Beam commissioning of J-PARC 3-GeV RCS (TUO3C06)

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WG-D of HB2012, Beijing, China

2012/09/18 (TUE)

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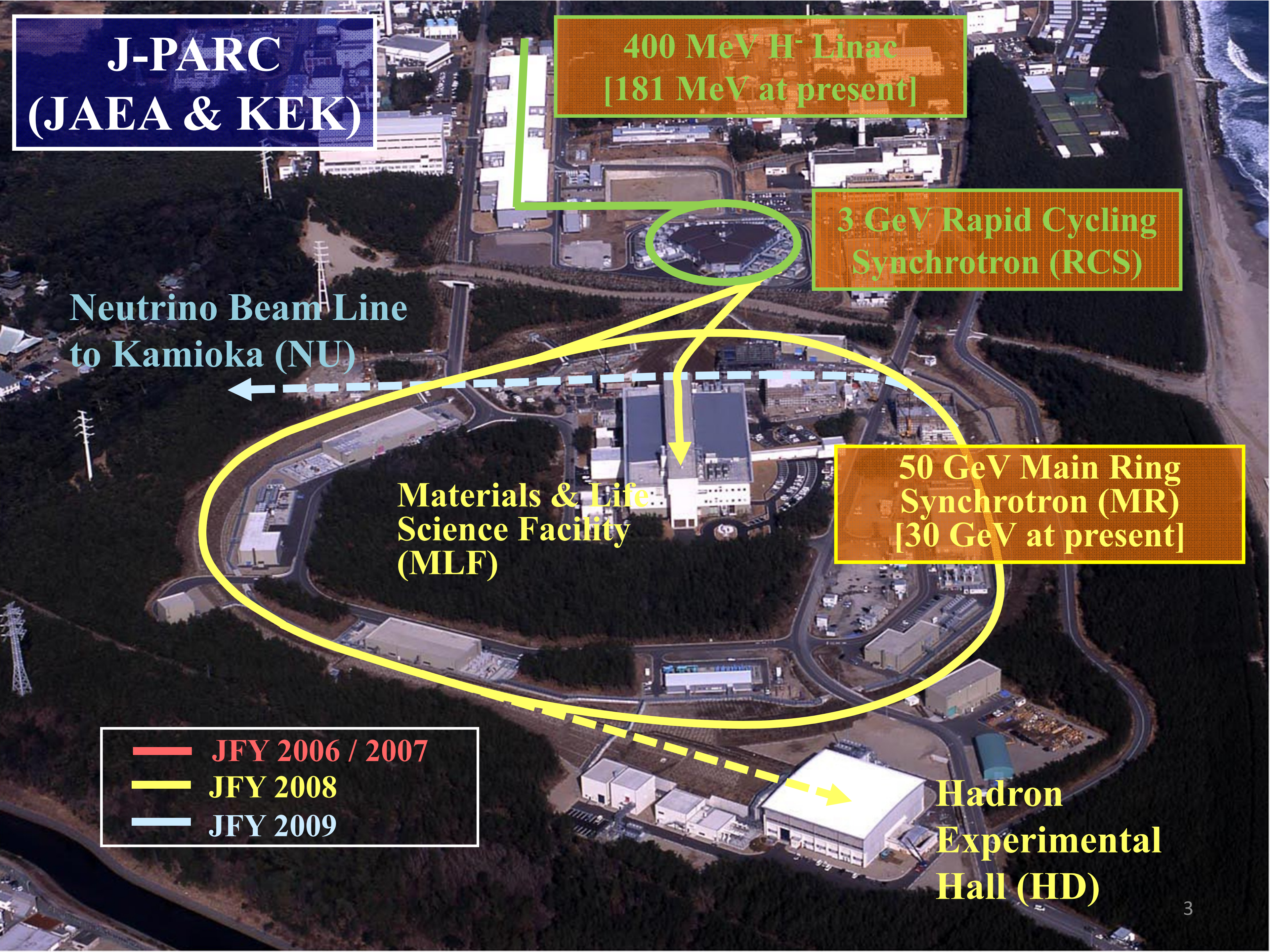
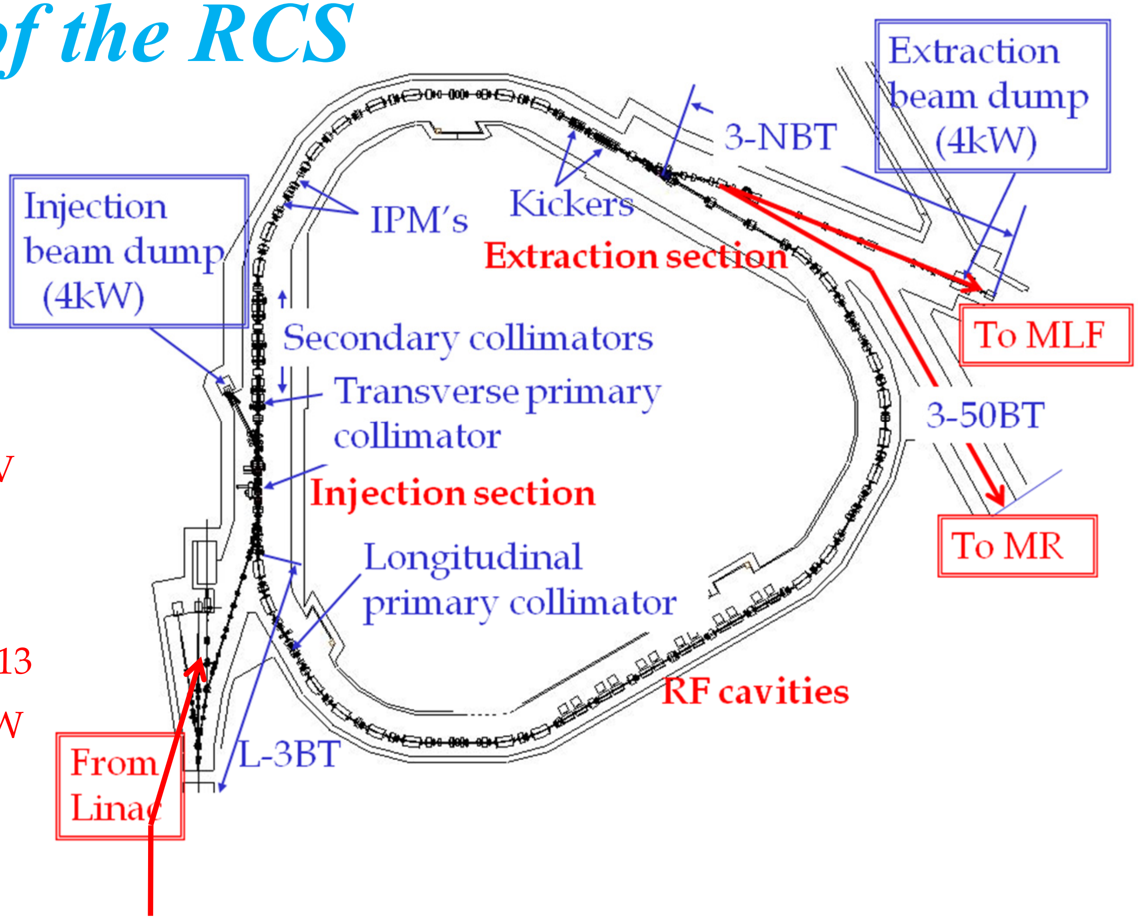


J-PARC
(JAEA & KEK)
400 MeV H- Linac
[181 MeV at present]
3 GeV Rapid Cycling
Synchrotron (RCS)
Neutrino Beam Line
to Kamioka (NU)
Materials & Life
Science Facility
(MLF)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
JFY 2006 / 2007
JFY 2008
JFY 2009
Hadron
Experimental
Hall (HD)

Design parameters of the RCS

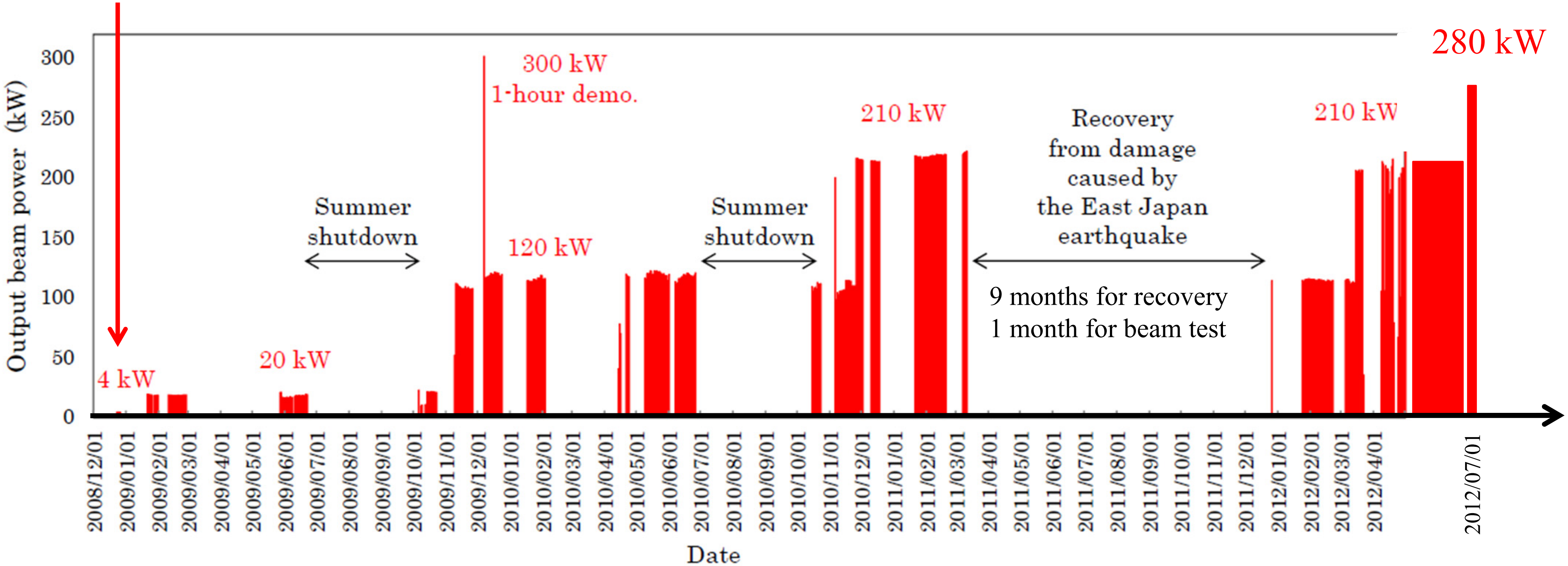
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
No of bunch	2
Injection energy	181 MeV ⇒ 400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	2.5e13 - 5e13 ⇒ 8.3e13
Output beam power	300–600 kW ⇒ 1 MW
Transition gamma	9.14 GeV
Number of dipoles	24
quadrupoles	60 (7 families)
sextupoles	18 (3 families)
steerings	52
RF cavities	12 (11 at present)
Collimator Limit	4 kW(3%@ injection for 1MW)



Upgrade of injection energy and peak current from Linac: Summer 2013

History of the RCS output beam power

- Beam commissioning of the linac ; November 2006~
- Beam commissioning of the RCS ; October 2007~
- Startup of the MLF user operation ; December 2008~

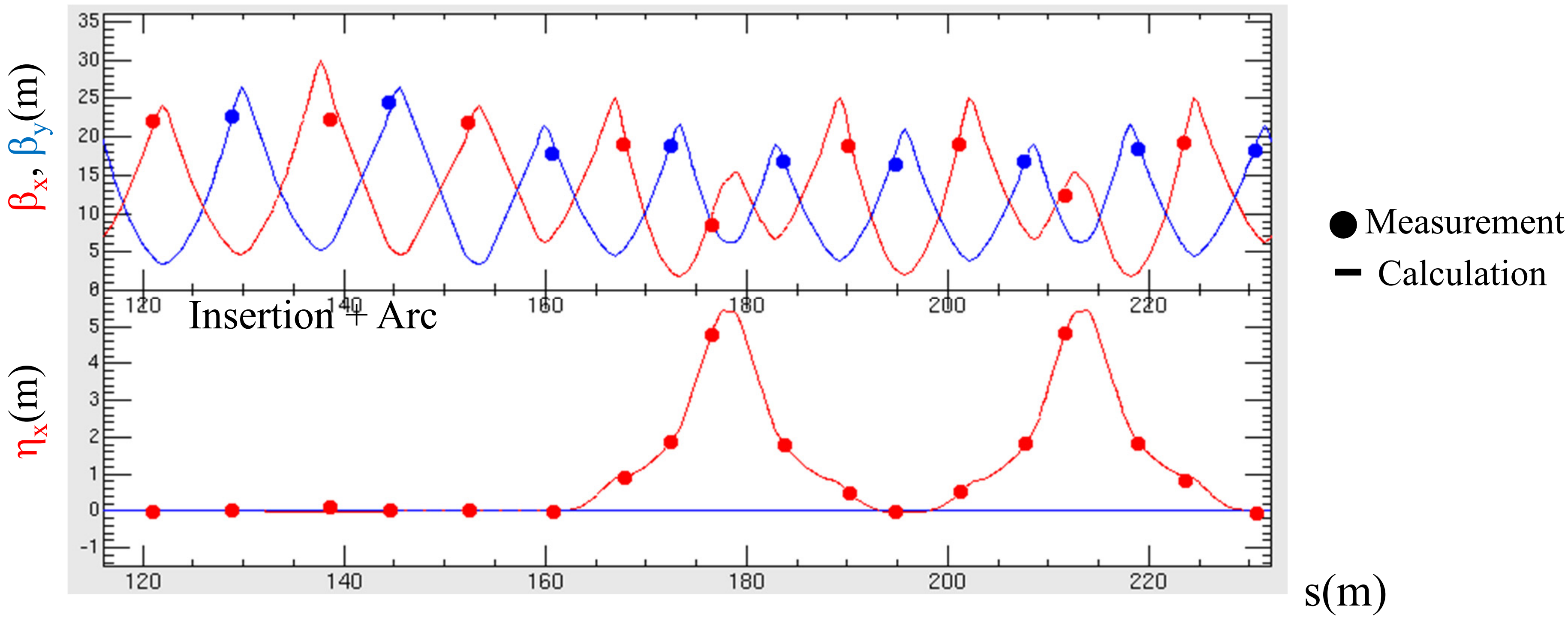


The RCS output beam power has been steadily increasing following;

- Progression of beam tuning,
- Hardware improvements,
- Careful monitoring of the trend of residual activation levels.

Current RCS output beam power of user operation : 280 kW
Maximum RCS output beam power of beam studies : 420 kW-eq. (1shot)

RCS lattice property

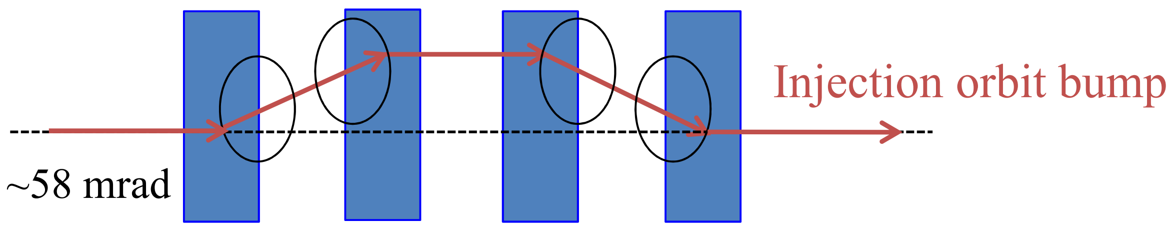


In the beam tuning, the RCS had several lattice imperfections.

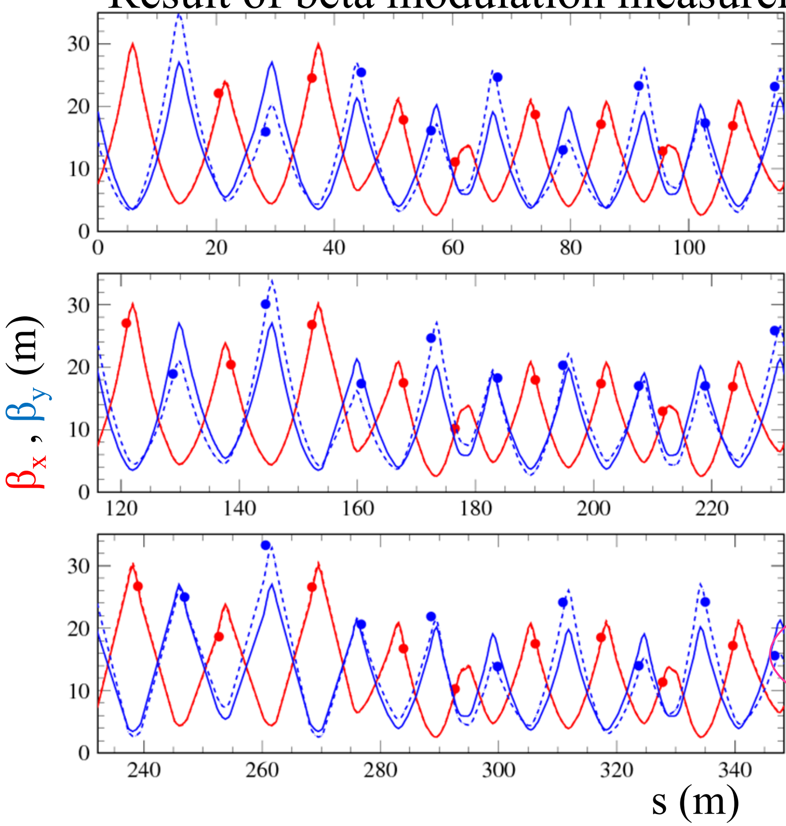
- Edge focus caused by injection orbit bump
- Leakage fields caused by extraction beam line DC magnets

Beam-based measurements of lattice imperfections in the RCS - I -

- Edge focus of the injection-bump magnets
  (0.5 ms flattop + 0.5 ms fall time)



Result of beta modulation measurements



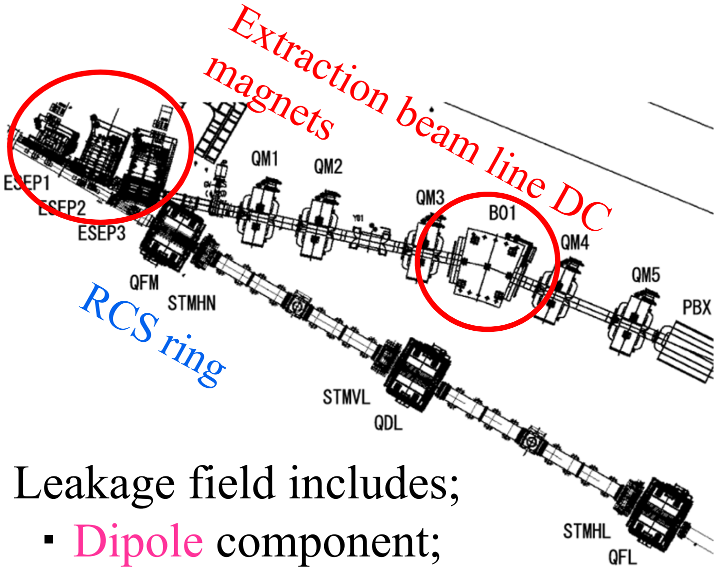
Beta modulation caused by the edge focus;
- makes a distortion of the lattice super-periodicity
- drives random lattice resonances.

Horizontal beta function
Vertical beta function
● measurement (injection bump ; ON)
···· calculation (injection bump ; ON)
— calculation (injection bump ; OFF)

Edge focus estimated; K_1~-0.003335m^{-1}

Beam-based measurements of lattice imperfections in the RCS - II -

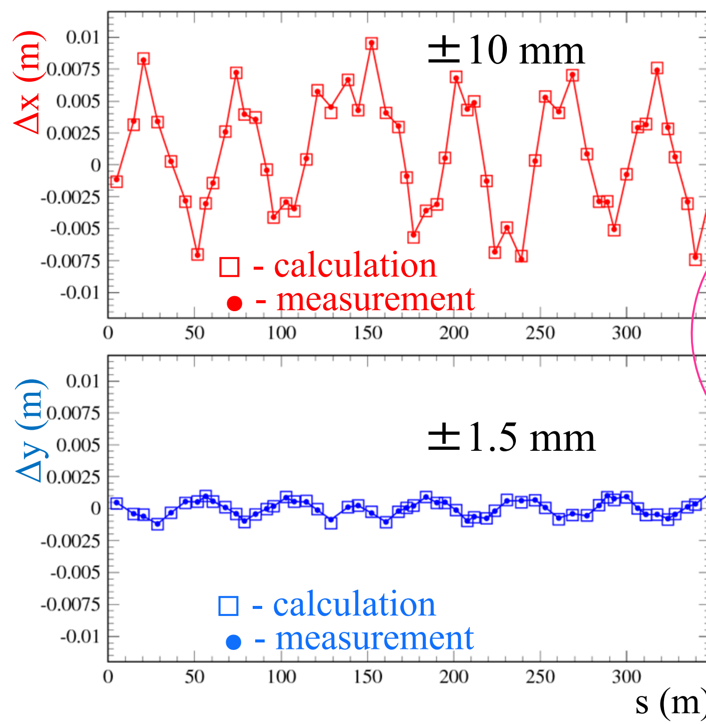
- Leakage fields from the extraction beam line DC magnets;
  - evaluation of dipole and normal quadrupole components



Leakage field includes;

- Dipole component;
  - makes COD
  (correctable by steering magnets)
- Normal quadrupole component;
  - makes a distortion of the lattice super-periodicity
  - drives random lattice resonances
- Skew quadrupole component;
  - causes linear coupling

COD caused by the leakage fields



Dipole component estimated;
-1.14 mrad (hor.)
-0.12 mrad (ver.)

Normal quadrupole component estimated from the optics measurements; 0.0048 m^{-1}

Beam-based measurements of lattice imperfections in the RCS - II -

- Leakage fields from the extraction beam line DC magnets;
  - evaluation of skew quadrupole component

Orbit leak (Δy) to the vertical plane by a horizontal single kick

Systematic measurement of two normal mode betatron tunes ($\nu_{\pm}$) near a linear coupling resonance

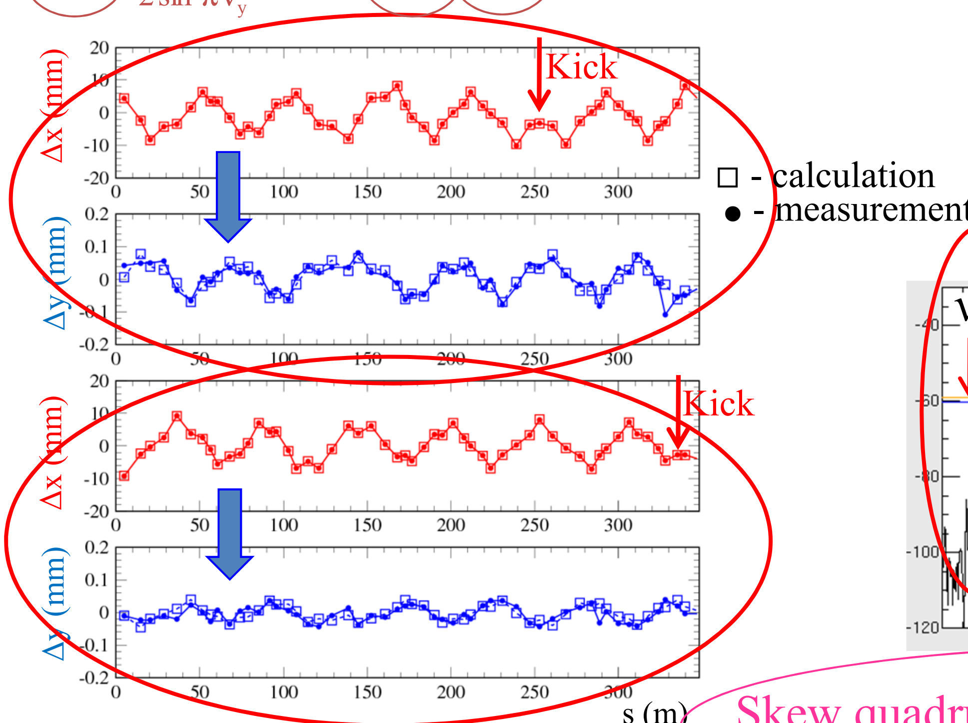
$$\Delta y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin \pi\nu_y} \oint \sqrt{\beta_y(s')}\, SK_1(s')\, \Delta x(s') \cos(|\phi_y(s') - \phi_y(s)| - \pi\nu_y)\, ds'$$

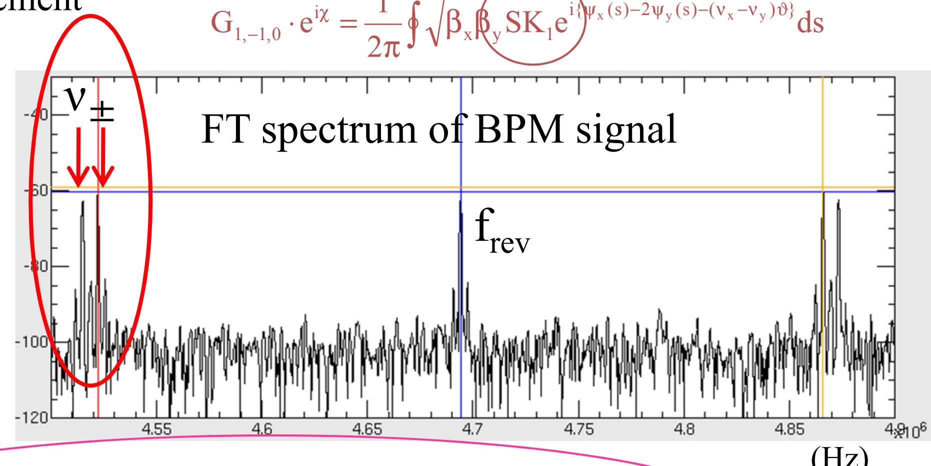
$$x_n = A_+ \cos(\nu_+\varphi + \xi_+) - \frac{G_{1,-1,0}}{\lambda + |\delta|} A_- \cos(\nu_-\varphi + \xi_-),$$

$$y_n = \frac{G_{1,-1,0}}{\lambda + |\delta|} A_+ \cos(\nu_+\varphi + \xi_+) + A_- \cos(\nu_-\varphi + \xi_-),$$

where $\nu_{\pm} = \frac{1}{2}(\nu_x + \nu_y) \pm \frac{1}{2}\sqrt{(\nu_x - \nu_y)^2 + |G_{1,-1,0}|^2},$

$$G_{1,-1,0} \cdot e^{i\chi} = \frac{1}{2\pi} \oint \sqrt{\beta_x \beta_y}\, SK_1 e^{i\{\psi_x(s) - 2\psi_y(s) - (\nu_x - \nu_y)\vartheta\}} ds$$

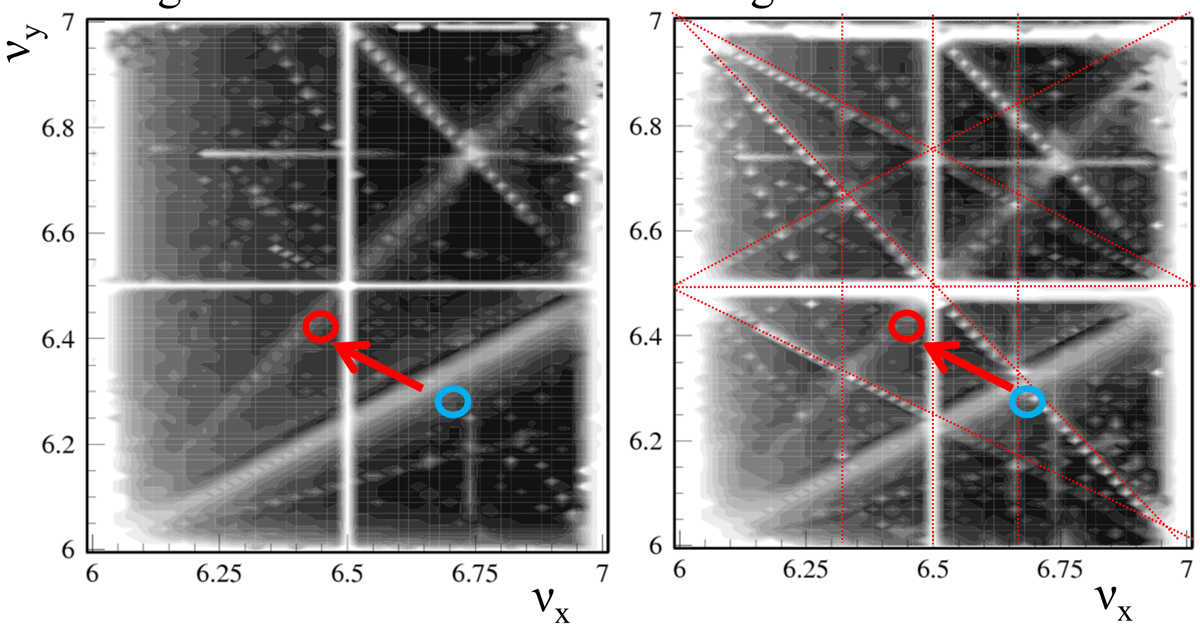




Skew quadrupole component estimated; $-0.00112\ m^{-1}$

Tune diagram and operating point

Without the measured "edge focus & leak fields" | With the measured "edge focus & leak fields"



: Designed operating point (6.68,6.27)

: Current operating point (6.45,6.42)

Edge focus and leakage field; enhance
- linear coupling resonance,
- 3-rd order random resonances,

make
- strong limit for tunability.
- smaller dynamic aperture

Transverse painting emittance decreases ⇒ large tune spread
Operating point for high-intensity beam were re-optimized to (6.45, 6.42).

In order to get more stable and flexible tune space,
we plan to
- install additional magnetic shields
  for reducing the leakage field (in 2012 Summer shutdown)
- introduce quadrupole correctors
  for compensating the edge focus effect (in 2013 Summer-Autumn shutdown)

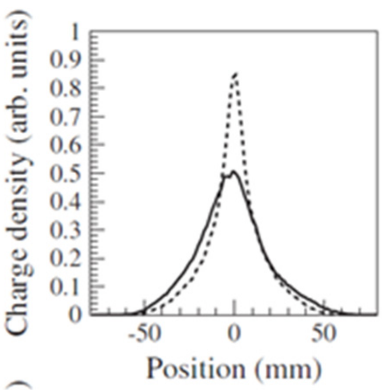
Painting injection technique for high-intensity beam

Transverse painting

Transverse painting makes use of a controlled phase space offset between the centroid of the injection beam and the ring closed orbit

Painting emittance tested in the present beam experiment;

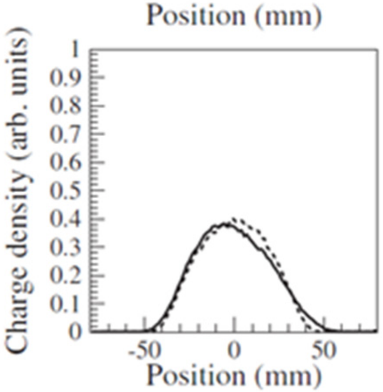
ε_{tp}= 100 π mm mrad



No painting

Horizontal

Vertical



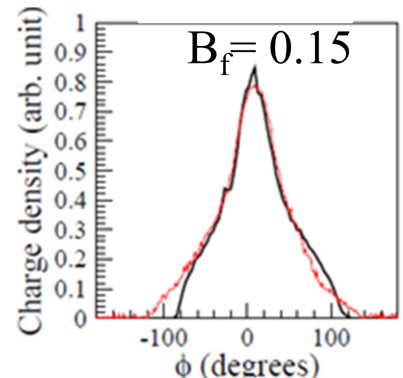
100π correlated painting

Longitudinal painting

Longitudinal painting makes use of a controlled momentum offset Δp/p to the rf bucket in combination with superposing a second harmonic rf voltage V_2 and phase sweep ϕ_2 of V_2

V_2/V_1=80%, ϕ_2=-100 to 0 deg

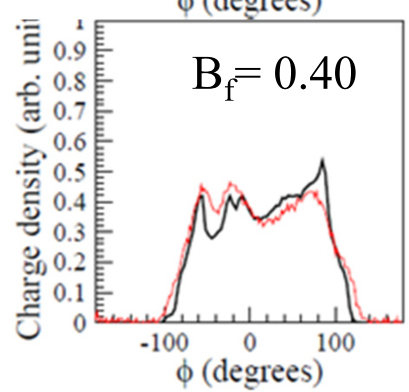
Δp/p= -0%, -0.1%, -<u>0.2%</u>



No painting

Measurements (WCM)

Numerical simulations



V_2/V_1=80%

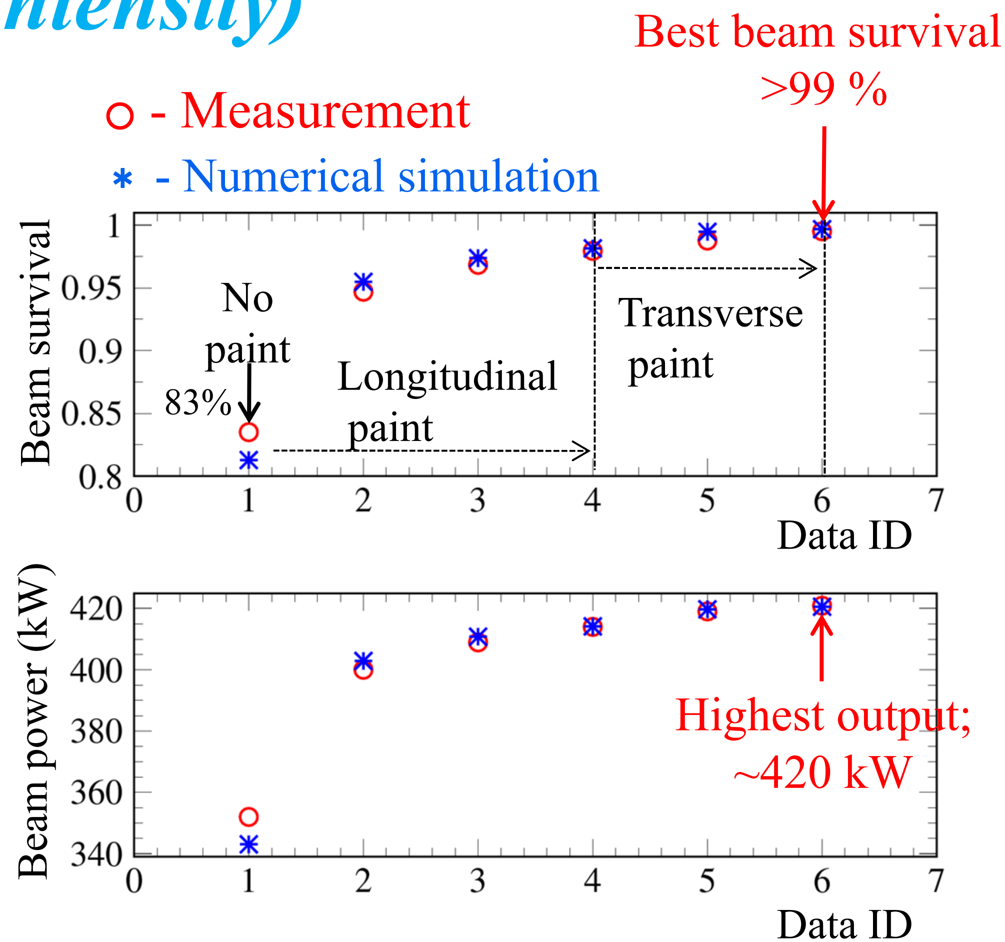
ϕ_2=-100 to 0 deg

Δp/p=-<u>0.2%</u>

Beam survival rate in the RCS (output intensity/input intensity)

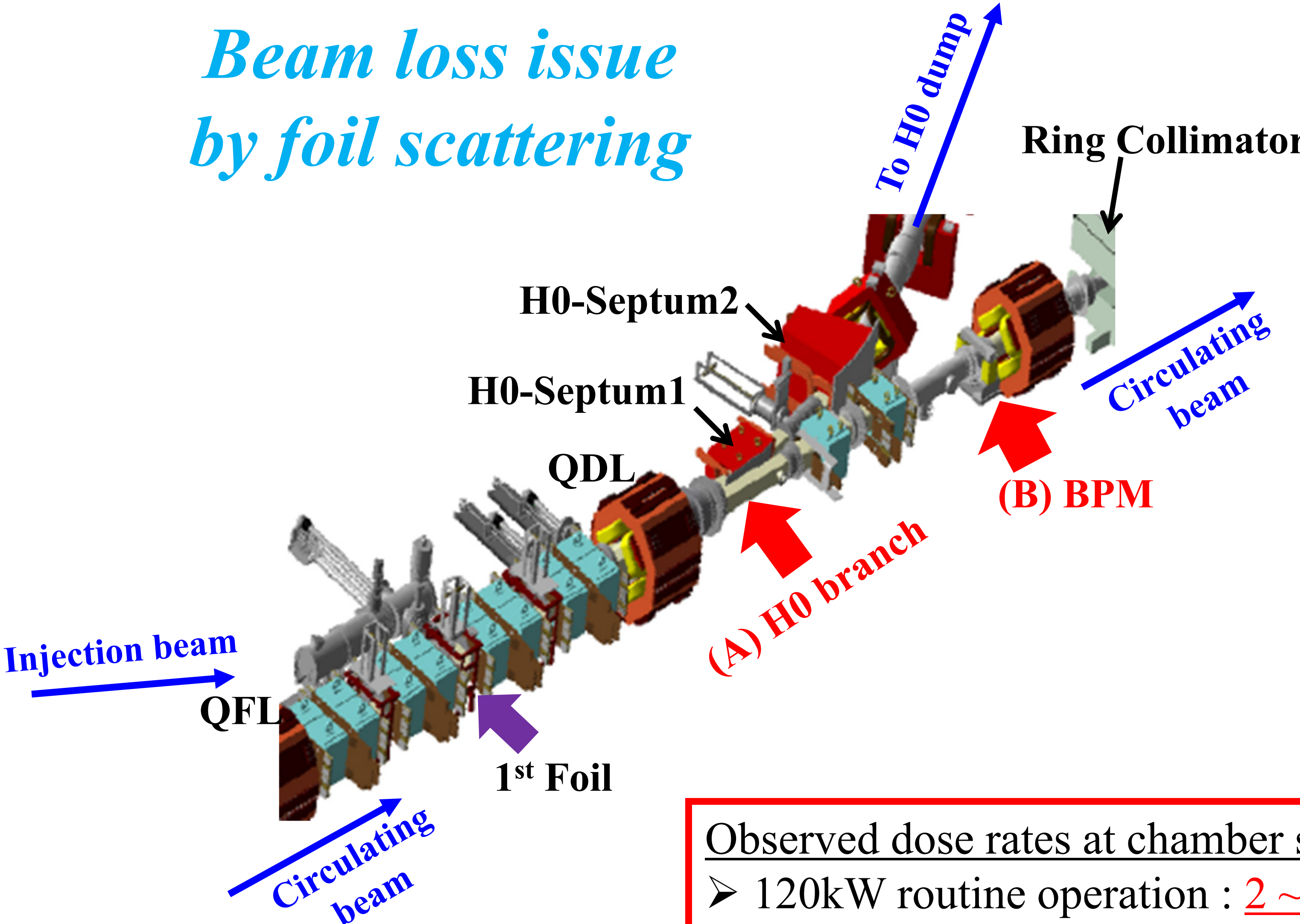
Painting injection parameters

ID	Transverse painting ε_{tp} (π mm mrad)	Longitudinal painting V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	-	80	-100	-0.0
3	-	80	-100	-0.1
4	-	80	-100	-0.2
5	50	80	-100	-0.2
6	100	80	-100	-0.2



- The main part of remaining beam loss arises from foil scattering during injection.
- The other beam loss is almost well minimized through the charge density control by painting injection.

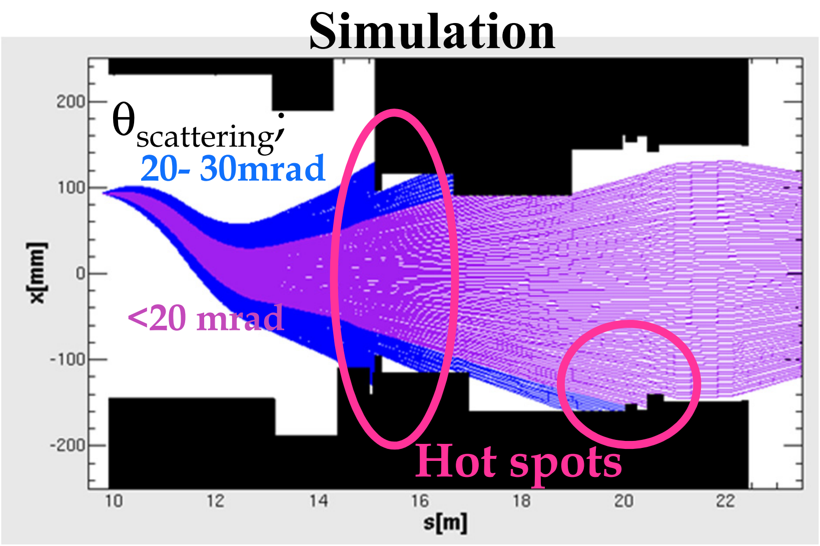
Beam loss issue by foil scattering



Observed dose rates at chamber surface

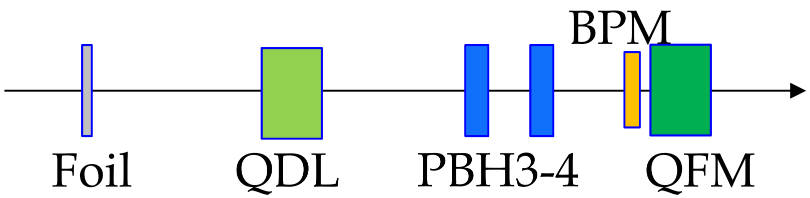
- 120kW routine operation : 2 ~ 3 mSv/h
- 220kW routine operation : 4 ~ 6 mSv/h

Measures for the beam loss by the foil scattering

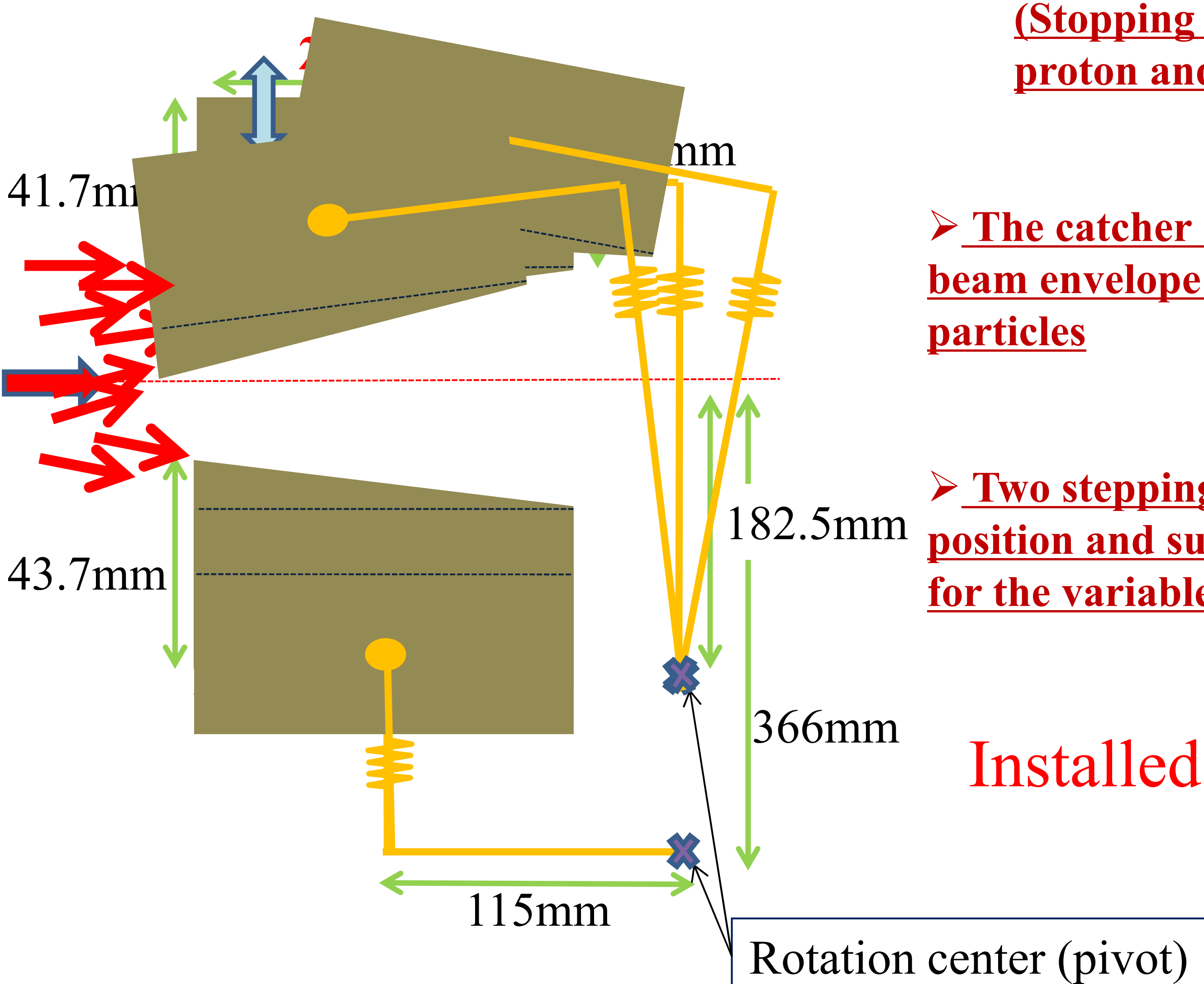


Install absorber to catch a foil scattered particles into hot spots (A)

Build a shield of (A) including the new absorbers



Structure and principle of the absorbers



- <u>Length of 200mm for longitudinal direction</u>
  <u>(Stopping range of the 400MeV proton and the Cu target ~ 130mm)</u>

- <u>The catcher surface angle follows the beam envelope of the large scattered particles</u>

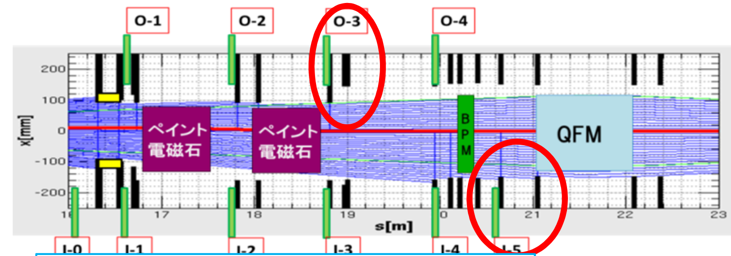
- <u>Two stepping motors to fine control the position and surface angle of the absorber for the variable operation parameters</u>

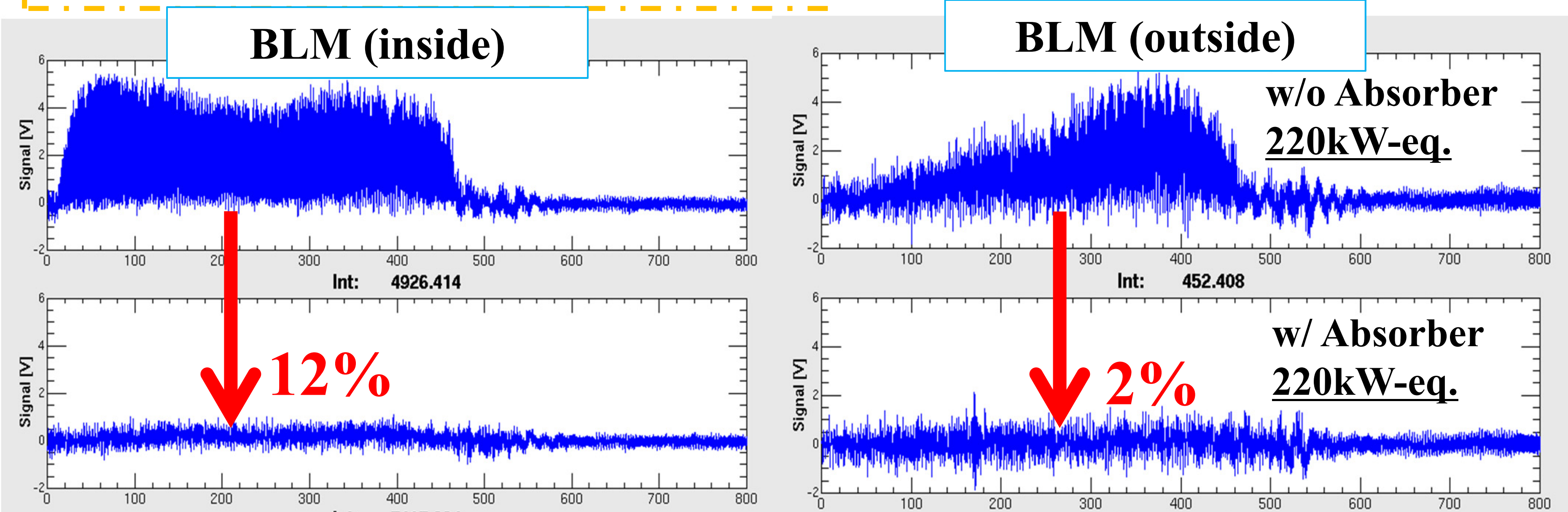
Installed in Summer 2011

Localization results of beam loss by the new collimator

- **Beam Power : 220kW-eq**
- **Absorber Positions**

  Outside : 66.0mm, Inside : -55.0mm





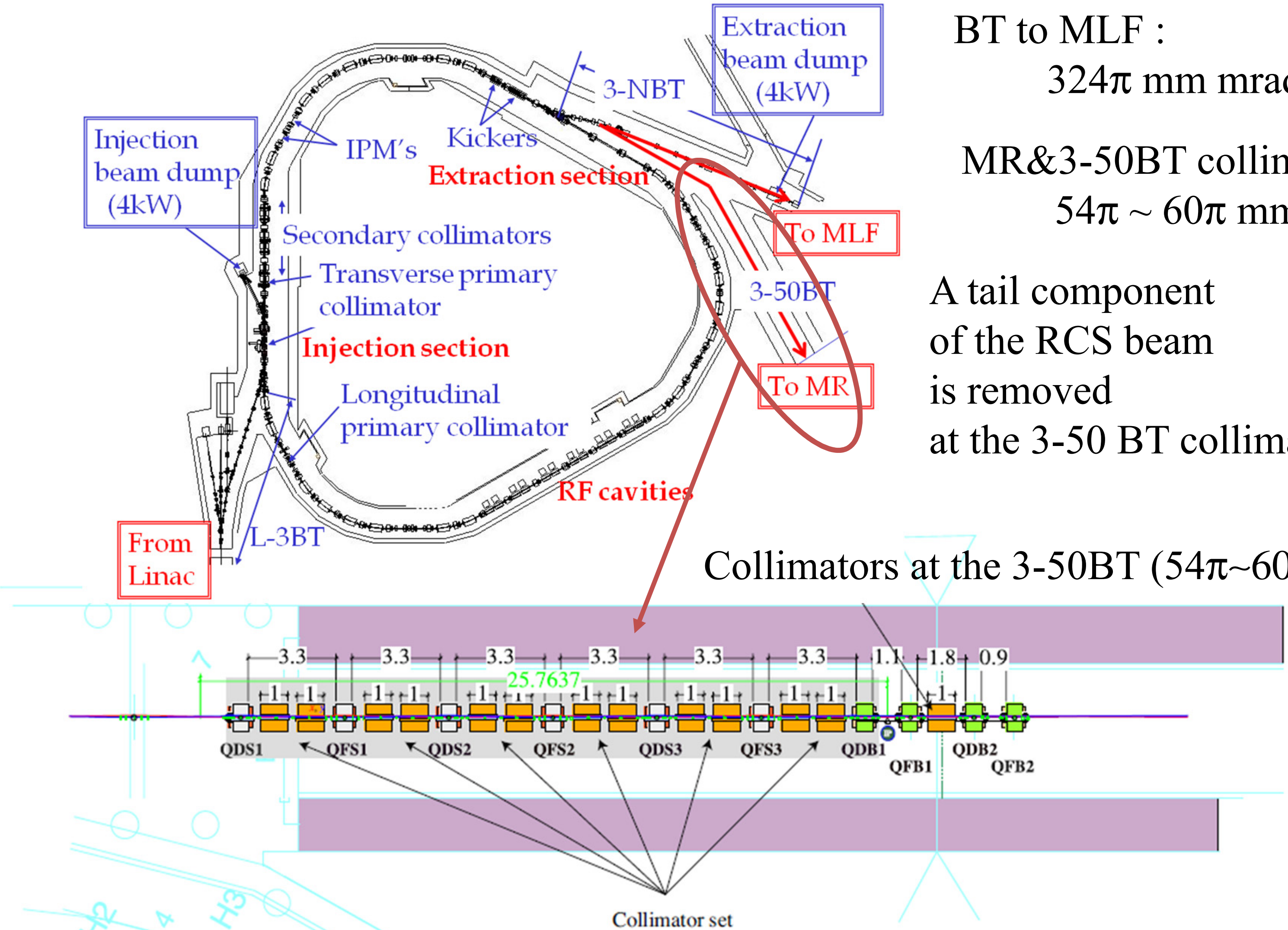
S. Kato

Successful to reduce the beam loss at the downstream of the new collimator
(Dose rate of BPM @ 220kW operation : 6.2mSv/h → ~0.7mSv/h)

The beam losses in the RCS were minimized and localized.

Another issue ; beam halo/tail reduction

Key issue especially for the beam injection to the MR



BT to MLF :
324π mm mrad

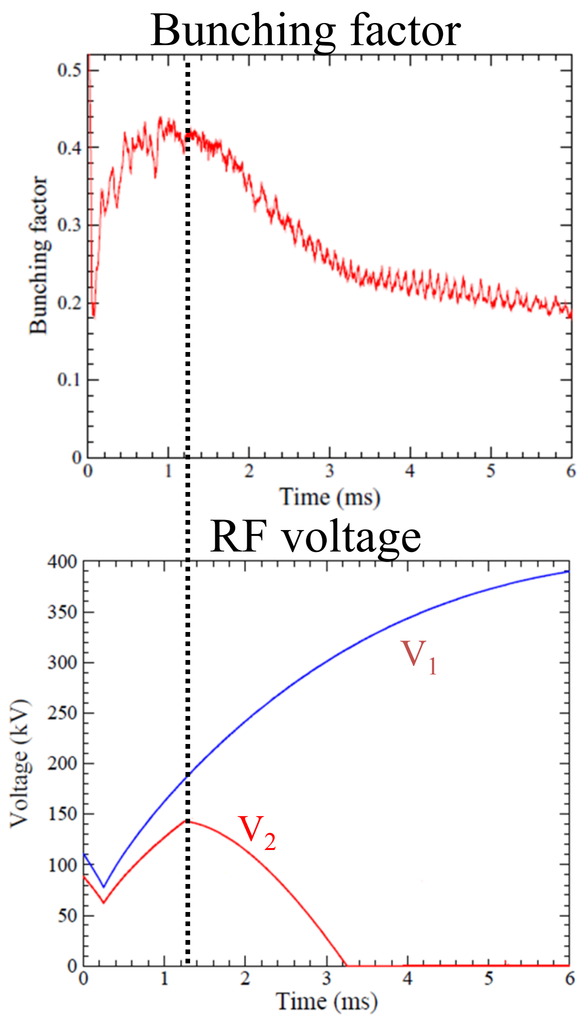
MR&3-50BT collimators :
54π ~ 60π mm mrad

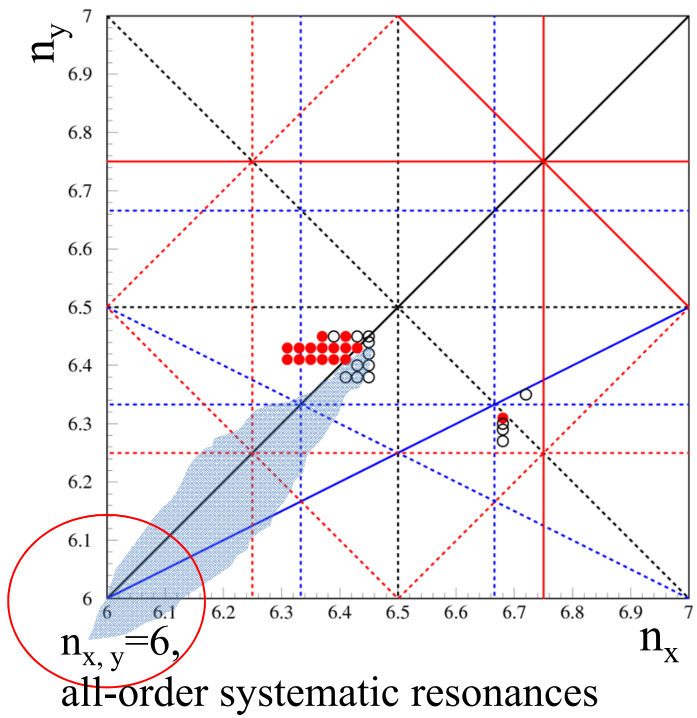
A tail component of the RCS beam is removed at the 3-50 BT collimators.

Collimators at the 3-50BT (54π~60π mm mrad)

The first matter for the MR injection is to pass the high intensity beam through the 3-50BT collimator within the permissible beam loss level (<2 kW).

Main cause of the emittance growth





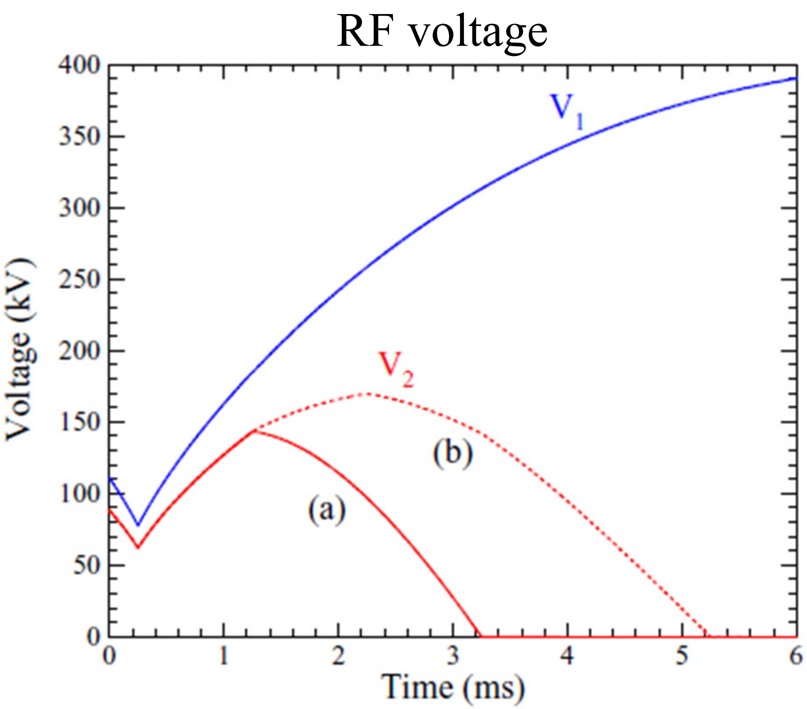
Bunching factor decreases at ~1 ms.

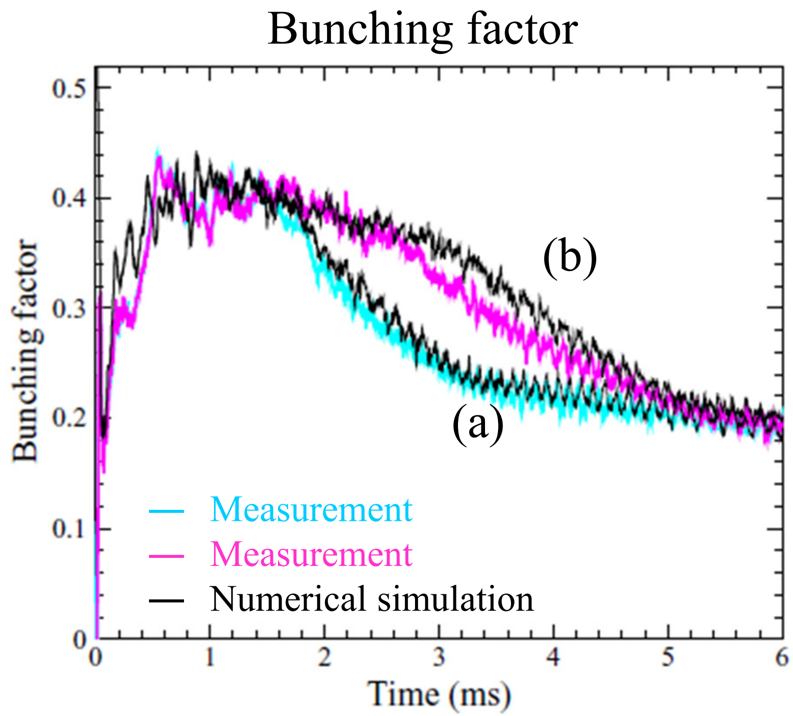
⇒ Then a part of the beam particles;

- reaches to the integer lines,
- suffers the emittance dilution.

The emittance growth can be suppressed by improving the bunching factor after 1 ms.

Improvement of bunching factor by introducing longer 2nd harmonic rf



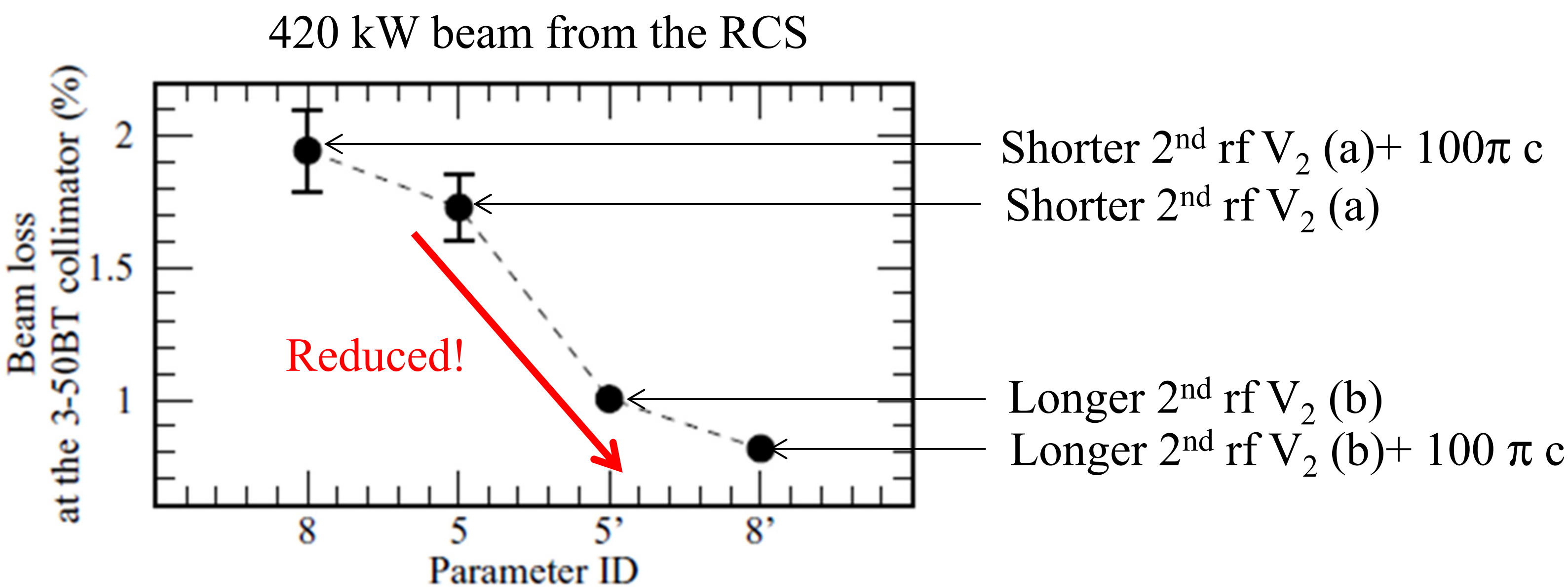


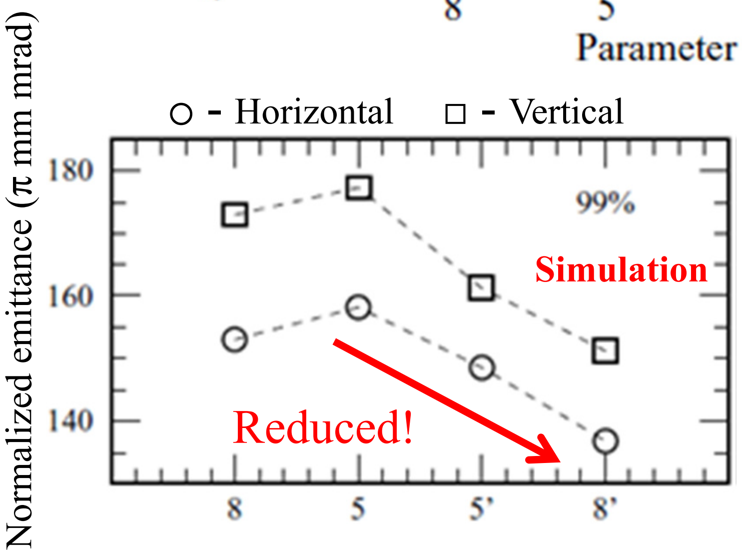
(a) Shorter pattern (original)
(b) Longer pattern (improved)

We measured beam loss at 3-50BT collimators in the beam experiment.

Beam halo/tail measurement at the 3-50BT

Parameter dependence of the beam loss at the 3-50BT collimator(SetH:54π,V:60π)





-The measured dependence is very similar to that of the emittance calculated in the low energy region.
-It can be interpreted this extraction beam halo reduction reflects the emittance growth mitigation in the low energy region.

Beam injection to the MR (4 pulses per 2.56 s)
3-50BT loss : 2.0% ⇒ 0.8%
(corresponds to 206 W << 3-50BT col. limit 2 kW)

Summary

- Beam commissioning of the RCS have started since October 2007.
- The RCS had several lattice imperfections in beam tuning.
- Operating point for high-intensity beam were re-optimized.
- The beam loss is almost well minimized through the charge density control by painting injection up to 420kW intensity beam.
- Remaining beam loss caused by foil scattering is localized well by the new collimator system.
- The extracted beam halo is successfully reduced by improvement of second harmonic RF voltage.
- The RCS output beam power has been steadily increasing with progress of beam tuning.