Commissioning the 400-MeV Linac at J-PARC and High Intensity Operation of the J-PARC RCS

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&
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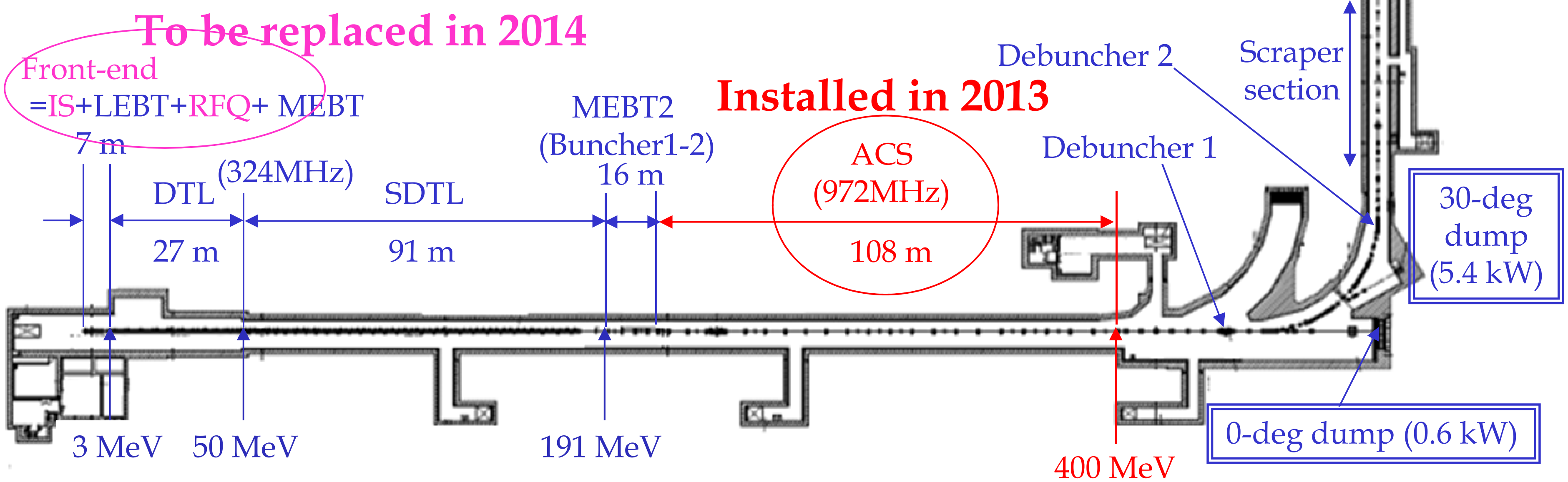
J-PARC
(JAEA & KEK)
400 MeV H- Linac
Main topic
of this talk
3 GeV Rapid
Cycling
Synchrotron (RCS)
1 MW
Neutrino Beam Line to
Kamioka (NU)
0.75 MW
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Materials &
Life Science
Facility (MLF)
Hadron
Experimental
Hall (HD)

- Outline of the linac and RCS, and their operational history
- Beam commissioning of the 400-MeV linac
- Beam commissioning of the RCS for E_{inj}=400 MeV
- High intensity beam tests of up to 550 kW recently performed in the RCS
    - Injection painting parameter dependence of beam loss
    - Time structure of beam loss
    - Consideration for the more detailed mechanism of the beam loss caused by the dipole field ripple
    - Intensity dependence of beam loss measured for E_{inj}=400 MeV
- 1-MW numerical simulation for the RCS
- Summary

Design parameters of the linac

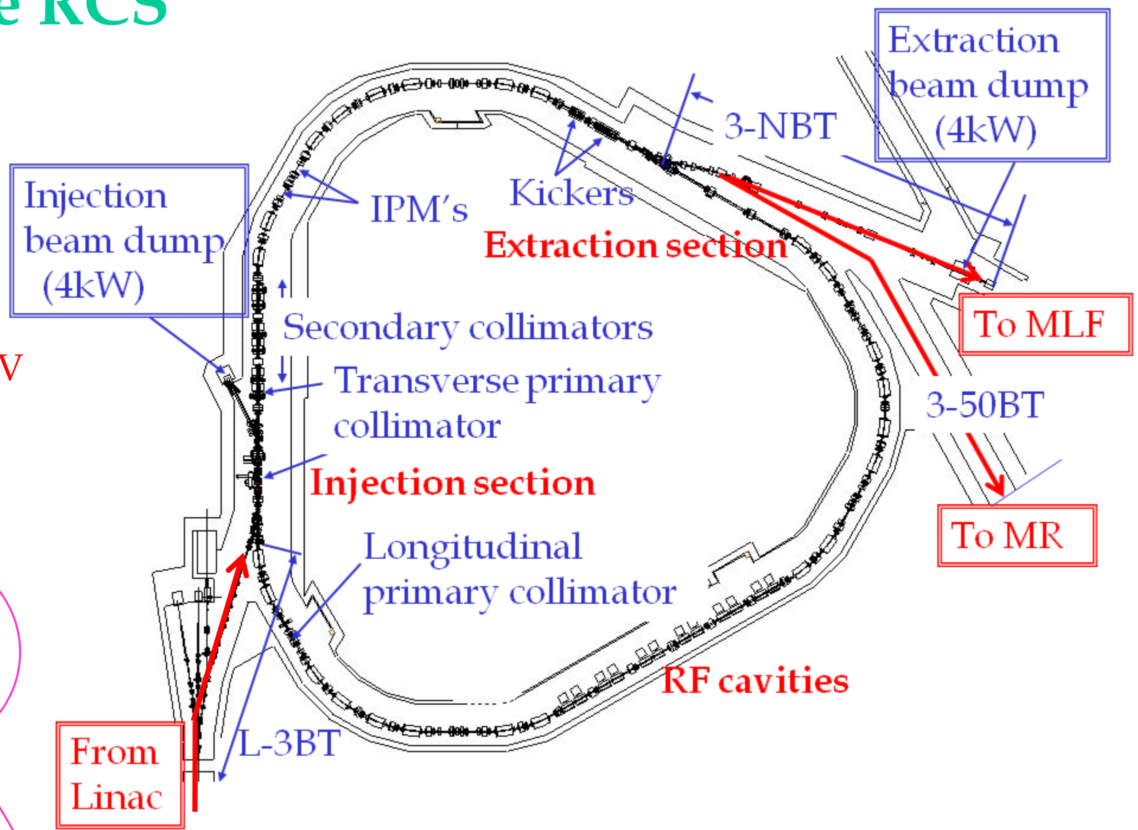
Particles	H⁻	
Output energy	181 MeV	⇒ 400 MeV in 2013 by adding an ACS linac section
Peak current	30 mA	⇒ 50 mA
Pulse width	0.5 ms	
Chopper beam-on duty factor	53.3%	
Repetition rate	25 Hz	
Output power	80 kW	⇒ 133 kW

The peak current will be increased
to 50 mA in this summer shutdown of 2014
by replacing the front-end system (IS & RFQ).



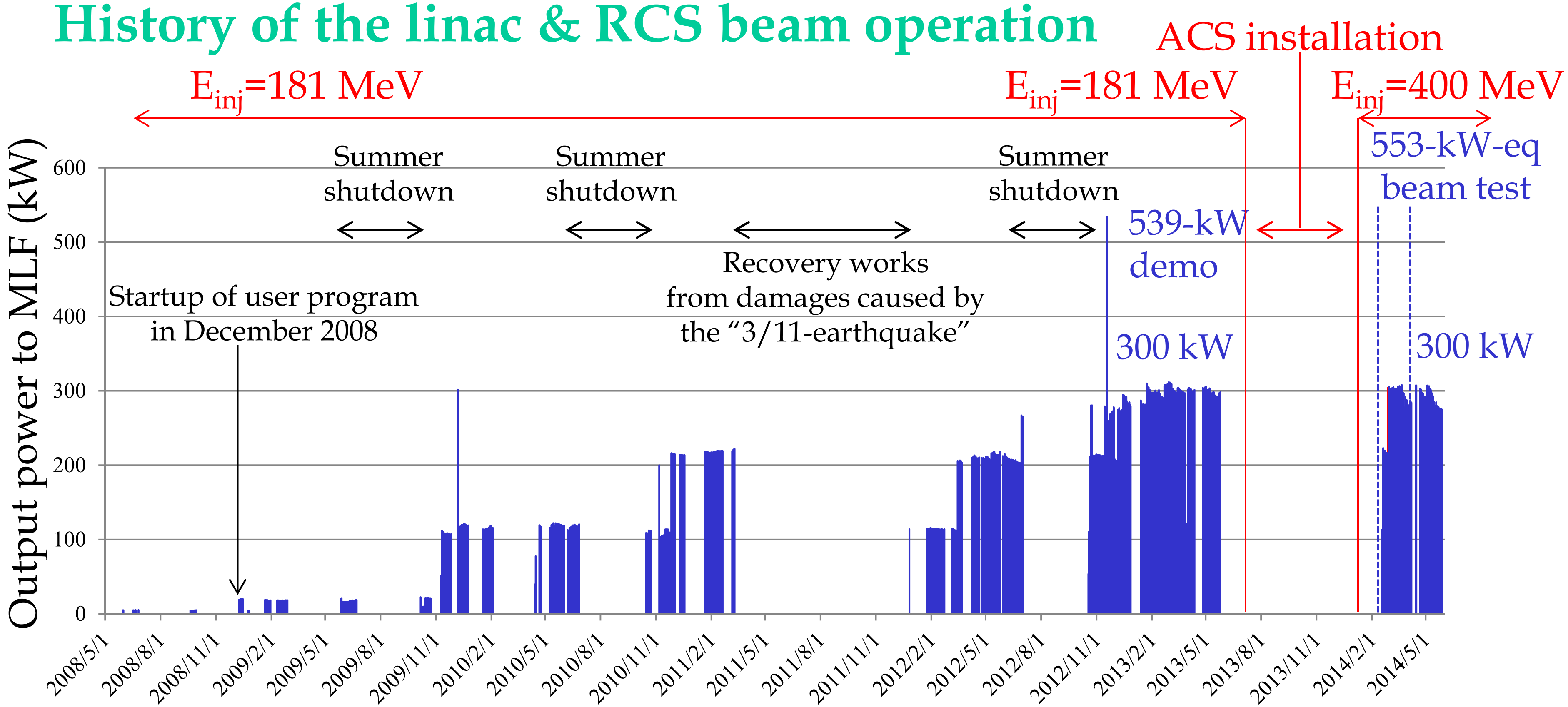
Design parameters of the RCS

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
Number of bunches	2
Injection energy	181 MeV ⇒ 400 MeV
Injection period	0.5 ms (307 turns)
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	5e13 ⇒ 8.3e13
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



The output beam power will be increased to the design value of 1 MW following the peak current upgrade of the linac in this summer.

History of the linac & RCS beam operation



- ✓ Output beam power has been steadily increasing following the progression in beam tuning & hardware improvements since the startup of user program in December 2008.

- ✓ Beam commissioning of 400-MeV linac : December 2013~
- ✓ Beam commissioning of RCS with E_{inj}=400 MeV : January 2014~
- ✓ Re-startup of user program (300 kW output beam power) : February 2014~

- ✓ So far the RCS has successfully achieved high intensity beam trials of up to **<u>~550 kW</u>** for both E_{inj}=181 MeV and E_{inj}=400 MeV.

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Beam commissioning of the 400-MeV linac

- ✓ Linac beam commissioning : Dec. 16, 2013~
- ✓ Achievement of 400-MeV acceleration : Jan. 17, 2014
- ✓ Beam delivery to the RCS : Jan. 30, 2014~

◆ Initial beam tuning (27 days : Dec. 16~29, 2013 & Jan. 7~30, 2014)

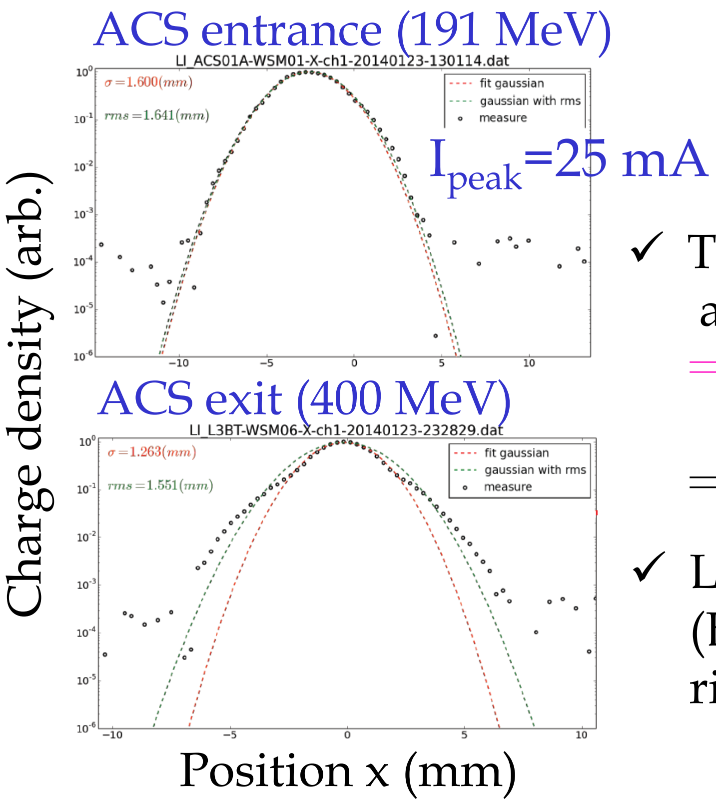
- LEBT tuning
- RFQ tank level scan
- MEBT1 buncher phase scan
- DTL phase scan
- SDTL phase scan
- MEBT2 buncher phase scan
- ACS phase scan
- Transverse matching at SDTL, MEBT2
- RF feed-back tuning
- LLRF feed-forward tuning
- Transverse matching at L3BT
- Chopper tuning
- ACS longitudinal acceptance measurement
- Beam halo & Beam loss studies

. . . . . etc.

✓ The 400-MeV linac successfully beam commissioned as planned, and is now stably delivering the 400-MeV beam to the RCS.

Beam halo formation observed in the linac

◆ Beam halo formation at ACS



✓ The most probable cause is a longitudinal mismatch in the ACS section.
$\Rightarrow$ Transverse-longitudinal coupling through space charge
$\Rightarrow$ Emittance growth

✓ Longitudinal matching with "Bunch Shape Monitors" (BSM) will be performed in October 2014 right after the summer shutdown.

◆ Beam halo formation at the second debuncher (DB2) installed in the L3BT

✓ The main cause is an over-focus of the longitudinal bunch by DB2.

✓ Now the debuncher operates to defocus the momentum spread following the requirement from the RCS, while it also acts to focus the longitudinal bunch.

✓ We will try re-optimization of the DB2 in the next beam study period.

Beam commissioning of the RCS for the upgraded injection energy of 400 MeV

✓ RCS beam commissioning : Jan. 30, 2014~

◆ Initial beam tuning (10 days : Jan. 30~Feb. 8, 2014)

- Tuning for the bending field, RF frequency, & injection beam energy
- COD correction
- Optics measurement & correction
- Chromaticity measurement & correction
- Tune measurement all over the acceleration process
  for estimating the BM-QM field tracking error
- Orbit adjustment & profile measurement for injection beam
- Adjustment for transverse injection painting
- 2^{nd}-harmonic RF tuning for longitudinal painting
- FF tuning for beam loading compensation
- Adjustment of the foil position & size
- Injection efficiency measurement
- Beam based alignment of the collimator gap center
- Adjustment for beam extraction
- Various imperfection measurements . . . . etc.

✓ The initial beam tuning of the RCS was rapidly completed by using the first 10 days.

◆ High intensity beam trials of up to ~**550 kW** (7 days : Feb. 9~11 & Apr. 9~12, 2014)

- Various parameter dependence of beam loss,
  transverse & longitudinal beam profiles . . . . etc.

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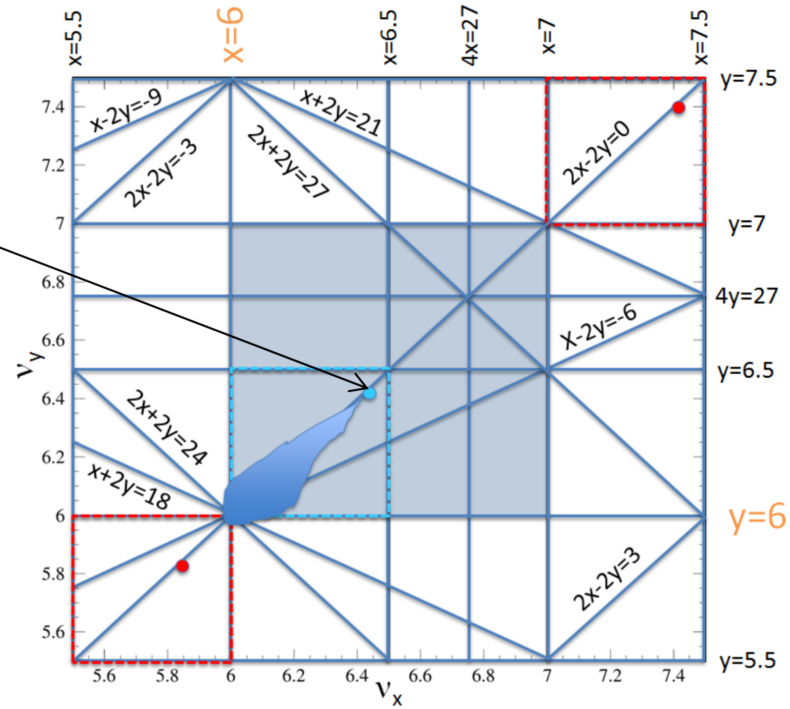
Experimental setup

- Injection beam condition
  Injection energy : 400 MeV
  Peak current : 24.6 mA
  Pulse length : 0.5 ms
  Chopper beam-on duty factor : 60%
  ⇒ 4.6E13/pulse, corresponding to **550 kW** at 3 GeV
- Operating point;
  (6.45, 6.42)



✓ Systematic beam loss measurements for various operational parameters and beam intensities

⇒ Comparison with ;
- Old data taken for E_{inj}=181 MeV
- Numerical simulation results

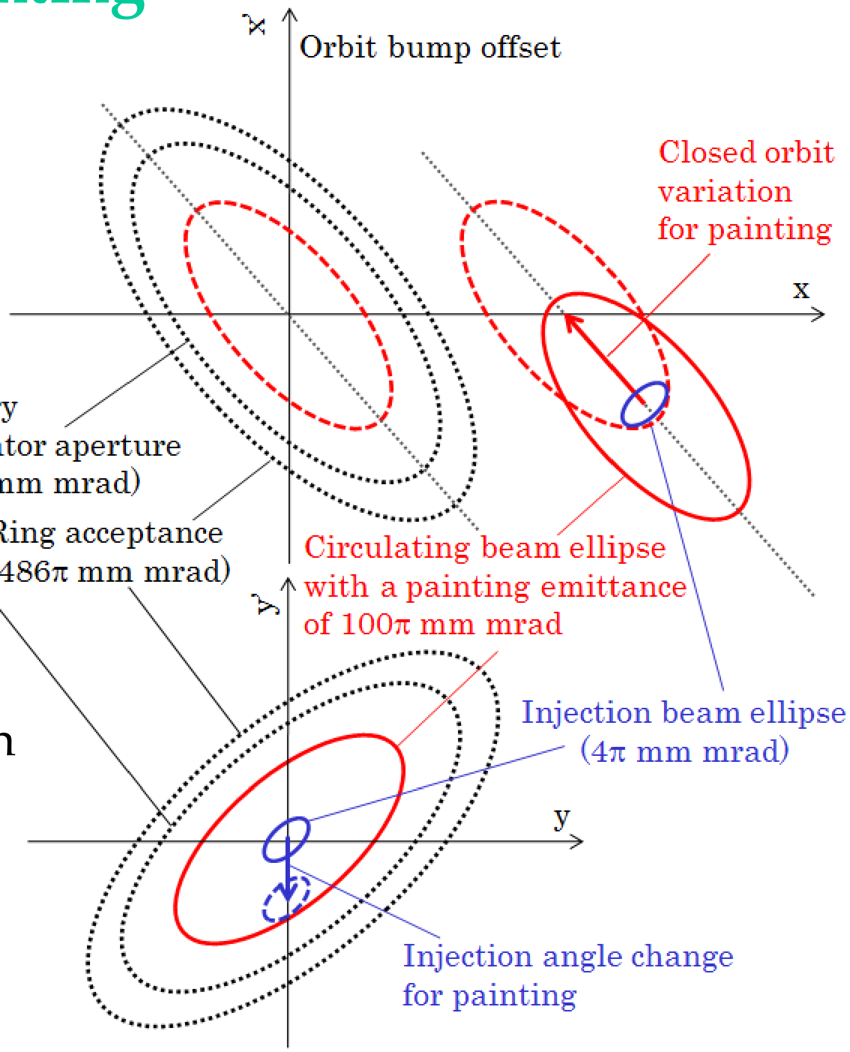
Injection painting parameter dependence of beam loss

In order to reduce space-charge induced beam loss,
the RCS employs transverse and longitudinal painting technique.

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

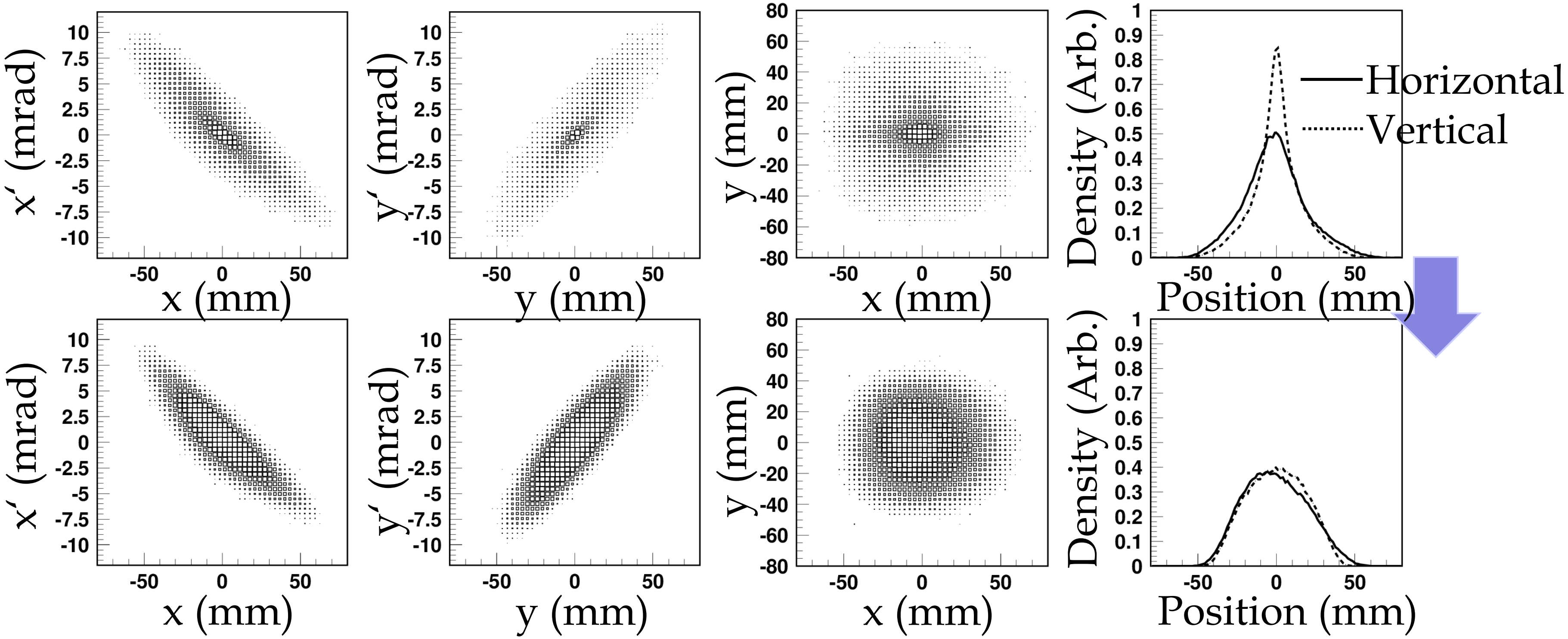
The injection beam is painted from the center to the outside
on both horizontal and vertical planes.

Transverse injection painting

Numerical simulations

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

No painting



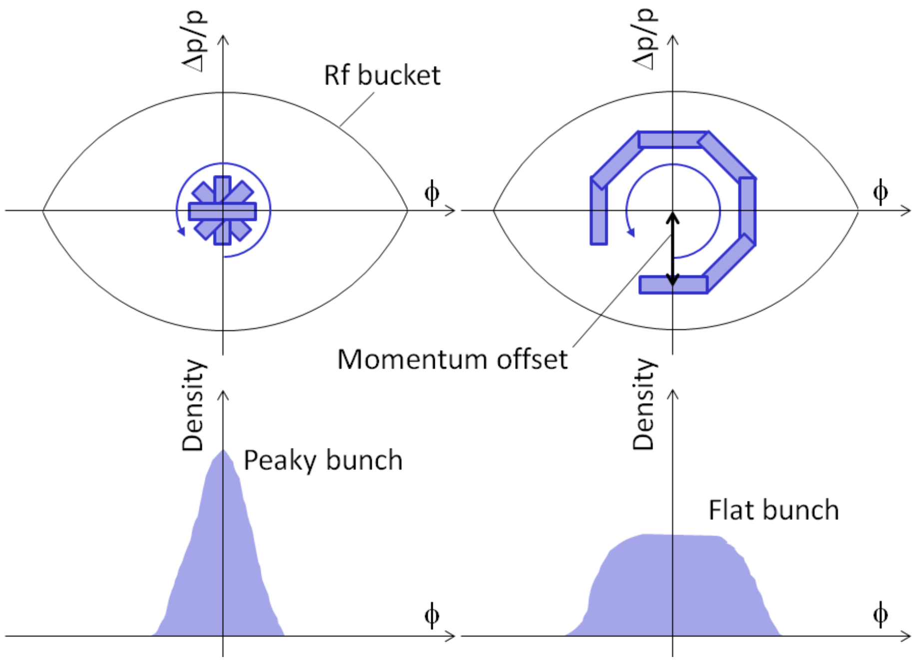
100π transverse painting

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

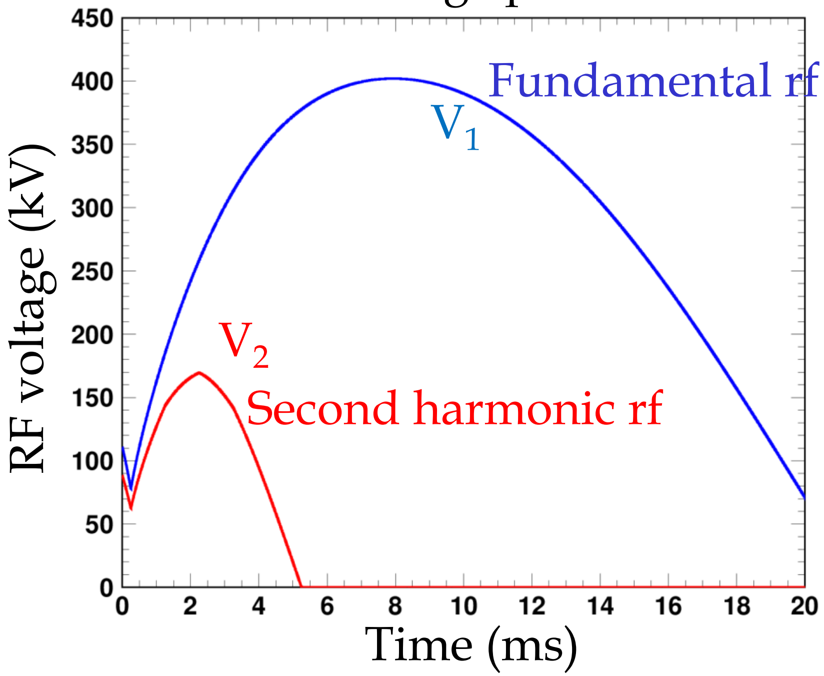
Longitudinal injection painting

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

Momentum offset injection



RF voltage pattern



$\Delta p/p$=0, –0.1 and –0.2%

V_2/V_1=80%

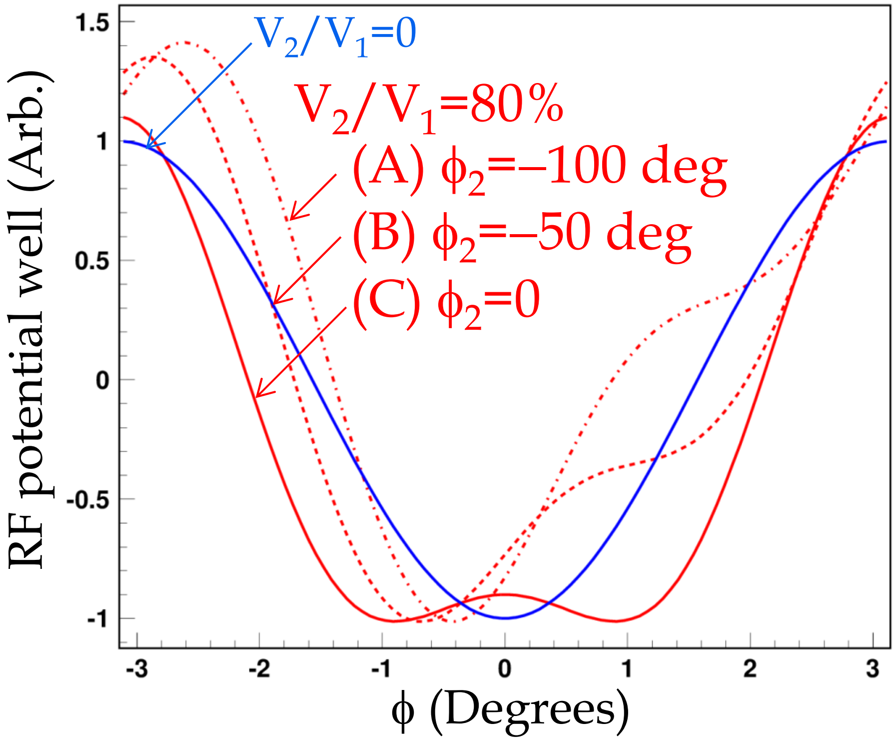
Uniform bunch distribution is formed through emittance dilution by the large synchrotron motion excited by momentum offset.

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

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

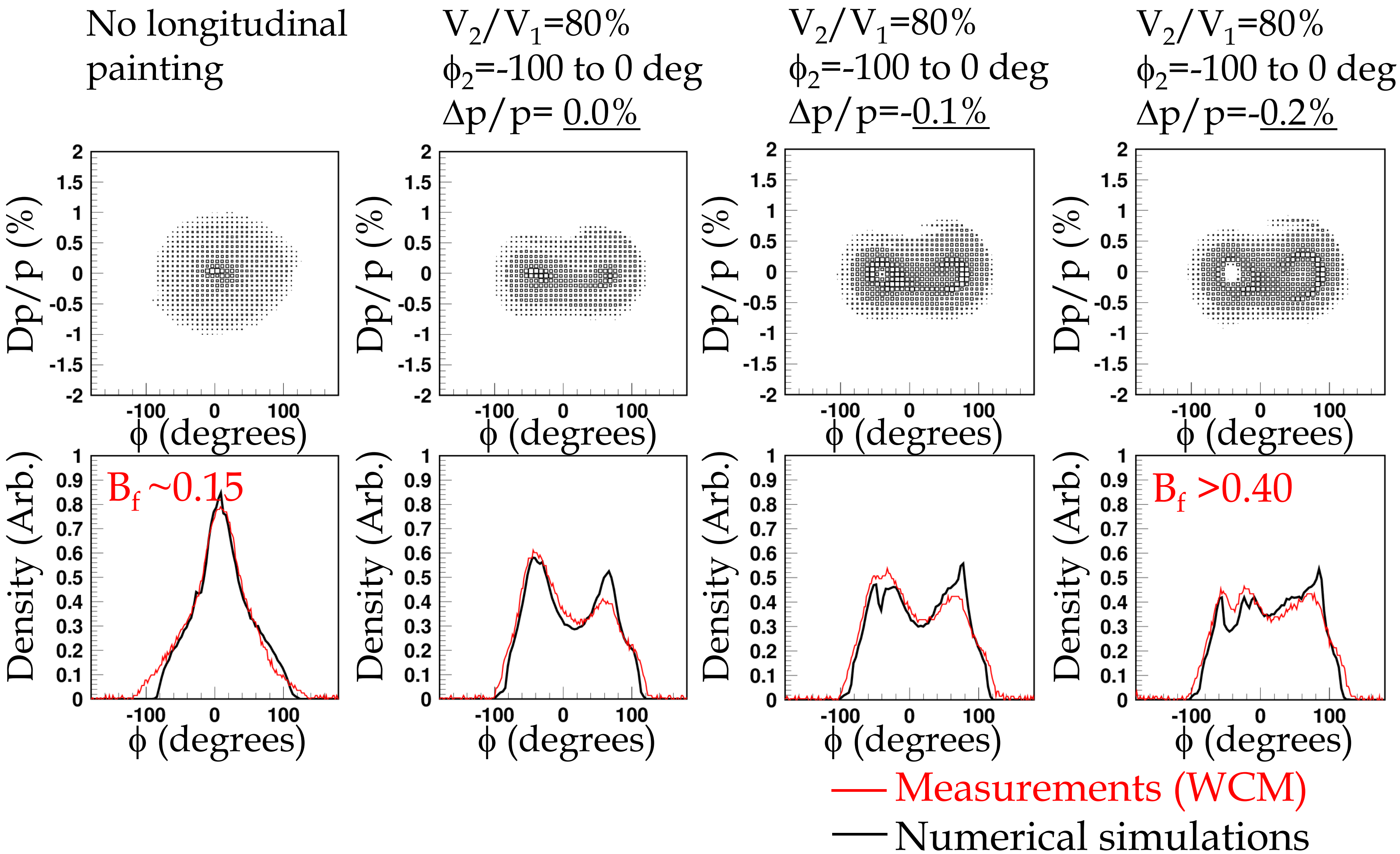


$\phi_2=-100\Rightarrow0$ deg

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

Longitudinal injection painting

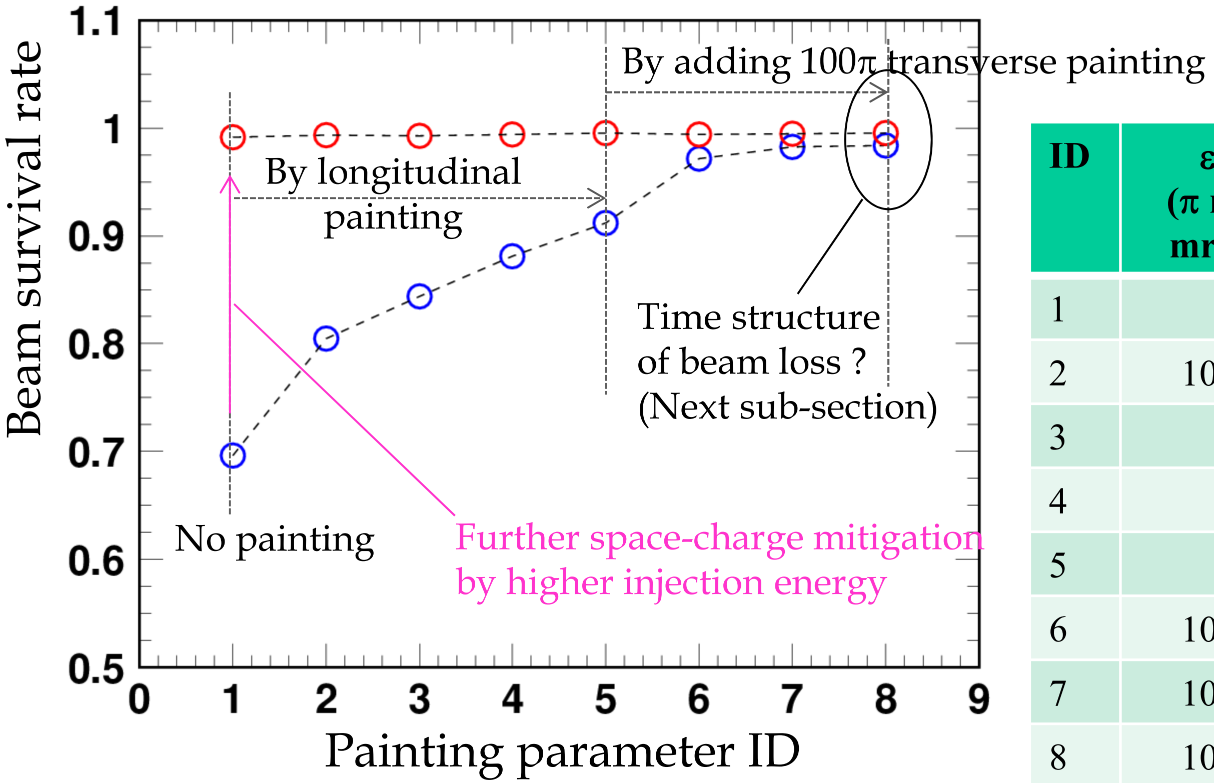
Longitudinal beam distribution just after beam injection (at 0.5 ms)



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)



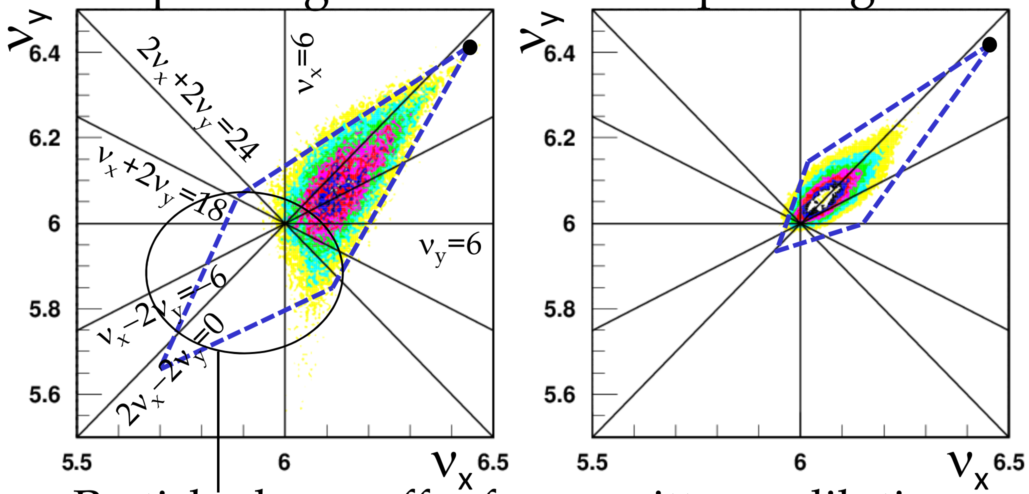
ID	ε_{tp} (π mm mrad)	RF V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
1	-	-	-	-
2	100π	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100π	80	-100	-0.0
7	100π	80	-100	-0.1
8	100π	80	-100	-0.2

✓ This experimental data clearly show the excellent ability of injection painting and also the big gain from the injection energy upgrade this time.

Space-charge tune depression calculated at E_{inj}=181 & 400 MeV

◆ E_{inj}=181 MeV, 539 kW-eq. intensity

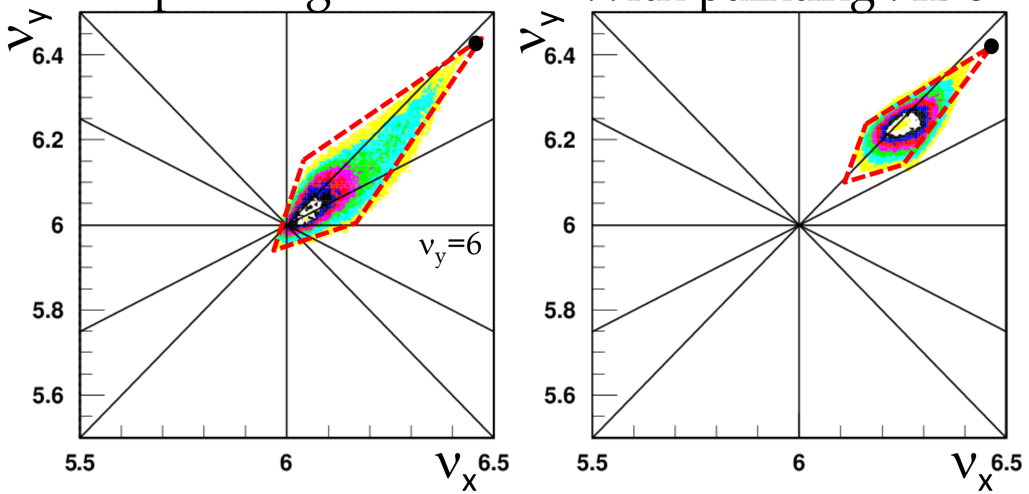
No painting : ID1 | With painting : ID8



Particles here suffer from emittance dilution, leading to large beam loss.

◆ E_{inj}=400 MeV, 553 kW-eq. intensity

No painting : ID1 | With painting : ID8



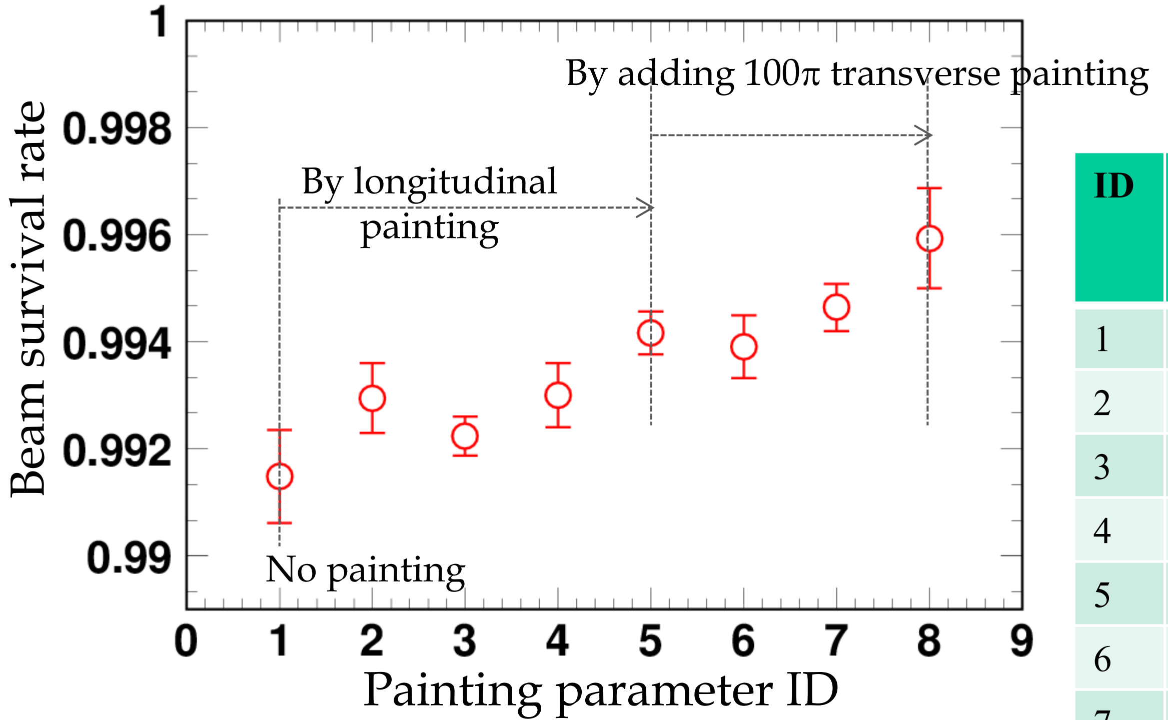
- ◆ Bare tune : (6.45, 6.42)
- ◆ 100π mm-mrad correlated painting
- ◆ Full longitudinal painting
  - V_2/V_1 : 80%
  - V_2 duration : 5 ms
  - $\Delta\phi_2$: -100 to 0 deg
  - $\Delta p/p$: -0.2%

$$\Delta\nu = -\frac{n_t r_p}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B_f}$$

✓ The Laslet tune shift is mitigated following the $\beta^2\gamma^3$ scaling law for the higher injection energy of 400 MeV.

Painting parameter dependence of beam survival rate

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



ID	ε_{tp} (π mm mrad)	RF V_2/V_1 (%)	ϕ_2 (deg)	$\Delta p/p$ (%)
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5	-	80	-100	-0.2
6	100π	80	-100	-0.0
7	100π	80	-100	-0.1
8	100π	80	-100	-0.2

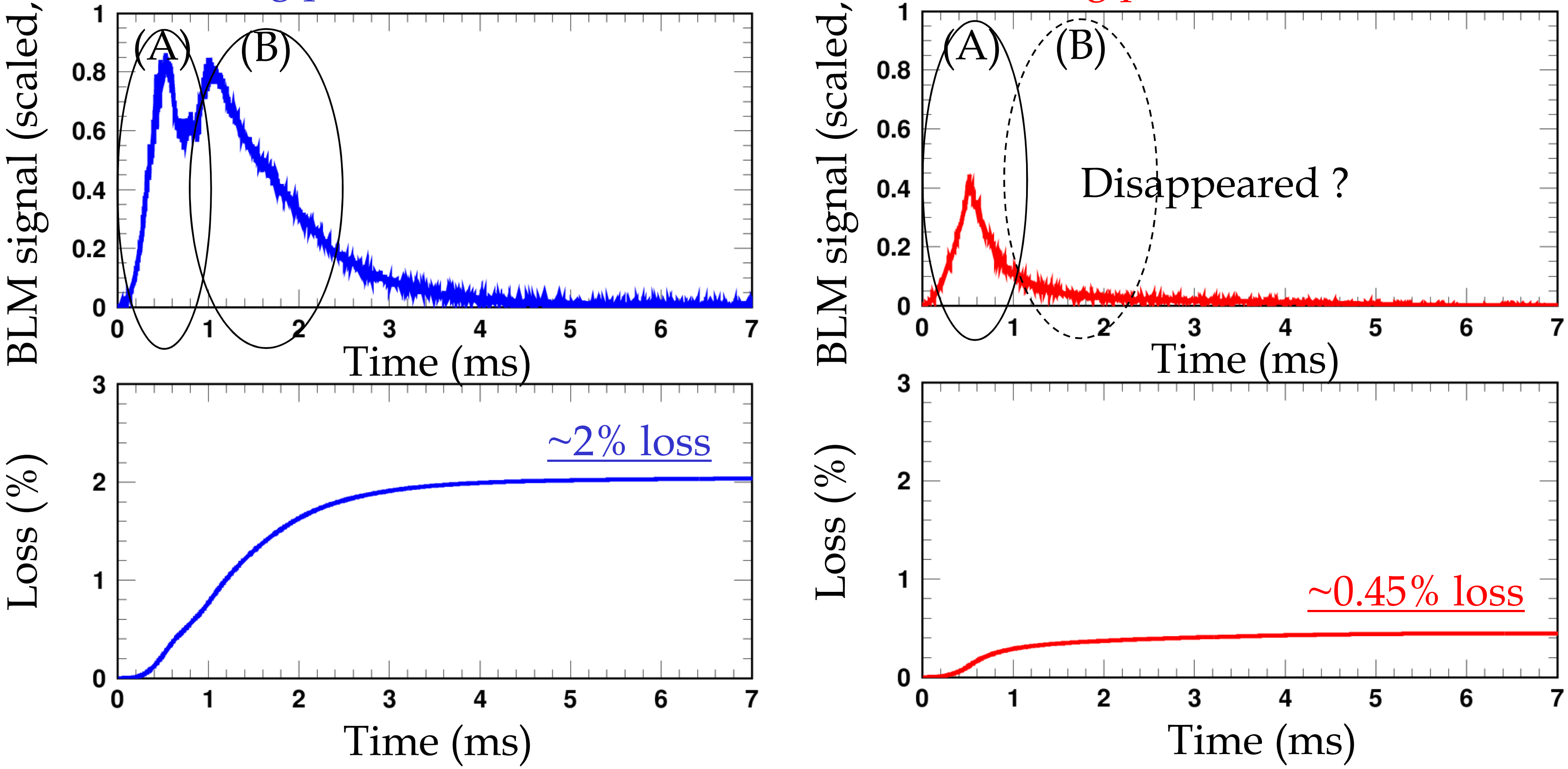
Time structure of beam loss

Time structure of beam loss

Scintillation-type BLM signal at the primary collimator

E_{inj}=181 MeV (Run#44)
Intensity : ~539 kW-eq
Painting parameter ID 8

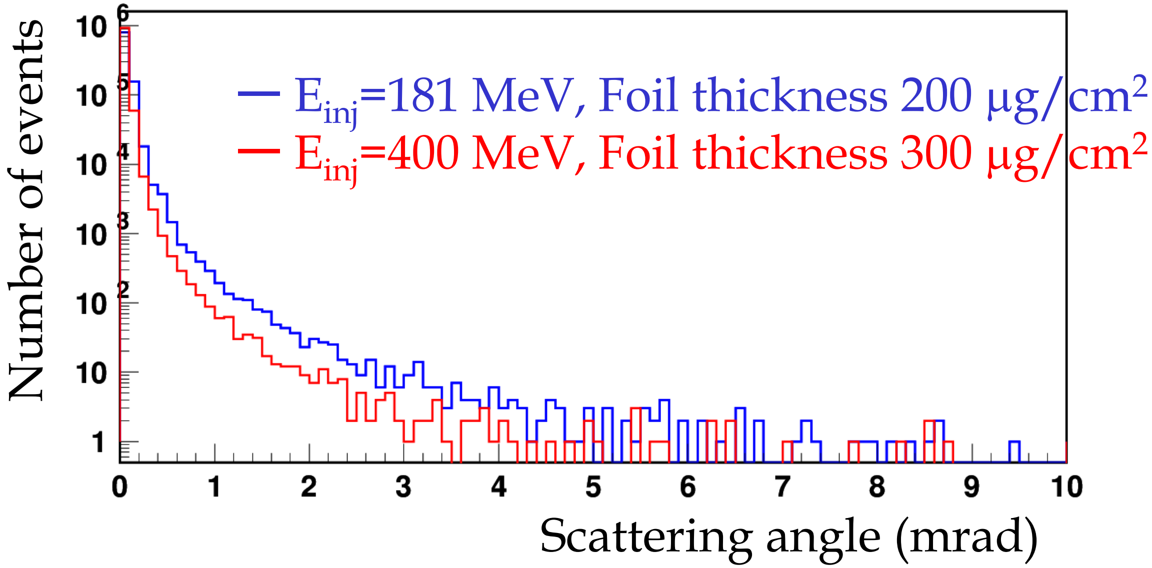
E_{inj}=400 MeV (Run#54)
Intensity : ~553 kW-eq
Painting parameter ID 8

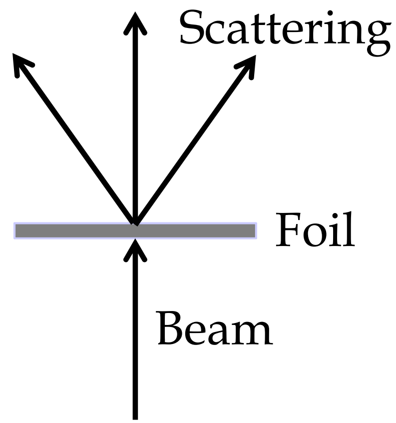


✓ Beam loss appears only for the first 4 ms in the low energy region.
(A) : Mainly from foil scattering during charge-exchange injection
(B) : Mainly from a dipole field ripple induced by the injection bump fields

Scattering angle distribution on the charge-exchange foil

Calculated by GEANT

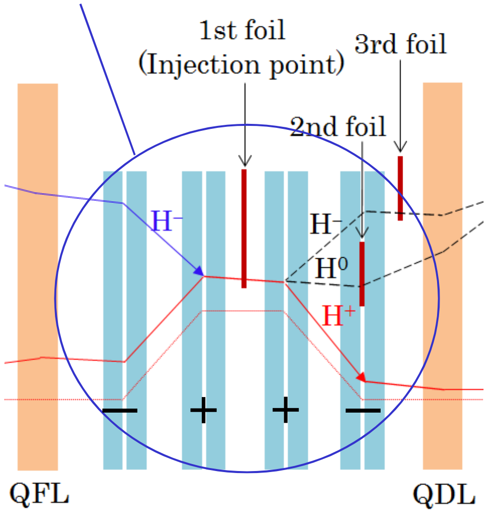




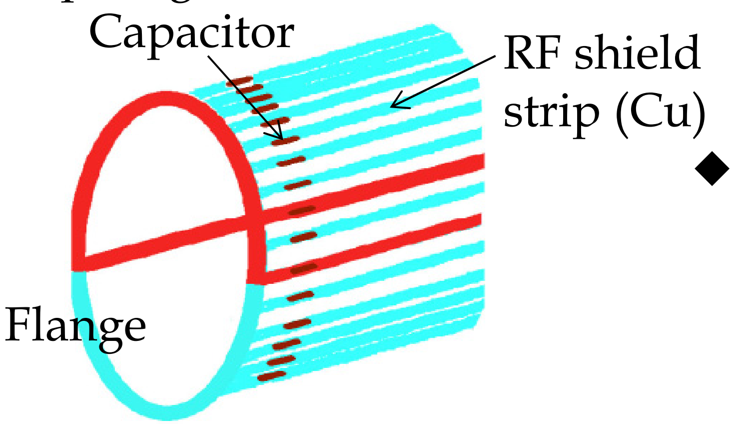
✓ The angular distribution shrinks for the higher injection energy of 400 MeV because of the Lorenz boost, leading to the reduction of a foil scattering part of beam loss by a factor of ~2.

Source of the dipole field ripple

Four sets of pulse-type injection bump magnets
used for the beam injection to the RCS



RF-shielded ceramics chamber
installed in the injection
bump magnets



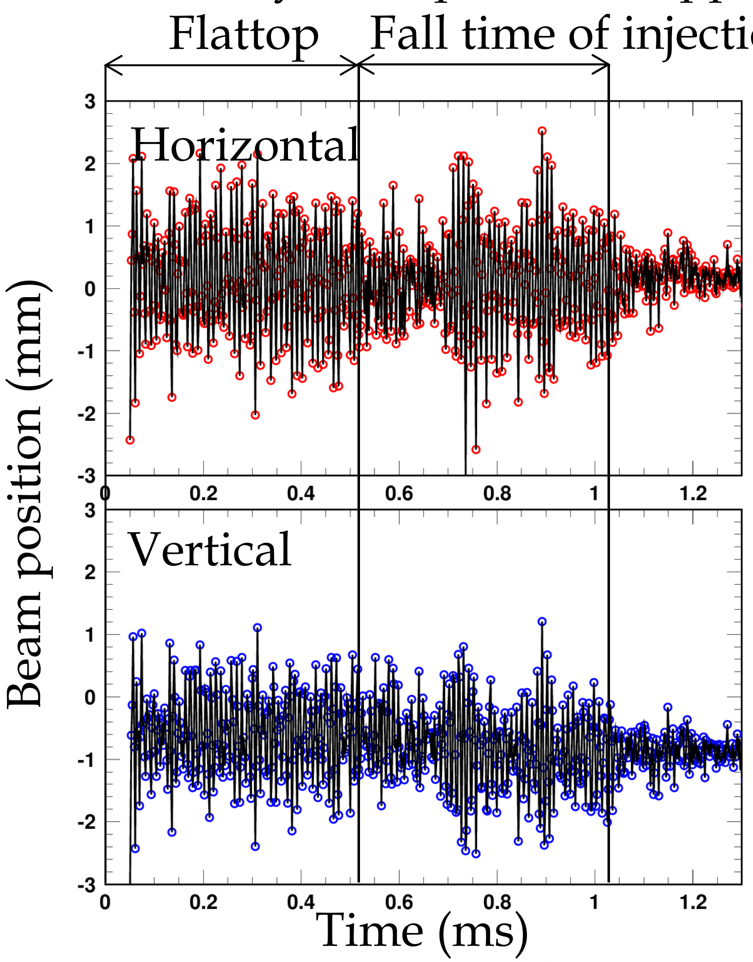
Y. Shobuda et al, PRST-AB **12**, 032401 (2009)

✓ The dipole field ripple causing the beam loss
was generated by resonant currents
in the RF shield loop induced by
$\Delta B/\Delta t$ of the injection bump field.

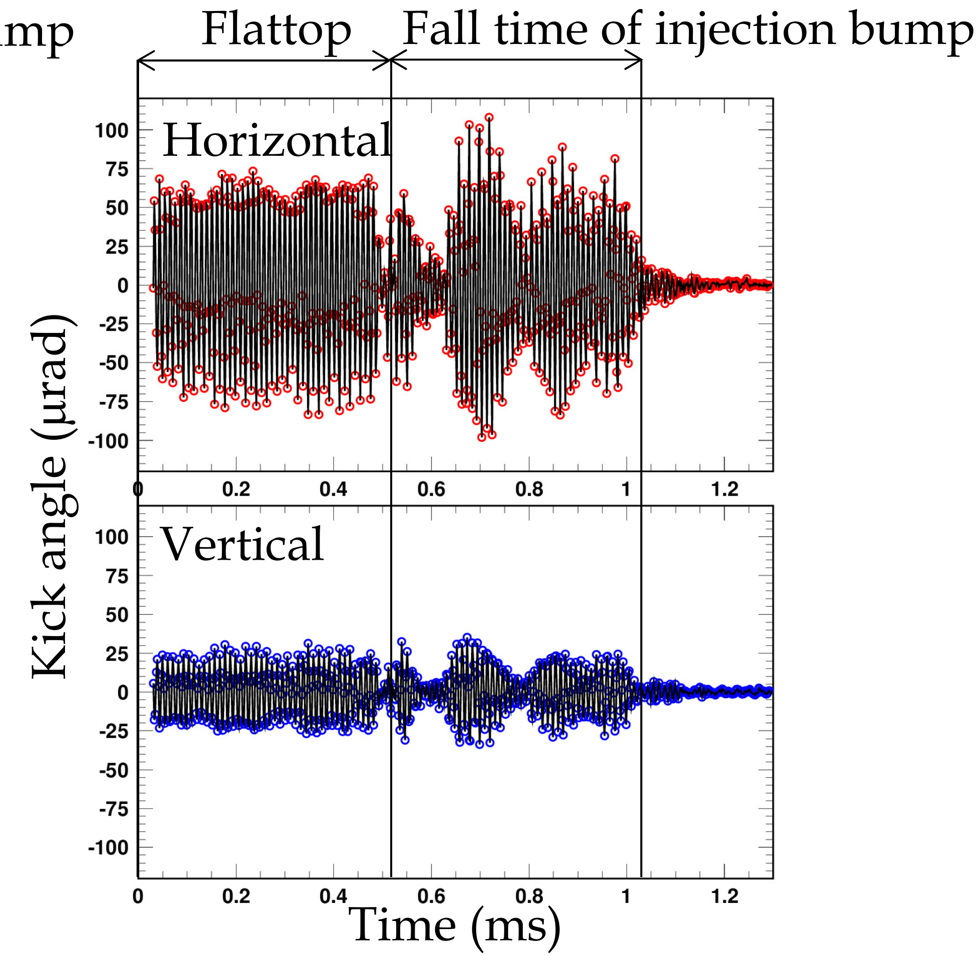
- If the RF shield keep a symmetric configuration,
the dipole field ripple can be canceled out
through the four injection bump magnets (− + + −).
- But then the symmetric condition was out of order,
since a part of capacitors was broken
by the injection bump field
because of the lack of their withstand voltage.
- The dipole ripple component left due to such an
asymmetric configuration of the RF shield
affected the beam.

Time structure of the dipole field ripple

Coherent beam oscillations
excited by the dipole field ripple



Kick angle of the dipole field ripple
estimated from the BPM data



- ✓ The dipole field ripple appears only for the first 1 ms when the injection bump is active.
- ✓ The frequency of the dipole field ripple is ~100 kHz which corresponds to 0.2 in tune.

Mitigation of the dipole field ripple

- The power supply of the injection bump magnets was replaced to match the higher injection energy of 400 MeV.

  IGBT chopping system $\Rightarrow$ Pulse forming network system by switching capacitors

  - ✓ The ripple component of injection bump field itself was reduced !
  - ✓ The driving force to excite the resonant current in the RF shield loop was reduced.

- The RF shield itself was repaired using new capacitors with the higher withstand voltage.

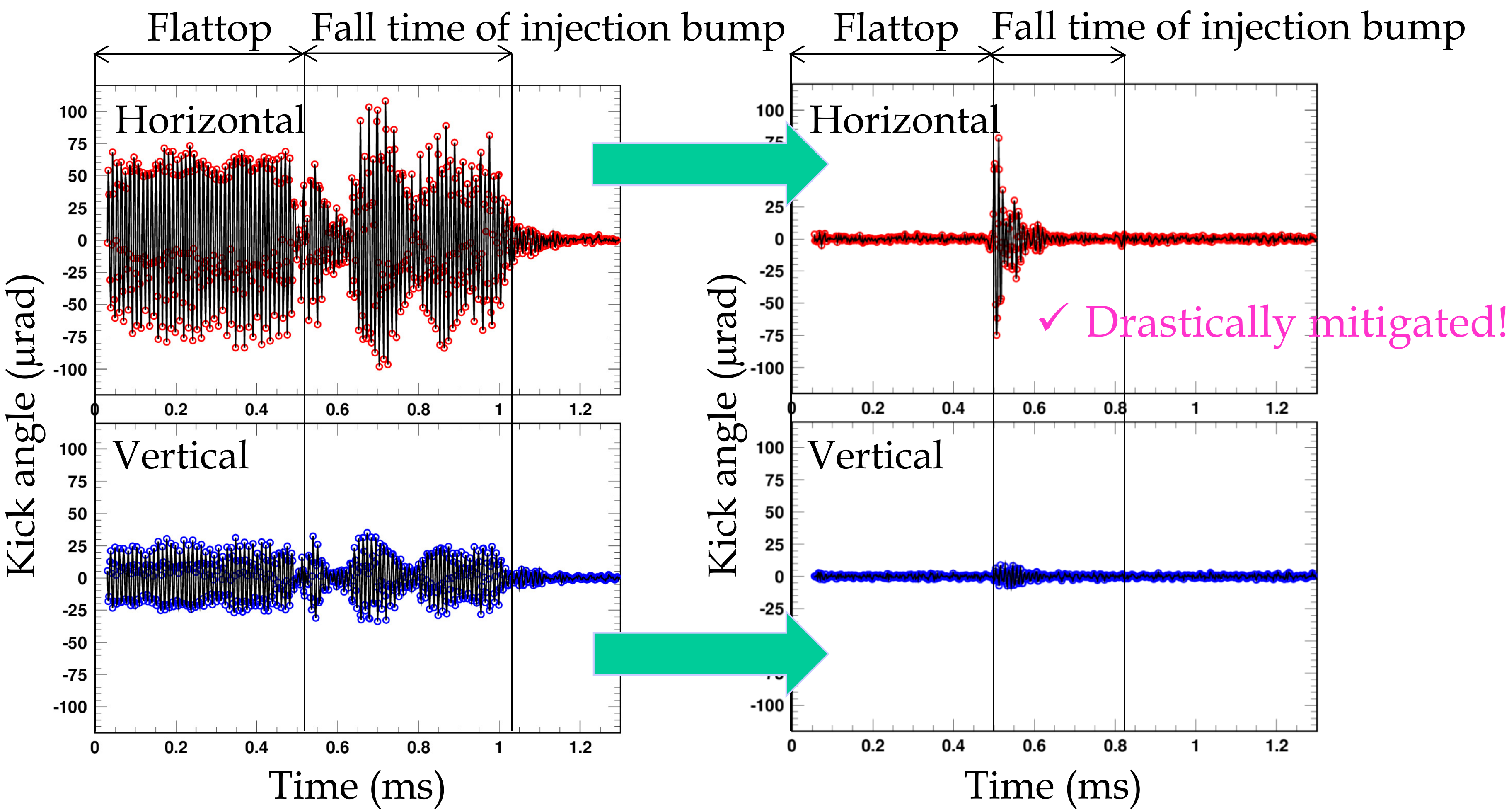
  - ✓ The more symmetric configuration of the repaired RF shield acts to well compensate the dipole field ripple through the four injection bump magnets ($- + + -$).

Mitigation of the dipole field ripple

Kick angle of the dipole field ripple estimated from the BPM data

"Old" power supply
& "Original" RF-shield
with the lack of capacitors

"New" power supply
& "Repaired" RF-shield
without the lack of capacitors

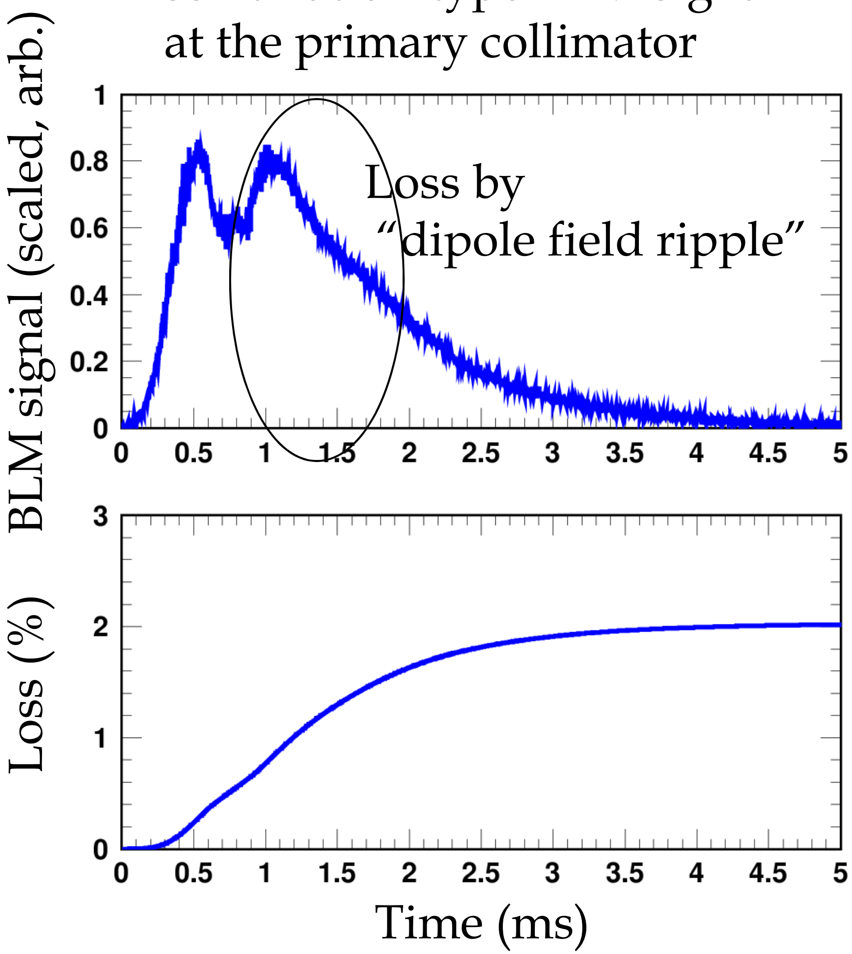


Consideration for
the more detailed mechanism of
the beam loss caused by the dipole field ripple

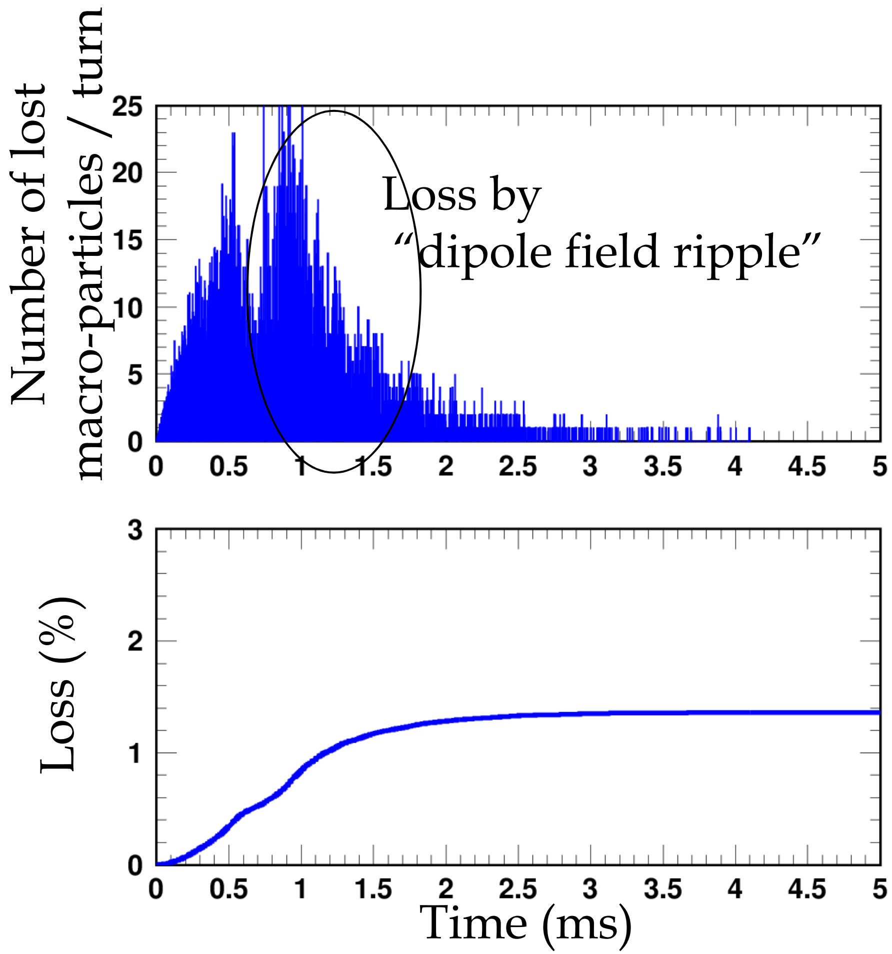
Measurement vs. Numerical simulation : Beam loss

E_{inj}=181 MeV (Run#44), Intensity : ~539 kW-eq

Measurement ;
scintillation-type BLM signal
at the primary collimator



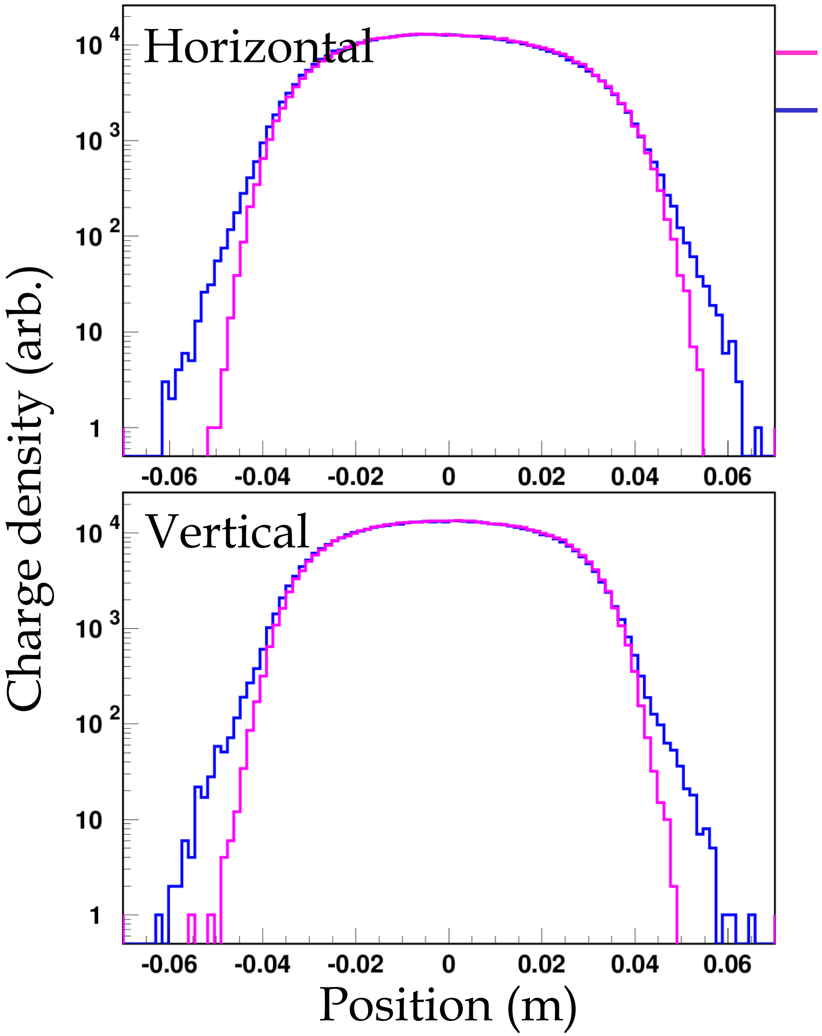
Calculation



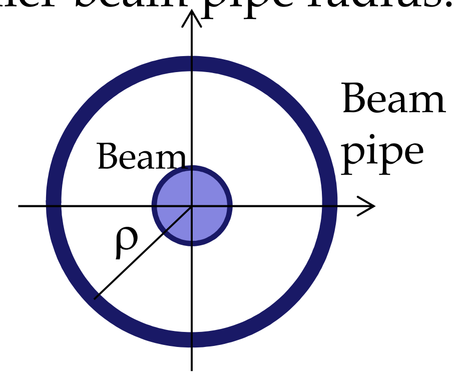
✓ The numerical simulations well reproduced the measure time structure of beam loss . . . also the beam profile and bunching factor.

Emittance growth caused by the dipole field ripple

Beam profile calculated just after the injection



- ✓ The dipole field ripple makes the emittance growth causing the observed beam loss.
- ✓ This emittance growth has significant dependences on the beam intensities and also the beam pipe radius (ρ); larger emittance growth appears for higher intensity beam and/or for smaller beam pipe radius.



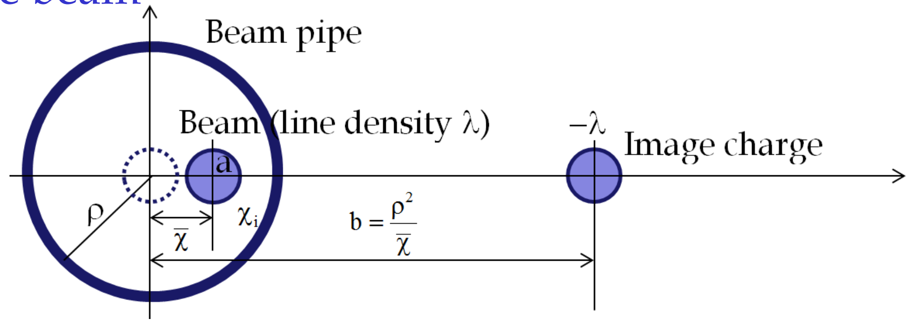
Suggestion from the numerical simulations

Emittance growth caused by the dipole field ripple
⇒Combined effect of "coherent beam oscillation" and "image charge"

- Equation of the coherent motion of the beam (beam center of mass) :

$$\bar{\chi}'' + k(s)\bar{\chi} = f(\theta, t) + \bar{w}$$

$$\bar{w} = \frac{2r_p\lambda}{e\beta^2\gamma}\left(\frac{\bar{\chi}}{\rho^2} + \frac{\bar{\chi}^3}{\rho^4} + \ldots\ldots\right)$$



- Equation of the incoherent motion for each particle (particle motion from the beam center of mass)

$$(\chi_i - \bar{\chi})'' + k(s)(\chi_i - \bar{\chi}) = \sum_j F_{sc\,ij} + (w_i - \bar{w})$$

F_{scij} ・・・ Space charge force
f ・・・ Dipole field ripple
w ・・・ Image charge force

$$\boxed{w_i - \bar{w} = \frac{2r_p\lambda\bar{\chi}^2}{e\beta^2\gamma\rho^4}(\chi_i - \bar{\chi})\cdots}$$

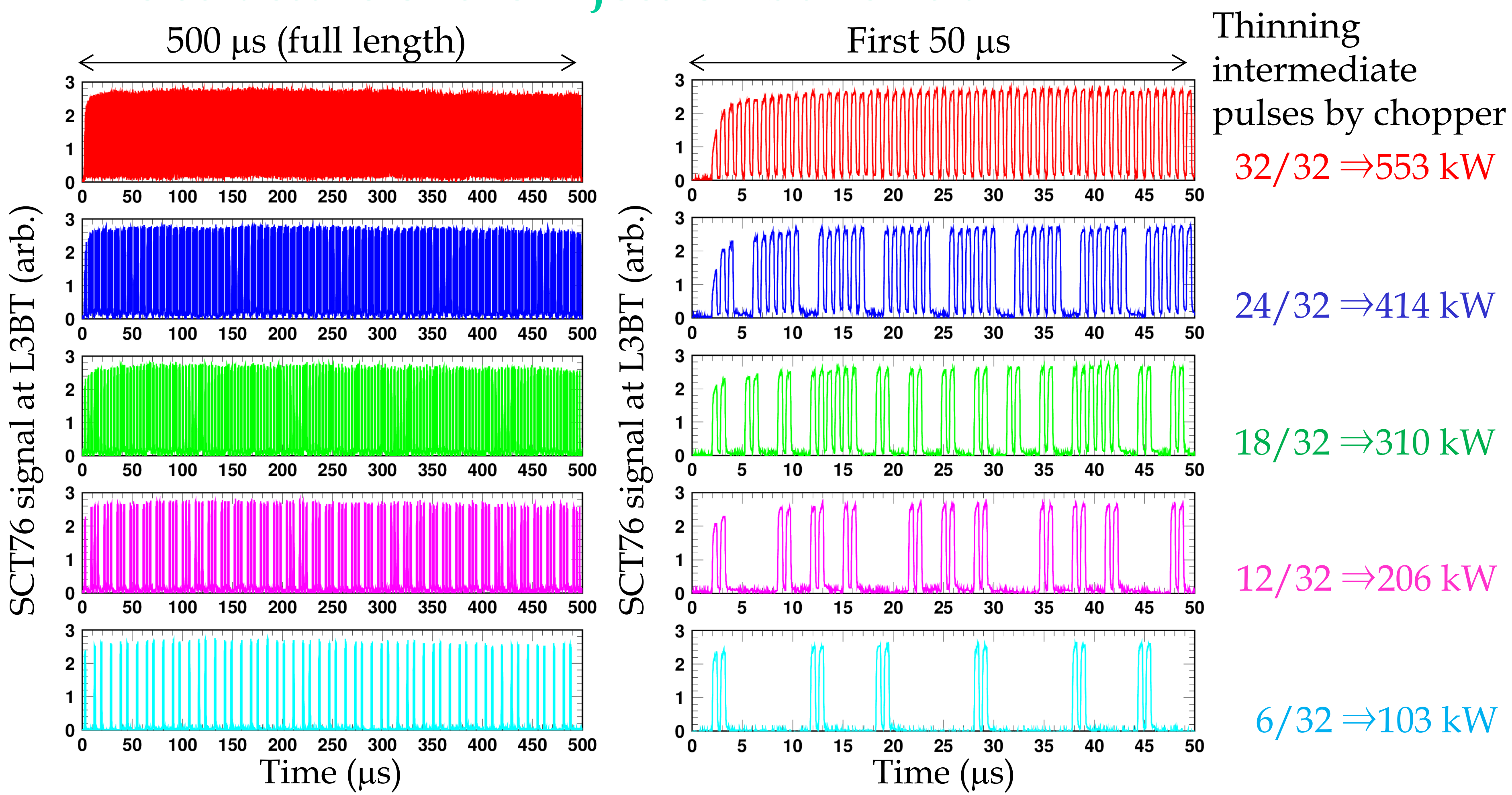
✓ The most probable driving force for the emittance growth and its resultant beam loss caused by the dipole field ripple.

- ✓ Focusing force proportional to the square of the coherent beam position.
- ✓ This force can excite a beam envelope oscillation with ~2 times higher frequency than that of the coherent beam position oscillation and can be a source of half-integer resonance of 2ν=0.4.
- ✓ This force also depends on the beam intensity (λ) and the beam pipe radius (ρ).

More detailed analysis is necessary to get the conclusion . . . .

Intensity dependence of beam loss measured with E_{inj}=400 MeV

Time structure of the injection bunch train



✓ The beam intensity was varied from 100 to 550 kW by uniformly thinning intermediate pulses while keeping the macro-pulse length of 0.5 ms.

⇒ Not changing;

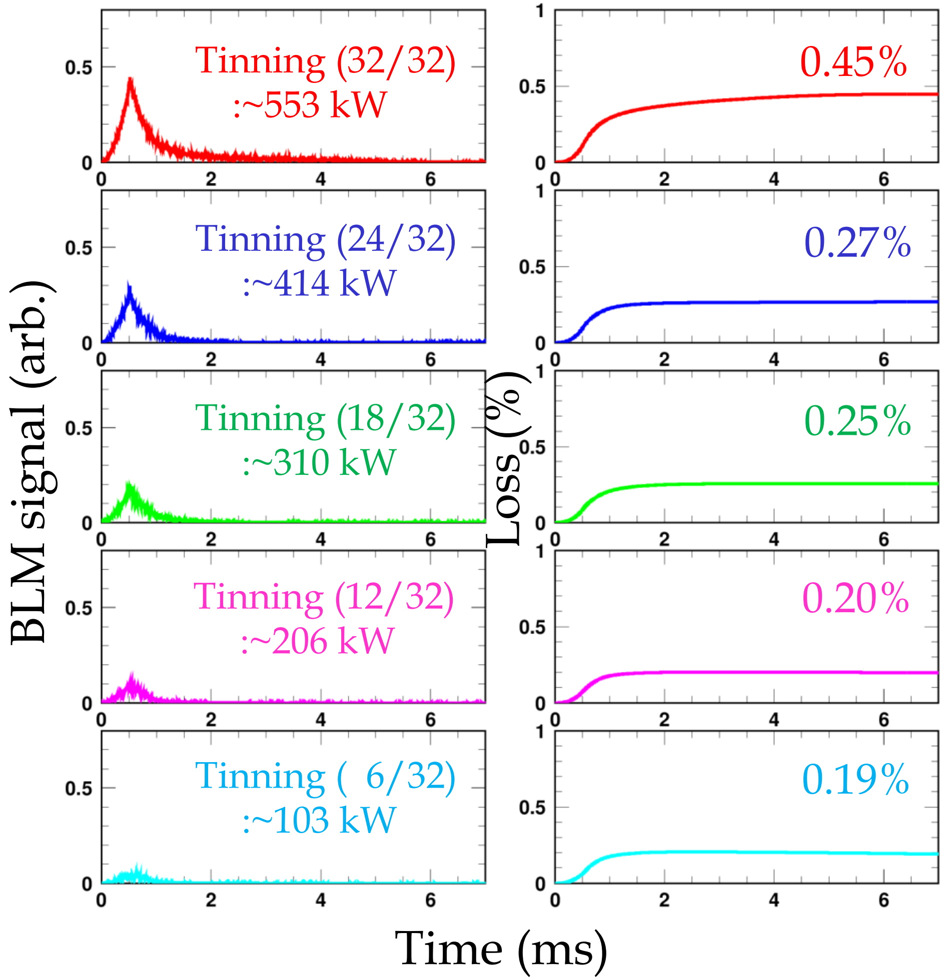
- the condition of injection painting process
- the average number of foil hits per particle during injection.

⇒ Data analysis is more straightforward!

Intensity dependence of beam loss

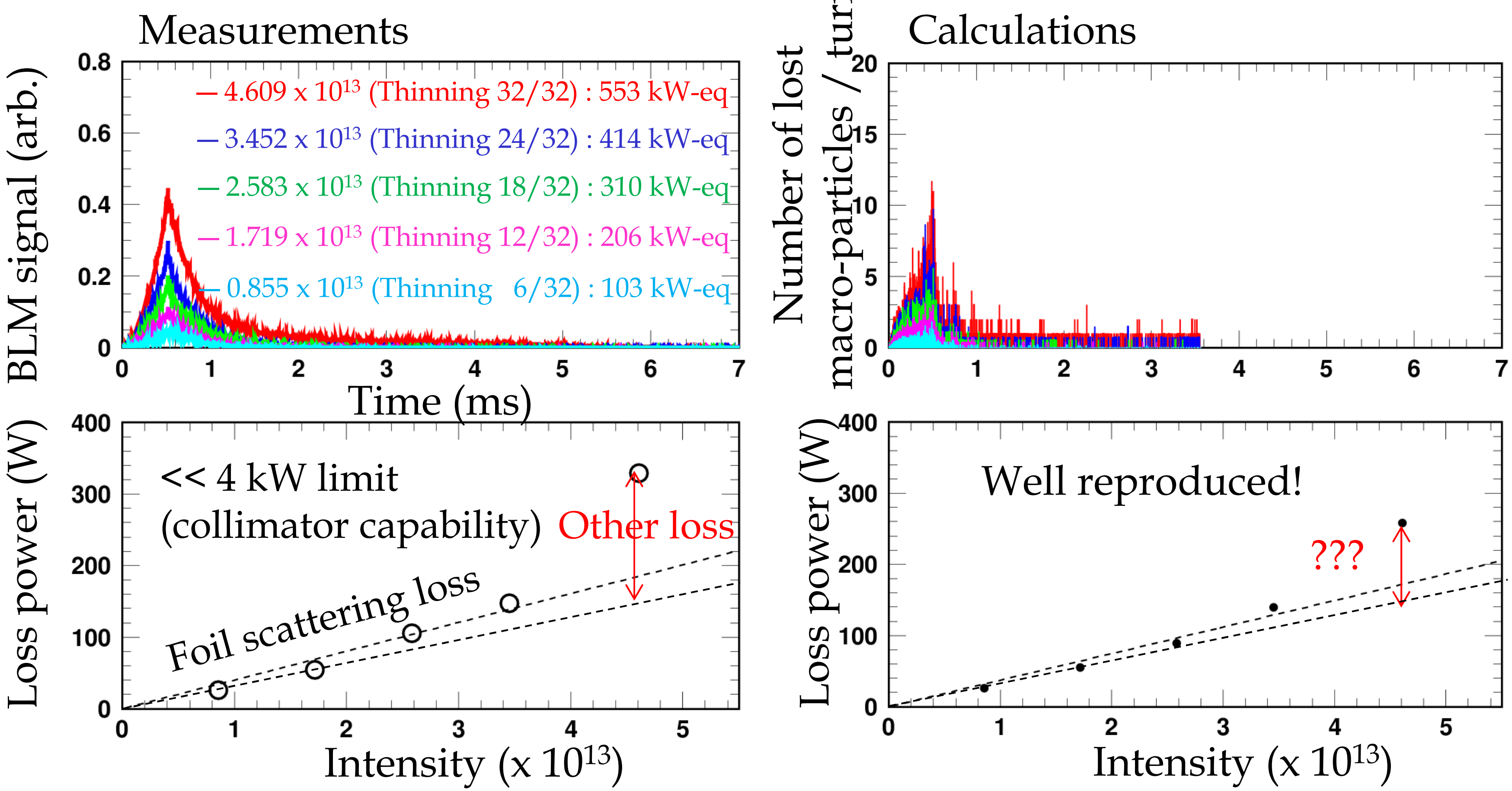
E_{inj}=400 MeV (Run#54)

24.6 mA, 0.5 ms, 60%, 2 bunches, Thinning 6/32~32/32 : 103~553 kW-eq.
Painting parameter ID 8 : 100π transverse painting + full longitudinal painting



✓ The beam loss appears only for the first a few ms in the low energy region for all the cases.

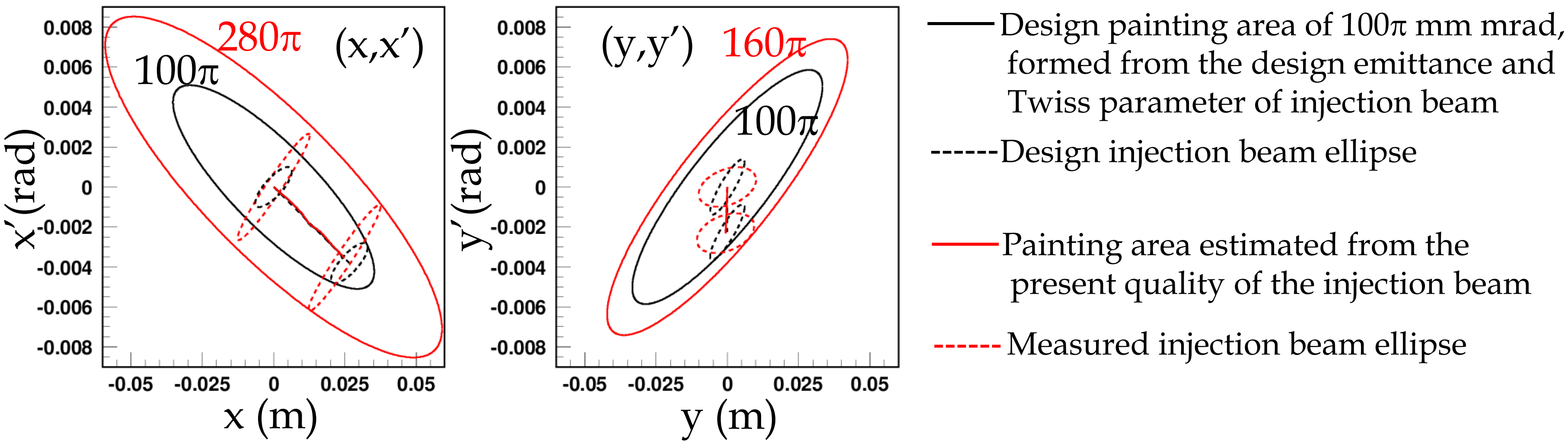
Intensity dependence of beam loss :measurement vs. calculation



- ✓ The beam losses in this intensity range are still much less than the beam loss limit of 4 kW (collimator capability).
- ✓ The beam loss up to 400 kW is well minimized, only from foil scattering.
- ✓ The beam loss for 550 kW still includes extra component other than the foil scattering beam loss.

Possible cause of the extra beam loss observed for the 550-kW intensity beam

Transverse painting area estimated with the present quality of the injection beam



✓ At present the linac beam has a relatively larger beam halo component (around 2 times larger beam emittance) and its Twiss parameter has not been adjusted yet at the RCS injection point.

⇒ deviates the painting area.
⇒ forms a terribly large amplitude particles during the injection painting process.
⇒ causes the extra beam loss observed for the 550-kW intensity beam.

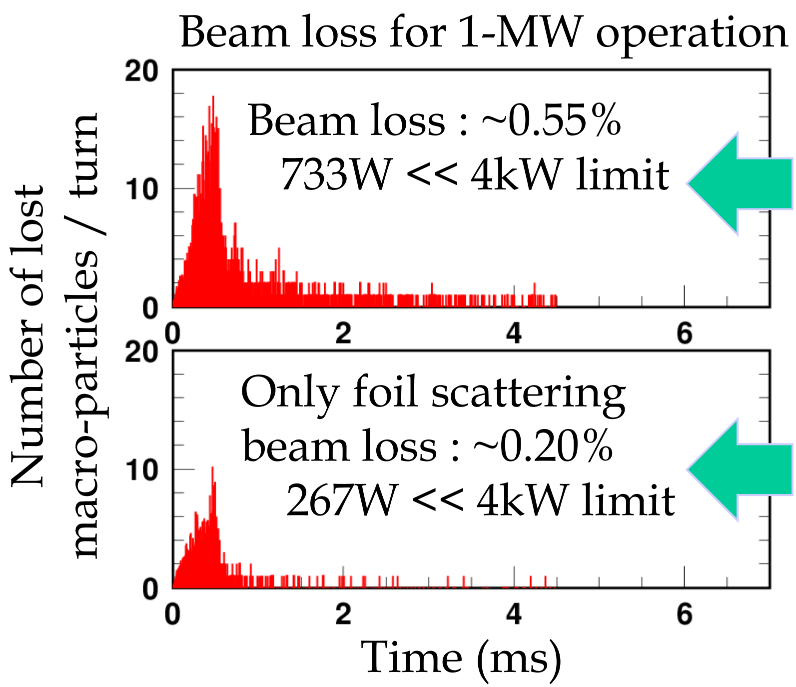
✓ Based on this analysis, we will try beam tuning for the injection beam in the next beam study period (June 26-30) in order to mitigate the extra beam loss observed for the 550 kW intensity beam.

- Outline of the linac and RCS, and their operational history
- Beam commissioning of the 400-MeV linac
- Beam commissioning of the RCS for E_{inj}=400 MeV
- High intensity beam tests of up to 550 kW recently performed in the RCS
  - Injection painting parameter dependence of beam loss
  - Time structure of beam loss
  - Consideration for the more detailed mechanism of the beam loss caused by the dipole field ripple
  - Intensity dependence of beam loss measured for E_{inj}=400 MeV
- **1-MW numerical simulation for the RCS**
- Summary

Beam loss in the RCS expected for the 1-MW design beam operation

E_{inj}=400 MeV

50 mA, 0.5 ms, 53.33%, 2 bunches : 1 MW at 25 Hz
Painting parameter ID8 : 100π transverse painting + full longitudinal painting



Calculated with the present quality of the injection beam assuming ;
- around 2 times larger emittance than the design
- Twiss parameter not adjusted yet at the RCS injection point

Calculated with the design injection beam

✓ The beam losses for both cases are still much less than the beam loss limit of 4 kW (collimator limit).

✓ The numerical simulation gives the positive result for the coming 1-MW design beam operation, but also specifies that the quality of the injection beam is a key to minimize its beam loss.

Summary

- The 400-MeV linac was successfully commissioned as planned.

- With the upgraded injection energy of 400 MeV,
  the RCS successfully demonstrated 550-kW high intensity beam acceleration
  at a low-level intensity loss of less than 0.5% (367 W in power).

- Most of the 0.5%-beam loss was well localized at the collimator section
  and its beam loss power is still much less than
  the beam loss limit of 4 kW (collimator capability).

- Now the linac and RCS is stably delivering the 300-kW beam
  for the user program. Its beam power will be increased to > 500 kW
  after replacing the neutron target at the MLF in this summer.

- Beam commissioning of the linac and RCS is surely progressing
  toward the design output beam power of 1 MW step by step.

- The 1-MW beam tuning is to start in October 2014
  after replacing the front-end system of the linac in this summer.