J-PARC MR Beam Commissioning and Operation

US-Japan Workshop on Accelerators and Beam Equipment for High-Intensity Neutrino Beams

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for the J-PARC MR Beam Commissioning Group

Contents

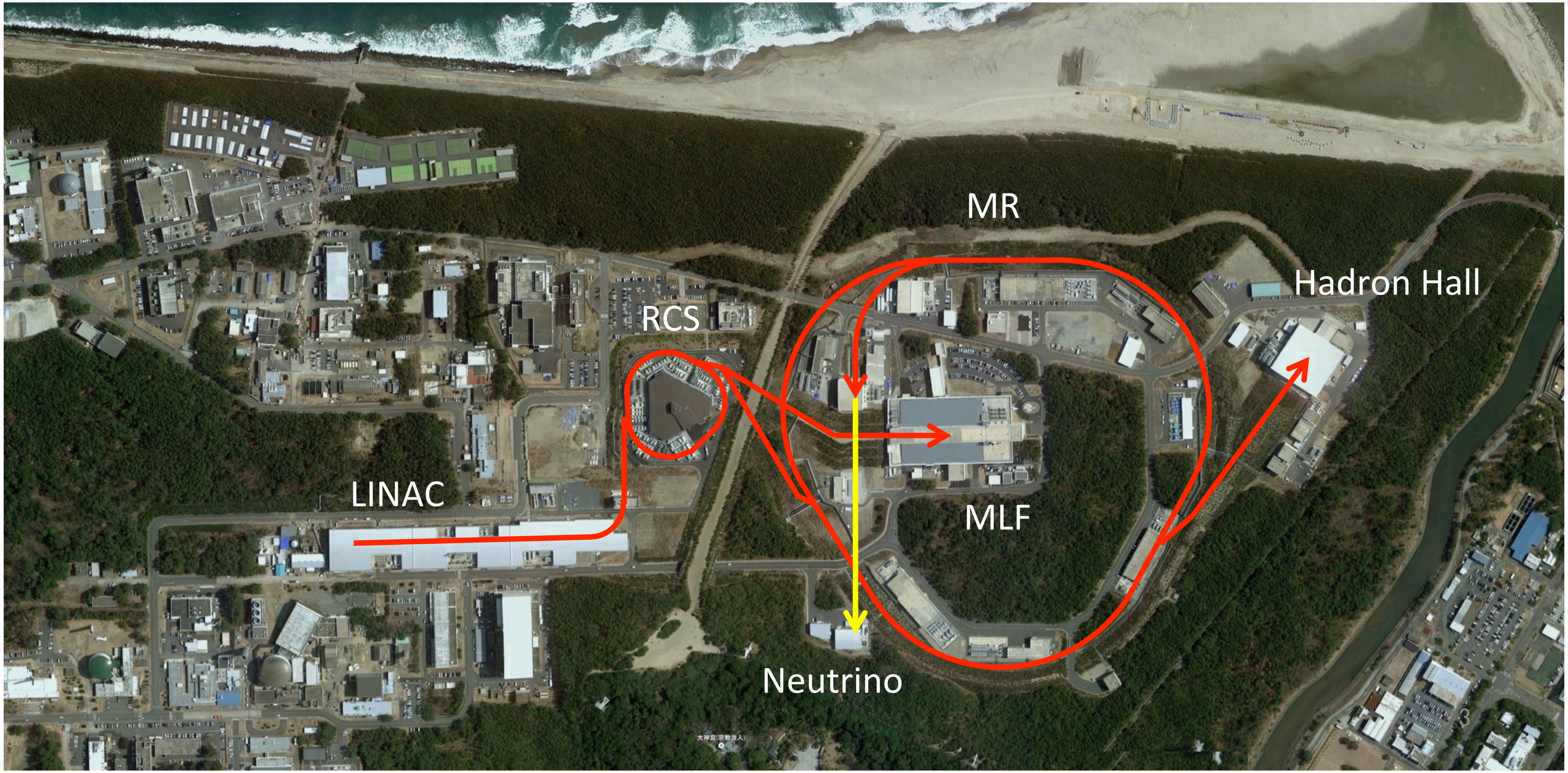
- Introduction to J-PARC main ring
- Operation status for the fast extraction
- Recent Improvements
  - Rf pattern optimization for fundamental and 2nd harmonic
  - Injection kicker improvements
  - Instability suppression
  - Optics correction
  - (Resonance corrections in Discussion Session)
- For Further Beam Intensity Improvement
  - Optimization of injection beam distribution by RCS tuning
  - Operation with the betatron tune of (21.35, 21.43)
- 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)

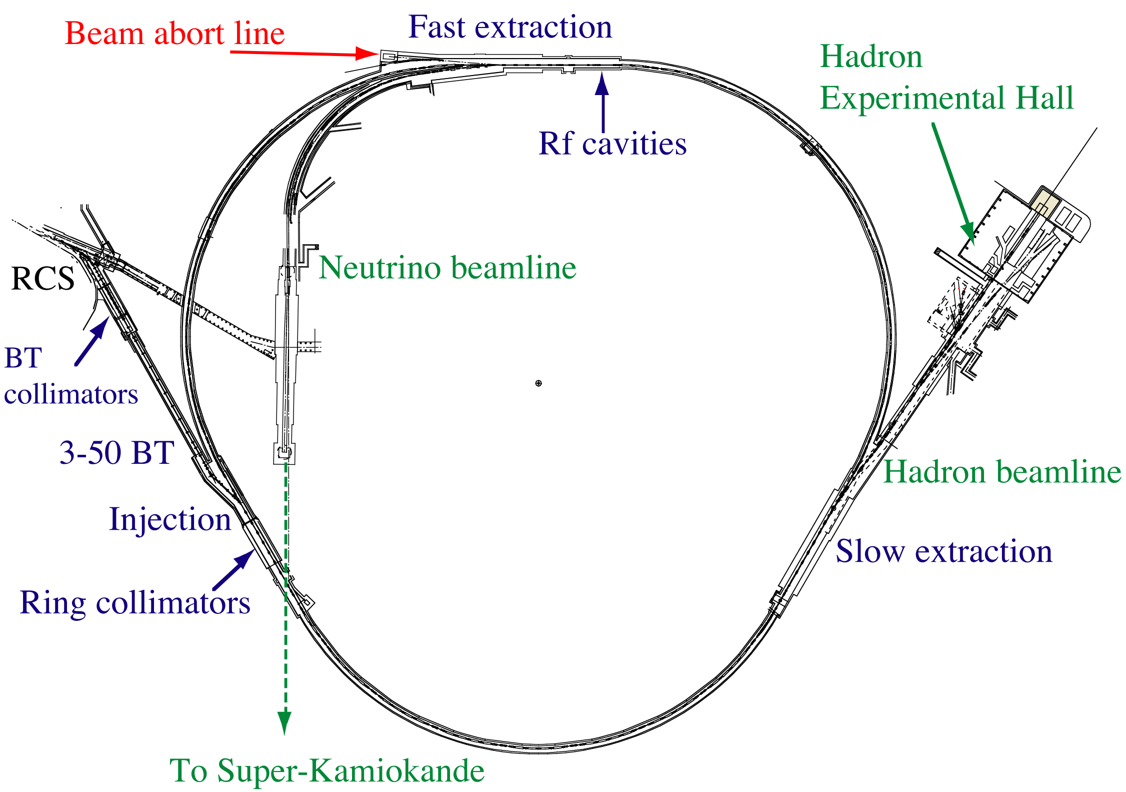
- LINAC (400 MeV)
- Rapid Cycling Synchrotron (RCS) (3 GeV)
  - Material and Life science Facility (MLF)

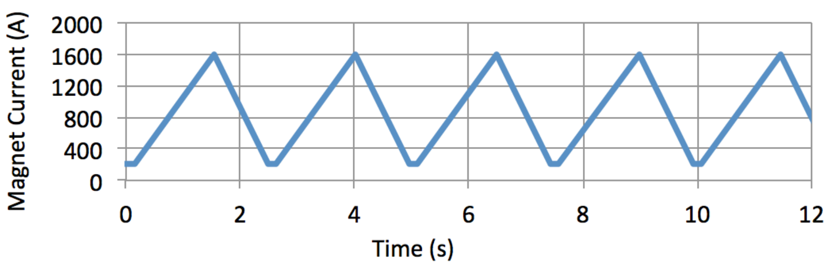
- Main Ring (MR) (30 GeV)
  - Neutrino Facility
  - Hadron Hall



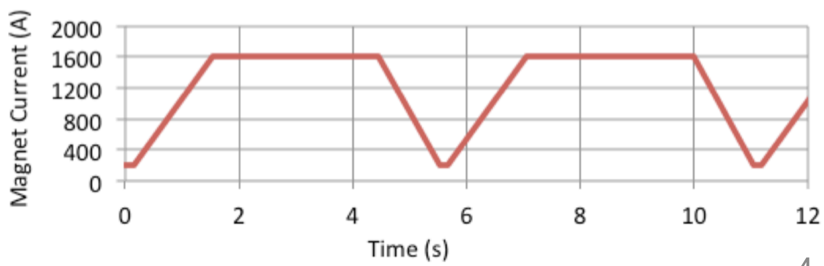
MR Design and Operation Modes

- 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 in May 2008
  - Acceleration and extraction in Dec. 2008
- Fast extraction mode (FX) for the neutrino oscillation experiment: 1 turn extraction.
- Slow extraction mode (SX) for the hadron hall experiments: 2 s extraction.





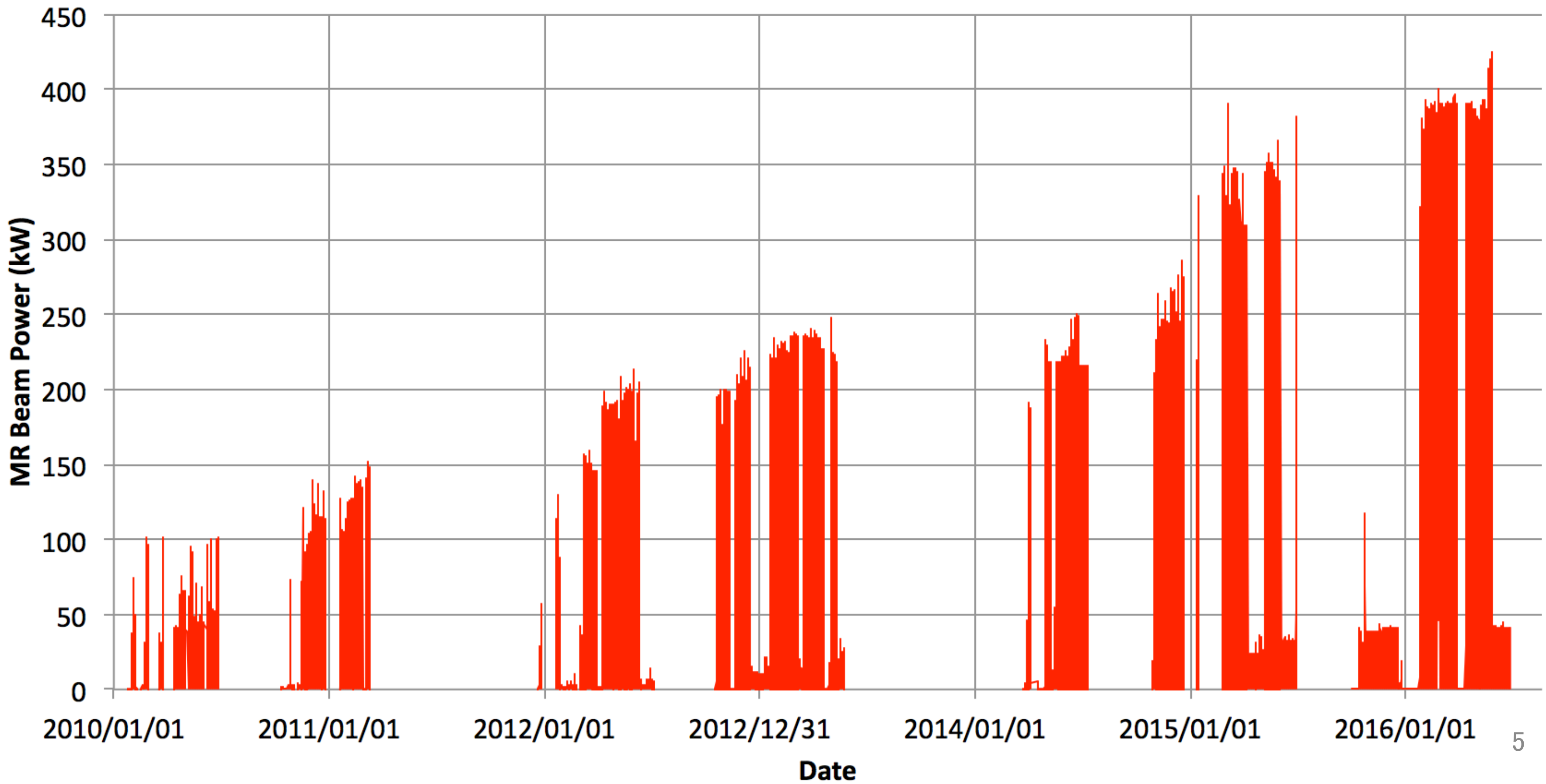
FX (2.48 s)



SX (5.52 s)

MR Beam Power History

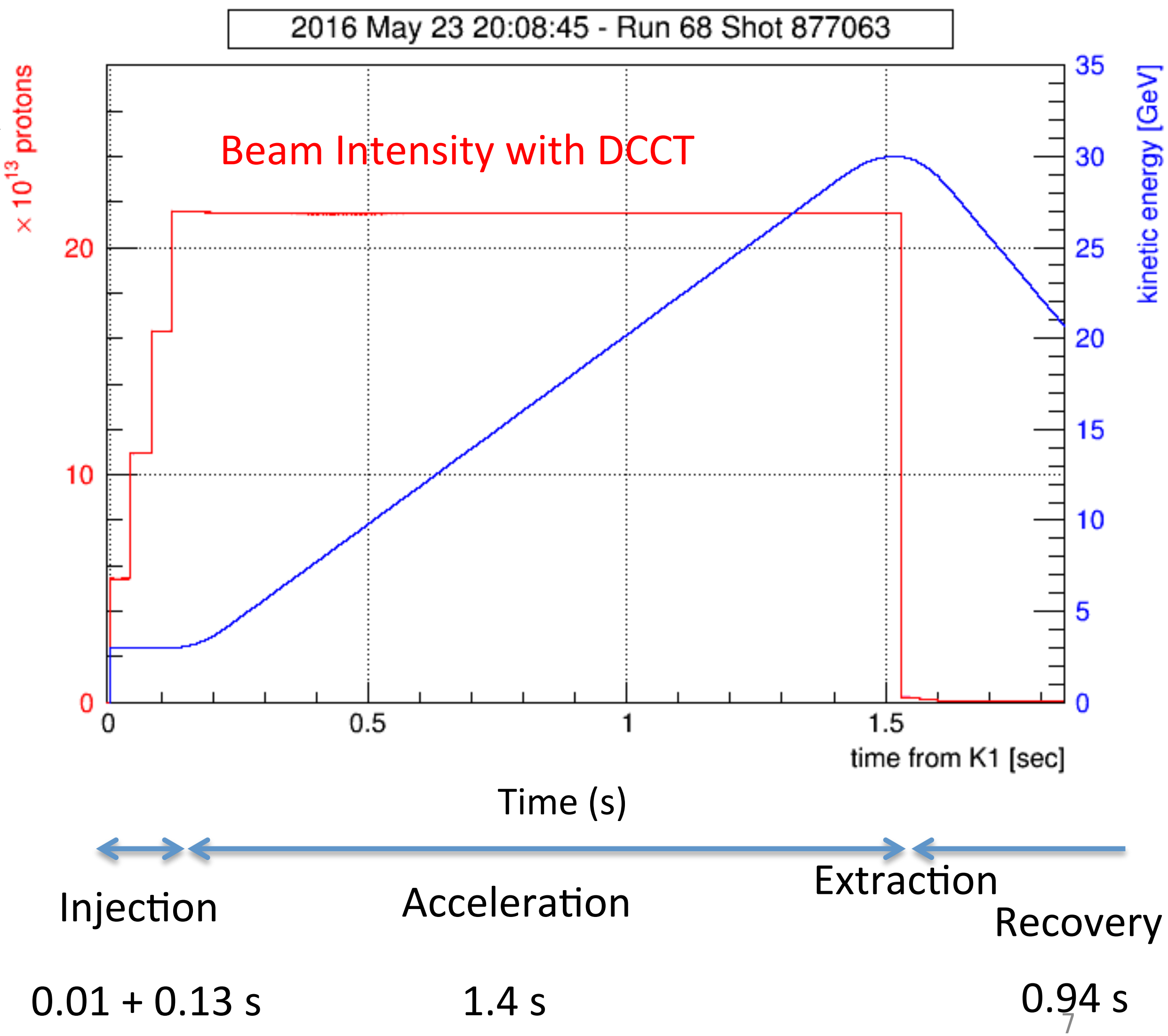
- MR beam power has been increasing since Dec. 23 2008 (30 GeV Acceleration).
- In the operation of Jan ~ May 2016, the beam power was mostly about 390 kW with 2×10^{14} protons per pulse.
- The target beam power is 750 kW and is planned to be achieved with the faster cycling 2.48 s to 1.3 s.
- The operation of 415 kW ~ 425 kW was successful for the last three days.



Operation Status for the Fast Extraction

Typical Operation Status for Fast Extraction

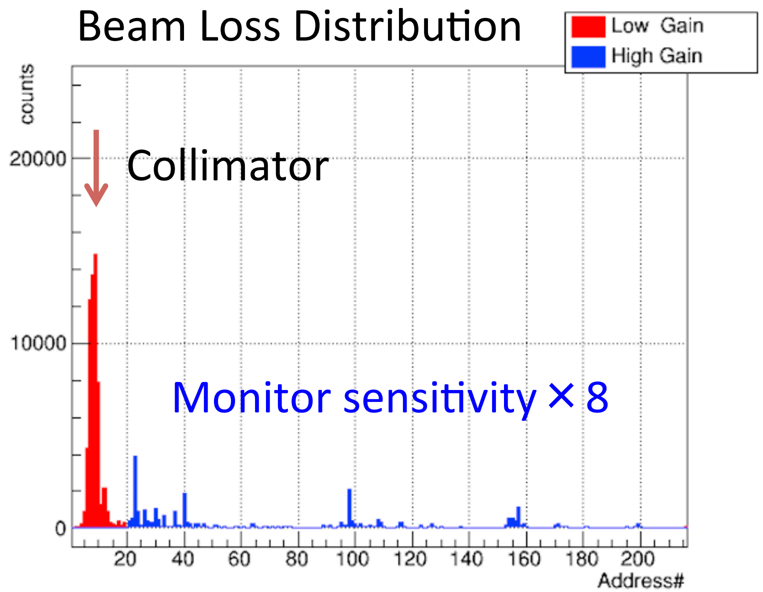
- Power : 416 kW
- Repetition : 2.48 sec
- 4 batch (8 bunch) injection during the period of 0.13 s
- 2.7e13 protons per bunch (ppb) × 8 @ Injection
- 2.15e14 ppp @ P3 (end of acceleration)
- Loss during the injection period : 170 W
- Loss in the beginning of acceleration (0.12 s) : 417 W
- Loss power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

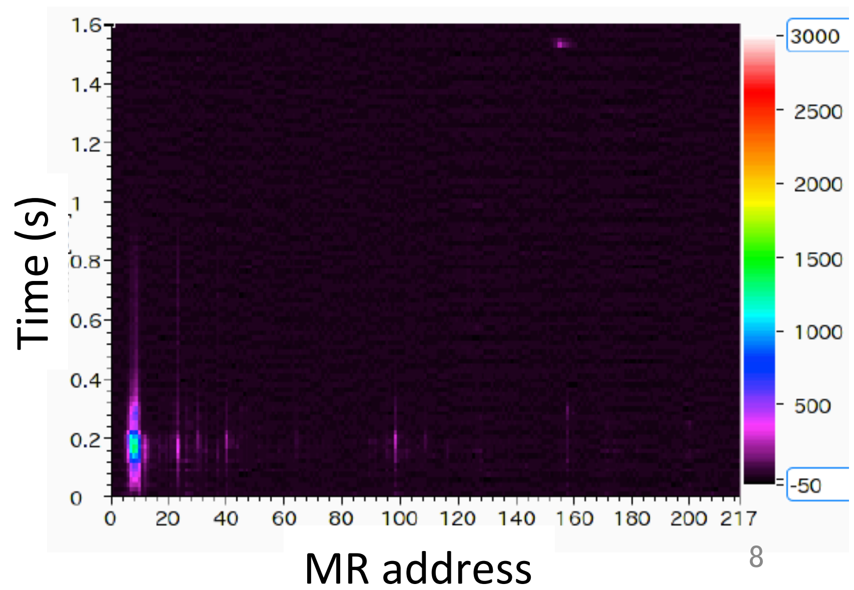


Tuning Items for Fast Extraction

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.

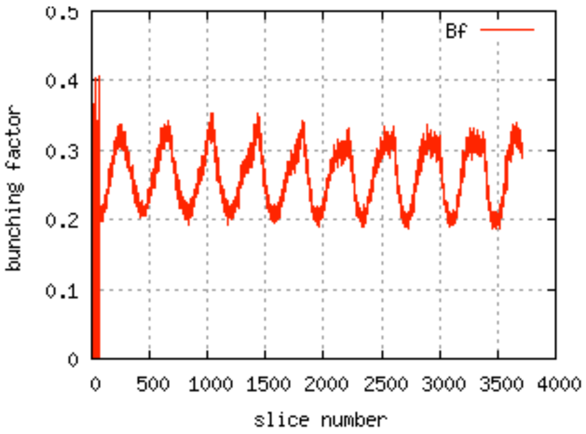




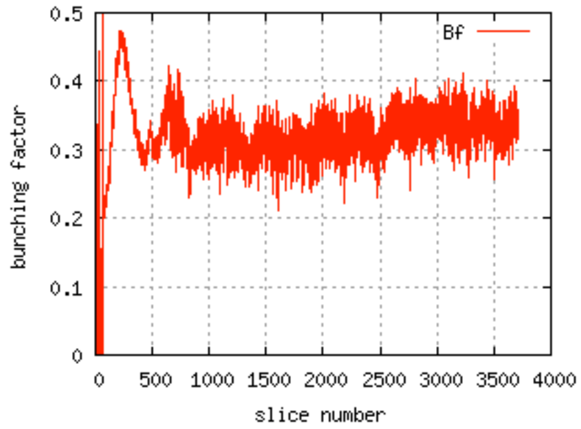
Recent Improvements

Longitudinal Profiles with High Intensity Beam of 500 kW equivalent

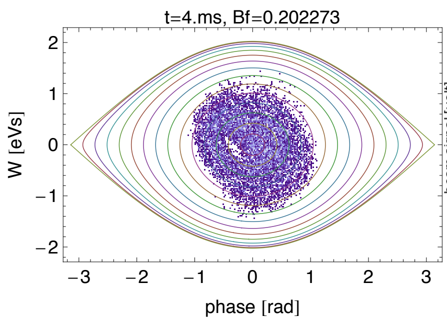
(100 kV, 0 kV)
Bunching factor
0.2 ~ 0.3
Bunch length
~200 ns

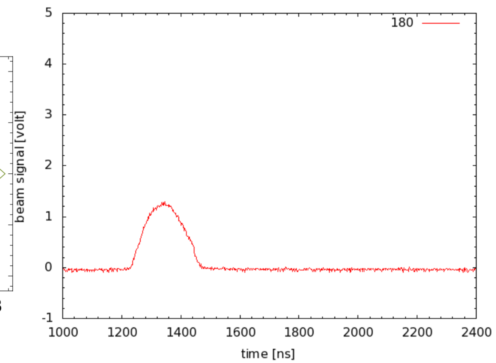


(100 kV, 70 kV)
Bunching factor
0.3 ~ 0.4
Bunch length
~400 ns

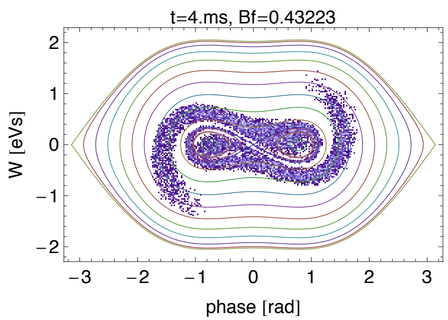


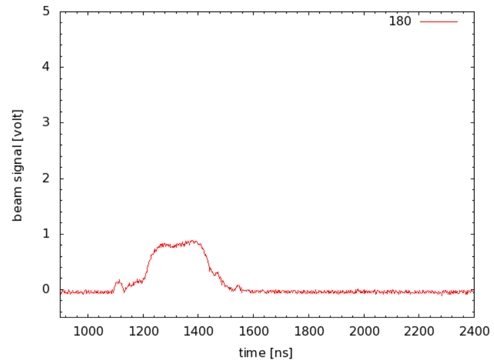
Simulation
(100 kV, 0 kV)

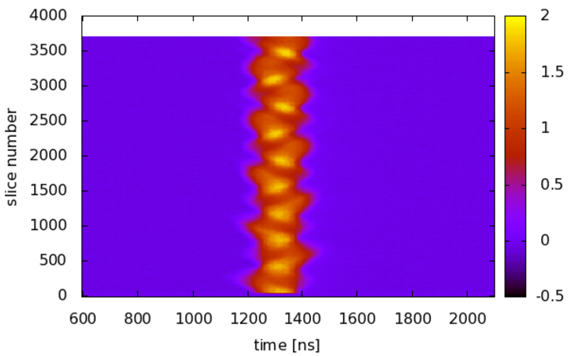


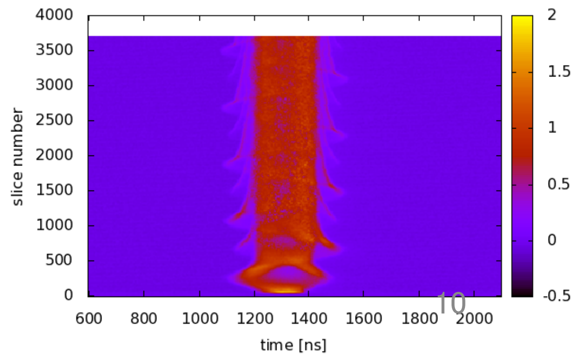


Simulation
(100 kV, 70 kV)





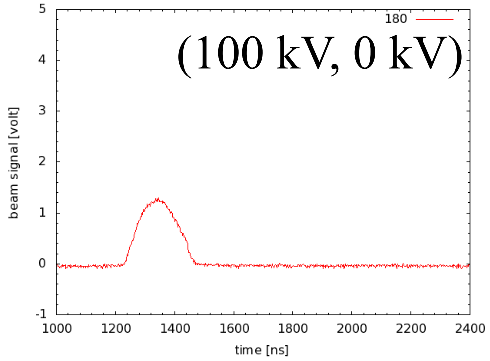




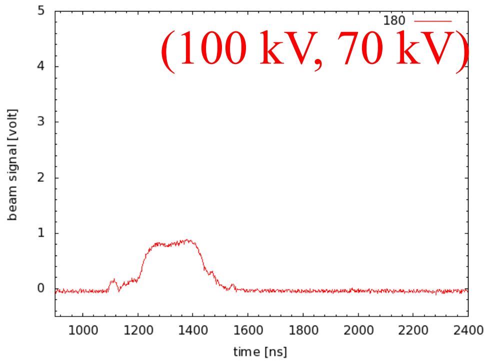
High Intensity 500 kW equiv. K1 1 bunch

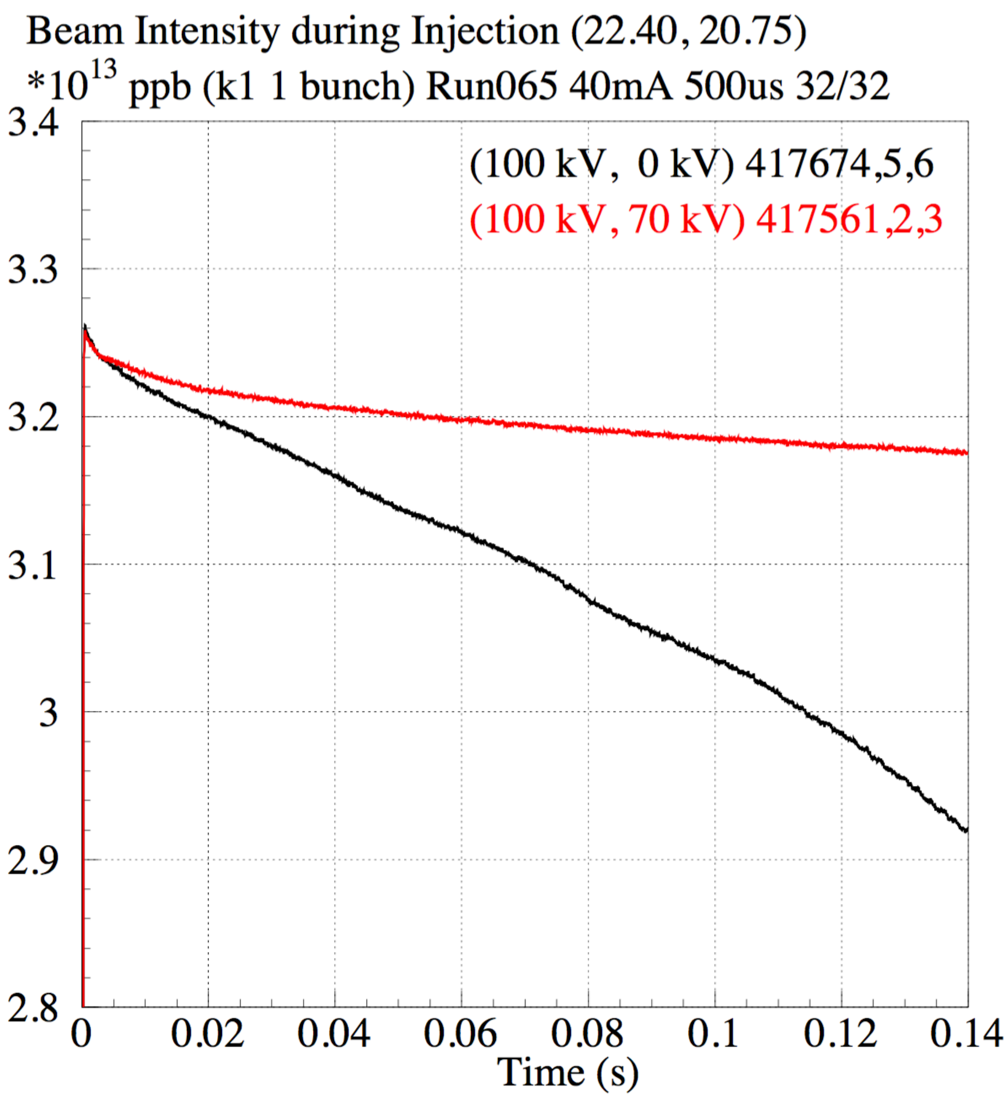
- Beam survival was measured with or without 2nd harmonic rf for high intensity beam of 500 kW equiv.
- Survival is better with 2nd harmonic rf.

Bunch Shape without 2nd harmonic rf



Bunch Shape with 2nd harmonic rf

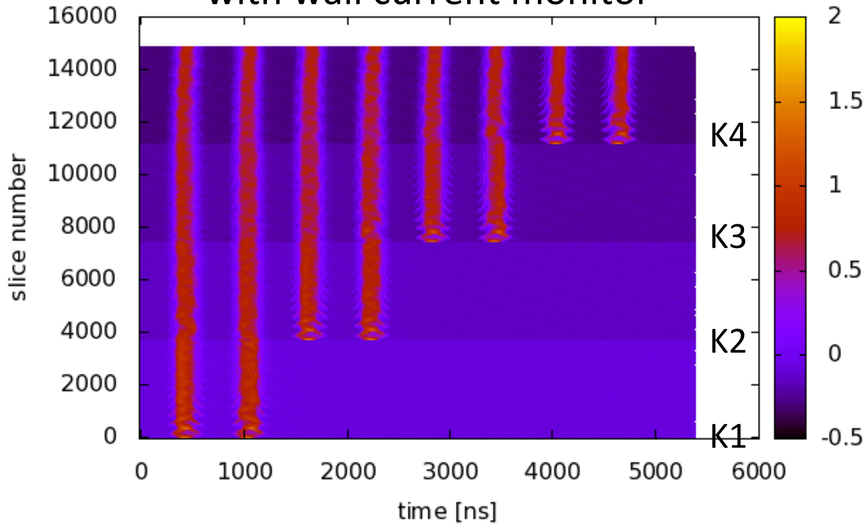




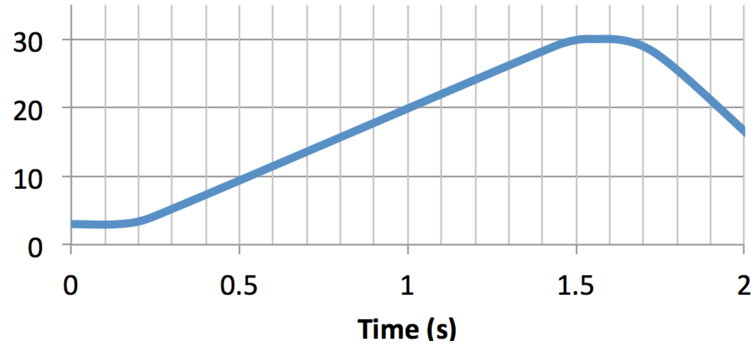
RF Pattern

- 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.

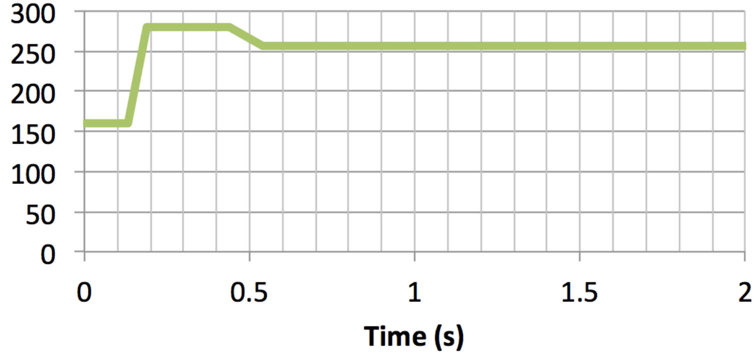
Longitudinal wave forms
during injection
with wall current monitor



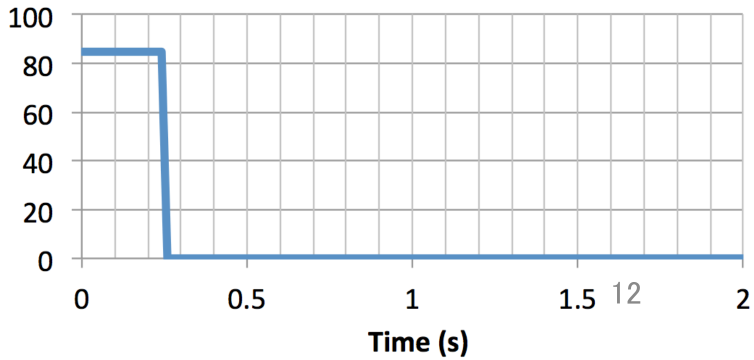
Kinetic Energy (GeV)



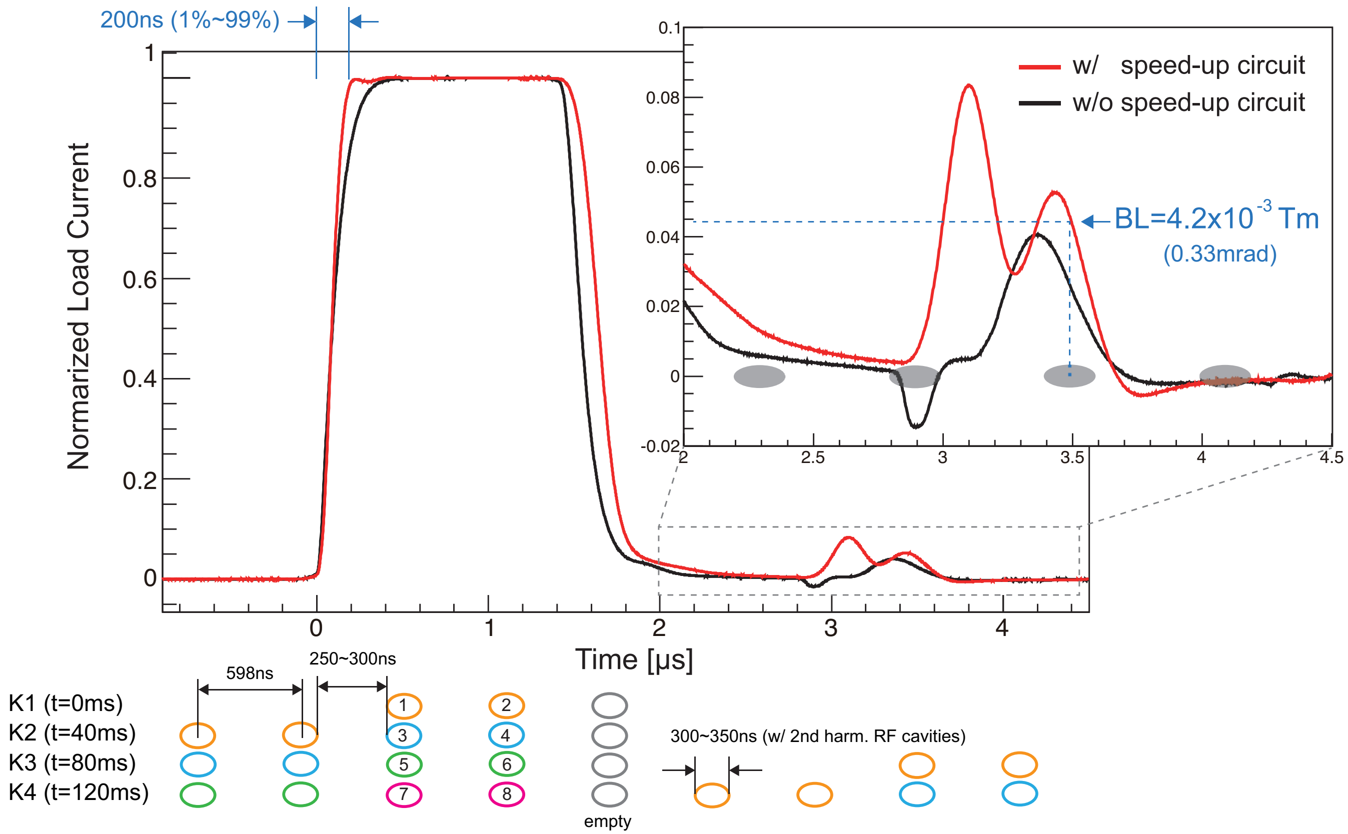
RF fundamental (kV)



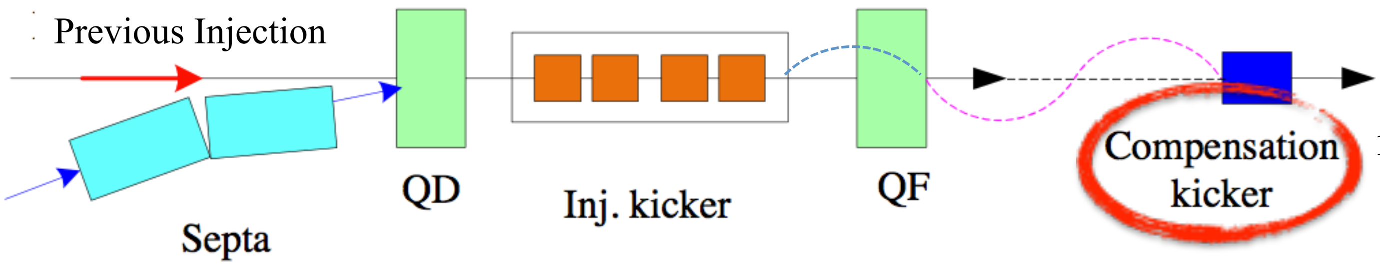
RF 2nd harmonic (kV)



Injection Kicker Waveform



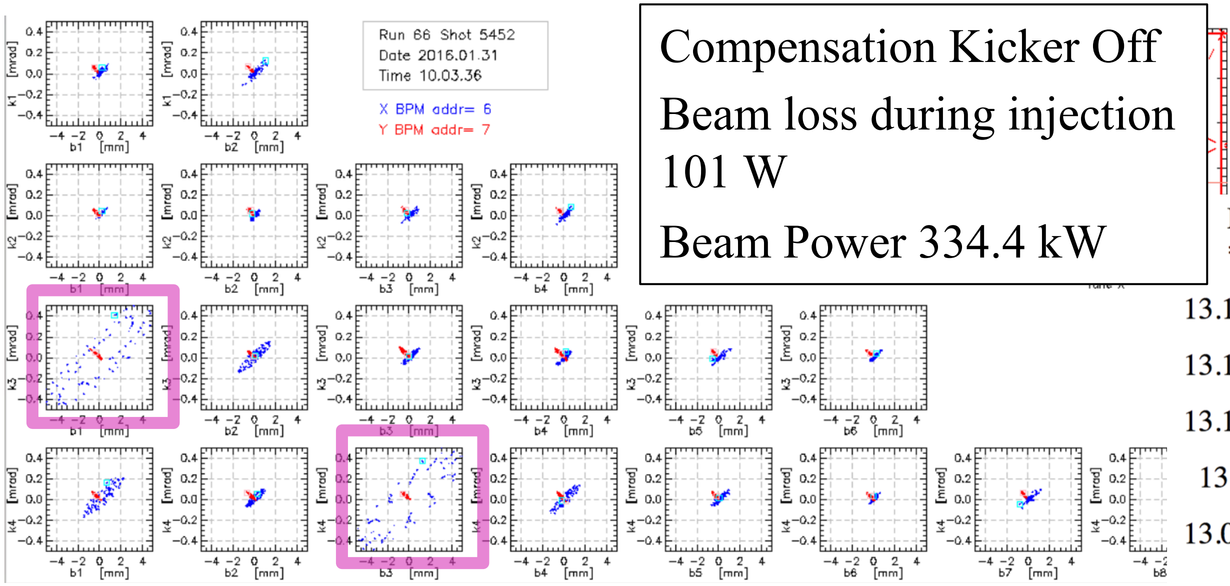
- Rise time is improved with speed up circuit.
- Tail is suppressed with tail matching circuit.
- Reflection kicks circulating beam.



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



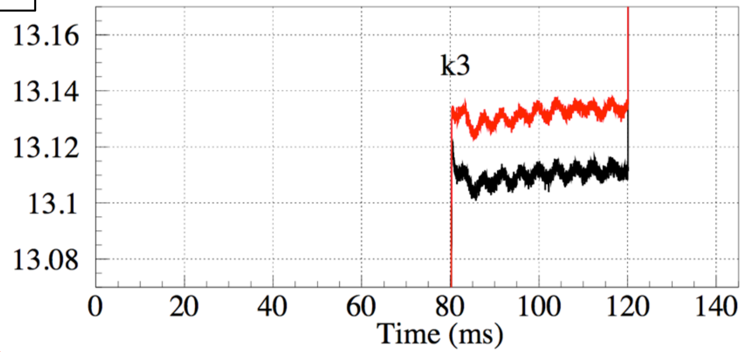
Compensation Kicker Off

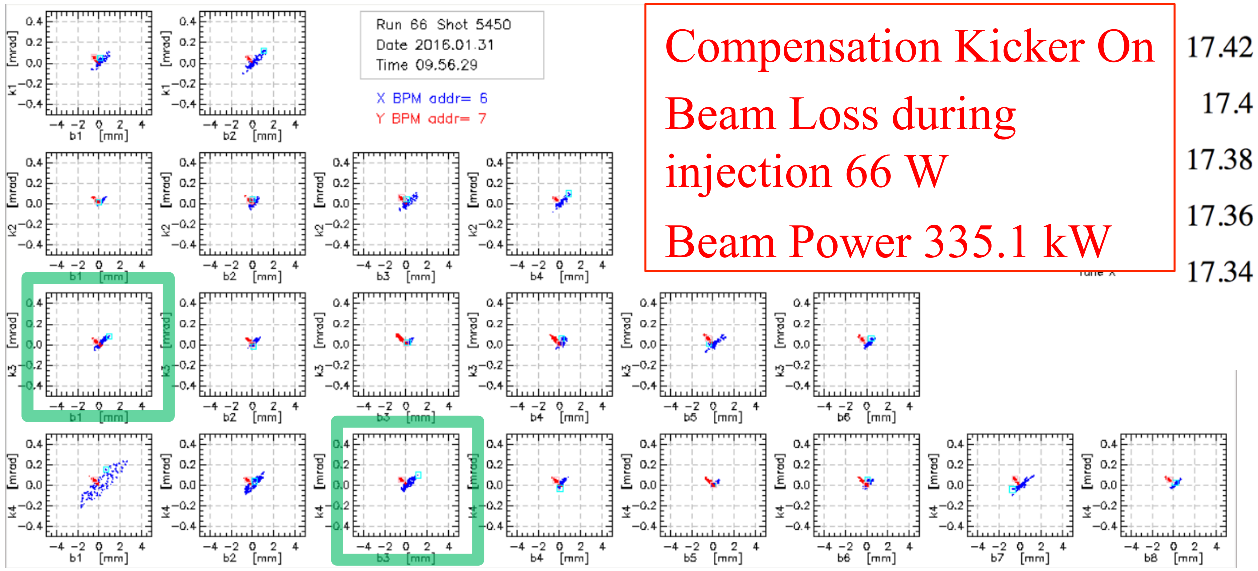
Beam loss during injection 101 W

Beam Power 334.4 kW

Beam Intensity Compensation Kicker On /Off

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

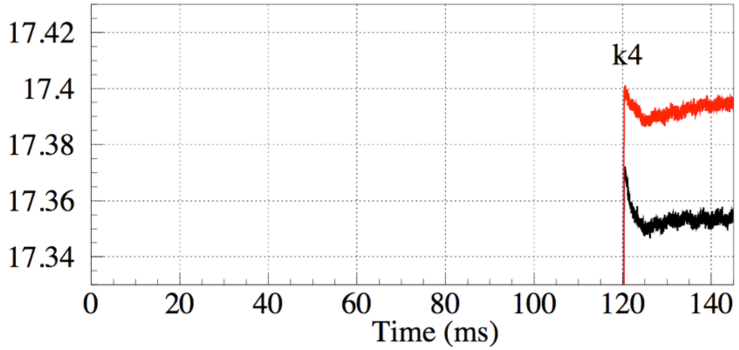




Compensation Kicker On

Beam Loss during injection 66 W

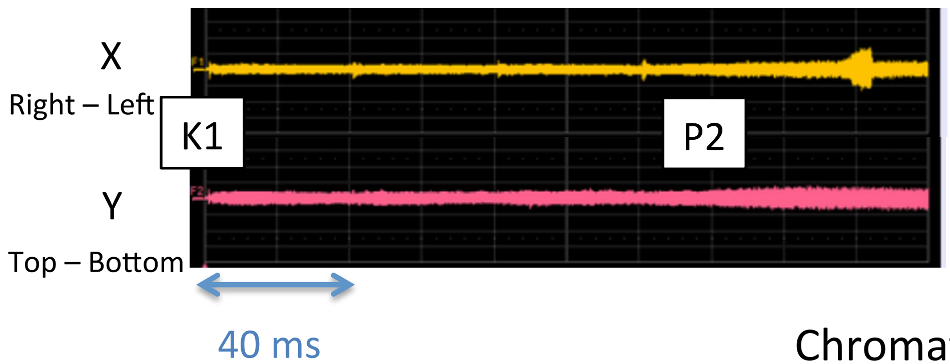
Beam Power 335.1 kW

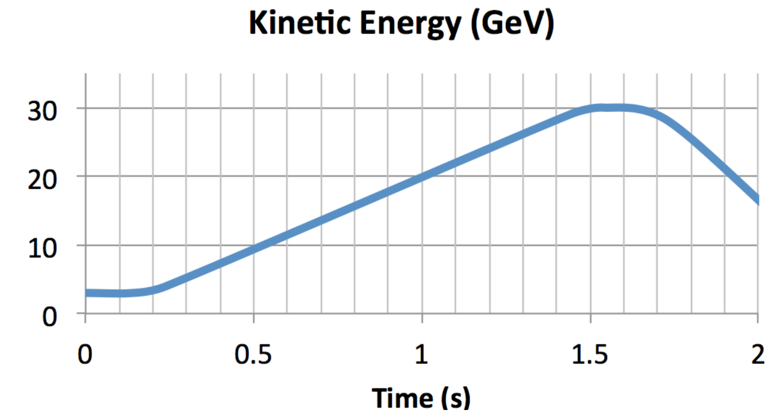


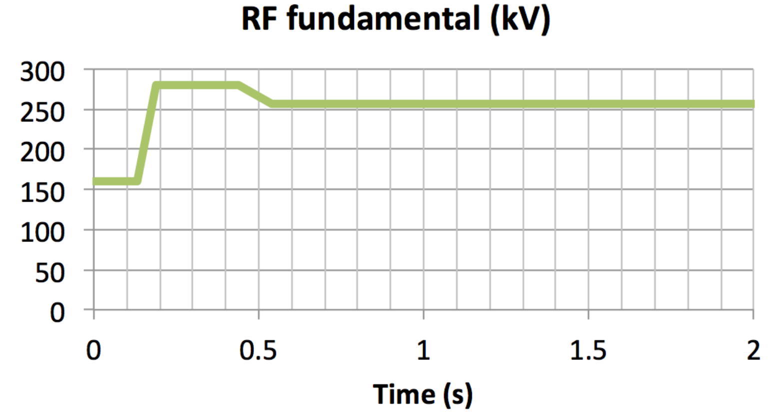
Chromaticity Pattern for Instability Suppression

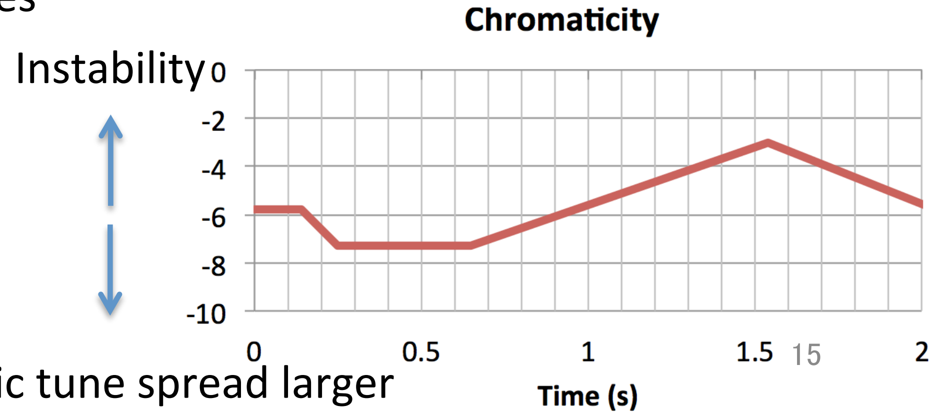
- The chromaticity pattern was optimized to minimize the beam loss.
- To suppress instabilities the chromaticity is kept to be negative, typically −6 during injection.
- If the chromaticity is too small in negative value, we observe instability.
- If the chromaticity is too large in negative value, we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

Single Pass Monitor   2.53e13 ppb * 8 bunches







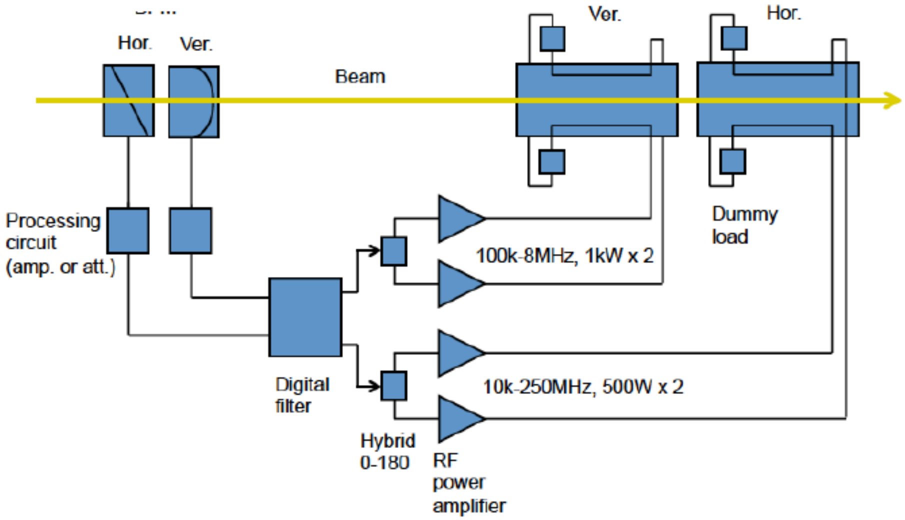


Chromatic tune spread larger

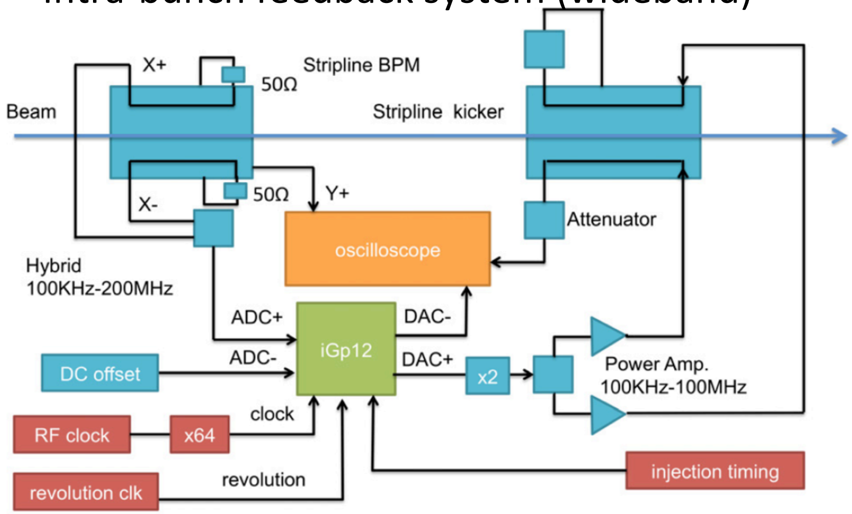
Bunch by Bunch and Intra-bunch Feedback

- 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)

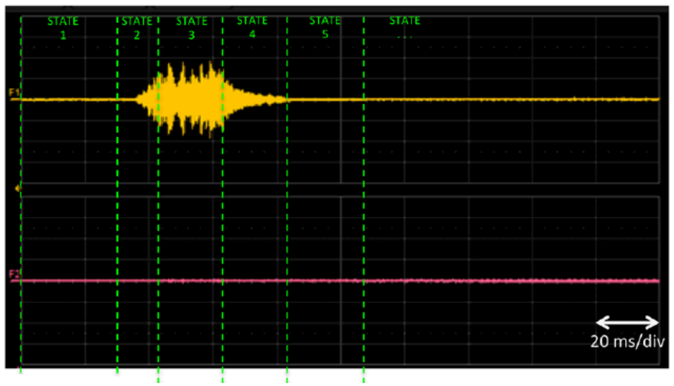


2.1e13 ppb
× 2 bunches

Beam Position with Intra-bunch FB off

Δx

Δy

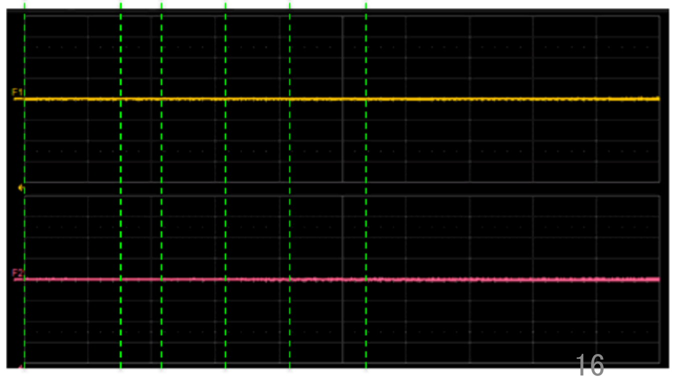


P1+100 ms P2

Beam Position with Intra-bunch FB on

Δx

Δy

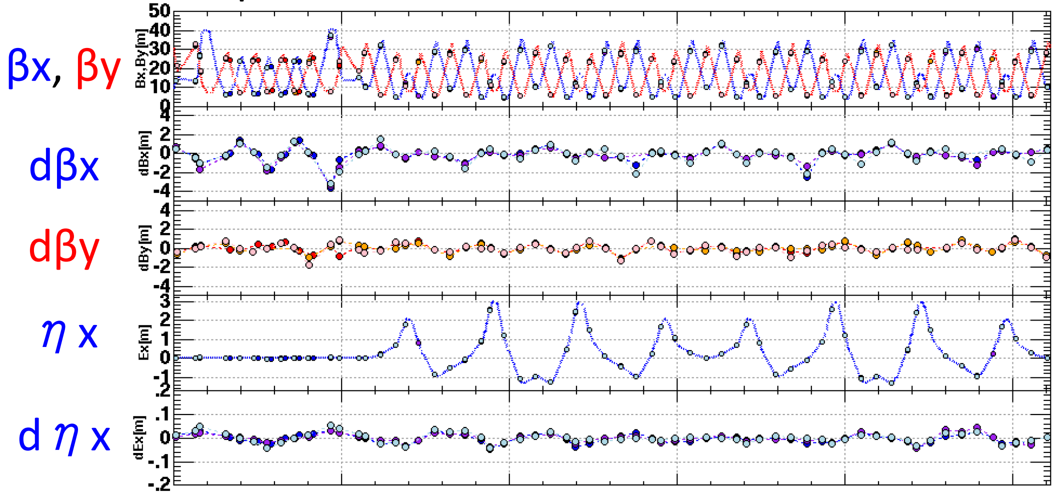


P1+100 ms P2

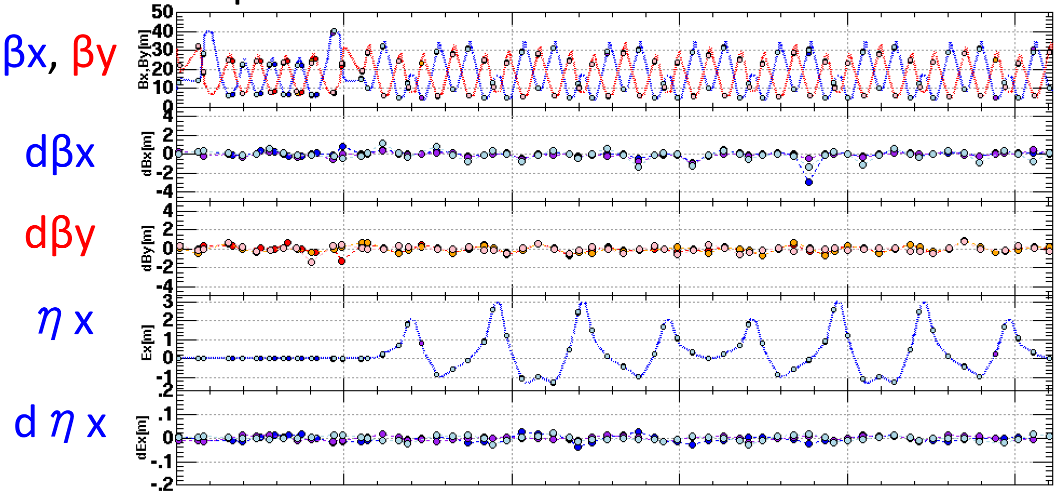
Optics Measurement and Correction

- 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.

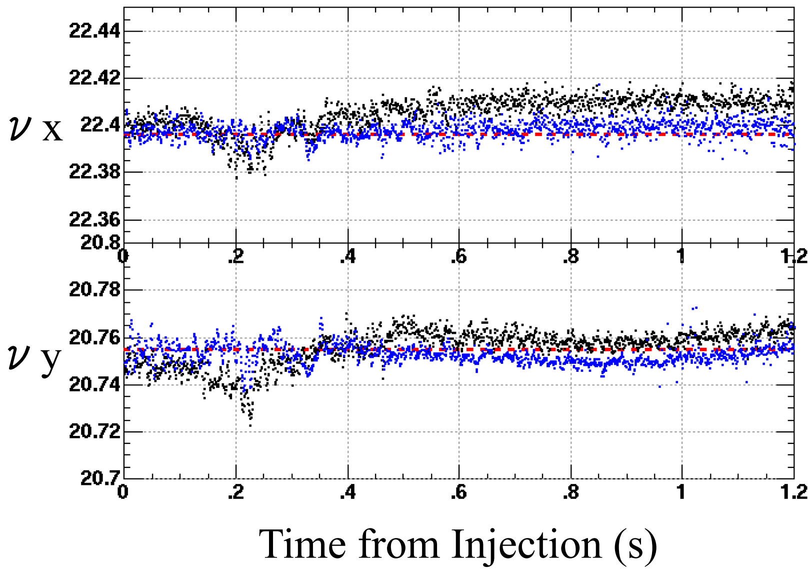
Optics before Correction at P1+300 ms



Optics after Correction at P1+300 ms



Tune before and after Correction

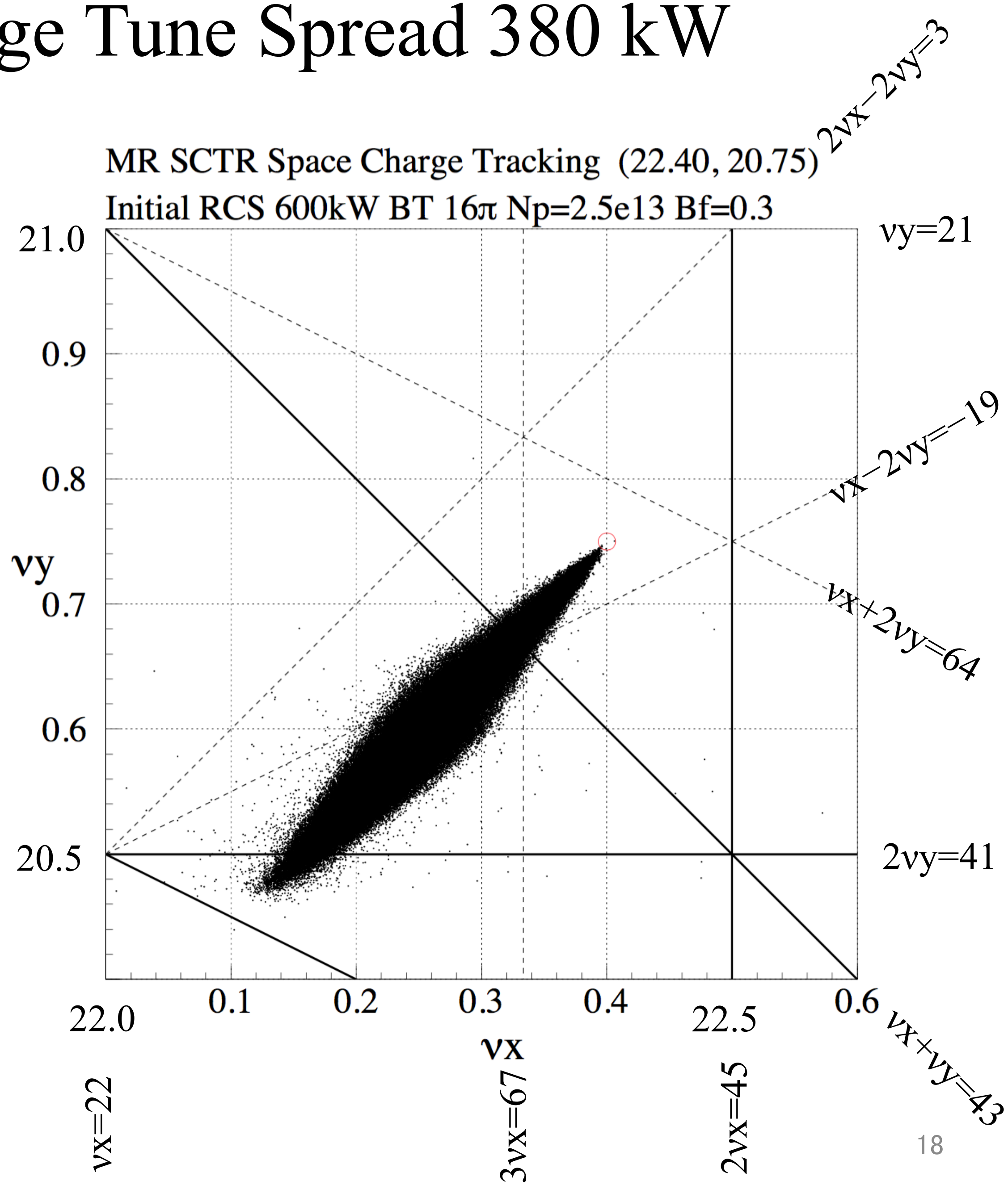


Space Charge Tune Spread 380 kW

- 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

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

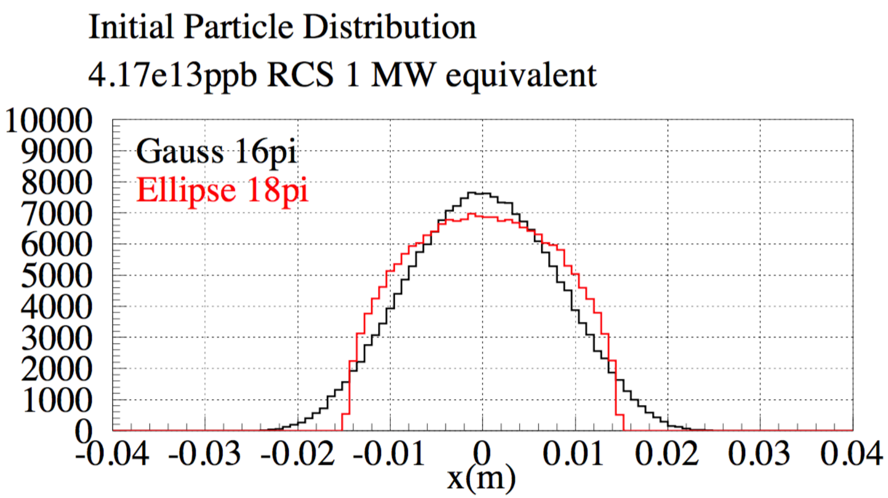
- E = 3 GeV
- $(v/c)^2\gamma^3$=69.751
- $2\pi RN = 2.5\times10^{13}\times9$: Intensity
- $4\pi\sigma^2/\beta$ = 16π mmmrad : Emittance
- B_f = 0.3 : Bunching factor

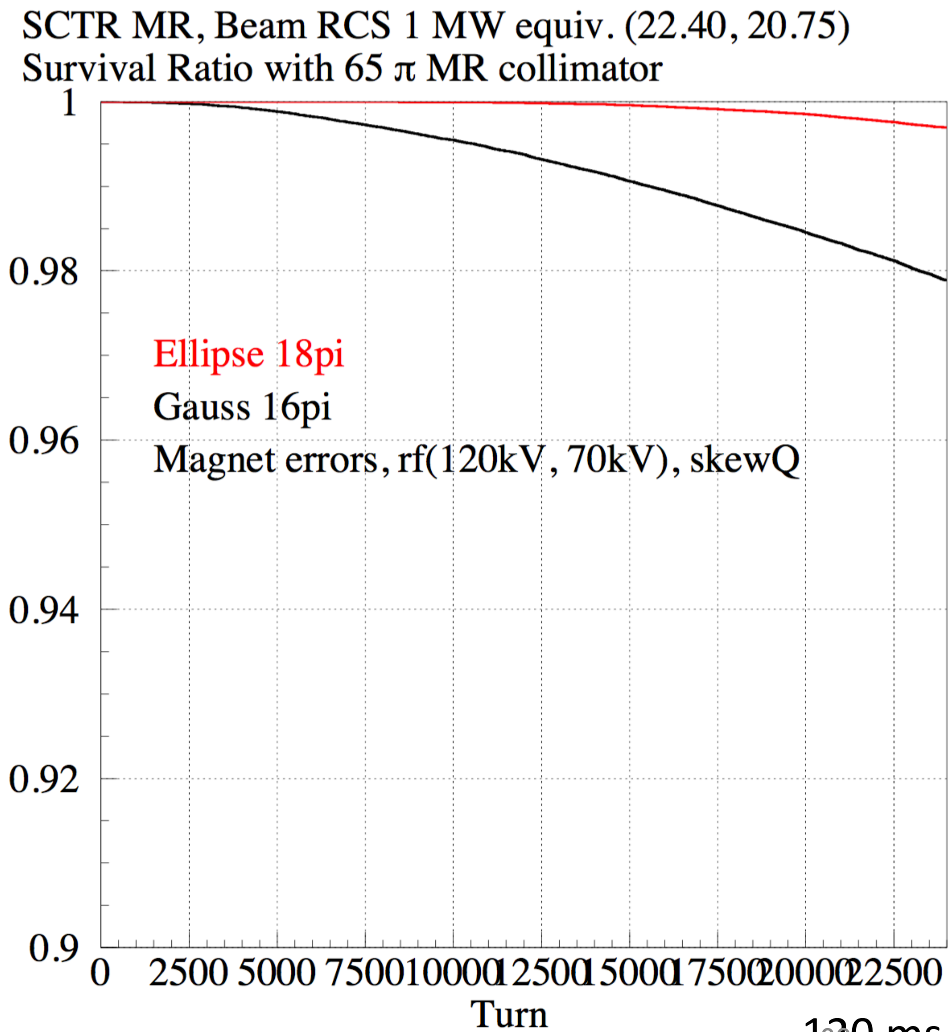


For Further Beam Intensity Improvement

Particle Tracking Simulation with Space Charge Effects

- Simulation results with Space Charge Tracking (SCTR)
- Multi particle tracking code by Ohmi san with the particle in cell method.
- RCS beam power : 1 MW equiv.
- Number of protons : 3.3e14 ppp
- MR cycle: 1.2 s
- MR beam power : 1.3 MW equiv. (if there is no beam loss)

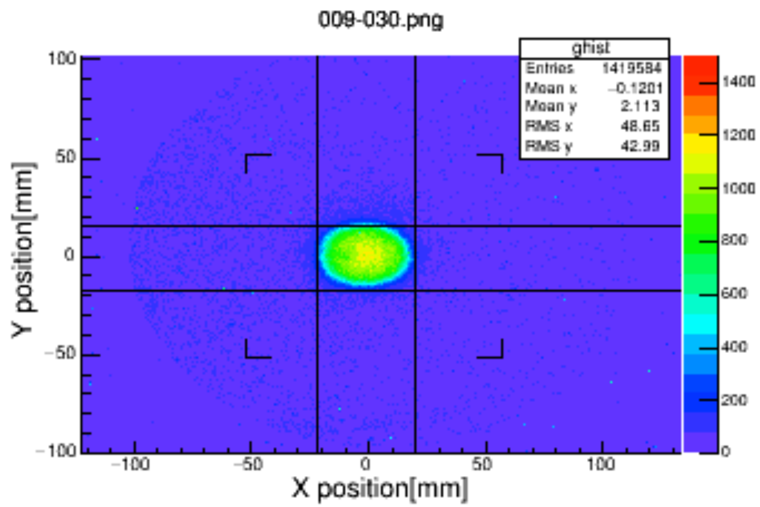




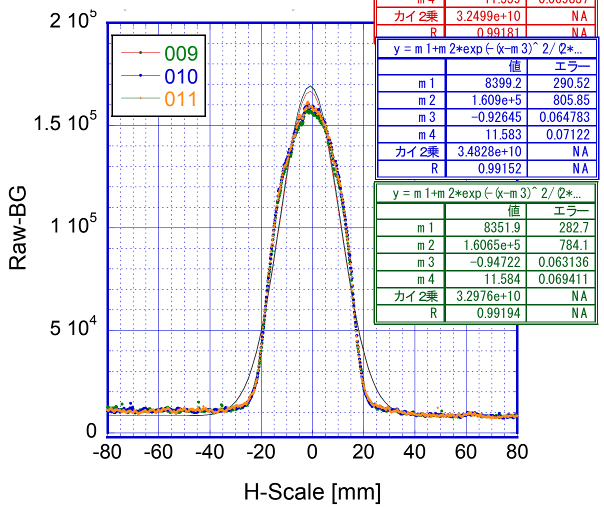
120 ms

Injection Beam Distribution

- One of the RCS study itmes is to optimize the parameters such as painting, operation tune and chromaticity for high intensity MR operation.
- Transverse beam profiles were measured with OTR at 3-50BT.
- Beam Intensity 3.48e13 ppb
- RCS 830 kW equiv., MR 540 kW equiv.
- RCS 50π correlated paint



Hori. emit. (full)
26.8π mmmrad

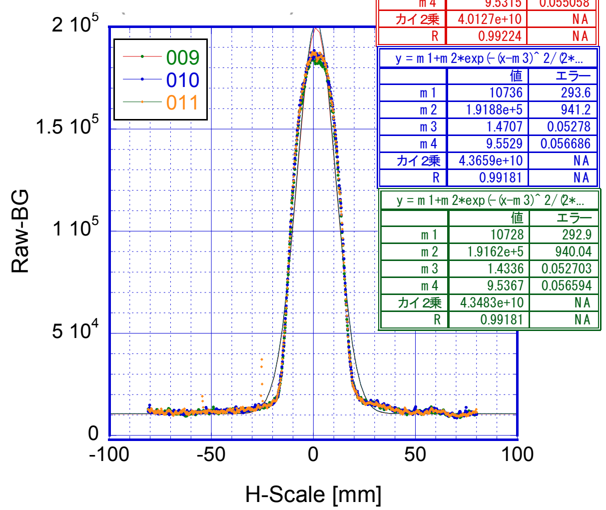


y = m 1+m 2*exp (- (x-m 3)^ 2/ (2*...	値	エラー
m 1	8379.2	280.46
m 2	1.5829e+5	779.15
m 3	-0.93994	0.063543
m 4	11.559	0.069837
カイ 2乗	3.2499e+10	NA
R	0.99181	NA

y = m 1+m 2*exp (- (x-m 3)^ 2/ (2*...	値	エラー
m 1	8399.2	290.52
m 2	1.609e+5	805.85
m 3	-0.92645	0.064783
m 4	11.583	0.07122
カイ 2乗	3.4828e+10	NA
R	0.99152	NA

y = m 1+m 2*exp (- (x-m 3)^ 2/ (2*...	値	エラー
m 1	8351.9	282.7
m 2	1.6065e+5	784.1
m 3	-0.94722	0.063136
m 4	11.584	0.069411
カイ 2乗	3.2976e+10	NA
R	0.99194	NA

Vert. emit. (full)
24.6 mmmrad



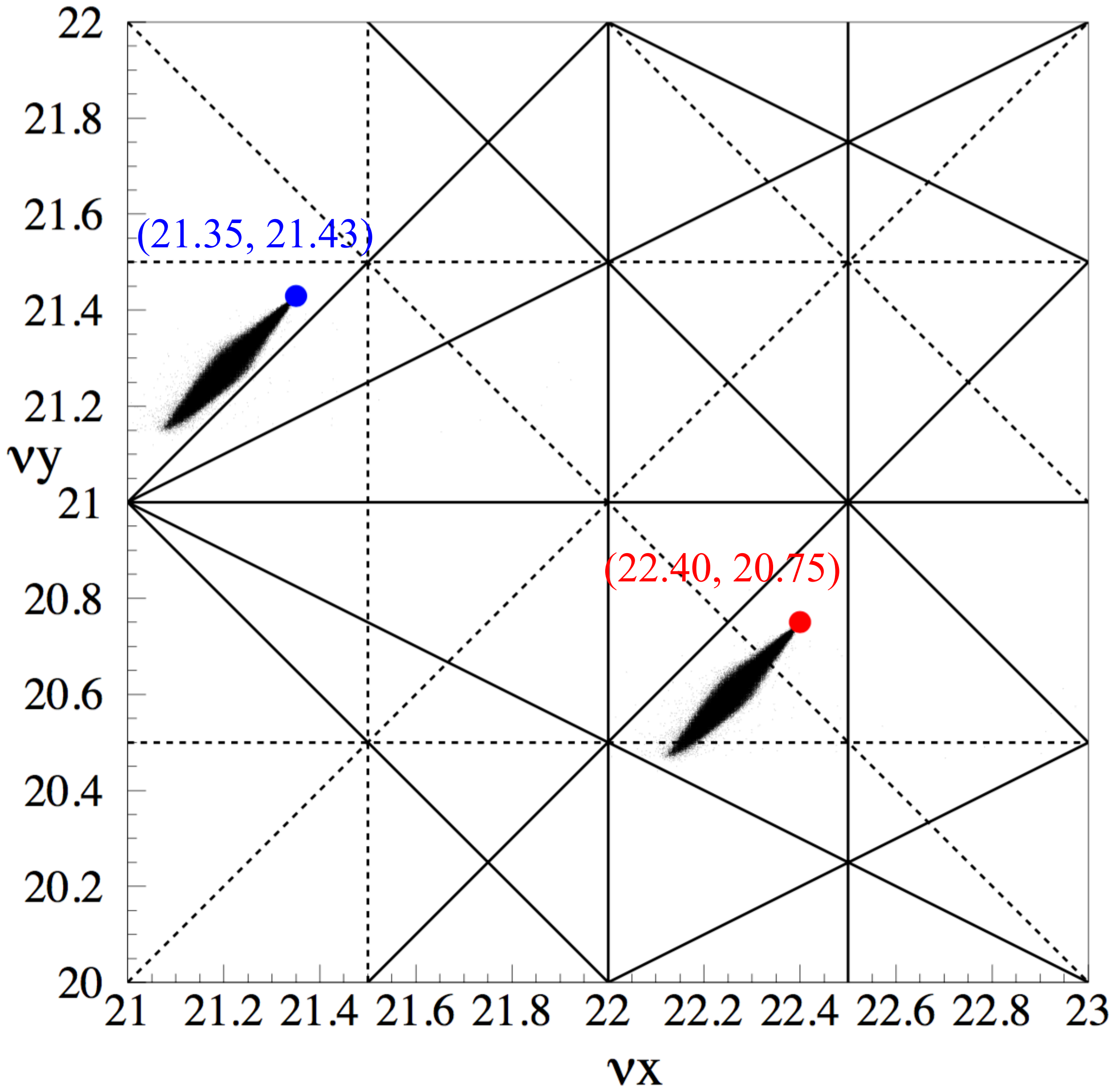
y = m 1+m 2*exp (- (x-m 3)^ 2/ (2*...	値	エラー
m 1	10628	281.33
m 2	1.8915e+5	903.26
m 3	1.4632	0.051275
m 4	9.5315	0.055058
カイ 2乗	4.0127e+10	NA
R	0.99224	NA

y = m 1+m 2*exp (- (x-m 3)^ 2/ (2*...	値	エラー
m 1	10736	293.6
m 2	1.9188e+5	941.2
m 3	1.4707	0.05278
m 4	9.5529	0.056686
カイ 2乗	4.3659e+10	NA
R	0.99181	NA

y = m 1+m 2*exp (- (x-m 3)^ 2/ (2*...	値	エラー
m 1	10728	292.9
m 2	1.9162e+5	940.04
m 3	1.4336	0.052703
m 4	9.5367	0.056594
カイ 2乗	4.3483e+10	NA
R	0.99181	NA

Operation with the Betatron Tune of (21.35, 21.43)

We search for the MR condition to accept the RCS beam of 1MW equivalent.



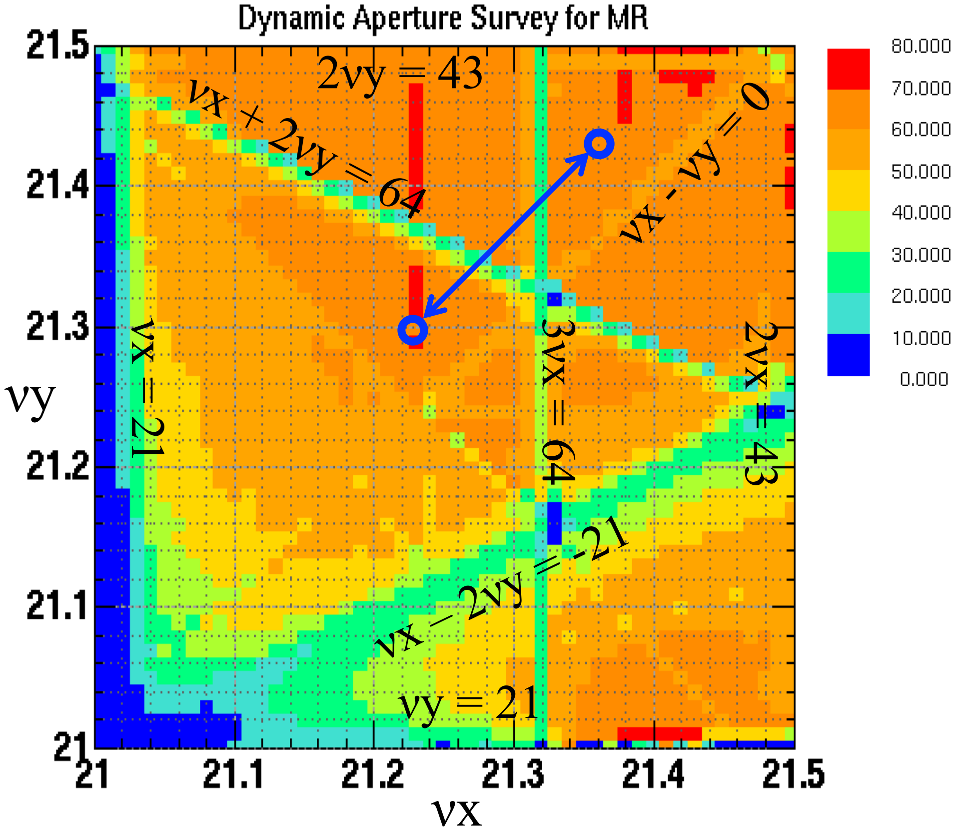
Space charge tune spread is for MR 380 kW equiv. and RCS 600 kW equiv.

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

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

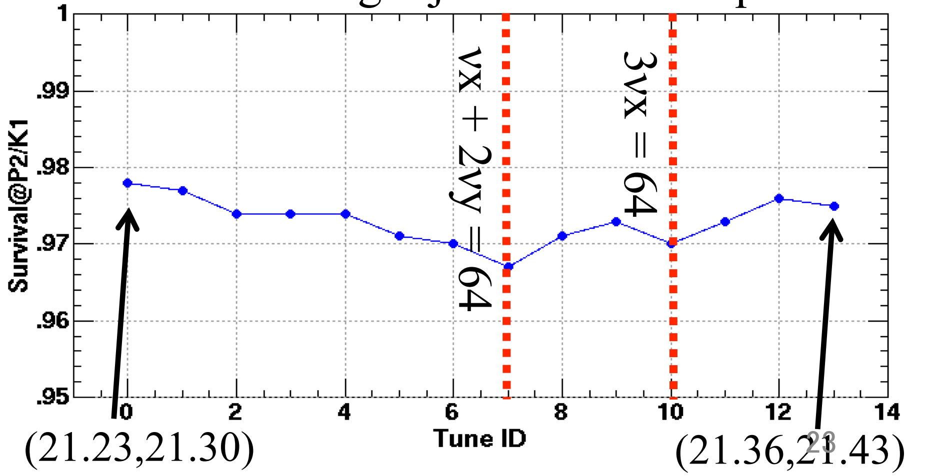
Optimization for (21.x, 21.x)

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



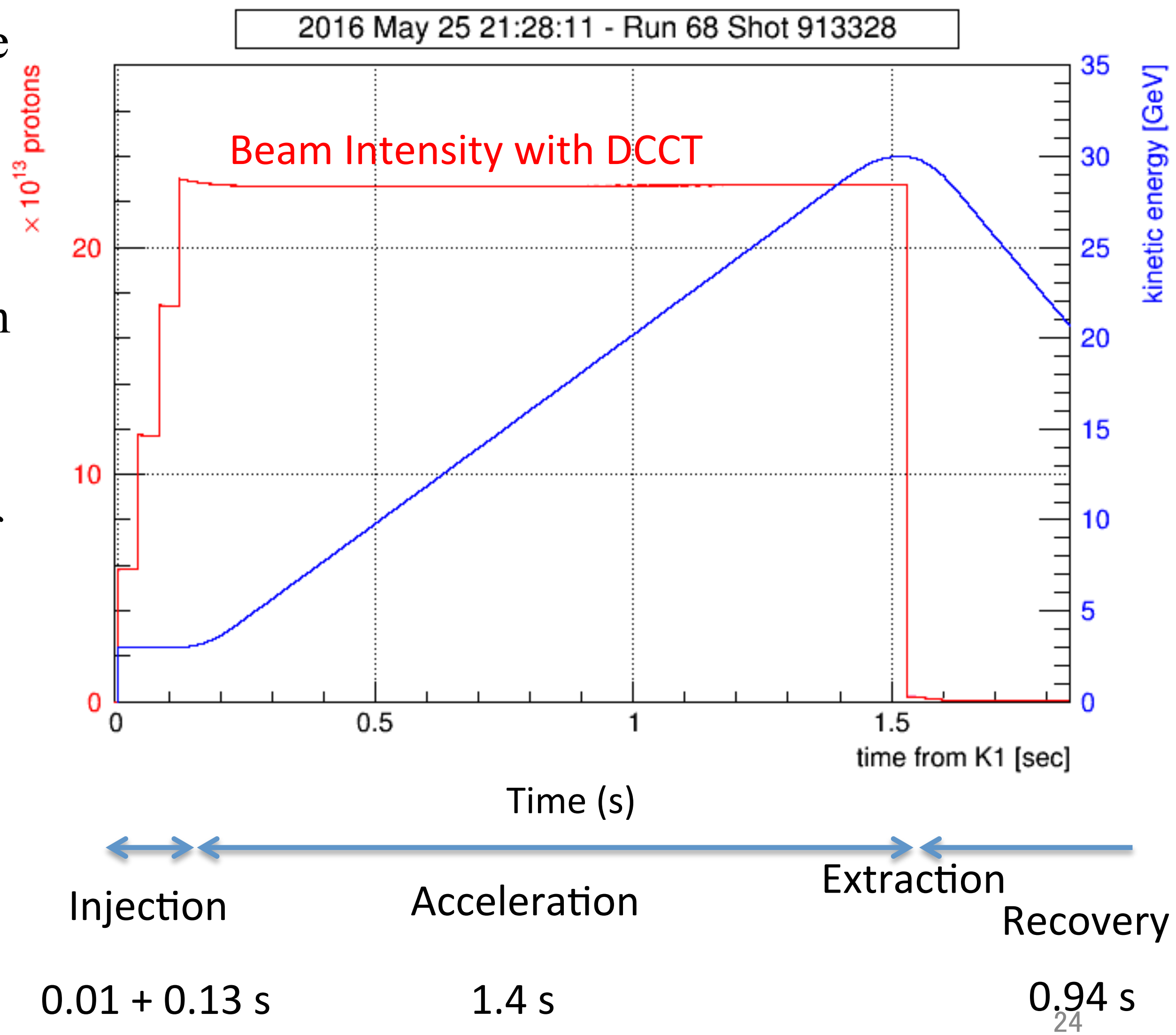
- Optics correction
- Tune scan
- 2nd rf operation
- Trim Q correction for FX septum mag.
- Trim S correction for 3rd order res.
- Skew Q correction for νx − νy = 0
- Octupole correction
- Instability suppression
  - Chromaticity: −7
  - Bunch by bunch and intra-bunch FB
- Extraction orbit for neutrino beamline

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.



Summary

- Beam power of 425 kW has been achieved for FX user operation with 2.2e14 ppp.
  - Rf pattern optimization for fundamental and 2nd harmonic
  - Injection kicker improvements
  - Bunch by bunch feedback and intra-bunch feedback
  - Optics correction
  - Resonance corrections
- We plan to achieve the target beam power of 750 kW and more with the faster cycling 2.48 s to 1.3 s and 2e14 ppp.
- For further beam intensity improvement
  - Optimization of injection beam distribution by RCS tuning
  - Operation with the betatron tune of (21.35, 21.43) has been started.