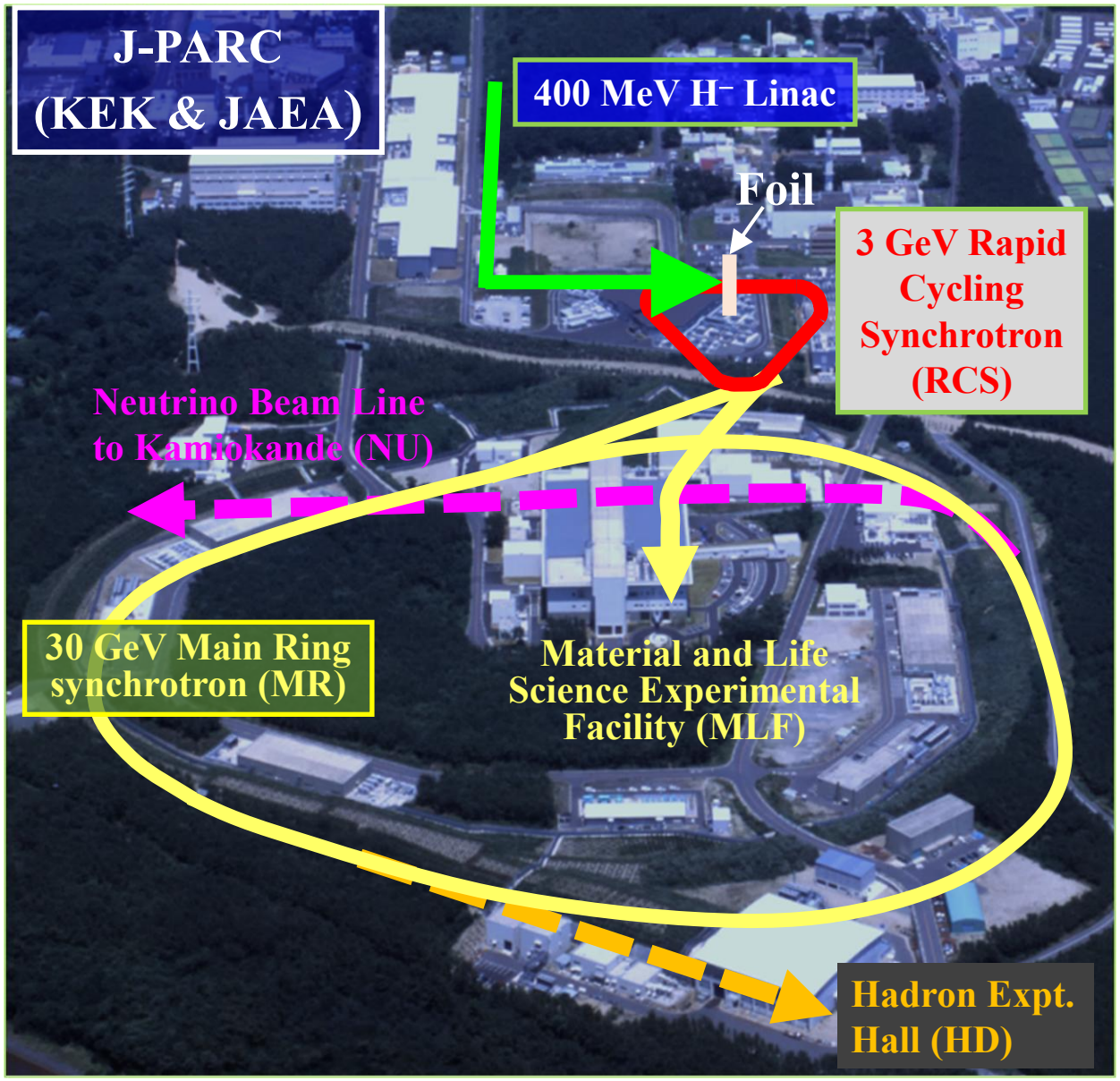
J-PARC Accelerators and Experimental facilities



Beam loss Minimization by well Mitigating the SC Effect at 1.5 MW Beam Power at J-PARC RCS

Pranab SAHA

On behalf of RCS beam commissioning team

Space Charge Workshop 2026, Oxford, UK
2026/9/30

Outline:

- Introduction and background
- Key optimizations for beam loss mitigation
- Results of beam loss minimization
- Summary and Outlook

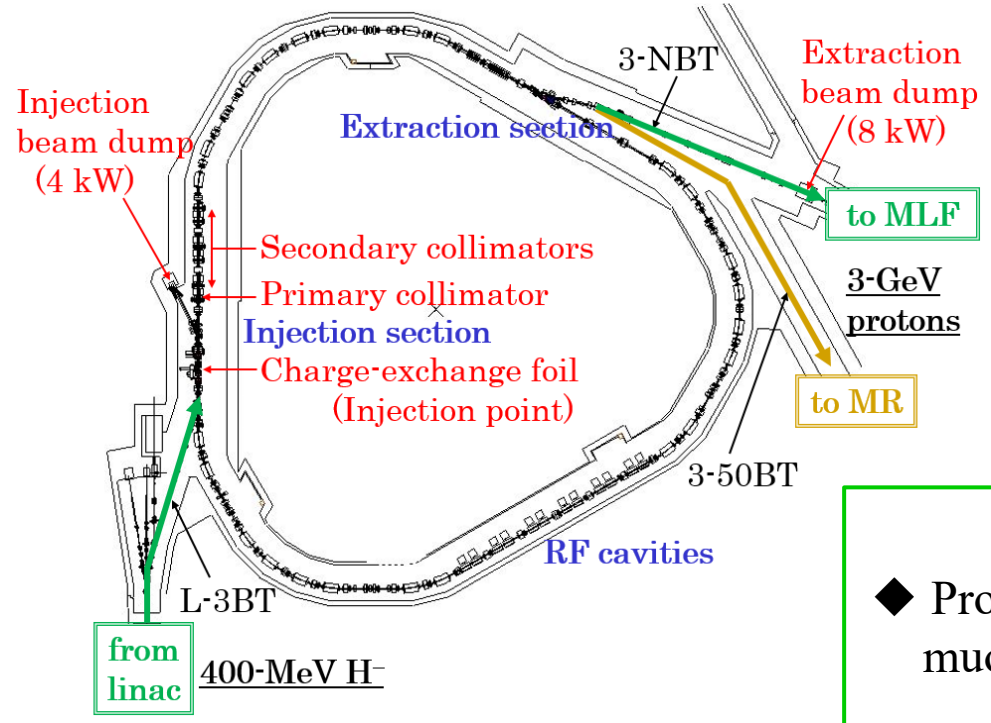
Brief introduction of the RCS

RCS key parameters

Circumference : 348.333 m
Superperiodicity : 3
Harmonic number : 2
Number of bunches : 2
Injection : H^- multi-turn charge-exchange injection
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

Collimator capacity: 4 kW



RCS has two functions:

◆ Proton driver for producing pulsed muons and neutrons at the MLF.
◆ Injector to the MR

◆ Beam sharing between MLF and MR: 88 : 12 or 96:4 depending on MR cycle

➢ **Beam loss mitigation for beam operation to the MLF is a high priority.**

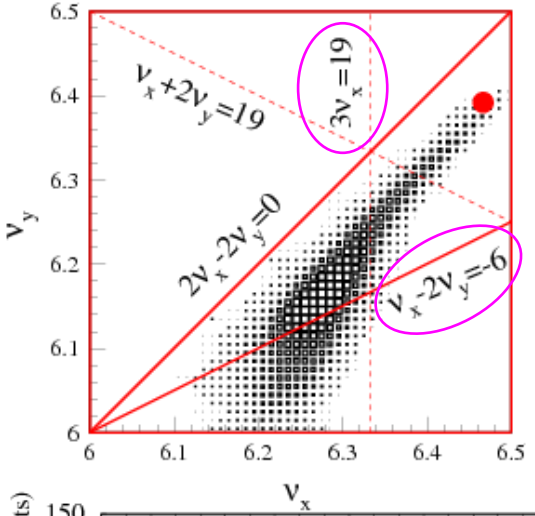
Background (1 MW beam tuning results)

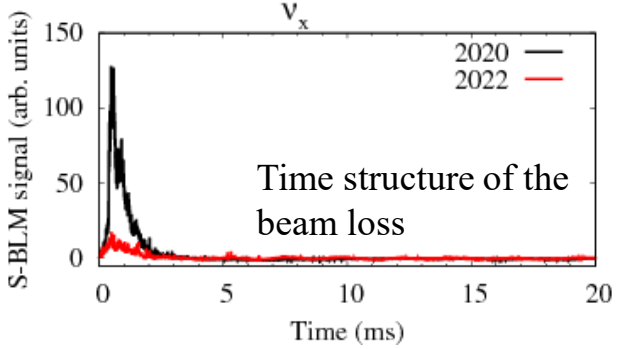
PHYSICAL REVIEW ACCELERATORS AND BEAMS **28,** 074201 (2025)

Editors' Suggestion

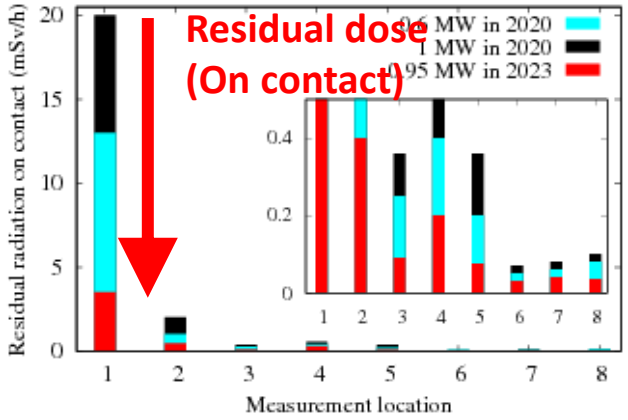
State-of-the-art beam loss minimization at high-intensity beam operation of the 3 GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex

P. K. Saha,* H. Harada, F. Tamura, K. Okabe, M. Yoshimoto, Y. Shobuda, H. Okita, K. Kojima, T. Nakanoya, S. Hatakeyama, T. Takayanagi, and K. Yamamoto, H. Hotchi

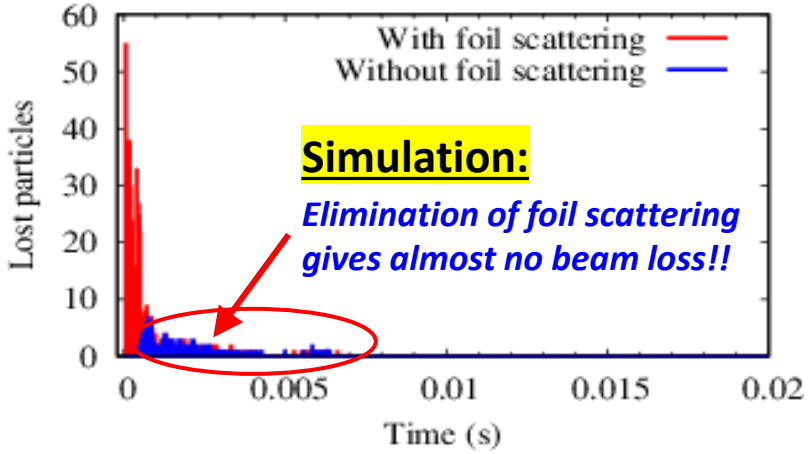




- ✓ Implemented alternative ways of resonance corr. and new ways for optimizing LP and TP.
- ✓ The residual beam loss at 1 MW is < 0.1%.
- ✓ Beam loss occurs only at lower energy localizing well in the collimator section.
- ✓ Beam loss is mostly caused by the foil scattering.
- ✓ **Loss power: < 0.1 kW << Collimator capacity (4 kW)!**



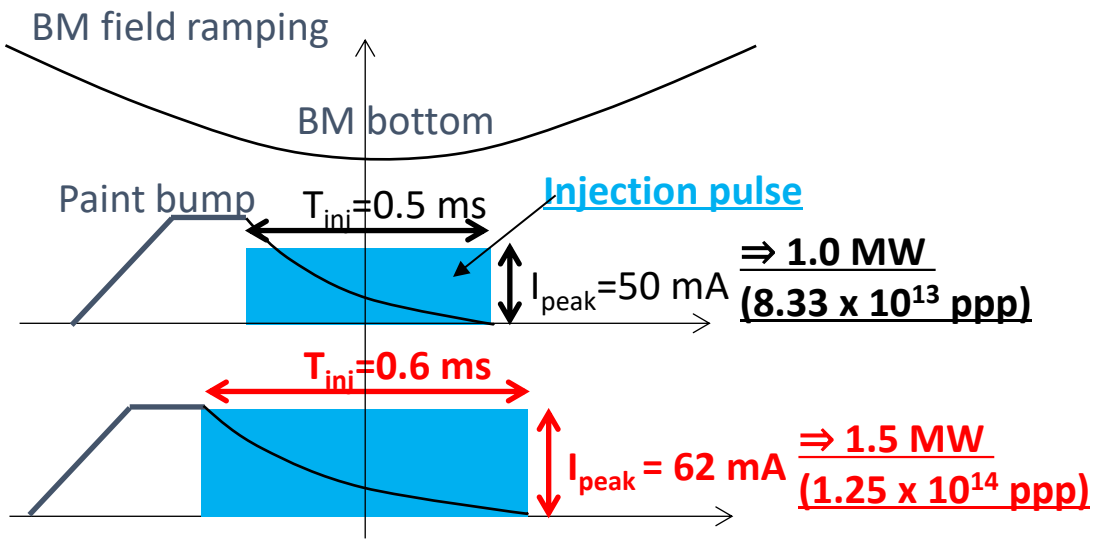
Simulation w/ and w/o foil scattering

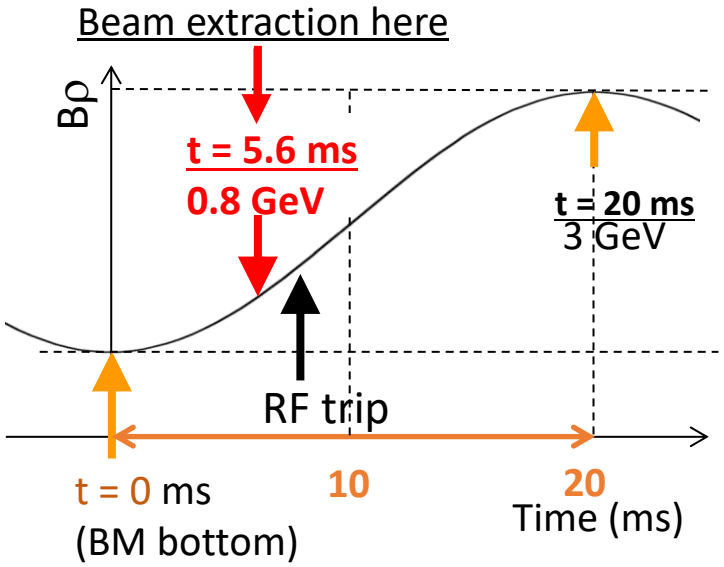


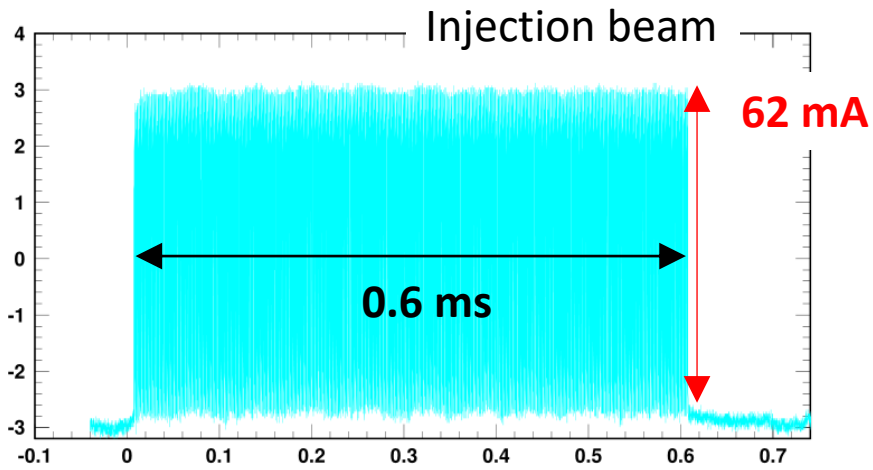
◆ We established reliable numerical simulation and feedback to systematic beam tests to address all considerable issues and practical solutions for beam loss mitigation at 1 MW.

✓ Similar procedures and further detail optimization of many parameters we have applied for beam loss mitigation at 1.5 MW.

Basic parameters for 1.5 MW

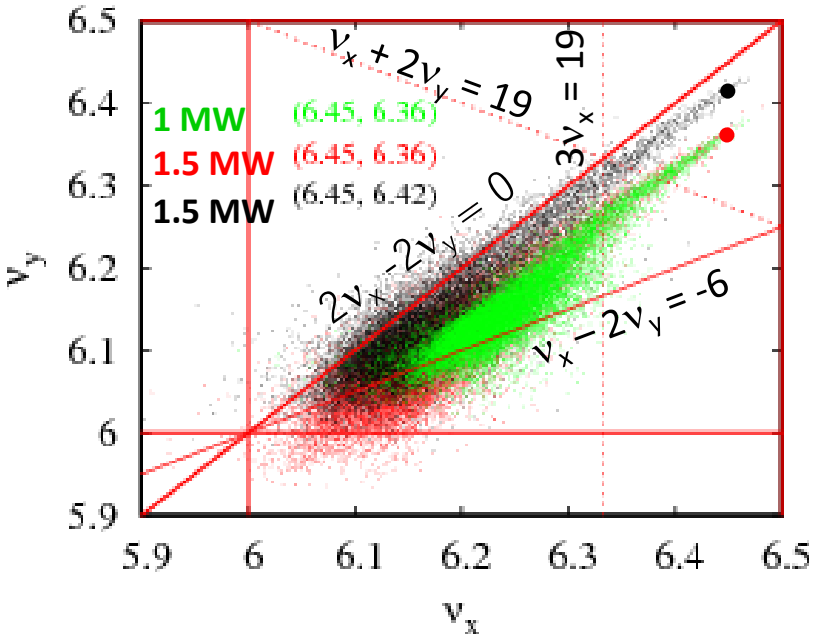






- ◆ Currently, acceleration is limited up to 0.8 GeV due io capacity of the RF anode power supply.
- ➢ Installing new RF cavities and will be completed in 2028.
- ◆ **However, for beam loss study and its mitigation can be done as beam loss occurs only at lower beam energy for the first few ms.**

Optimization of the operating point



◆ At 1 MW, the bare tune at injection is set at (6.46, 6.36).

◆ However, further SC detuning at 1.5 MW forces the beam core beyond $\nu_y = 6$.

➢ Simulation results shows a significant increase of the beam loss. As a result, the operating point is optimized, especially the vertical tune is moved to 6.42 setting the bare tune at (**6.45, 6.42**).

◆ Then, next concern is $\nu_x - \nu_y = 0$ resonance, for which the painting/beam emittance controlling is a key issue.

The $\nu_x - 2\nu_y = -6$ resonance correction is optimized according change of beam intensity.

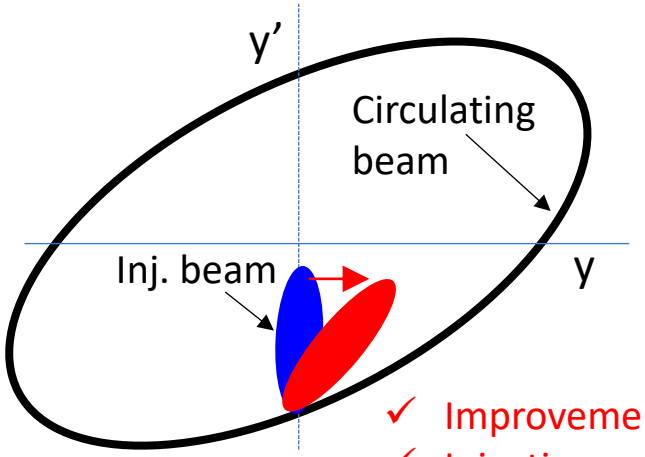
➢ Basically, we figured out almost all possible sources causing beam emittance growth/beam halos and applied realistic counter measures.

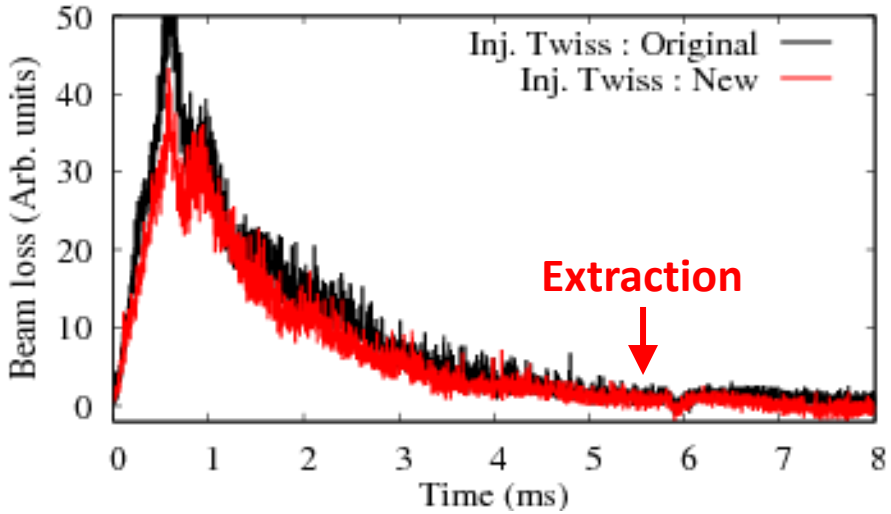
Optimization of injection twiss

In the latest beam test in 2025, we optimized the injection beam parameters better than the previous study.

Measured injection twiss parameters at the foil

Run# Time	α_x	α_y	β_x [m]	β_y [m]	ε_x (rms) [π mm mrad]	ε_y (rms) [π mm mrad]
92 (March '25)	-0.69	**-0.75**	6.64	2.13	**0.42**	0.31
92 (Dec '24)	-0.55	**-0.11**	6.33	1.93	**0.47**	0.31



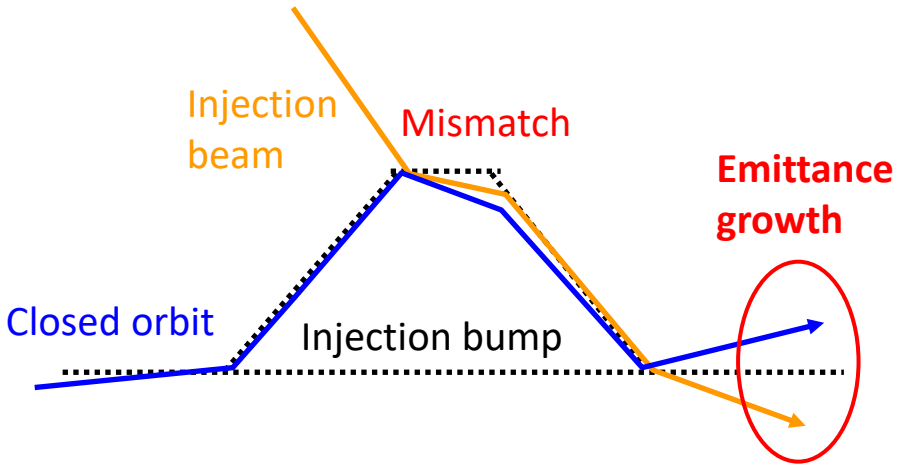


Time structure of the beam loss taken by a BLM at the collimator section.

✓ **Additional beam loss partly reduced.**

✓ Improvement of injection beam emittance.
✓ Injection α_y optimization towards matching to the ring.
◆ Foil size limits a further optimization.
➢ A bigger foil size increases foil scattering beam loss.

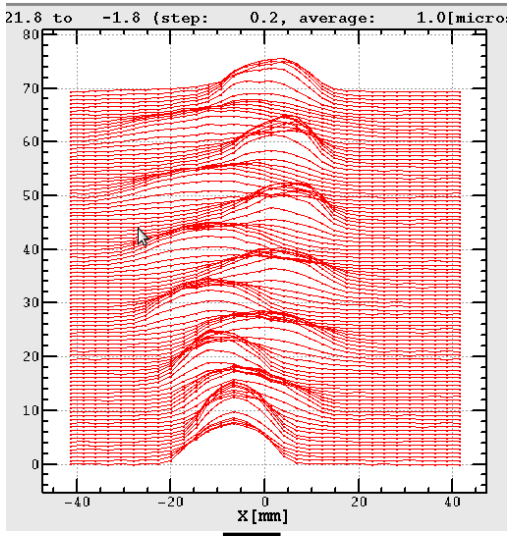
Injection error correction

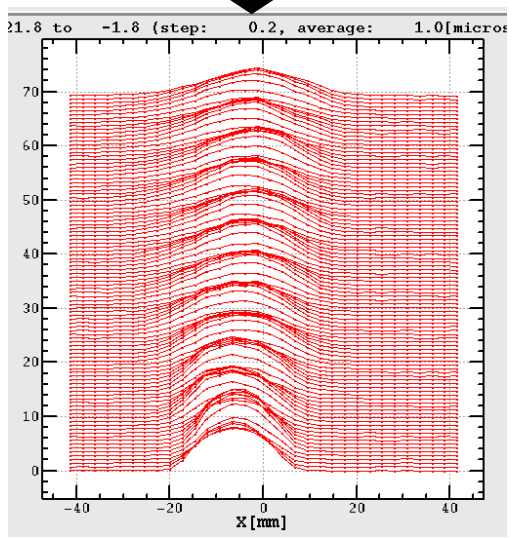


◆ Injection errors causes beam emittance growth beyond the painting emittance.

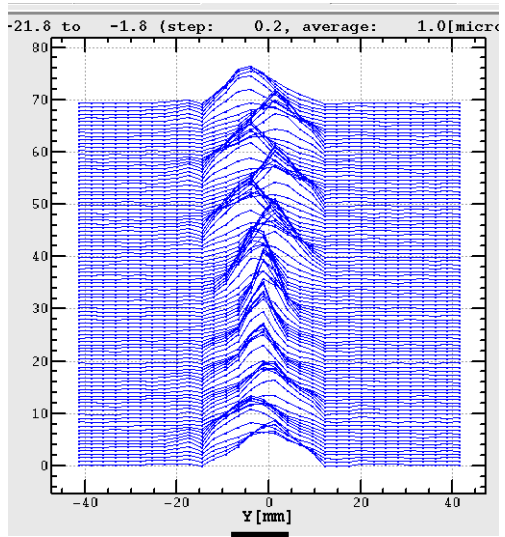
➢ Injection orbit matching to the closed orbit was done well by using IPM.

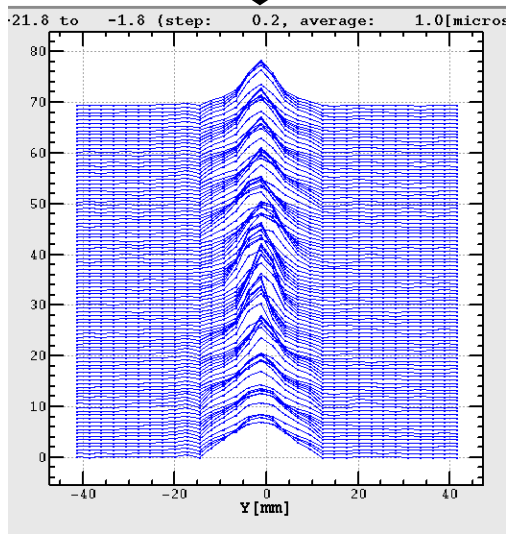
Horizontal





Vertical

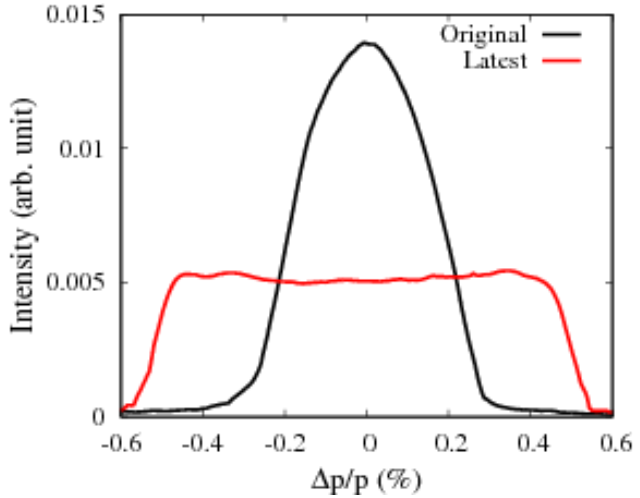


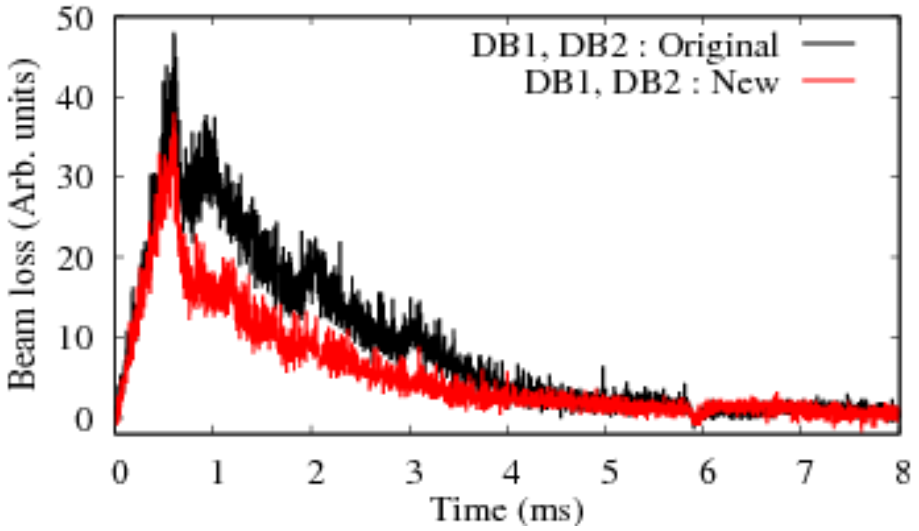


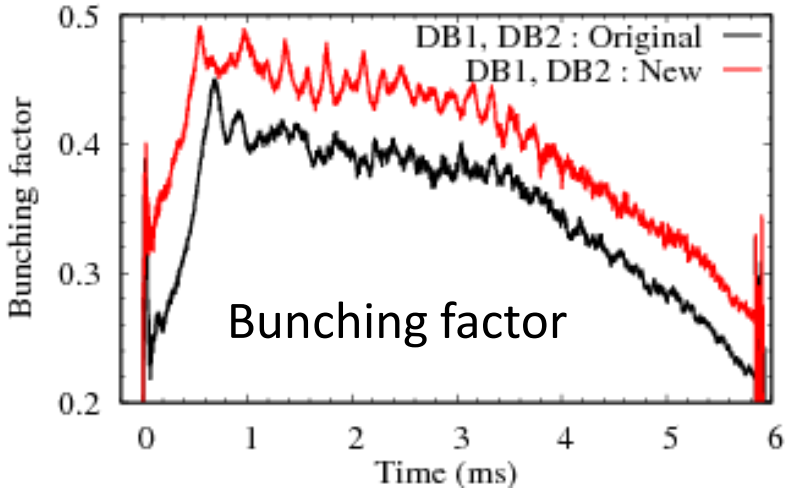
Application of wider injection energy spread

An extremely wider and uniform energy spread of the injection beam is used obtained by huge change of amplitudes of last 2 RF cavities of the Linac called Debunchers.

- **We inject the beam at the bucket center instead of an offset injection.**



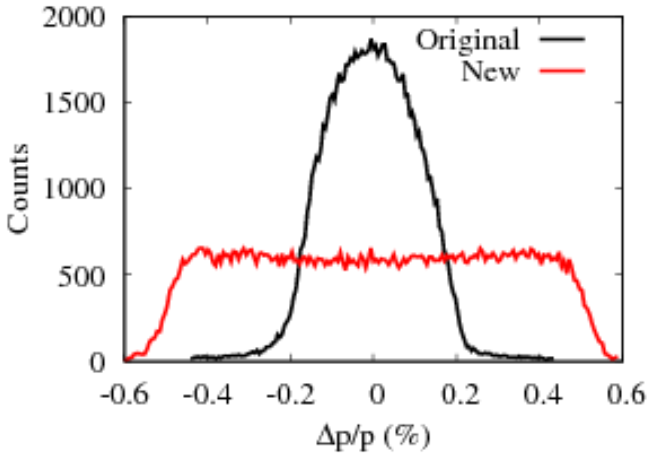


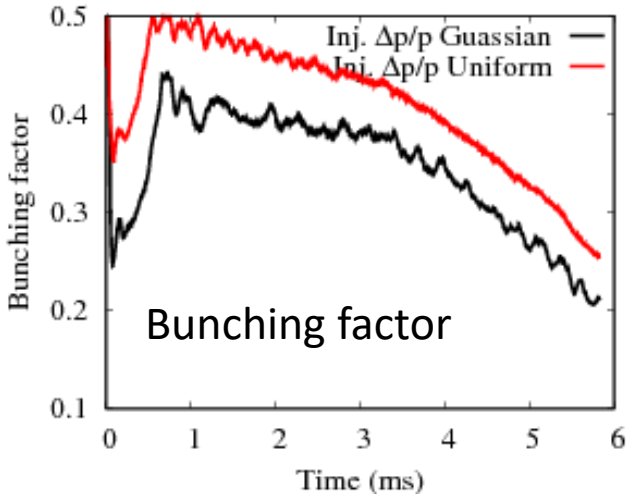


- ✓ Bunching factor is significantly improved.
- **The SC effect is reduced, and beam becomes more stable in the longitudinal plane giving a significant beam loss mitigation.**

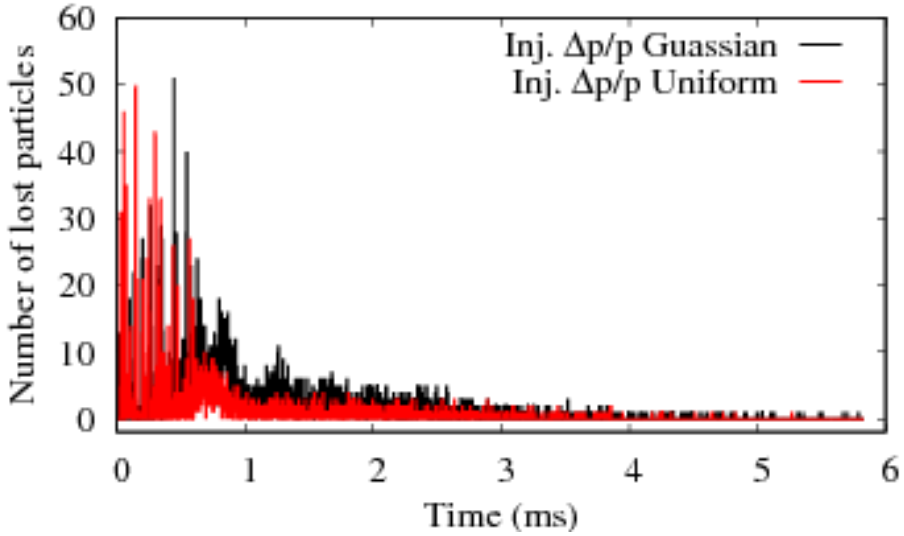
Numerical simulation using higher inj. energy spread

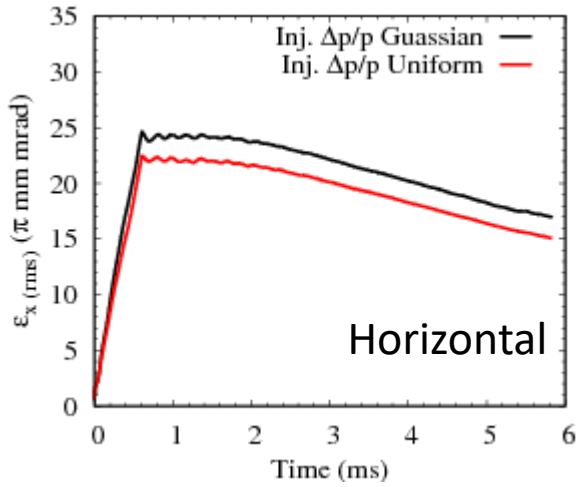
Measured data was incorporated in the simulation



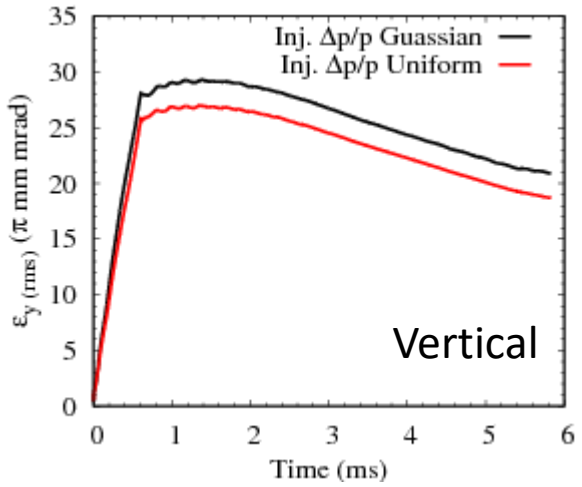


Bunching factor





Horizontal



Vertical

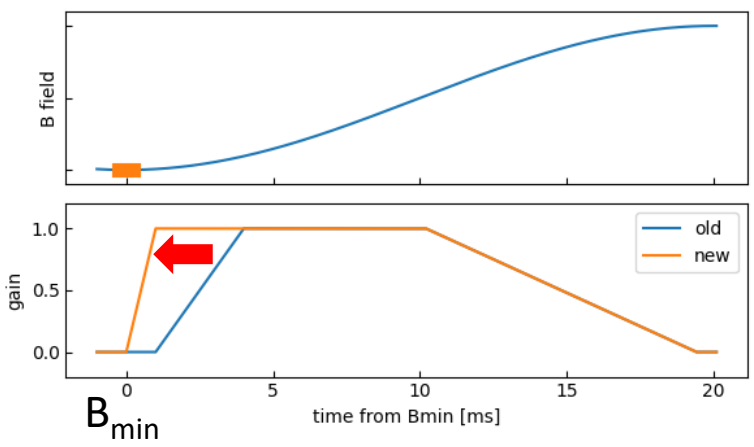
Unnormalized rms emittance

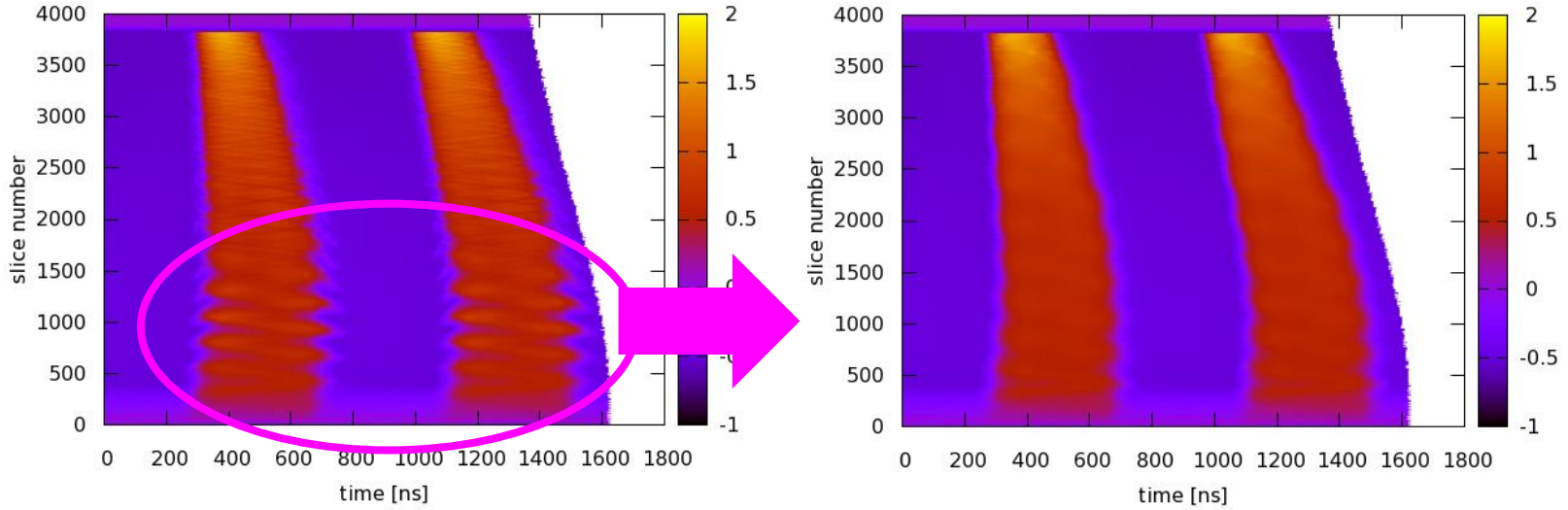
✓ Similar to the measurement, an application of higher energy spread of the injection beam gives a significant improvement of bunching factor.

✓ The SC effect is reduced keeping a lower beam emittance.

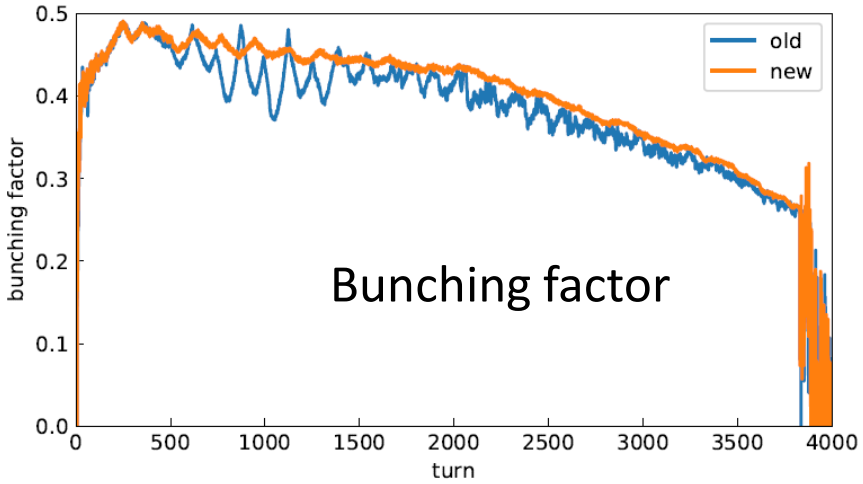
✓ The SC induced beam losses (except foil scattering ones) are well mitigated.

Optimization of the RF phase feedback pattern





- ◆ RF PFB gain to max is done much faster to 1 ms from that of 4 ms so far.
- ✓ Dipole oscillation is significantly suppressed.
- ✓ **Bunching factor is substantially improved.**
- → ***Beam is well stabilized!***

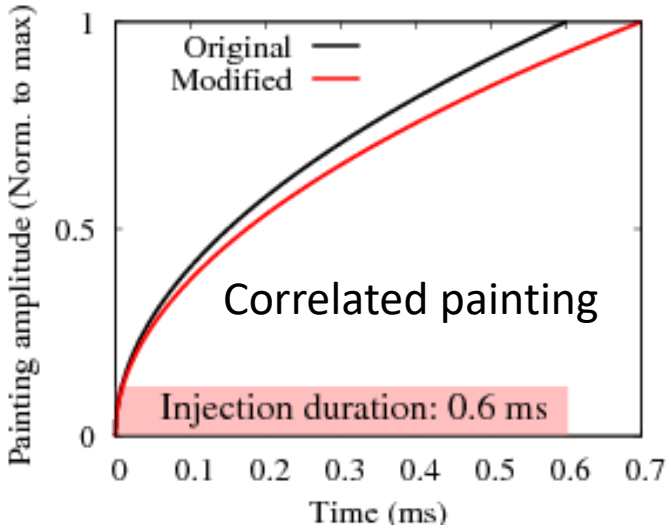


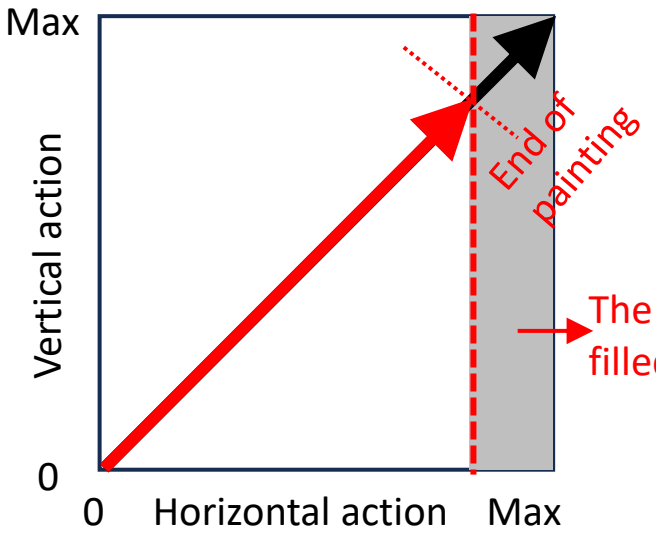
Optimization of Transverse painting: Simulation

We manipulate painting functions to produce as much as uniform beam distributions for reducing the SC effect and keeping beam emittance smaller.

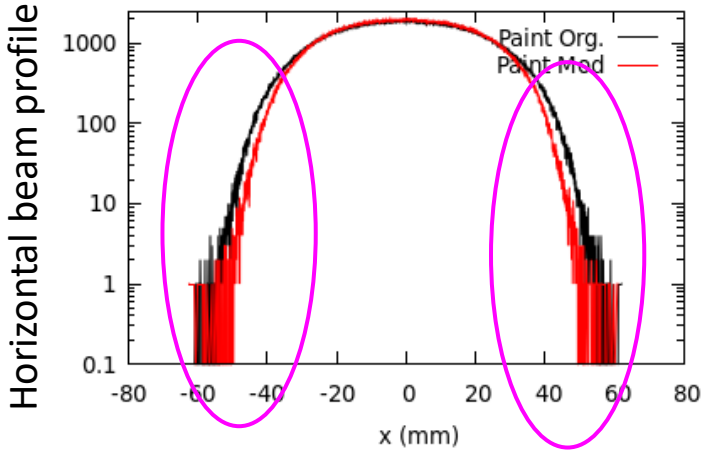
$$x = x_{max}\sqrt{\frac{t}{T} * f}\ ;\quad x' = x'_{max}\sqrt{\frac{t}{T} * f}$$

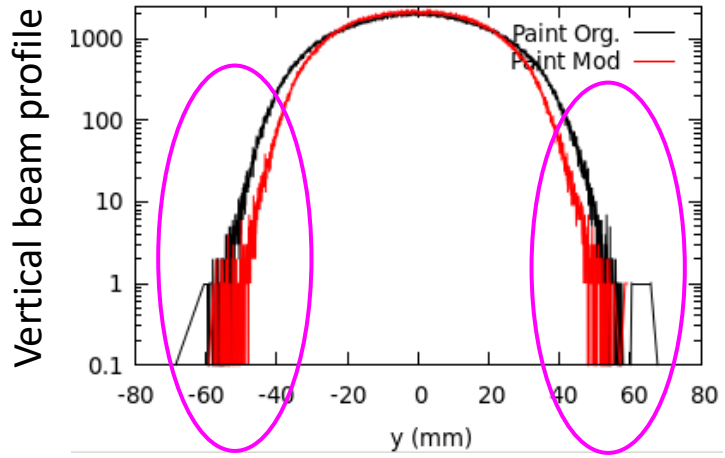
$$y = 0\ ;\qquad y' = -y'_{max}\sqrt{\frac{t}{T} * f}$$





The unpainted area is filled by the SC effect.

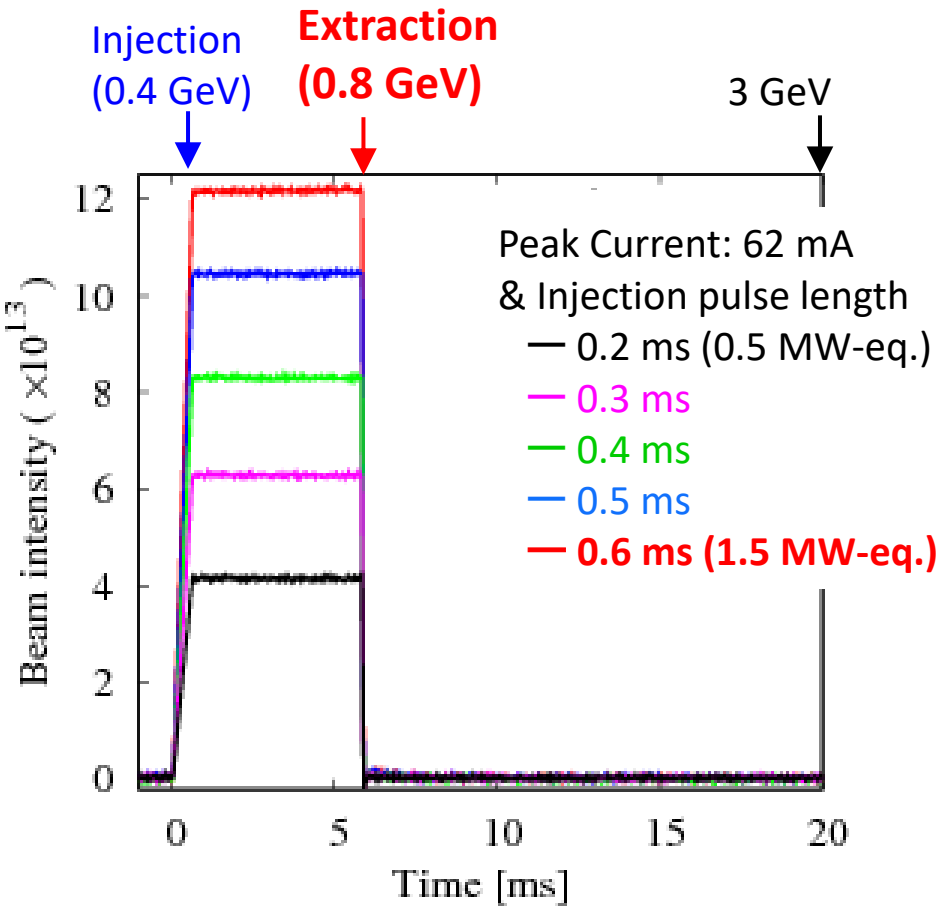




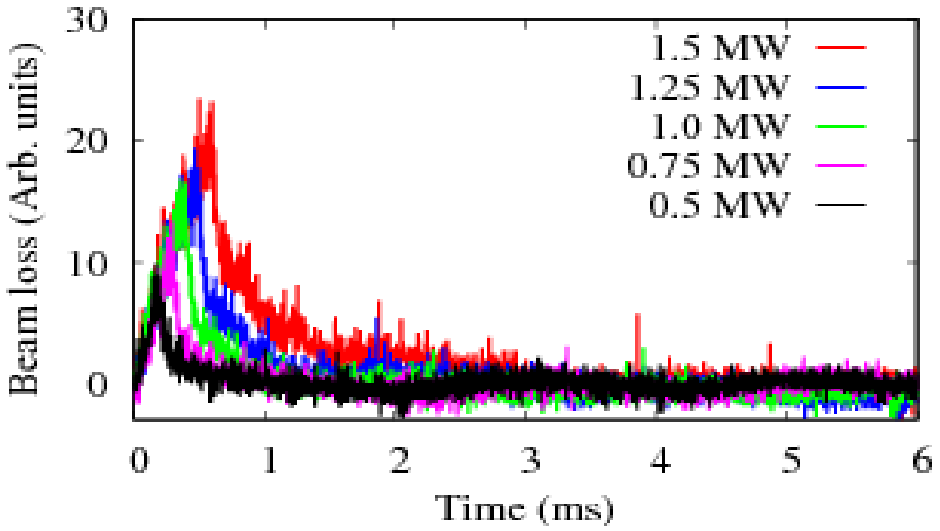
Simulated beam profiles at the end of injection

✓ Beam distribution is improved reducing beam halos and the corresponding beam loss.

Results of beam loss mitigation in 2025



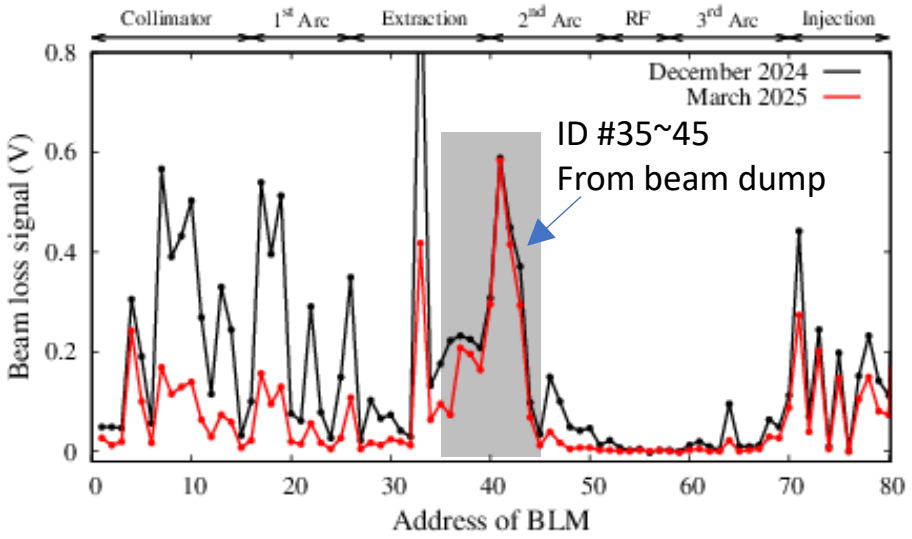
Circulating beam current measured by the DCCT.



✓ No beam intensity loss can be seen up to the highest beam intensity of 1.5 MW.

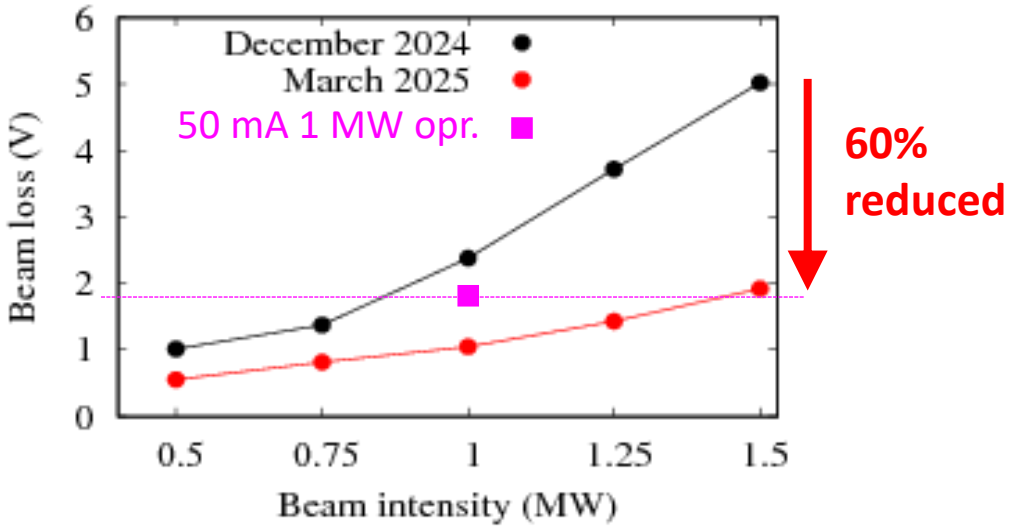
✓ **Beam loss occurs only at lower energy** and is just proportional to the beam intensity (inj. Pulse length) corresponding to foil scattering of the circulating beam.

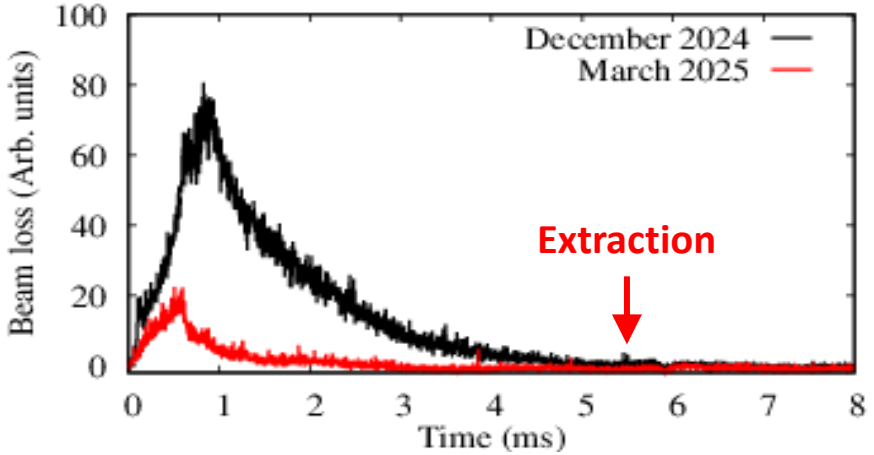
Estimation of the beam loss at 1.5 MW



Beam loss throughout the RCS integrated over inj. to exr.

Integrated beam loss at the collimator to 1st arc.





Temporal structure of the beam loss at the collimator.

- ✓ Beam loss is significantly reduced in latest beam test.
- ✓ Beam loss at 1.5 MW is <0.1%.
- ➢ Corresponding **beam loss power: < 0.1 kW !**
  << Collimator capacity of 4 kW!

→ **Beam loss is almost same as 1 MW opr. at present with 50 mA peak.**

➢ Residual radiation in the RCS at 1.5 MW operation can be kept sufficiently lower level as the current 1 MW operation.

Beam instability at 1.5 MW

◆ Transverse impedance of the extraction kicker magnets is the significant beam instability source in the RCS. **The beam instability occurs at higher beam energy.**

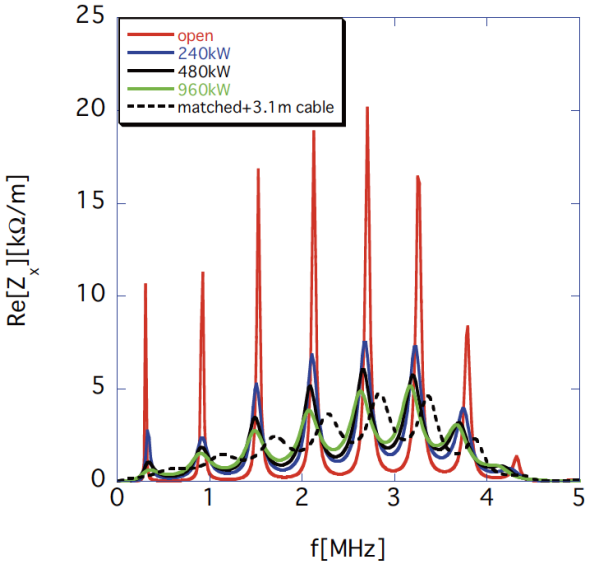
✓ Recently, we have installed impedance damper to 4 KMs out of 8 in total (Y. Shobuda et al., PRAB 26, 053501 (2023)).

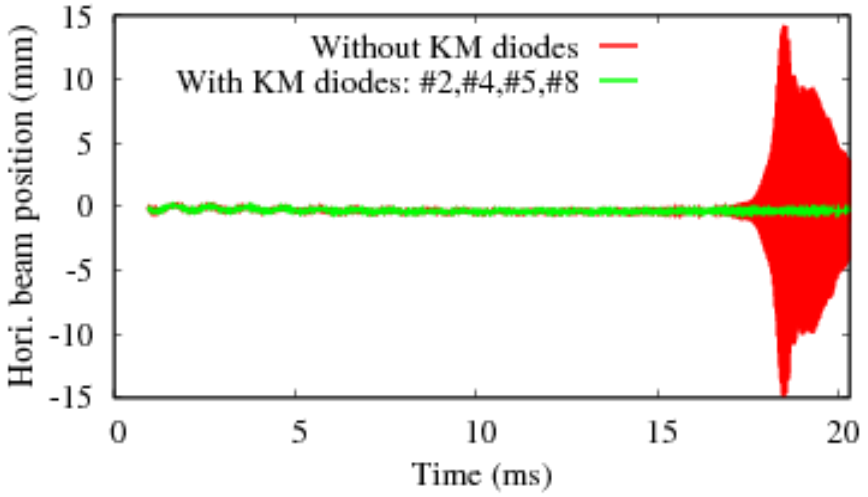
➢ **The impedance is successfully reduced by half.**

◆ However, due to beam is accelerate up to 0.8 GeV (not to 3 GeV) for 1.5 MW, we can't check yet the instability.

➢ **As a result, we checked the beam instability in the simulation.**

✓ The simulation can simulate realistic beam instability in the RCS (P.K. Saha et al., PRAB 23, 024203 (2018)).





Kicker impedance (Y. Shobuda)

We simulate 1.5 MW beam power with the given reduced impedance of the KMs.

We believe **no beam instability occurs** at 1.5 MW as with the present reduced impedance to half.

Summary and outlook

・In addition to the optimization applied for beam loss mitigation at 1 MW, we have further **tuned all possible sources of beam emittance growth** by optimizing many parameters of the Injection beam as well as in the RCS.

・Injection twiss was optimized and an **extremely wider and uniform energy spread** was applied.

・In the RCS, optimized betatron tune, injection error corrected perfectly and as well as fine optimization of the RF phase FB was done.

・As a result, the beam loss at 1.5 MW has been well minimized in the latest beam test in 2025.

・**The residual beam loss at 1.5 MW is estimated to be as low as < 0.1% and is mostly caused by foil scattering of the circulating beam.**

・**The beam loss power is ~0.1 kW, which is kept far less than the collimator capacity of 4 kW.**

・Similar to present 1 MW operation, the machine activation at 1.5 MW can be thus kept to a lower level as to realize a sustainable operation.

・In the simulation, we have confirmed that no beam instability occurs as the kicker impedance is reduced to half.

■ Next, we will try to use a further smaller size foil to reduced the foil scattering beam loss.

■ We are studying to correct nx = 6.5 and nx + ny = 13 for further tunability beyond 1 MW (K. Kojima).

Backups

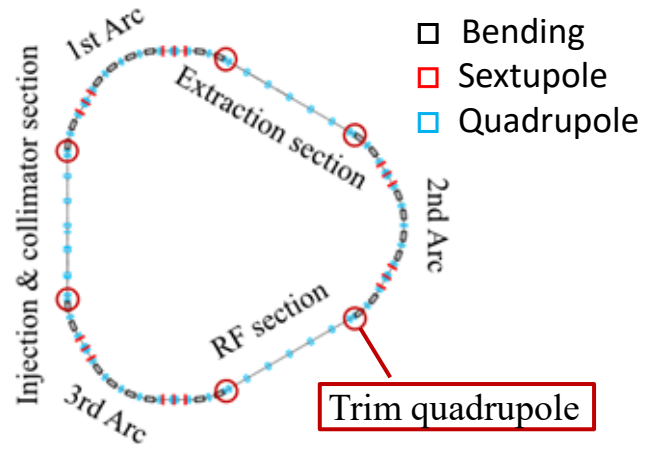
Study of $\nu_x = 6.5$ & $\nu_x + \nu_y = 13$ resonance corrections

K. Kojima, H. Harada

- The space charge effect pushes the tune spread toward the lower tune side.
- The operating point should be shift to avoid the overlapping of structure resonance.
- We are studying to correct $\nu_x = 6.5$ and $\nu_x + \nu_y = 13$ resonances to enhance the tunability.

◆ $\nu_x = 6.5$ can be corrected by the using trim quadrupoles (ATAC 2025)

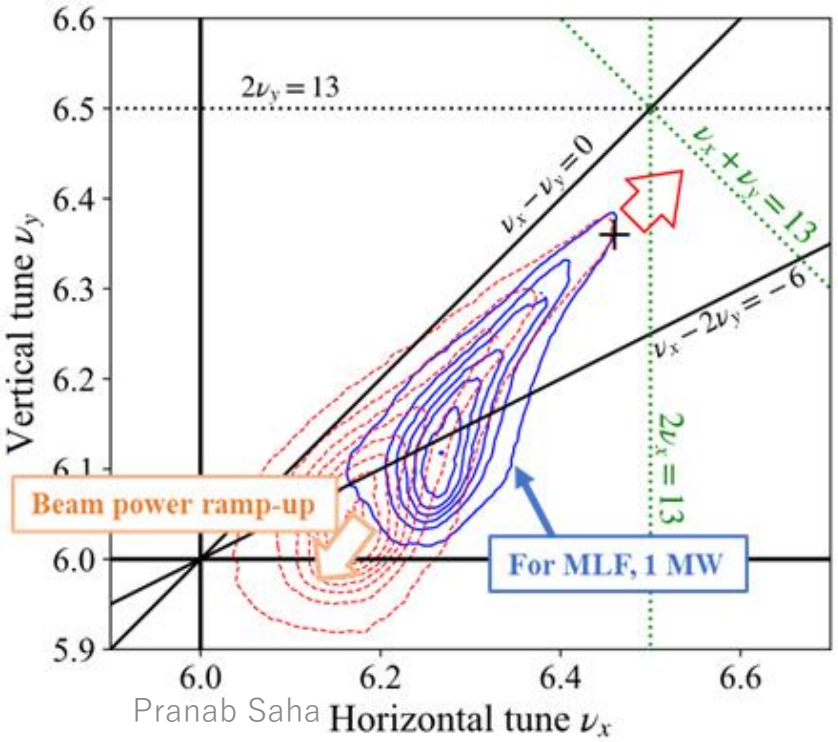
◆ **$\nu_x + \nu_y = 13$ correction** → Tested for a low intensity beam:
(5 kW-eq. with Hori. & Vert. large amplitudes)

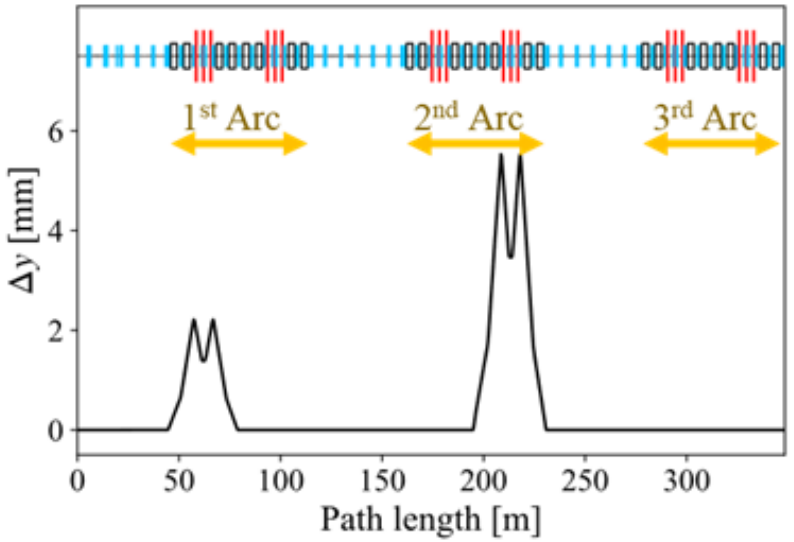


Sextupole field Small orbit distortion

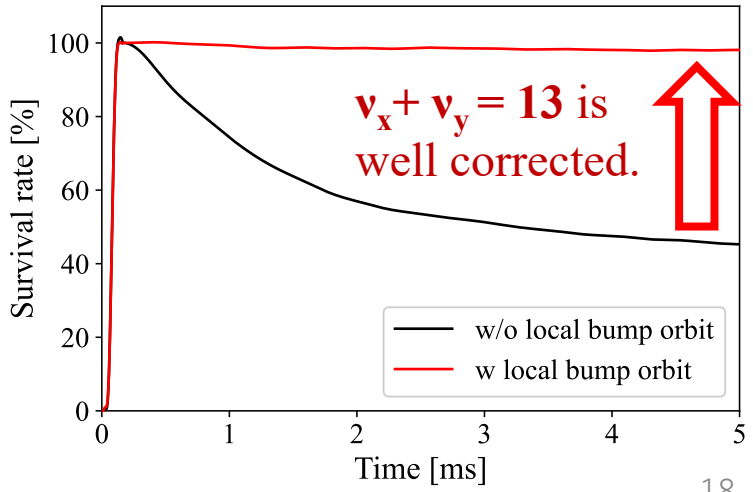
$$A_3 = -\frac{B\rho K_2}{6L}[x^3 - 3x(y+\Delta y)^2] \approx -\frac{B\rho K_2}{6L}(x^3 - 3xy^2) + \frac{K_2 B\rho \Delta y}{L}(xy)$$

Skew quadrupole

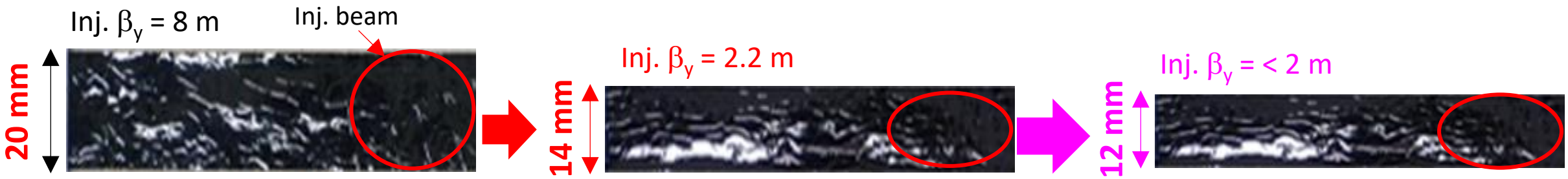




Beam survival at (**6.55, 6.45**)



Possibility of further reducing vertical foil size



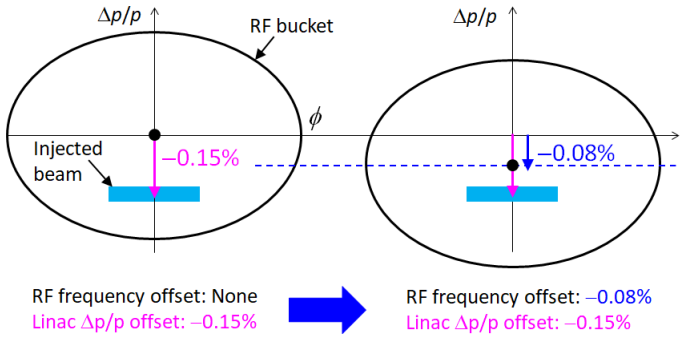
Since 2022

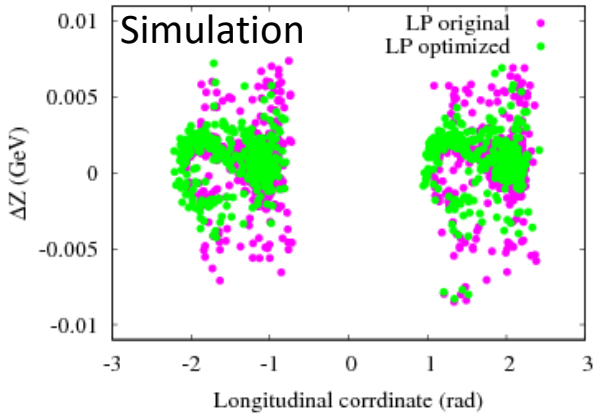
Test run from Feb. 18, 2026

Current Carbon foil in service has a satisfactory longer lifetime at high-intensity operation.
Ideally, almost no missing foil H- exists for the current vertical foil size of 14 mm.
Foil degradation becomes prominent when supporting fibers are broken.
We have a scope to reduce vertical size from 14 to 12 mm without any significant increase of the missing H- component.
Foil scattering uncontrolled beam loss can be further 10% reduce.

LP and TP optimization schemes at 1 MW

LP optimization:

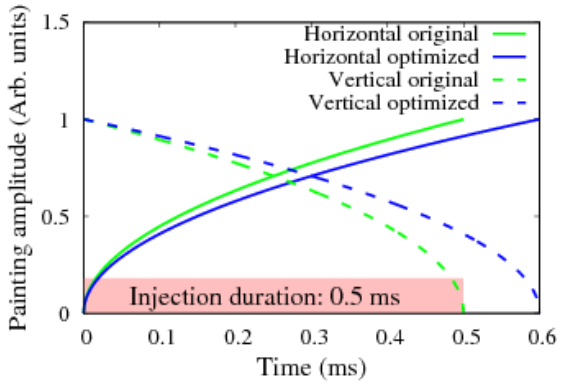




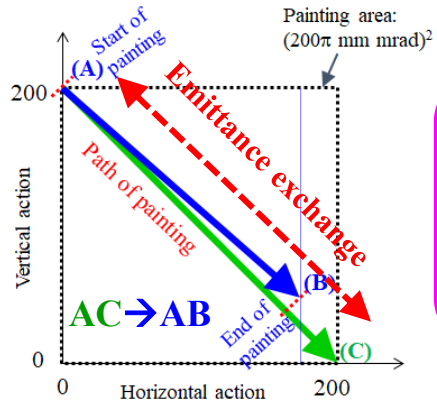
Beam loss occurred due to large Δp/p.

➢ Reduced by LP optimization

TP optimization:



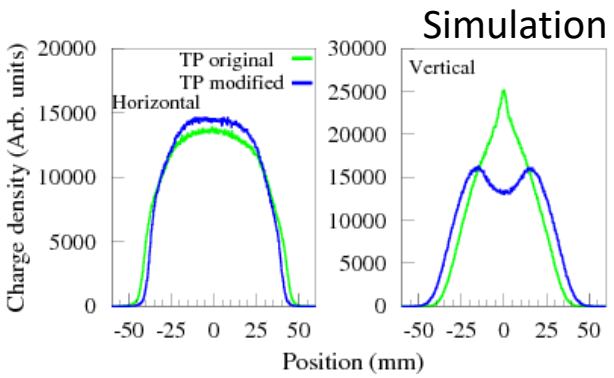
Slow variation of painting

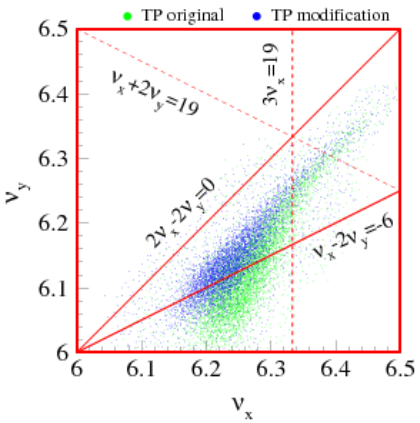


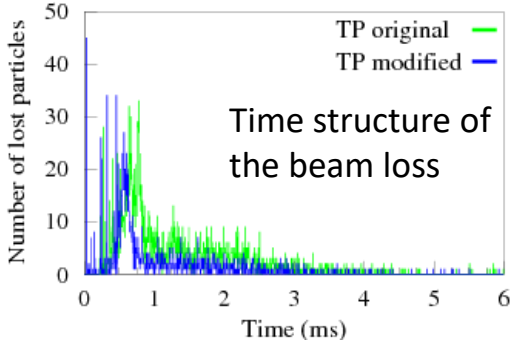
$$x = x_{max}\sqrt{\frac{t}{T} * f} \quad ; \quad x' = x'_{max}\sqrt{\frac{t}{T} * f}$$

$$y = 0 ; \qquad y' = -y'_{max}\sqrt{1 - \frac{t}{T} * f}$$

The unpainted area is filled by the SC effect and emittance exchange







・ High spatial charge concentration. ・ Asymmetric tune distribution.

→ More particles trapping on the resonance → Additional beam loss.

➢ **Well optimized by TP modification.**