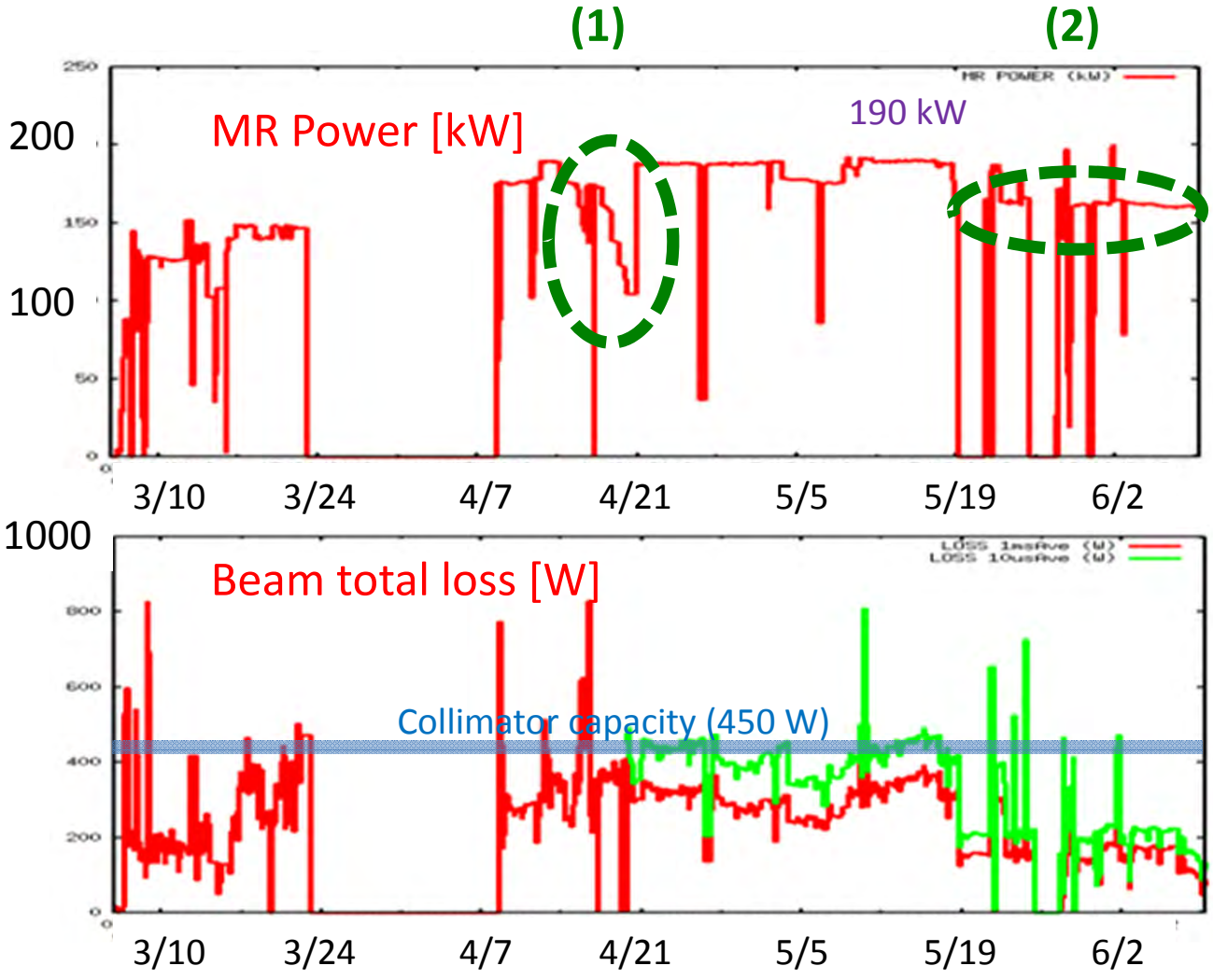


Present limit of beam loss:
Collimator capacity (450 W)
→ 2 kW after this summer

Beam loss
MR INJ1msAveLoss+P2Loss
Beam loss
MR INJ10usAveLoss+P2Loss

The beam power was limited by beam losses in the collimator area except for machine study and troubles.

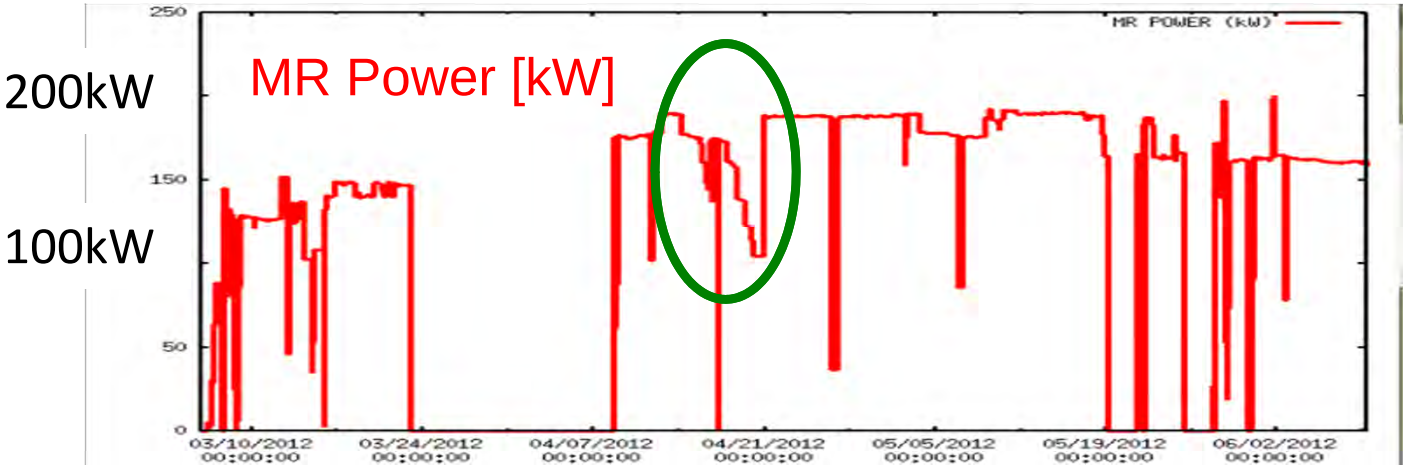
Troubles in high-Intensity operation MR



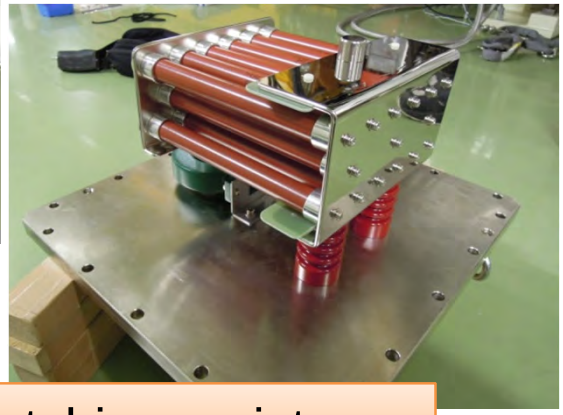
Beam loss
MR INJ1msAveLoss+P2Loss
Beam loss
MR INJ10usAveLoss+P2Loss

The beam power was limited by beam losses in the collimator area
except for the periods shown in the dotted circle.

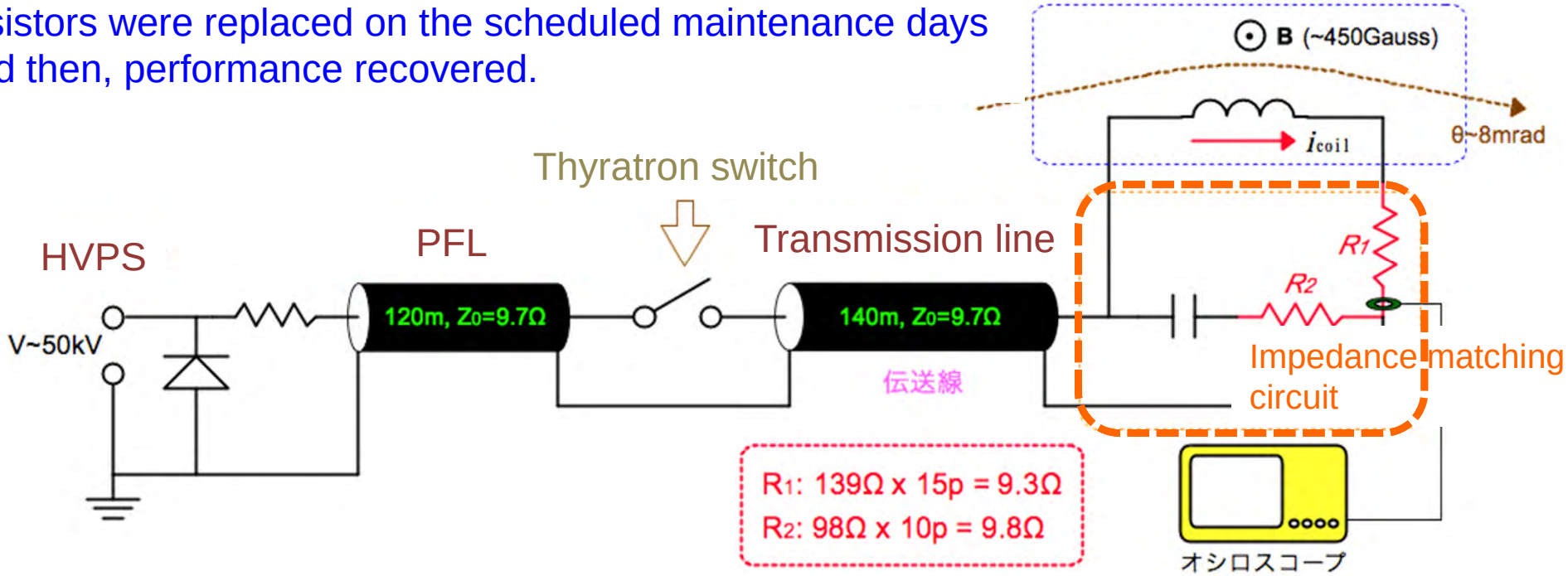
Power limitation in this run (1) : Deterioration of matching resistors



The beam power was limited by beam loss in the injection timing by deterioration of injection kicker performance due to discharge problem of matching resistors. The damaged resistors were replaced on the scheduled maintenance days and then, performance recovered.

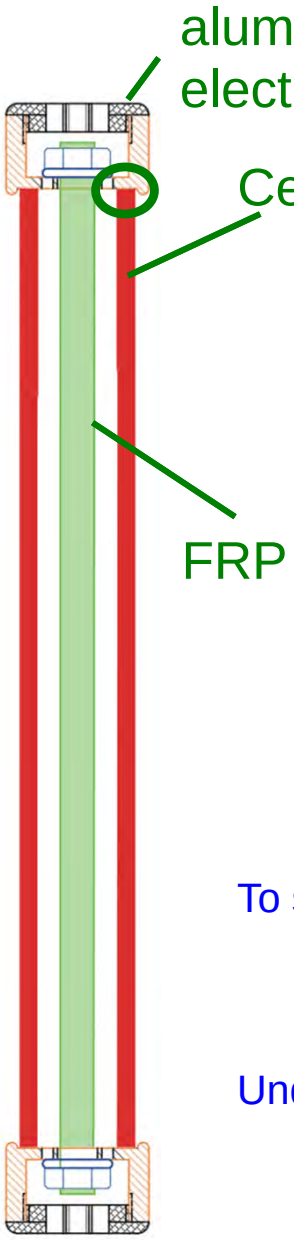


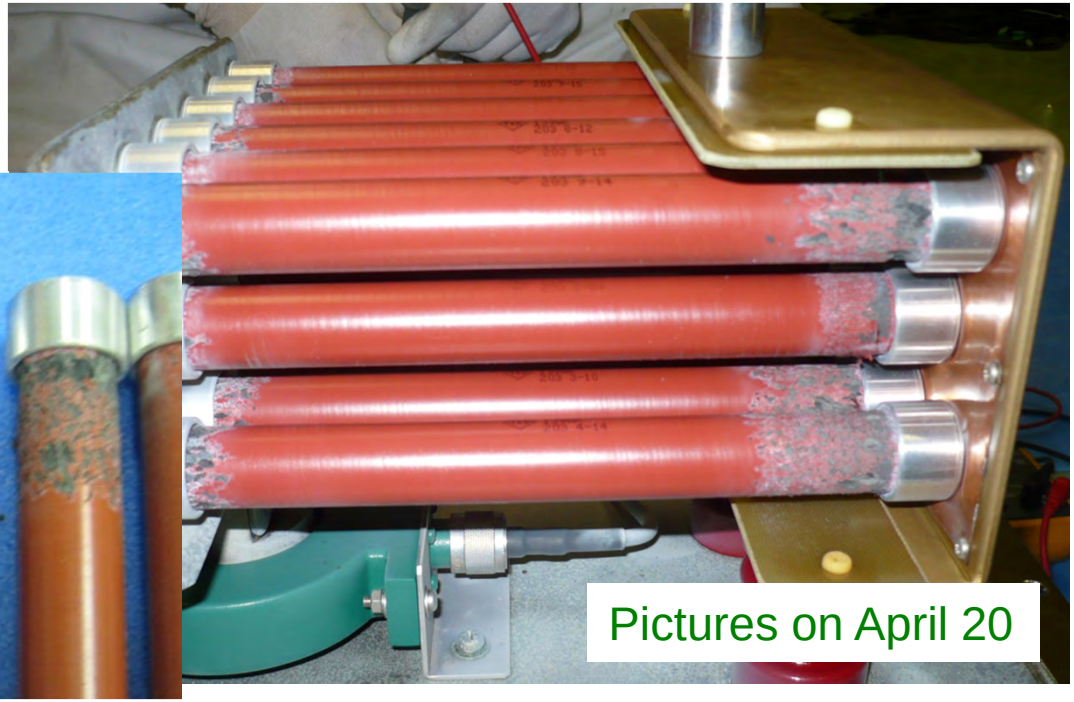
Matching resistors 1



Discharge on the resistors

The cause of the discharge in the matched resistors is poor electric contact between aluminum electrode and ceramics. The resistance gradually increased.



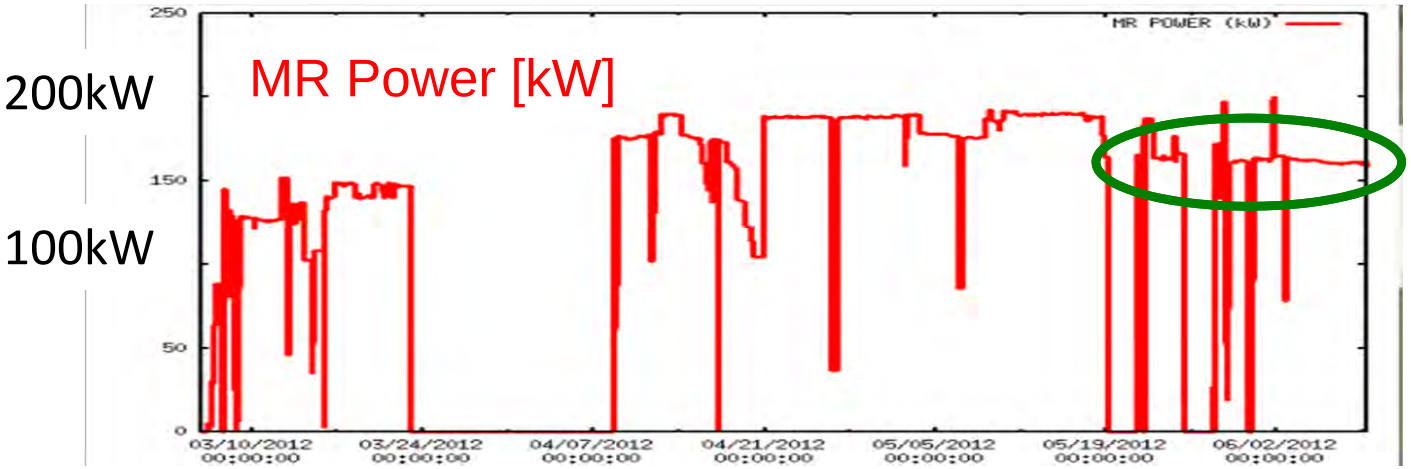


To solve the discharge problem;

1. To metalize contact surface of the ceramics and braze to the aluminum electrode.
2. To replace the FRP rod with ceramics rod

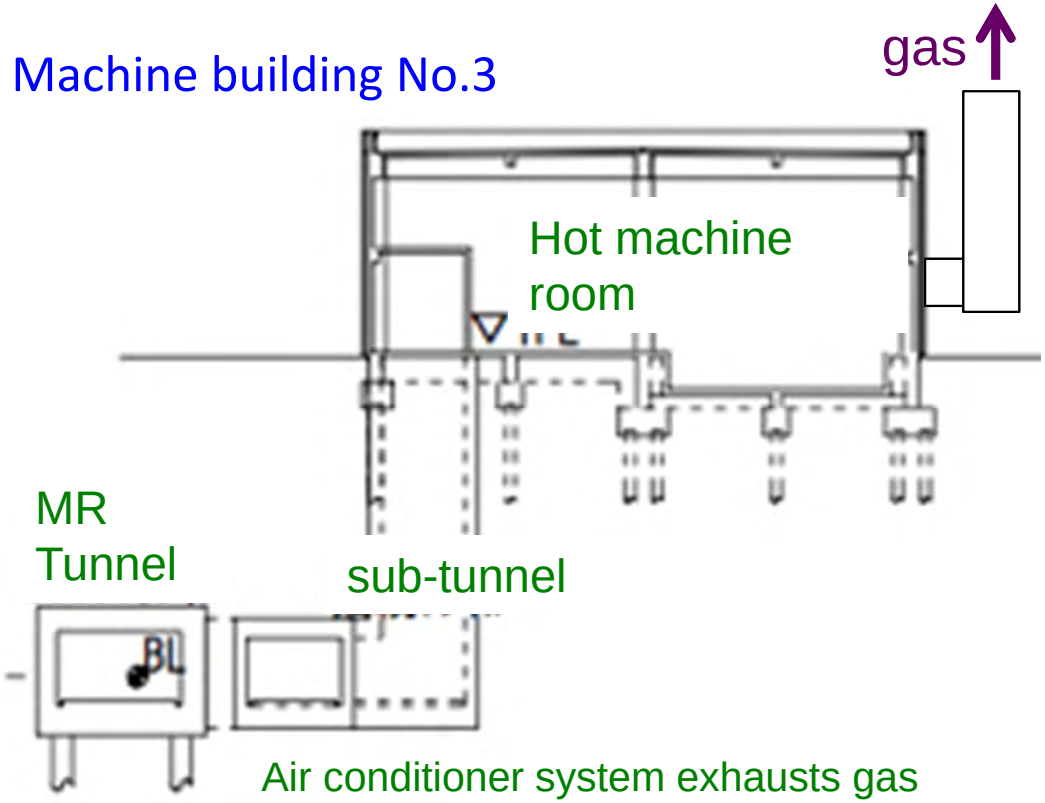
Under R&D: SiC (better for high frequency region)

Power limitation in this run (2) : Radioactivity in exhaust gas



The beam power was limited to ~ 160 kW to suppress the radioactive level of the exhaust gas at the machine building No.3 of the MR .

Machine building No.3



Air conditioner system exhausts gas during beam operation to keep negative pressure in the sub-tunnel.

The averaged radioactive level in the exhaust gas becomes higher.
Over 180 kW operation was postponed not to exceed the permitted value by law (0.5 mBq/cc as average).

- Dampers of the air conditioner system are replaced by new ones which has a better airtightness.
- Gas leak will be investigated in the air conditioner systems in this summer shutdown.

Beam Commissioning in fast extraction operation of the MR

- Improvements during the shutdown in 2011 and the corresponding beam commissioning

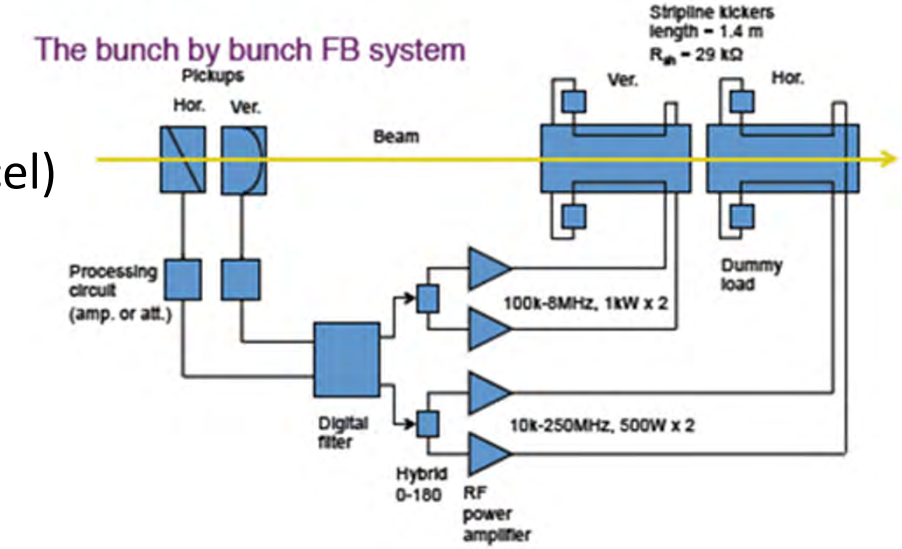
- Operation and troubles

- Beam loss control --- tools to reduce beam losses

Effect of Bunch by Bunch Feedback

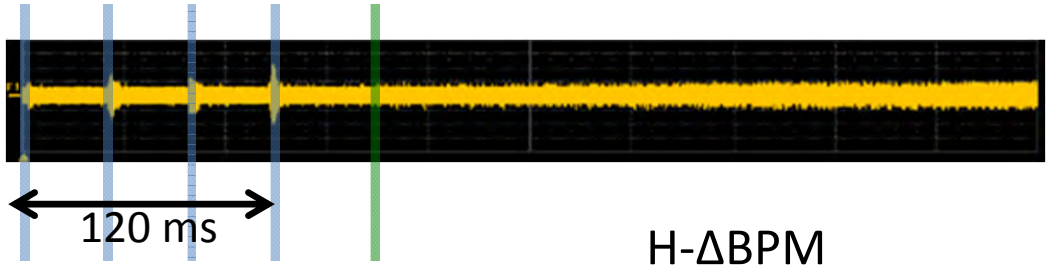
BPM/bunch → Digital Signal Processing
→Calc. kick angle and timing (injection and accel)
→Strip line kicker though power amplifier

Y. Kurimoto, et. al. Proc. DIPAC 2011, p482



BxB FB effect for 9E13 ppp

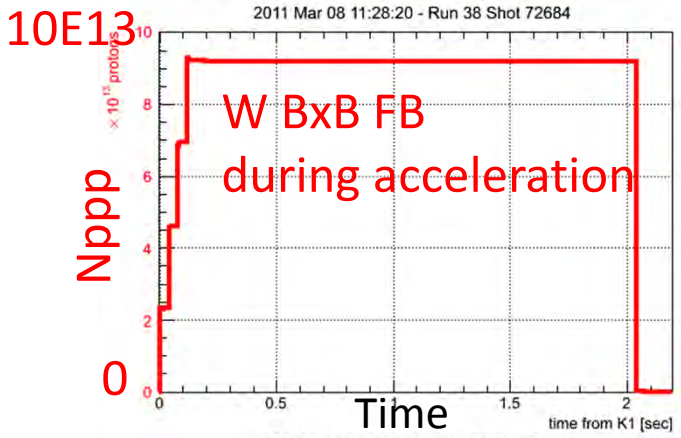
W BxB FB during Acceleration

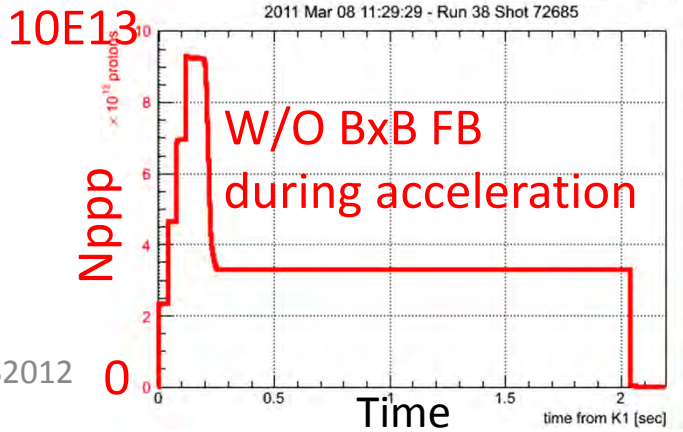


H-ΔBPM

W/O BxB FB during Acceleration

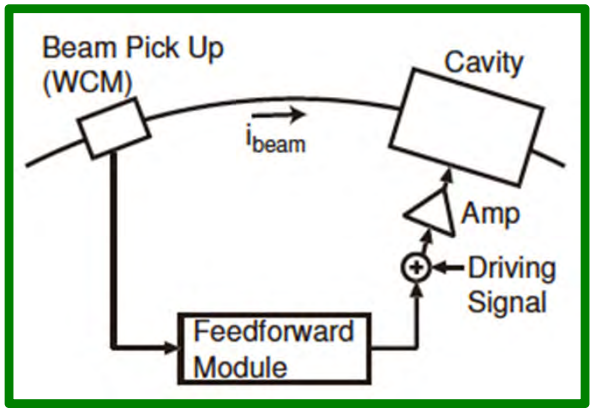
Beam injection | Acceleration strat





Beam loading compensation using FF

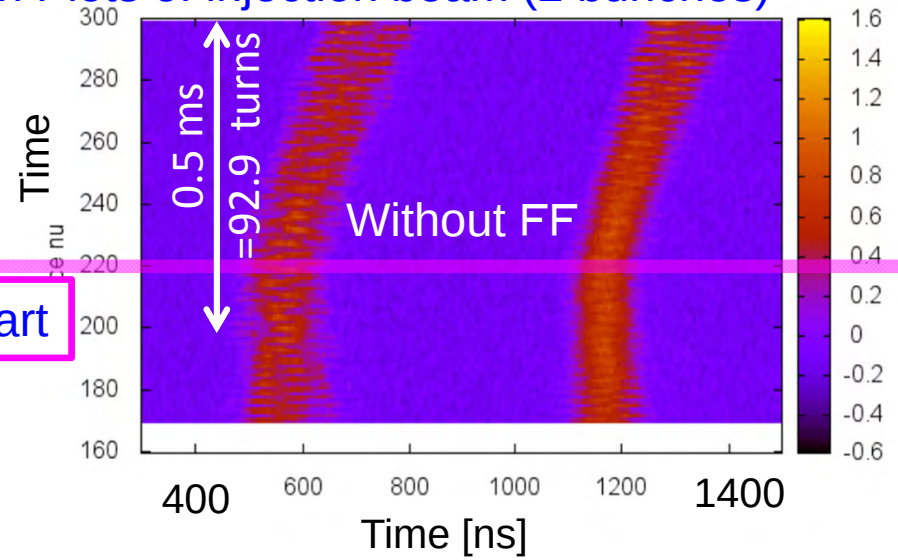
M. Yoshii
WEO1C04

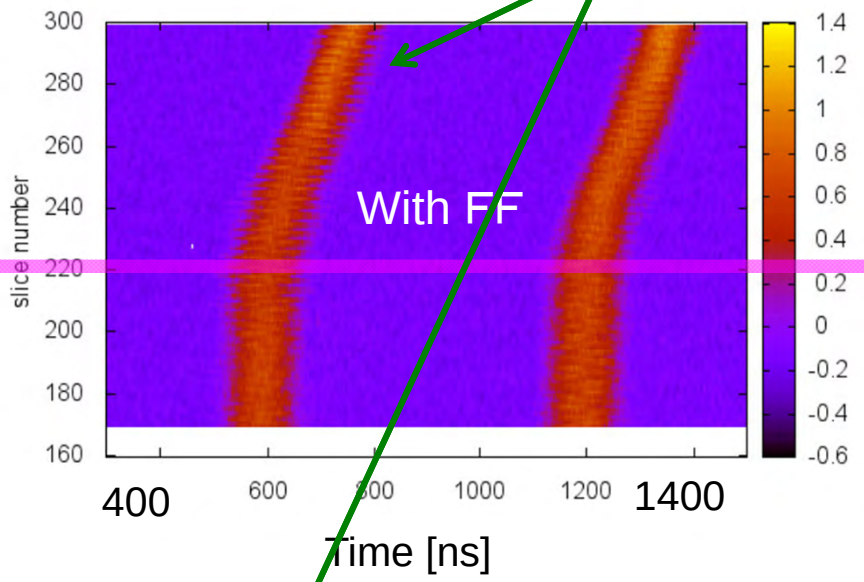


Beam signal picked up by WCM is fed into the FF module of LLRF system. The module makes driving signal for rf cavity to cancel wake voltage in the cavity.

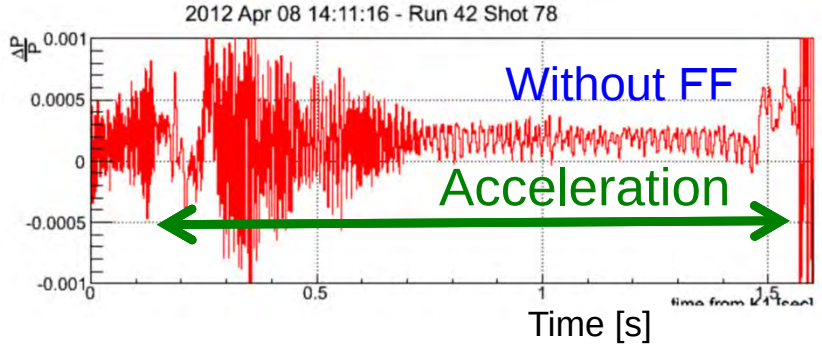
Longitudinal oscillation growth during the acceleration suppressed with FF

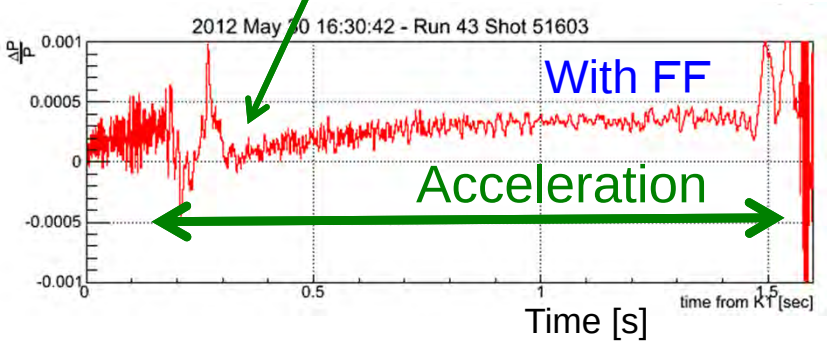
Mountain Plots of injection beam (2 bunches)





dp/p measured by BPM





Other tunings

- Patterned corrected chromaticity (-1 ~ -5)
- Tune flatness at the beginning of acceleration
- RF frequency feed-back, injection kicker timing, and so on.

Beam loss observation

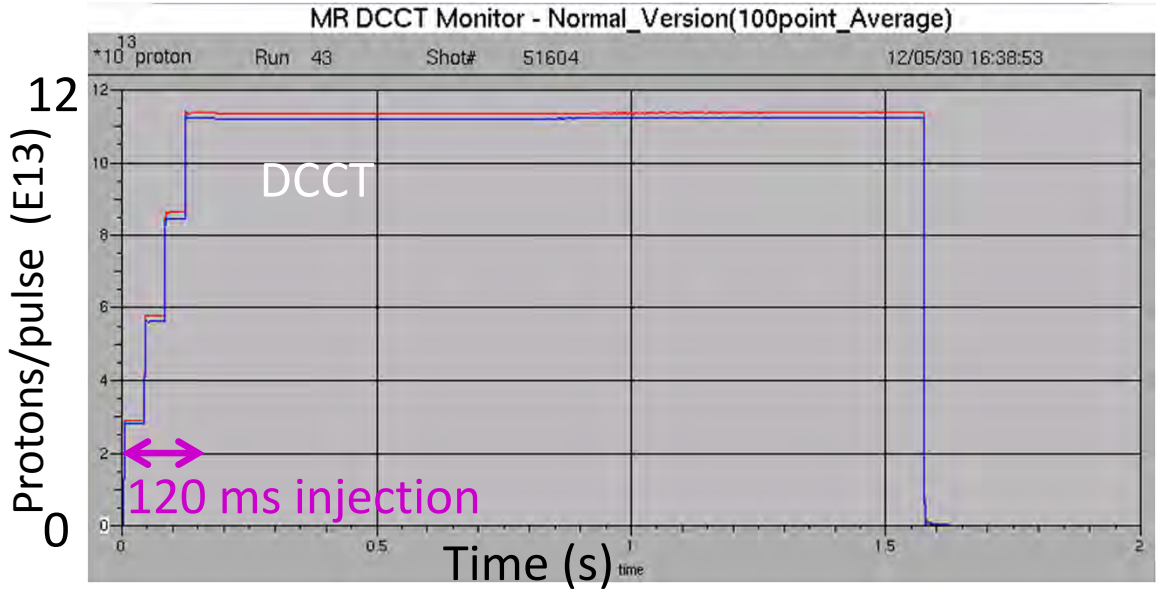
- Loss power counter

→DCCT w corrected response function
(100 us resolution)

- Fast loss in a single turn
  - timing tuning for new kickers
  - trouble of injection kickers

→Not only BLM, injection errors, corrected DCCT
but air-ion-chambers

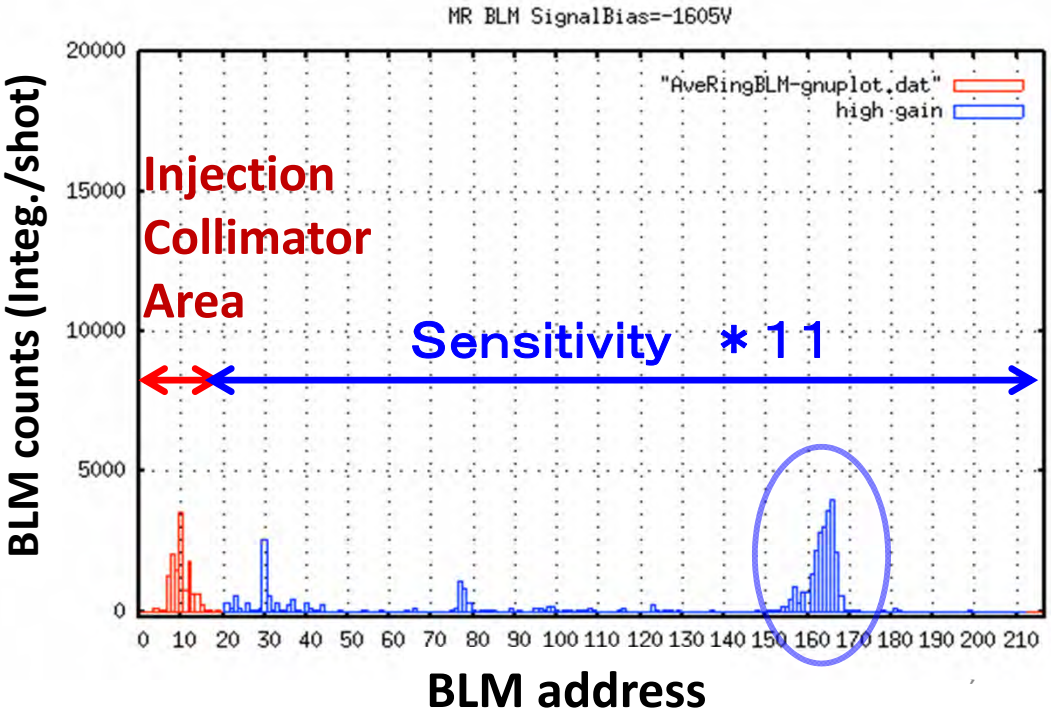
Demo. of 210kW equivalent operation

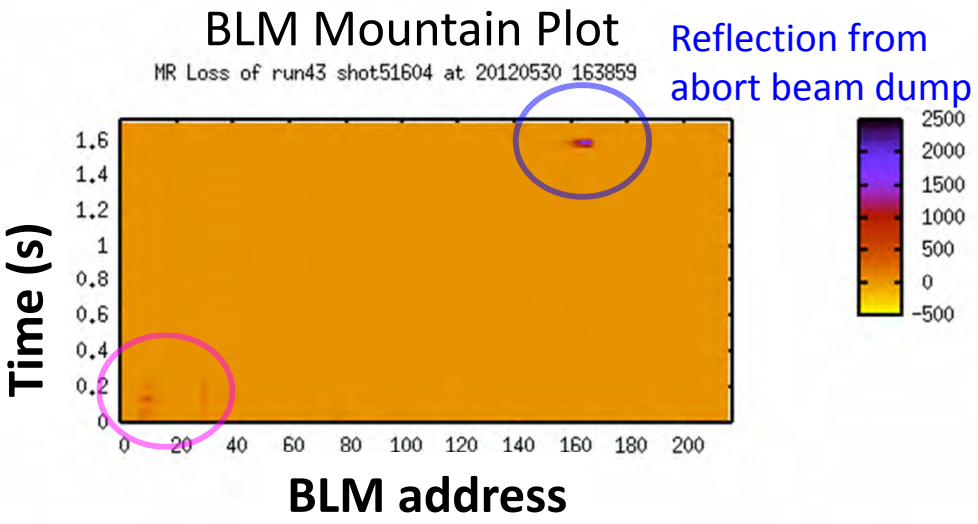


Extracted beam: 1.14E14 ppp
Demonstrated 213 kW at 2.56 s cycle

Measure beam loss were localized and 410 - 520 W in 210 kW (demo) operation.

In normal operation, power was 200 kW.





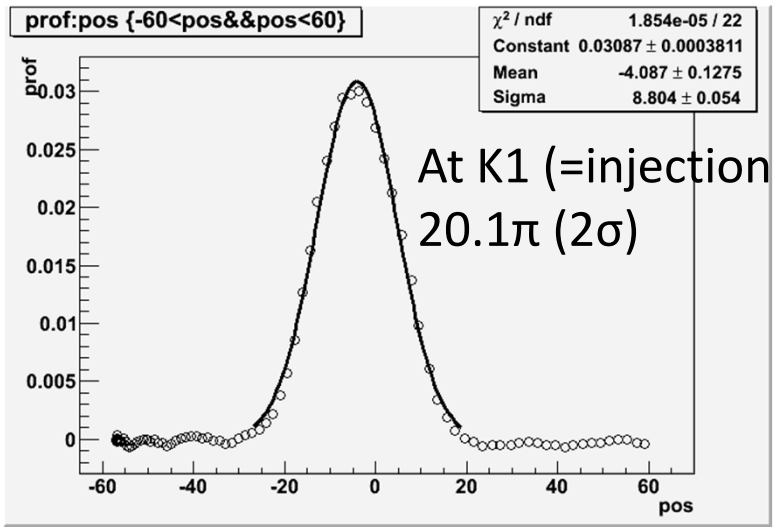
Loss was localized at collimator area and injection time

Simulations and near upgrade plan of the MR

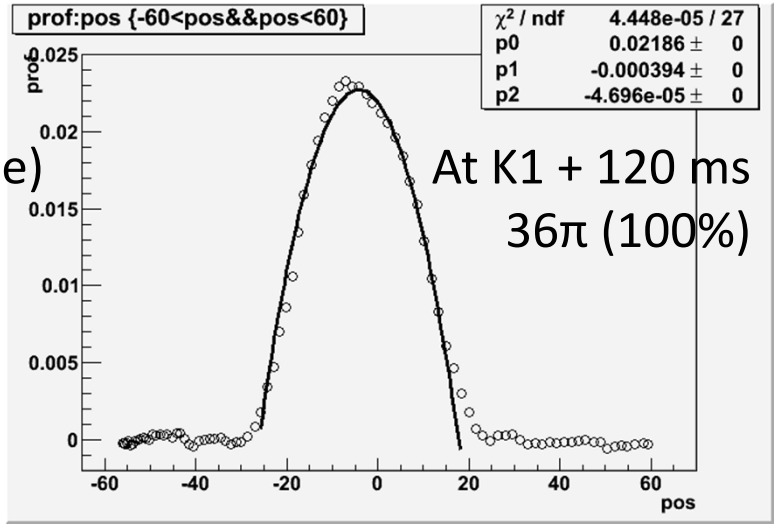
- Simulation benchmarks (comparison w experiments)
- Effects of 2nd harmonic RF in experiments and simulations
- Operation summary and near upgrade-plan

2.5D simulation and Measurement

FW H-profile, 1.19E13 ppb

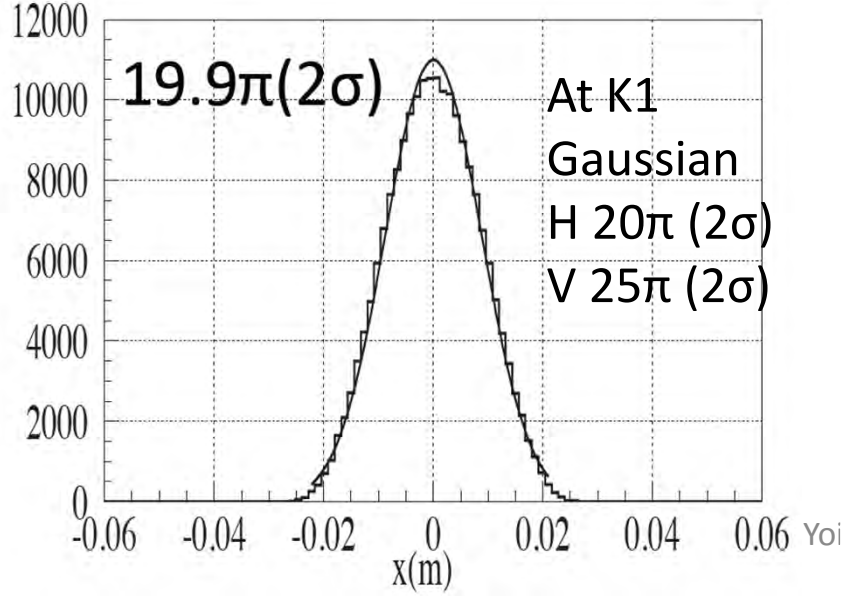


At K1 (=injection time)
20.1π (2σ)

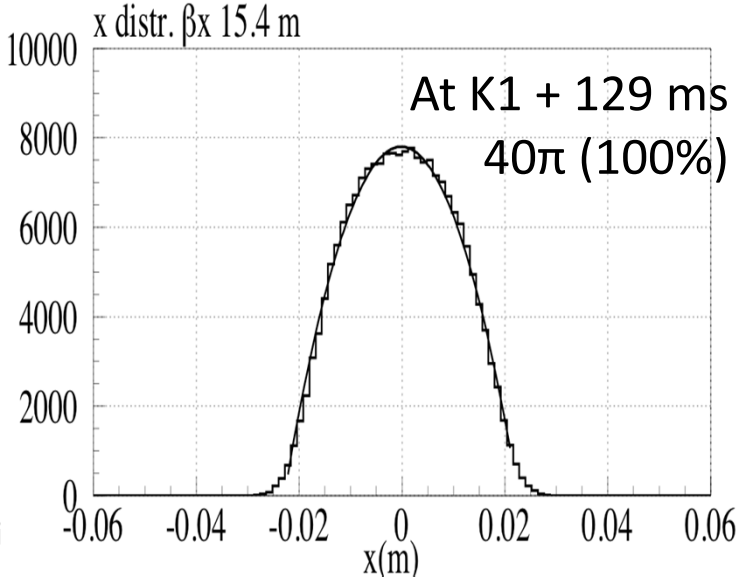


At K1 + 120 ms
36π (100%)

2.5 D simulation (SCTR code by K. Ohmi): SC 1.17E13 ppb



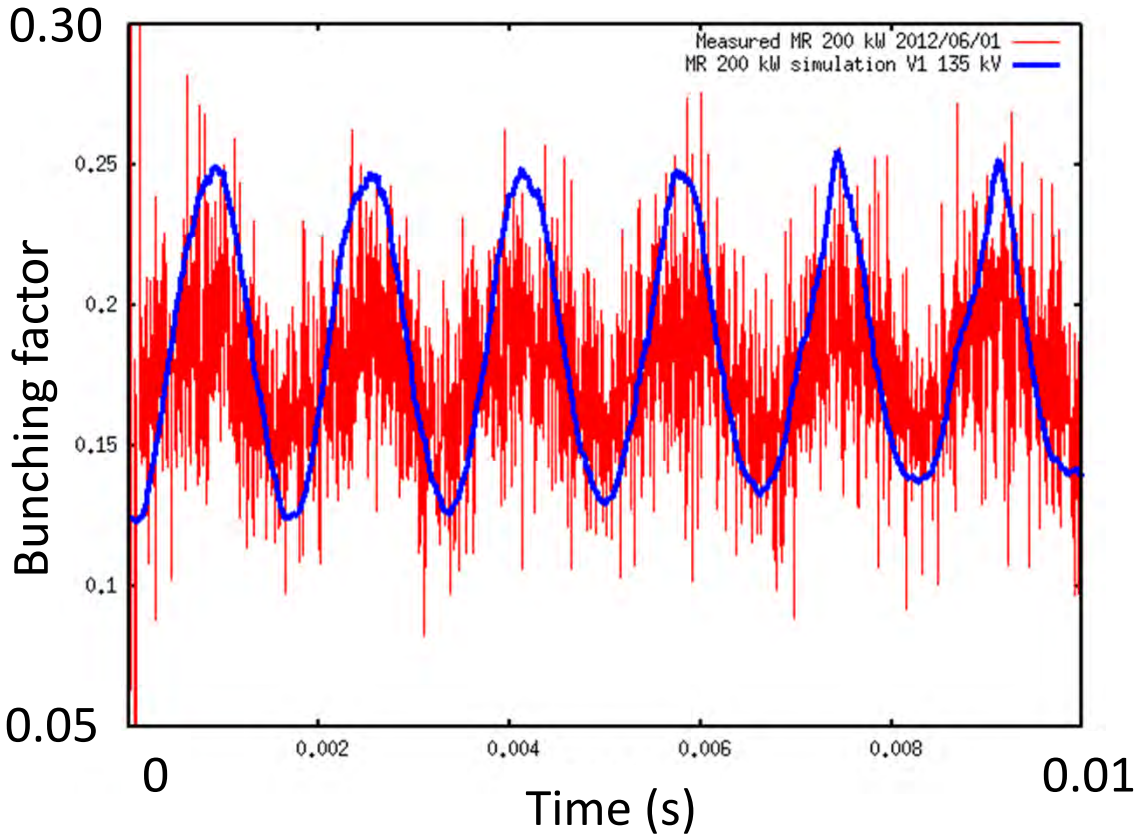
At K1
Gaussian
H 20π (2σ)
V 25π (2σ)



At K1 + 129 ms
40π (100%)

Magnet multipoles: measured
Magnet rotation: Gaussian σ=0.1 mrad

2.5D simulation and Measurement



Bunching factor
MR 200 kW, V1=135 kV
Red : Measurement
Blue : 2.5D simulation (SCTR)

Survival ratio of injected protons during 60 ms at 3 GeV
in MR 200kW equivalent operation:

DCCT measurement : 0.992±0.002 (shot-by-shot)
SCTR simulation : 0.988

Simulations and near upgrade plan of the MR

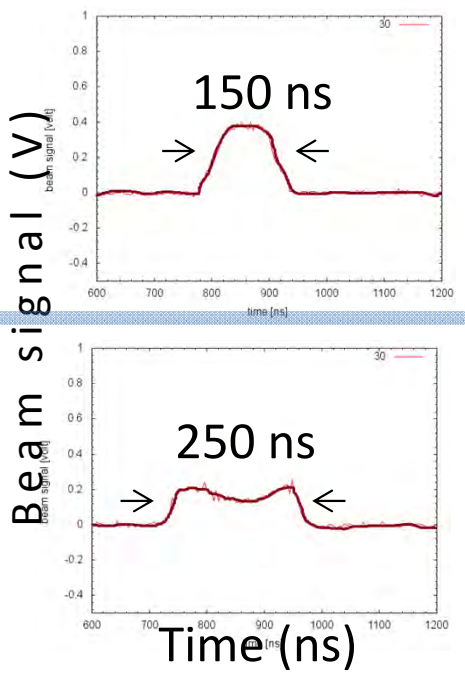
- Simulation benchmarks (comparison w experiments)
- Effects of 2nd harmonic RF in experiments and simulations
- Operation summary and near upgrade-plan

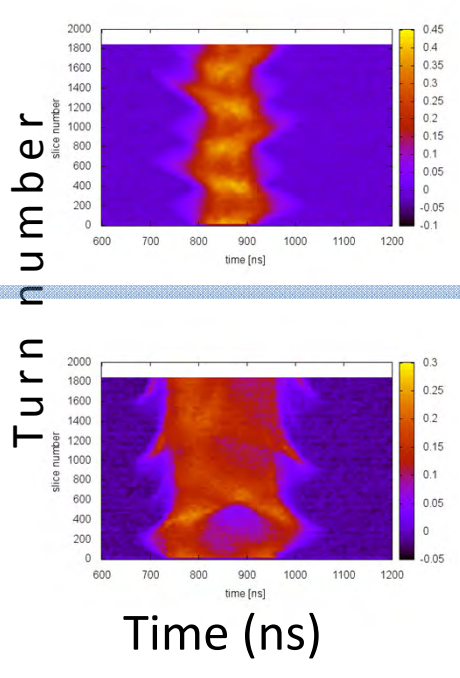
Effects of 2nd Harmonic RF

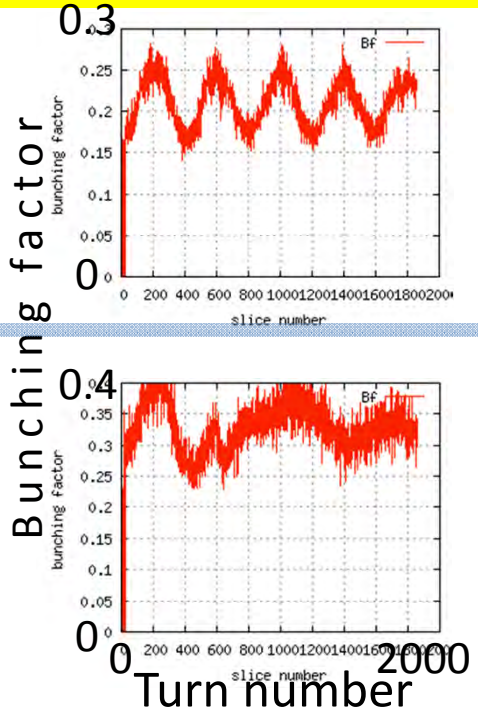
Measurements: Larger bunching factor was achieved with 2nd harmonic RF at 3 GeV

Fundamental only

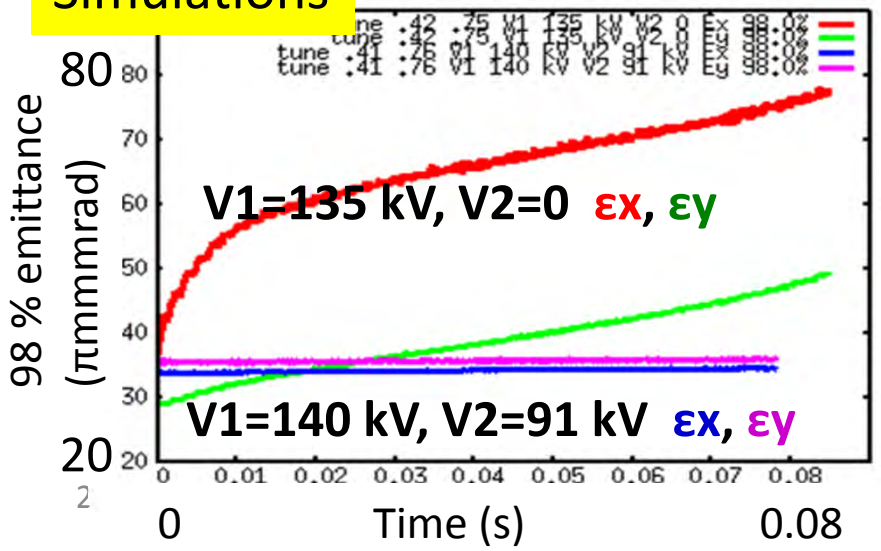
RCS ext.2nd 70%
MR 1st 40kV,
2nd 26kV







Simulations



Bunching factor is increased, and space charge effects are compensated with 2nd harmonic RF.
User operation is capable after the 9th RF cavity is installed this fall.
However, present rise time of the injection kickers have no margin for the operation w 2nd harmonic RF.
It is 350 ns for 600-ns bucket.
To shorten the rise time is planned
(→ 250 ns with 50 kV inj. kickers).

Simulations and near upgrade plan of the MR

- Simulation benchmarks (comparison w experiments)
- Effects of 2nd harmonic RF in experiments and simulations
- Operation summary and near upgrade plan

Operation Summary and near future plan

Periods	Beam power	Improvement/ Cycle time
2011. 1 – 3	145 kW	Bunch by bunch feed-back
2011. 3 – 11	Shutdown	Ring collimator shields 7th and 8th RF systems New Injection Kicker
2011. 12 – 2012. 6	100 – 200 kW (RCS 300 kW eq.)	Cycle time 3.2 → 2.56 s Beam loading compensation
2012. 7 – 9	Shutdown	Ring collimator upgrade 0.45 → 2 kW 9th RF system
2012. 10 – 2013. 7	> 200 kW (2012. 10~) (RCS 300 – 400 kW eq.)	Cycle time 2.48 → 2.4 s Second harmonic cavities
2013. 8 – 2013. 1	shutdown	Ring collimator upgrade (2 kW -> 3.5 kW) Linac upgrade
2014. 2 – 2014. 6	> 300 kW (RCS > 600 kW eq.)	Cycle time 2.4 s

Conclusions

- **Beam power was upgraded w higher repetition and beam loss suppression. As user operation, 200 kW beam was performed by June 2012.**
- **MR was re-aligned after the Tohoku earthquake. Optics were re-measured, and they reproduced the designs well.**
- **Key issues to reduce beam loss were bunch-by-bunch feed-back (Transverse) and RF Feed-forward systems, besides normal procedures as tune flatness, chromaticity tuning, and so on.**
- **Troubles on injection kickers and air-tightness were controlled.**
- **From this fall, we will upgrade the MR power with higher repetition, collimator upgrade, 2nd harmonic RF.**