Recent progress of J-PARC RCS beam commissioning

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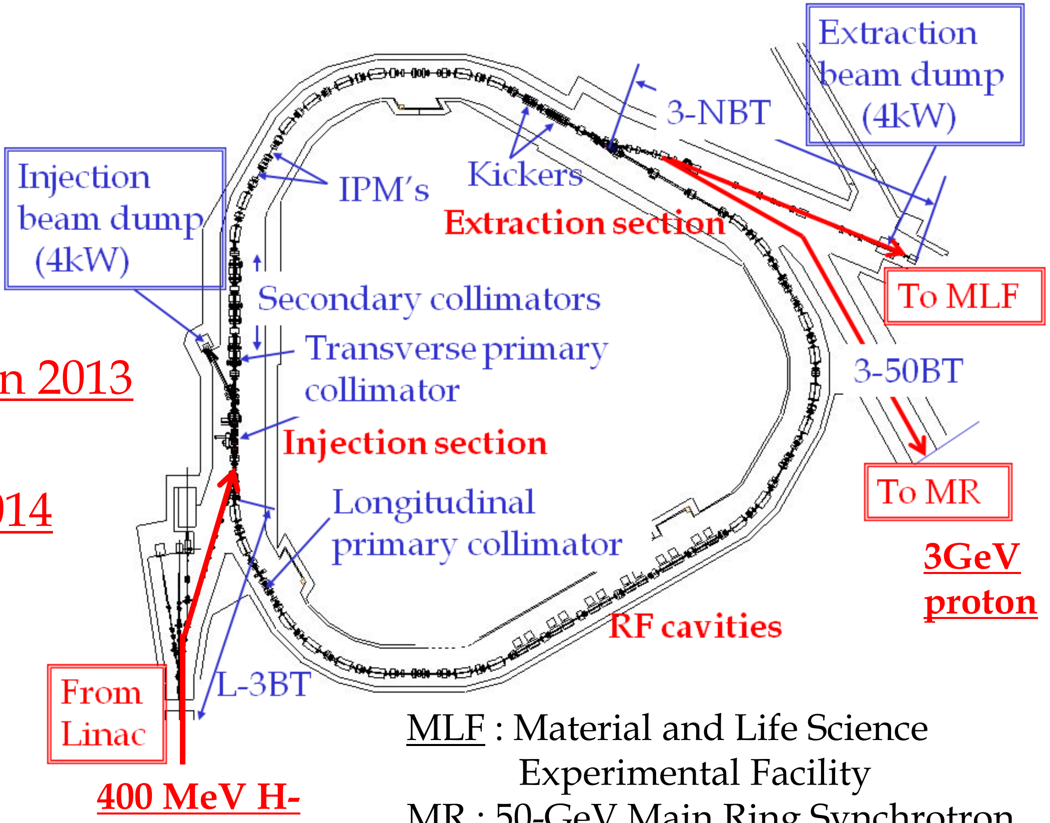
Contents

Outline of the J-PARC RCS

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
Number of bunches	2
Injection	Multi-turn, Charge-exchange
Injection energy	181 MeV ⇒ 400 MeV in 2013
Injection period	0.5 ms (307 turns)
Injection peak current	30 mA ⇒ 50 mA in 2014
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	5×10^{13} ⇒ 8.3×10^{13}
Output beam power	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

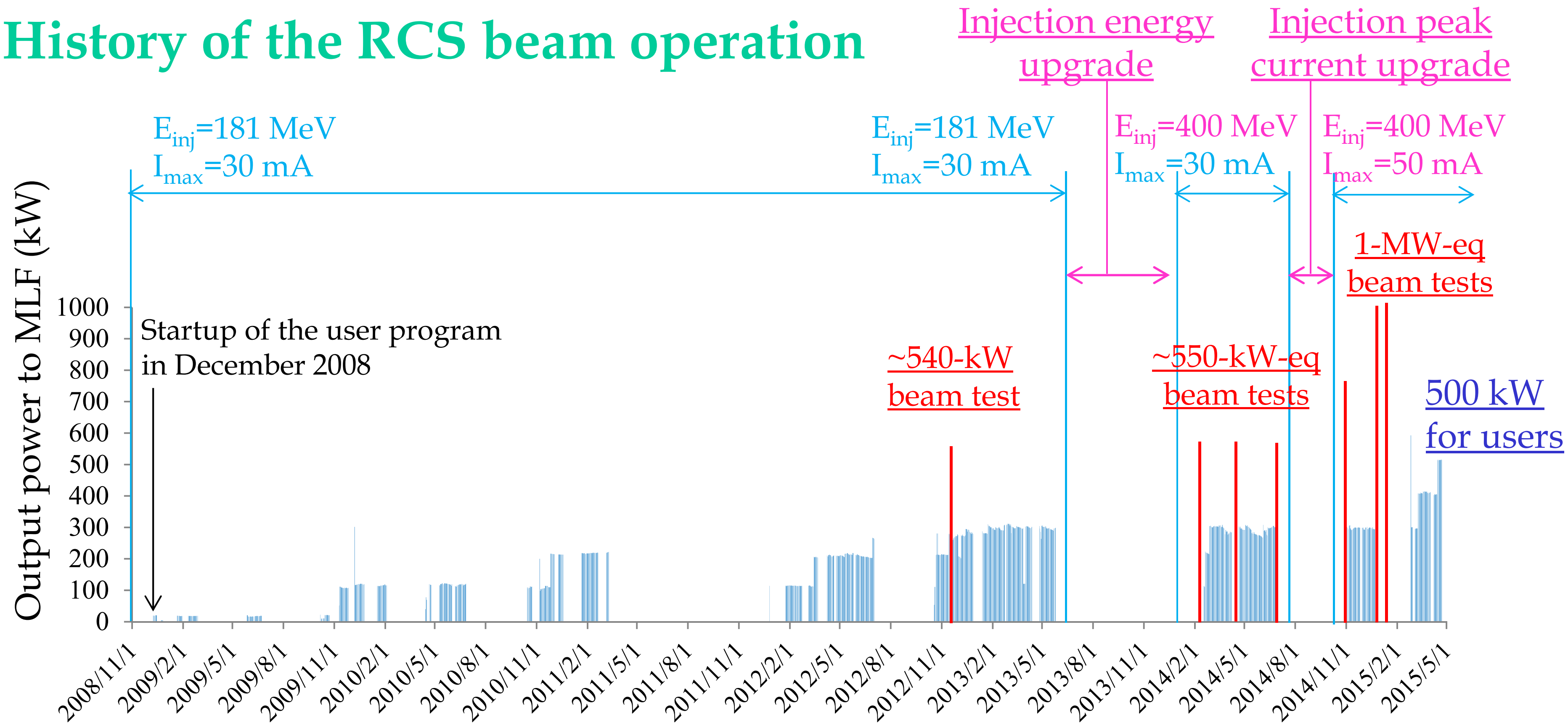


MLF : Material and Life Science Experimental Facility

MR : 50-GeV Main Ring Synchrotron

- ✓ Recently the hardware improvement of the injector linac has been completed.
- ✓ Now the RCS is in the final beam commissioning phase aiming for the design output beam power of 1 MW.

History of the RCS beam operation



✓ The output beam power from the RCS has been steadily increasing following progressions in beam tuning and hardware improvements.

✓ Present output beam power for the routine user program : 500 kW

✓ High intensity beam tests of up to ~550 kW for both injection energies of 181 MeV and 400 MeV

✓ 1-MW beam tests from October 2014

The main topic of this talk is to discuss our approaches to beam loss issues that we faced on the process of these high intensity beam tests.

550-kW beam tests conducted after the injection energy upgrade from 181 to 400 MeV (Run#54)

- ◆ Date; Apr. 9-12, 2014 (Run#54)
- ◆ Injection beam condition

Energy : **400 MeV**

Peak current : 24.6 mA @ the entrance of RCS

Pulse length : 0.5 ms

Chopper beam-on duty factor : 60%

⇒ 4.604×10^{13} particles/pulse, corresponding to **553 kW** at 3 GeV

✓ The injection energy was upgraded by adding an ACS linac section

- ◆ Operating point;

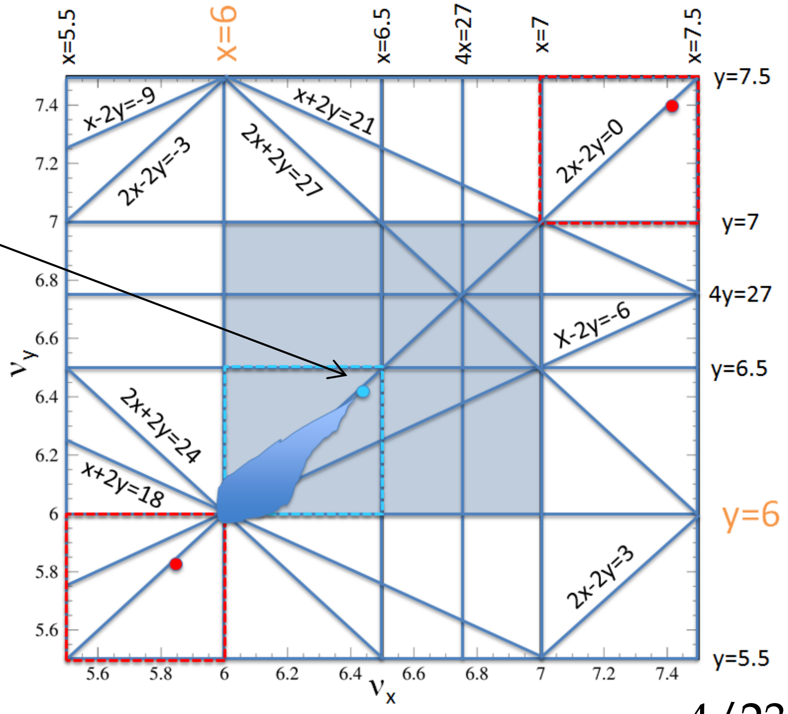
(6.45, 6.42)

allows the space-charge tune shift to avoid serious multipole resonances

In the RCS, transverse and longitudinal injection painting is employed to mitigate the space-charge induced beam loss.

✓ Systematic beam loss measurements for various injection painting parameters

✓ Comparison with the old data taken with E_{inj}=181 MeV



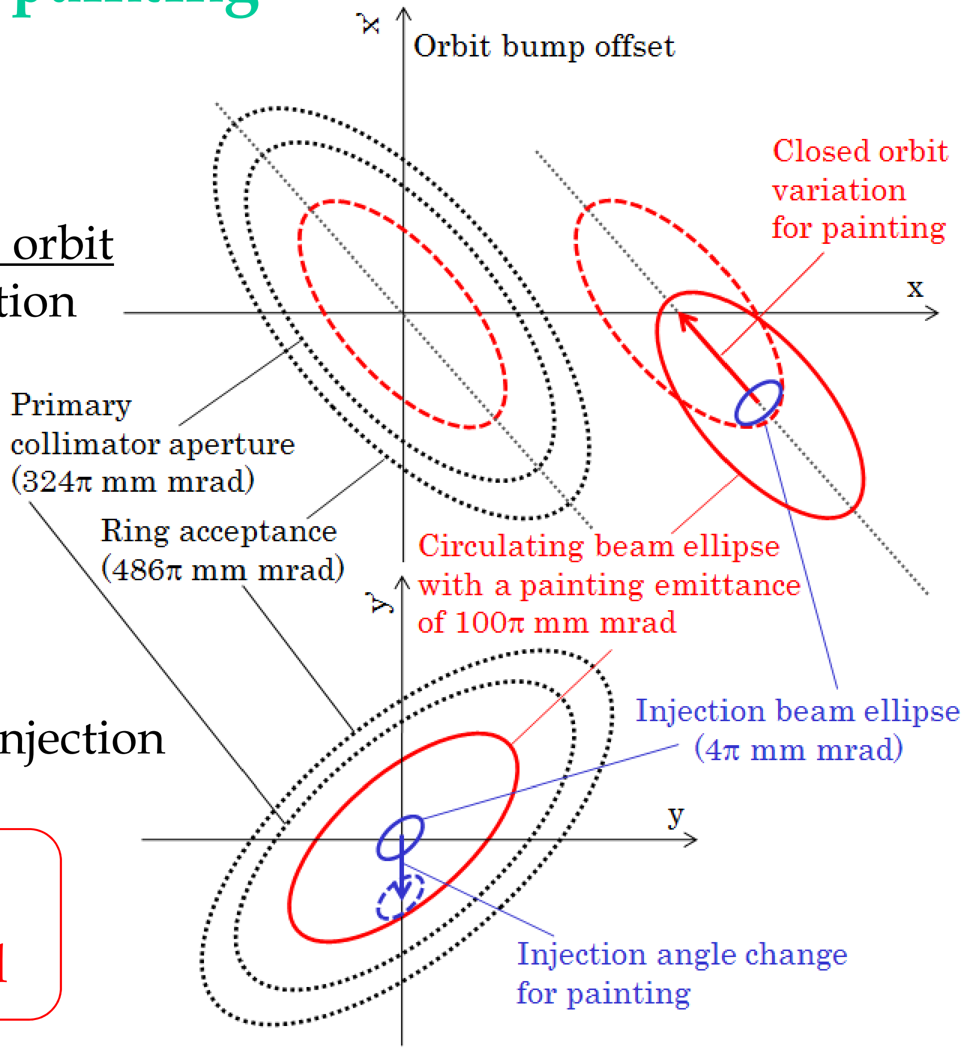
Transverse injection painting

◆ Horizontal painting
by a horizontal closed orbit
variation during injection

◆ Vertical painting
by a vertical injection
angle change during injection

Correlated painting

ε_{tp} = 100 π mm mrad



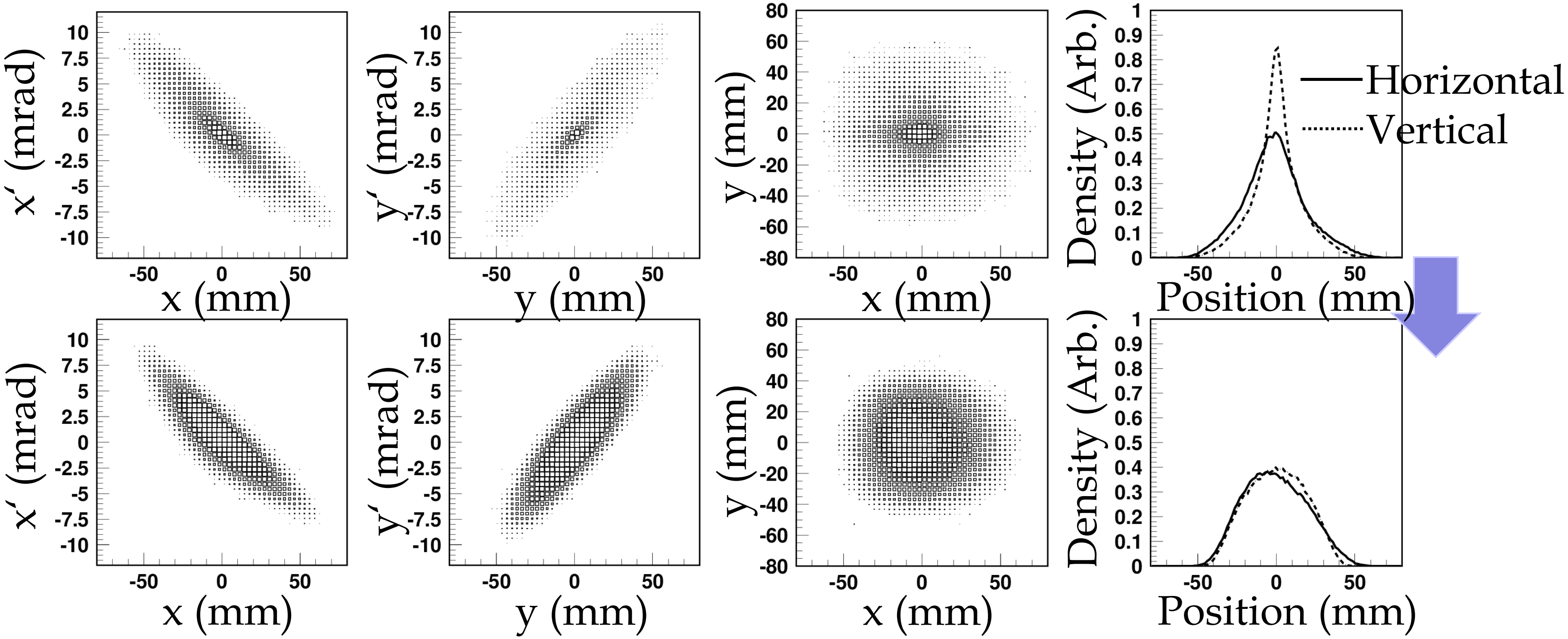
The injection beam is painted from the middle to the outside on both horizontal and vertical planes.

Transverse injection painting

Numerical simulations

Transverse beam distribution just after beam injection calculated without and with transverse painting

No painting



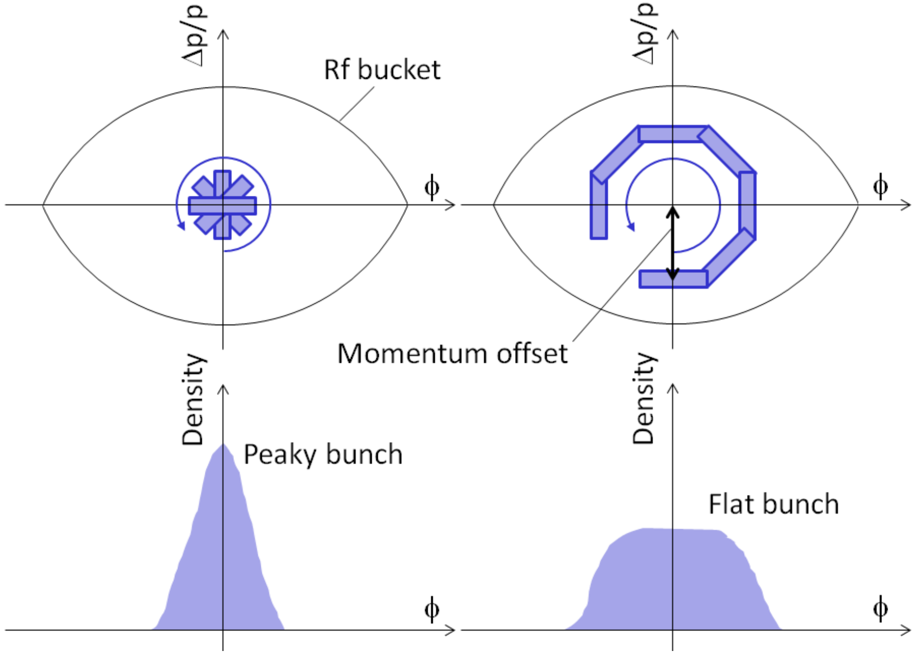
100π transverse painting

from H. Hotchi et. al., PRST-AB **15**, 040402 (2011).

Longitudinal injection painting

F. Tamura et al, PRST-AB **12**, 041001 (2009).
M. Yamamoto et al, NIM., Sect. A **621**, 15 (2010).

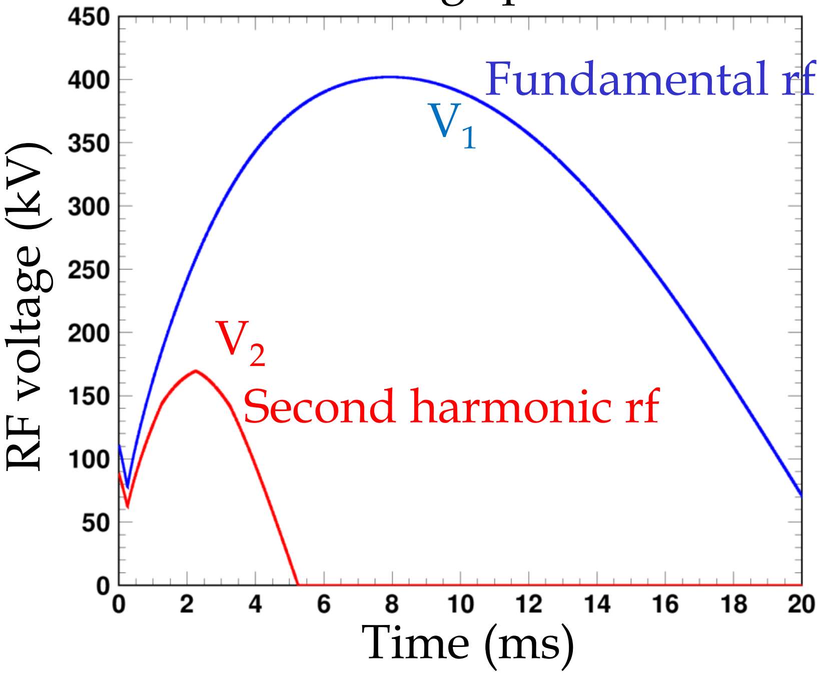
Momentum offset injection



$\Delta p/p = 0, -0.1 \text{ and } -0.2\%$

Uniform bunch distribution is formed through emittance dilution by the large synchrotron motion excited by momentum offset.

RF voltage pattern



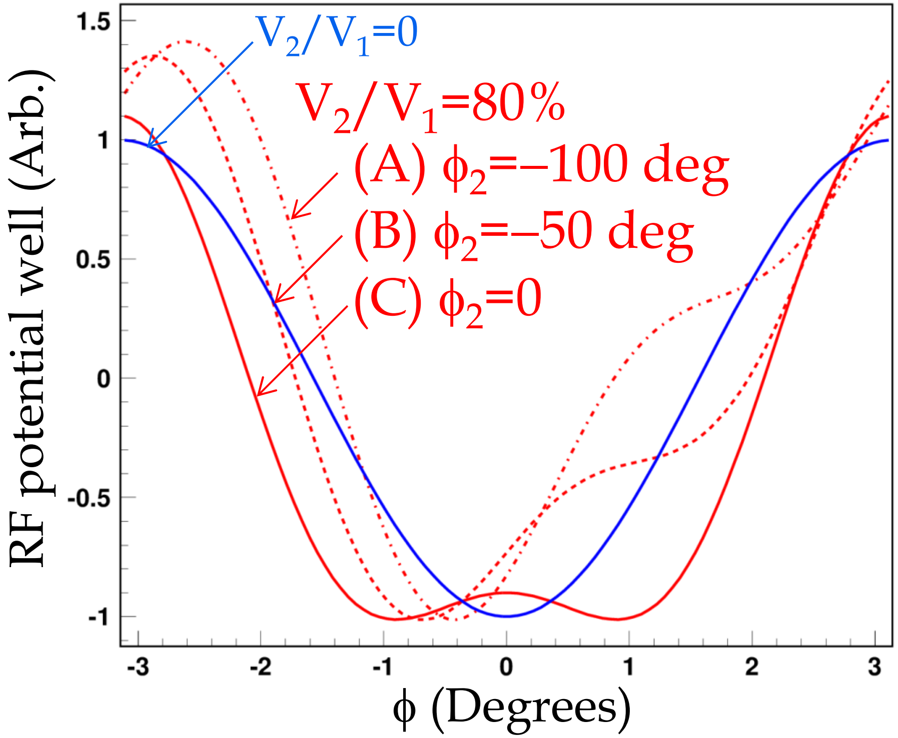
$V_2/V_1 = 80\%$

The second harmonic rf fills the role in shaping flatter and wider rf bucket potential, leading to better longitudinal motion to make a flatter bunch distribution.

Longitudinal injection painting

Additional control in longitudinal painting ; phase sweep of V_2 during injection

$$V_{rf}=V_1\sin\phi-V_2\sin\{2(\phi-\phi_s)+\phi_2\}$$



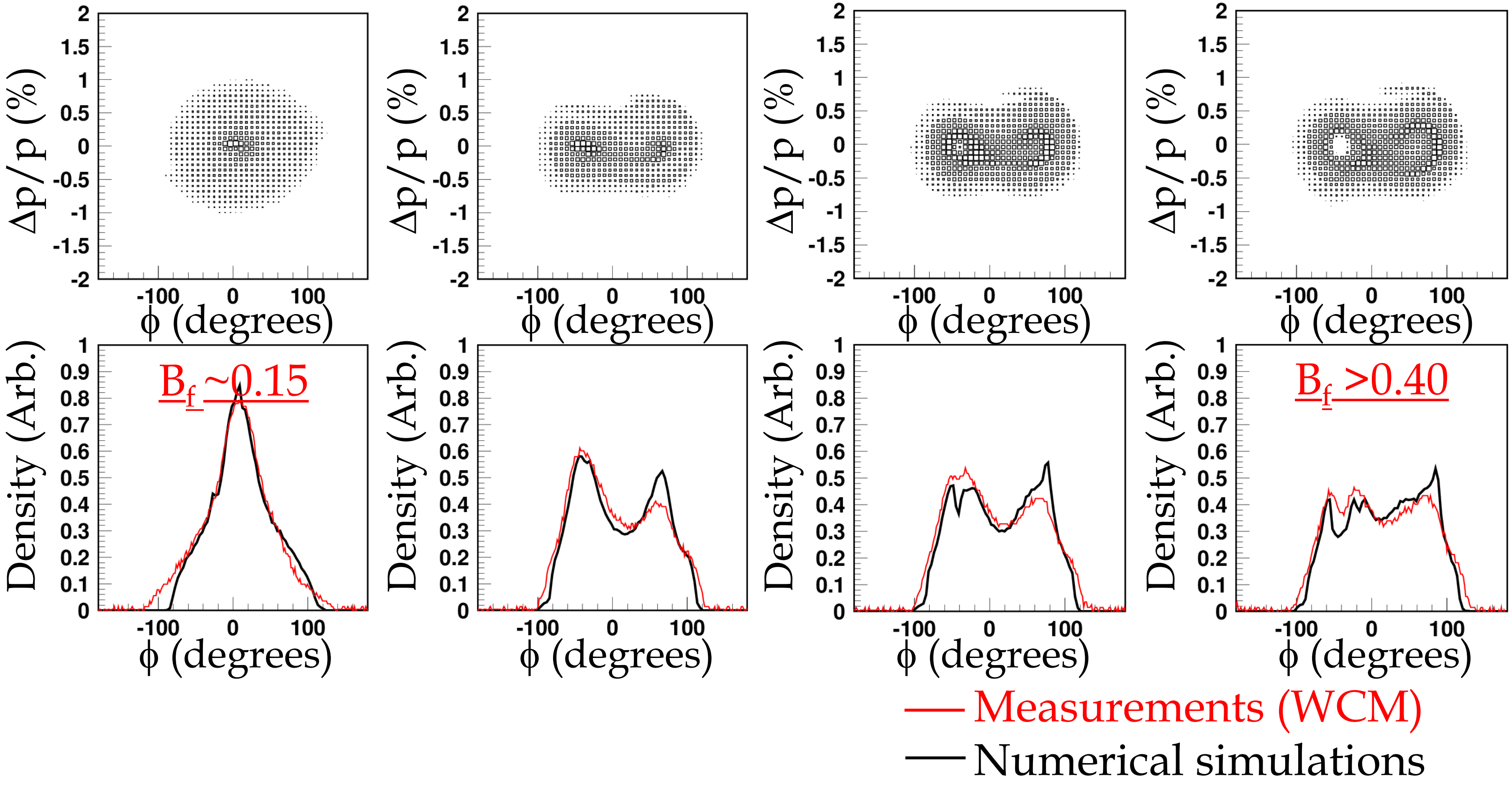
$\boxed{\phi_2=-100\Rightarrow 0\text{ deg}}$

The second harmonic phase sweep method enables further bunch distribution control through a dynamical change of the rf bucket potential during injection.

Longitudinal injection painting

Longitudinal beam distribution just after beam injection (at 0.5 ms)

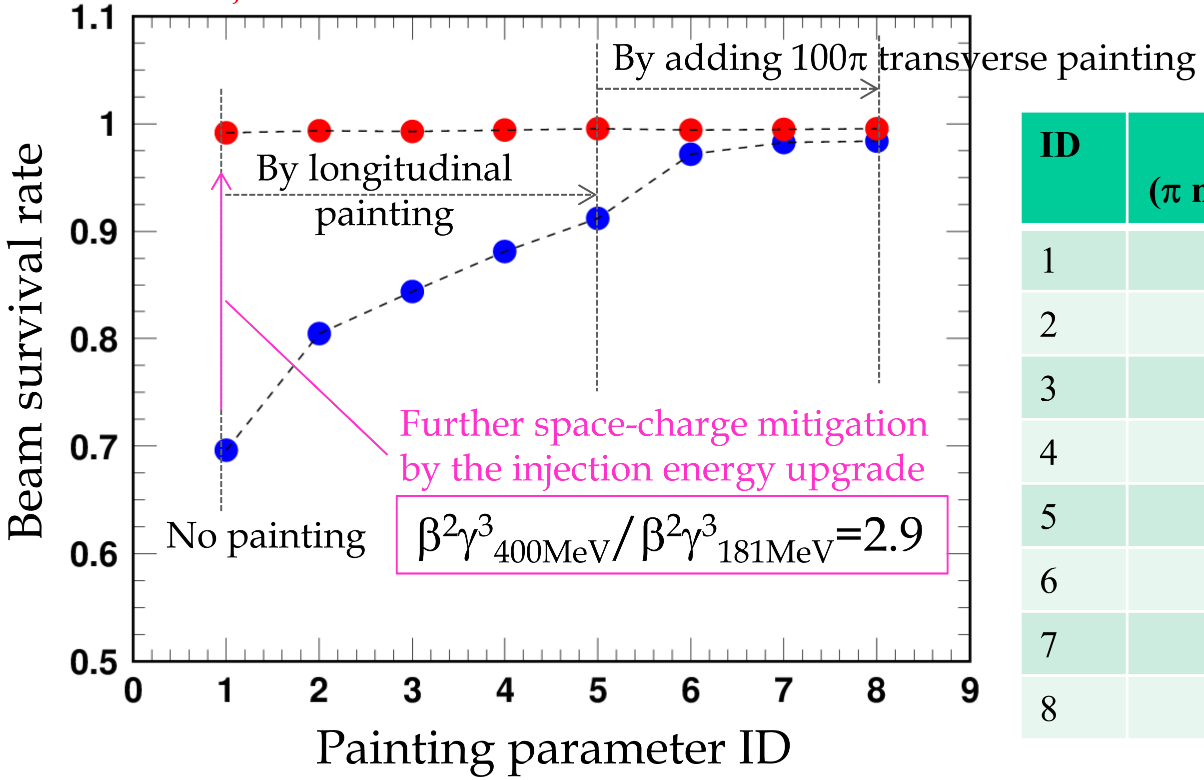
No longitudinal painting	V_2/V_1=80%	V_2/V_1=80%	V_2/V_1=80%
	ϕ_2=-100 to 0 deg	ϕ_2=-100 to 0 deg	ϕ_2=-100 to 0 deg
	$\Delta p/p$= 0.0%	$\Delta p/p$=-0.1%	$\Delta p/p$=-0.2%



from H. Hotchi et. al., PRST-AB **15**, 040402 (2011).

Painting parameter dependence of beam survival rate

- ● E_{inj}=181 MeV, 539 kW-eq. intensity (Run#44, Nov., 2012)
- ● E_{inj}=400 MeV, 553 kW-eq. intensity (Run#54, Apr., 2014)

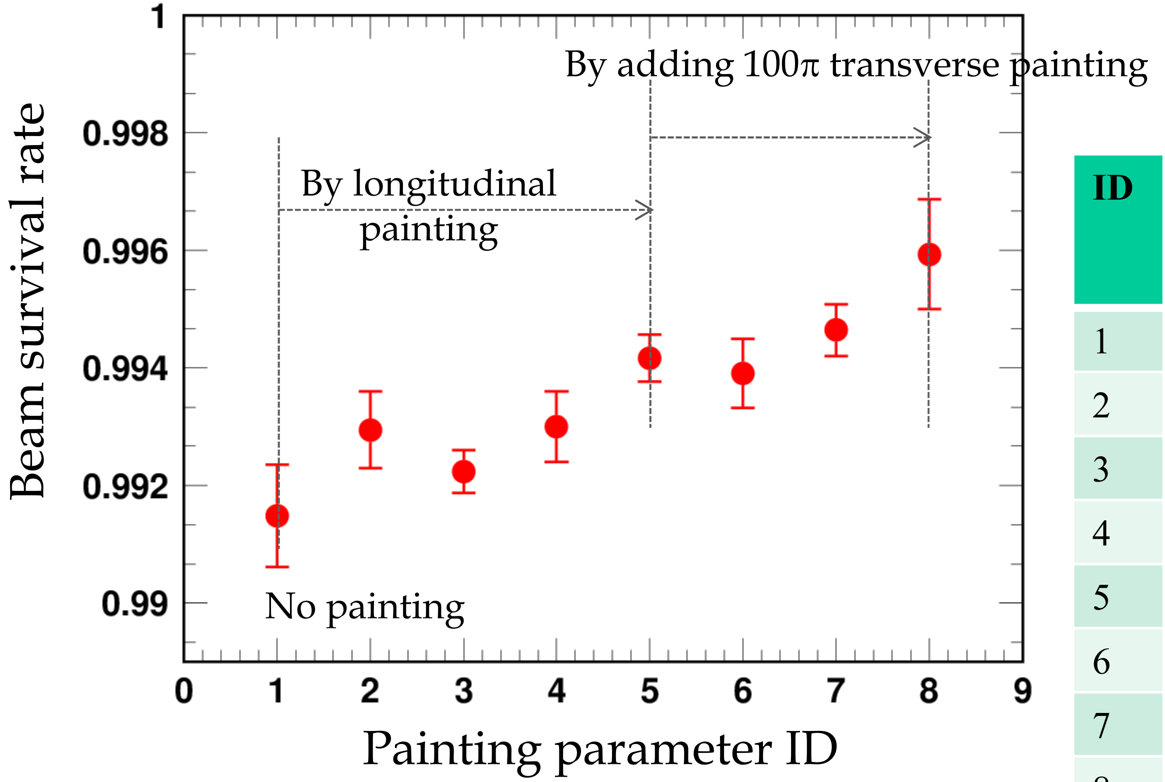


ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	$\Delta\phi_2$ (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	100π	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100π	80	-100	-0.0
7	100π	80	-100	-0.1
8	100π	80	-100	-0.2

✓ This experimental data clearly show the big gain from the injection energy upgrade as well as the excellent ability of injection painting for the space-charge mitigation.

Painting parameter dependence of beam survival rate

- E_{inj}=400 MeV, 553 kW-eq. intensity (Run#54, Apr., 2014)



ID	**ε_{tp} (π mm mrad)**	**V_2/V_1 (%)**	**$\Delta\phi_2$ (deg)**	**$\Delta p/p$ (%)**
1	-	-	-	-
2	100π	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100π	80	-100	-0.0
7	100π	80	-100	-0.1
8	100π	80	-100	-0.2

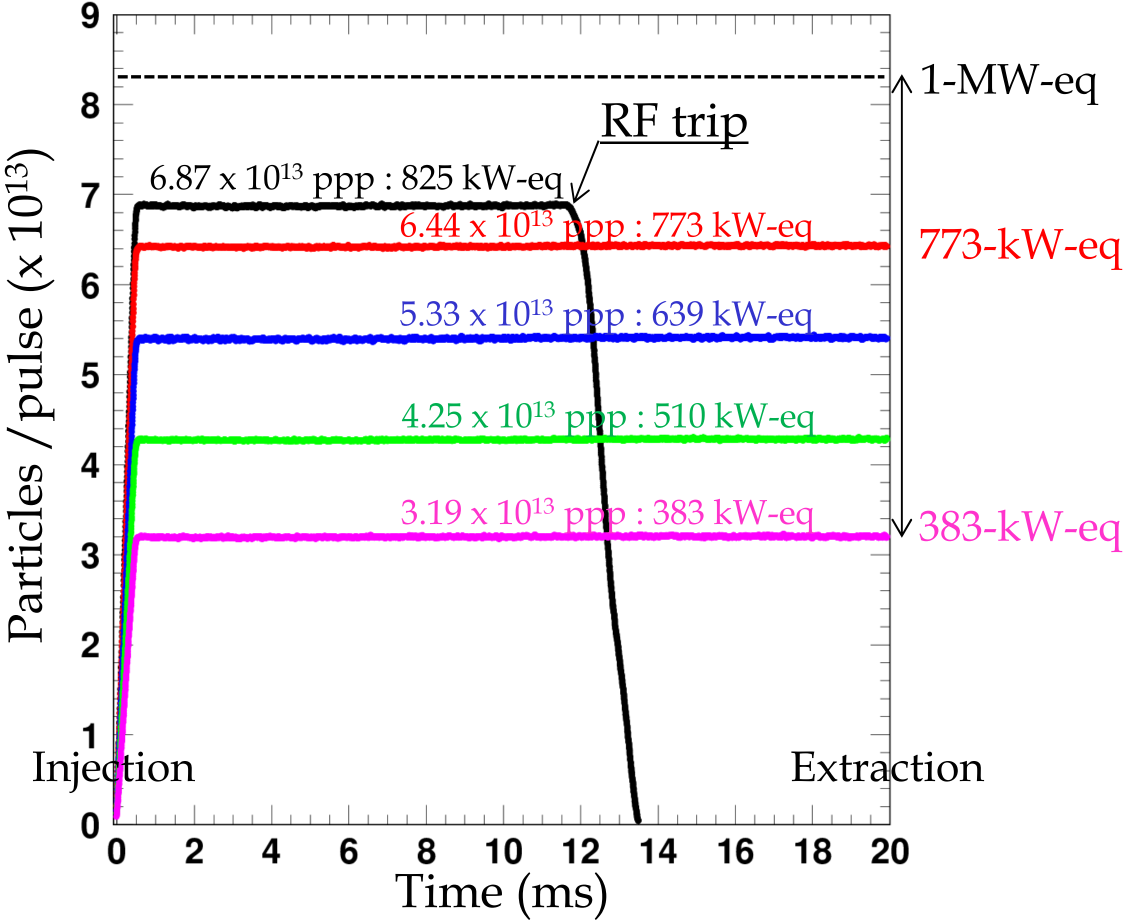
1-MW beam tests conducted after the injection peak current upgrade (Run#57, #59 & #60)

- Date : Oct 21-26, 2014 (Run#57),
  Dec. 26, 2014 (Run#59)
  Jan. 8-11, 2015 (Run#60),
- Injection beam condition
  Injection energy : 400 MeV
  Peak current : **45.0 mA** @ the entrance of RCS
  Pulse length : 0.5 ms
  Chopper beam-on duty factor : 60%
  ⇒ 8.4 x 10^{13} particles/pulse, corresponding
  to **1010 kW** at 3 GeV
- Operating point;
  (6.45, 6.42)
- Injection painting parameter;
  ID8 (100π transverse painting
  + full longitudinal painting)

✓ The injection peak current was upgraded by replacing the front-end system (IS & RFQ) in the linac.

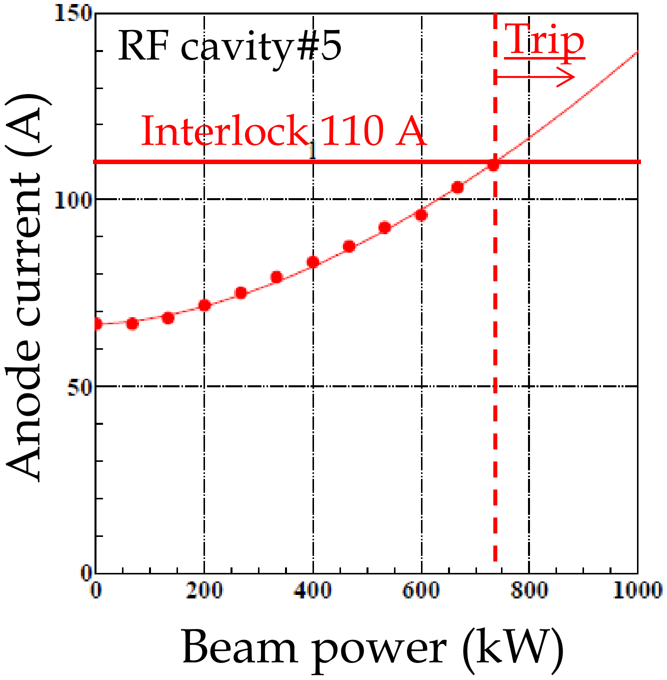
Result of the first 1-MW trial in Oct. 2014 (Run#57)

Circulating beam intensity over the 20 ms
from injection to extraction measured by CT



Anode current vs. Beam power

W/ multi-harmonics (h=2,4,6)
feed-forward for
beam loading compensation

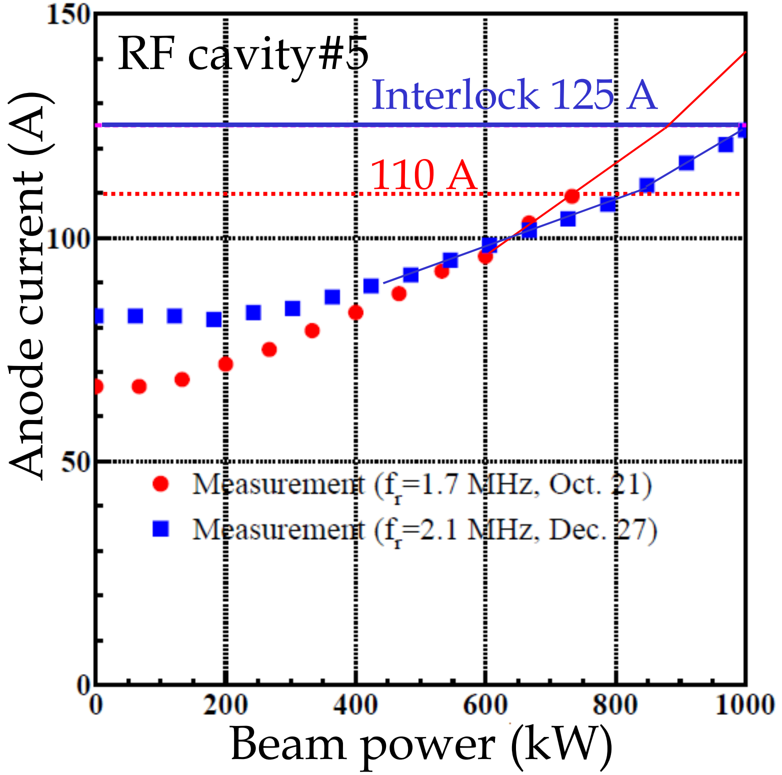


- ✓ The beam accelerations of up to 773 kW was achieved with no significant beam loss.
- ✓ But, the 1-MW beam acceleration was not reached due to the over current of the anode power supply of the RF system.

Result of the 1-MW trial in Jan. 2015 (Run#60)

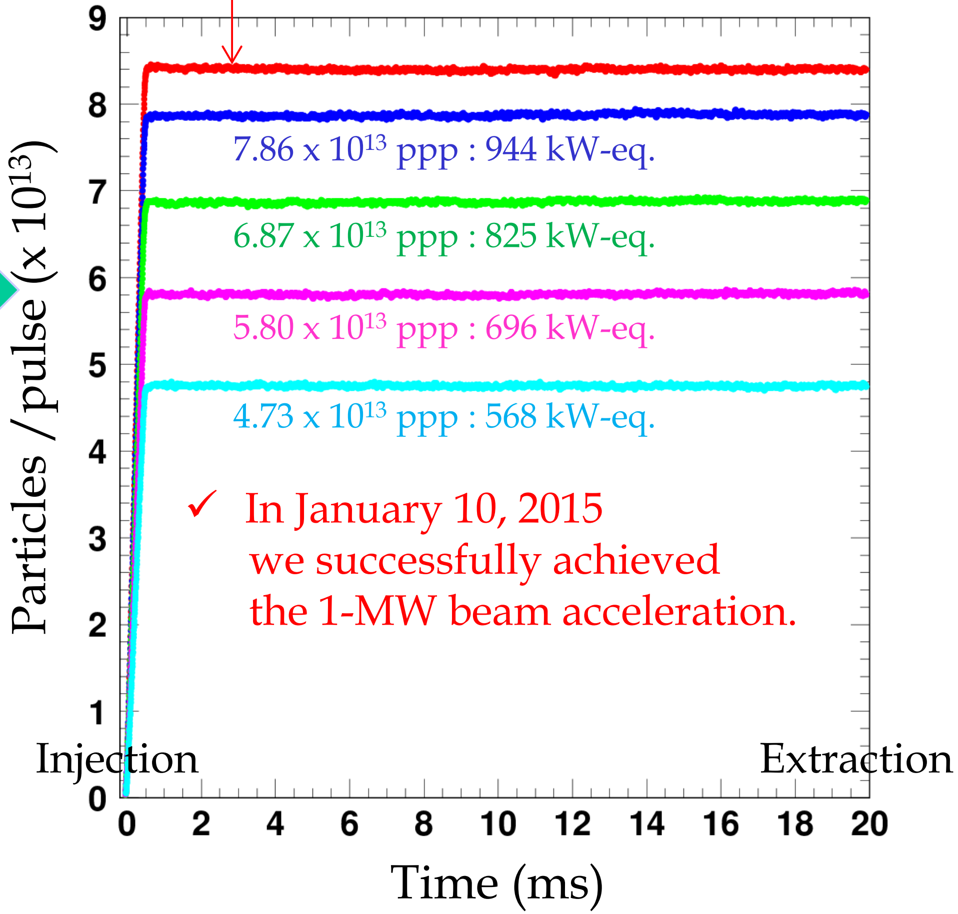
- Quick measures against the RF trip
  - ✓ The resonant frequency of the RF cavity was shifted to decrease the anode current required for the 1-MW beam acceleration;
    1.7 MHz ⇒ 2.1 MHz
  - ✓ The interlock level was turned up to use all of margin of the anode power supply;
    110 A ⇒ 125 A

Anode current vs. Beam power



Circulating beam intensity over the 20 ms from injection to extraction measured by CT

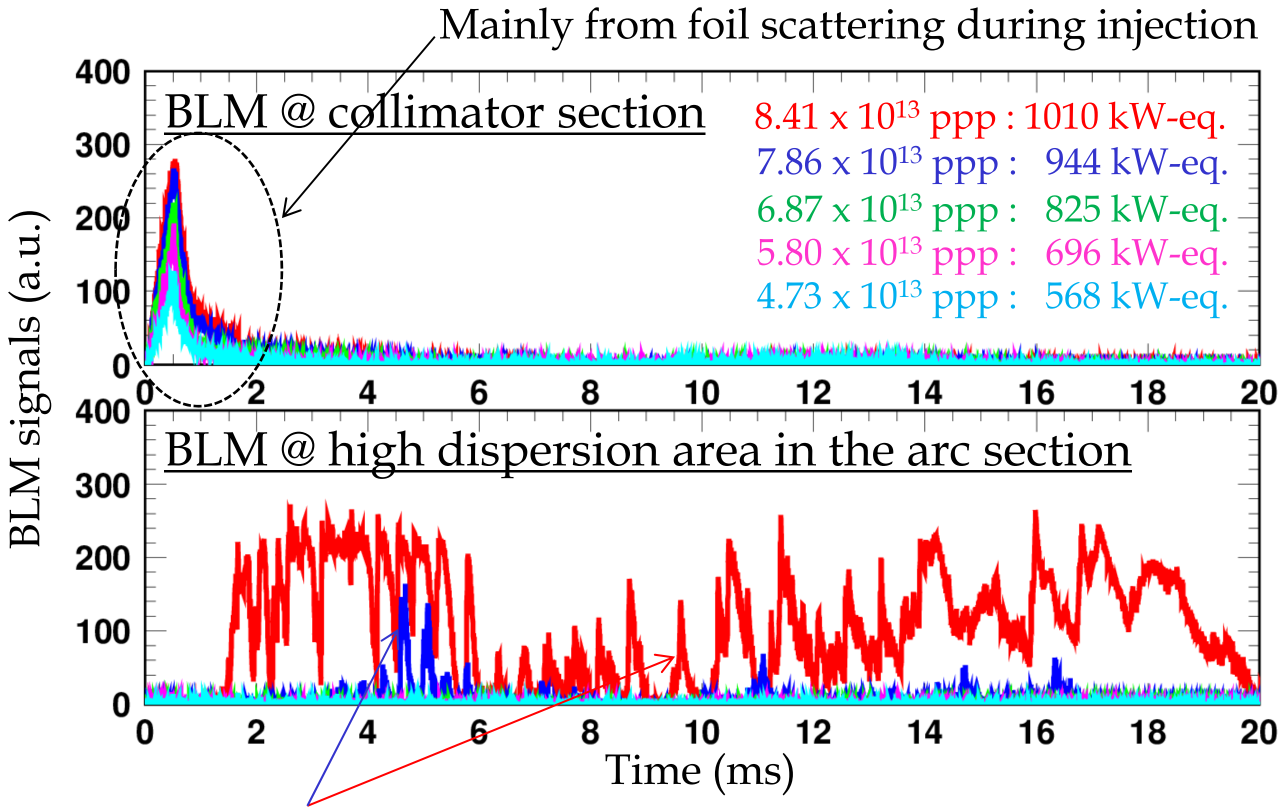
8.41 x 10^{13} ppp : 1010 kW-eq.



✓ In January 10, 2015 we successfully achieved the 1-MW beam acceleration.

✓ There is no terrible beam loss, but some un-localized beam losses are now still detected at the arc section.

BLM signals at the collimator & the arc sections



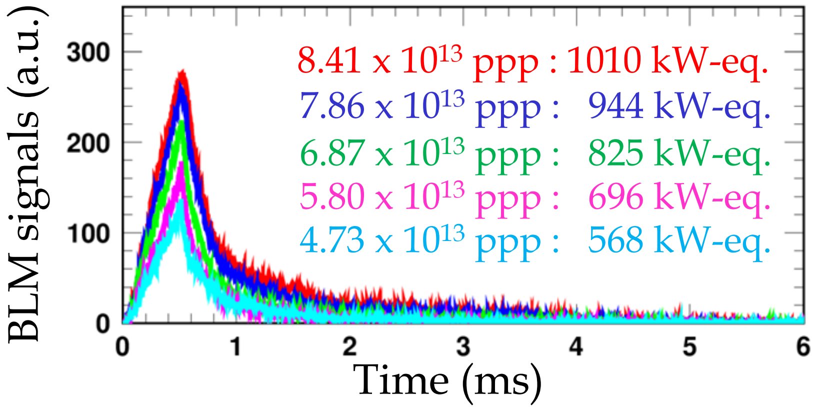
Mainly from foil scattering during injection

- ✓ The beam losses observed for the 944-kW (blue) and 1010 kW (red) beams can be interpreted as longitudinal beam loss arising from beam particles leak from the RF bucket.
- ✓ Such beam particles suffer large momentum excursion and most of them are lost in the high dispersion area, not at the collimator section located in the dispersion-free section.

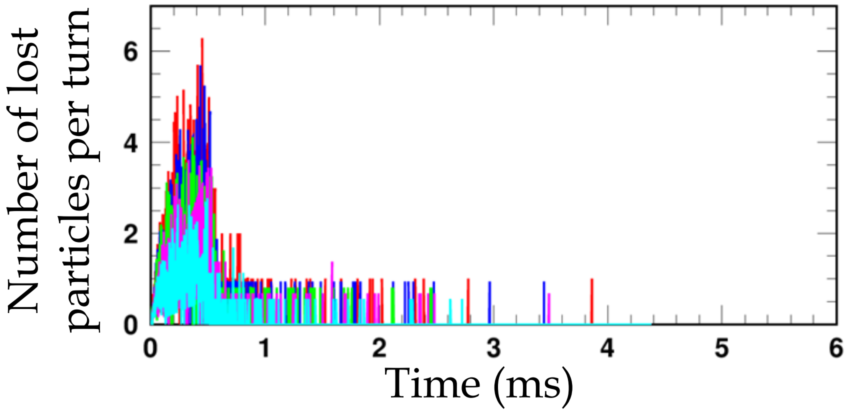
- ✓ This type of longitudinal beam loss should be cured by increasing the RF voltage, but now the anode power supply in the RF system reaches the limit, and there is no margin at all.
- ✓ For this issue, we plan to upgrade the anode power supply using this summer maintenance period. This longitudinal beam loss will be suppressed by this hardware improvement.

Beam loss at the collimator

Measurements : BLM signals at the collimator over the first 6 ms



Calculations



- ✓ The beam loss at the collimator section appears for the first 1-ms region.
- ✓ The remaining beam loss mainly arises from foil scattering during injection.
- ✓ The other beam loss, such as space-charge induced beam loss, was well minimized by injection painting even for the 1-MW beam.
- ✓ The remaining beam loss for the 1-MW beam was estimated to be 0.17% (240 W in power) << Collimator limit of 4 kW.
- ✓ We expect the 1-MW routine beam operation will be ready after this summer maintenance period, namely by solving the remaining longitudinal beam loss after completing the RF anode power supply upgrade.

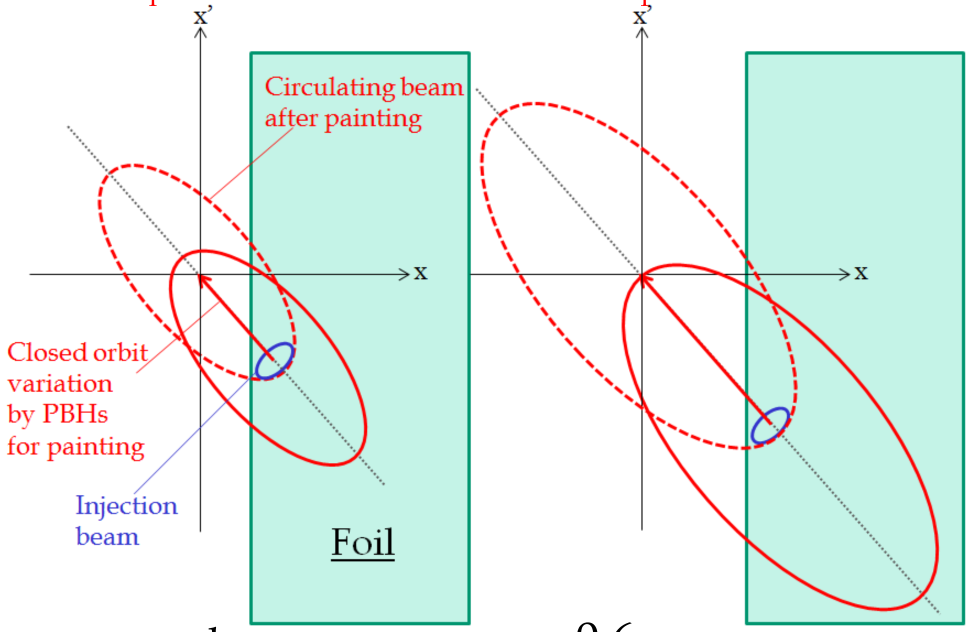
Recent efforts for further beam loss mitigation

H. Hotchi et al, NIM, Sect. A **778**, 102 (2015).

Next issue : further mitigation of the foil scattering beam loss

- ✓ Most of the foil scattering beam loss is well localized at the collimators, but some of them with large scattering angles cause un-localized beam loss, making relatively high machine activations near the charge-exchange foil;
  ~15 mSv/h @ chamber surface for the 400-kW routine beam operation.
- ✓ The machine activation is expected to be within the permissible level even if assuming the 1-MW routine beam operation, but we tried further beam loss mitigation to keep the machine activation as low as possible.

Present : ε_{tp}=100 π mm mrad ε_{tp}=150 π mm mrad



Average number of foil-hits/particle: ~42

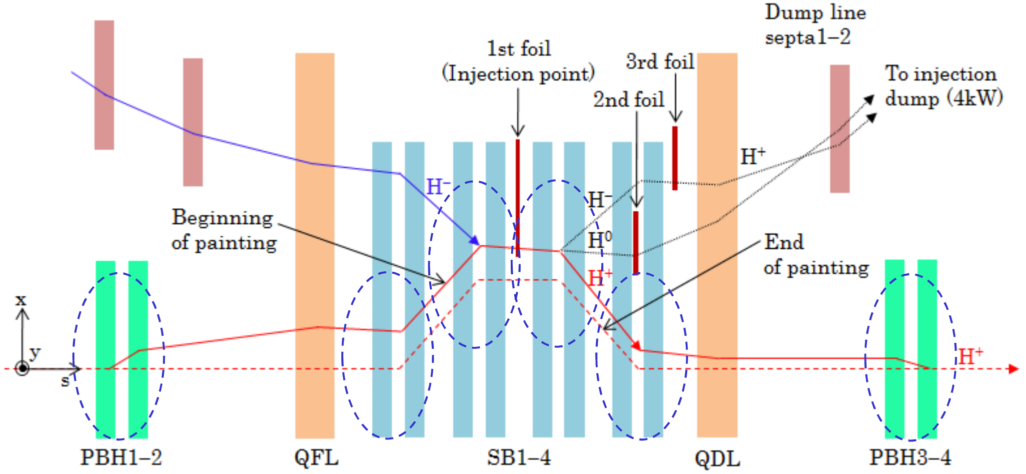
x 0.6

~27

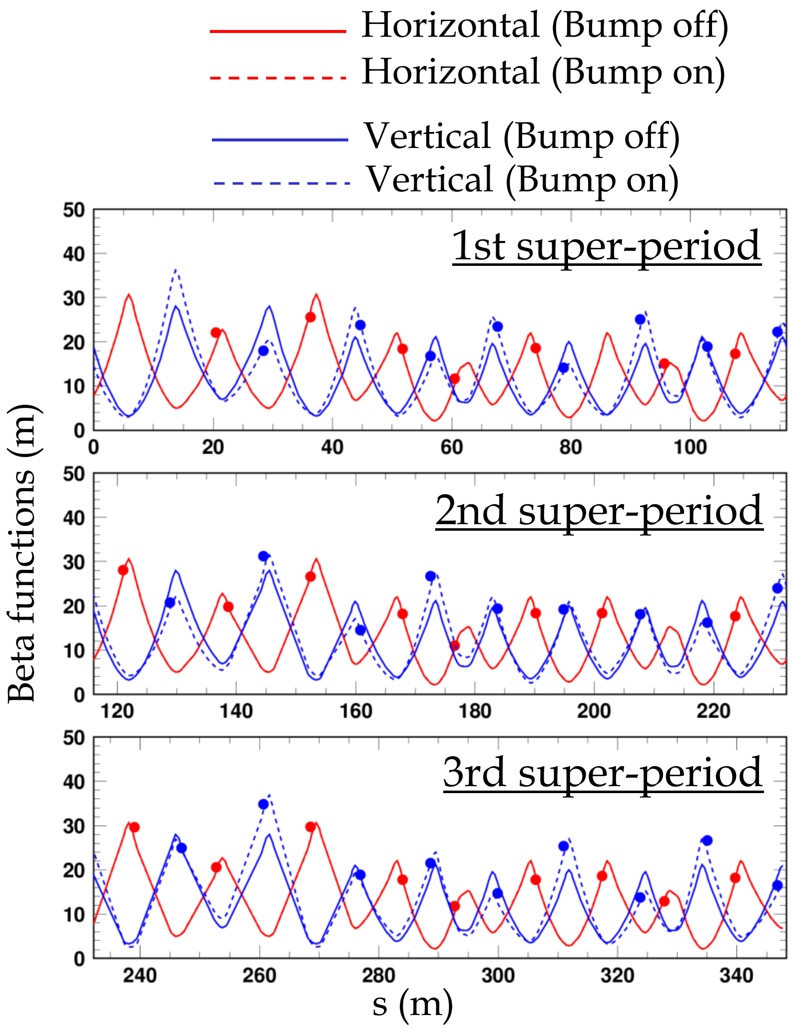
- ✓ The foil scattering beam loss can be reduced by larger transverse painting, especially on the horizontal plane.
- ✓ But such a large transverse painting had not been realized until recently due to beta function beating caused by the edge focus of the injection bump magnets.

Beta function beating caused by the injection bump magnets

Beam injection is performed with a time dependent horizontal local bump orbit by using 8 sets of rectangular pulse dipoles magnets (SB1-4 & PBH1-4).



Beta function beating caused by the edge focus of the injection bump magnets



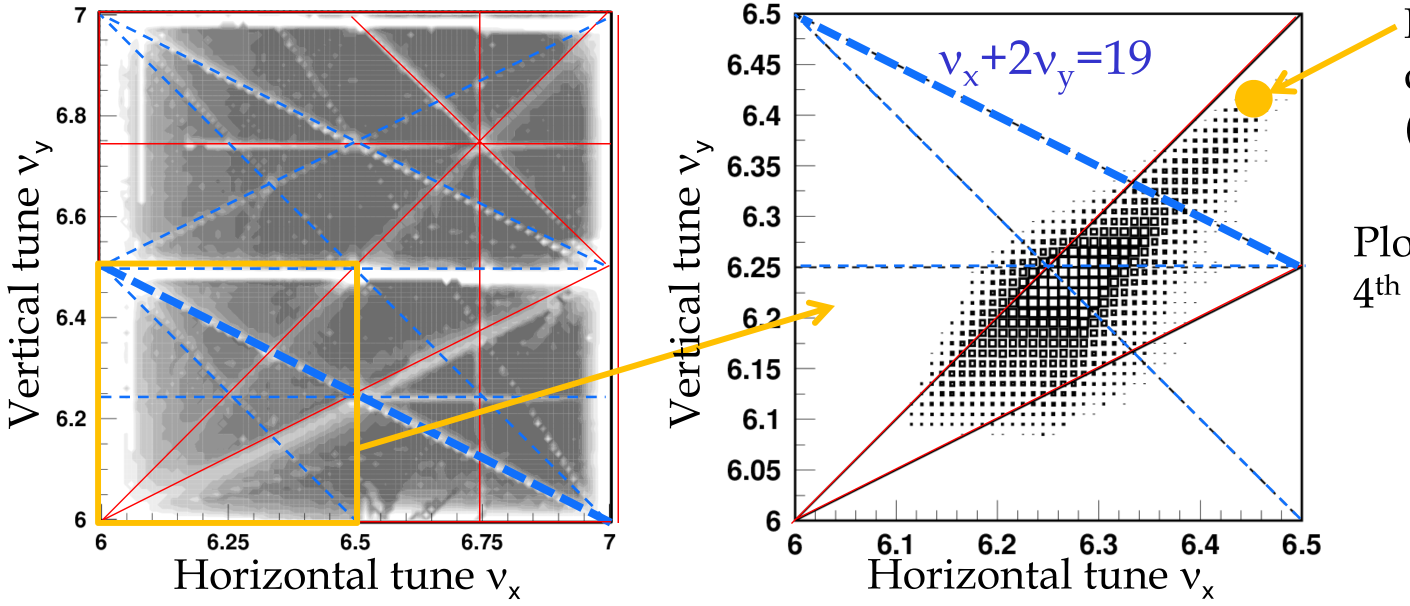
- ✓ Edge focuses are generated at the entrance and exit of the injection bump magnets.

- ✓ There is no beta function beating on the horizontal plane, because the horizontal edge focus effects are canceled out by another focusing property intrinsic on the bending plane.

- ✓ The vertical edge focus affect the beam as is, making 30% beta function beating on the vertical plane at maximum during injection period.

- ✓ Beta function beating makes a distortion of the lattice super-periodicity and additionally excites various random betatron resonances.

Random betatron resonances excited through a distortion of the super-periodicity



Present
operating point
(6.45,6.42)

Plotted up to
4th order resonances

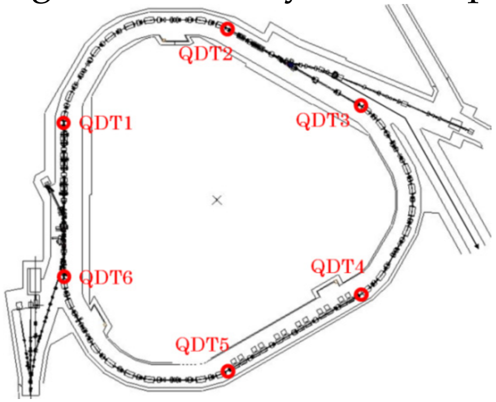
— Systematic resonances

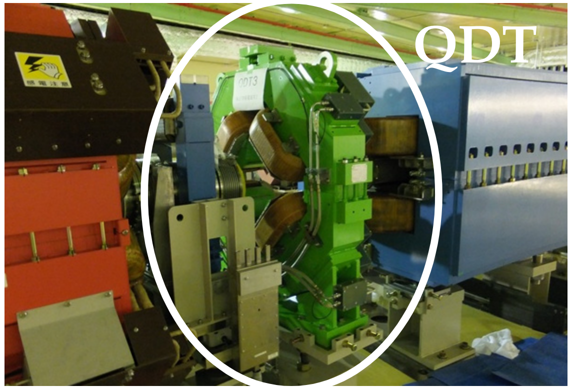
------- Random resonances
that can be additionally excited through a distortion of the super-periodicity on the vertical plane caused by the edge focus of the injection bump magnets

- ✓ These random resonances cause an additional shrinkage of the dynamic aperture during the injection period, and leads to extra beam loss when applying large transverse painting.
- ✓ Especially, the random 3rd order sum resonance ($\nu_x+2\nu_y=19$) strongly affects the beam in the present operational condition.

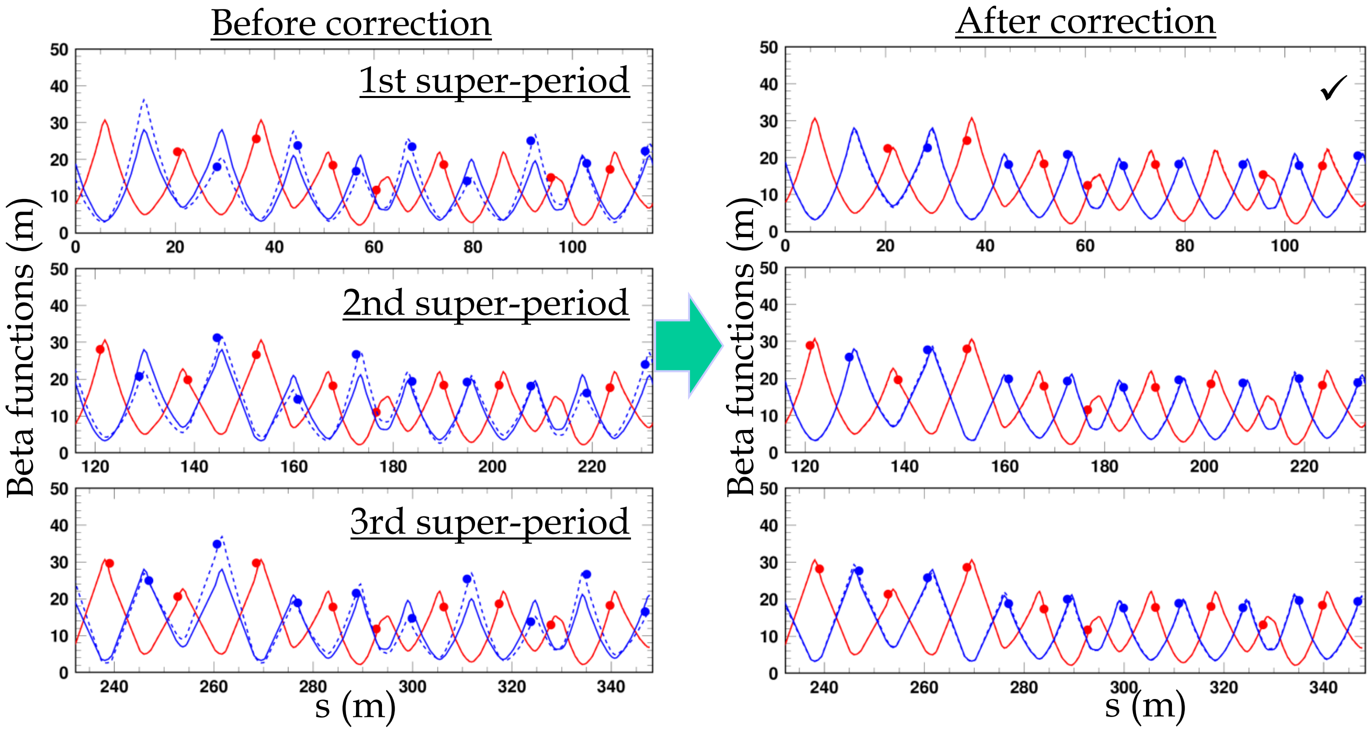
Correction of beta function beating

- ✓ We have recently installed 6 sets of pulse type quadrupole correctors (QDTs), to compensate beta function beating, and to minimize the effect of the random resonances through the recovery of the super-periodic condition.





Beta function beating correction by the quadrupole correctors.


Before correction

After correction

✓ Vertical beta function beating was successfully corrected by QDTs, while keeping the super-periodic condition on the horizontal plane.

Beam loss reduction by QDTs (Run#62)

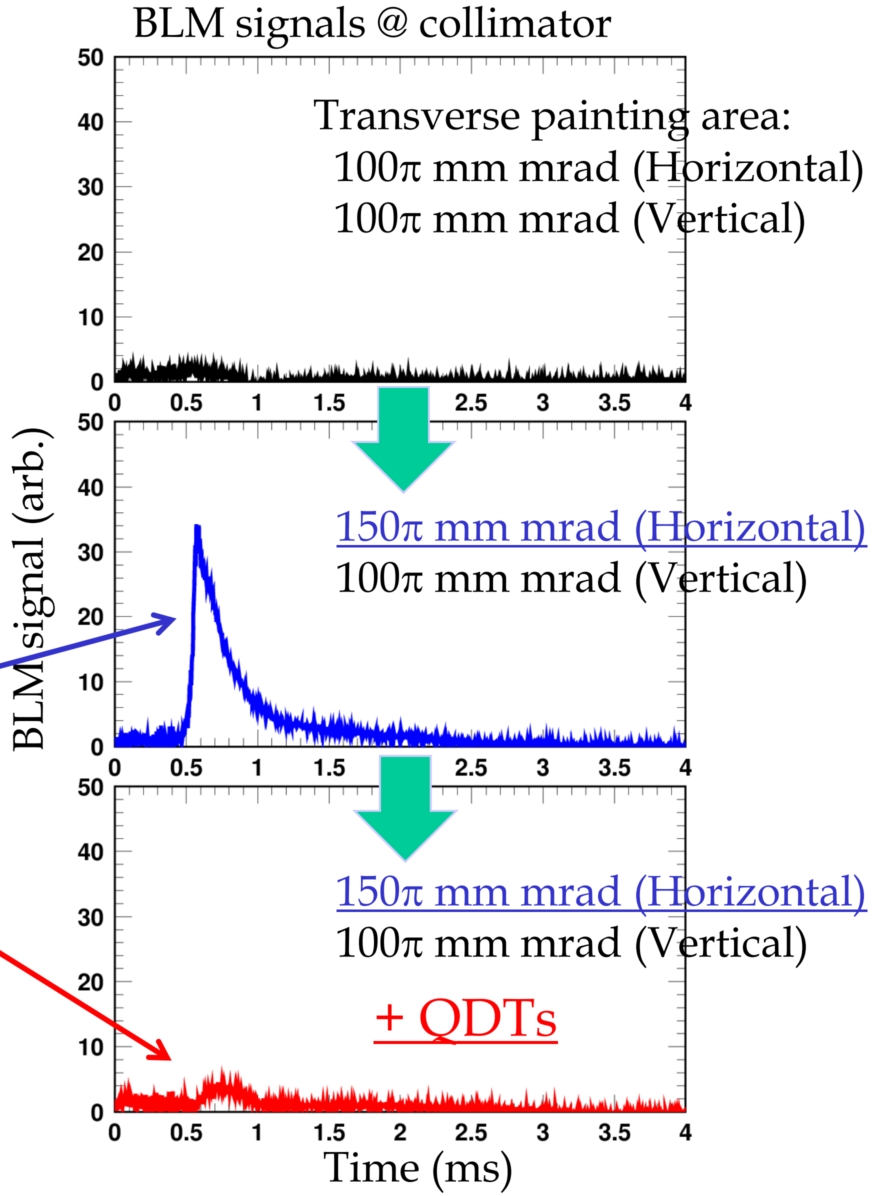
Experimental condition

- ◆ Date : Apr. 3-8, 2015 (Run#62)
- ◆ Injection beam condition
  - Injection energy : 400 MeV
  - Peak current : 29.8 mA @ the entrance of RCS
  - Pulse length : 0.5 ms
  - Chopper beam-on duty factor : 60%
  - ⇒ 5.58 x 10^{13} particles/pulse, corresponding to 670 kW at 3 GeV
- ◆ Operating point; (6.45, 6.42)

✓ When expanding the horizontal painting area to 150π mm mrad, significant extra beam loss appeared.

✓ But this beam loss was well mitigated as expected by introducing QDTs.

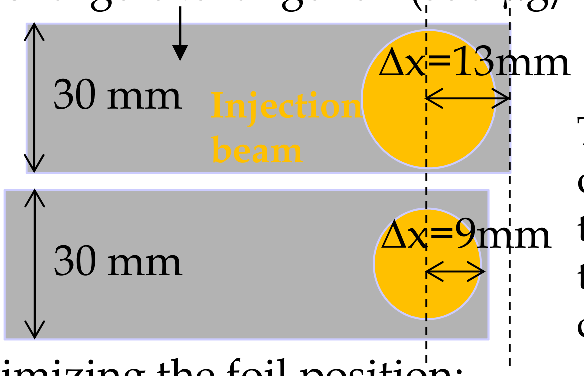
Now we are conducting the 500-kW routine beam operation with this large transverse painting using QDTs.



By this large transverse painting, and also by re-optimizing the foil position, the residual radiation level near the charge exchange foil was well reduced as expected.

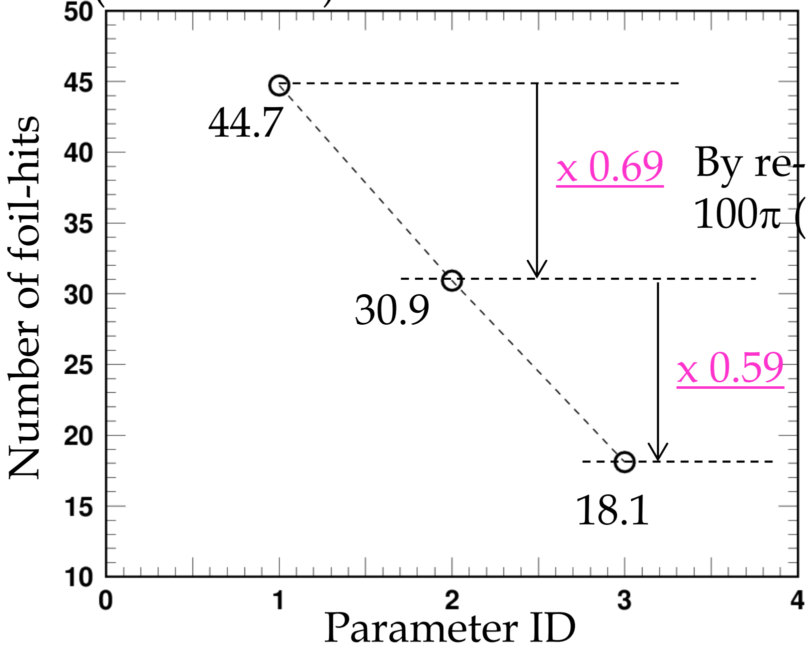
Residual dose level at the charge exchange foil

Charge-exchange foil (330-μg/cm^2-thick HBC)



The foil was pulled out by 4 mm following the improvement of the injection beam quality.

Average number of foil-hits per particle (Calculation)



By re-optimizing the foil position;
100π (Hor.)-100π (Ver.) mm mrad, Δx=9mm

By expanding horizontal painting area;
150π (Hor.)-100π (Ver.) mm mrad, Δx=9mm

Reduction rate in total ; x 0.4

✓ By these attempts, the foil scattering beam loss was reduced, and as a result, the residual dose level near the charge exchange foil was well reduced as expected;

~15 mSv/h @ chamber surface (2-hour after the 400-kW beam operation).

~8 mSv/h @ chamber surface (2-hour after the 500-kW beam operation).

Expectation ; (15 mSv/h) x 0.4 x (500 kW/400 kW) = 7.5 mSv/h

✓ RCS beam tuning is in progress well towards realizing 1-MW routine beam operation.

Summary

- We started 1-MW beam tuning from October 2014,
  and successfully achieved 1-MW beam acceleration in January 2015.
- Major part of beam loss, such as space-charge induced beam loss,
  was well minimized by the injection painting technique.
  The remaining beam loss is mainly from foil scattering during injection.
- Very recently, the transverse painting area was successfully expanded by correcting
  beta function beating caused by the edge focus of the injection bump magnets,
  by which the remaining foil scattering beam loss was further reduced.
- By these efforts, now the beam loss is at the permissible level for the 1-MW routine
  beam operation, except for the remaining longitudinal beam loss observed
  for higher intensity beams of more than 900 kW.
- The 1-MW routine beam operation will be ready after this summer maintenance period,
  namely by solving the remaining longitudinal beam loss
  after completing the RF anode power supply upgrade.
- Now we are gradually increasing the routine output beam power by a 100-kW step
  every one month. If this beam power ramp-up scenario is going well,
  the 1-MW routine beam operation is to start up from the next spring
  via the summer maintenance period.

Back-up slides

Tune footprint calculated at the end of injection

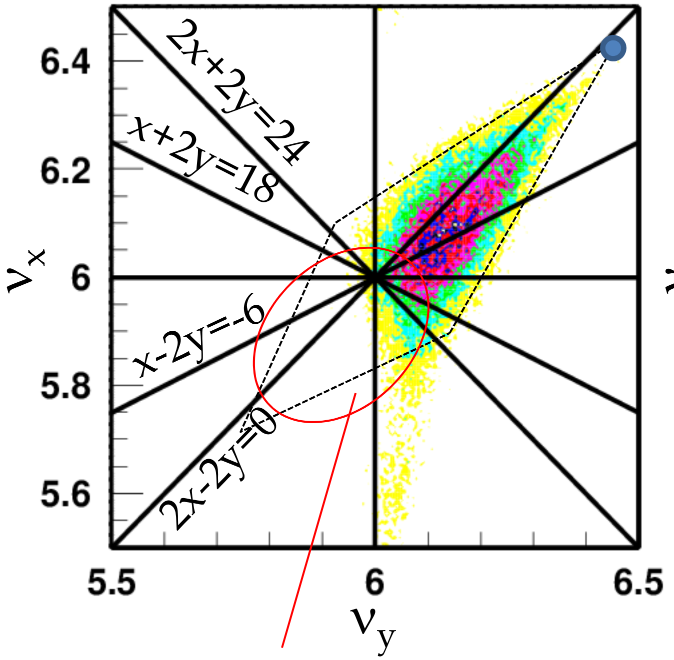
E_{inj}=181 MeV

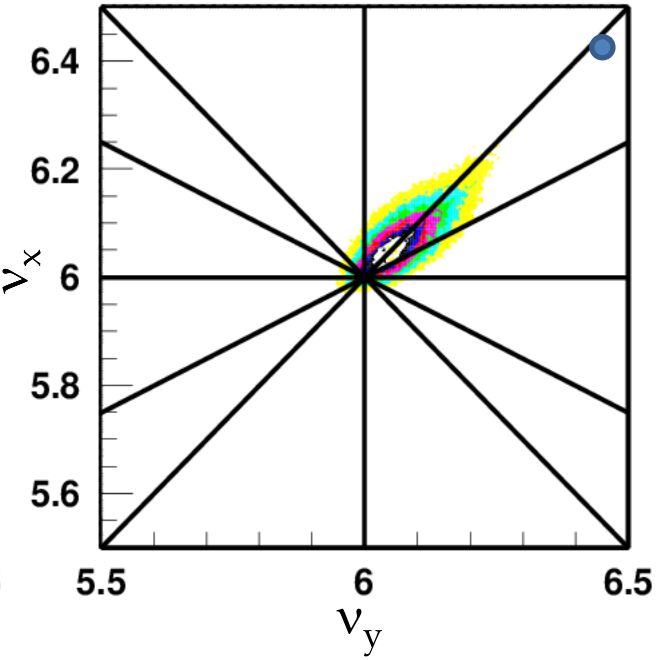
<u>ID1</u>

- No transverse painting
- No longitudinal painting

<u>ID8</u>

- 100π transverse painting
- Full longitudinal painting
  (V_2/V_1=80%, ϕ_2=-100 to 0 deg, $\Delta p/p$=-0.2%)



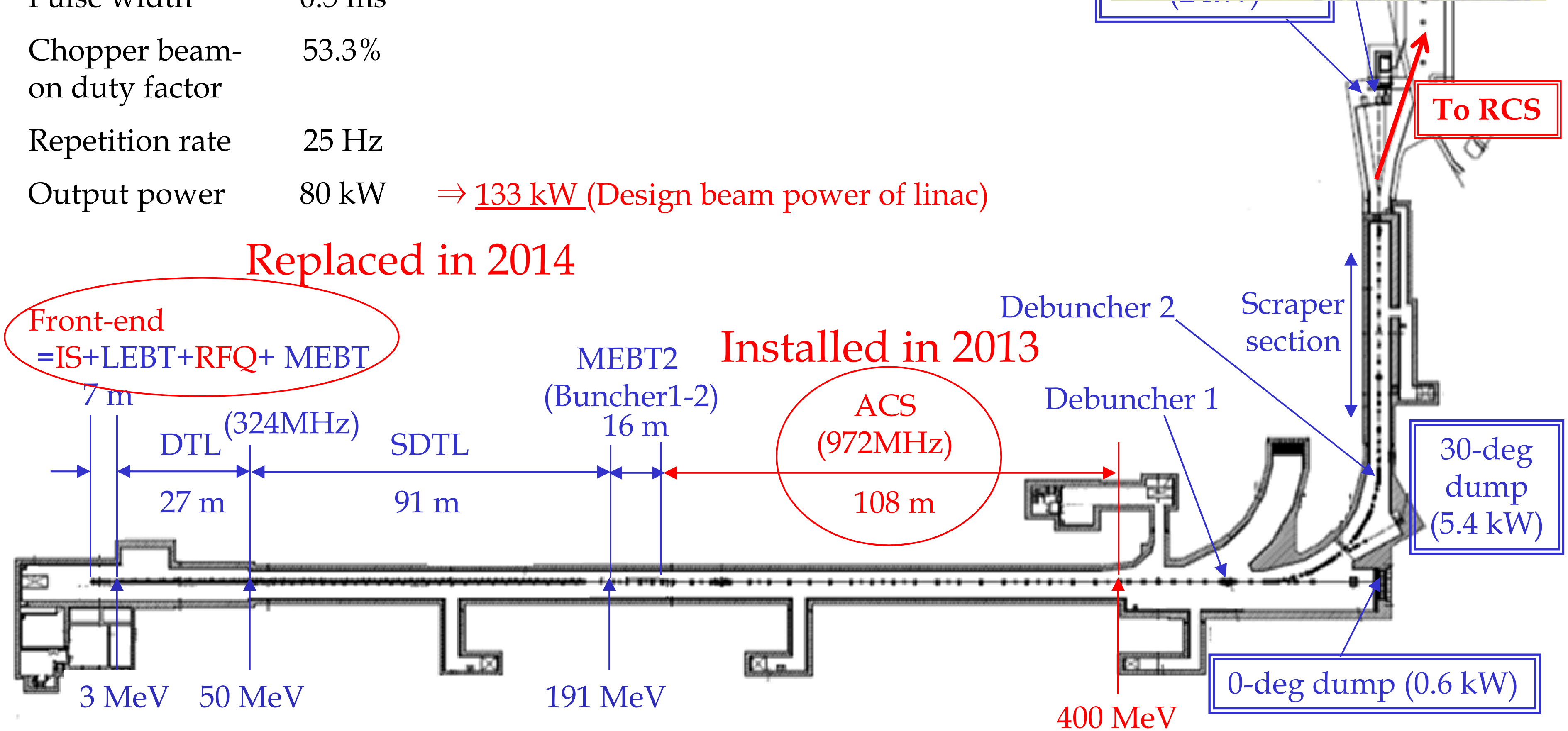


Particles here suffer from emittance dilutions, leading to beam loss.

Design parameters of the linac

Particles	H^-	
Output energy	181 MeV	⇒ "400 MeV" in 2013 by adding an ACS linac section
Peak current	30 mA	⇒ "50 mA" in 2014 by replacing the front-end system (IS &RFQ)
Pulse width	0.5 ms	
Chopper beam-on duty factor	53.3%	
Repetition rate	25 Hz	
Output power	80 kW	⇒ 133 kW (Design beam power of linac)


ACS installed in 2013



✓ The hardware improvements of the injector linac have been completed.