1-MW beam operation at J-PARC RCS with minimum beam loss

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J-PARC, Japan

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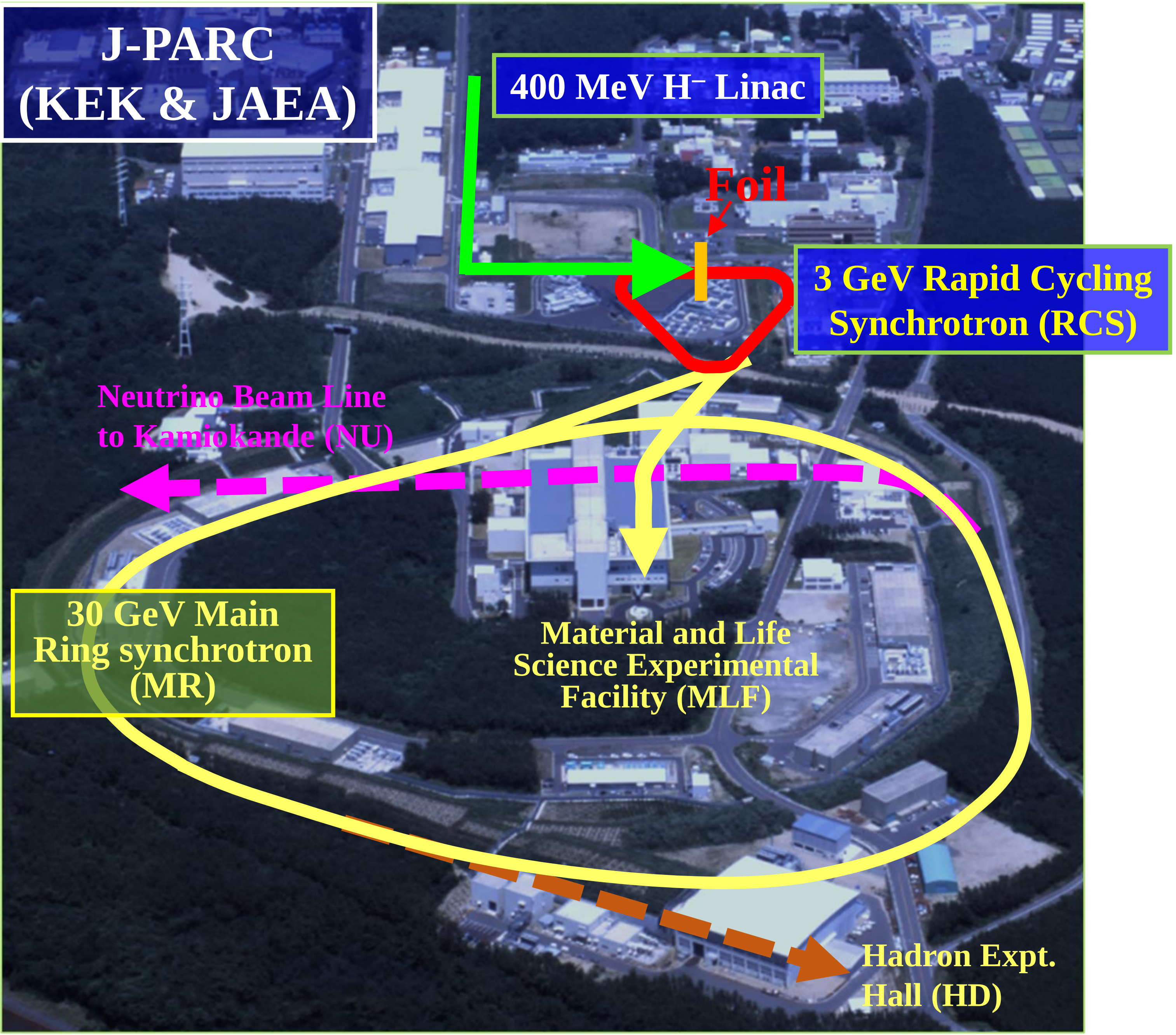
Accelerators at J-PARC



J-PARC is a high-energy proton accelerator complex comprising

- ● A 400 MeV H^- Linear Accelerator (LINAC)
- ● **A 3-GeV Rapid Cycling Synchrotron (RCS)**
- ● A 30 GeV Main Ring (MR)

J-PARC provides high intensity proton beams for multi-dimensional experimental research for

- ◆ Material and Life Science
- ◆ Particle Physis
- ◆ Nuclear Physics

…….

Outline:

- Brief overview of the 3-GeV RCS of J-PARC
- Beam loss minimization at 0.7 MW and SC effect at higher intensity
- **Beam loss mitigation at 1 MW by**
  - Resonance correction
  - Optimization of longitudinal painting
  - Optimization of transverse painting
  - Optimization of betatron tune at injection
- Summary and outlook

Overview of the J-PARC RCS (Rapid Cycling Synchrotron)

Key parameters:

Circumference : 348.333 m

Superperiodicity : 3

Harmonic number : 2

Number of bunches : 2

Injection : Multi-turn charge-exchange injection of H^- beam

Injection energy : 400 MeV

Injection period : 0.5 ms (307 turns)

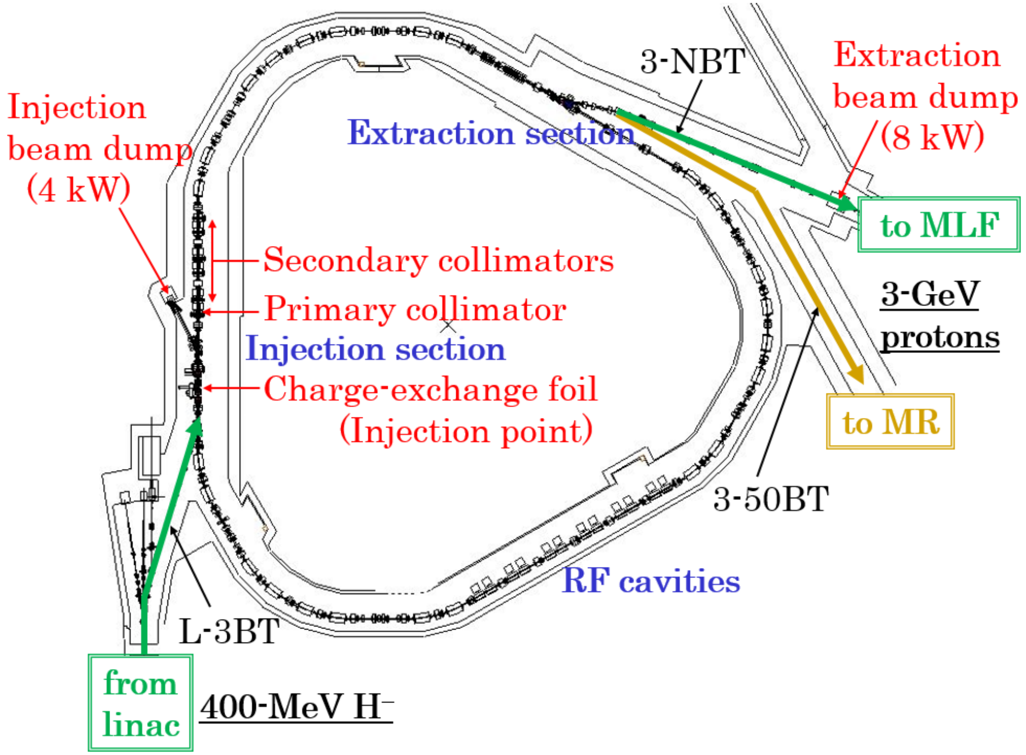
Injection peak current : 50 mA

Extraction energy : 3 GeV

Repetition rate : 25 Hz

Particles per pulse : 8.33 x 10^{13}

Beam power : 1 MW



RCS has two functions:

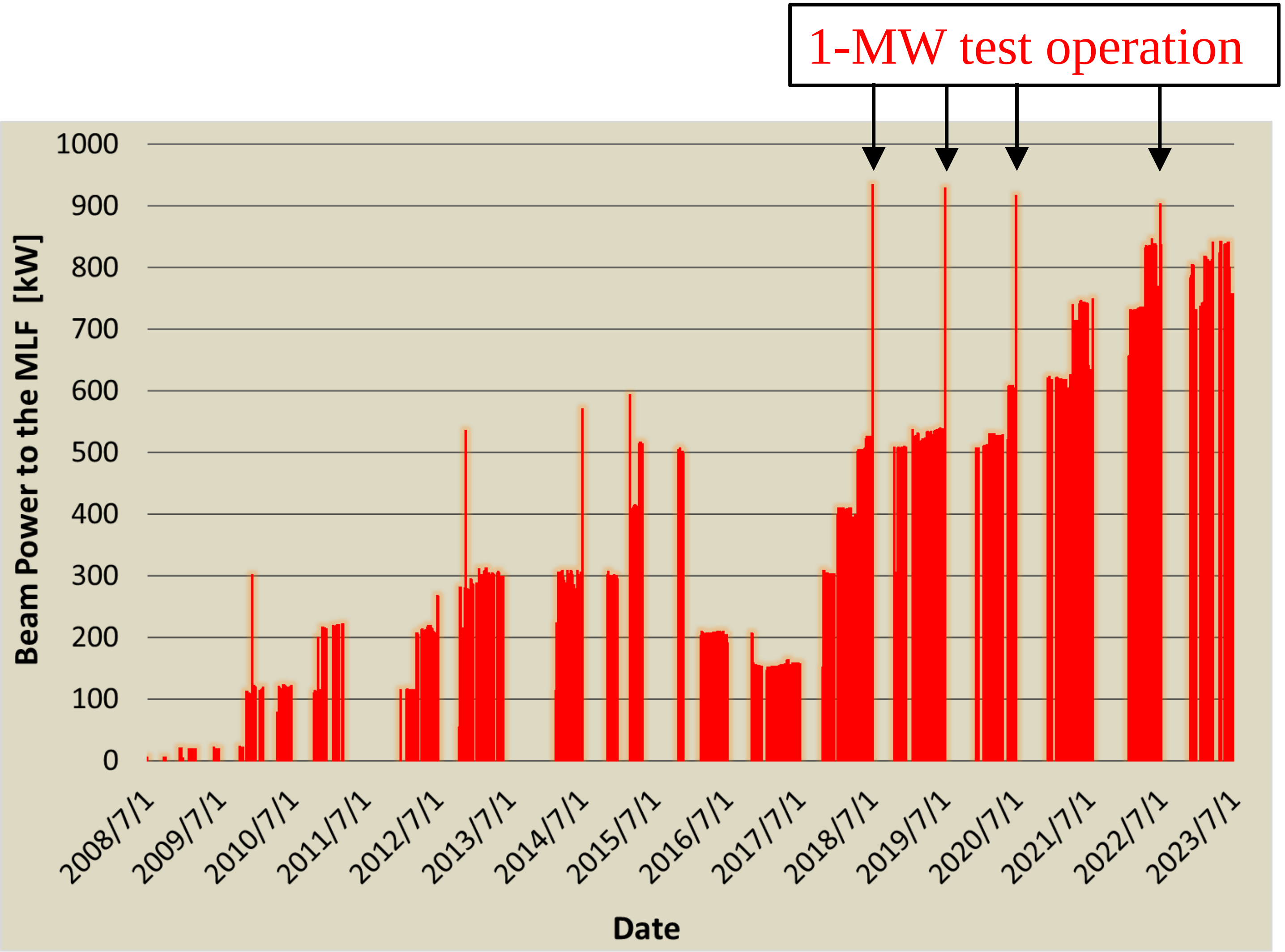
- Proton driver for producing pulsed muons and neutrons at the MLF.
- Injector to the MR.

◆ Beam sharing between MLF and MR ~ 9:1

→ Beam loss mitigation for beam operation to the MLF is essential.

◆ We also need to provide a beam with lower emittance to the MR.

History of the RCS beam power to the MLF



◆ We have demonstrated 1 MW operation at 25 Hz several times.

◆ Beam power to the MLF at present: ~ 1MW
PPP: 8.0E13 ppp → 950 kW-eqv.
(Net beam power: 840 kW at 88% duty.)

- Due to absence of one RF cavity, RF trips occurs at full intensity operating at 25 Hz.
- The beam intensity is thus slightly reduced.
- It will be back in service from April 2024.

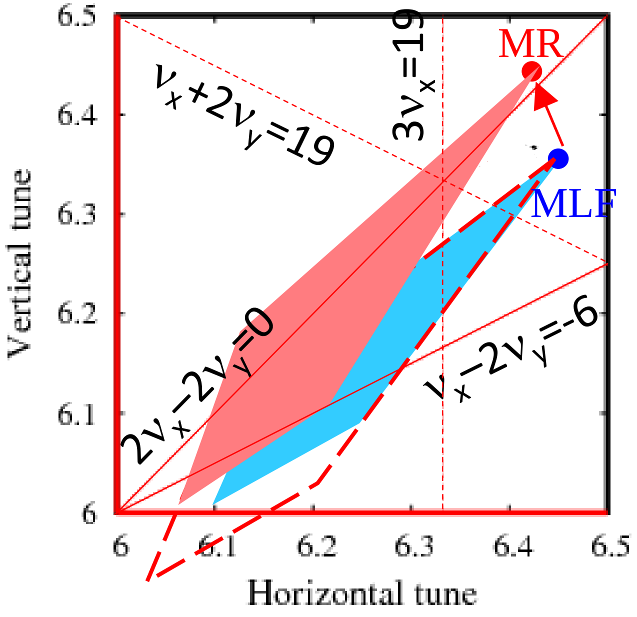
Operational strategy of the RCS

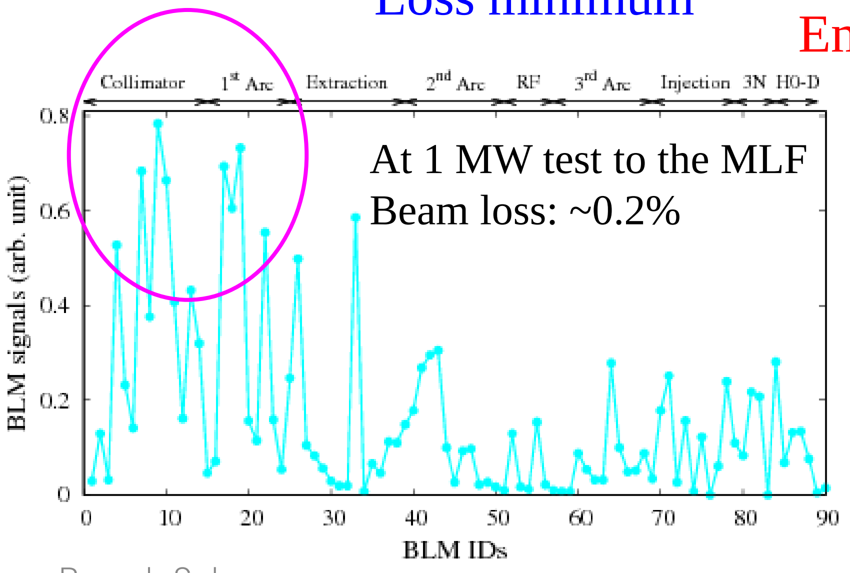
Optimization of many parameters and their switching pulse-by-pulse to the MLF and MR is done according to the demand.

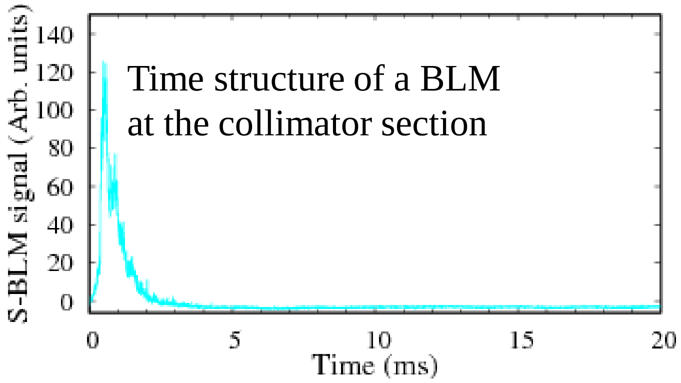
Parameter	For MLF	For MR
Beam power	~1 MW	800 kW-eq. (FX), ~200 kW-eq.(SX)
Tune@ inj. → ext.	(6.46, 6.36) → (6.37, 6.35)	(6.417, 6.447) → (6.37, 6.35)
Transverse painting & type	200π mm mrad (anti-correlated)	50π mm mrad (correlated)
Longitudinal painting	V_2 duration: 6 ms Δp/p offset: -0.15% + RF freq. offset -0.08%	V_2 duration: 7 ms Δp/p offset: -0.15%
Sextupoles	$\nu_x - 2\nu_y = -6$ Resonance correction	**ξ manipulation** Partial cor. at lower energy but extra ξ at higher energy by bipolar Sext. → **SC and beam instability mitigation**

Loss minimum

Emittance minimum



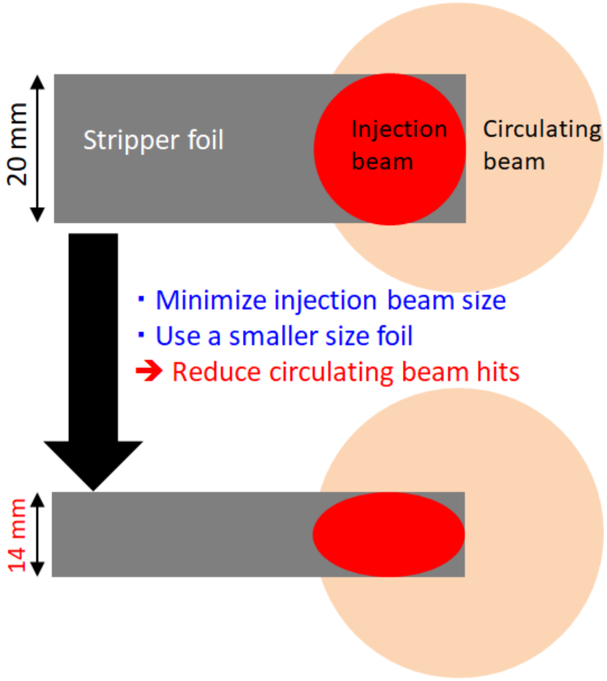


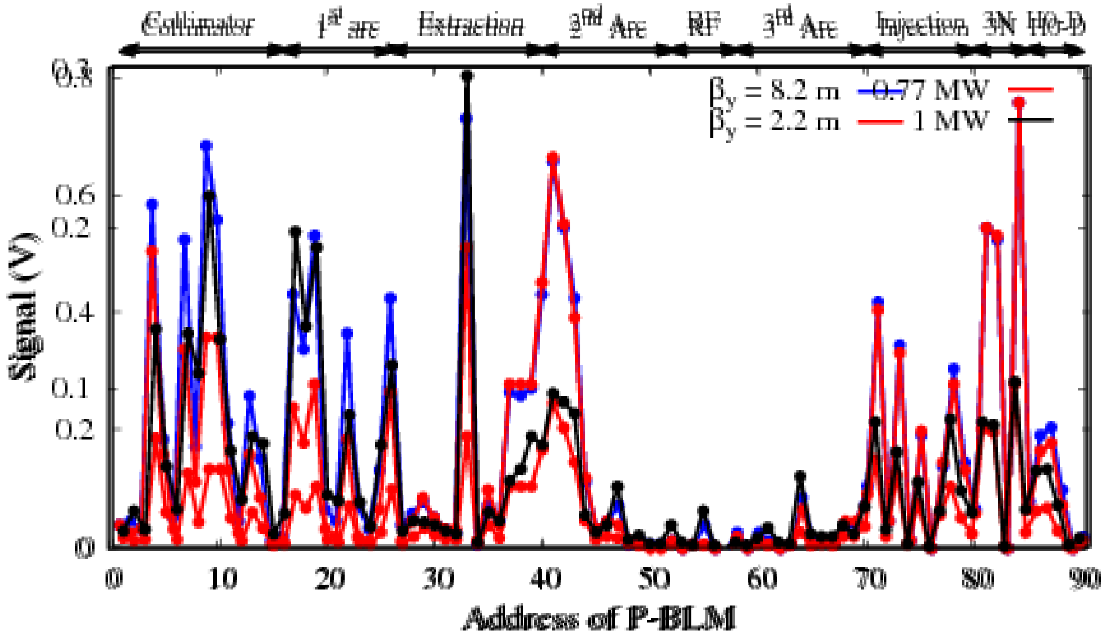


- Beam loss is well mitigated and controlled to occur only at inj. energy and localized mostly at the collimator section.
- However, the residual radiation at the injection, collimator and at the 1st arc sections are still high.
- Further beam loss mitigation is necessary.

Overview of beam loss mitigation measures since 2021

Starting with 0.7 MW, we minimized the injection beam size and placed a smaller size foil.
We obtained a significant beam loss mitigation at the injection, collimator and the 1st arc sections.





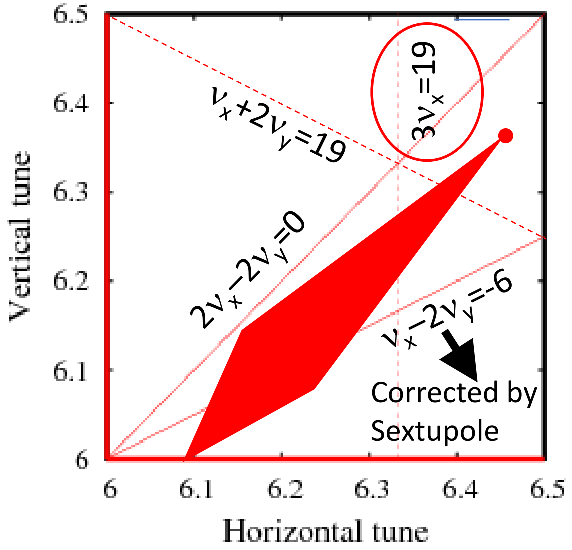
- **However, due to the SC effect, the beam loss at 1 MW was 4 times higher than that at 0.7 MW.**
- ➢ We continued systematic experimental and simulations studies for minimizing the beam loss at 1 MW.

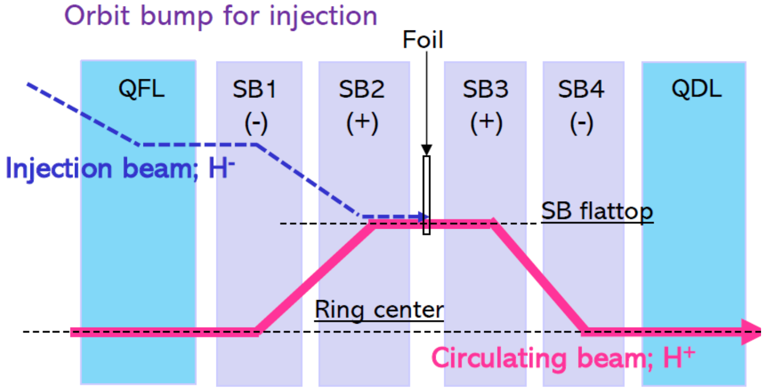
Beam loss mitigation measures at 1 MW:

- Partial correction of the $3\nu_x = 19$ resonance
- Optimization of the LP
- Modification of the TP
- Optimization of tune at injection

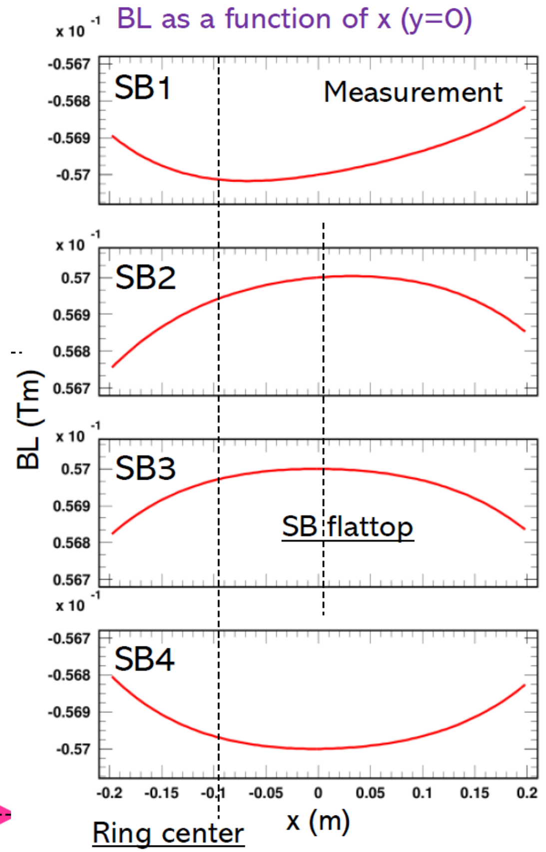
Reduction of the effect of $3\nu_x = 19$ resonance

The $3\nu_x = 19$ resonance is driven by the sextupole field component intrinsic in the injection chicane bumps (**SB**).

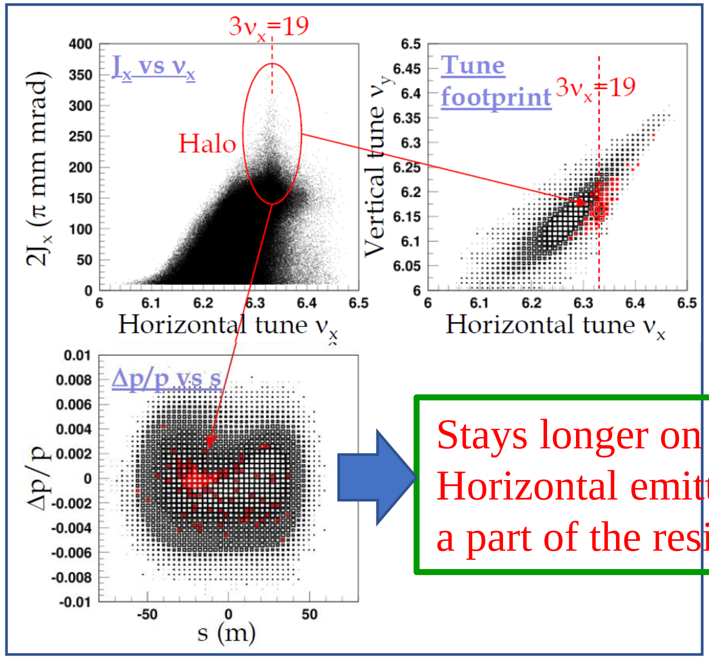




H. Hotchi, HB 2021



Simulation results:



Stays longer on the resonance.
Horizontal emittance growth making a part of the residual beam loss.

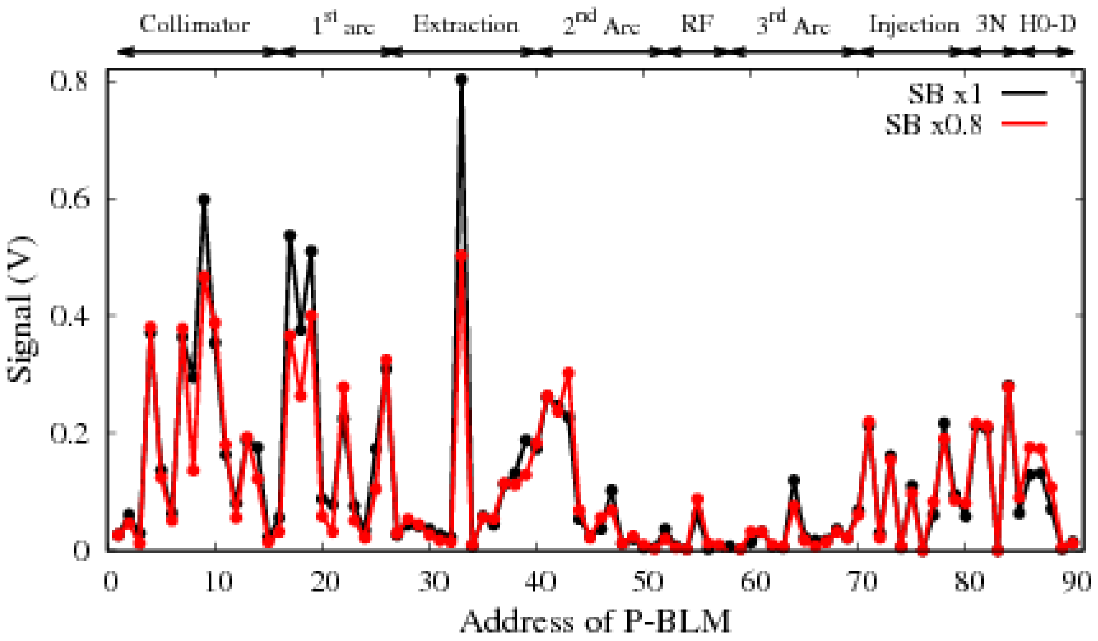
— Dipole fields of SBs are compensated through integration over SB 1-4
— But for higher order field components, such a compensation is incomplete due to magnetic interferences in reality.

◆ **Remains K2 = 0.012 m^{-2} and excites $3\nu_x=19$**

No additional sextupoles exist for correction.
→ Try for a partial correction by 20% reducing the SB magnetic fields.

Beam test with SB ×0.8

For direct suppression of the SB effects by applying 20% less magnetic field.
(Further reduction difficult due to injection matching)

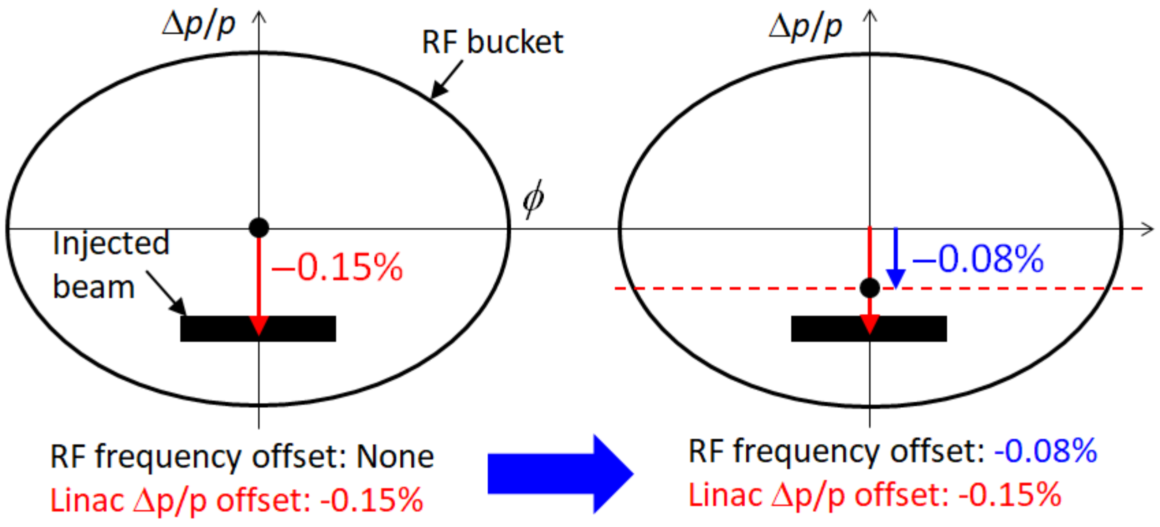


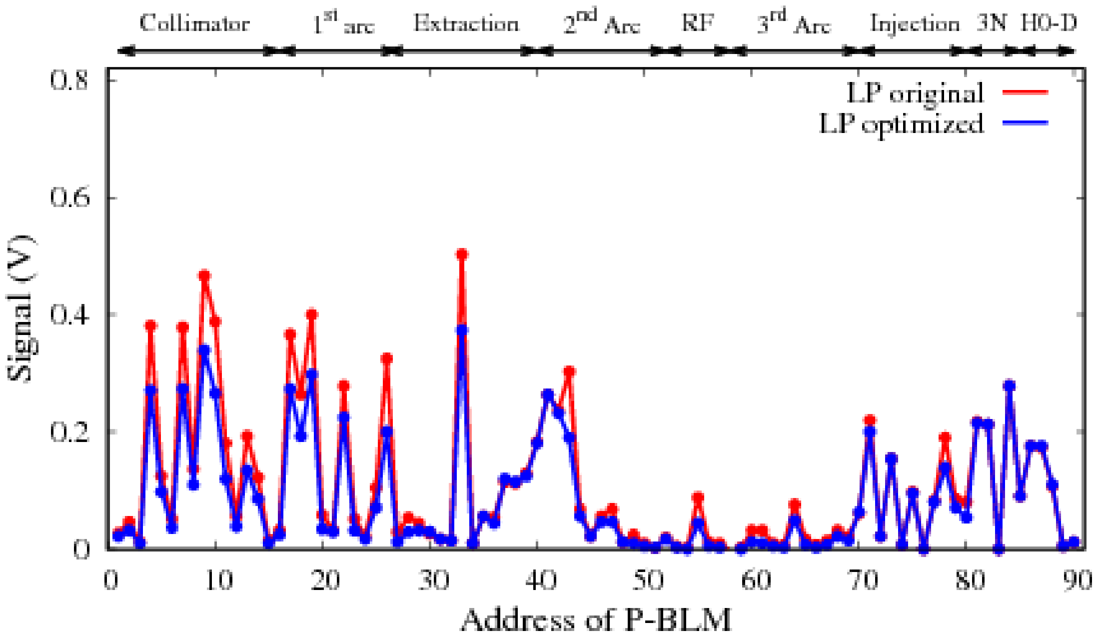
- ✓ The SB with ×0.8 gives ~**20% beam loss mitigation** at the collimator and 1st arc sections.
- ✓ The hori. rms beam **emittance also 10% reduced**.

-- It has other advantages such as H0 excited state loss in the SB field, beta beating……

> ✓ SB with×0.8 magnetic fields has already been implemented to the RCS operation.

Optimization of the Longitudinal painting (LP)





✓ Optimization of the LP gives further **30% beam loss mitigation.**

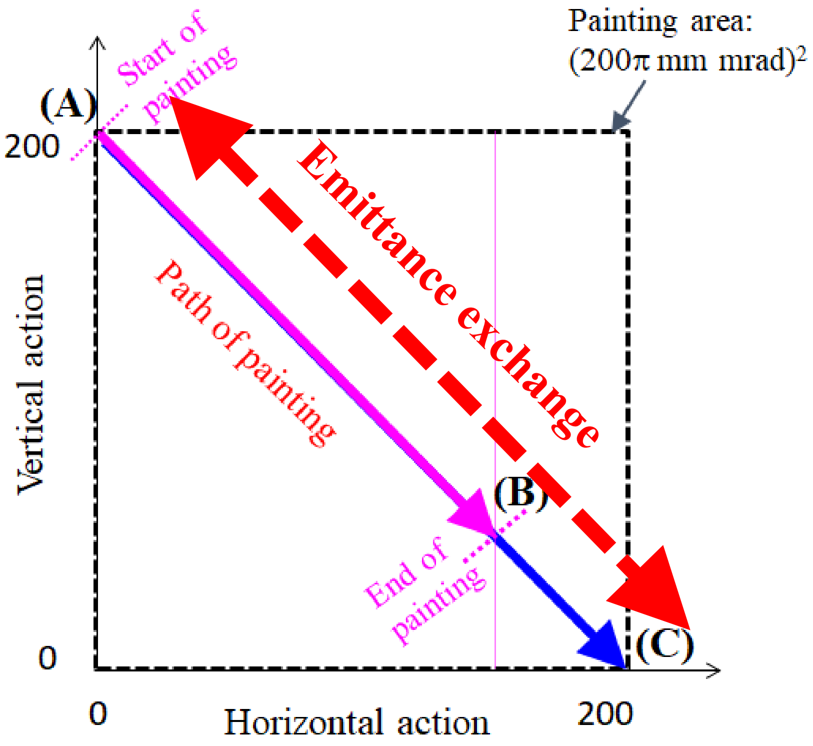
◆ However, the beam emittances remain unchanged.

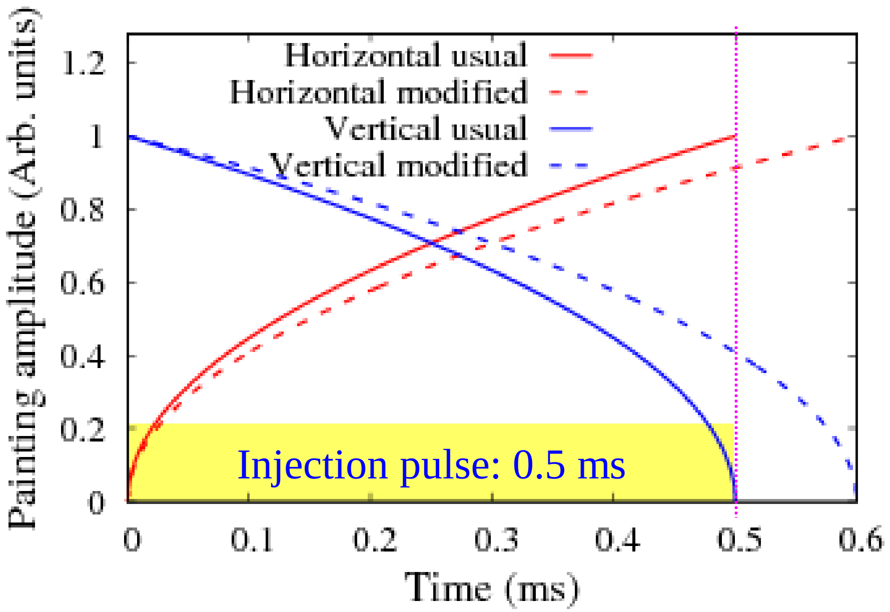
✓ Therefore, the longitudinal beam motion improved and reduced the longitudinal beam halos lost by the chromaticity effects.

➢ Longitudinal beam halos reduced in the simulation for an optimized LP.

Optimization of the Transverse painting (TP)

- TP is optimized by modifying the range of beam painting (AC → AB)
- The unpainted region is filled by the emittance exchange due to the SC effect.
- The spatial charge concentration of the transverse beam distribution (mainly vertical) can be reduced.
- Produce a symmetric tune distribution to reduce particles trapping on the resonances.

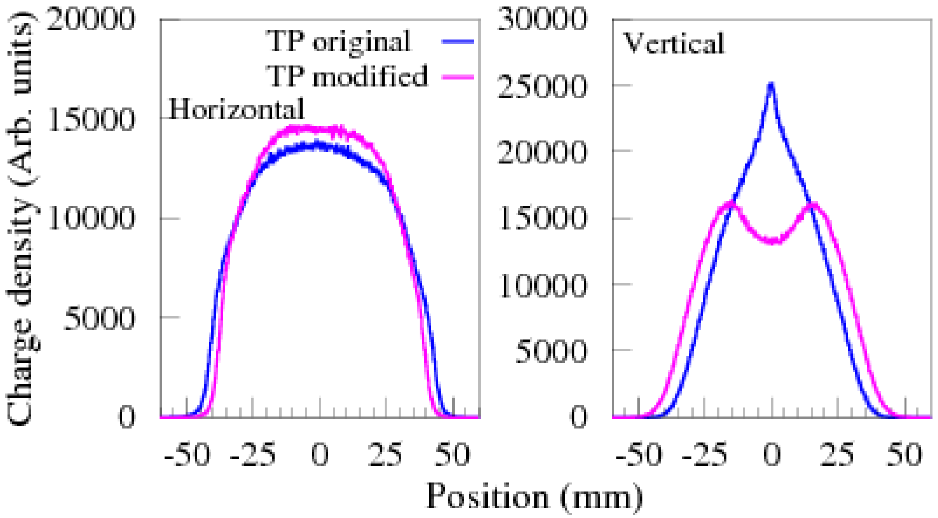


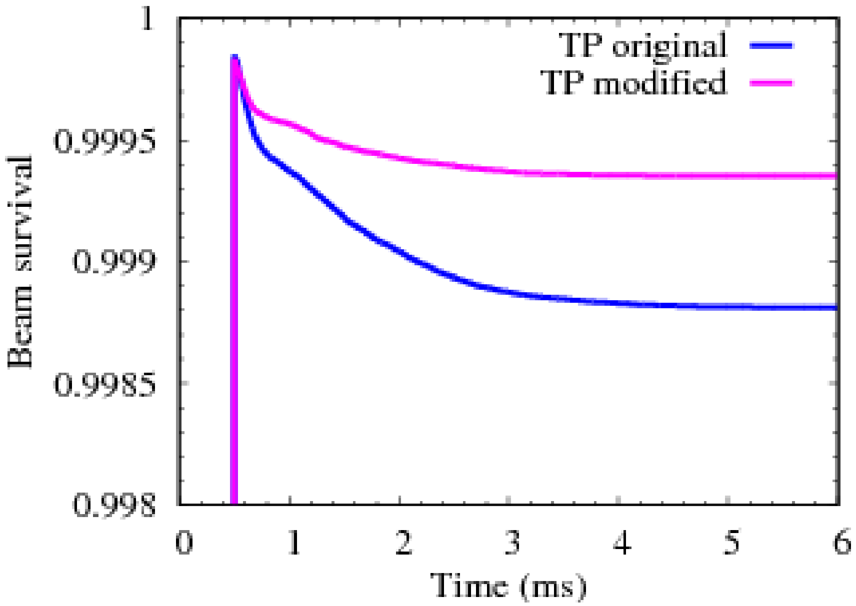


Simulation results by optimizing the TP

Beam profiles at the end of injection.

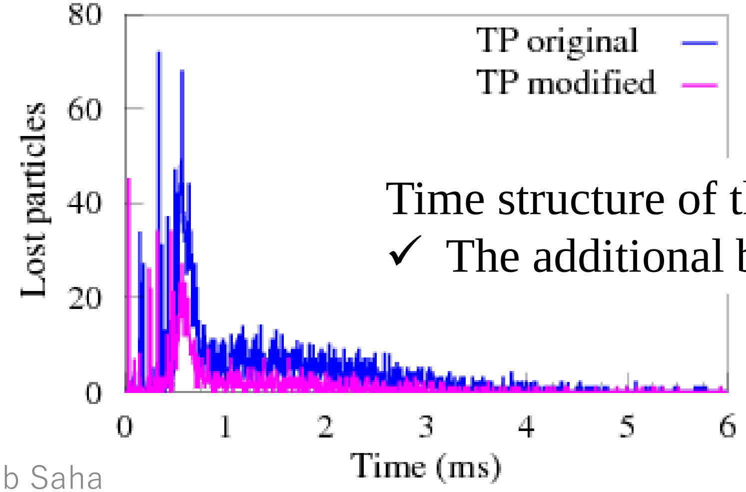
✓ Minimized vertical spatial charge concentration.





Beam survival at 1 MW.

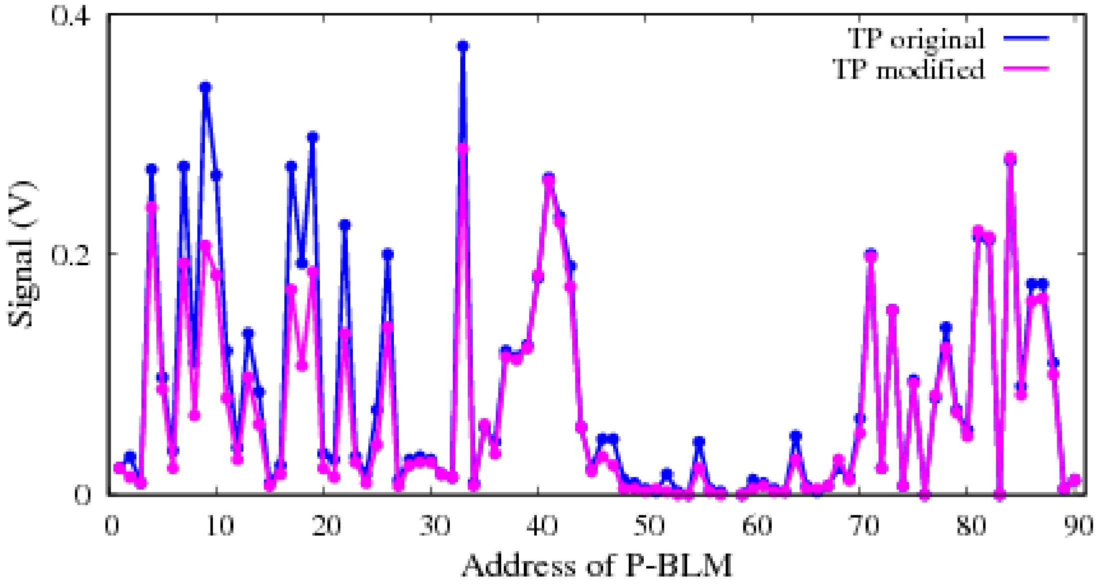
✓ Beam survival is more than 40% improved by applying a modified TP.



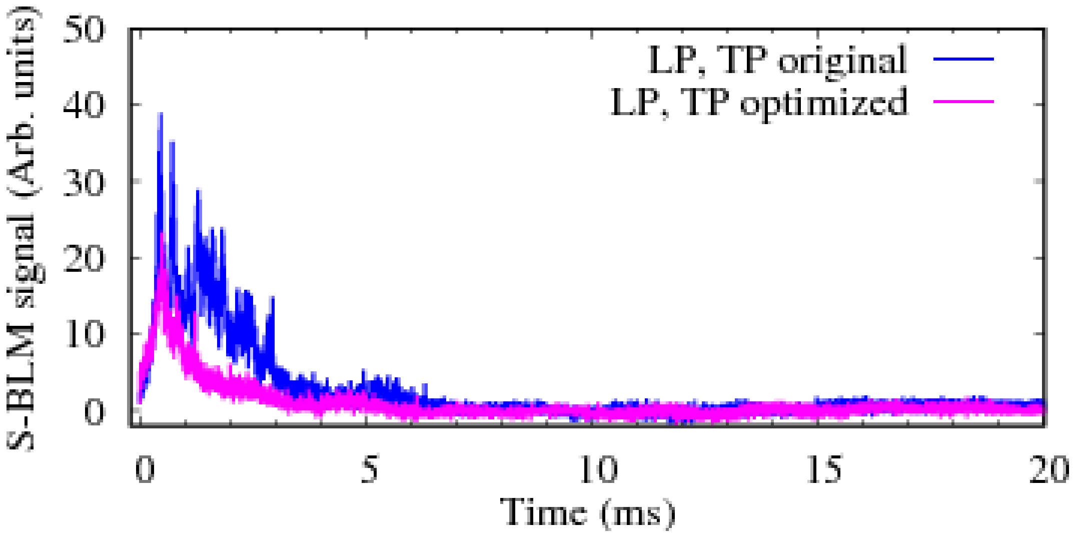
Time structure of the beam loss.

✓ The additional beam losses have almost mitigated.

Measurement results by modifying the TP

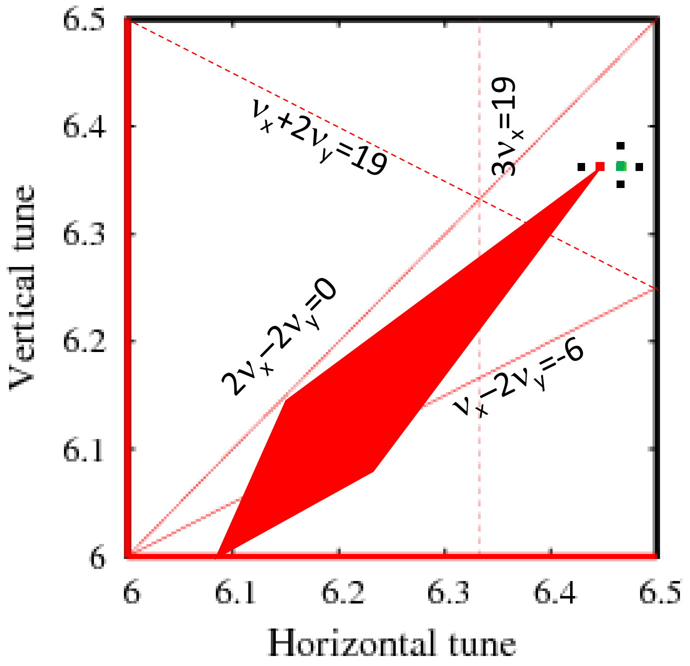


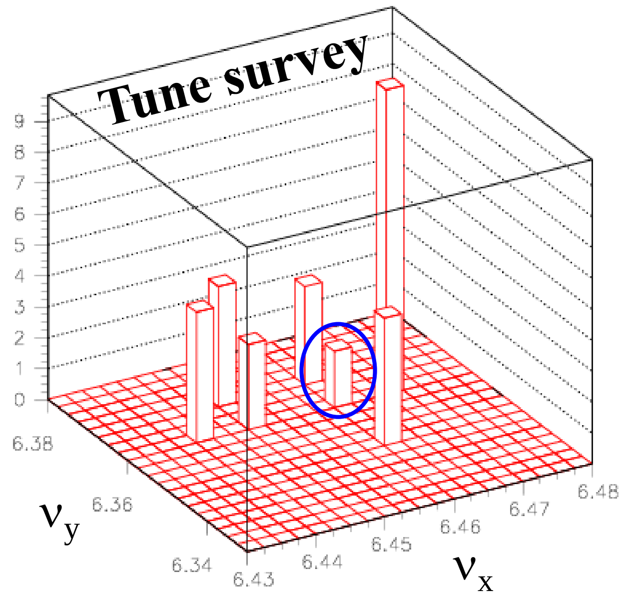
Time structure of the beam loss measured by a plastic scintillator at the collimator section.



- ✓ As expected, the beam loss at 1 MW is further ~35% mitigated by applying a modified TP.
- ✓ The rms emittance of the extracted beam (horizontal) is also ~20% improved.

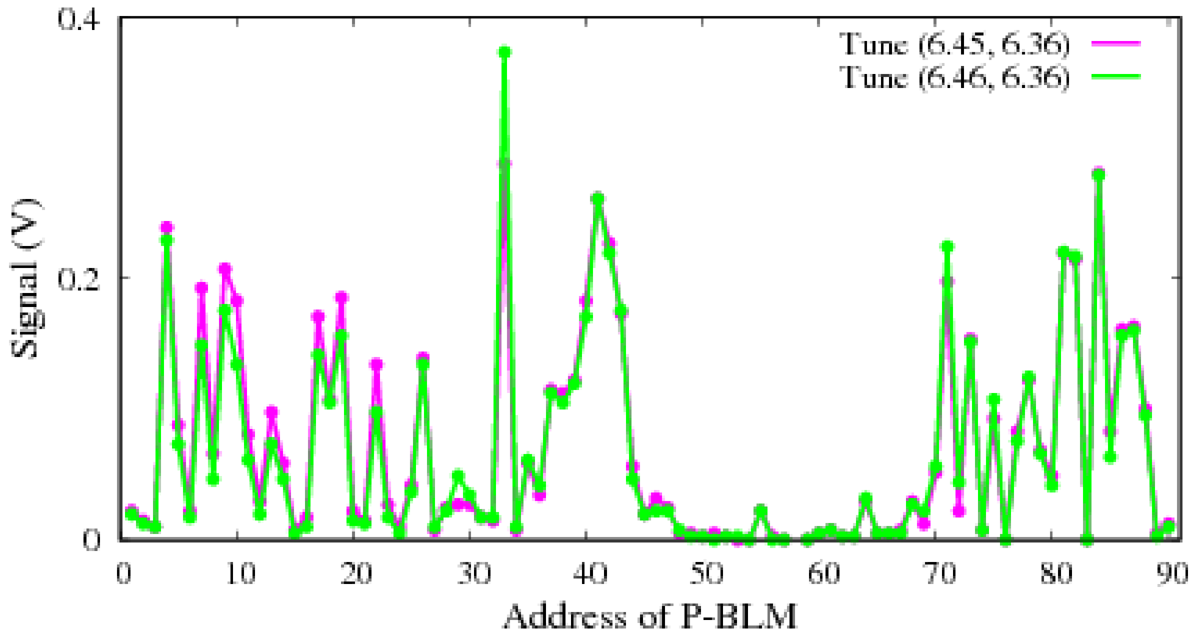
- ✓ The beam loss remains only around injection period caused by the foil scattering.





Optimization of the betaron tune at injection

Tune at inj.: (6.45, 6.36) → (**6.46, 6.36**)

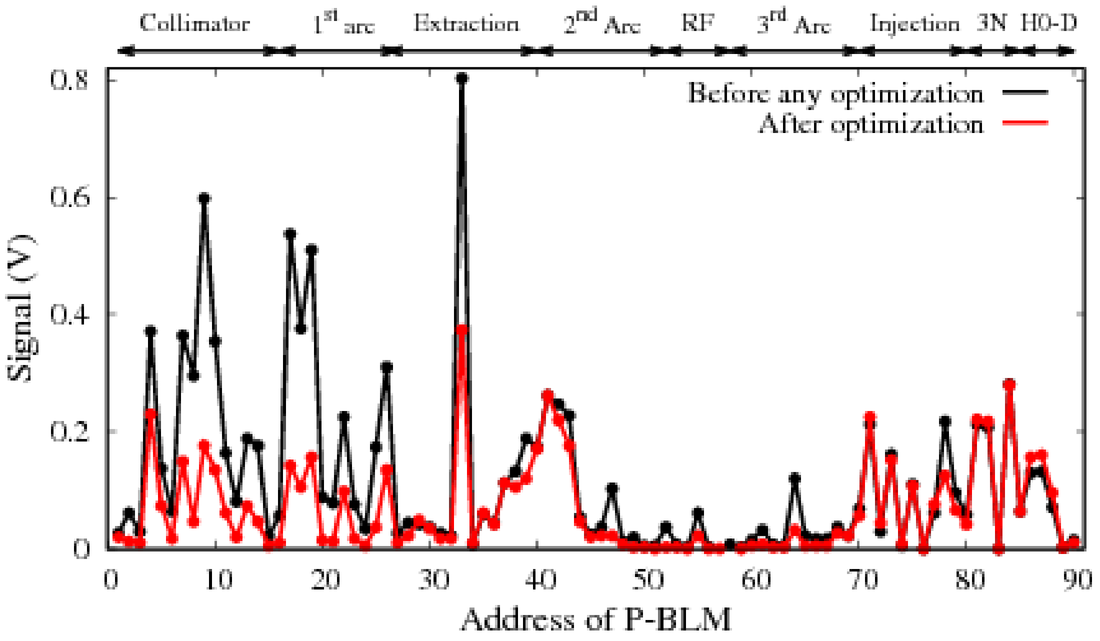


- ✓ Obtained another ~20% beam loss mitigation by tune optimization.
- ✓ Extracted beam emittance was also slightly improved.

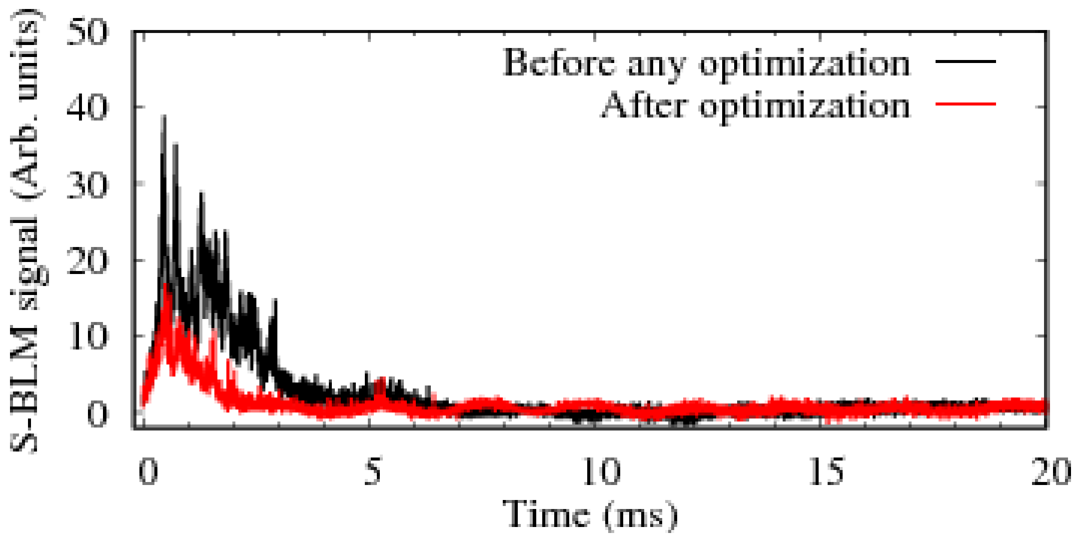
- ✓ Based on the tune survey, the present optimized one (6.46, 6.36) gives a minimum beam loss.

Summary of beam loss mitigation for a smaller β_y

- Partial correction of $3\nu_x = 19$ resonance
- LP optimization,
- TP modification
- Tune optimization



Time structure of the beam loss.



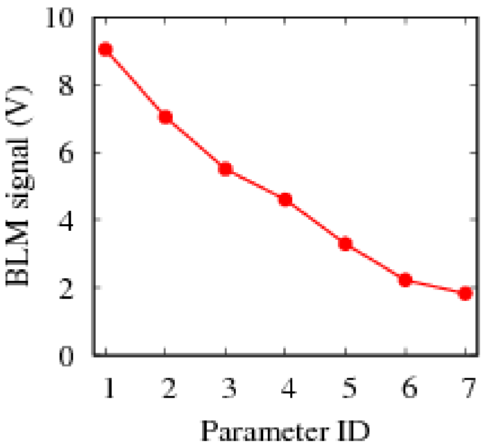
✓ We have obtained ~70% beam loss reduction at 1 MW by using a smaller injection β_y with a smaller size foil and implementing some important optimizations of the machine parameters by sufficient mitigation of the SC.

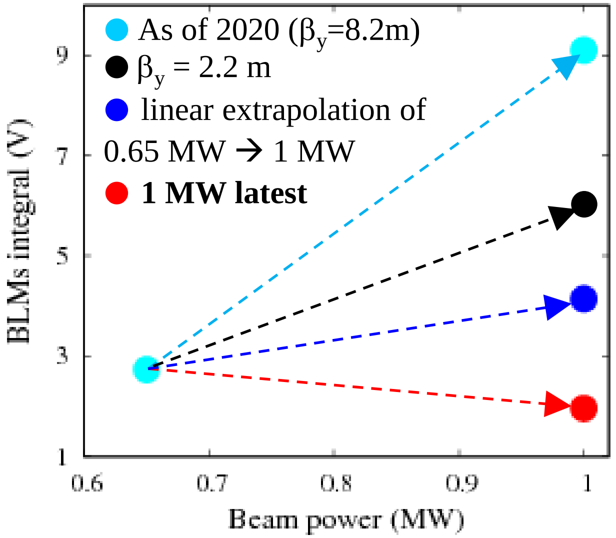
✓ The residual beam loss is mainly due to the foil scattering of the circulating beam.

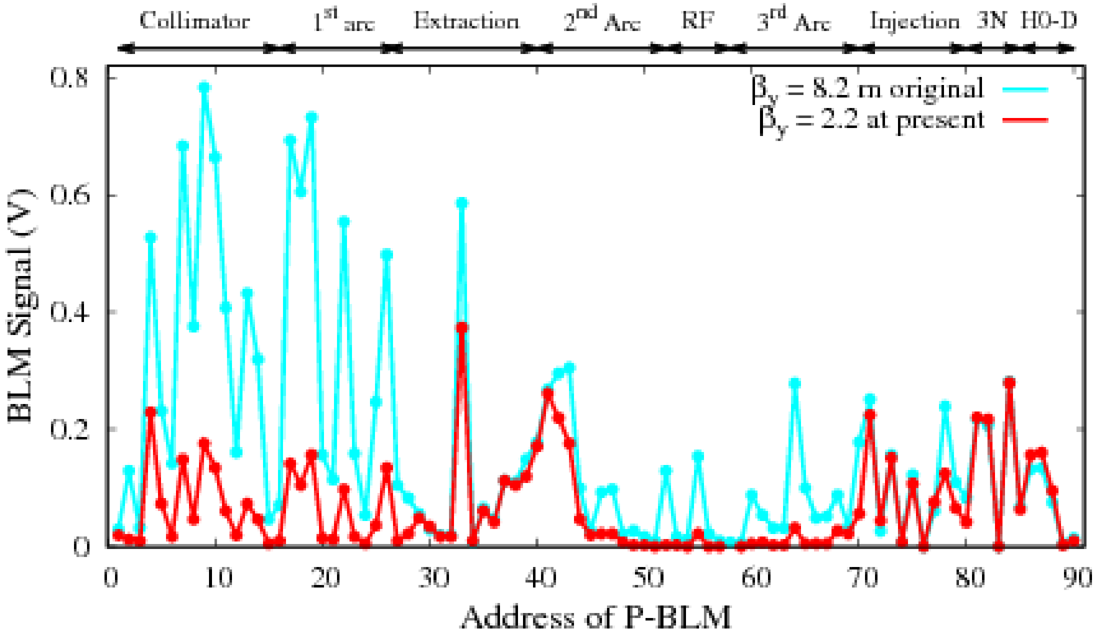
✓ The rms emittance of the extracted beam is also ~25% improved.

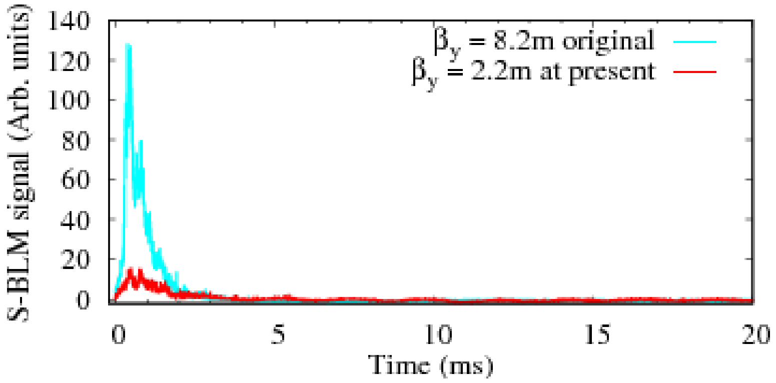
Beam loss mitigation as compared to previous 1 MW operation

ID	Parameters	BLMs integral (V)
1	Original: Tune (6.46, 6.32), β_y = 8.2m	9.04
2	Tune: (6.45, 6.36) LP by Δp/p offset of inj. beam	7.05
3	β_y = 2.2m ; Foil Vert. 20mm → 14mm	5.5
4	SB x0.8 for $3\nu_x$ = 19 partial correction	4.6
5	LP optimization (LI Dp/p + RF freq. offset)	3.28
6	TP modification	2.22
7	Tune optimization	1.82









- The residual beam loss is <<0.1%, caused by the foil scattering.
- ➢ The SC effect has sufficiently been mitigated.
- *A laser stripping can thus give almost no beam loss at 1MW!*

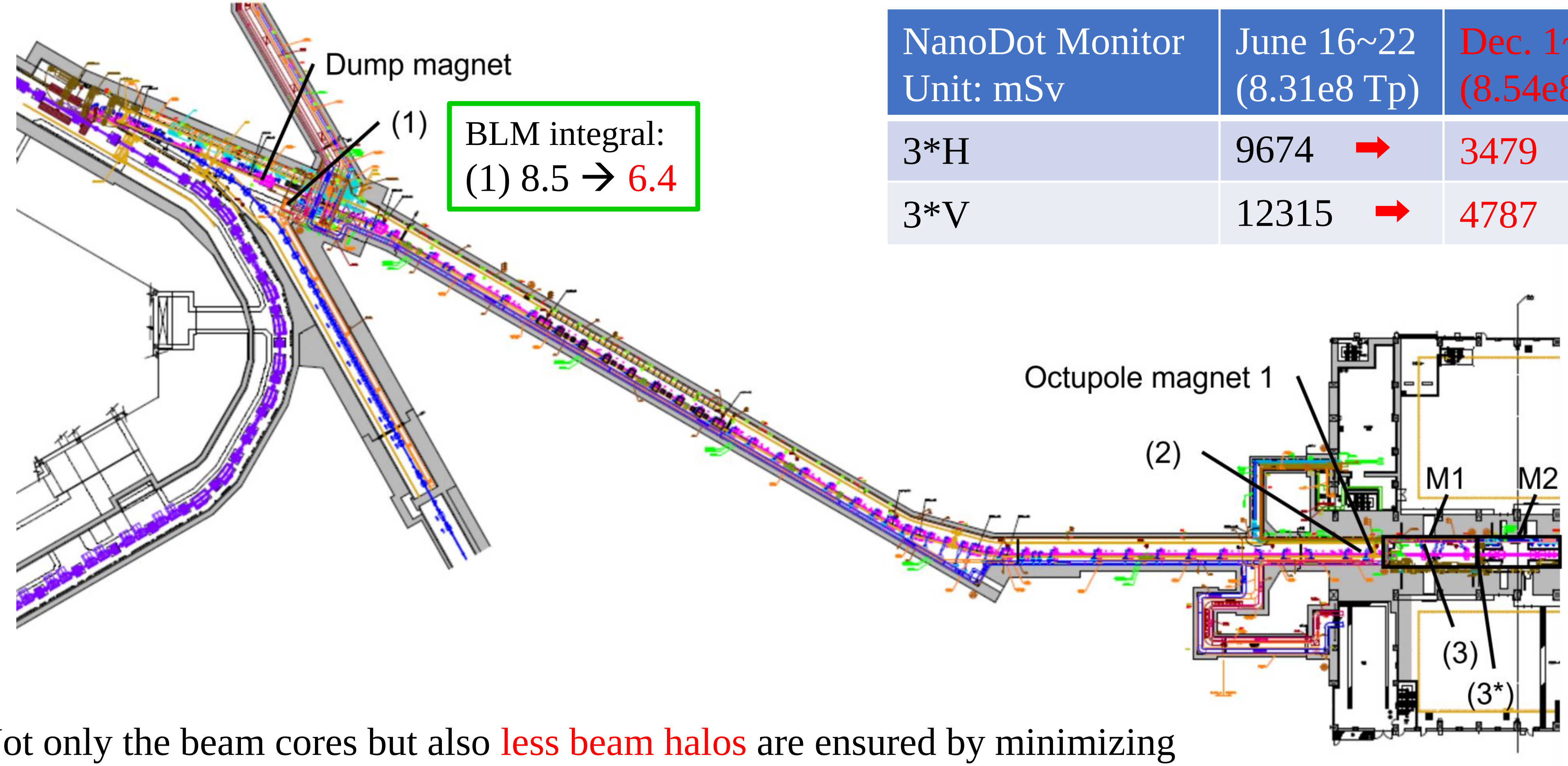
✓ Obtained 80% beam loss mitigation as comparted to the previous 1 MW test operation.

✓ Extracted beam emittances (rms) also >30% improved.

Beam loss reduction at the extracted beam transport (3-NBT)

Courtesy: Y. Yamaguchi, S. Meigo

NanoDot Monitor Unit: mSv	June 16~22 (8.31e8 Tp)	Dec. 1~7 (8.54e8 Tp)
3*H	9674 ➡	3479
3*V	12315 ➡	4787



✓ Not only the beam cores but also less beam halos are ensured by minimizing foil hits and optimizing many parameters in the RCS.

➢ Useful for beam broadening (flat beam) by Octupole magnets at the 3-NBT.

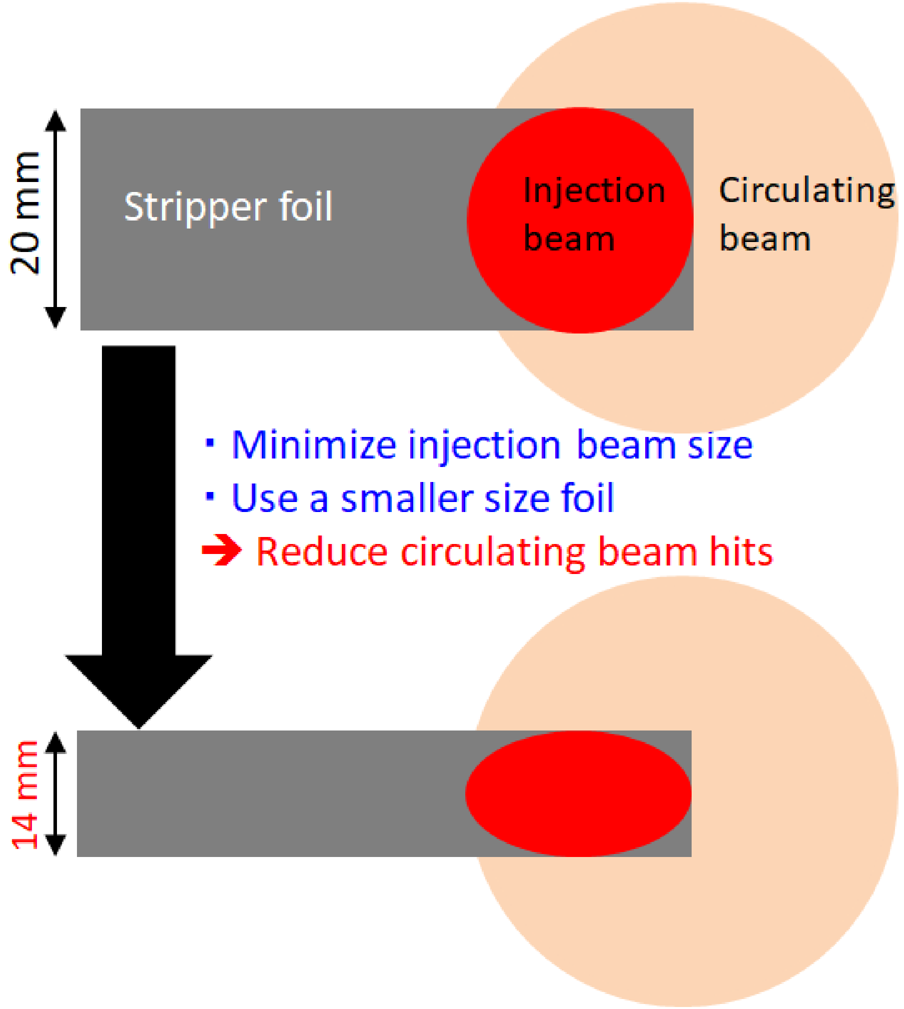
Summary and outlook:

- We have implemented a smaller size foil by minimizing the injection beam size and obtained nearly 40% beam loss mitigation at the injection, collimator and the 1st arc sections at 0.7 MW.
- However, due to the SC effect at 1 MW, the beam loss is 4 times higher than 0.7 MW for only around 40% increase of the beam intensity.
- We have done systematic studies for resonance correction, optimization of the LP and TP as well as the tune at injection.
  - We have obtained 80% beam loss mitigation at 1 MW and more than 30% improvement of the rms emittances of the extracted beam emittance as compared to that of previous 1 MW trail operation.
  - The residual beam loss is <<0.1%, occurs only at injection period mainly caused by the foil scattering.
  - Less beam loss at the extracted BT has also been ensured by reducing the beam halos.
  - We are now operating at ~1 MW beam power to the MLF with a minimum beam loss and less machine activation.
  - That allows us a sustainable operation of the RCS with 99% availability.
- We aim to mitigate any remaining additional beam losses by correcting all other resonances including the half-integer resonance as well as the foil scattering loss by a using a further smaller size foil.

Backup slides

Approaches for uncontrolled beam loss mitigation

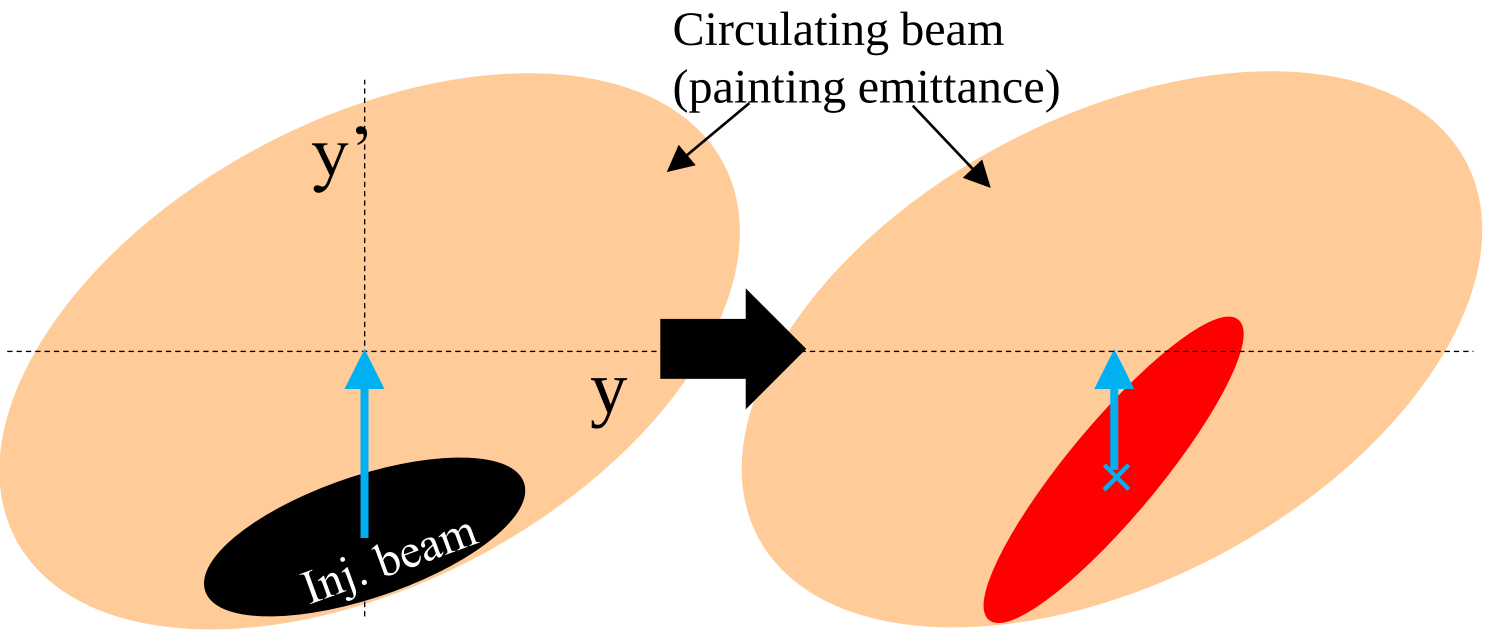
1. Minimize foil scattering beam losses by reducing foil hits of the circulating beam.



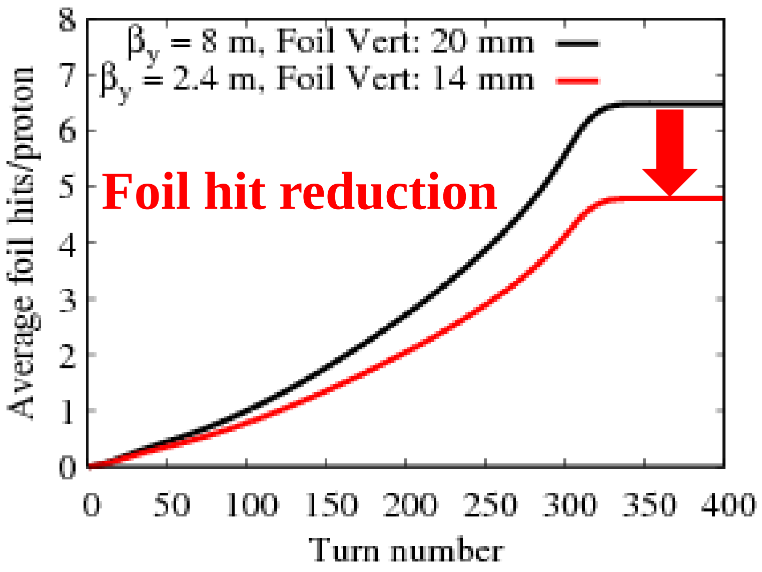
2. Optimize transverse painting (vertical)
to reduce large amplitude particles (beam halos).

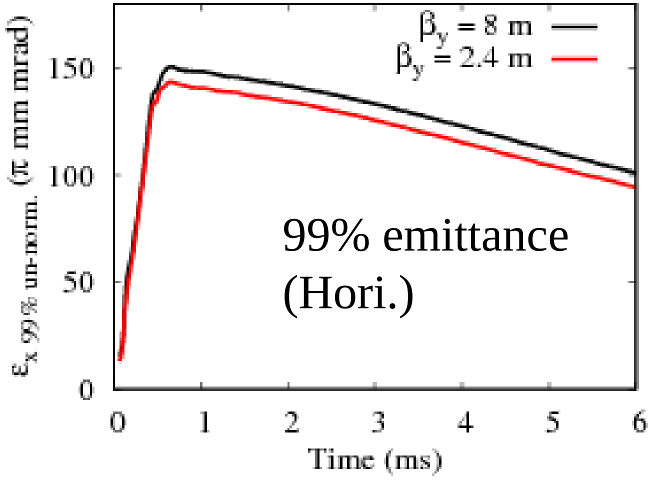
Y' of the injection beam is varied during injection for vertical painting.
The edge of the injection beam determines the painting area.
For a smaller β_y, the injection beam can be put more inside of the circulating phase space.

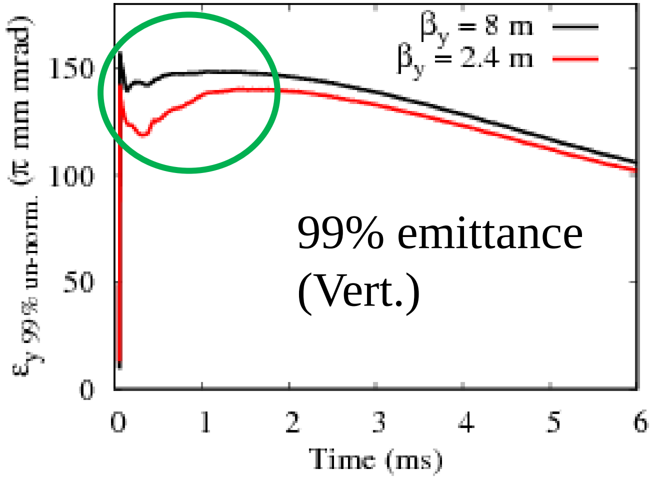
→ Reduce large amplitude particles.



Simulation results at 700 kW



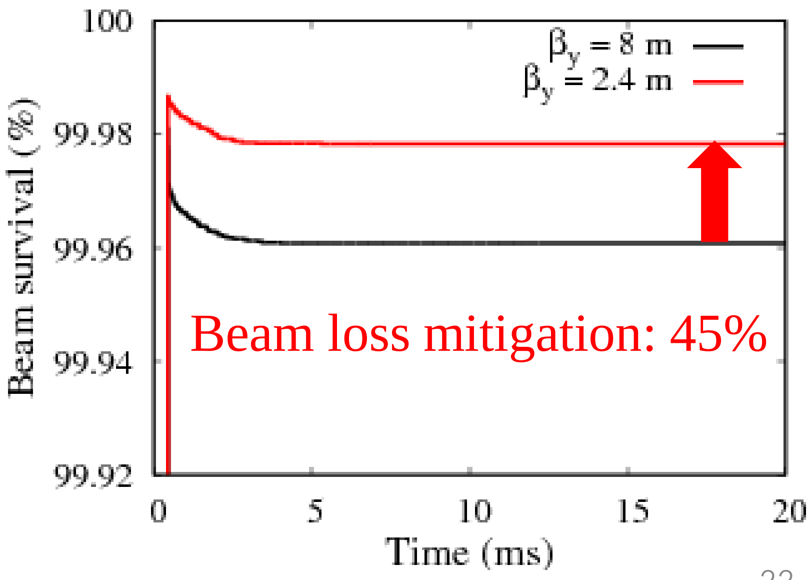




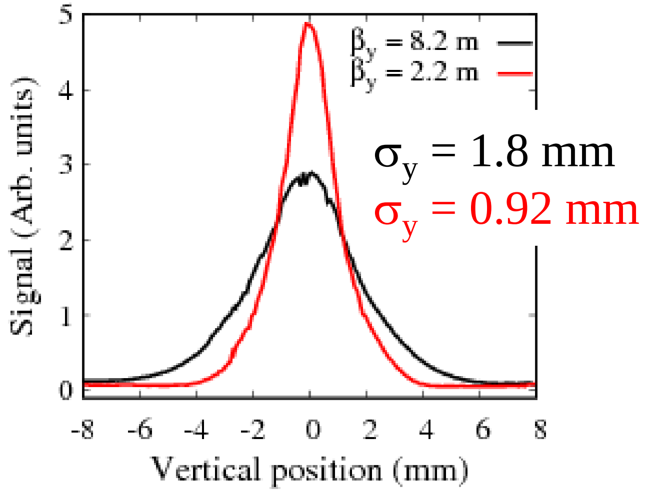
◆ Foil hit can be reduced to 27% by minimizing injection β_y and using a smaller size foil.

◆ An optimization of vertical painting area gives a significant reduction of the transverse emittance.

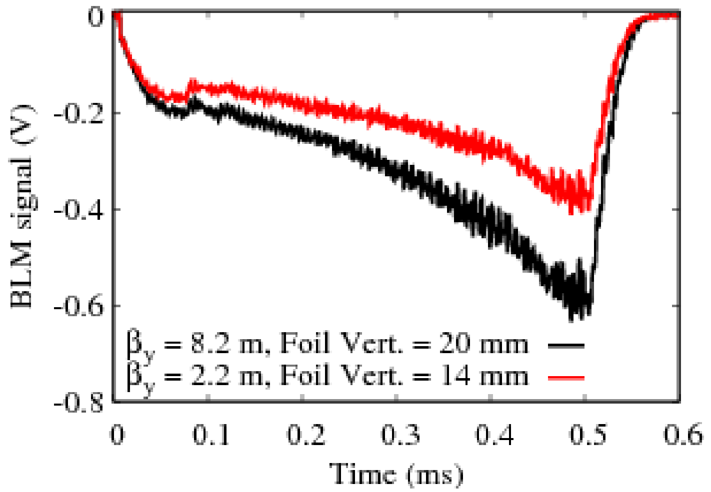
◆ Beam survival at 700 kW is expected to improve by reducing the beam loss as much as 45%.



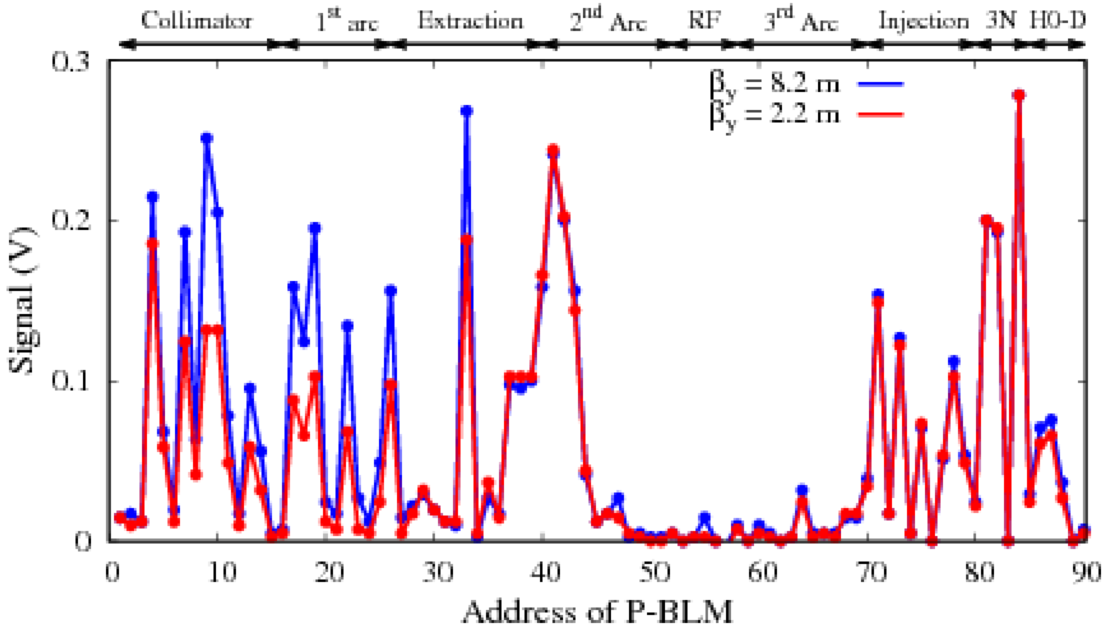
Measurement results at 700 kW



Measured vertical injection beam profile

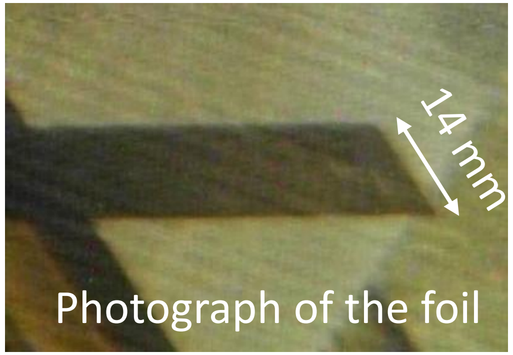


Measured foil scattering loss is 30% reduced.



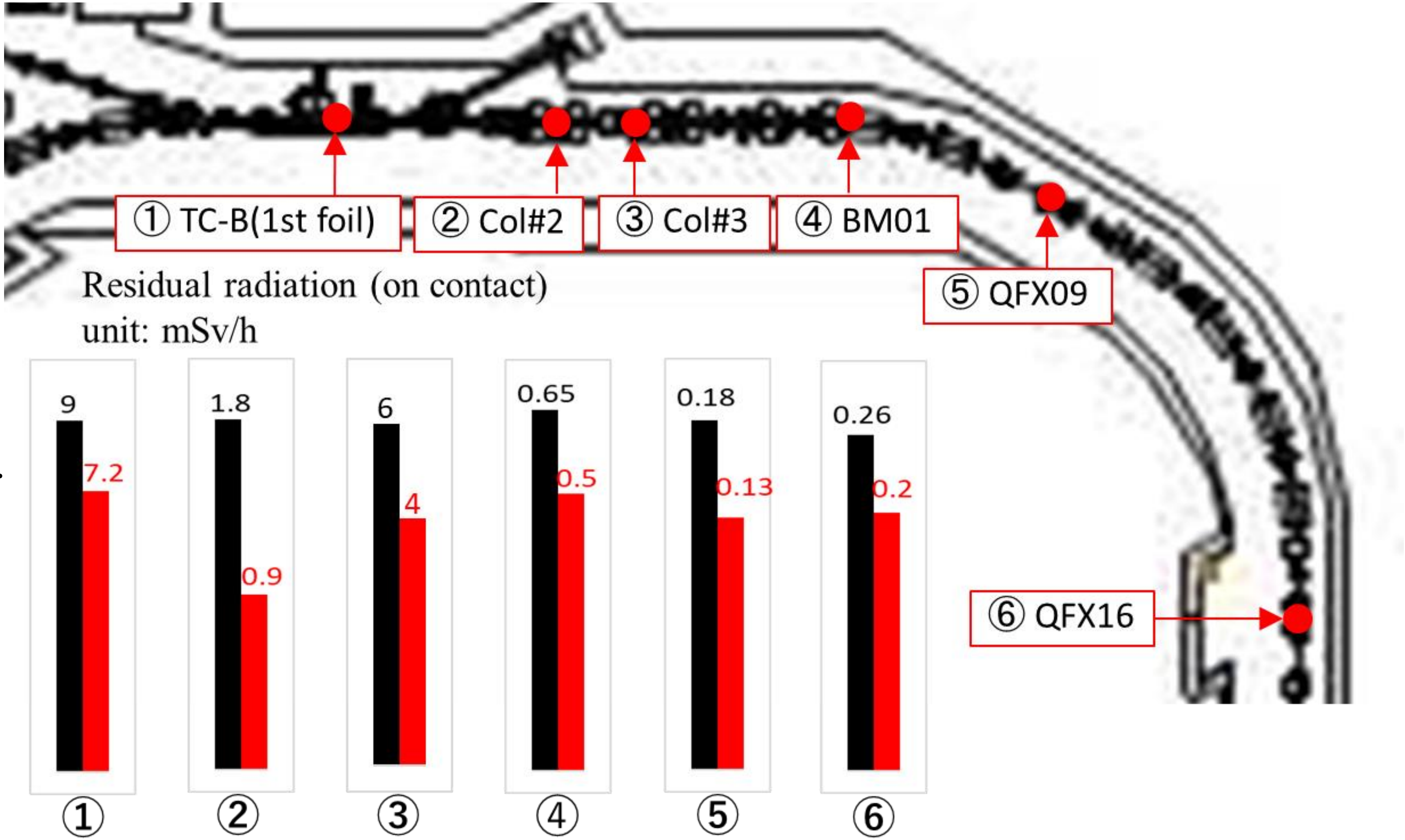
Beam loss at 0.7 MW at the collimator and 1st arc section is 40% mitigated.

Residual radiation by using a smaller β_y for RCS operation



1 month operation each at 700 kW. Measured (on contact) after 4h cooling.

β_y = 8.2 m (black)
β_y = 2.2 m (red)



Residual radiation at injection, collimator section and also at the 1st arc were significantly reduced by implementing a smaller β_y and a smaller size foil.

Beam loss reduction by modifying painting pattern

H. Hotchi,
Phys. Rev. Accel. Beams 23, 050401 (2020)