Beam loss and its mitigation in the J-PARC RCS

Space charge 2013

April 16-19, 2013 @ CERN

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RCS beam commissioning team
&
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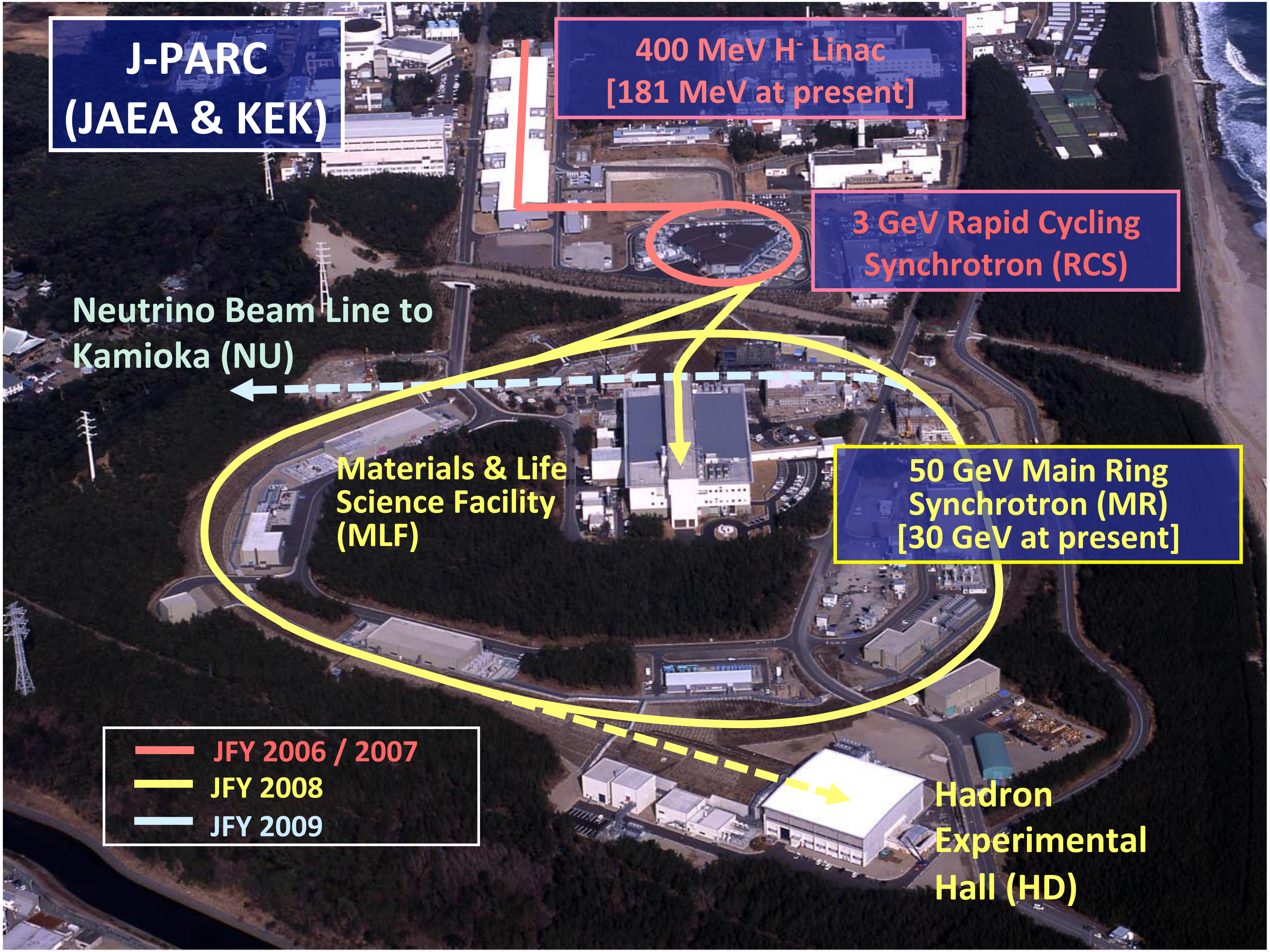


J-PARC (JAEA & KEK)

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)

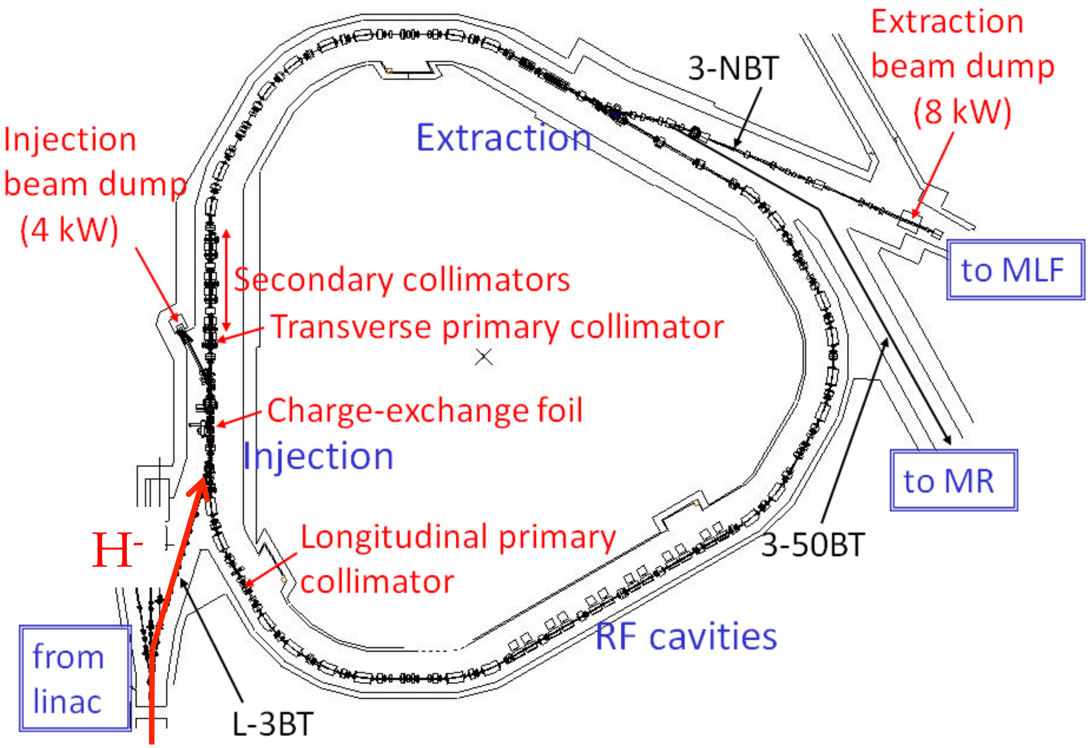
50 GeV Main Ring Synchrotron (MR)
[30 GeV at present]

Hadron Experimental Hall (HD)

- — JFY 2006 / 2007
- — JFY 2008
- — JFY 2009

Design parameters of the J-PARC RCS

Circumference	348.333 m
Super-periodicity	3
Injection	Charge-exchange, Multi-turn
Injection period	0.5 ms
Injection energy	181 MeV ⇒ 400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Harmonic number	2
Number of bunches	2
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)



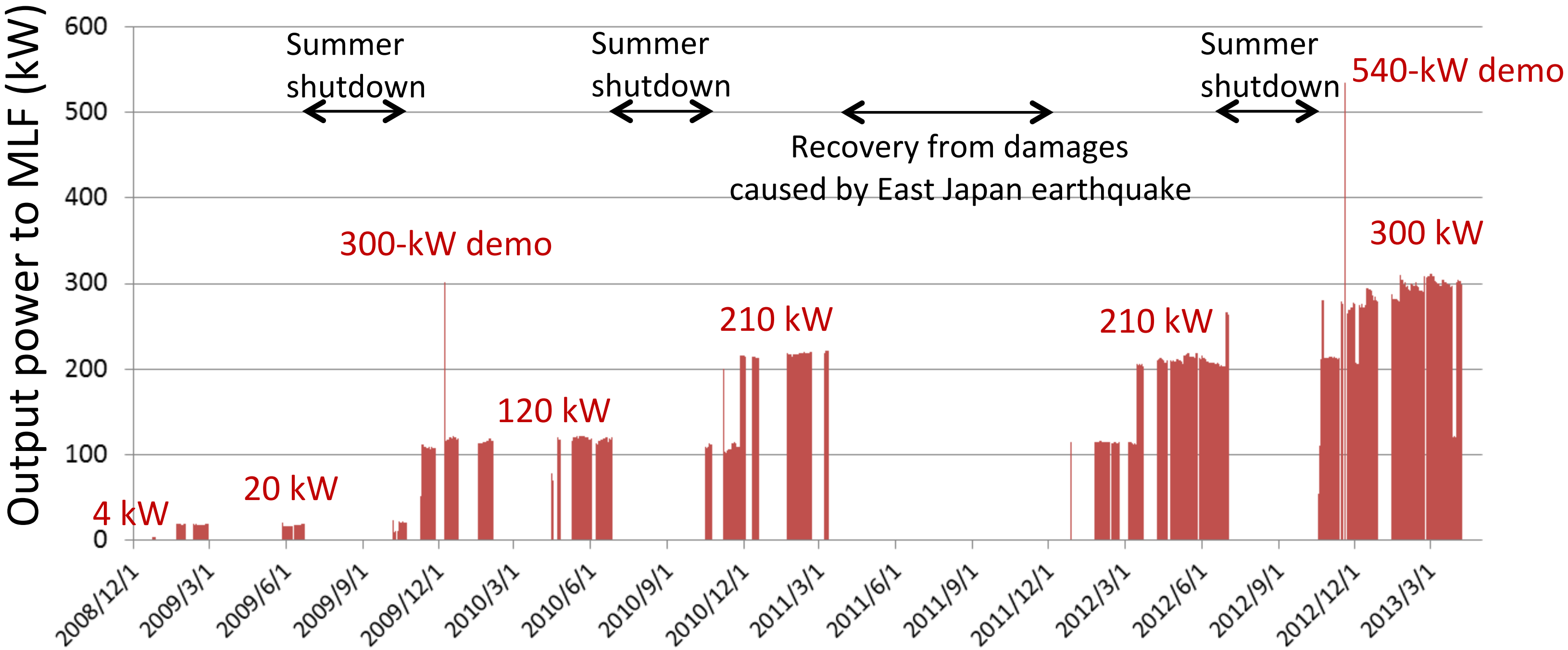
Linac upgrade :

- Installation of ACS in 2013 Summer-Autumn:
  Injection energy 181 MeV ⇒ 400 MeV
- Replacement of IS and RFQ in 2014 Summer:
  Intensity 5.0E13 ⇒ 8.3E13/pulse

We plan to start 1-MW beam tuning from Oct. 2014.

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;

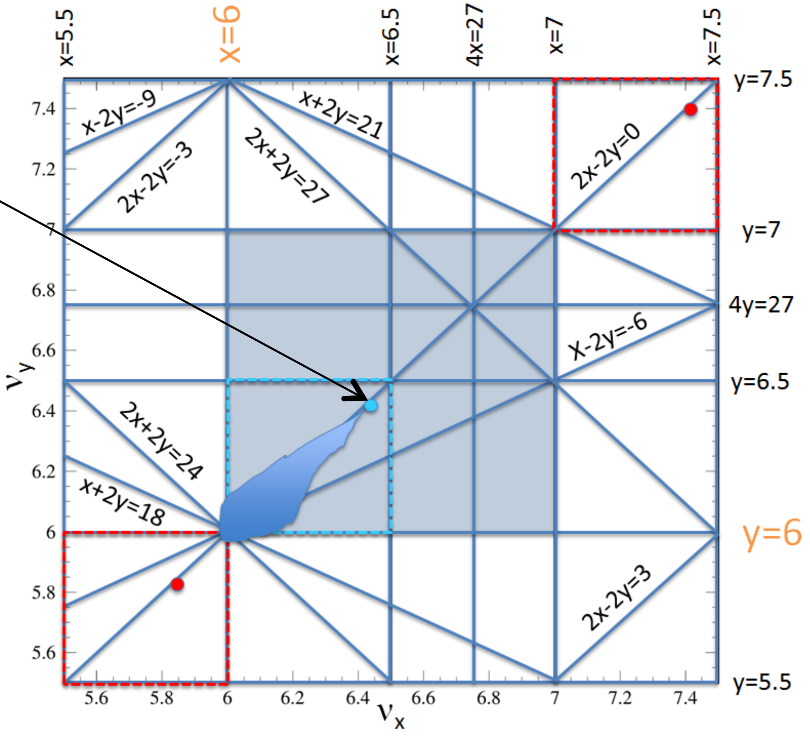
- Progression of beam tuning,
- Hardware improvements,
- Careful monitoring of the trend of residual activation levels.

- Maximum output beam power demonstrated so far : ~540 kW
- Current output beam power for the routine user program : ~300 kW

*** Output beam power is now limited by the capability of the neutron target.

High intensity beam trial of up to 540 kW

- Date ; Nov. 2012
- Injection beam;
  181 MeV/24.5 mA/0.5 ms/0.60 chopper beam-on duty factor
  ⇒ 4.5E13/pulse, corresponding to 540 kW output at 25 Hz.
- Operating point; (6.45, 6.42)



In this experiment, we measured;

- Injection painting parameter dependence of beam loss
- Intensity dependence of beam loss
- Time structure of beam loss
- Transverse & longitudinal beam profiles, and bunching factor . . . . . .

In this talk, we present
the above experimental results
together with the corresponding numerical simulation results.

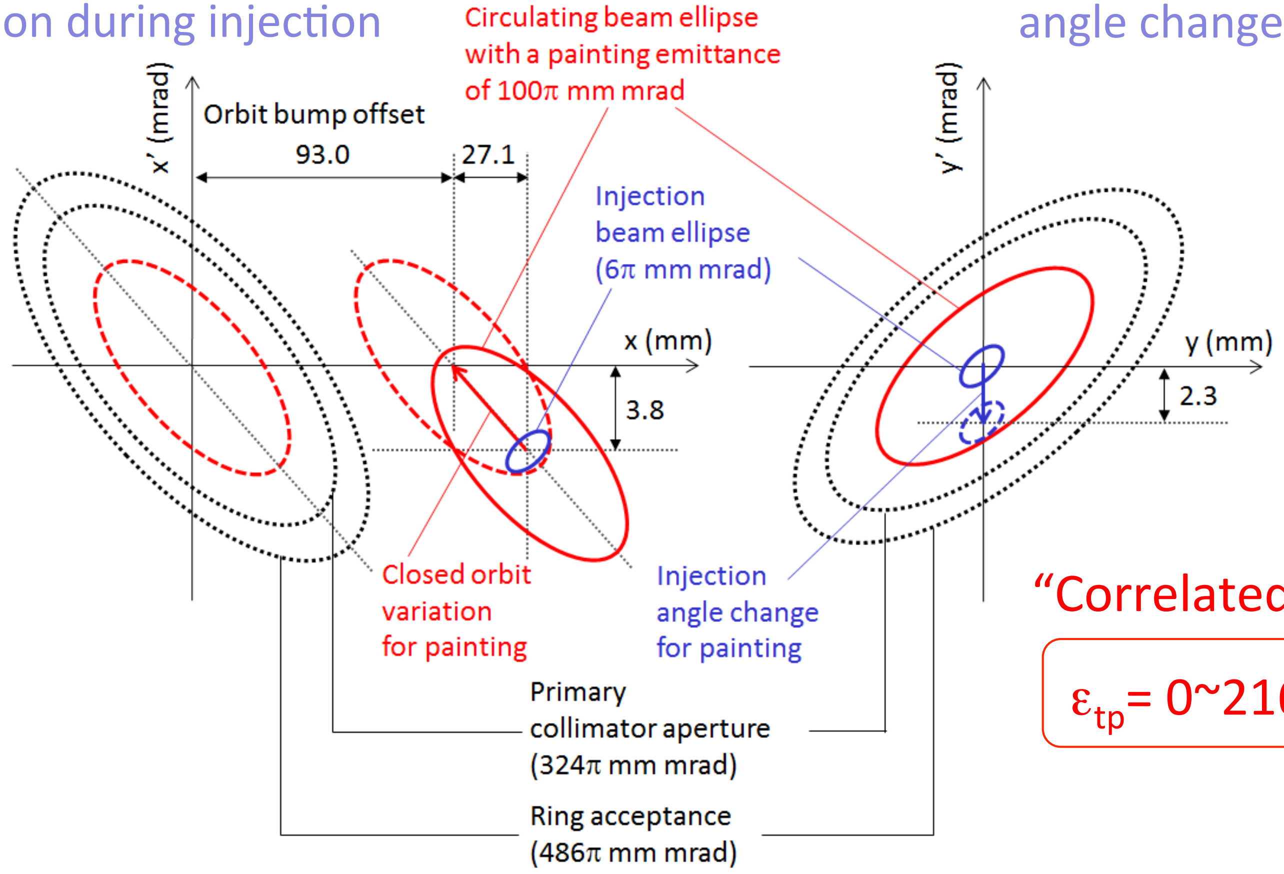
Beam loss reduction by injection painting

Transverse painting

Transverse painting makes use of a controlled phase space offset between the centroid of the injection beam and the ring closed orbit to form a different particle distribution of the circulating beam from the multi-turn injected beam.

Horizontal painting
by a horizontal closed orbit
variation during injection

Vertical painting
by a vertical injection
angle change during injection



Circulating beam ellipse
with a painting emittance
of 100π mm mrad

Injection
beam ellipse
(6π mm mrad)

Closed orbit
variation
for painting

Injection
angle change
for painting

Primary
collimator aperture
(324π mm mrad)

Ring acceptance
(486π mm mrad)

“Correlated painting”

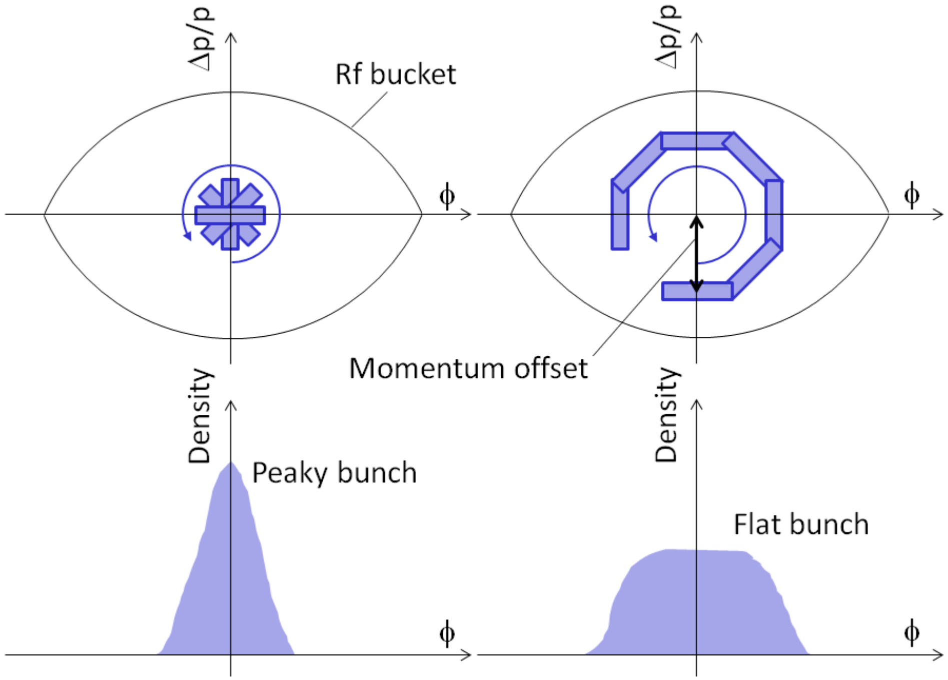
ε_{tp}= 0~216π mm mrad

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

Longitudinal painting

Longitudinal painting makes use of a controlled momentum offset to the rf bucket in combination with superposing a second harmonic rf to get a uniform bunch distribution after the multi-turn injection.

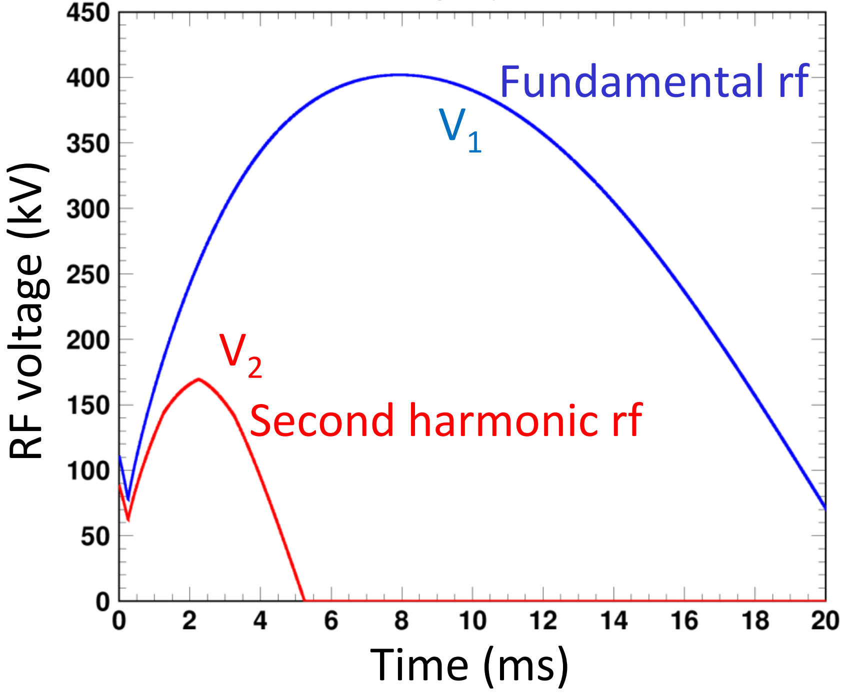
Momentum offset injection



$\Delta p/p$=0, -0.1 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%

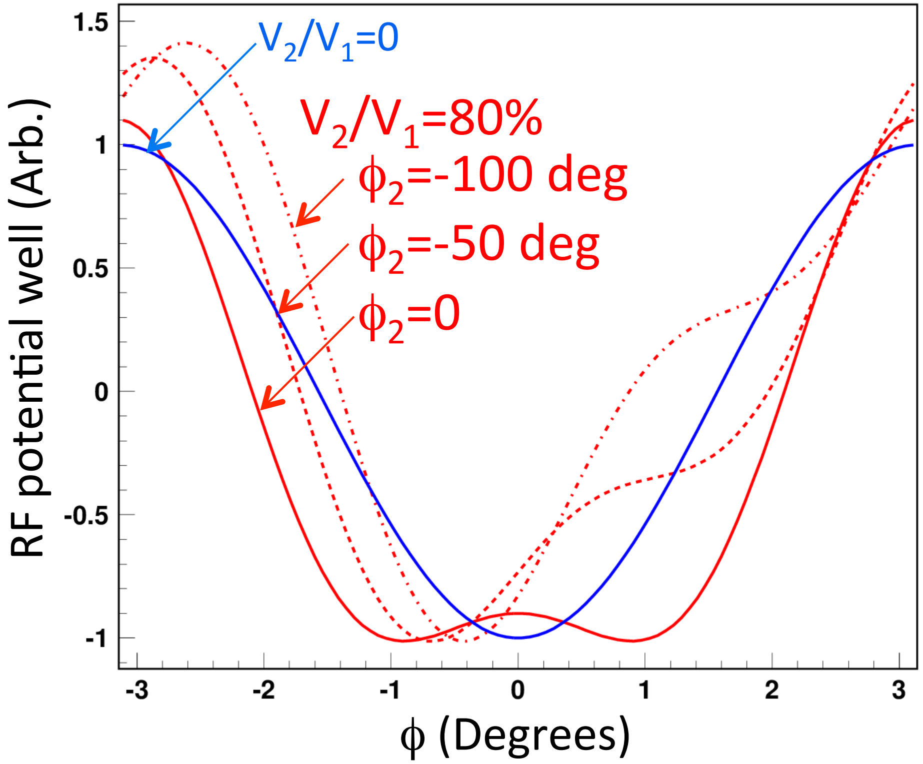
The second harmonic rf fills the role in shaping flatter and wider rf bucket potential, leading to better longitudinal motion to make a flatter bunch distribution.

Longitudinal painting

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

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

Phase sweep of the second harmonic rf



$\phi_2=-100\Rightarrow0$ deg

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

Numerical simulation setup

Simpsons (PIC particle tracking code developed by Dr. Shinji Machida)

Imperfections included:

◆ Time independent imperfections

- Multipole field components for all the main magnets:
  BM ($K_{1\sim6}$), QM ($K_{5,\,9}$), and SM (K_8) obtained from field measurements
- Measured field and alignment errors

◆ Time dependent imperfections

- Static leakage fields from the extraction beam line:
  $K_{0,1}$ and $SK_{0,1}$ estimated from measured COD and optical functions
- Edge focus of the injection bump magnets:
  K_1 estimated from measured optical functions
- BM-QM field tracking errors
  estimated from measured tune variation over acceleration
- 1-kHz BM ripple
  estimated from measured orbit variation
- 100-kHz ripple induced by injection bump magnets
  estimated from turn-by-turn BPM data

Time-dependent imperfections can be included easily, because “Simpsons” takes “time” as an independent variable.

◆ Foil scattering:

Coulomb & nuclear scattering angle distribution calculated with GEANT

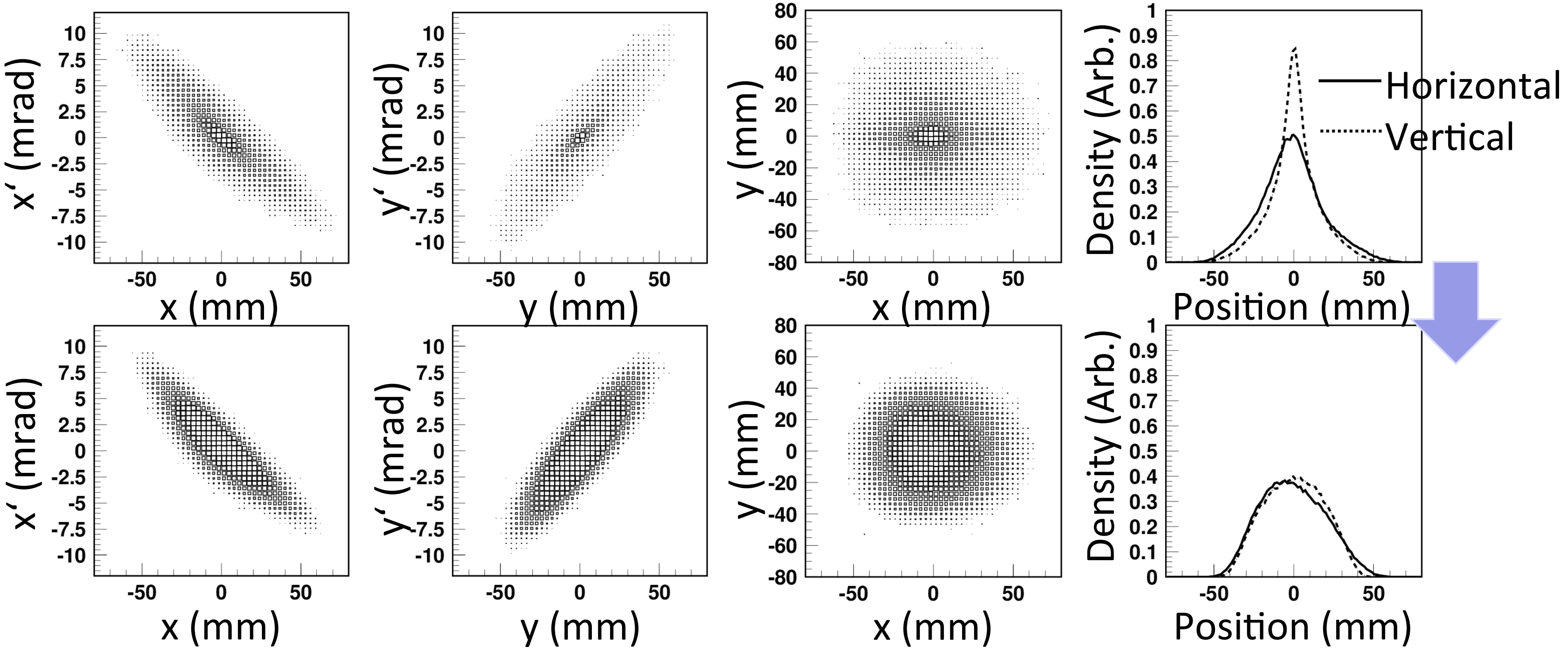
We improve calculation model following the progression of beam experiment in collaboration with Dr. S. Machida, discussing space-charge effect and its combined effects with imperfections.

Transverse painting

Numerical simulations

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

No painting



100π transverse painting

Longitudinal painting

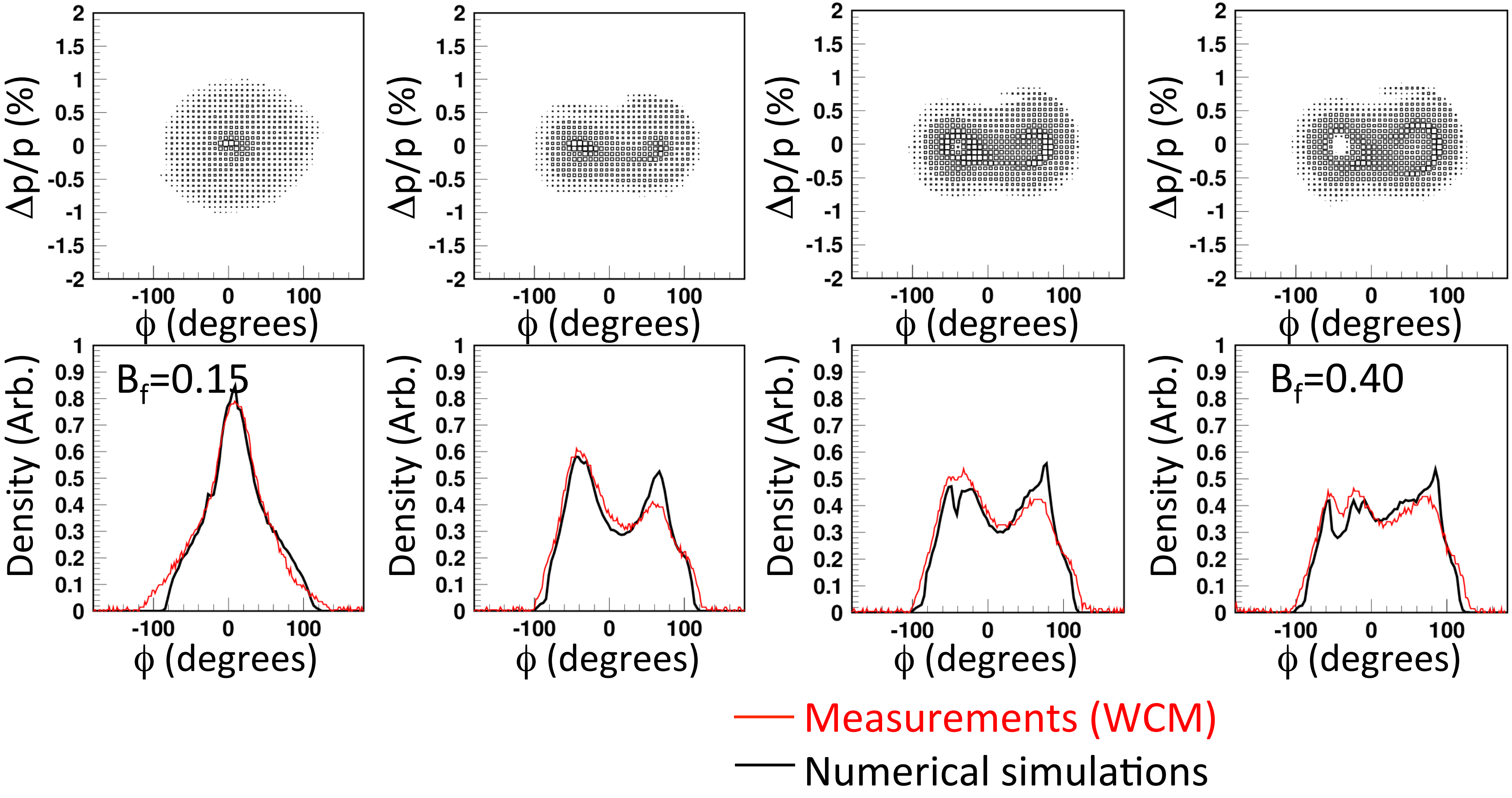
Longitudinal beam distribution just after beam injection (at 0.5 ms)

No longitudinal painting

V_2/V_1=80%
ϕ_2=-100 to 0 deg
$\Delta p/p$= 0.0%

V_2/V_1=80%
ϕ_2=-100 to 0 deg
$\Delta p/p$=-0.1%

V_2/V_1=80%
ϕ_2=-100 to 0 deg
$\Delta p/p$=-0.2%

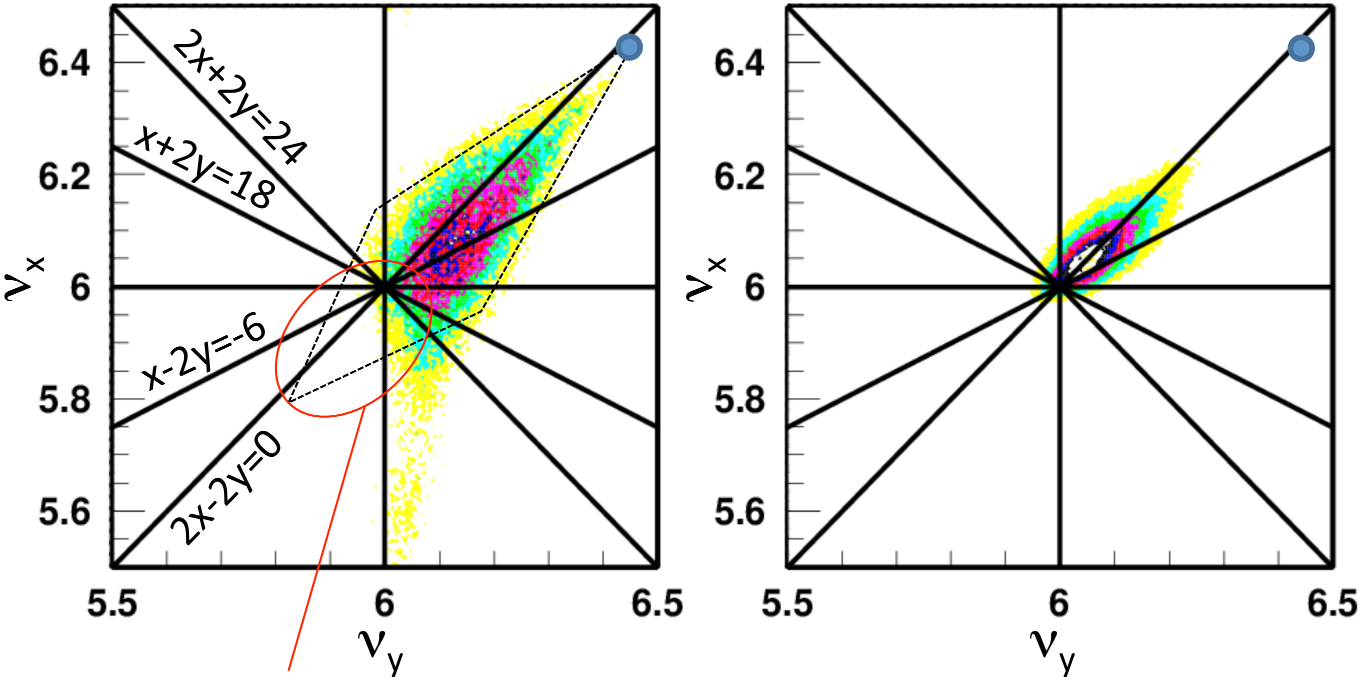


Tune footprint at the end of injection

Numerical Simulation

- No transverse painting
- No longitudinal painting

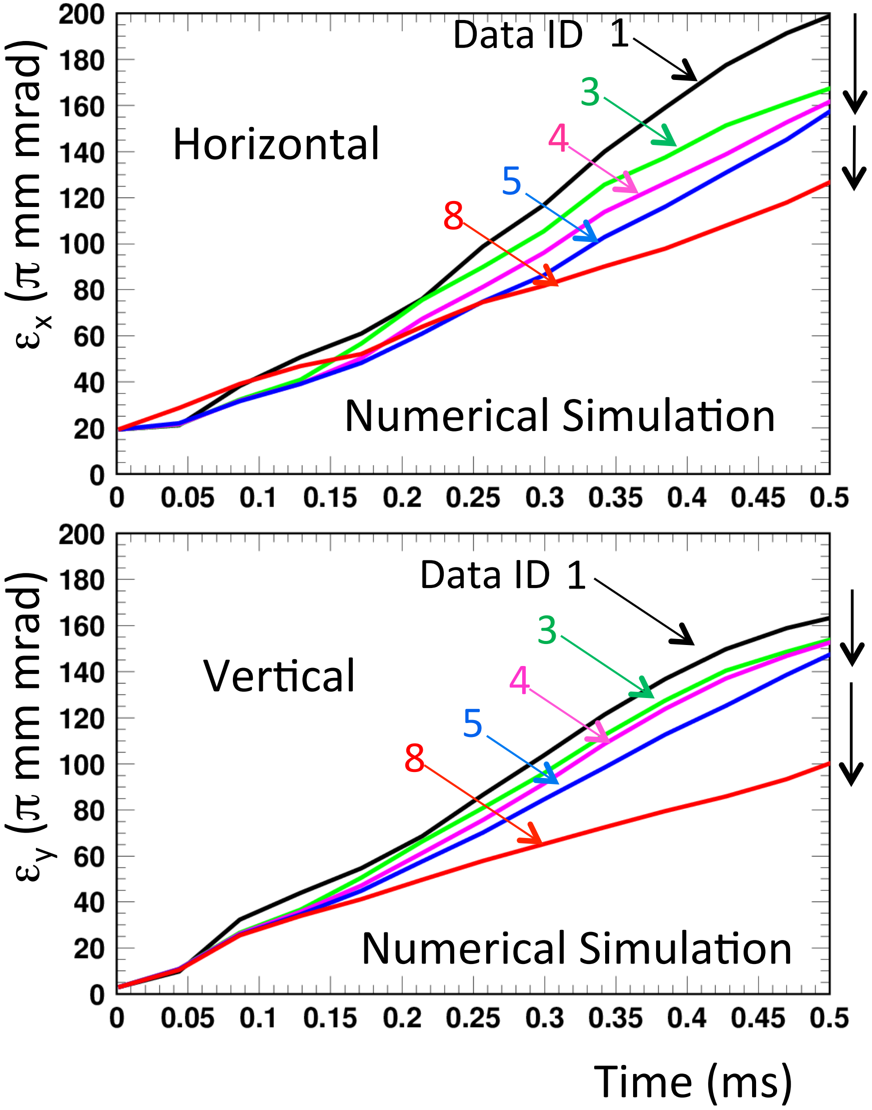
- 100π transverse painting
- Full longitudinal painting
  $(V_2/V_1=80\%, \phi_2=-100$ to 0 deg, $\Delta p/p=-\underline{0.2\%})$



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

Emittance growth mitigation by painting

99 % normalized emittance



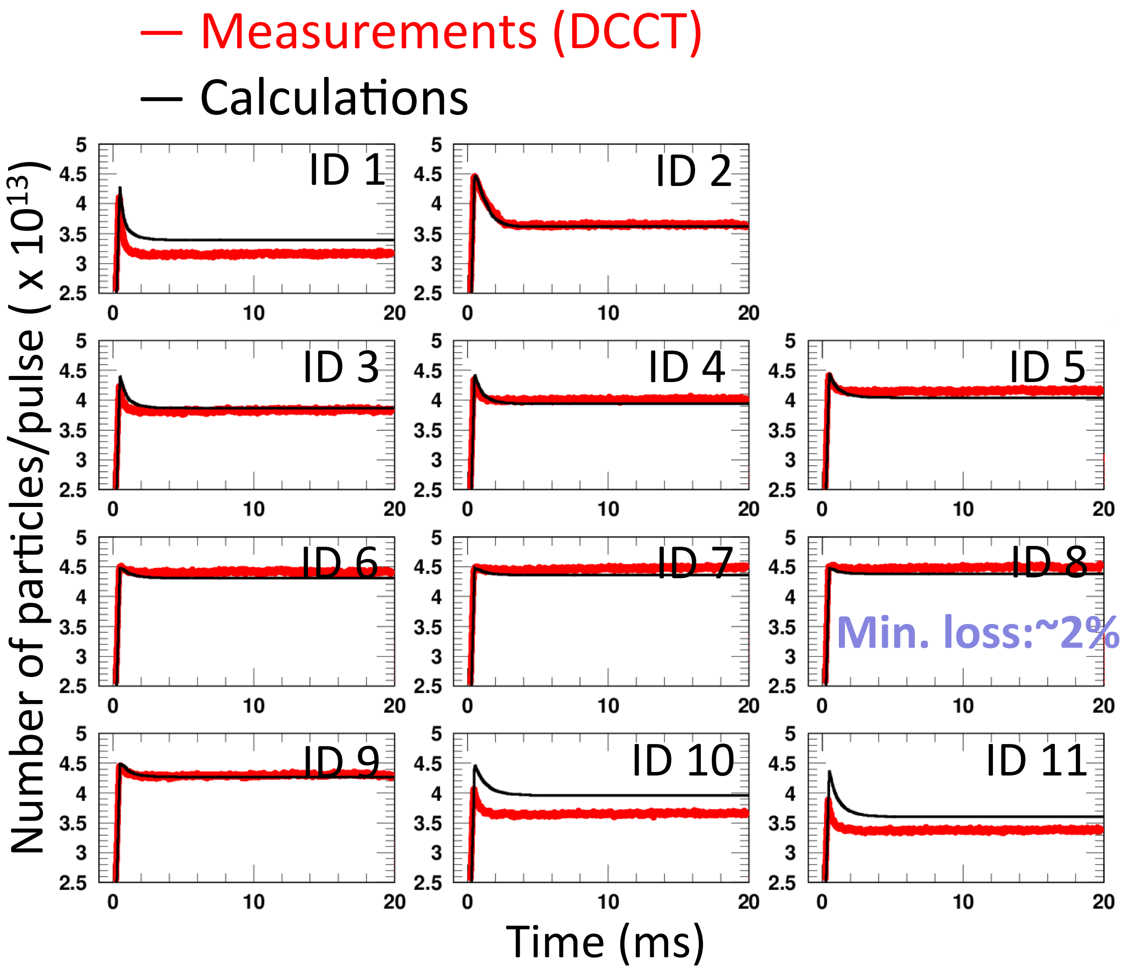
By longitudinal painting

By adding 100π transverse painting

ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	100	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100	80	-100	-0.0
7	100	80	-100	-0.1
8	100	80	-100	-0.2
9	150	80	-100	-0.2
10	200	80	-100	-0.2
11	216	80	-100	-0.2

We experimentally investigated the effectiveness of injection painting on the beam loss reduction for 540 kW intensity beam.

Beam loss reduction by painting

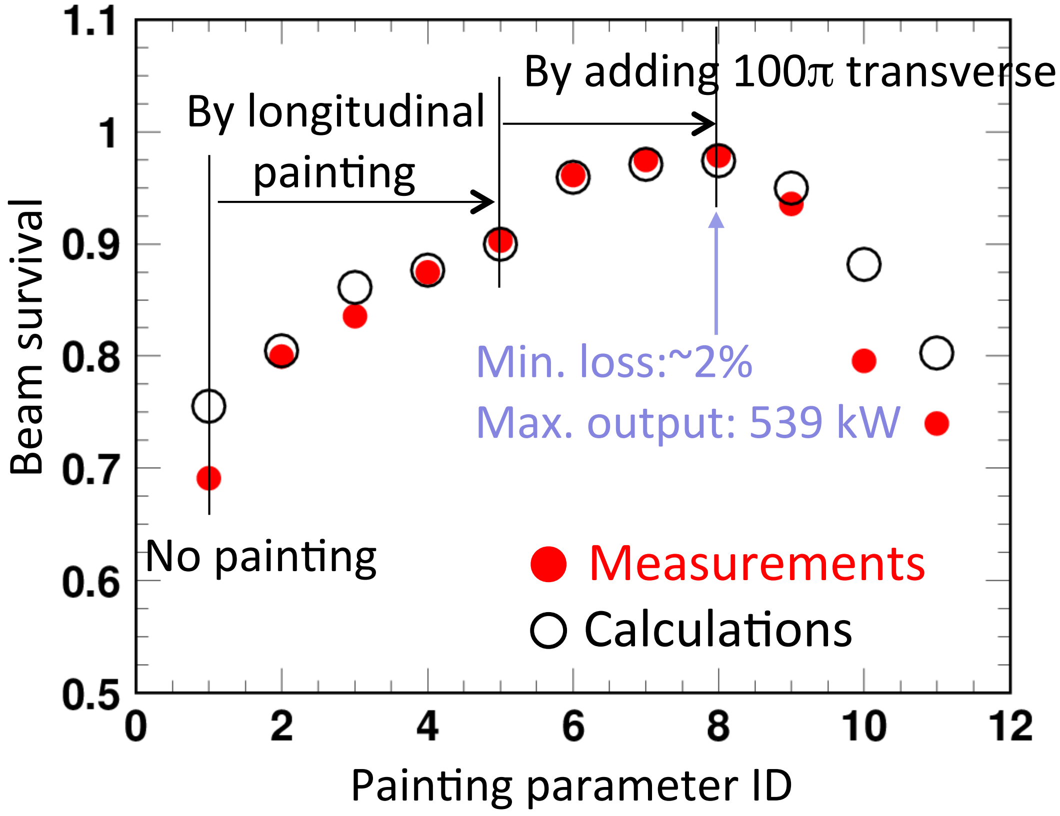


ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	100	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100	80	-100	-0.0
7	100	80	-100	-0.1
8	100	80	-100	-0.2
9	150	80	-100	-0.2
10	200	80	-100	-0.2
11	216	80	-100	-0.2

- Beam loss takes place only for the first 4 ms in the low energy region for all the cases.
- Beam loss of ~30% observed with no painting (ID1) was decreased to ~2% by the combination of 100π transverse painting and full longitudinal painting (ID8).
- Most of the remaining 2% beam loss was well localized at the collimator section.
- The 2% beam loss corresponds to 650 W in power, which is still less than 1/6 of the collimator limit of 4 kW.

Beam loss reduction by painting

Beam survival: output intensity (DCCT) /input intensity (SCT76)



By longitudinal painting

By adding 100π transverse painting

No painting

Min. loss:~2%

Max. output: 539 kW

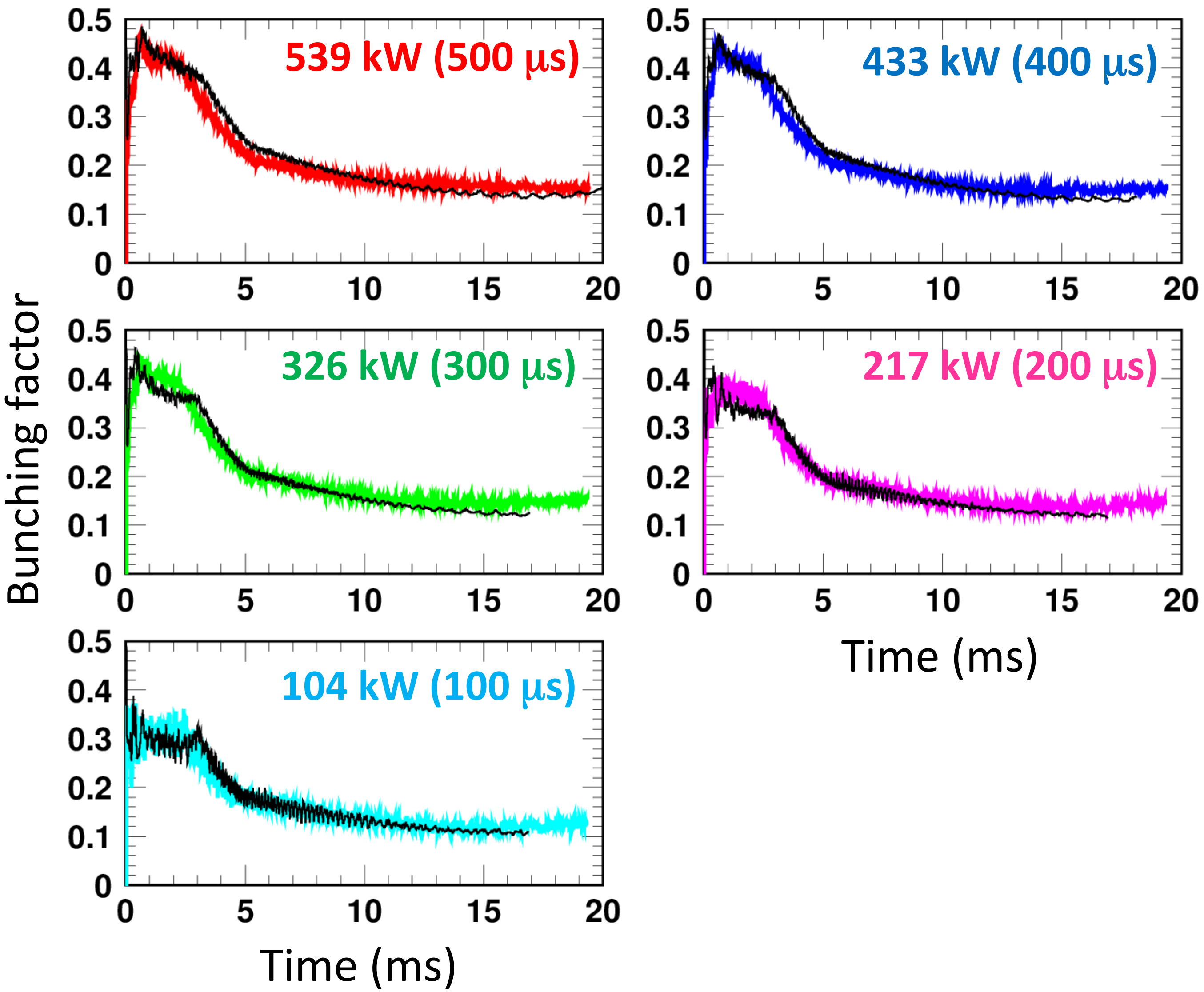
ID	ε_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	100	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100	80	-100	-0.0
7	100	80	-100	-0.1
8	100	80	-100	-0.2
9	150	80	-100	-0.2
10	200	80	-100	-0.2
11	216	80	-100	-0.2

ID1⇒ID8 Beam loss reduction by painting

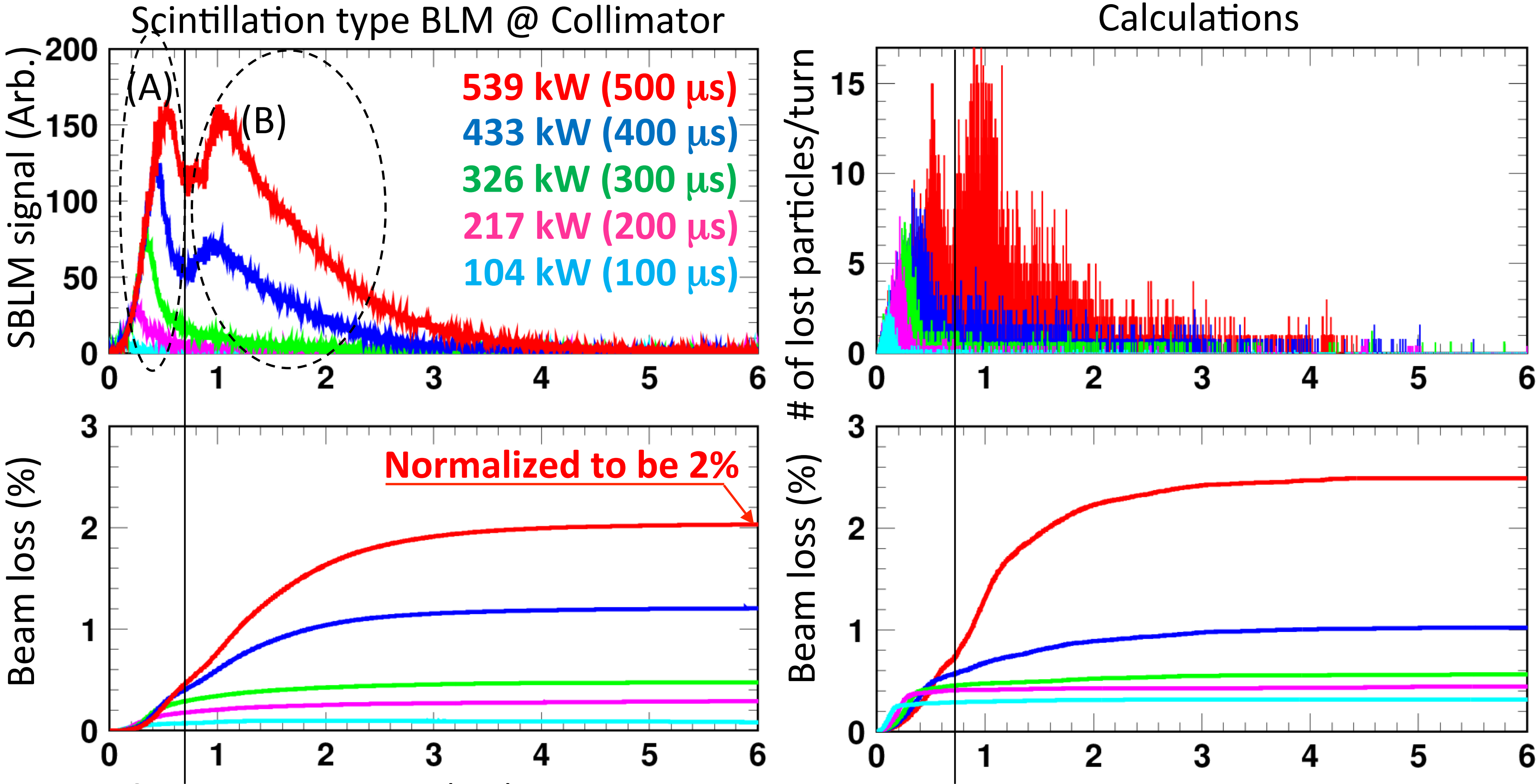
ID8⇒ID11 Beam loss increase caused by large transverse painting (ε_{tp}>150π) due to the dynamic aperture limit.

Intensity dependence of beam loss, bunching factor, extraction beam profile･･･

Measurements vs. Calculations
: Bunching factor



Measurements vs. Calculations
: Time structure of beam loss



0.7 ms :
End of foil scattering

0.7 ms :
End of foil scattering

The beam loss appears only for the first 4 ms in the low energy region:

(A) mainly from foil scattering during injection

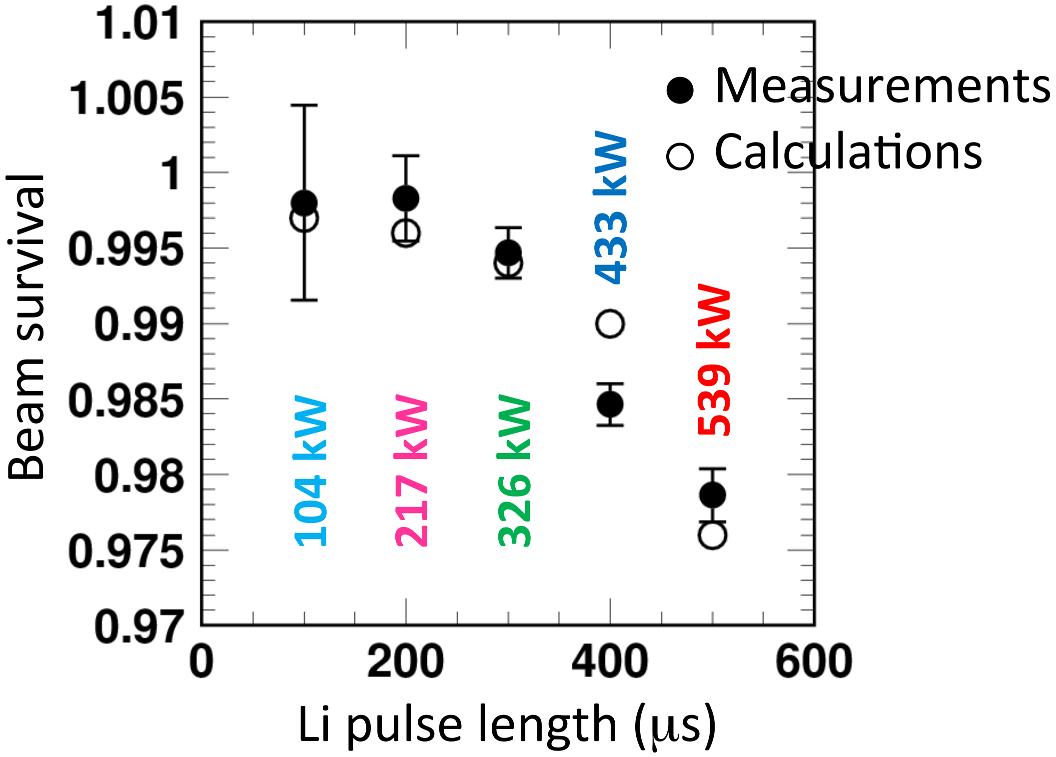
(B) Origin? ･･･to be discussed later

Measurements vs. Calculations
: Intensity dependence of beam loss

Painting parameter ID8 :
- 100π transverse painting
- Full longitudinal painting

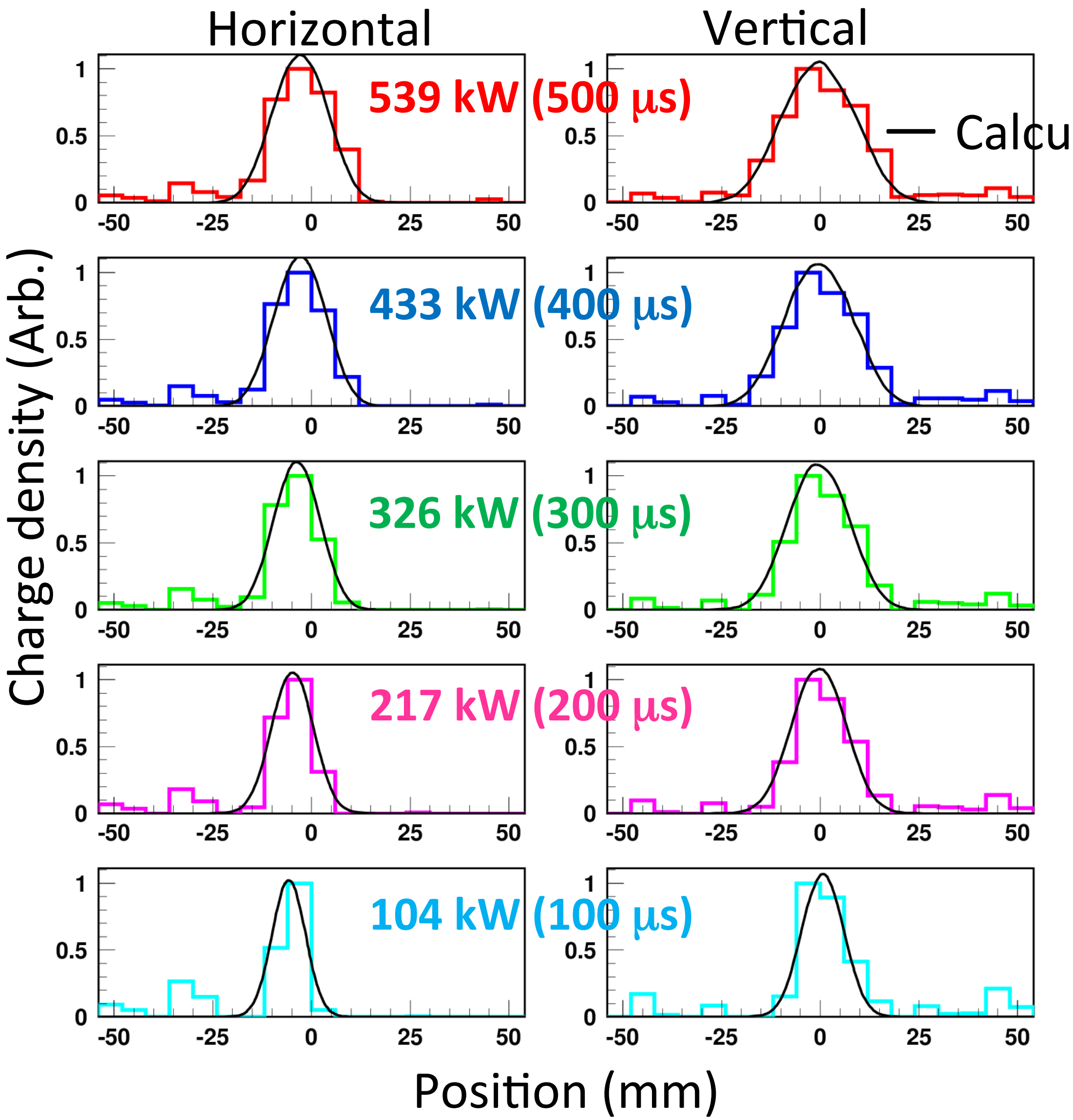
539 kW (Li pulse 500 μs)
433 kW (Li pulse 400 μs)
325 kW (Li pulse 300 μs)
217 kW (Li pulse 200 μs)
104 kW (Li pulse 100 μs)

Beam survival :
ratio of output intensity (DCCT)
to input intensity (SCT76)

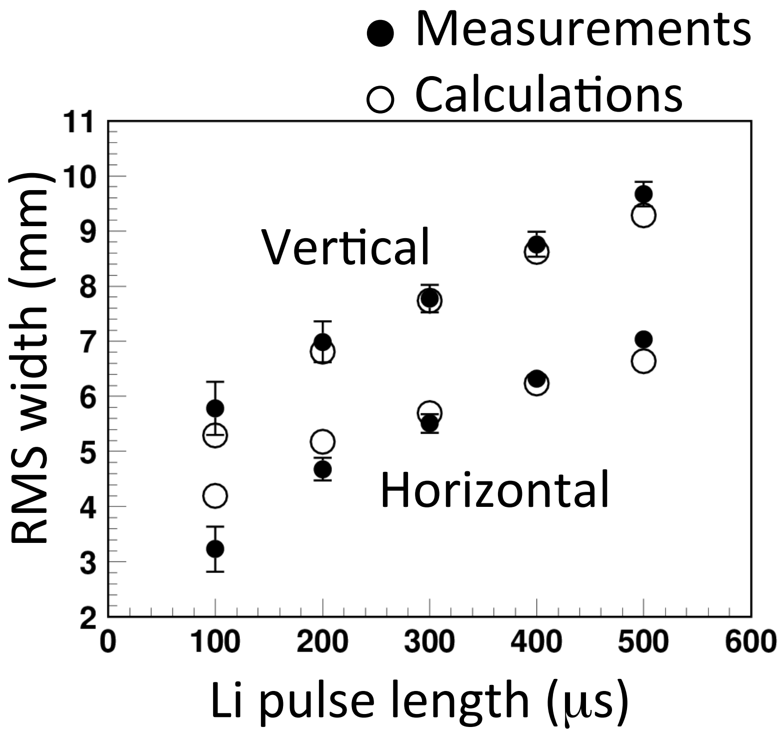


Measurements vs. Calculations
: Extraction beam profile at 3 GeV

MWPM @ extraction beam line

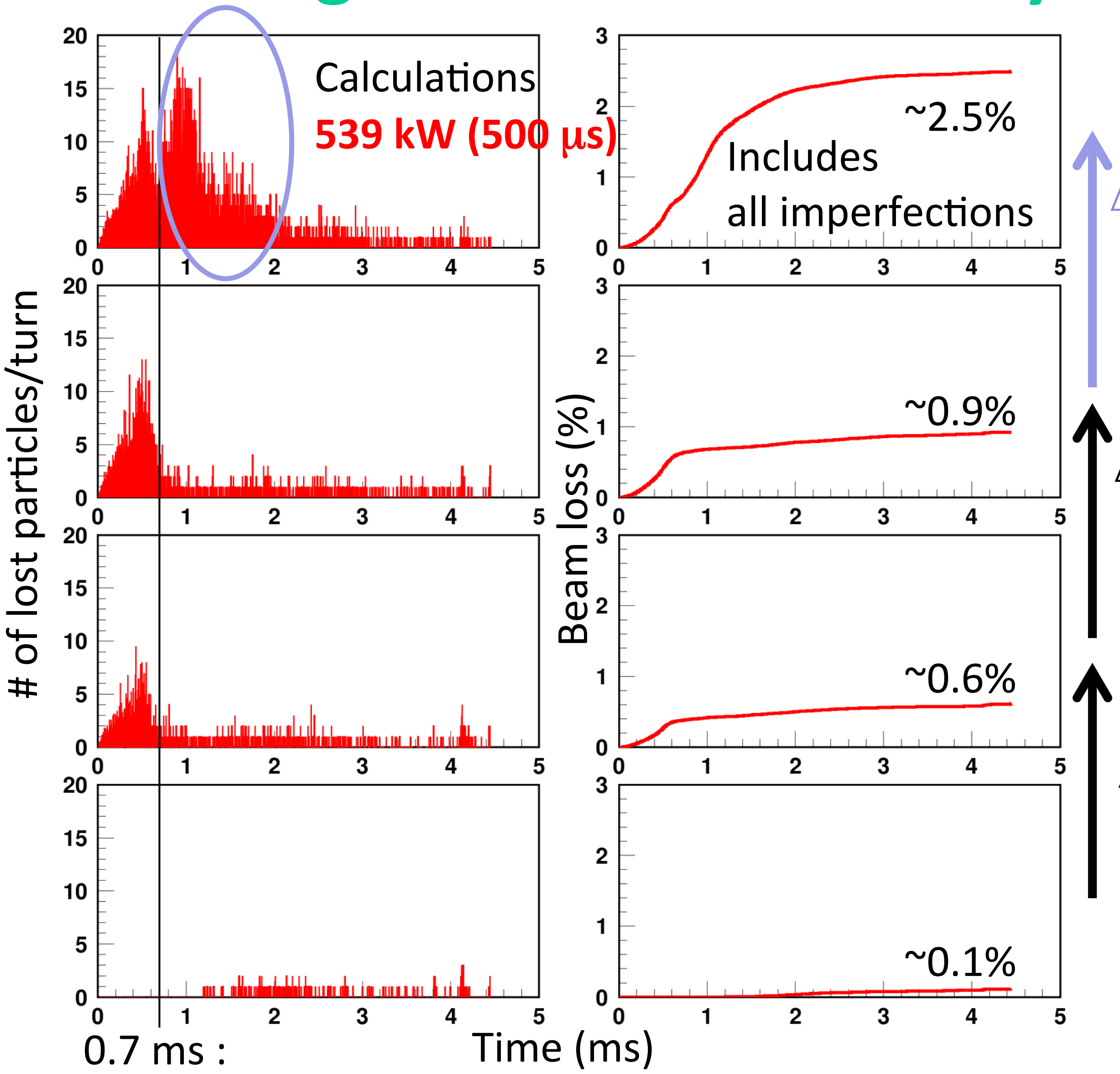


Intensity dependence of RMS beam width



Discussions for ~2%-loss remaining for 540-kW intensity beam

Possible causes of ~2-% loss remaining for 540-kW intensity beam



Δ~+1.6%
by 100-Hz ripple induced
by injection bump magnets

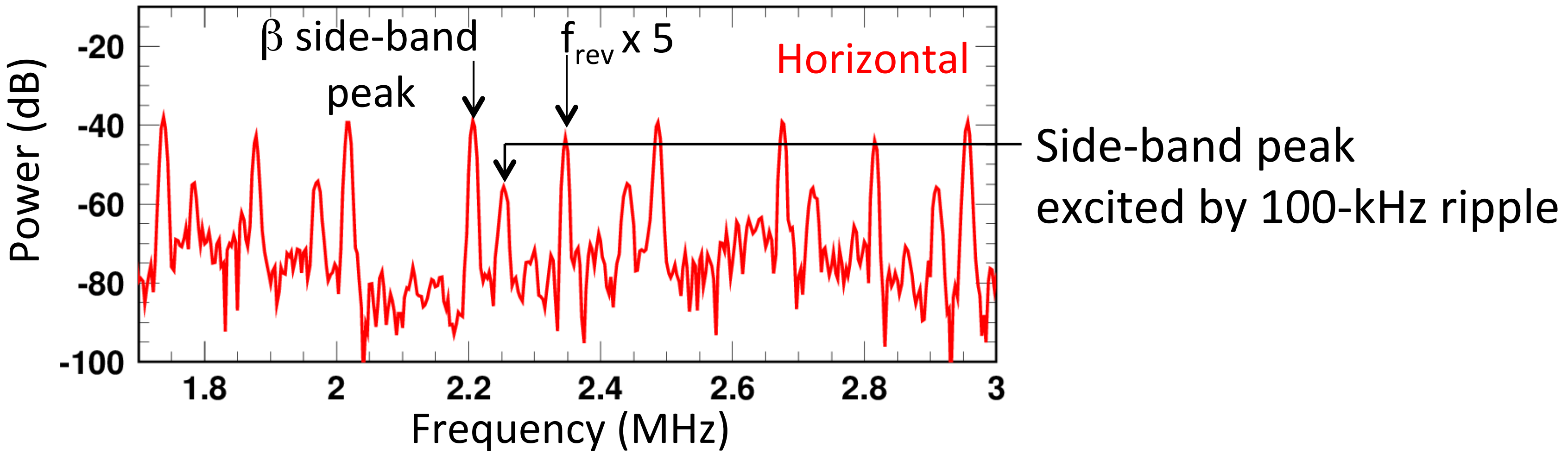
Δ~+0.3%
by 1-kHz BM ripple;
collimator aperture reduction
caused by orbit variation

Δ~+0.5%
by foil scattering

0.7 ms :
End of foil scattering

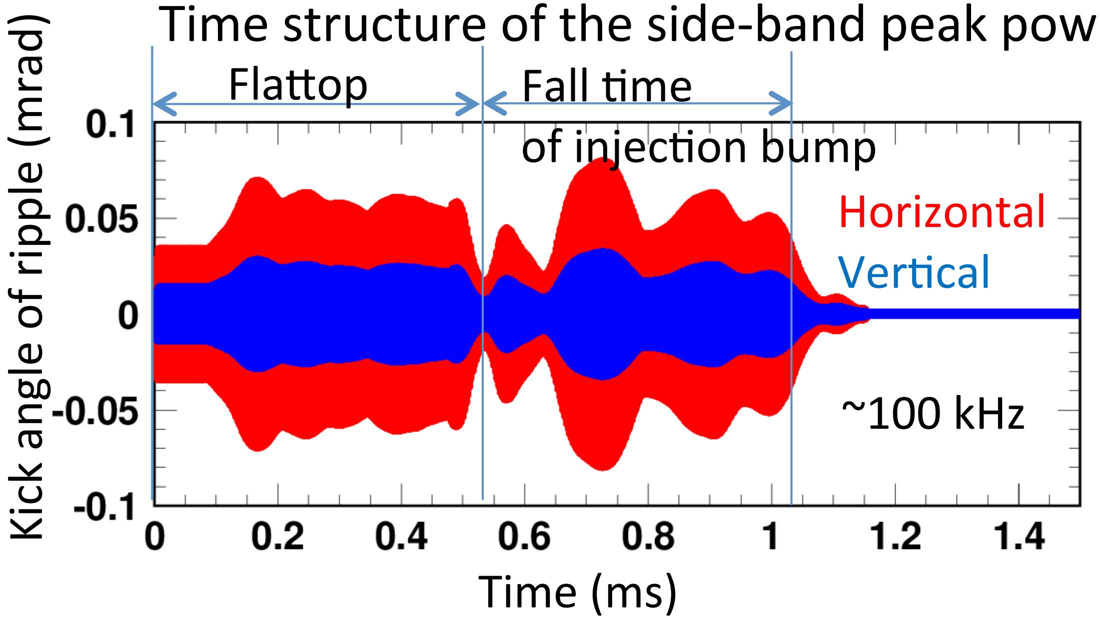
100-kHz resonance ripple induced in the ceramic vacuum vessel screening strips by injection bump field

FFT of BPM signal



Side-band peak excited by 100-kHz ripple

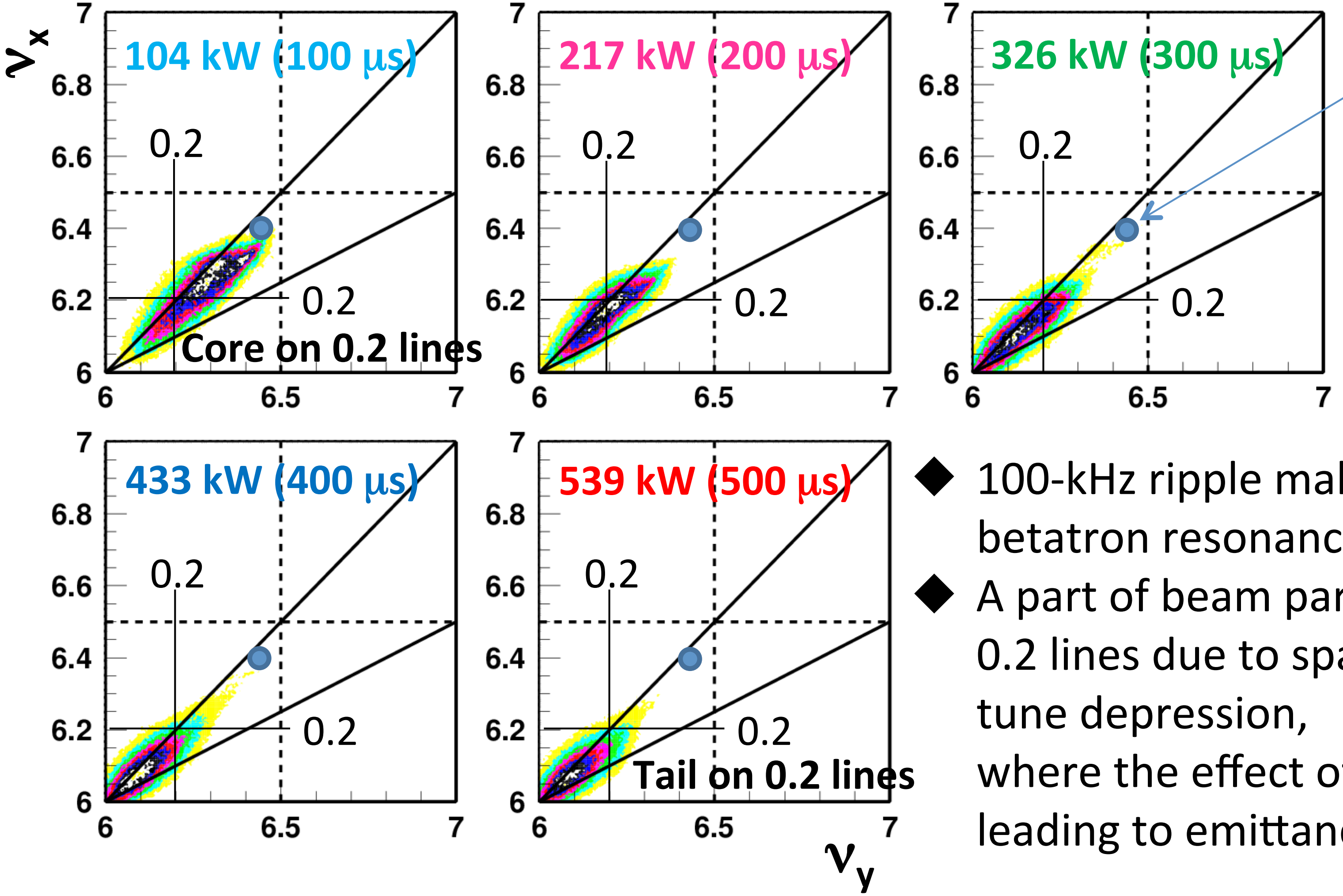
Time structure of the side-band peak power



This fast ripple excites additional betatron resonances at 0.2 (0.8) during injection (first ~1 ms).

Effect of 100-kHz ripple

Tune footprint calculated at the end of injection



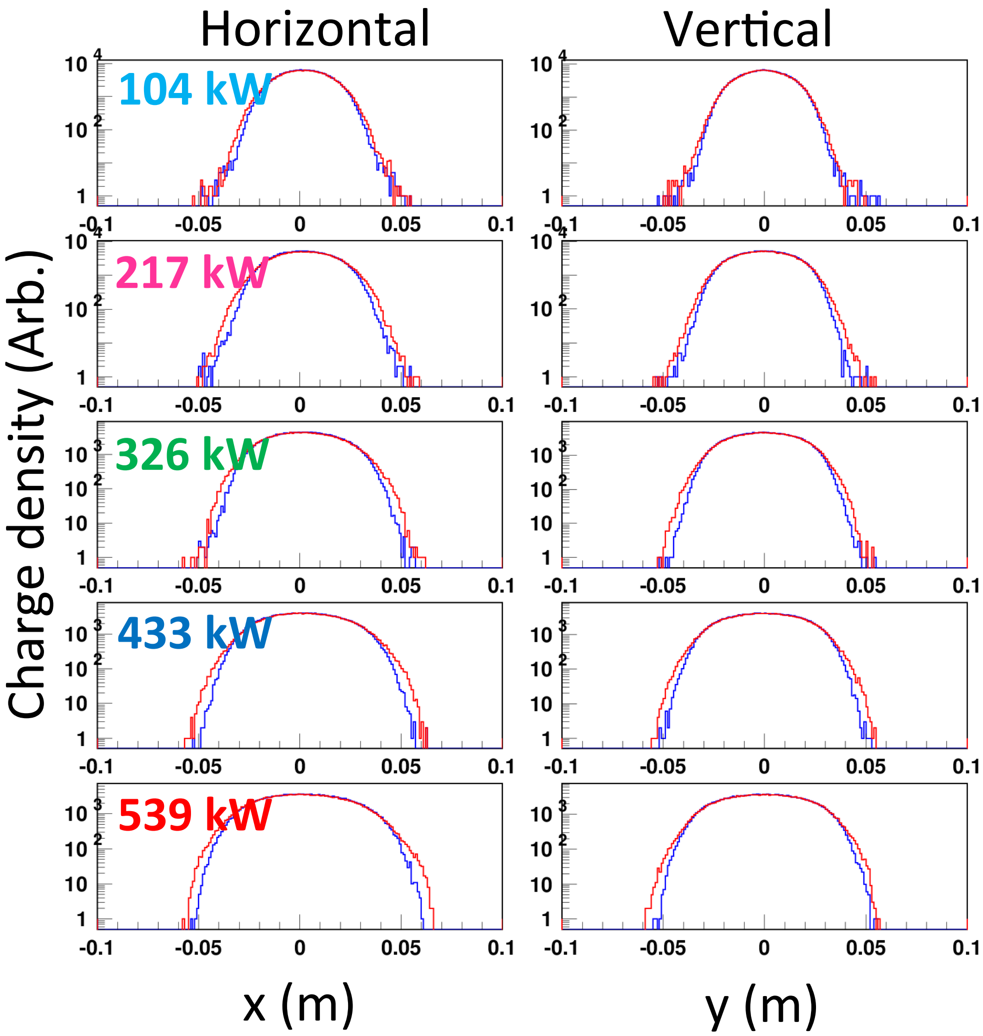
Present operating point

- ◆ 100-kHz ripple makes additional betatron resonances at 0.2 (0.8).
- ◆ A part of beam particles reaches to 0.2 lines due to space-charge tune depression, where the effect of ripple builds up, leading to emittance growth.

The situation for higher intensity beam is more severe, because the 100-kHz ripple directly affect the tail part of the beam.

Effect of 100-kHz ripple

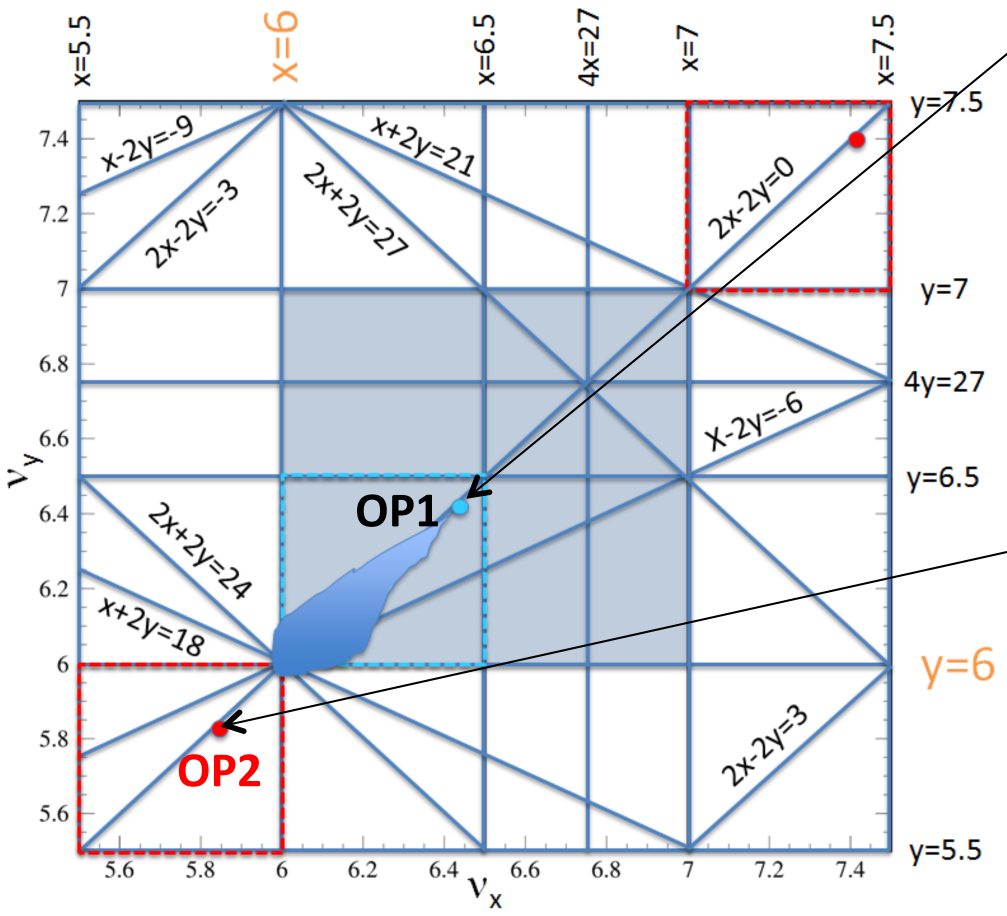
Beam profile calculated at the end of injection (plotted in log scale)



Larger beam halo/tail formation takes place for higher intensity beam, leading to beam loss.

Possible scheme for further beam loss reduction

Re-optimization of operating point



◆ **OP1** : Current operating point

- Systematic resonances of ν=6, $2\nu_x+2\nu_y=24$ and $\nu_x+2\nu_y=18$ strongly affect the beam, though their effects can be mitigated sufficiently by painting.
- 100-kHz ripple (0.2 resonances) also strongly affect the beam.

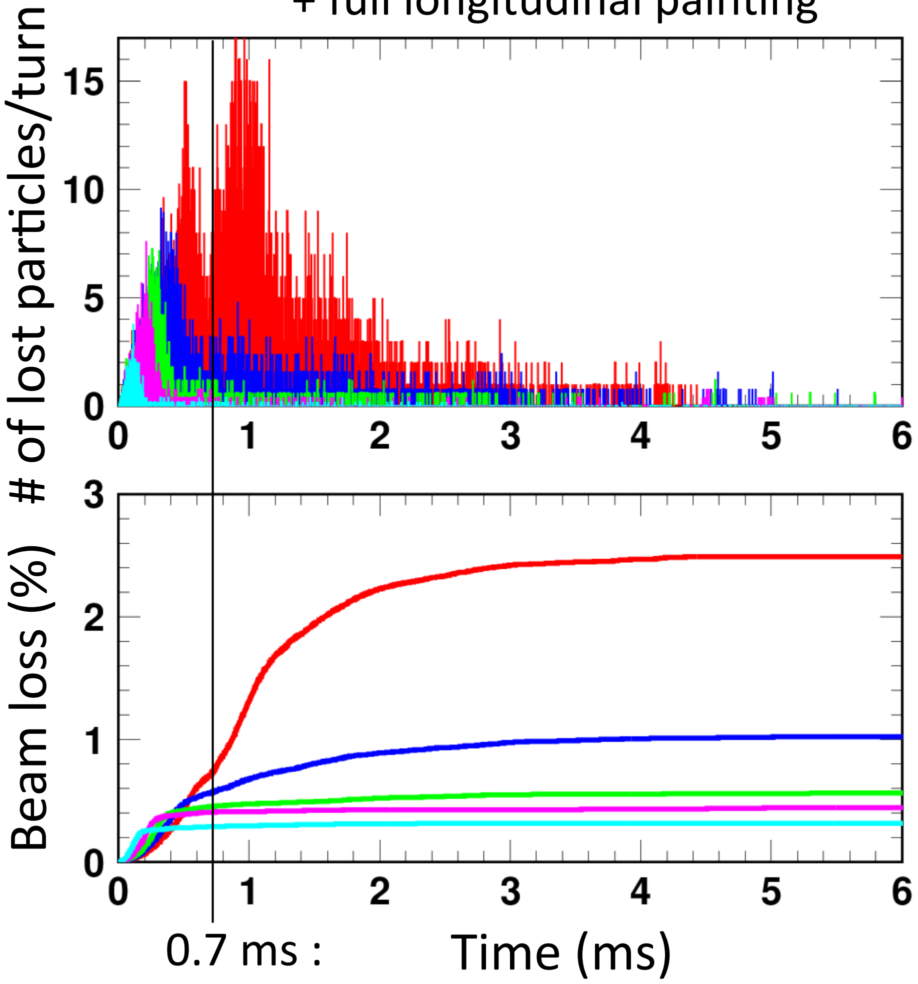
◆ **OP2 : Alternate operating point**

- Half integer lines of ν=5.5 can affect the beam, but the effect of low-order systematic nonlinear resonances (3rd & 4th) can be decreased.
- No chromatic correction is necessary.
- **Larger dynamic aperture**
  ⇒ Larger transverse painting (150π) is available.
- **Effect of 100-kHz ripple (0.8 resonances in this case) is less.**

OP1 vs. OP2 : Time structure of beam loss

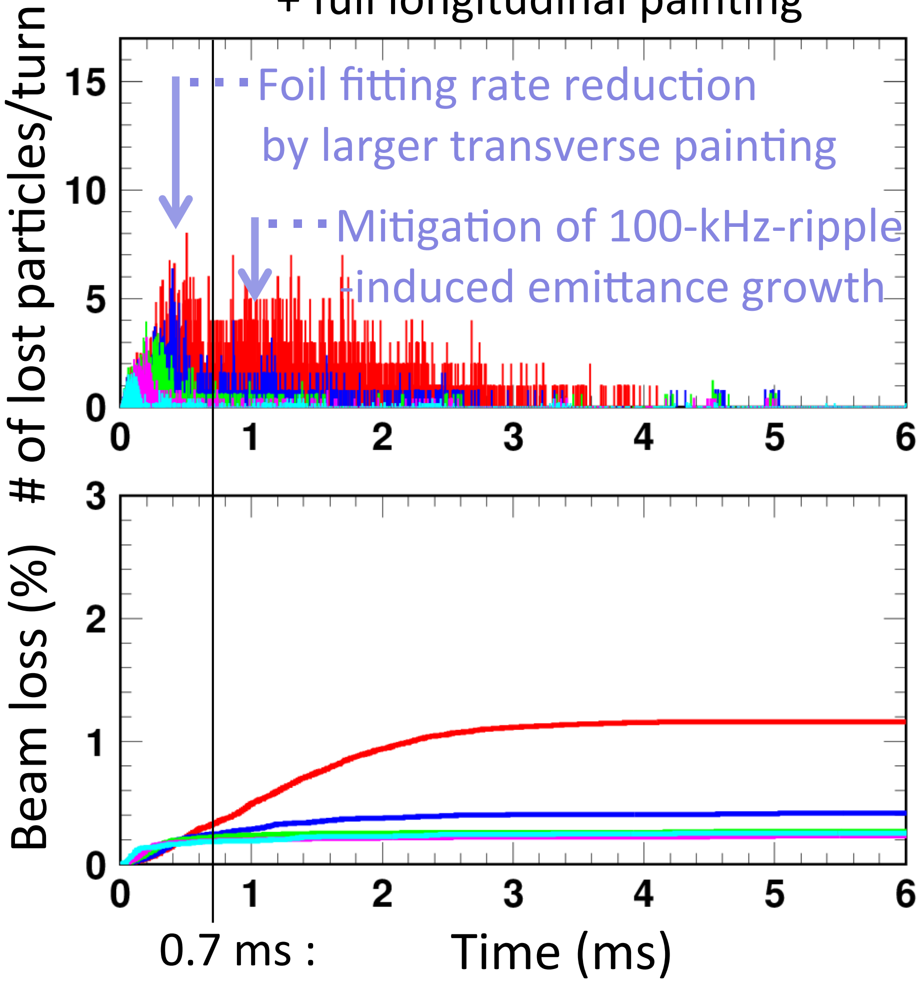
Numerical simulations

OP1, 100π transverse painting
+ full longitudinal painting



0.7 ms :
End of foil scattering

OP2, 150π transverse painting
+ full longitudinal painting



Foil fitting rate reduction
by larger transverse painting

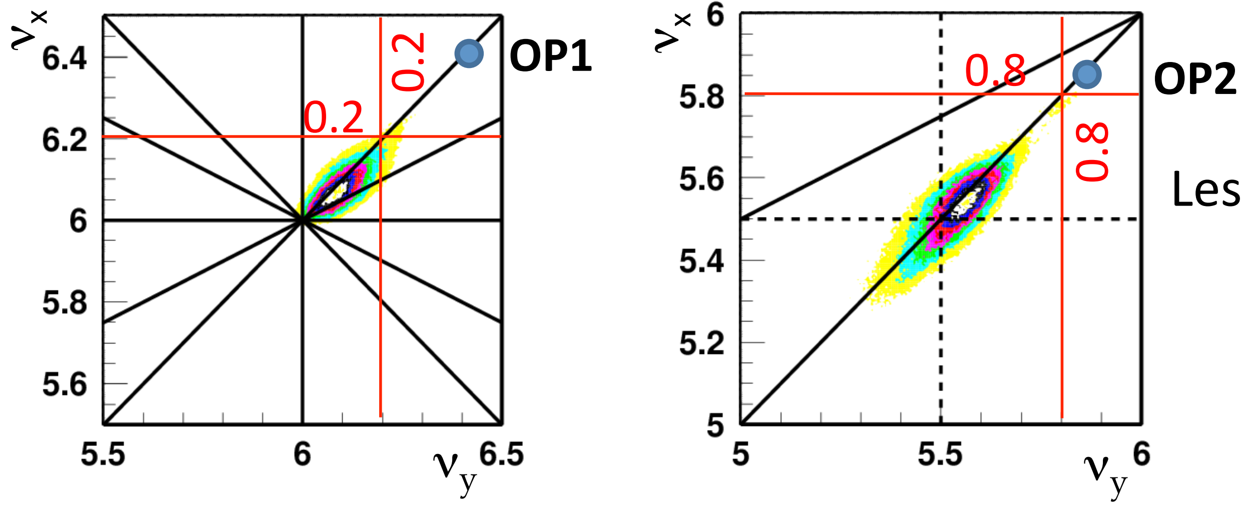
Mitigation of 100-kHz-ripple
-induced emittance growth

0.7 ms :
End of foil scattering

We will try “OP2” in the next high intensity trial experiment (Apr. 15-20).

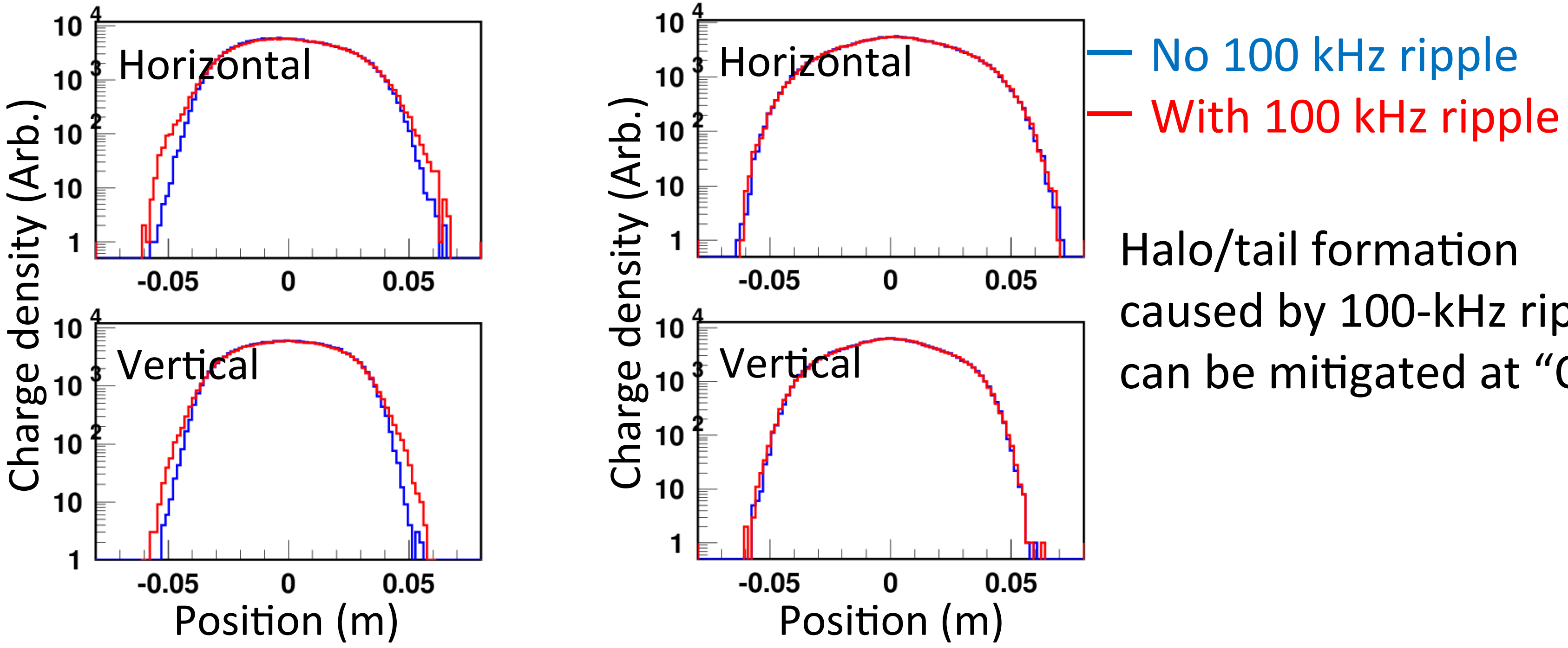
OP1 vs. OP2 : Effect of 100-kHz ripple

Tune footprint calculated at the end of injection



Less particles on 0.8 lines

Beam profile calculated at the end of injection



Halo/tail formation caused by 100-kHz ripple can be mitigated at “OP2”.

Reference:
H. Hotchi, et. al., Phys. Rev. ST Accel. Beams **15**, 040402 (2012).

Summary

1) Modeling of high intensity proton synchrotron and quantitative benchmarking between experiment and simulation becomes feasible.
2) Key factors are, to include all known imperfections in addition to the correct modeling of transverse and longitudinal dynamics, injection process, space charge tune spread, etc.
3) Several beam loss mitigation idea were proposed with help of simulation and verified by experiment.
4) Based on the study, there is a good reason that we could use simulation as a tool of the performance improvement in future.