Realizing a high-intensity low-emittance beam in the J-PARC 3-GeV RCS

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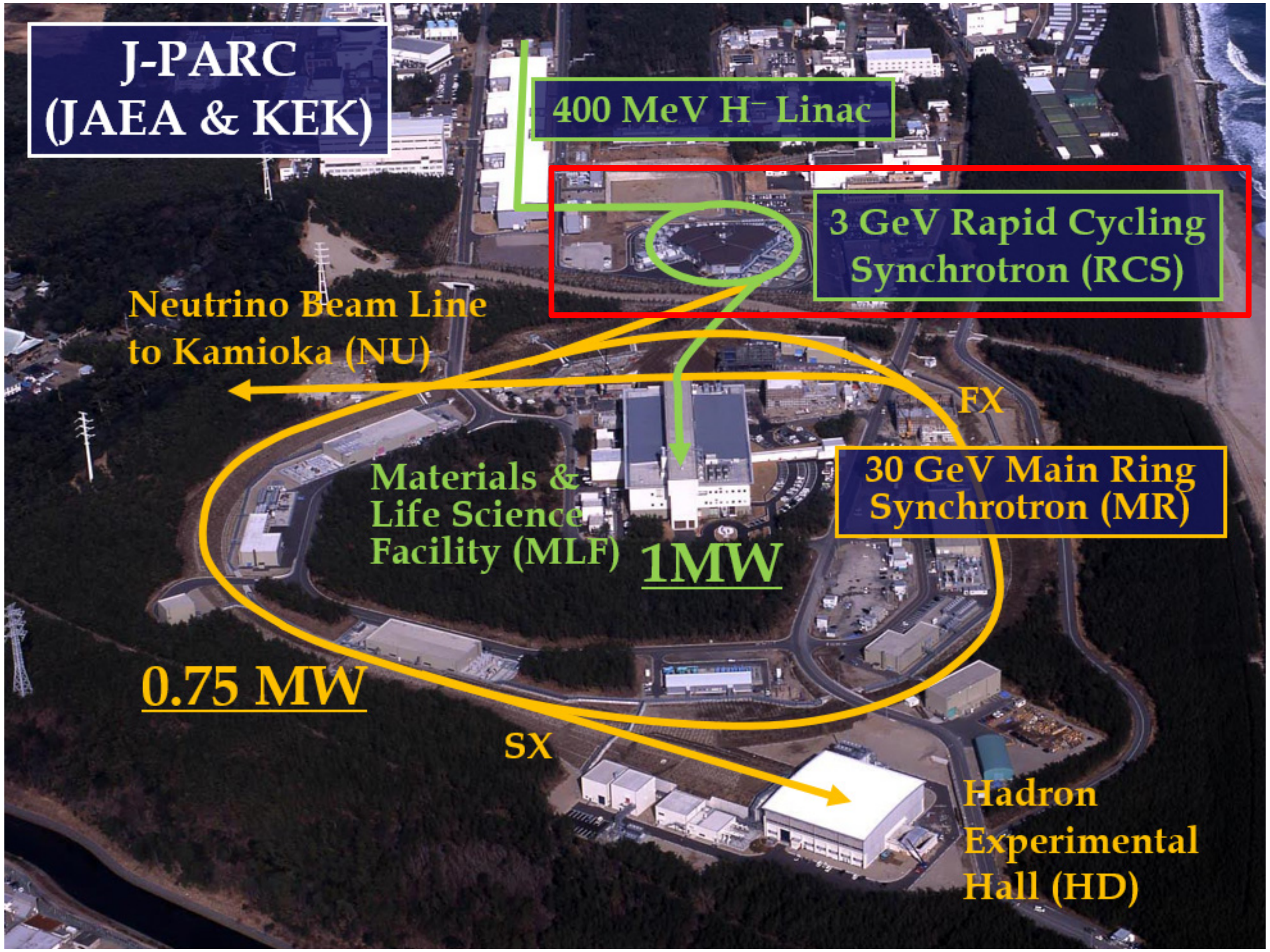
H. Hotchi,
H. Harada, S. Kato, K. Okabe, P.K. Saha, Y. Shobuda,
F. Tamura, N. Tani, Y. Watanabe, & M. Yoshimoto
Accelerator division, J-PARC center, JAEA

Japan Proton Accelerator Research Complex; J-PARC

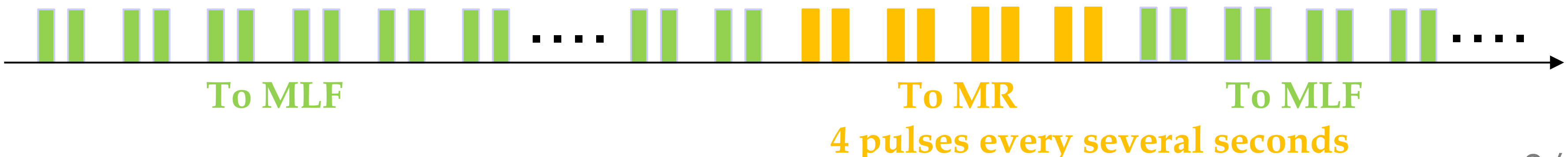


◆ **Linac**
- Particles : H^-
- Energy : 400 MeV
- Repetition : 25 Hz

◆ **RCS**
- Super-periodicity : 3
- Multi-turn charge-exchange injection
- Particles : protons
- Energy : 400 MeV to 3 GeV
- Repetition : 25 Hz

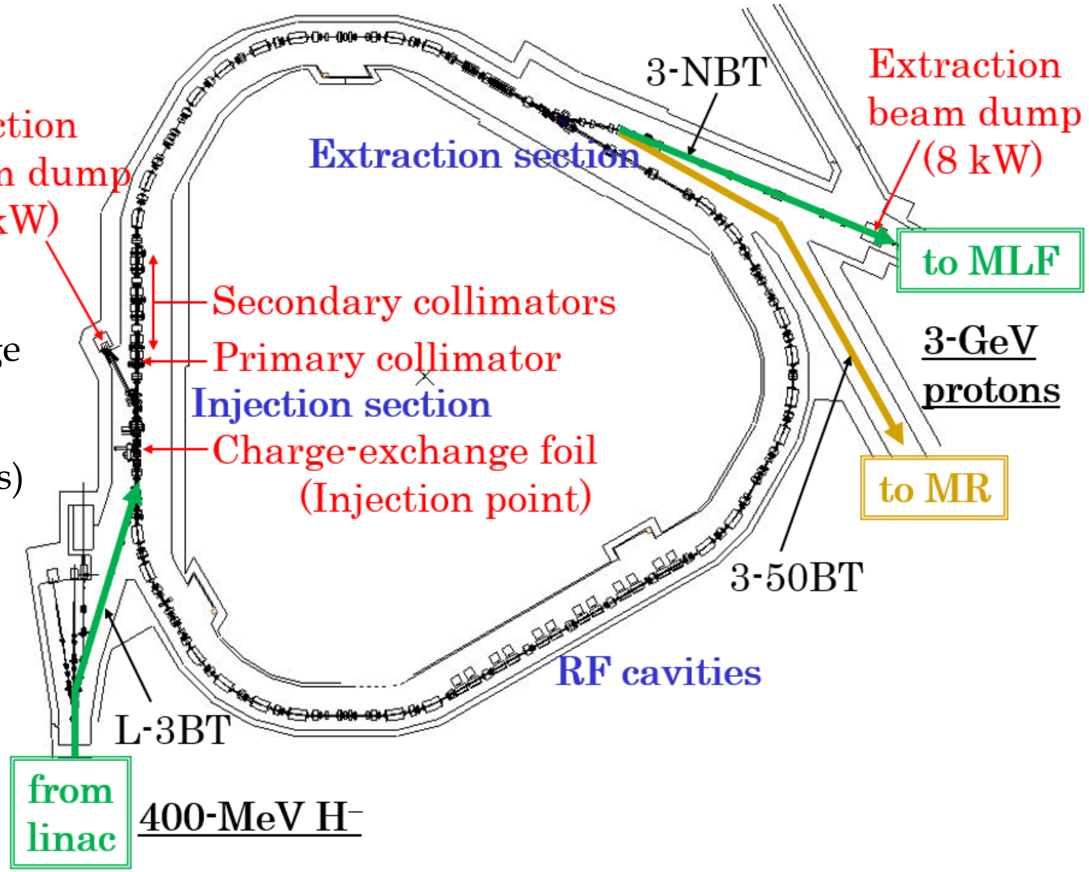
◆ **MR**
- Super-periodicity : 3
- Bucket-to-bucket injection
- Particles : protons
- Energy : 3 to 30 GeV
- Repetition : 0.4 Hz for FX
  0.16 Hz for SX

RCS beam pulses @ 25 Hz



J-PARC 3-GeV Rapid Cycling Synchrotron (RCS)

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
Number of bunches	2
Injection	Multi-turn, Charge-exchange
Injection energy	400 MeV
Injection period	0.5 ms (307 turns)
Injection peak current	50 mA
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	8.33×10^{13}
Beam power	**1 MW**



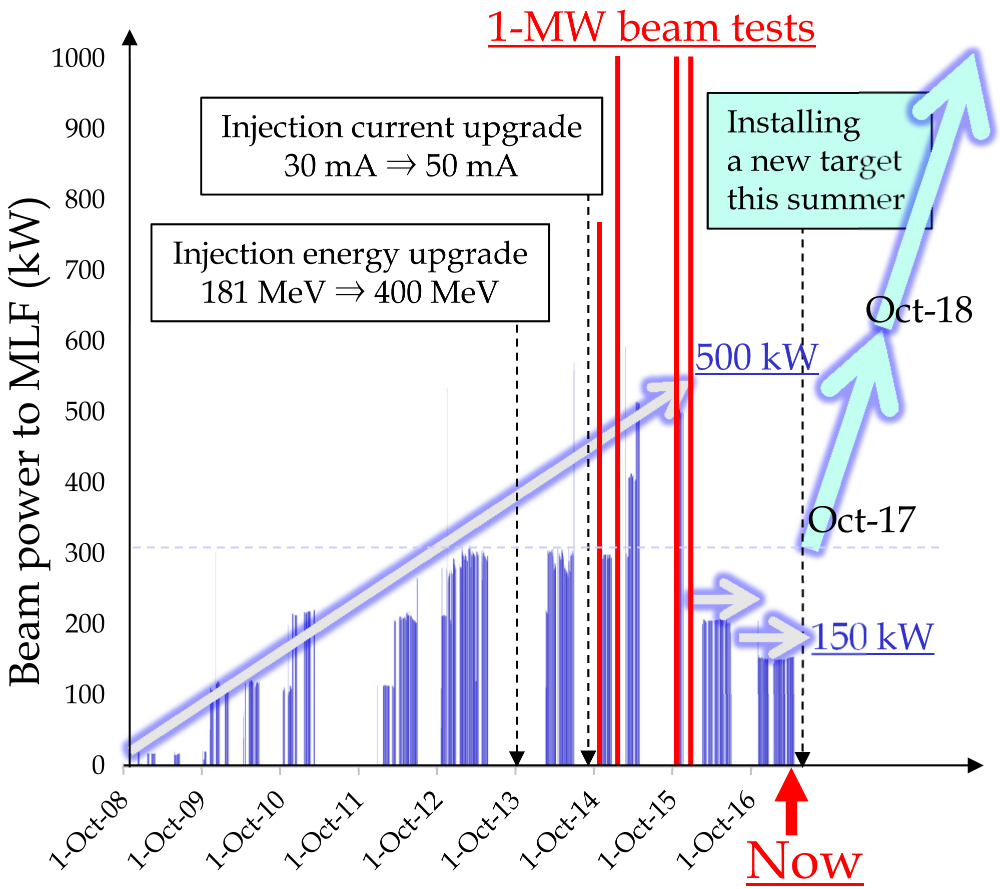
- ✓ RCS has two functions as;
  - Proton driver for producing pulsed muon and neutrons at MLF,
  - Injector to MR.
- ✓ The requirements for the beam operations to MLF and MR are different. Thus, different parameter optimizations are required for each.

Requirements for the beam operation to MLF

- Machine activations of RCS are mainly determined by the beam operation to MLF.
  ⇒ **Sufficient beam loss mitigation**
- To ensure a sufficient life-time of the neutron target at MLF, a shockwave on the neutron target has to be mitigated.
  ⇒ **Wide-emittance beam with less charge density**

Reported in IPAC'16

✓ Successfully demonstrated a 1-MW beam operation to MLF
- Wide-ranging transverse injection painting (ε_{tp}=200π mm mrad)
- Betatron resonance correction
- RF power supply upgrade



✓ The output beam power for MLF;
- is now temporally limited to 150 kW due to a malfunction of the neutron target.
- will be increased gradually toward 1 MW after installing a new target this summer.

✓ The accelerator itself is now ready to test a continuous 1-MW beam operation to MLF.

Requirements for the beam operation to MR

- **Beam loss mitigation in MR**
  - **⇒ A low-emittance beam with less beam halo**

Beam tuning for the beam operation to MR;

✓ Optimizations of;

- transverse injection painting
  for minimizing emittance growth during injection
- tune & chromaticity manipulations over the acceleration process
  for mitigating additional emittance growth during acceleration

▪ Beam intensity; ~7.0 x 10^{13} ppp (~84% of the RCS design intensity)
corresponds to the MR beam power
of ~535 kW for a operation cycle of 2.48 s

Main topic of this talk;

- Recent efforts for realizing a high-intensity low-emittance beam required from MR
- Discussions for the emittance growth and its mitigation mechanisms

Optimization of transverse injection painting

for minimizing emittance growth during injection

Transverse injection painting

- Horizontal painting by a horizontal closed orbit variation during injection

  The injection beam is filled

  - (a) from the middle to the outside

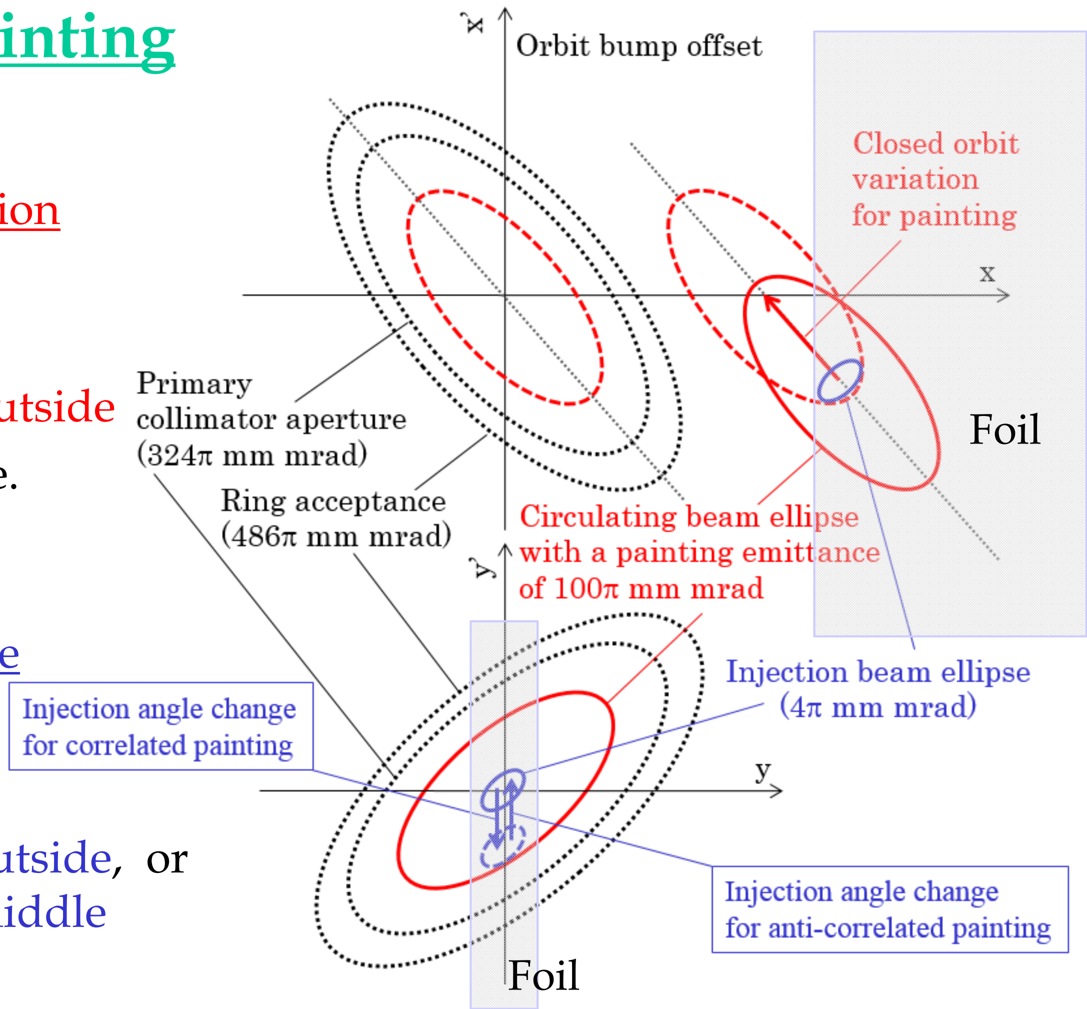
  on the horizontal phase space.

- Vertical painting by a vertical injection angle change during injection

  The injection beam is filled

  - (b) from the middle to the outside, or
  - (c) from the outside to the middle

  on the vertical phase space.



(a)+(b) ⇒ Correlated painting

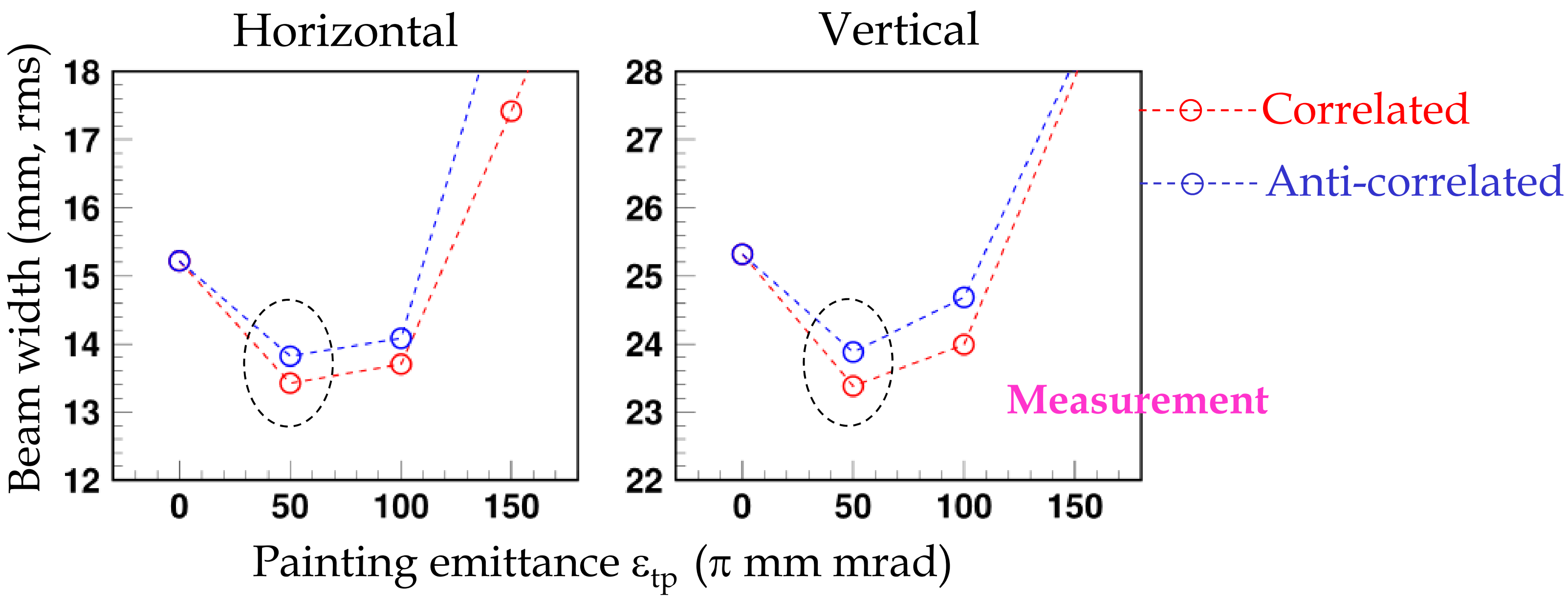
(a)+(c) ⇒ Anti-correlated painting

Painting emittance; ε_{tp}= 0 ~ 216 π mm mrad

✓ To minimize emittance growth during injection, we optimized transverse injection painting.

Painting parameter dependence of the beam width

- **RMS beam widths at the end of injection measured as a function of the painting emittance**



✓ The minimum beam width is achieved for a small painting emittance of ε_{tp}~50π mm mrad.

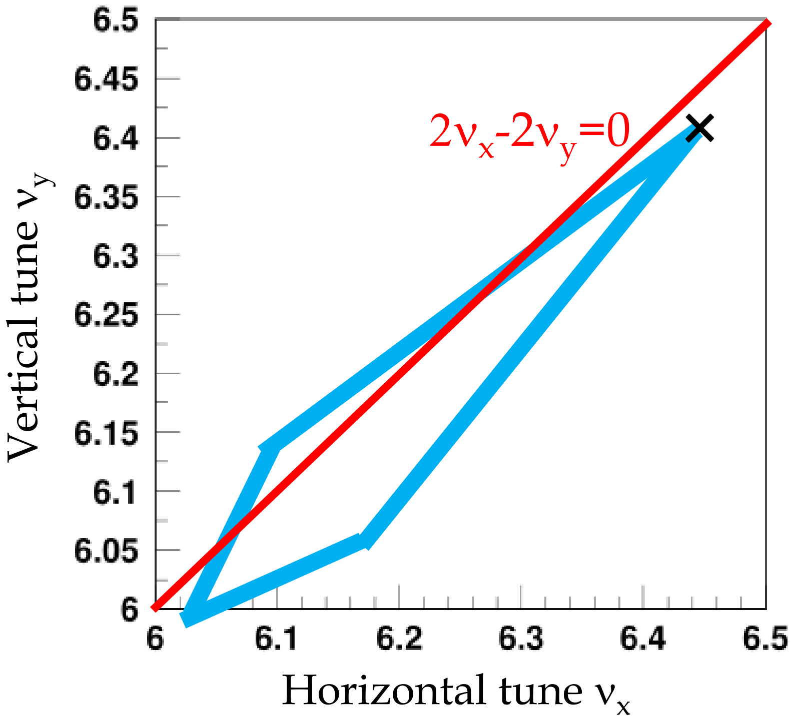
. . . This dependence is ascribed to the balance of painting emittance and its resultant space charge mitigation.

✓ Correlated painting provides narrower beam width.

. . . This situation can be understood by considering the effect of $2\nu_x - 2\nu_y = 0$.

Effects of the $2\nu_x - 2\nu_y = 0$ resonance

- **Tune diagram near the operating point**



✓ The $2\nu_x - 2\nu_y = 0$ resonance is;

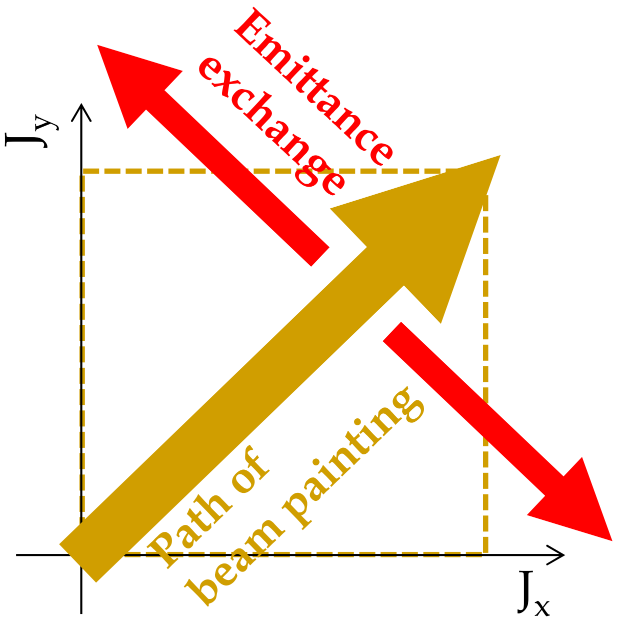
- a 4th order systematic resonance,
- excited mainly by the octupole component in the space-charge field,
- causes emittance exchange between the horizontal and the vertical planes.

✓ The emittance exchange leads to two major effects (I) and (II) during the beam painting process.

Effects of the $2\nu_x - 2\nu_y = 0$ resonance (I)

- ✓ Additional emittance growth caused by the direct effect of emittance exchange
- ✓ More enhanced in correlated painting

Correlated painting

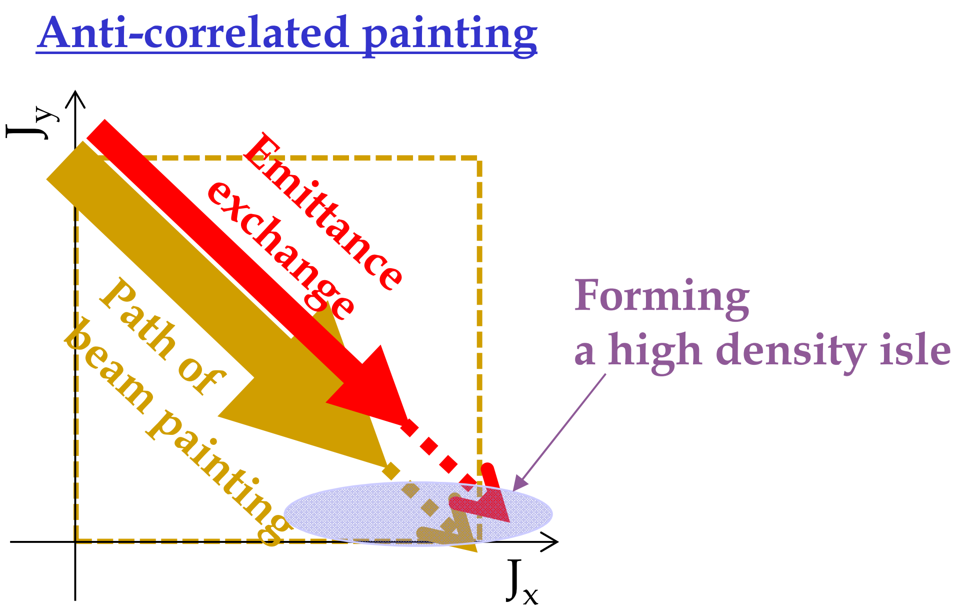


- ✓ The emittance exchange occurs in the orthogonal direction to the direction of beam painting.

  ⇒ The emittance exchange is directly connected to emittance growth over the painting area.

Effects of the $2\nu_x - 2\nu_y = 0$ resonance (II)

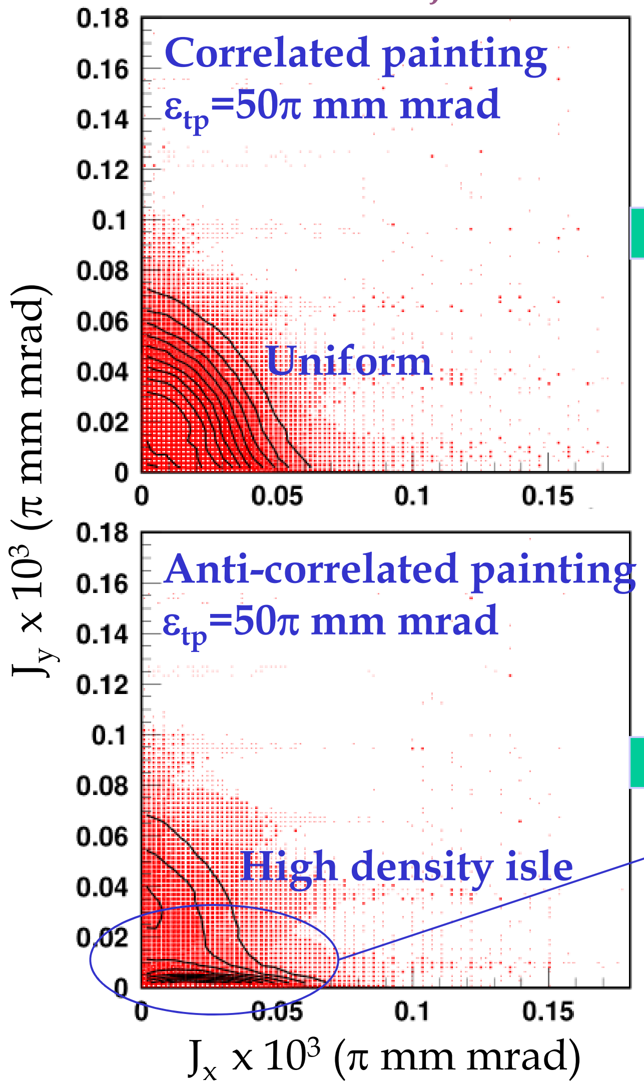
- ✓ Additional emittance growth caused by the secondary effect of emittance exchange namely, by a modulation of the charge density.
- ✓ More enhanced in anti-correlated painting.



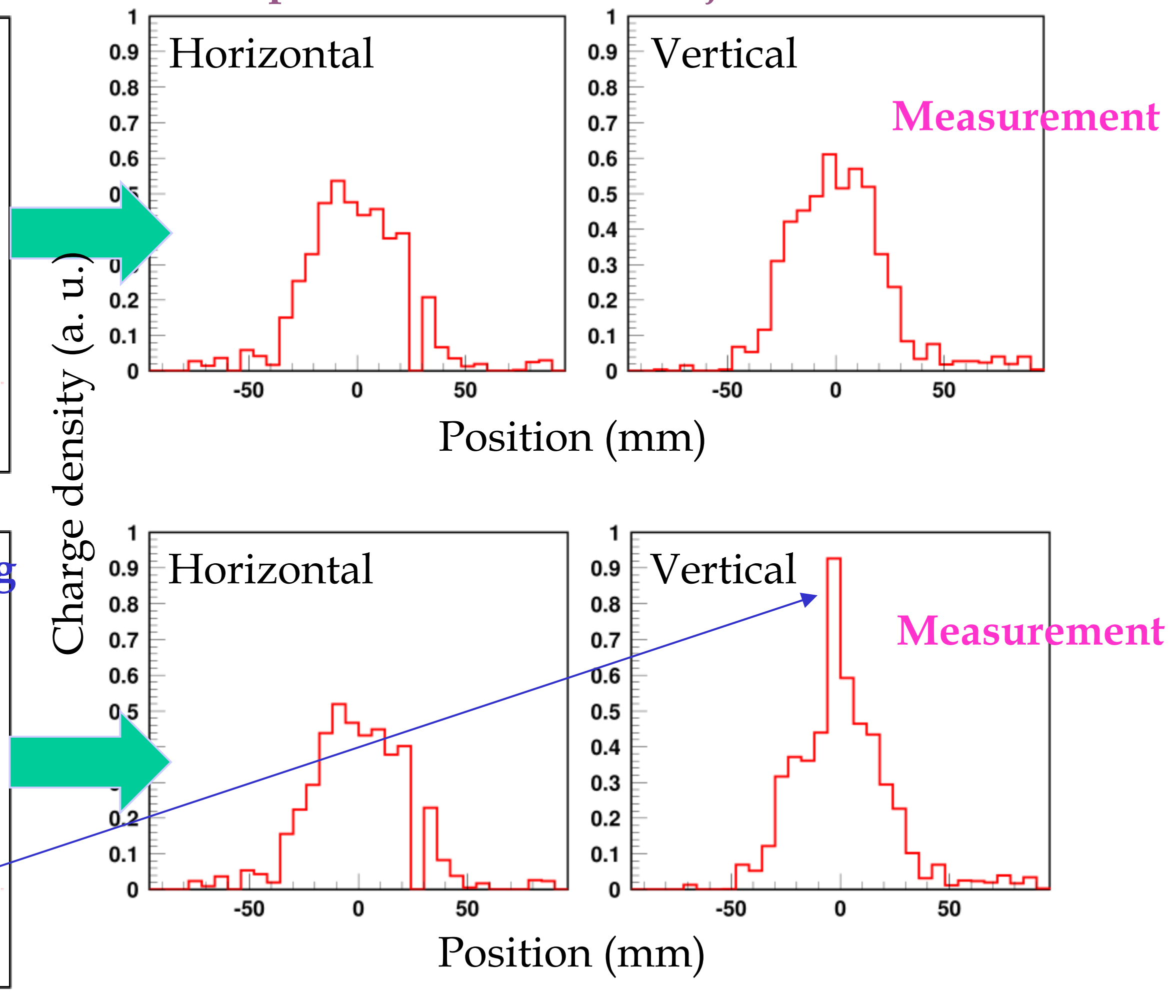
- ✓ The direction of beam painting is the same as the direction of emittance exchange.
  ⇒ Additional emittance growth caused by the direct effect of the emittance exchange is well suppressed.
- ✓ But, this situation causes a significant modulation of the charge density by synchronism between beam painting and emittance exchange.

Beam profile measurement

- 2d plot of (J_x, J_y) calculated at the end of injection



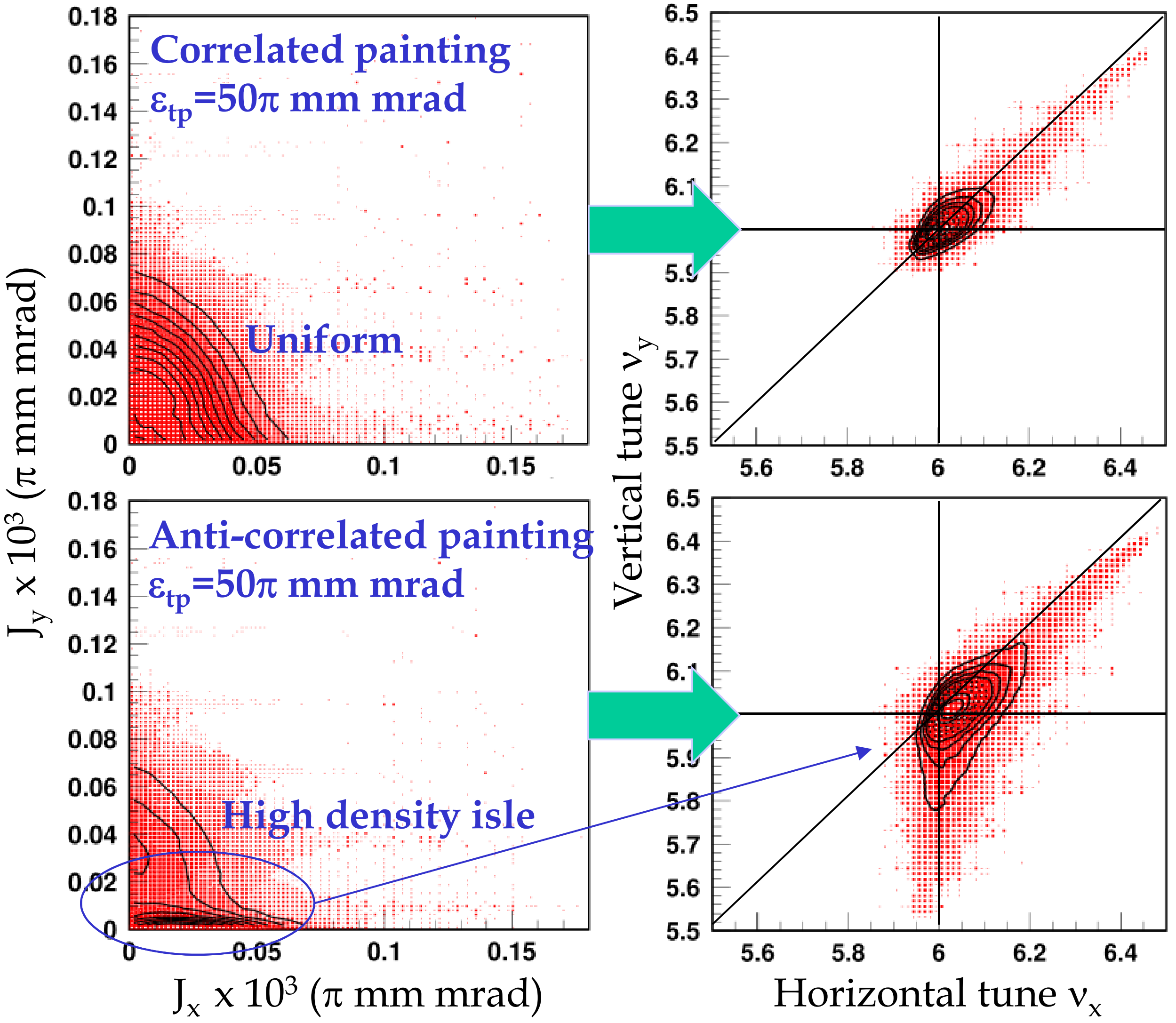
- Beam profile at the end of injection



✓ A high-density peak structure was observed for anti-correlated painting as predicted by the numerical simulation.

Space-charge de-tuning

- 2d plot of (J_x, J_y) calculated at the end of injection
- Tune footprint calculated at the end of injection



✓ The high density isle produces large space-charge detuning, leading to significant emittance growth afterwards.

Correlated painting vs. anti-correlated painting

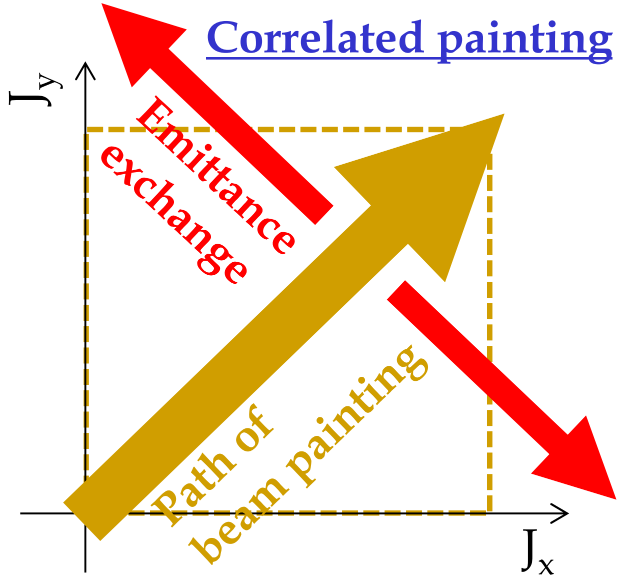
✓ The **emittance exchange caused by $2\nu_x$-$2\nu_y$=0** leads to two major effects during the beam painting process.

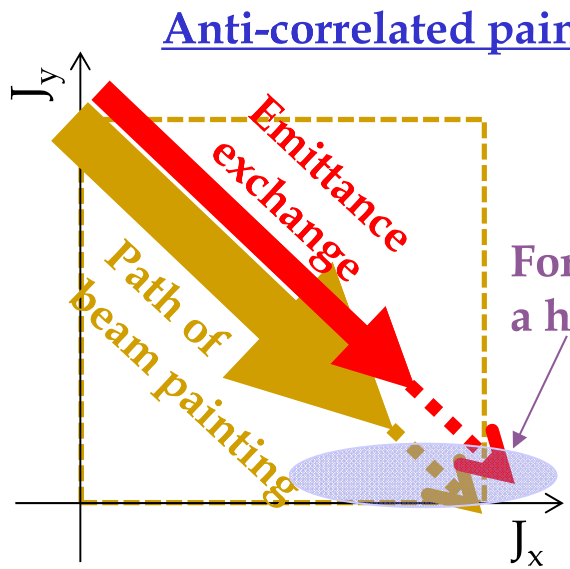
◆ **Effect (I);**

- Additional emittance growth caused by the direct effect of emittance exchange
- More enhanced in correlated paining

◆ **Effect (II);**

- Additional emittance growth caused by the secondary effect of emittance exchange, namely, by a modulation of the charge density
- More enhanced in anti-correlated painting





✓ In the present operational condition, the emittance growth caused by (II) is more critical.

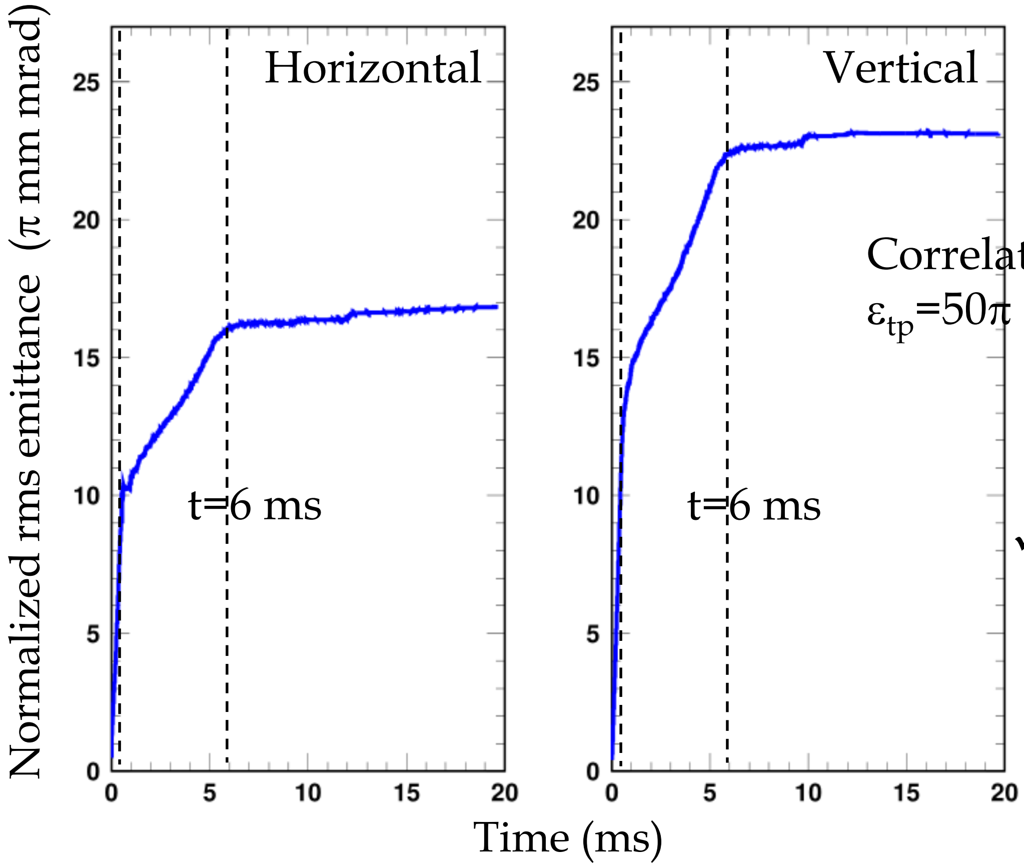
✓ Correlated painting avoids the effect. This is the main reason why narrower beam emittance is achieved for correlated painting.

Optimization of the tune and the chromaticity manipulations over the acceleration process

for mitigating additional emittance growth during acceleration

Emittance growth after injection

- **Time dependence of the beam emittance calculated over 20 ms**

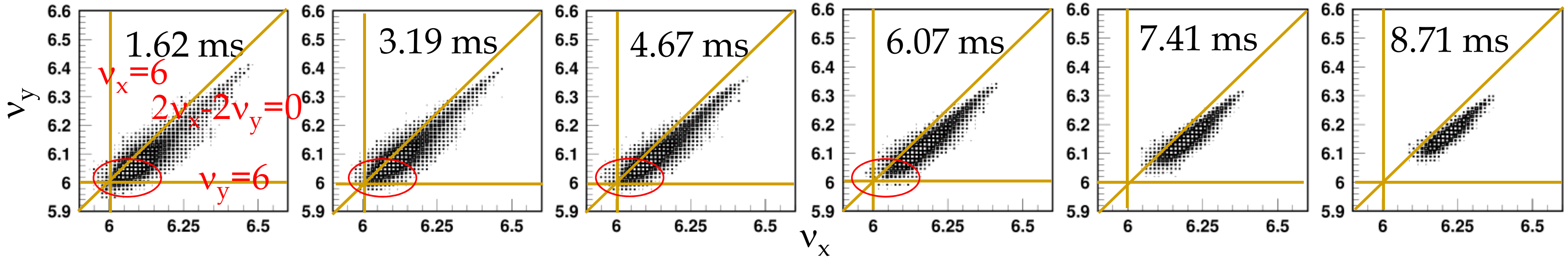


Correlated painting
$\varepsilon_{tp}=50\pi$ mm mrad

✓ Significant additional emittance growth occurs for the first 6 ms after injection.

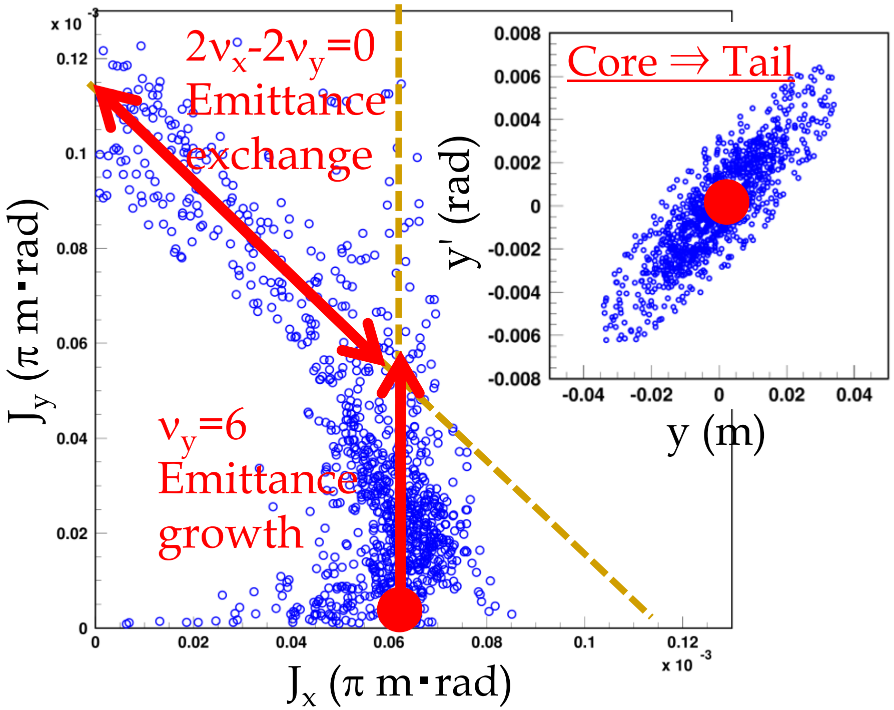
Mechanism of the emittance growth

- **Time dependence of the tune footprint calculated at the first 1.6 ms to 8.7 ms**



✓ Main cause of the emittance growth ; $\nu_{x,y}$=6 & $2\nu_x$-$2\nu_y$=0

- **2d plot of turn-by-turn (J_x, J_y) of one macro-particle causing a large emittance growth on the vertical plane**



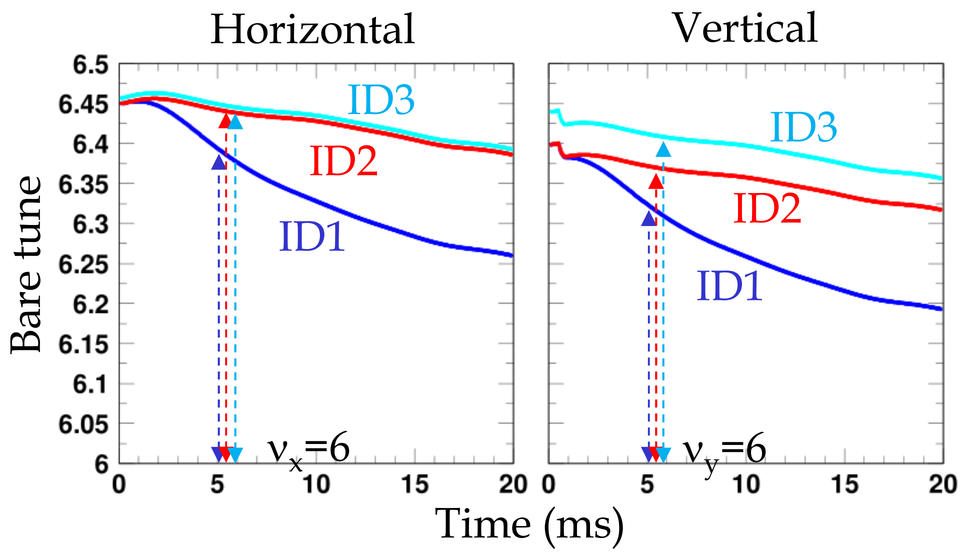
✓ Similar emittance growth is generated also on the horizontal plane by ν_x=6 & $2\nu_x$-$2\nu_y$=0.

✓ Receiving the numerical simulation result, we tried to mitigate a part of emittance growth arising from $\nu_{x,y}$=6;

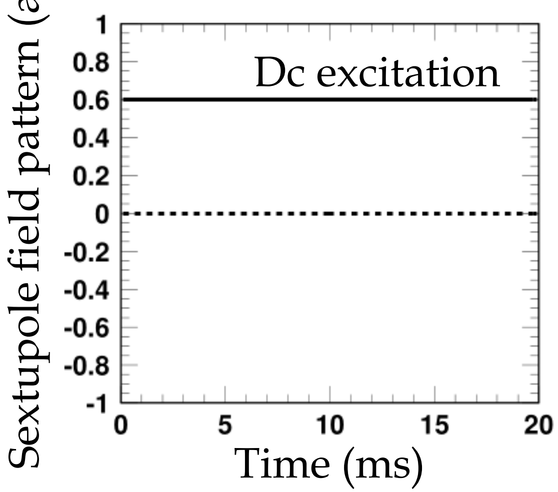
- The tune & chromaticity were manipulated so as to separate the beam from $\nu_{x,y}$=6.

Operational parameters tested for emittance mitigation

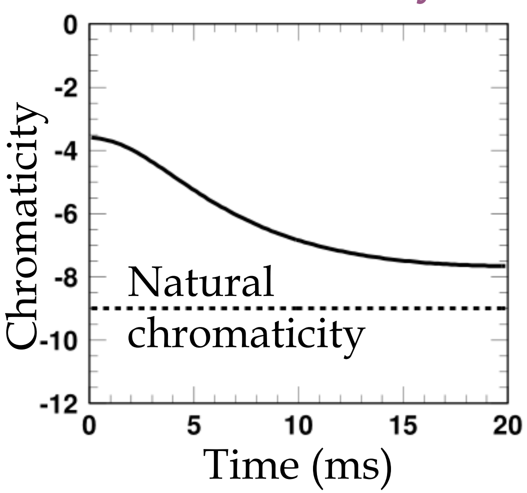
- **Tune variation from injection to extraction**



- **Sextupole field pattern**



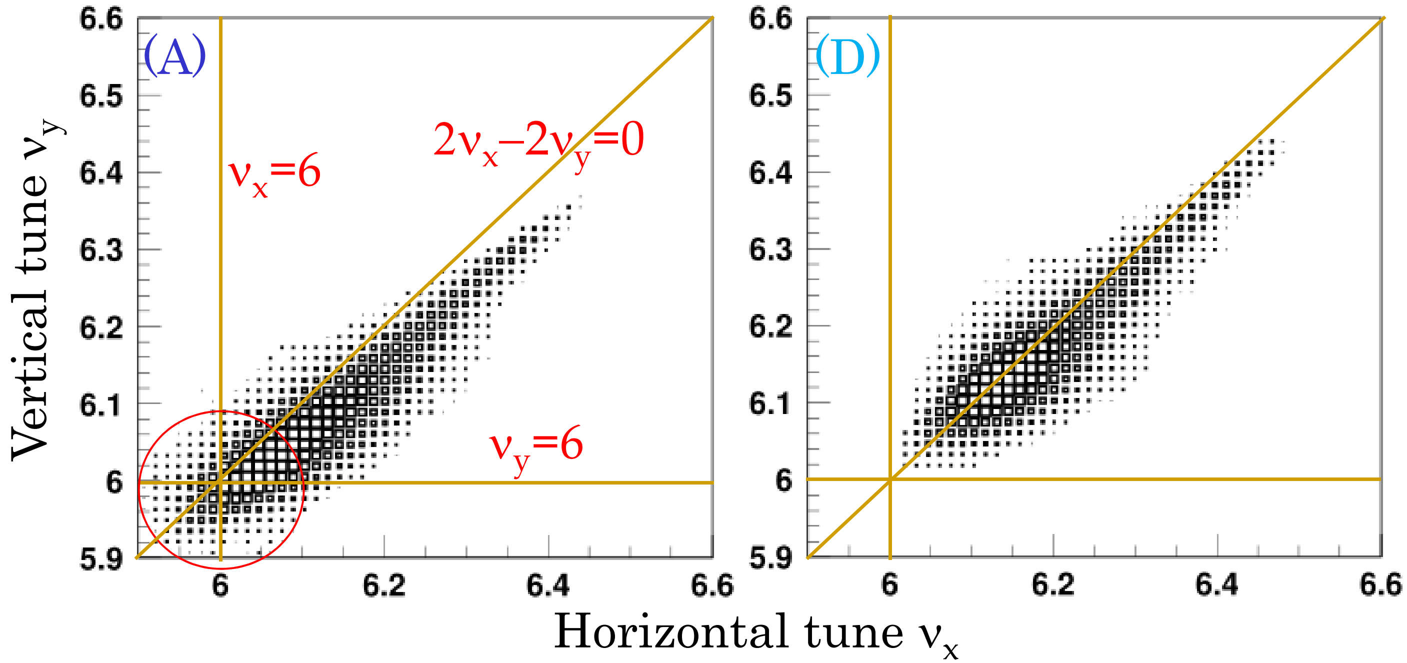
- **Chromaticity**



IDs	Bare tune	Chromaticity correction
A	ID1	OFF
··· original parameter		
B	ID2	OFF
··· separates the beam from $\nu_{x,y}$=6		
C	ID2	ON with dc sextupoles
··· further separates the beam from $\nu_{x,y}$=6 through a shrinkage of the tune spread		
D	ID3	ON with dc sextupoles
··· further separates the beam from ν_y=6		

Situation of the resonance cross to $\nu_{x,\,y}=6$

- **Tune footprint at 4.67 ms**



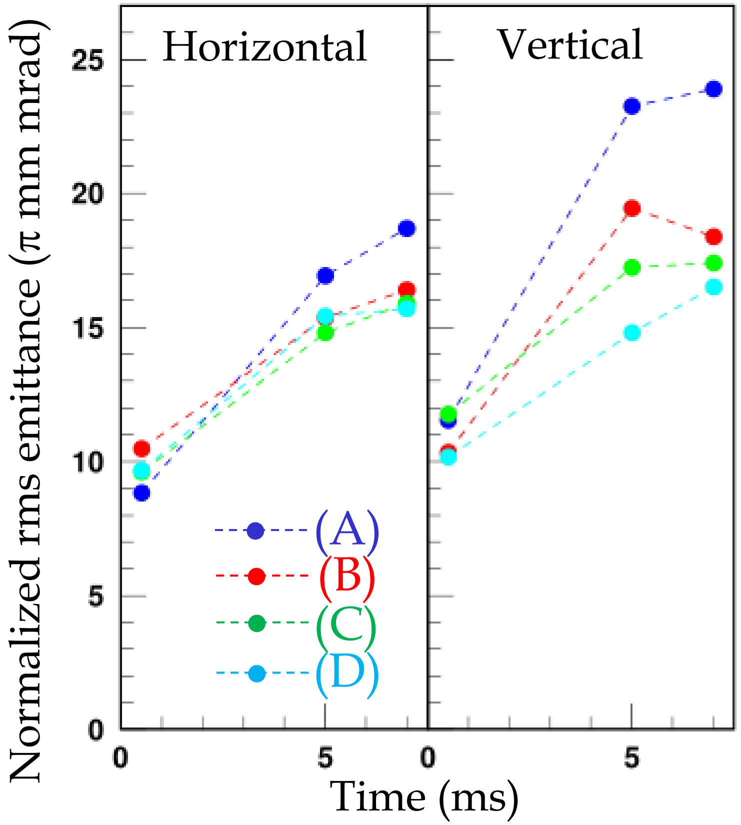
✓ The separation from the integer lines is improved in the order (A)⇒(B)⇒(C)⇒(D).

✓ The emittance growth should be mitigated step by step in this order.

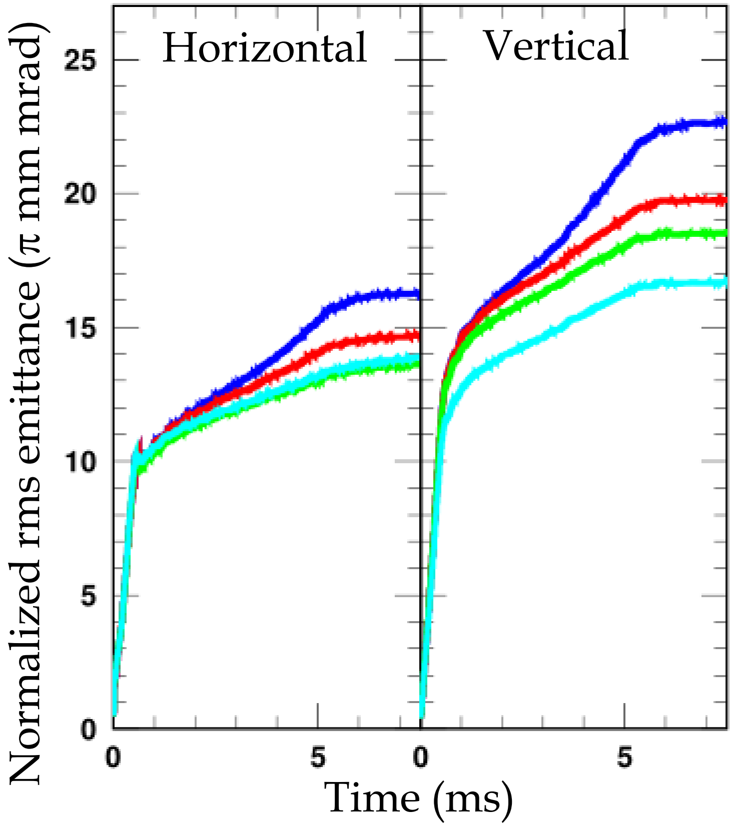
Result of the emittance measurement

- **Time dependence of the rms emittance for the first 7 ms**

Measurement



Numerical simulation



✓ The emittance growth was well mitigated in the order from (A) to (D), as predicted by the numerical simulation.

Remaining issue for the use of new parameters & its solution

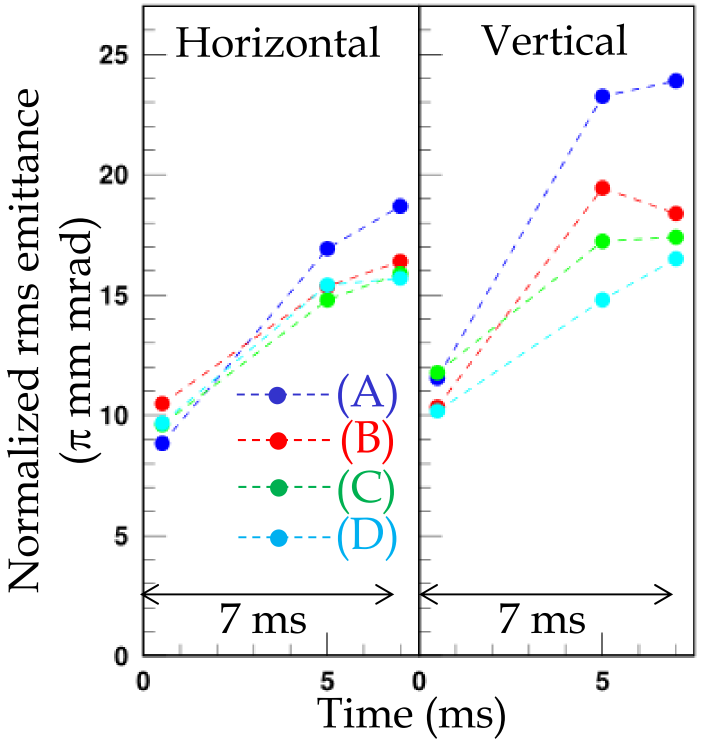
Beam instability & its suppression

Beam instability

- ✓ **Most dominant impedance source ; extraction pulse kickers**
  . . . causing horizontal beam instability depending on
  the operational parameters such as the choice of the tune and chromaticity.

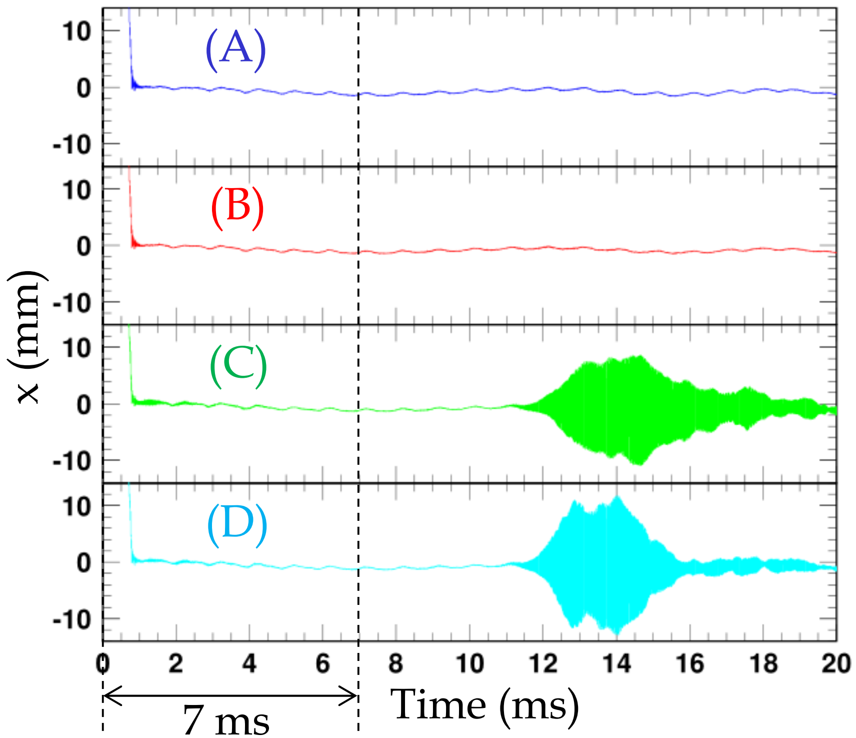
- **Time dependence of the rms emittance for the first 7 ms**

Measurement



- **Turn-by-turn horizontal beam position over 20 ms**

Measurement

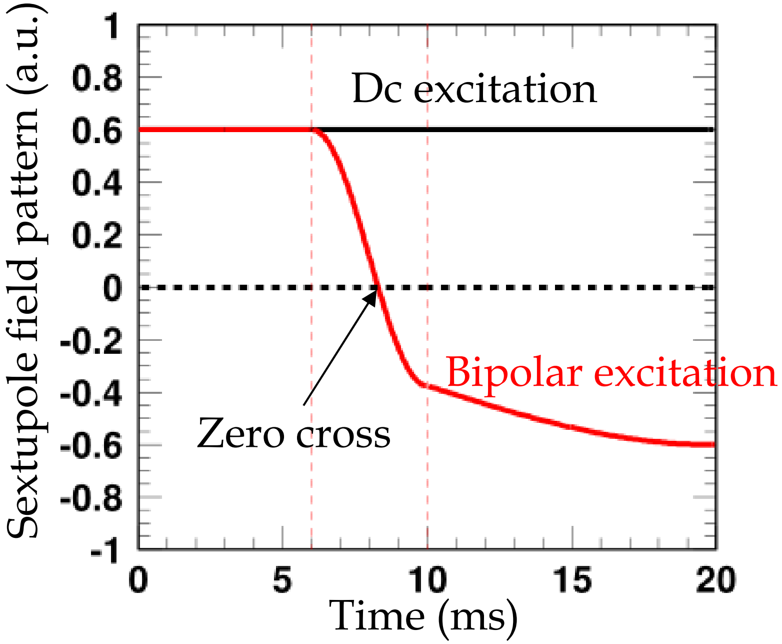


- ✓ The parameters (C) and (D) well mitigate emittance growth for the first 6 ms, but enhance beam instability after 10 ms.
- ✓ This beam instability has to be solved for realizing the modified parameters (C) and (D).

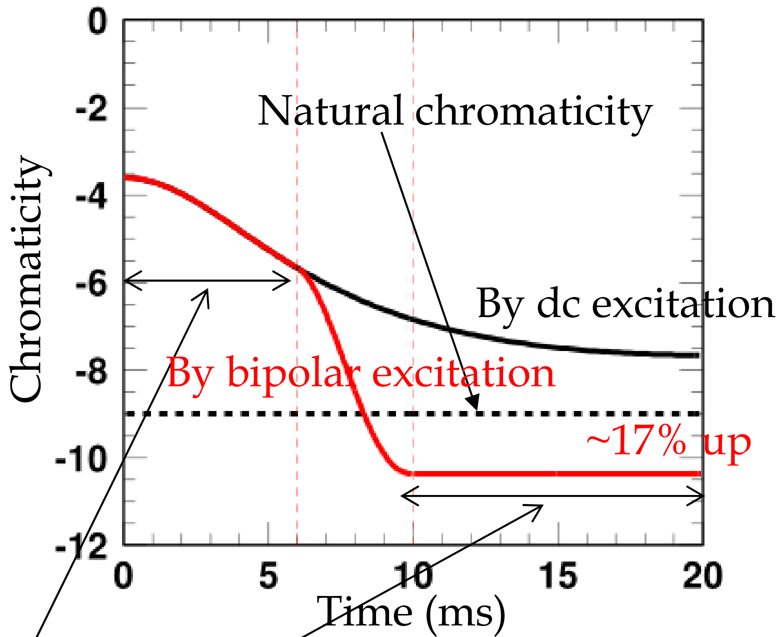
Practical solution

✓ Dynamically manipulating chromaticity over the acceleration process

- Sextupole field pattern over 20 ms



- Time dependence of chromaticity over 20 ms



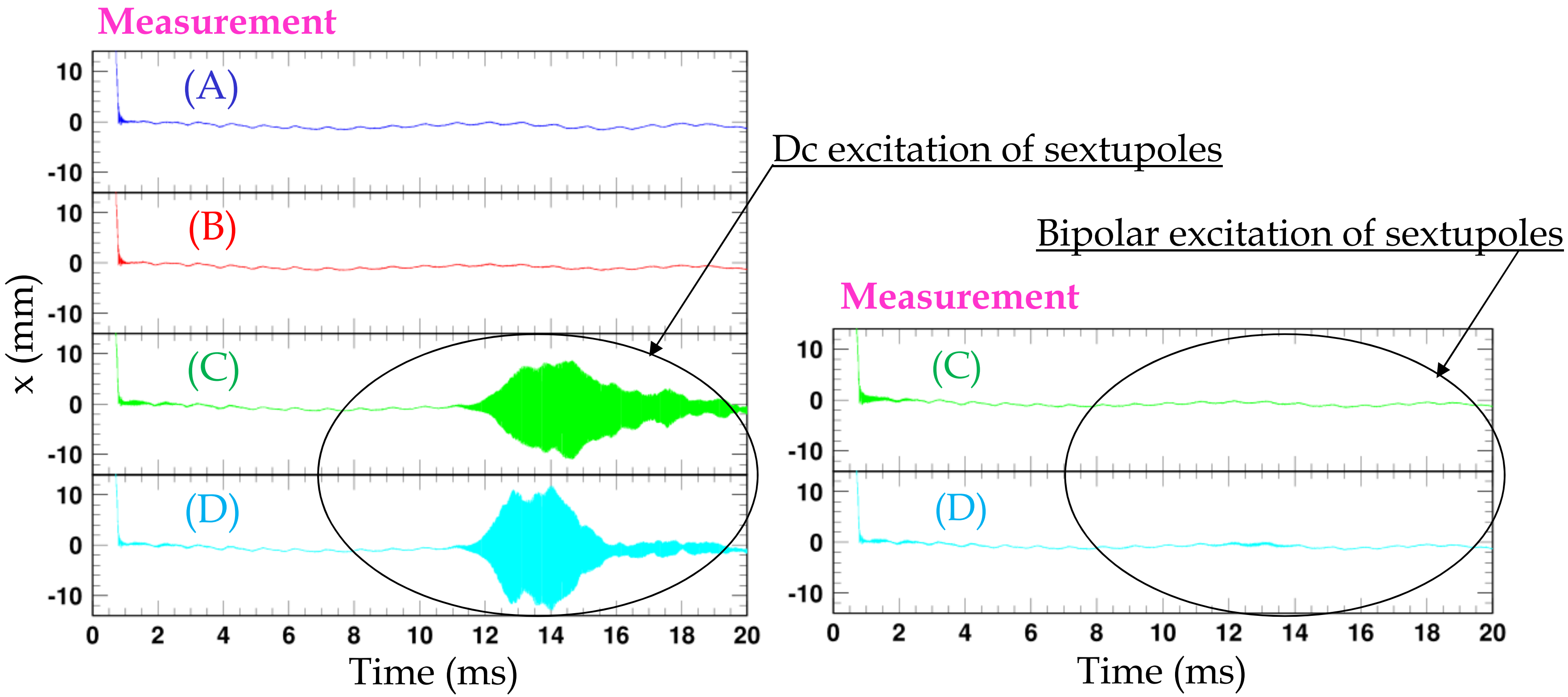
✓ Small chromaticity
  - required for mitigating the emittance growth for the first 6 ms

✓ Large chromaticity
  - enhancing the Landau damping through momentum spread
  - favoring the suppression of beam instability after 10 ms

✓ To realize the bipolar excitation of sextupole field, we improved the sextupole magnet power supply in the summer maintenance period in 2016.

Experimental result
with the bipolar excitation of sextupole field

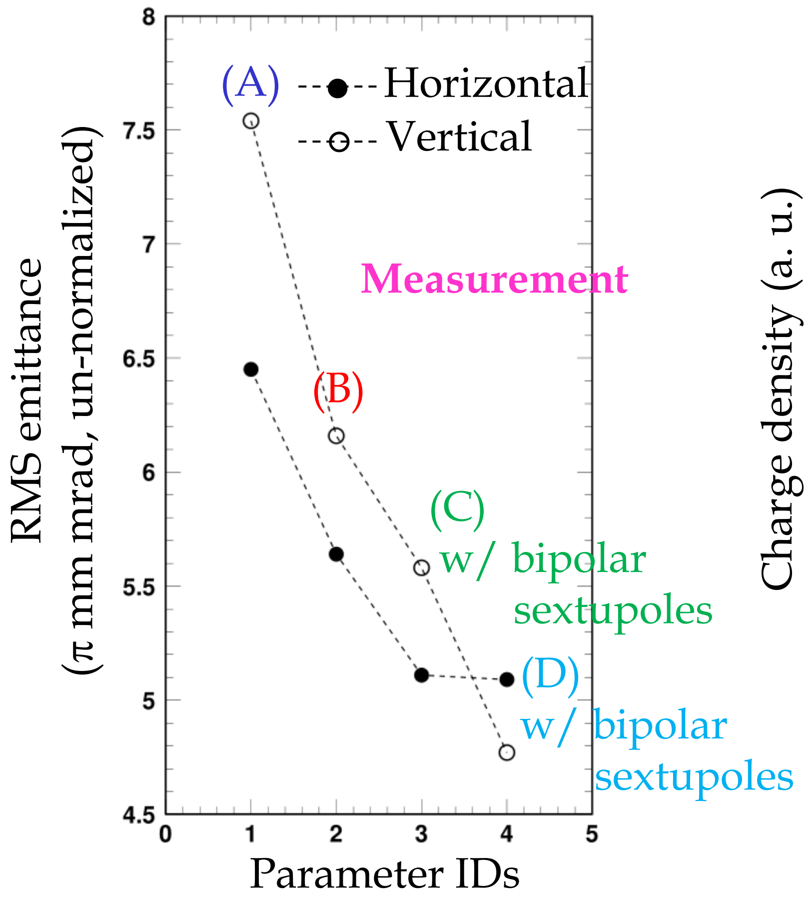
- **Turn-by-turn horizontal beam position over 20 ms**



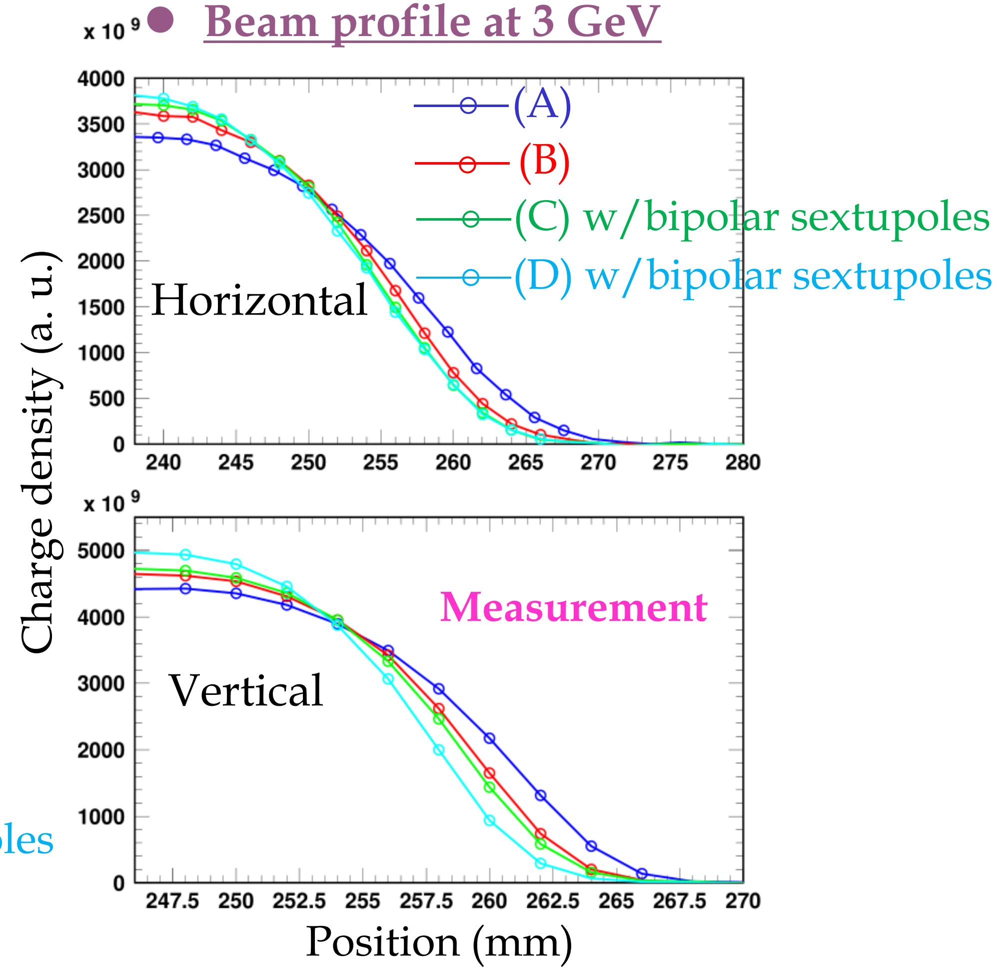
✓ The beam instability was sufficiently damped as expected by introducing the bipolar excitation of the sextupole field.

Results of the extraction beam emittance & profile measurements

- RMS beam emittance at 3 GeV



- Beam profile at 3 GeV

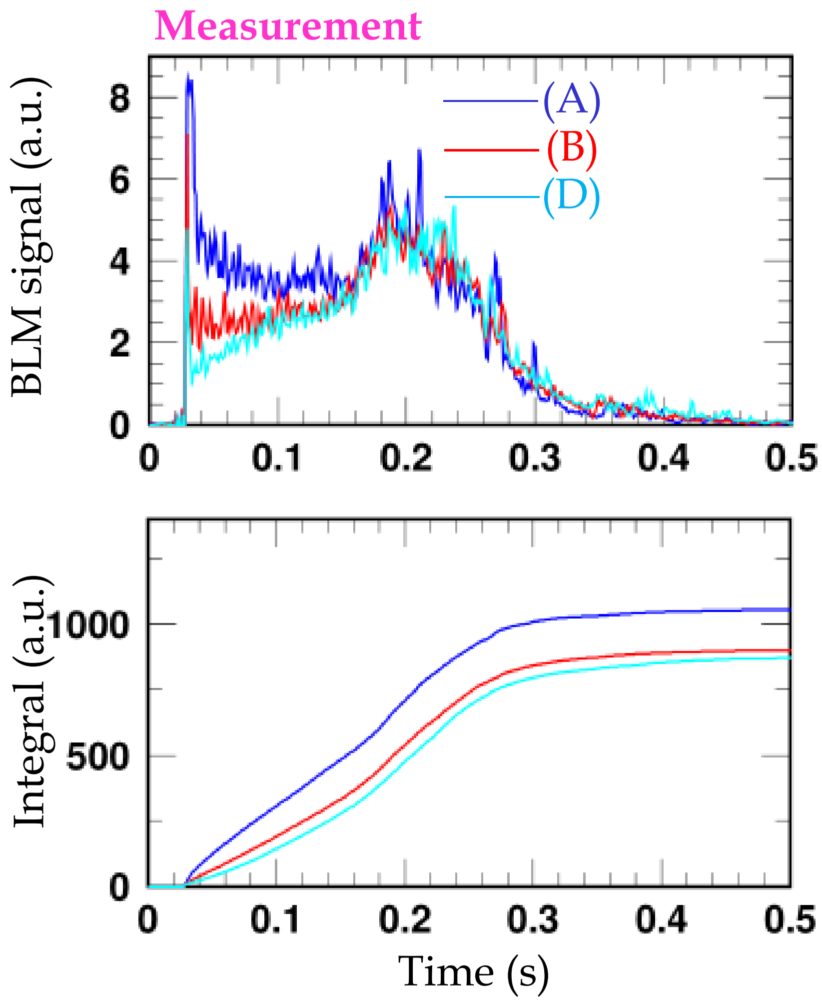


✓ The extraction beam emittance including its tail part was successfully decreased from (A) to (D).

✓ This improvement of the extraction beam quality reflects the emittance growth mitigation achieved for the first 6 ms.

RCS parameter dependence of beam loss in MR

- BLM signals at the MR collimator
  measured for the RCS parameters of (A), (B) and (D)



✓ The MR beam loss was well reduced by 20% by the RCS parameter change from (A) to (B), while it was almost unchanged for the parameter change from (B) to (D).

✓ This result shows that the MR beam loss, arising from the RCS beam quality, is almost minimized by the parameter (D).

✓ MR beam tuning is in progress now with the improved RCS beam while steadily increasing the output beam power.

✓ The MR beam power for the NU experiment has recently reached a new record of ~470 kW.

Summary

- RCS is now ready to demonstrate
  a continuous 1-MW beam operation to MLF.

  - It will be conducted after
    the new high-power neutron target gets available.

- For this past year, RCS intensively developed beam studies
  to realize a high-intensity low-emittance beam required from MR.

  - The RCS beam emittance including its tail part
    was successfully decreased by optimizing
    - transverse injection painting,
    - tune & chromaticity manipulations,

    where
    - bipolar sextupole field patterns

    were newly introduced to simultaneously realize
    emittance growth mitigation at the early stage of acceleration and
    beam instability suppression after the middle stage of acceleration.

  - In addition, in this work, characteristic behaviours of
    beam particles during injection painting,
    appearing coupled with emittance exchange, was revealed.