Lessons from 1-MW Proton RCS Beam Tuning

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

Contents

- Outline of the linac and RCS, and their operational history
- High intensity beam tests of up to 573 kW
  performed just after the injection energy upgrade to 400 MeV
  - Beam loss mitigation by injection painting
    (Run#54, Apr., 2014)
  - Comparison with the old data taken
    for the lower injection energy of 181 MeV
  - Further beam loss mitigation by adjusting
    the Twiss parameter of the injection beam
    (Run#56, June 2014)
- First 1-MW trial
  (Run#57, Oct., 2014)
- Summary & future plan

◆ **Outline of the linac and RCS, and their operational history**

◆ **High intensity beam tests of up to 573 kW performed just after the injection energy upgrade to 400 MeV**

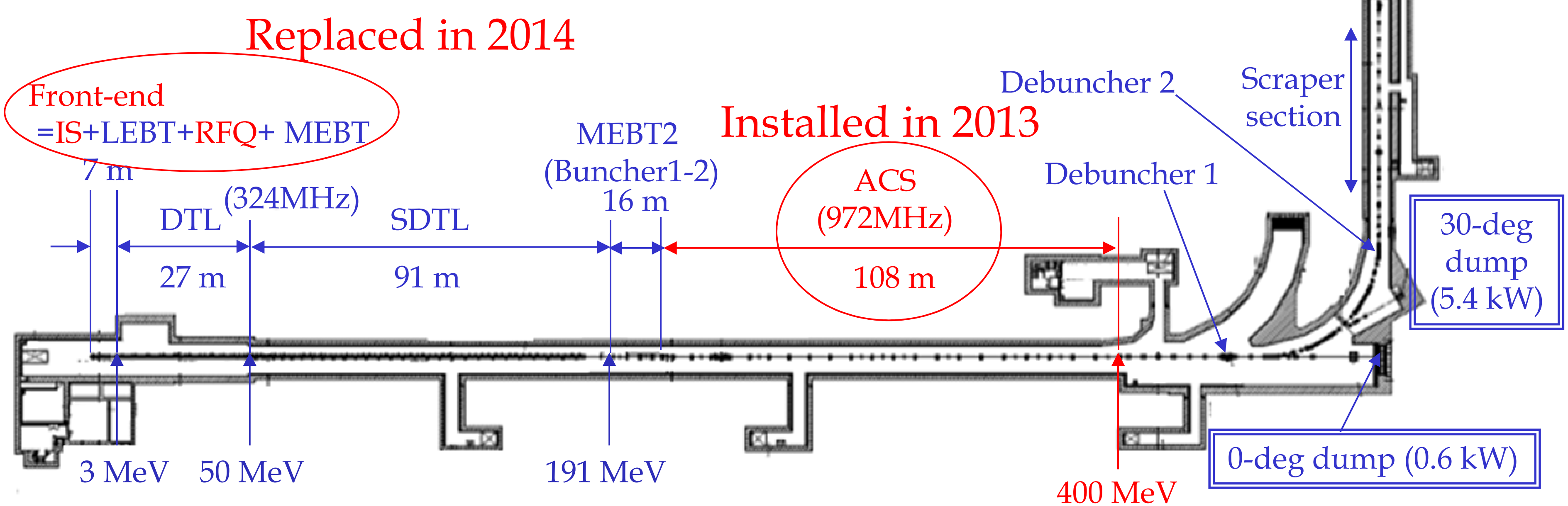
- **Beam loss mitigation by injection painting (Run#54, Apr., 2014)**
- **Comparison with the old data taken for the lower injection energy of 181 MeV**
- **Further beam loss mitigation by adjusting the Twiss parameter of the injection beam (Run#56, June 2014)**

◆ **First 1-MW trial (Run#57, Oct., 2014)**

◆ **Summary & future plan**

Design parameters of the linac

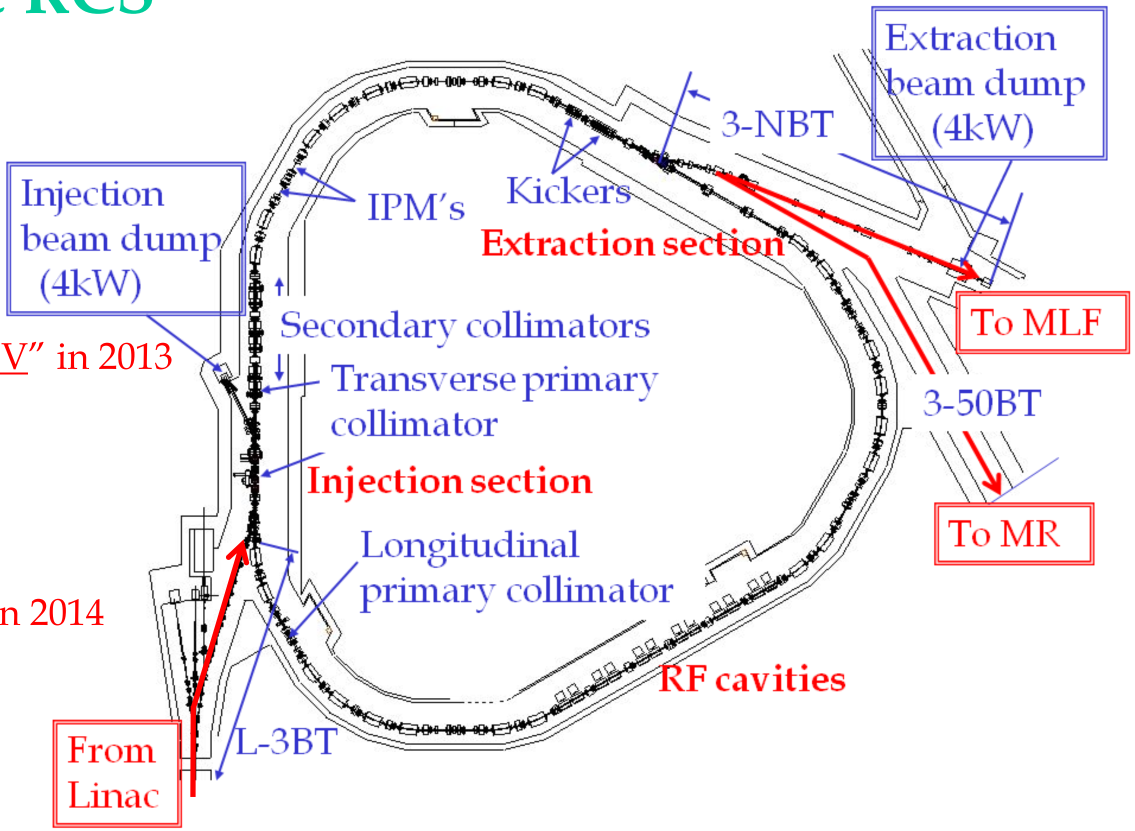
Particles	H^-	
Output energy	181 MeV	⇒ "400 MeV" in 2013 by adding an ACS linac section
Peak current	30 mA	⇒ "50 mA" in 2014 by replacing the front-end system (IS &RFQ)
Pulse width	0.5 ms	
Chopper beam-on duty factor	53.3%	
Repetition rate	25 Hz	
Output power	80 kW	⇒ 133 kW (Design beam power of linac)



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

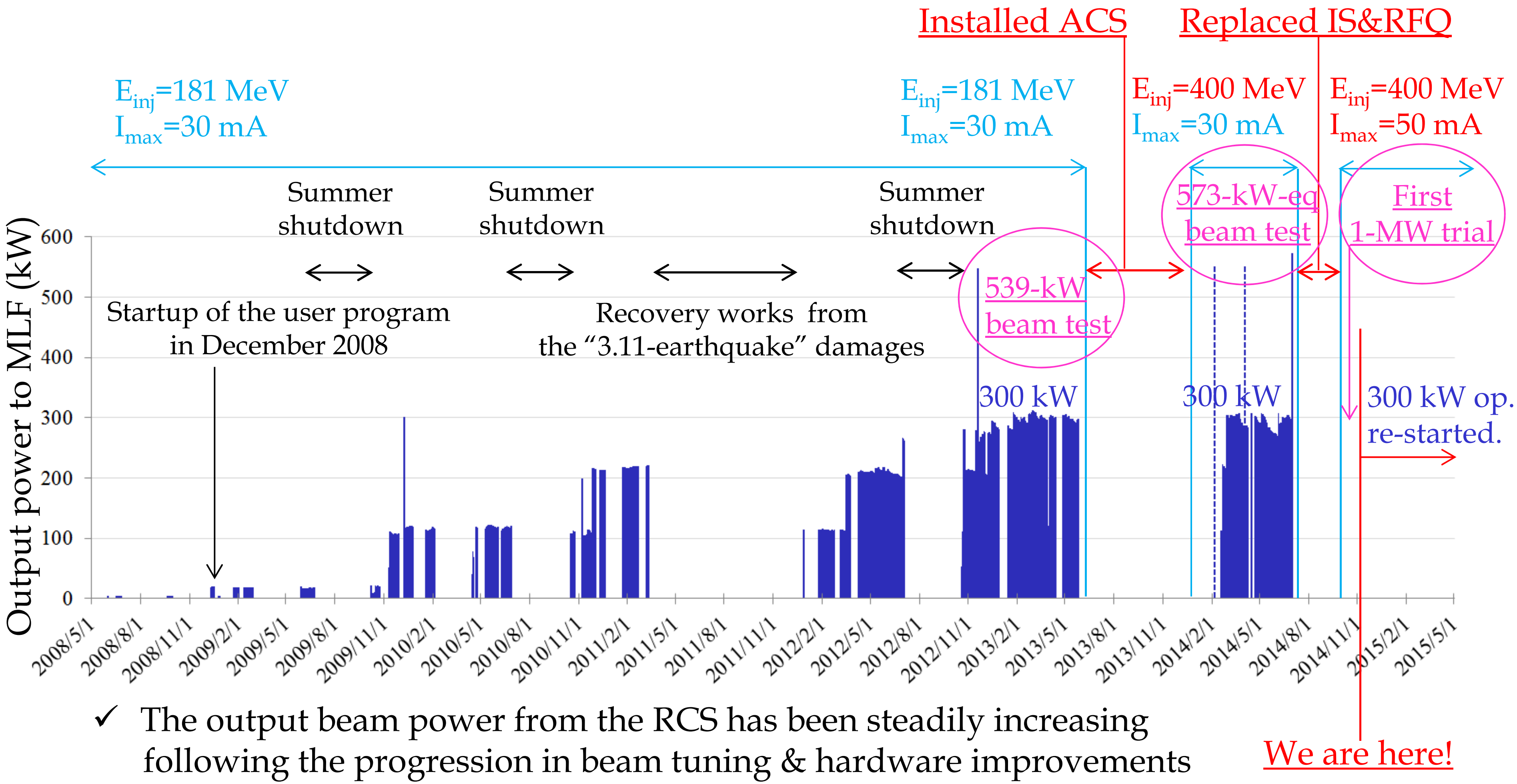
Design parameters of the RCS

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
Number of bunches	2
Injection energy	181 MeV ⇒ "400 MeV" in 2013
Injection period	0.5 ms (307 turns)
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	5e13 ⇒ "8.3e13" in 2014
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 linac and RCS have just got all the design hardware parameters to try the 1-MW design beam operation.

History of the linac & RCS beam operation



- ✓ The output beam power from the RCS has been steadily increasing following the progression in beam tuning & hardware improvements since the startup of user program in December 2008.
- ✓ The present output beam power for the routine user program is 300 kW.
- ✓ High intensity beam tests of up to 573 kW for both injection energies of 181 MeV and 400 MeV
- ✓ First 1-MW beam trial

Main topic of this talk

◆ Outline of the linac and RCS, and their operational history

◆ **High intensity beam tests of up to 573 kW performed just after the injection energy upgrade to 400 MeV**

- **Beam loss mitigation by injection painting (Run#54, Apr., 2014)**
- **Comparison with the old data taken for the lower injection energy of 181 MeV**
- **Further beam loss mitigation by adjusting the Twiss parameter of the injection beam (Run#56, June 2014)**

◆ First 1-MW trial (Run#57, Oct., 2014)

◆ Summary & future plan

Beam commissioning of the 400-MeV linac

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

◆ Initial beam tuning (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 commissioning of the RCS with the upgraded injection energy of 400 MeV

- ✓ Beam commissioning of the RCS: Jan. 30, 2014~
- ✓ Achievement of the beam acceleration from 400 MeV to 3 GeV : Feb. 6, 2014

◆ Initial beam tuning (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 just 10 days.

↓

High intensity beam tests

High intensity beam test of up to 553 kW

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

  Energy : 400 MeV

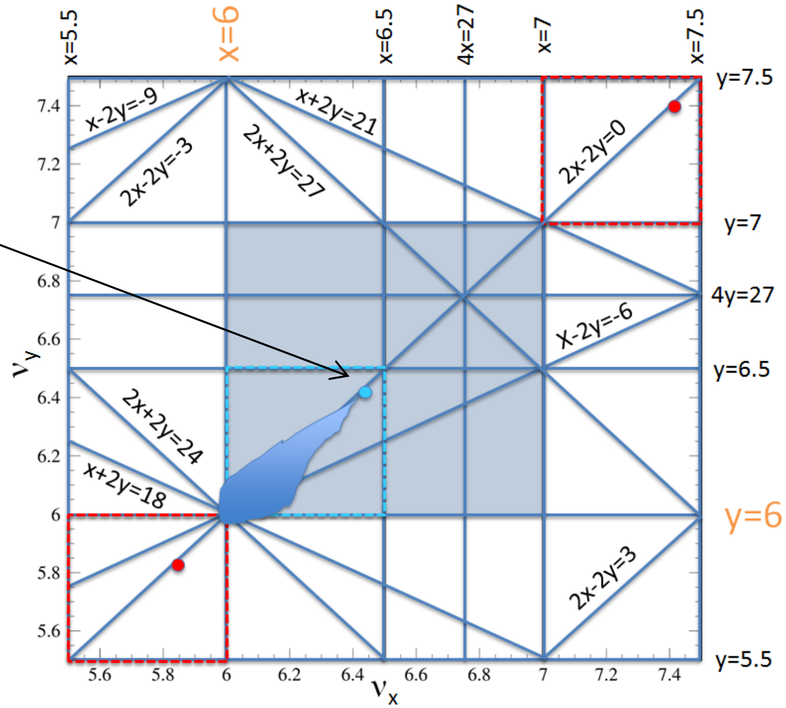
  Peak current : 24.6 mA @ the entrance of RCS

  Pulse length : 0.5 ms

  Chopper beam-on duty factor : 60%

  ⇒ 4.604 x 10^{13} particles/pulse, corresponding to **553 kW** at 3 GeV
- Operating point;

  (6.45, 6.42)



In the RCS, transverse and longitudinal injection painting techniques are employed to mitigate space-charge induced beam loss in the low energy region.

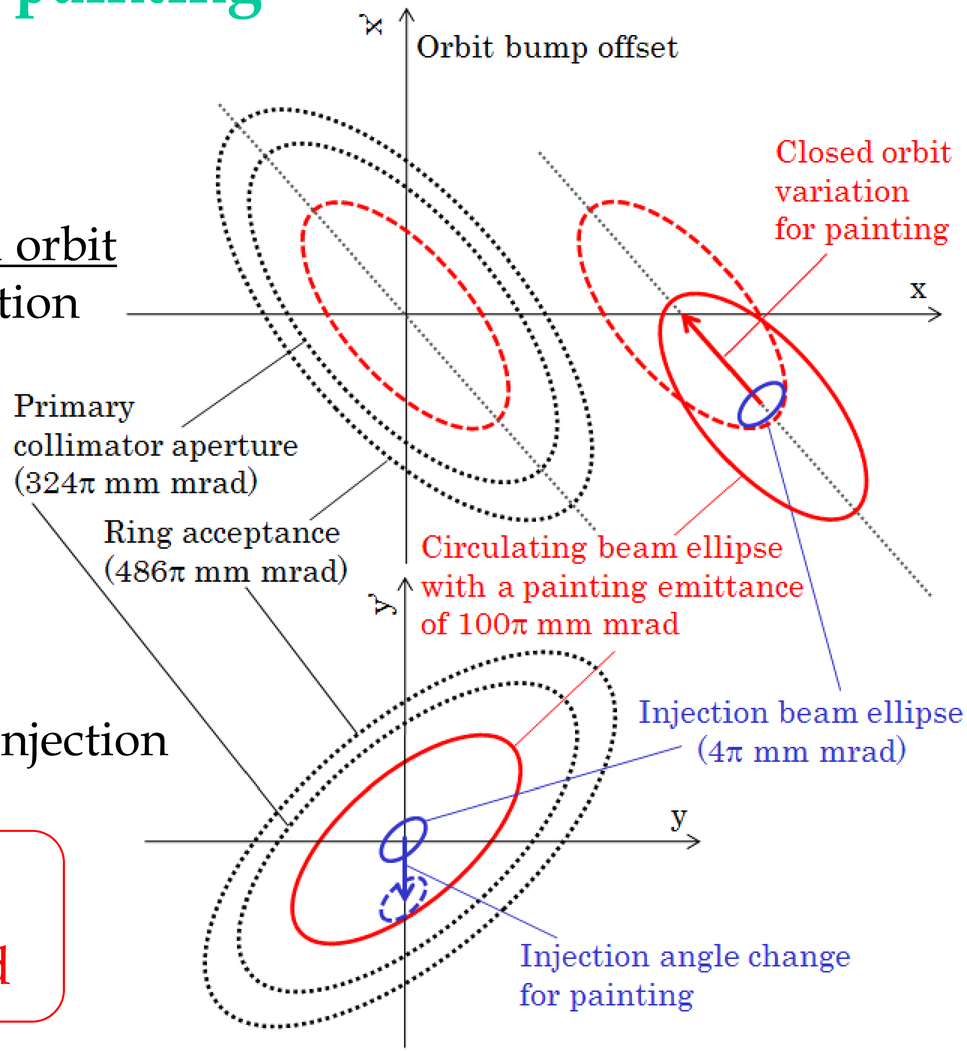
✓ Systematic beam loss measurements for various injection painting parameters

✓ Comparison with old data taken for 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

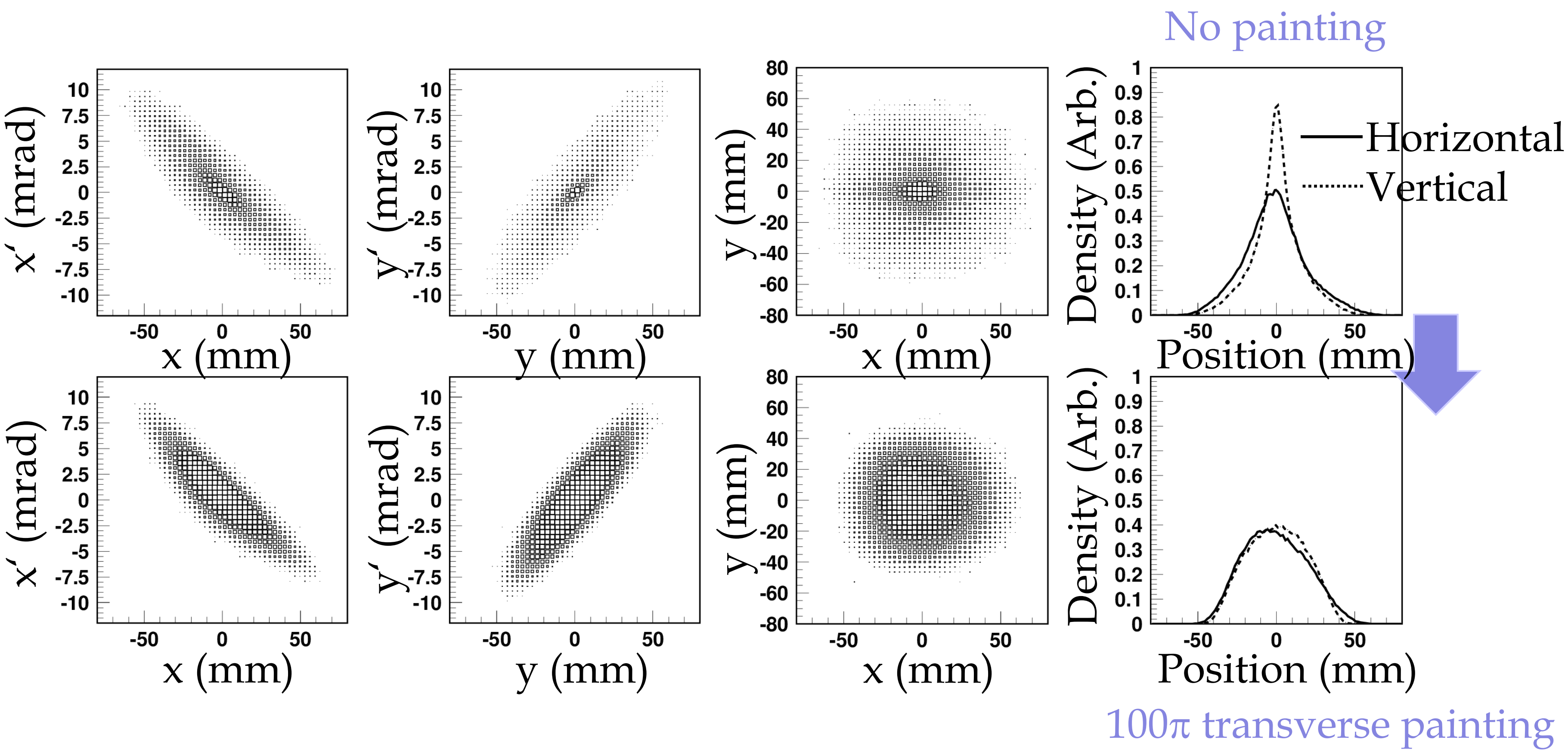
ε_{tp}= 100 π mm mrad

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

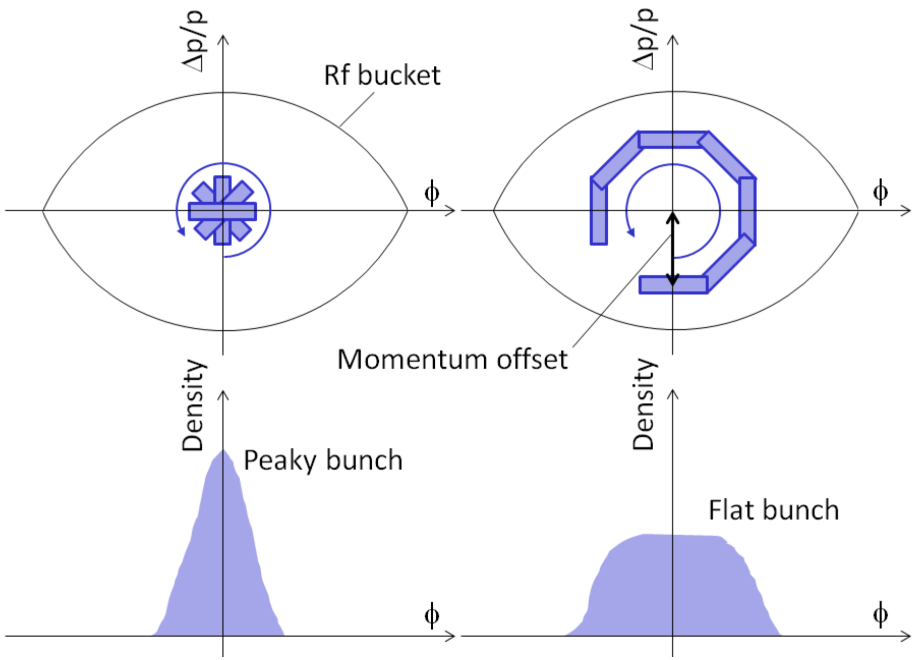


from H. Hotchi et. al., PRST-AB **15**, 040402 (2011).

Longitudinal injection painting

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

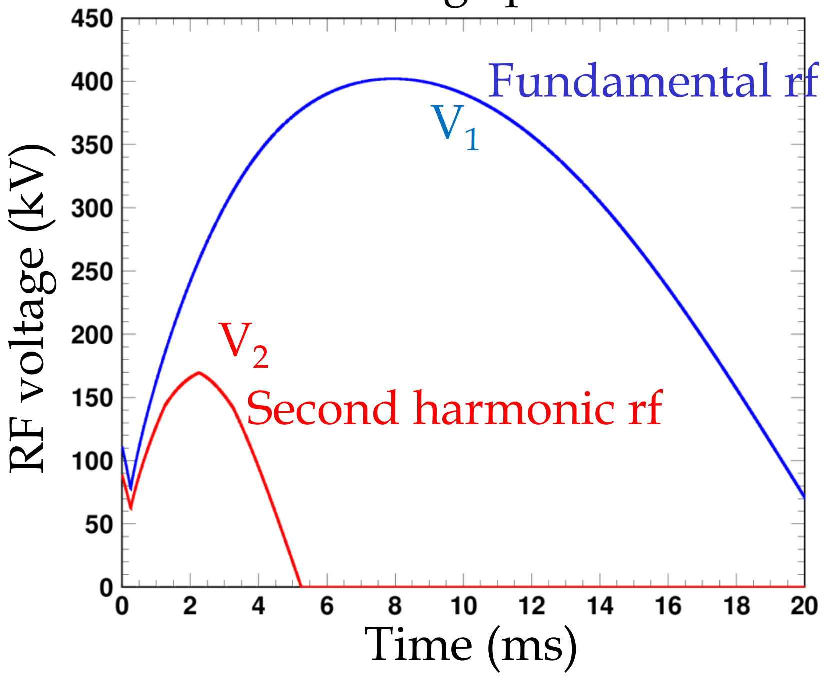
Momentum offset injection



$\Delta p/p$=0, –0.1 and –0.2%

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

RF voltage pattern



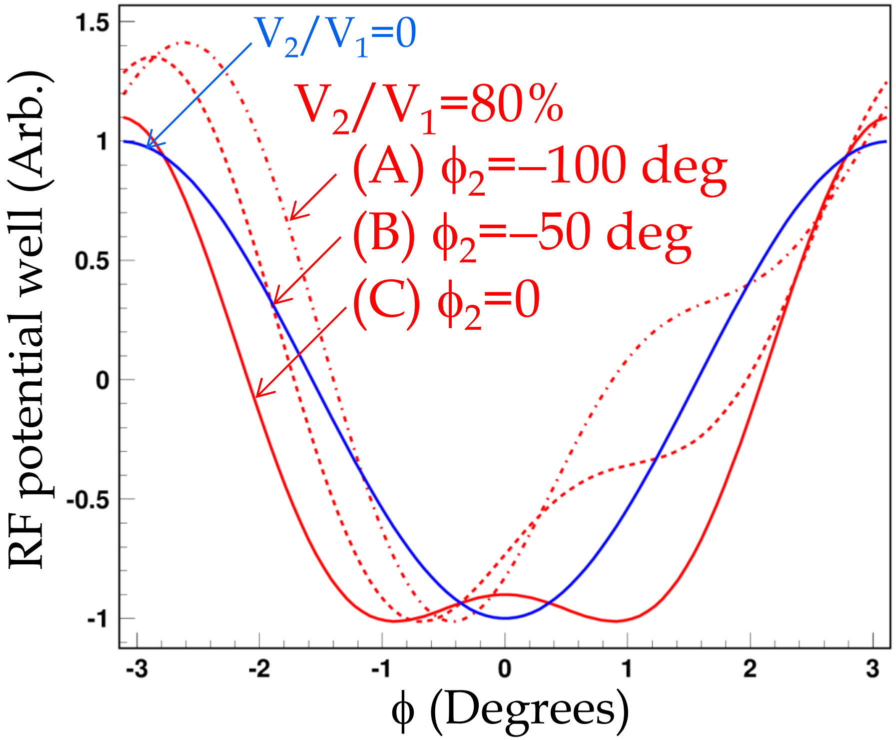
V_2/V_1=80%

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

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

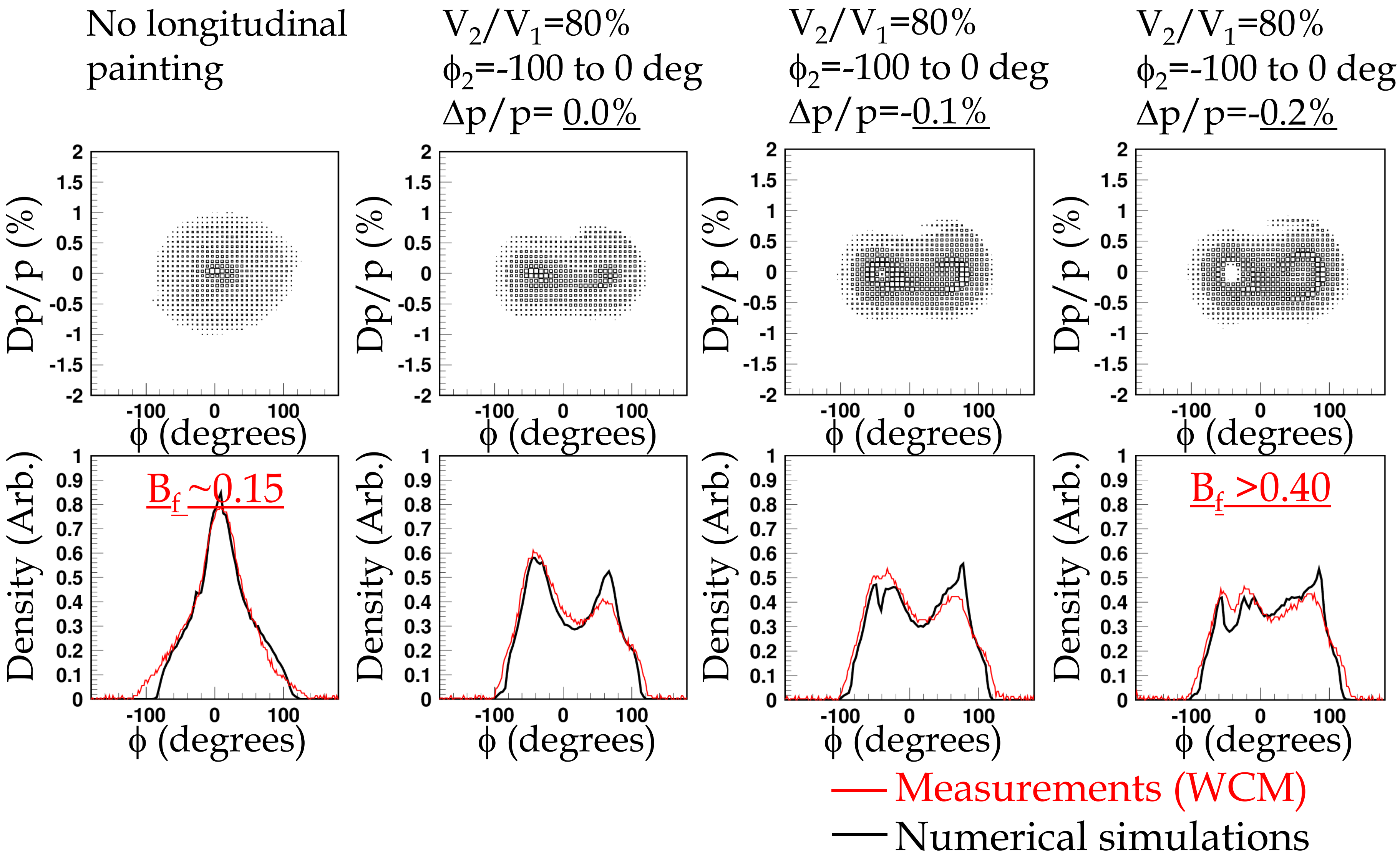


ϕ_2=–100⇒0 deg

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

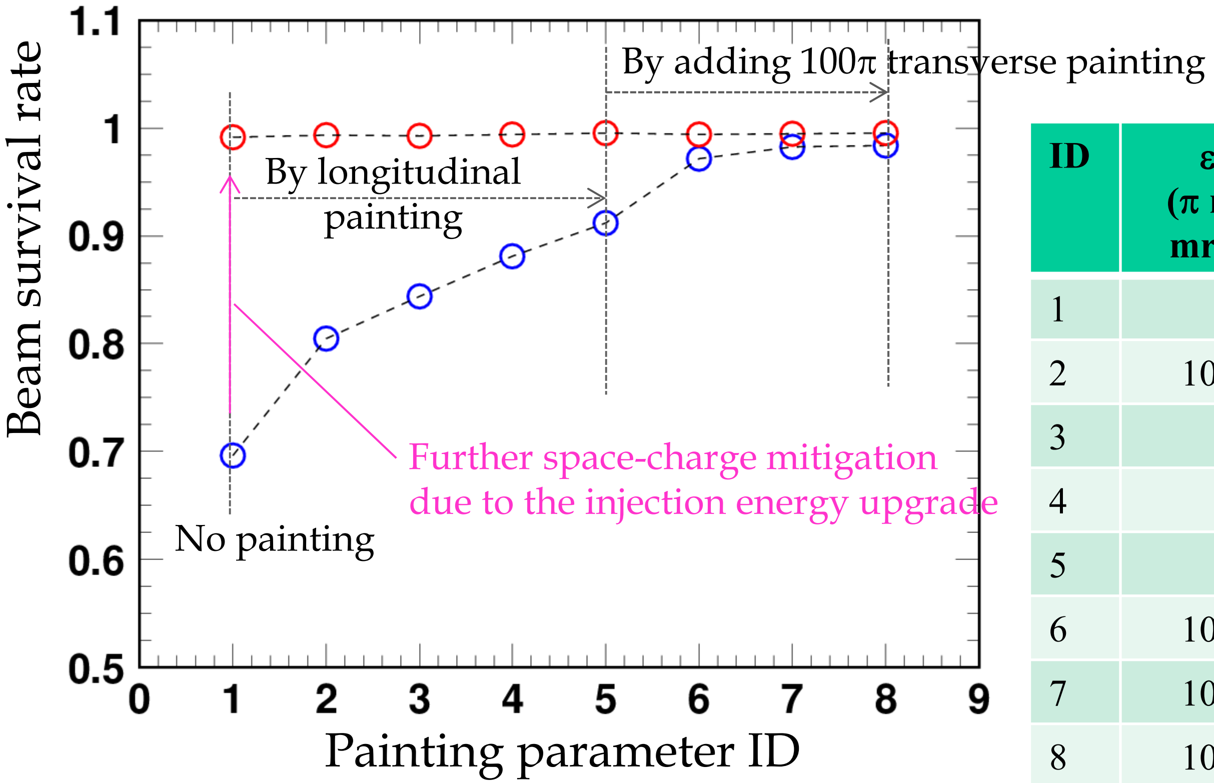
Longitudinal beam distribution just after beam injection (at 0.5 ms)



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)

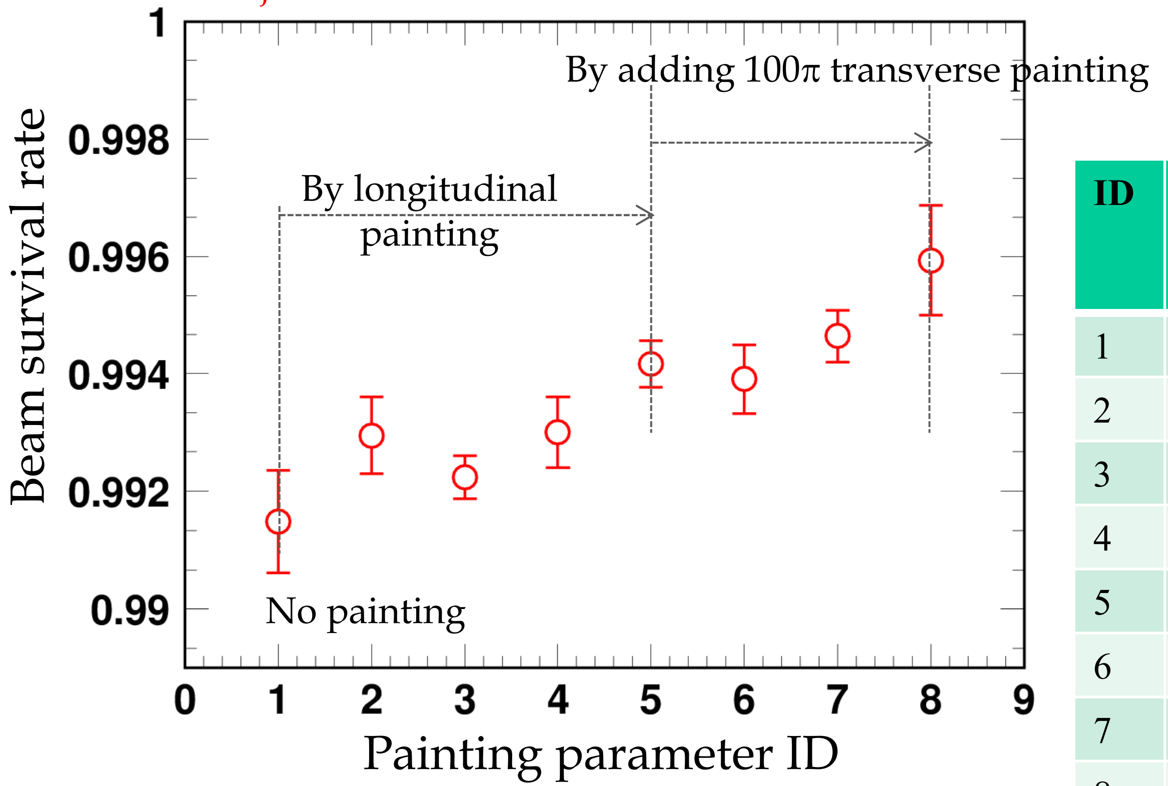


ID	ε_{tp} (π mm mrad)	RF V_2/V_1 (%)	ϕ_2 (deg)	Δp/p (%)
1	-	-	-	-
2	100π	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100π	80	-100	-0.0
7	100π	80	-100	-0.1
8	100π	80	-100	-0.2

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

Painting parameter dependence of beam survival rate

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

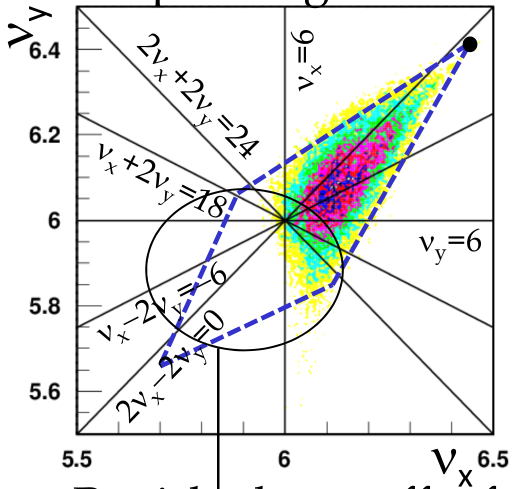


ID	ε_{tp} (π mm mrad)	RF V_2/V_1 (%)	ϕ_2 (deg)	Δp/p (%)
1	-	-	-	-
2	100π	-	-	-
3	-	80	-100	-0.0
4	-	80	-100	-0.1
5	-	80	-100	-0.2
6	100π	80	-100	-0.0
7	100π	80	-100	-0.1
8	100π	80	-100	-0.2

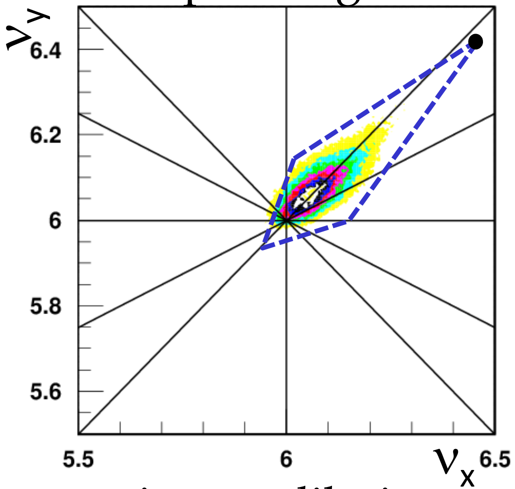
Space-charge tune depression calculated at E_{inj}=181 & 400 MeV

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

No painting : ID1



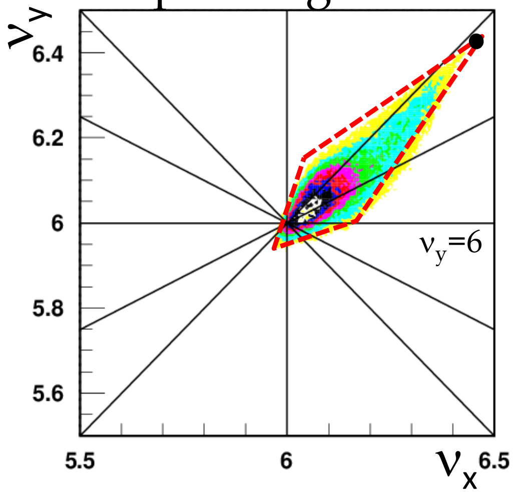
With painting : ID8



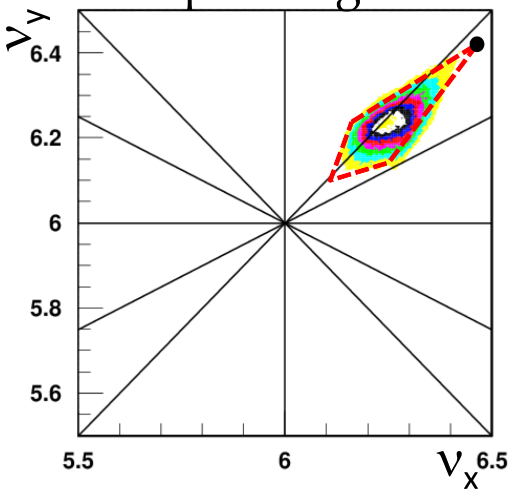
Particles here suffer from emittance dilution, leading to large beam loss.

◆ 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.

High intensity beam test of up to 573 kW

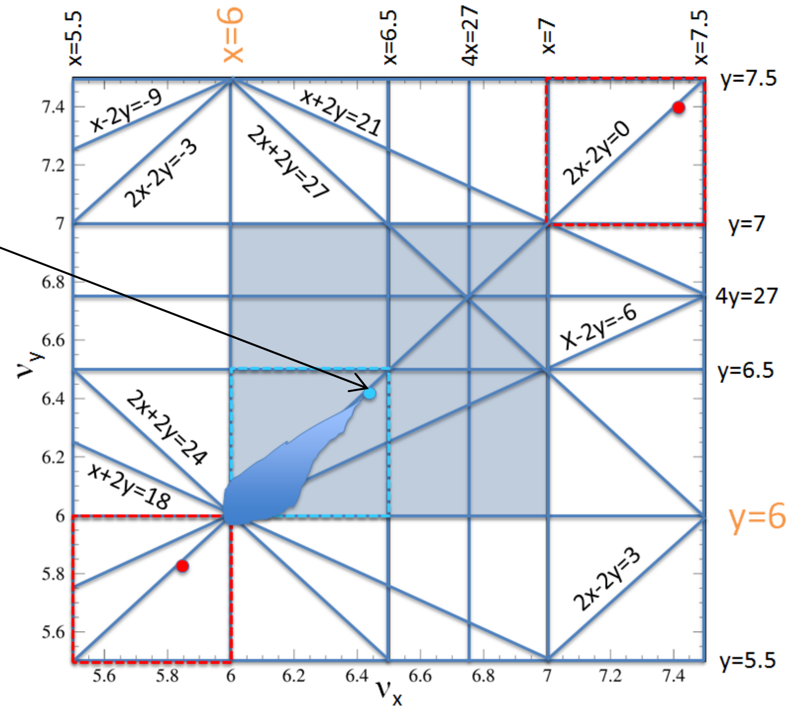
- Date; June 28-30, 2014 (Run#56)
- Injection beam condition;

  Injection energy : 400 MeV
  Peak current : 25.5 mA @ the entrance of the RCS
  Pulse length : 0.5 ms
  Chopper beam-on duty factor : 60%

  $\Rightarrow$ 4.775 x 10^{13} particles/pulse, corresponding to **573 kW** at 3 GeV
- Operating point;

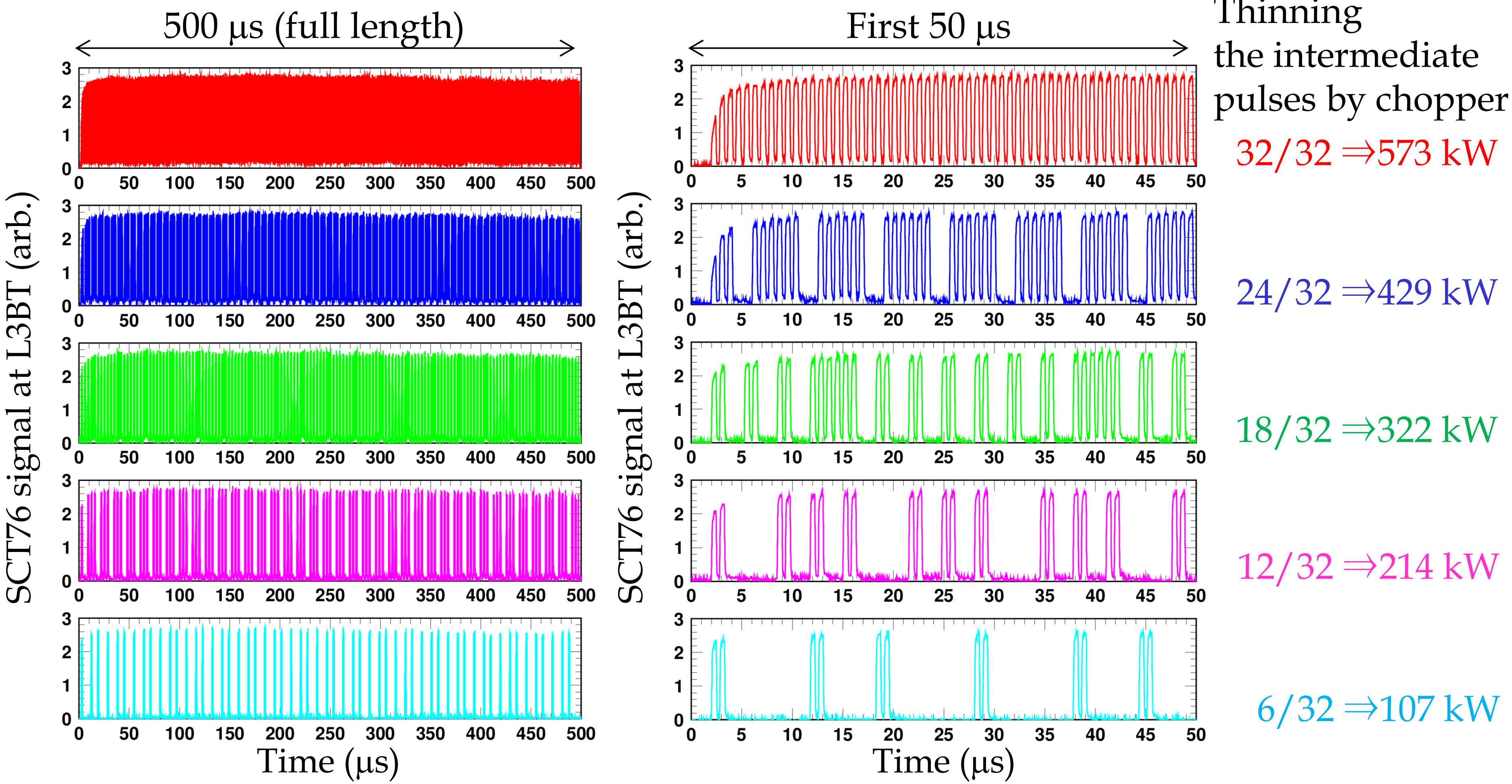
  (6.45, 6.42)
- Injection painting parameter;

  ID8 (100π transverse painting
  + full longitudinal painting)



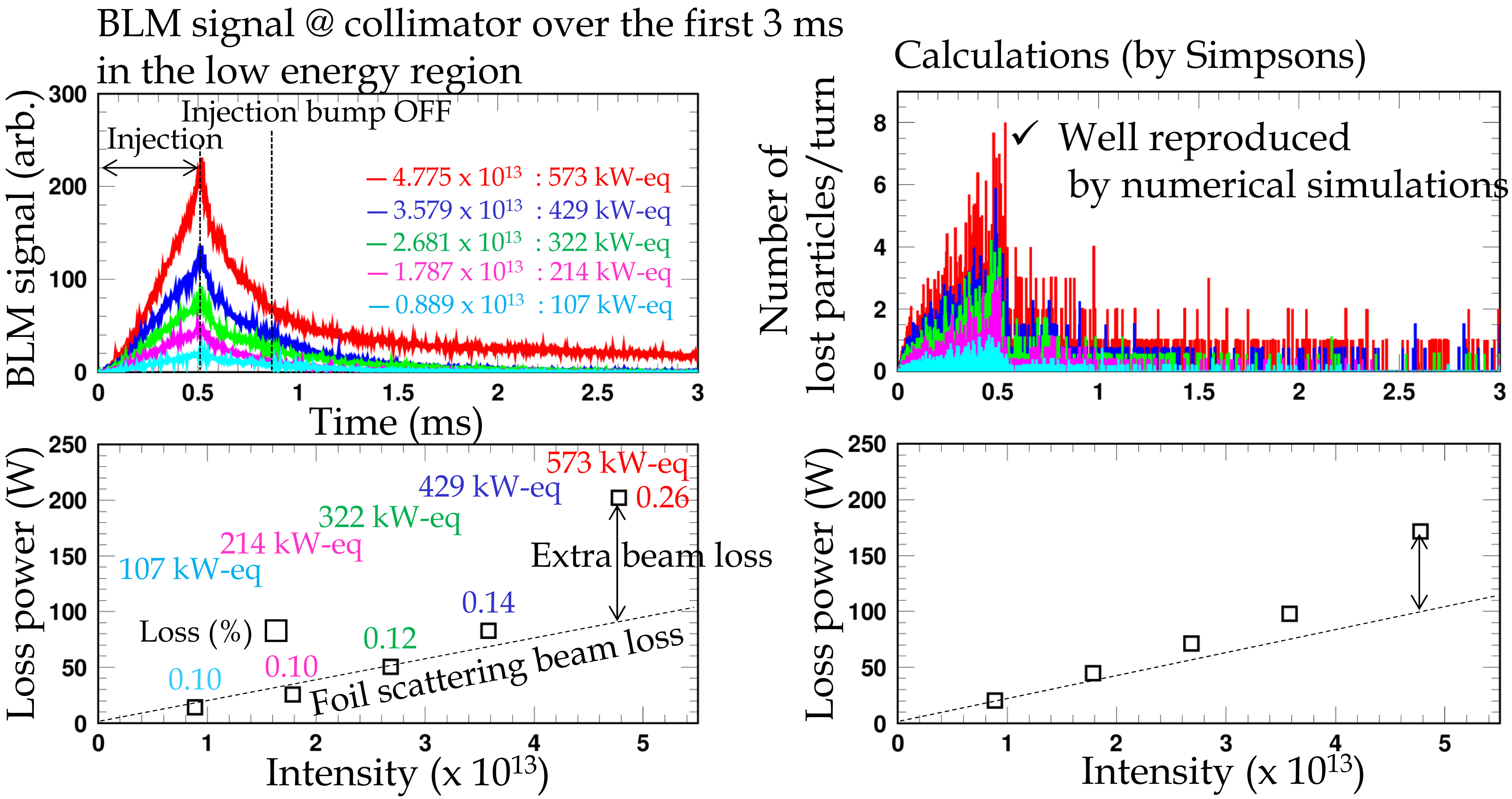
✓ Intensity dependence of beam loss
✓ Further beam loss mitigation
by adjusting the Twiss parameter
of the injection beam

Time structure of the injection bunch train



- ✓ The beam intensity was varied from 107 to 573 kW by uniformly thinning the intermediate pulses while keeping the macro-pulse length of 0.5 ms.
  - The condition of injection painting process does not change.
  - The foil hitting rate during injection does not change.
- ✓ The beam thinning technique used for intensity variations makes data analysis more straightforward.

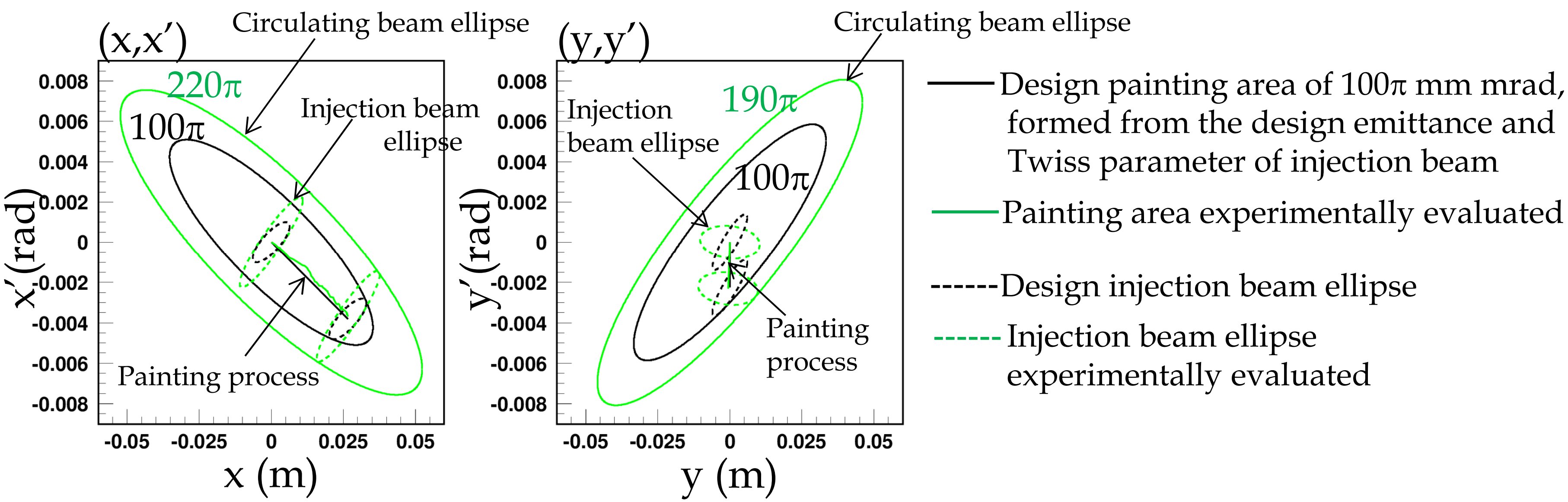
Intensity dependence of beam loss



- ✓ The beam loss powers in this intensity range are still much less than the 4-kW beam loss limit (collimator capability) of the RCS.
- ✓ The beam loss of up to 429-kW intensity beam is nearly minimized, and its remaining beam loss is mainly from foil scattering during injection.
- ✓ But the beam loss for 573-kW intensity beam still includes extra component other than the foil scattering beam loss.

Possible cause of the extra beam loss observed for the 573-kW intensity beam

Transverse injection painting area



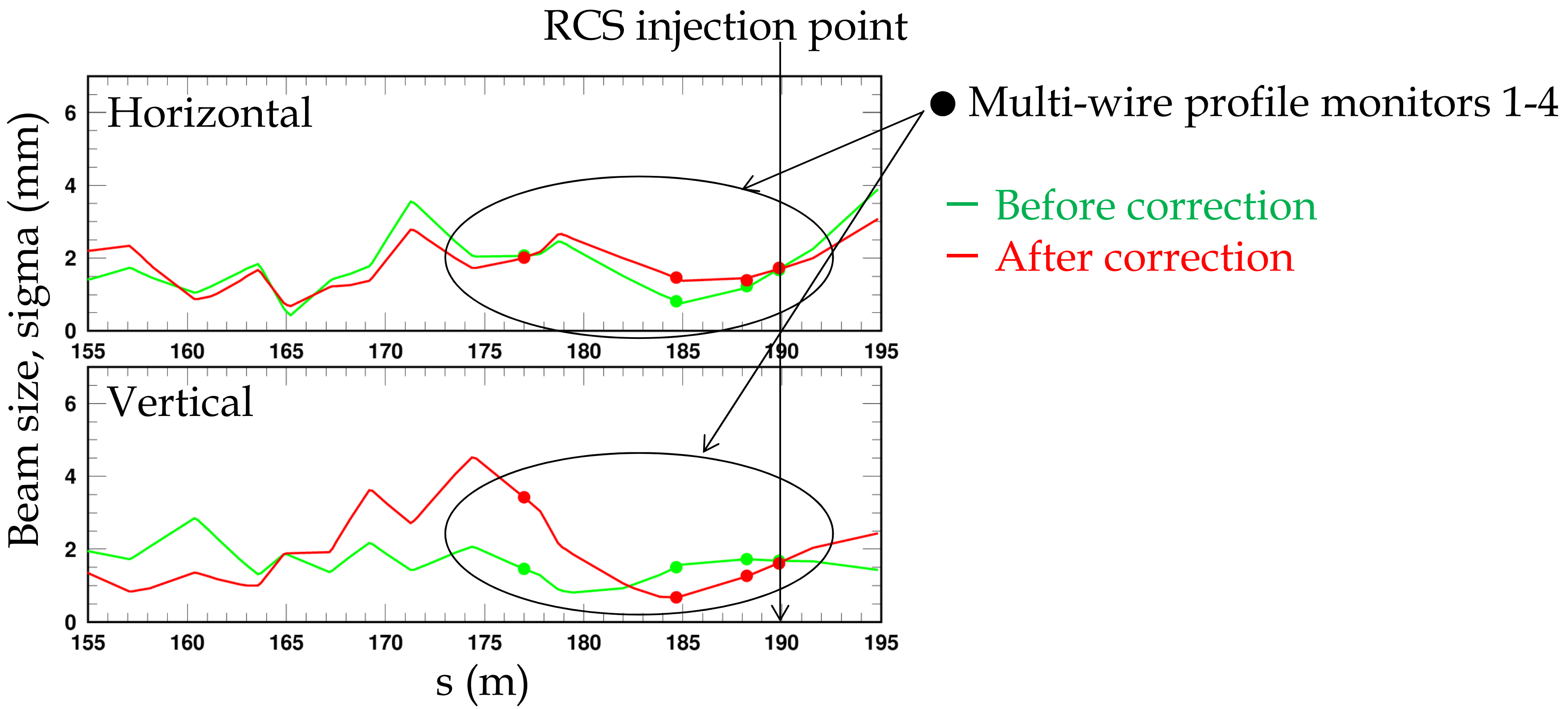
✓ The linac beam had a relatively large beam halo component (~2 times larger beam emittance) and its Twiss parameter had not been adjusted yet at that time.
  ⇒ deviate the painting area.
  ⇒ form a terribly large amplitude particles during the injection painting process.

✓ The numerical simulation confirmed that such a large amplitude particle causes the extra beam loss in combination with space charge for higher intensity beam.

✓ Based on this analysis, we tried to mitigate the extra beam loss observed for the 573-kW intensity beam by adjusting the Twiss parameter of the injection beam.

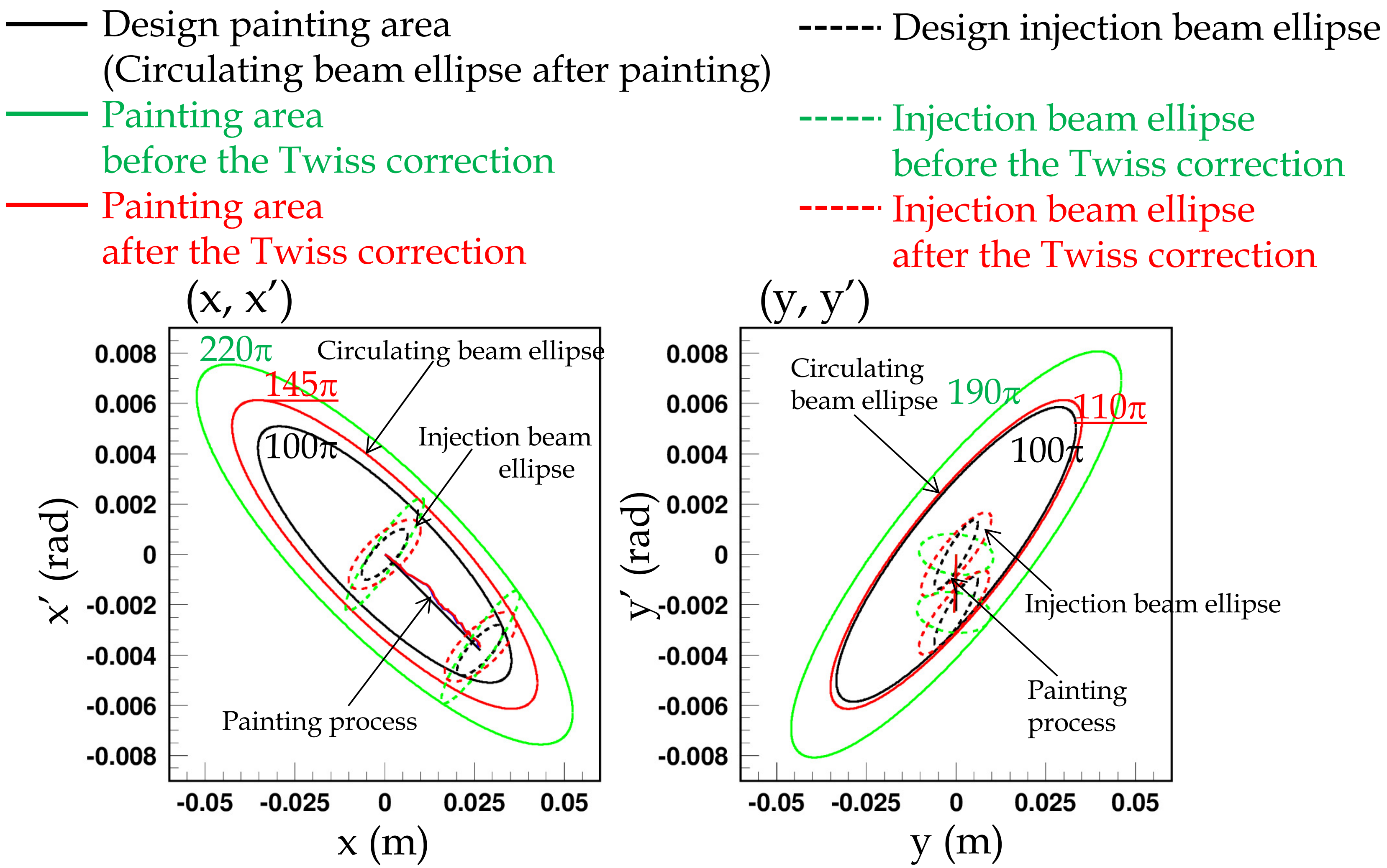
Twiss parameter correction of the injection beam

Beam envelop along the injection beam transport line
reconstructed by the model fitting to the measured injection beam profiles



✓ We estimated the injection beam Twiss parameter at the RCS injection point by the beam envelop analysis and corrected it so that the injection beam ellipse fits the design painting area.

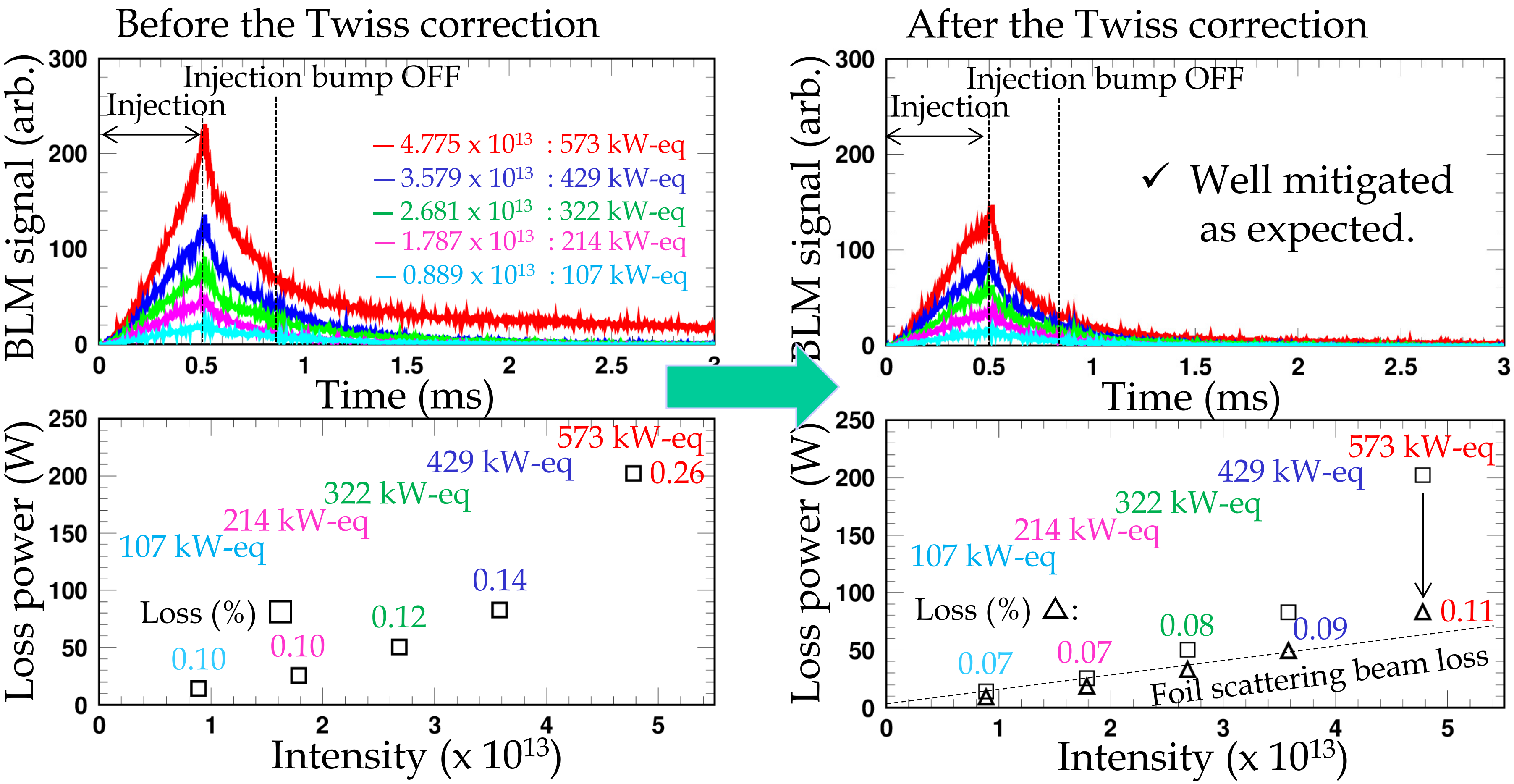
Transverse painting area before and after the Twiss parameter correction of the injection beam



✓ By the Twiss parameter correction of the injection beam (dashed green to dashed red), the transverse painting area was well corrected to the acceptable level (solid green to solid red).

Beam loss mitigation
by the Twiss parameter correction of the injection beam

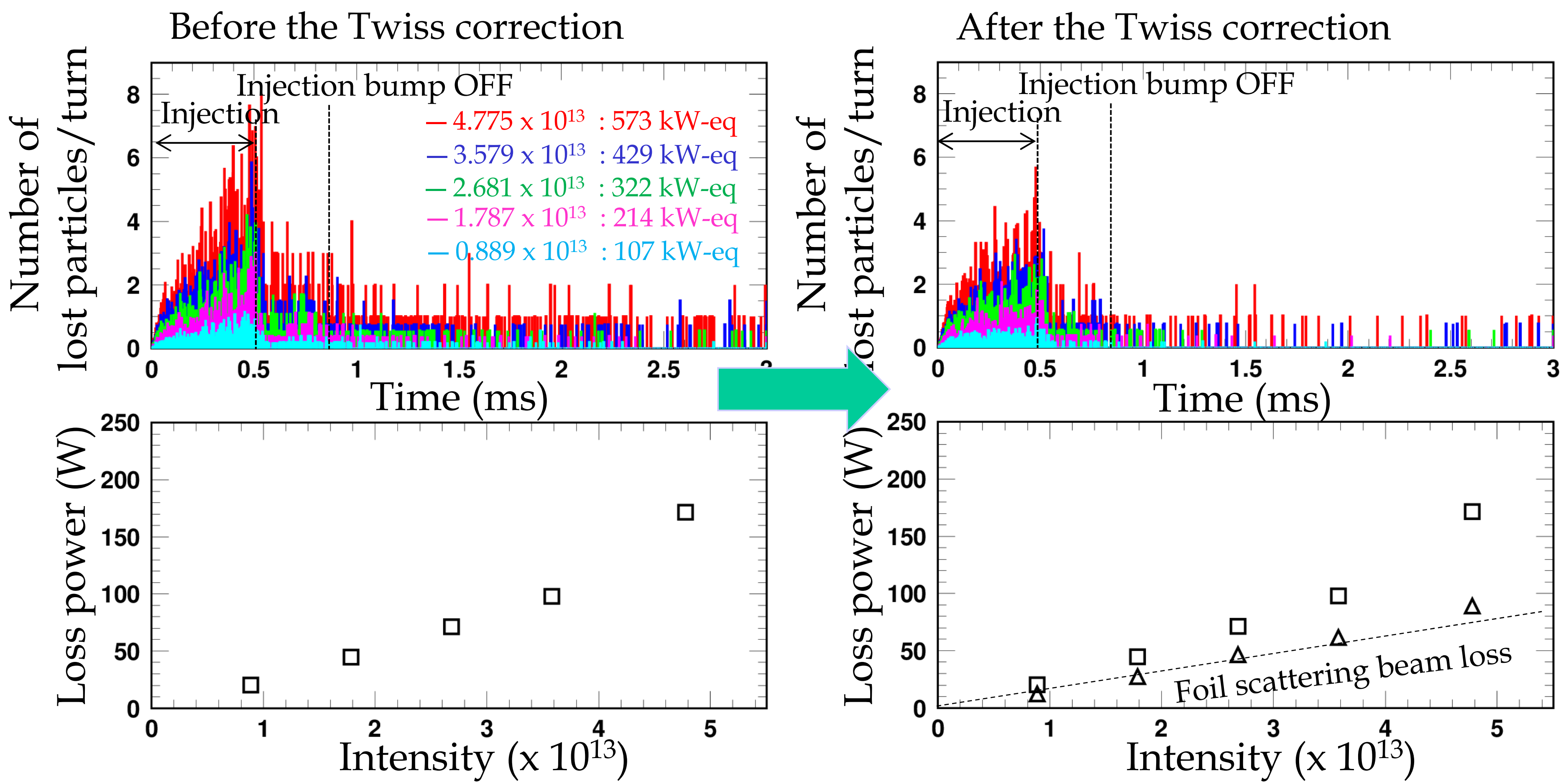
BLM signal @ collimator over the first 3 ms in the low energy region



- ✓ The beam loss appears only for the first 1 ms of the beam injection.
- ✓ The intensity dependence of beam loss amount got to have a linear response.
- ✓ The beam loss of up to 573-kW intensity beam is well minimized, and its remaining beam loss is mainly from foil scattering during injection.

Beam loss mitigation
by Twiss parameter correction of the injection beam

Calculations (by Simpsons)



✓ The numerical simulations well reproduced the observed beam losses.

◆ Outline of the linac and RCS, and their operational history

◆ High intensity beam tests of up to 573 kW performed just after the injection energy upgrade to 400 MeV

- Beam loss mitigation by injection painting (Run#54, Apr., 2014)
- Comparison with the old data taken for the lower injection energy of 181 MeV
- Further beam loss mitigation by adjusting the Twiss parameter of the injection beam (Run#56, June 2014)

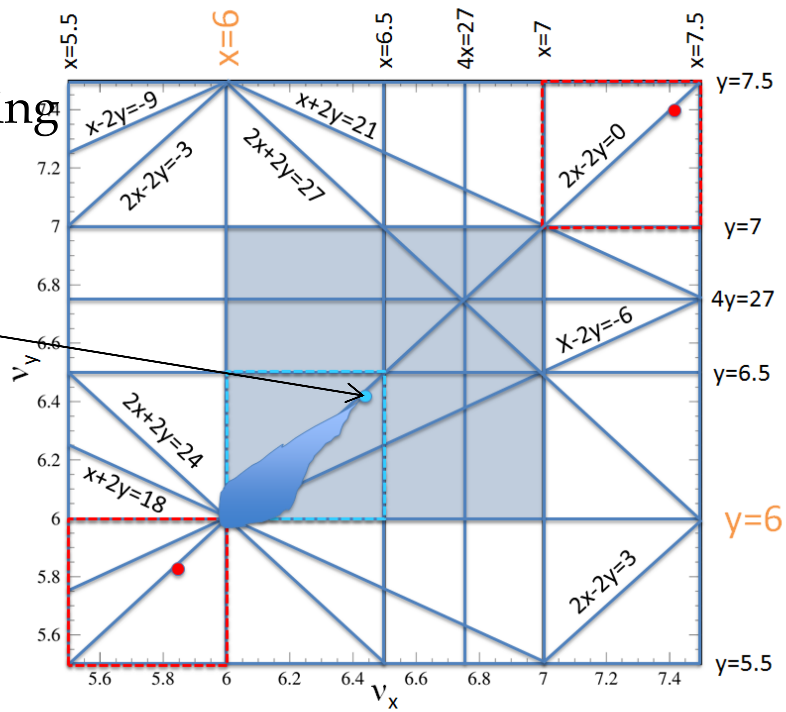
◆ **First 1-MW trial**
(Run#57, Oct., 2014)

◆ Summary & future plan

First 1-MW trial

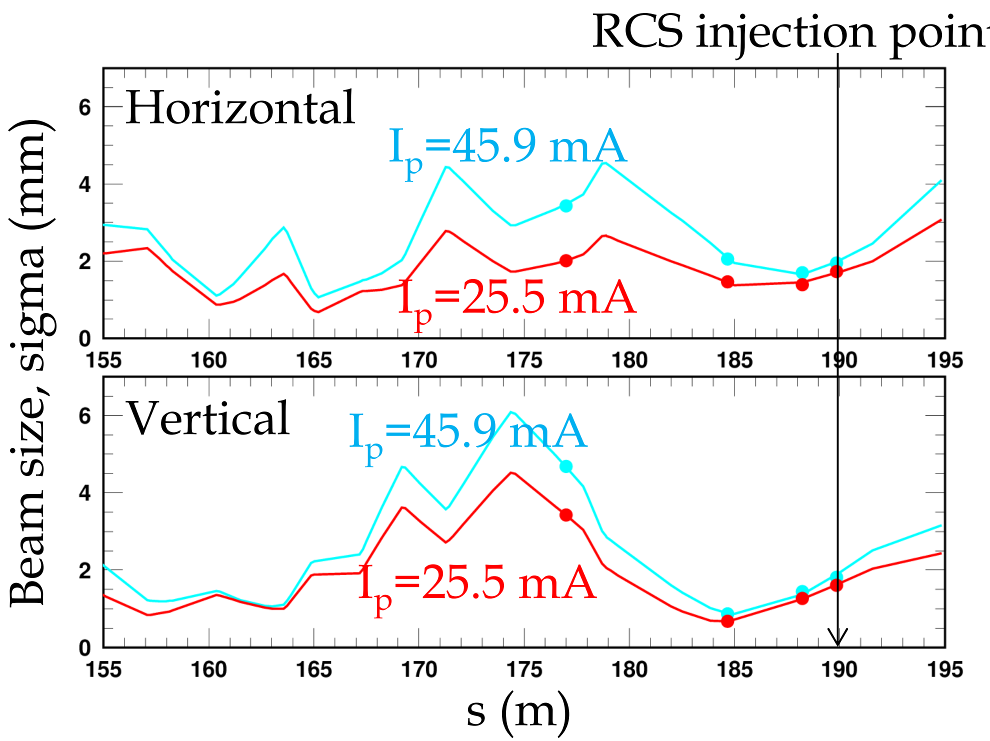
- ✓ High intensity beam tests of up to 573 kW; Apr. & June 2014
- ✓ Beam shutdown to install the new front-end system (IS &RFQ) ; July-Sep., 2014
- ✓ Resumption of the beam tests & tuning ; End of Sep. 2014~

- ✓ First 1-MW trial
  - ◆ Date : Oct. 21-26, 2014 (Run#57)
  - ◆ Injection beam condition
    - Injection energy : 400 MeV
    - Peak current : 45.9 mA @ the entrance of RCS
    - Pulse length : 0.5 ms
    - Chopper beam-on duty factor : 60%
    - ⇒ 8.61 x 10^{13} particles/pulse, corresponding to **1033 kW** at 3 GeV
  - ◆ Operating point; (6.45, 6.42)
  - ◆ Injection painting parameter; ID8 (100π transverse painting + full longitudinal painting)



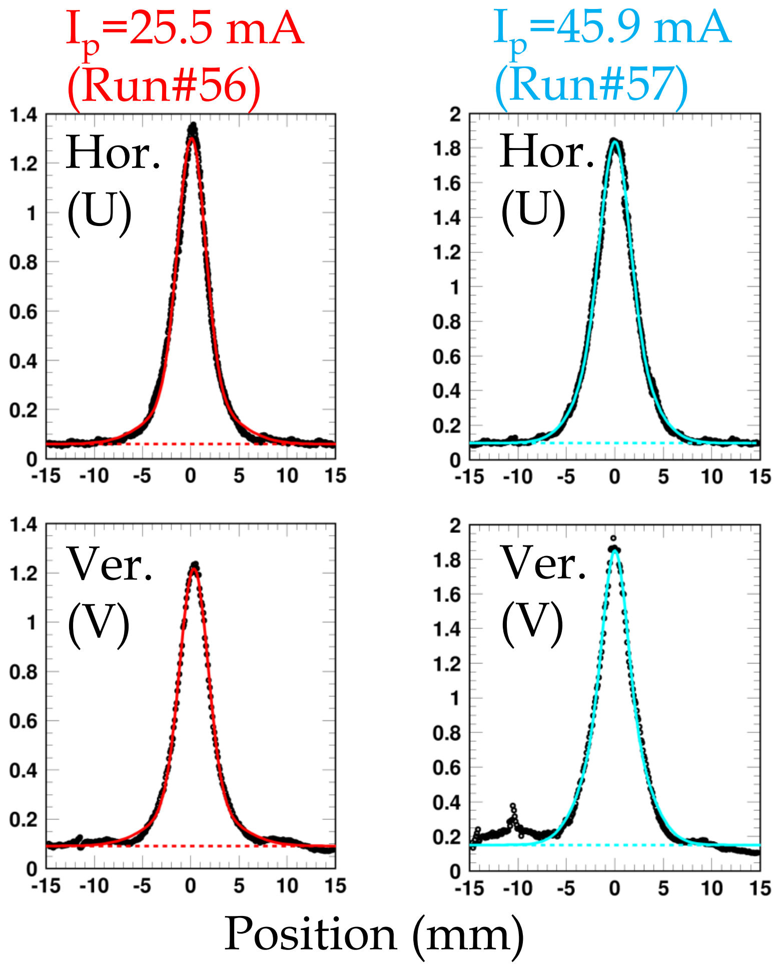
Quality of the injection beam with I_p=46 mA

Beam envelop along the injection beam transport line reconstructed by the model fitting to the measured injection beam profiles



● Multi-wire profile monitors 1-4

Beam profile @ RCS injection point

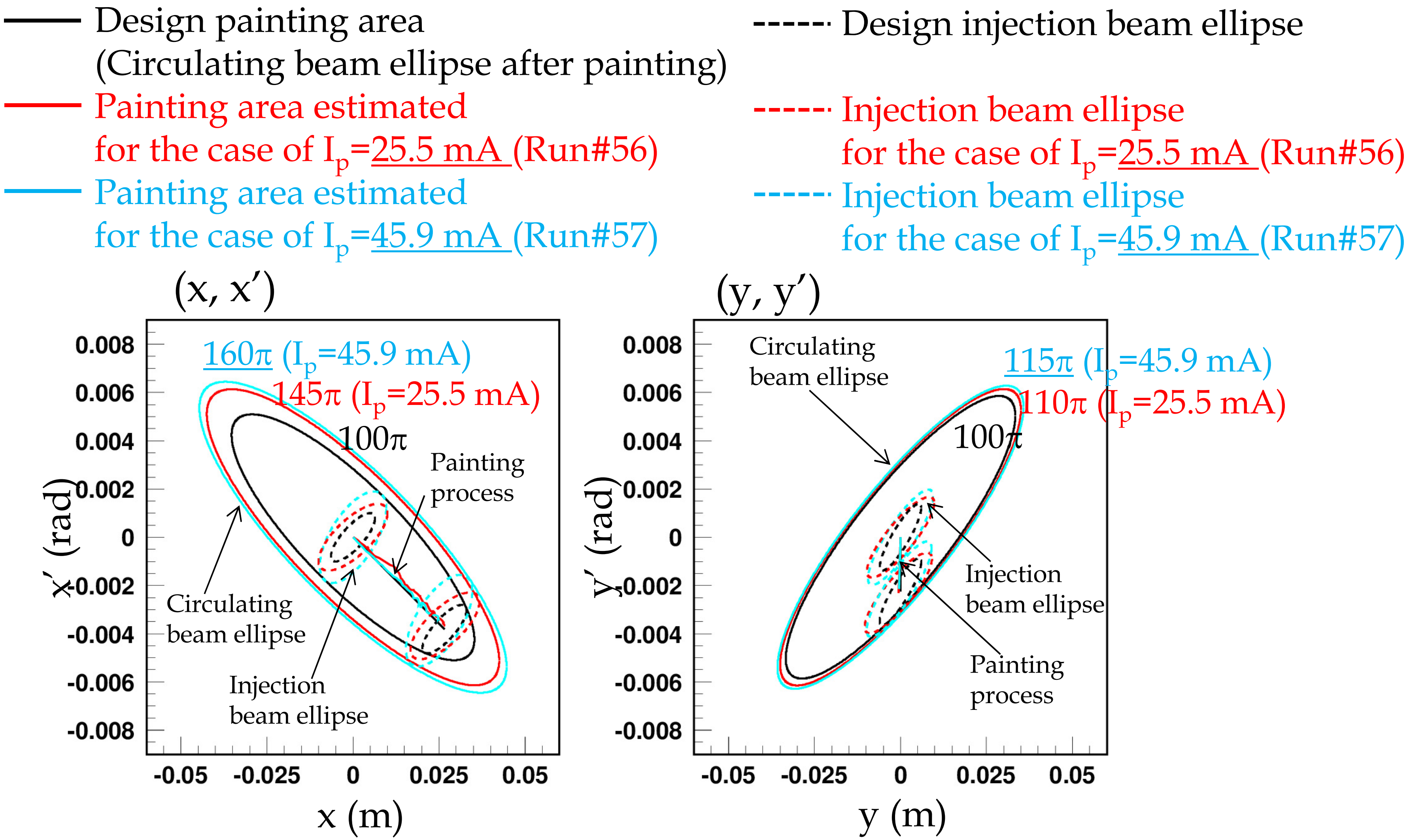


RMS emittance (un-normalized)

I_p=25.5 mA (Run#56) ε_x=0.600π mm mrad, ε_y=0.537π mm mrad

I_p=45.9 mA (Run#57) ε_x=$\underline{0.889}$π mm mrad, ε_y=$\underline{0.587}$π mm mrad

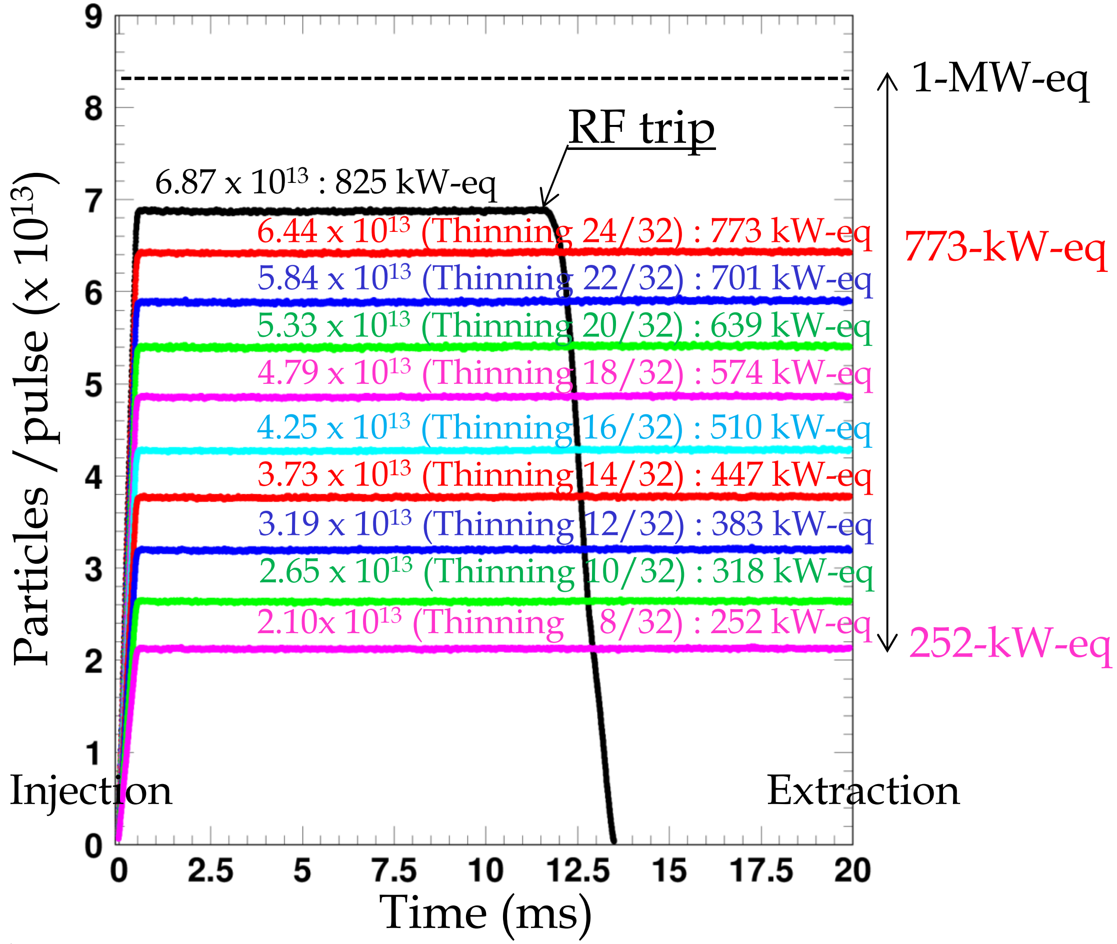
Transverse injection painting area estimated for the 46.0-mA injection beam



✓ We adjusted the Twiss parameter of the injection beam again so that the painting area has a similar value to that in the previous high intensity beam test performed with I_p=25.5 mA (Run#56).

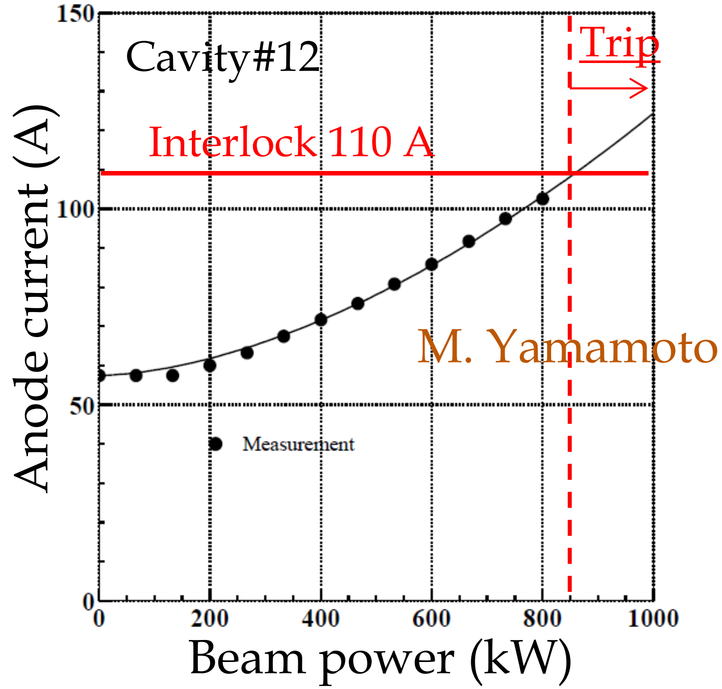
Result of the first 1-MW trial

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



Anode current measured as
a function of the beam power

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

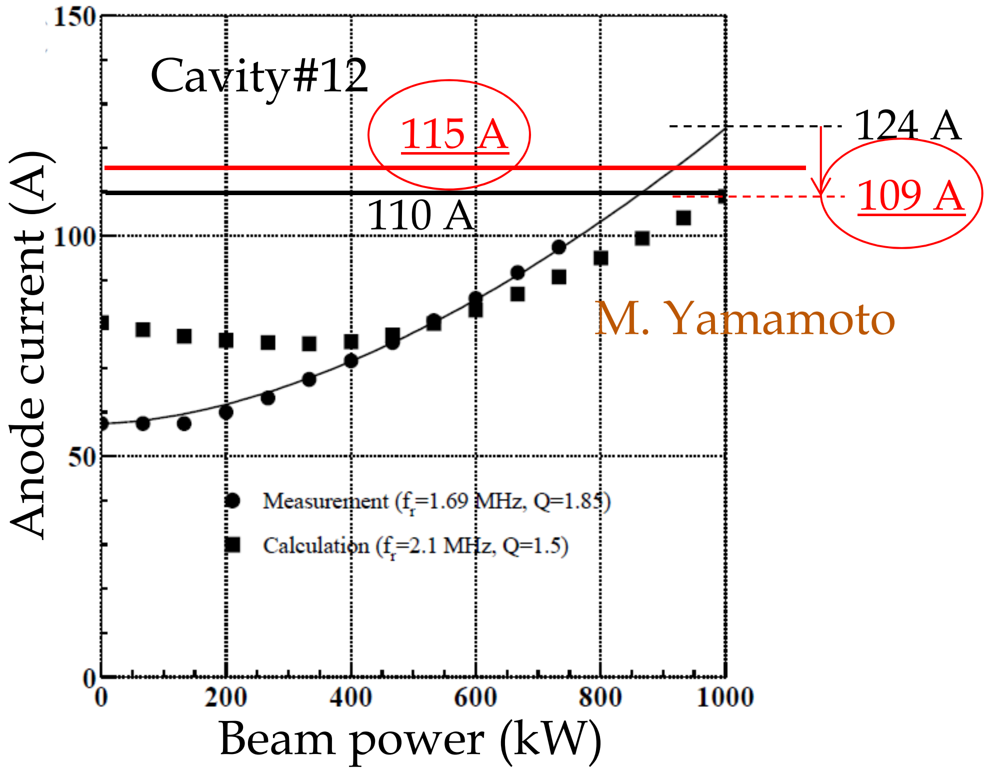


- ✓ The beam intensity was smoothly increased up to 770 kW with no significant beam loss, but when the beam intensity got to over 800 kW, the accelerating RFs suddenly tripped; the anode power supply of the RF system tripped due to the over current.
- ✓ In the present condition, the required anode current surpasses the interlock level when the beam intensity gets to over 800 kW.

Possible measures against the RF trip & plan

Anode current measured as a function of the beam power

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



Load map to 1 MW newly made after the beam test

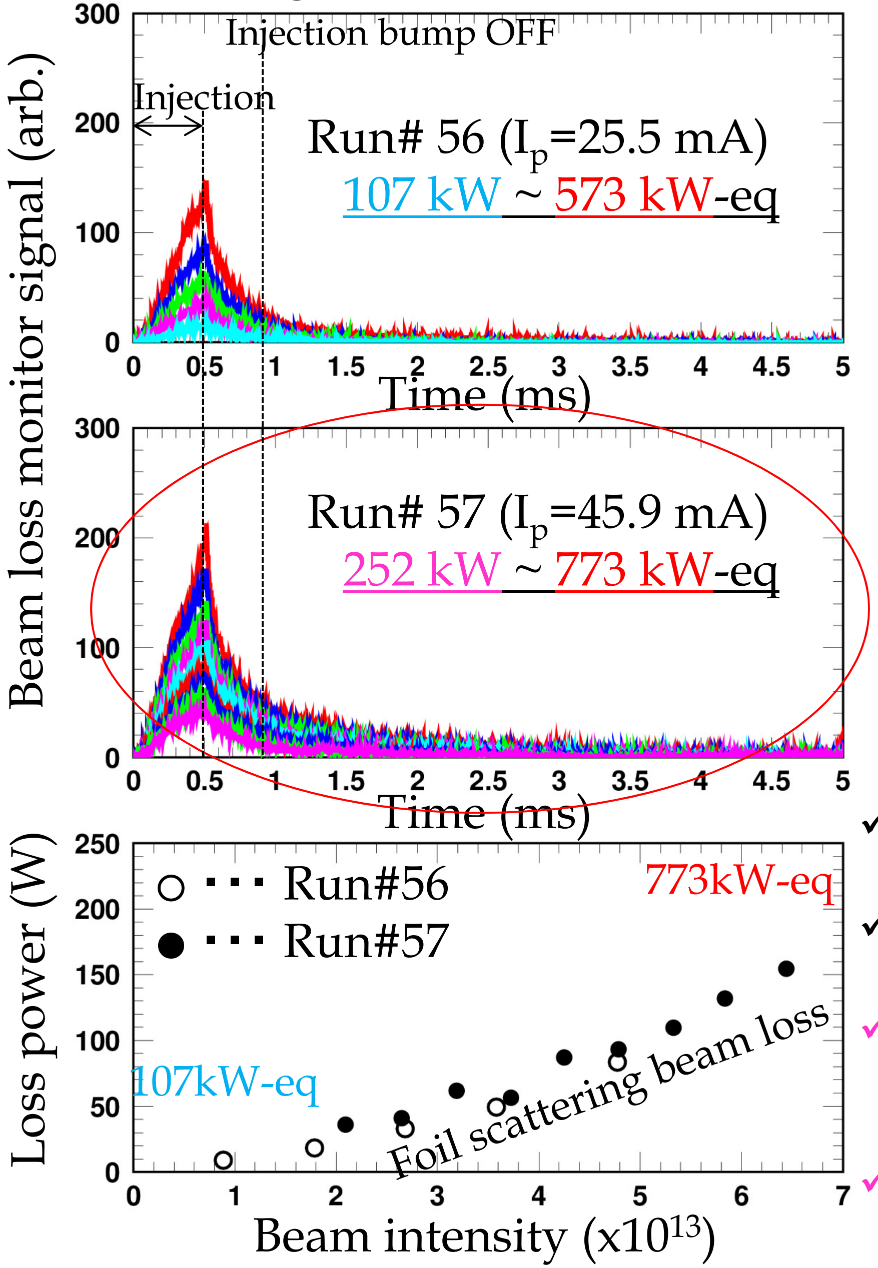
- ✓ Use a remaining margin of the anode power supply; 110 A to 115 A
- ✓ Reduce the required anode current by shifting the resonant frequency of the RF cavity; 124 A to 109 A

By taking these possible measures, the required anode current for the 1-MW beam acceleration will get to be within the limit.

- ✓ Re-try 1-MW beam acceleration in Dec., 2014 & Jan., 2015
- ✓ Increase the anode power supply itself to get sufficient margin using the next summer shutdown period of 2015; 115 A (15 sets of inverter units) ⇒ 138 A (18 sets of inverter units)
- ✓ Start up the 1-MW user operation from Oct. 2015 as originally planned

Intensity dependence of beam loss

BLM signal @ collimator over the first 5 ms in the low energy region



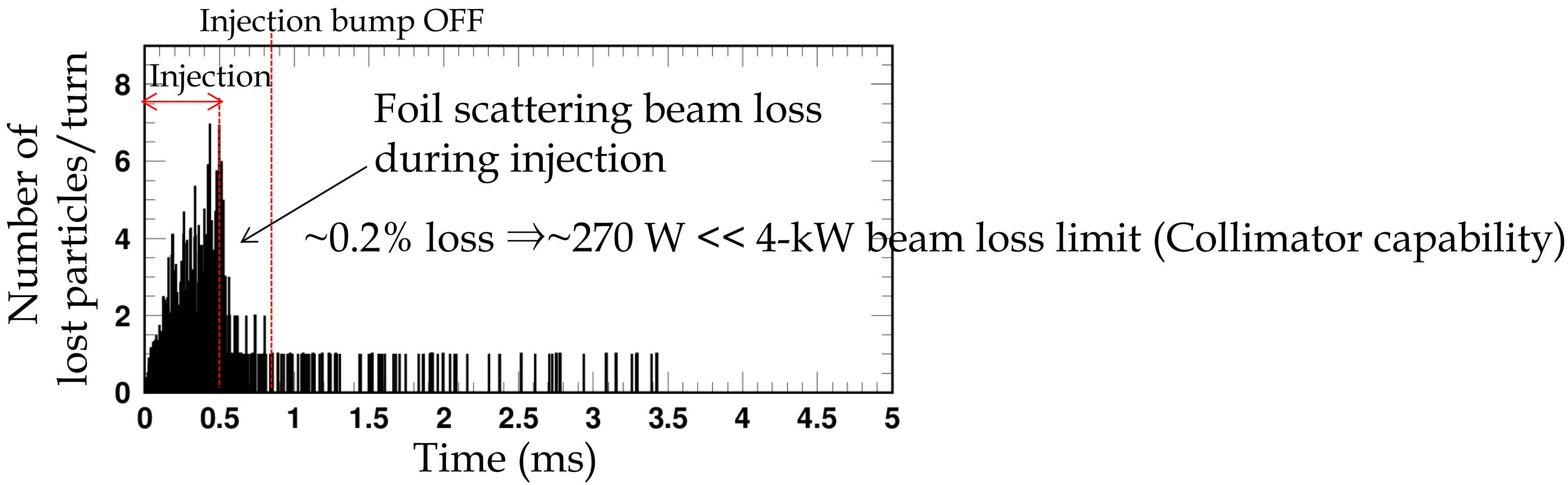
4.78×10^{13} (Thinning 32/32) : 573 kW-eq
3.58×10^{13} (Thinning 24/32) : 429 kW-eq
2.68×10^{13} (Thinning 18/32) : 322 kW-eq
1.79×10^{13} (Thinning 12/32) : 214 kW-eq
0.89×10^{13} (Thinning 6/32) : 107 kW-eq

6.44×10^{13} (Thinning 24/32) : 773 kW-eq
5.84×10^{13} (Thinning 22/32) : 701 kW-eq
5.33×10^{13} (Thinning 20/32) : 639 kW-eq
4.79×10^{13} (Thinning 18/32) : 574 kW-eq
4.25×10^{13} (Thinning 16/32) : 510 kW-eq
3.73×10^{13} (Thinning 14/32) : 447 kW-eq
3.19×10^{13} (Thinning 12/32) : 383 kW-eq
2.65×10^{13} (Thinning 10/32) : 318 kW-eq
2.10×10^{13} (Thinning 8/32) : 252 kW-eq

- ✓ The beam loss appears mainly for the first 1 ms of the beam injection.
- ✓ The beam loss amount almost has a linear response for the beam intensity.
- ✓ The beam loss of up to 773-kW intensity beam is nearly minimized, and its remaining beam loss is mainly from foil scattering during injection.
- ✓ Beam loss estimated for 773 kW intensity beam; <0.2% (160 W << 4-kW collimator limit).

1-MW numerical simulation result (by Simpsons)

Time dependence of beam loss calculated for the 1-MW beam operation



✓ The numerical simulation shows that the 1-MW beam operation can be achieved nearly with the minimum beam loss mainly from foil scattering during injection, if solving the present issue of RF.

✓ We will re-try 1-MW beam acceleration next month after taking several quick measures against the RF trip.

Summary & future plan

◆ By a series of hardware improvements in 2013 and 2014,
the linac and RCS have just got all the design hardware parameters
to try the 1-MW design beam operation.

◆ We performed the first 1-MW trial in Oct., 2014.
- The RCS successfully demonstrated 773-kW high intensity beam acceleration at a low-level intensity loss of less than 0.2% mainly from foil scattering during injection.
- Most of the 0.2%-beam loss was well localized at the collimator section.
- Its beam loss power (~160 W) is still much less than the 4-kW beam loss limit of the RCS (collimator capability).

◆ We faced a lack of the RF power for the 1-MW beam acceleration.
- We will re-try the 1-MW beam acceleration in Dec., 2014 after taking several quick measures for the RF system.
- We are also planning to increase the anode power supply of the RF system to get sufficient margin for the 1-MW beam acceleration using the next summer shutdown period of 2015, aiming to start up the 1-MW user operation in Oct., 2015 as originally planned.

◆ The 1-MW beam acceleration was not reached by one step this time,
but we are nearly approaching it.

Back-up slides

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
- Foil scattering:
  Coulomb & nuclear scattering angle distribution calculated with GEANT

We are improving calculation model step by step following the progression of beam experiment.