(Recent) Beam Commissioning of the J-PARC RCS

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MS10奥野プロジェクトワークショップ

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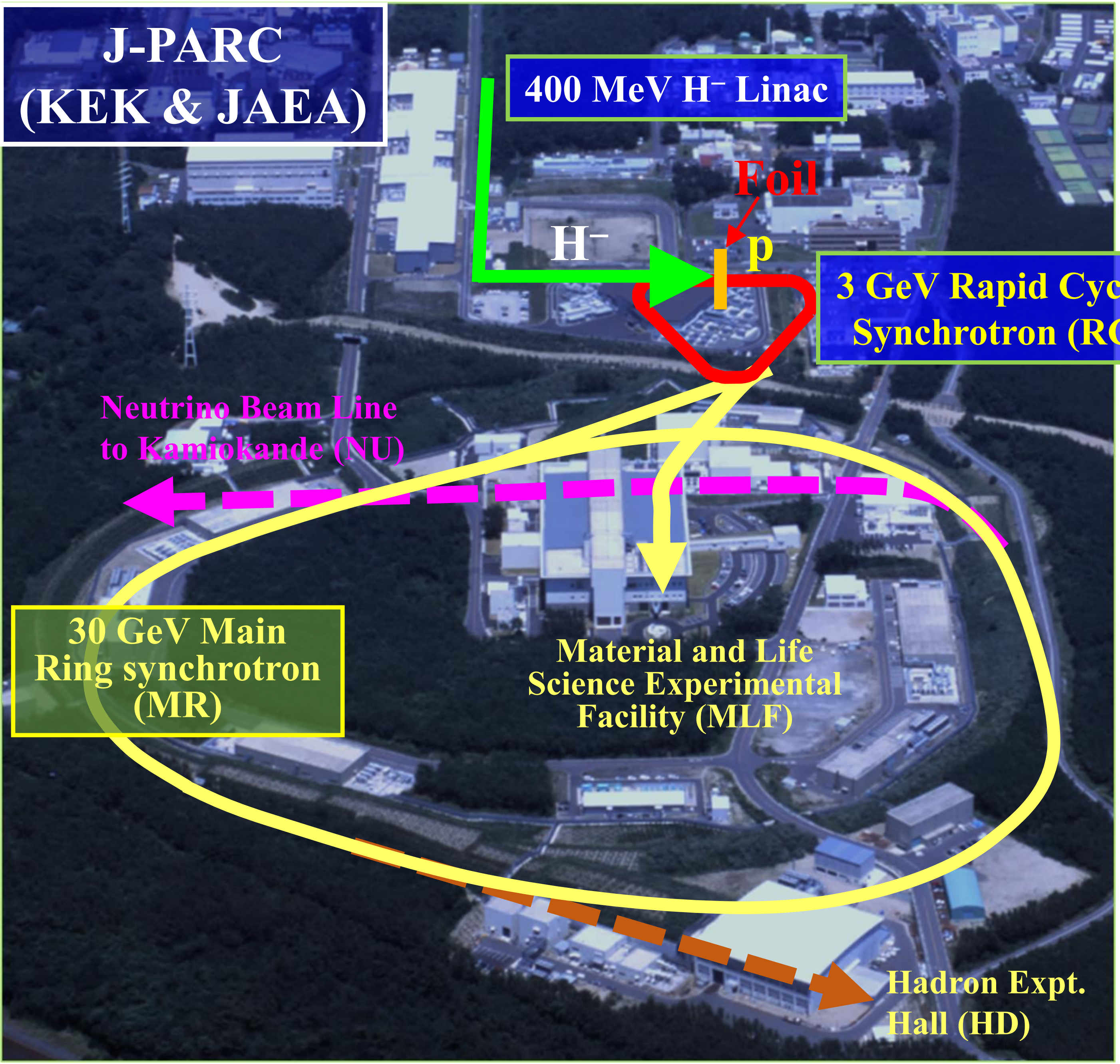
Outline:

- Brief overview of the J-PARC RCS
- RCS commissioning approach and operational strategy
- Minimization of the foil scattering beam losses
- Mitigation of the Space Charge (SC) effect at high-intensity
- Suppression of machine activation and operational performance
- Summary

J-PARC facility



Overview of J-PARC

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

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

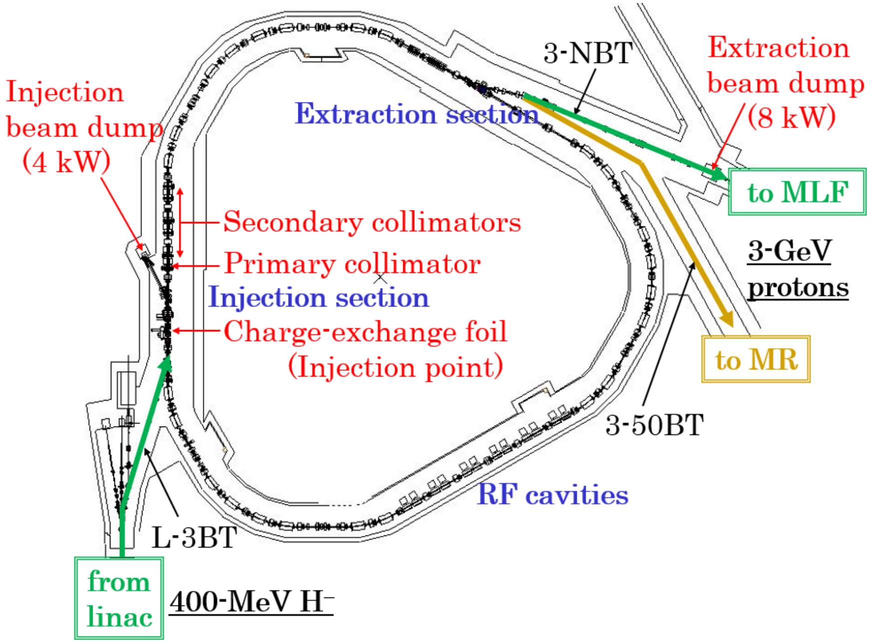
J-PARC provides high intensity proton beams for multi-dimensional experimental research for

◆ Material and Life Science
◆ Particle Physics
◆ Nuclear Physics
…….

Brief overview of the 3-GeV 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
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 btw MLF and MR: 88:12 for MR-FX, 96:4 for MR-SX

➢ **Beam loss mitigation for beam operation to the MLF is highly essential!**

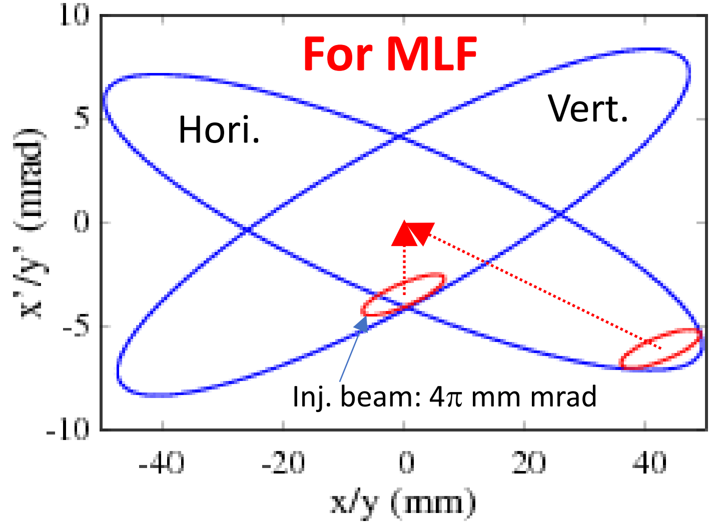
While maintaining

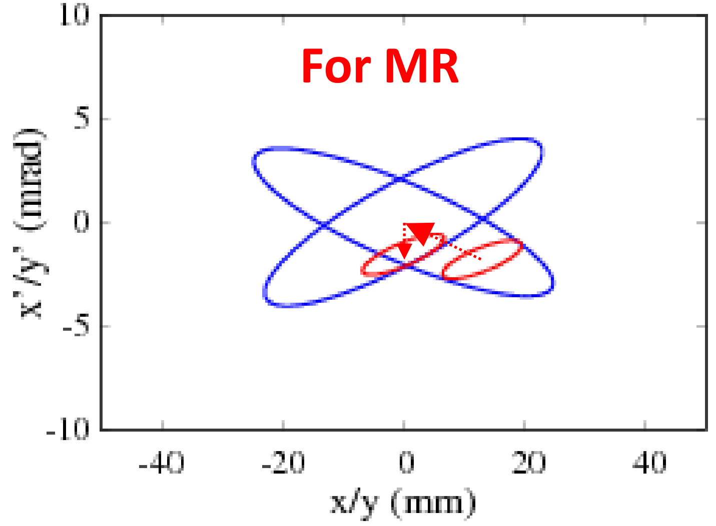
◆ A bigger beam emittance for the MLF to reduce pitting damage of the neutron target.
◆ An extremely smaller beam emittance for the MR to minimize beam loss at the BT and MR.

➢ Transverse painting is changed pulse to pulse for beam emittance control btw MLF and MR.
➢ The SC effect is suppressed by adopting advanced approaches to mitigate the beam emittance growth, beam halos and the loss.

Beam emittance control pulse-by-pulse

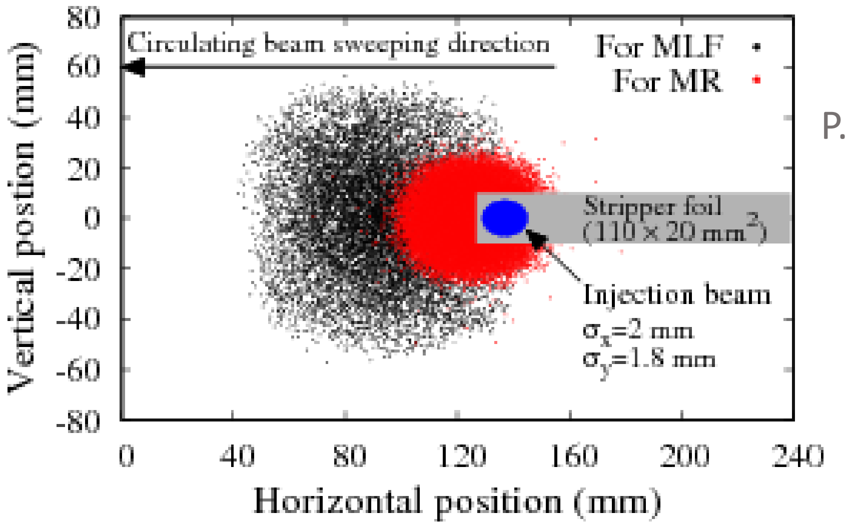
Transverse painting (TP) area and its type are changed pulse-to-pulse mode to control transverse beam emittance between MLF and MR. **Foil scattering strongly depends on the TP area.**





- For MLF: **200π** mm mrad (Anti-correlated)
- For MR: **50π** mm mrad (Correlated)

➢ Foil hitting and the corresponding foil scattering beam loss is significantly higher for the MR beam.



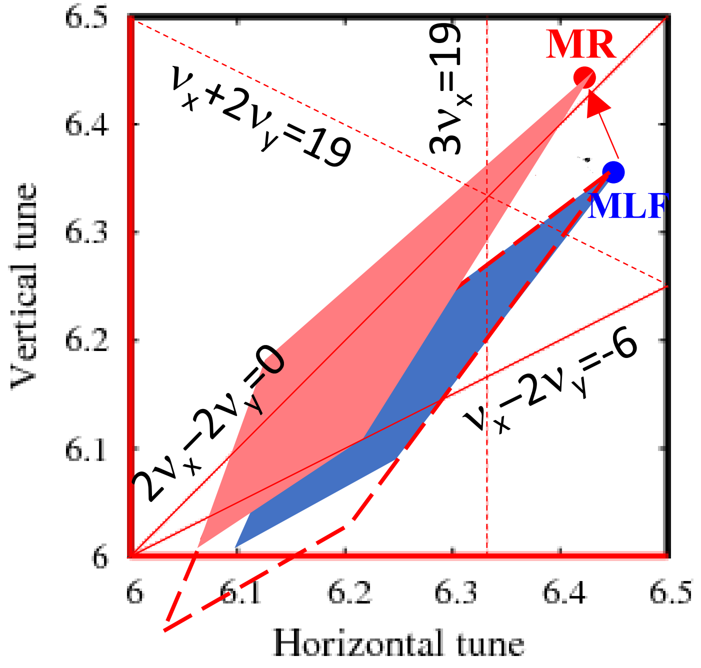
P.K. Saha, PRAB23 (2020)

- Avg. foil hits for MLF is **6.5**, which is **63** for the MR beam.

➢ **Further foil hits reduction is highly essential.**

Beam loss and beam emittance minimization strategy

- The SC and the resonance effects are complicated at high-intensity for simultaneous beam optimizations.
- Systematic studies done for optimization of many parameters and their **switching pulse-by-pulse** for beam loss and beam emittance minimization to the MLF and MR



Tune at injection for the MR is optimized to avoid $\nu_y = 6$

List of main parameters changed pulse-by-pulse

Parameter	For MLF	For MR
Tune at inj. & ext.	(6.46, 6.36) & (6.38, 6.35)	(6.417, 6.447) & (6.38, 6.35) by Trim Quads
Trans. painting (TP) & type	200π mm mrad anti-correlated	50π mm mrad correlated
Longitudinal Painting (TP)	Inj. Δp/p offset: -0.15% 2nd harmonic duration: 6ms RF freq. offset: -600Hz (Δp/p = -0.1%)	Inj. Δp/p offset: -0.15% 2nd harmonic duration: 7 ms RF freq. offset: None
Sextupoles	ν_x-2ν_y = -6 Resonance correction	**ξ manipulation by bipolar Sextupole** Partial ξ cor. at lower energy but extra ξ at higher energy. → SC effect reduction at lower energy and beam instability mitigation at higher energy

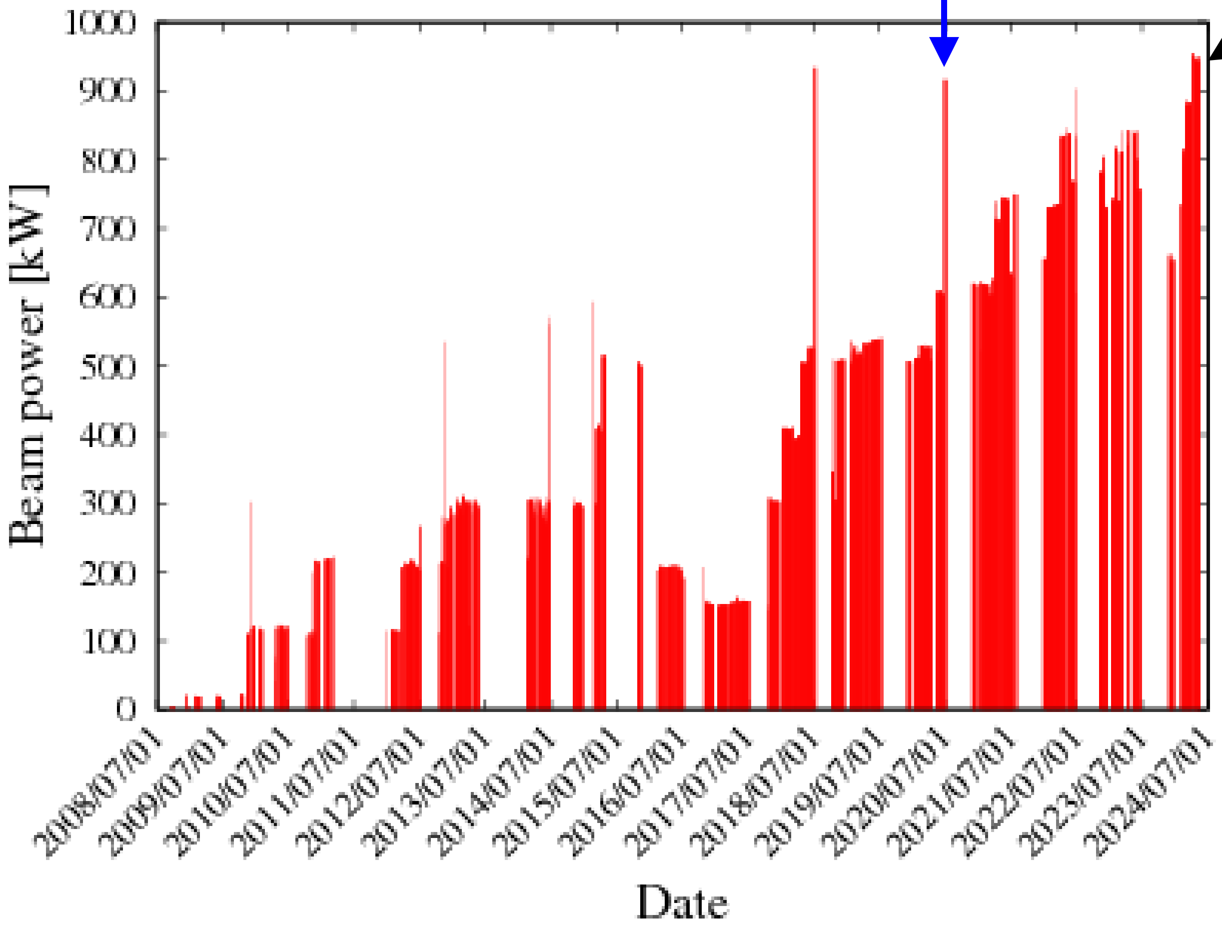
Loss minimum

Emittance minimum

RCS beam power history to the MLF

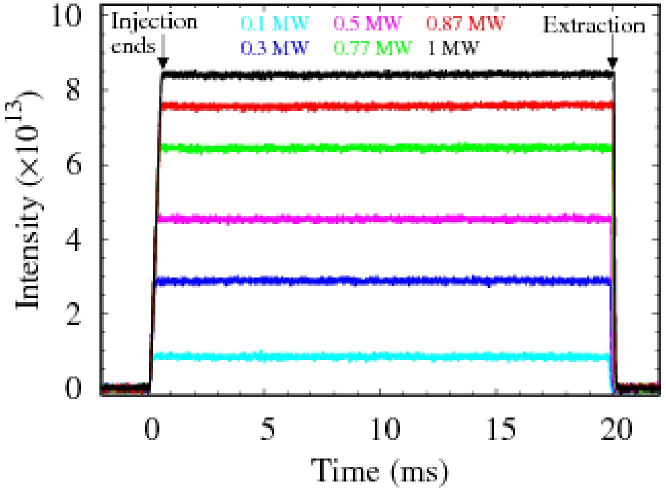
1 MW trial operation in 2020 (**1.5 days**)

1 MW routine operation to the MLF since 2024 April



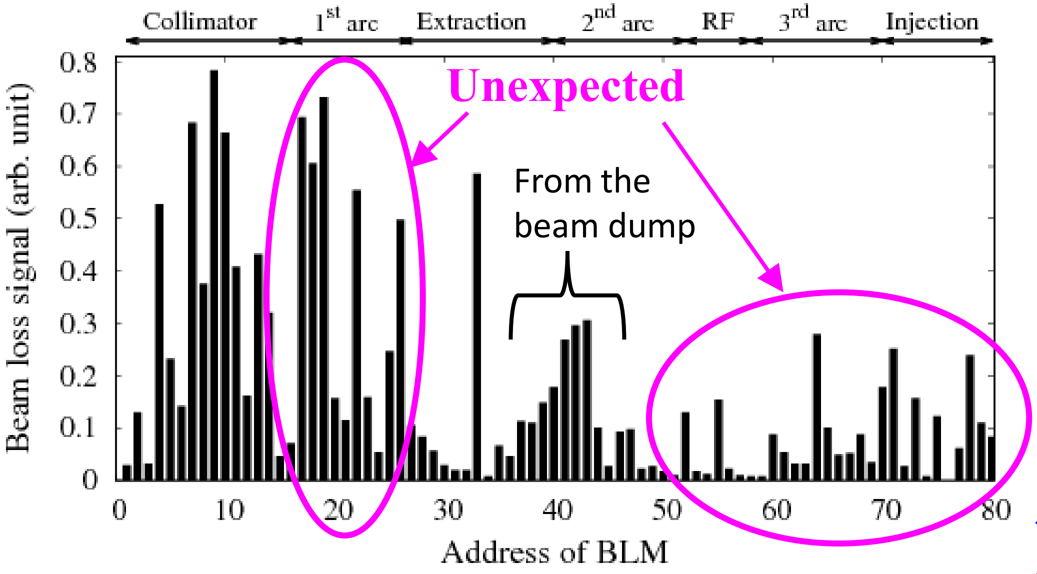
- We have demonstrated 1 MW trial operation at 25 Hz several times.
- The beam power for routine operation to the MLF is reached to ~1 MW since April 2024. 8.25E13 ppp (0.99 kW-eq.) → **0.95 kW** (net)

Beam loss at 1 MW operation in 2020



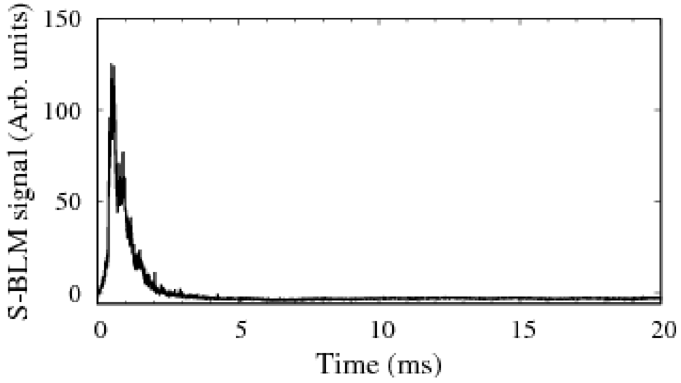
✓ No intensity loss can be seen.

➢ Unique among any similar accelerator



Measured beam loss throughout the RCS

Time structure of the beam loss at the collimator



✓ The beam loss occurs lower energy.

◆ But there exists some additional beam losses after the injection

◆ Estimated beam loss at 1 MW: ~0.2% << 3% of collimator capacity.

◆ **However**, residual radiation especially at the **injection, collimator and 1st arc sections** after 1.5 days trial operation was measured to considerably high.

➢ Serious issues for routine operation and regular maintenance works.

■ **Foil scattering uncontrolled beam loss is one of the main concern!**

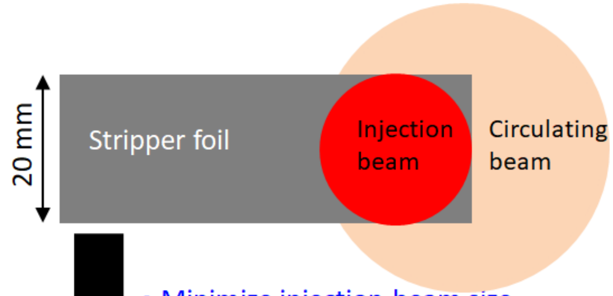
■ The SC effect has also to be mitigated for minimizing additional beam losses.

Minimization of foil scattering beam loss

By using a smaller size stripper foil and the injection beam size.

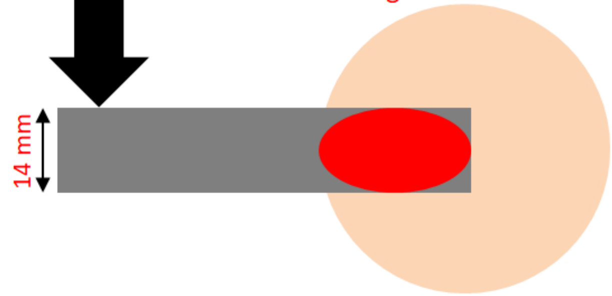
Inj. beam: β_y = 8.2 m

β_y = 2.2 m

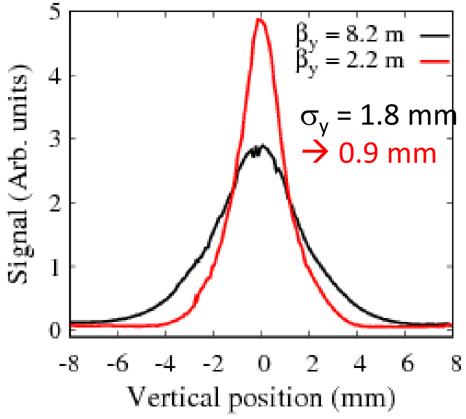


- Minimize injection beam size
- Use a smaller size foil

→ Reduce circulating beam hits

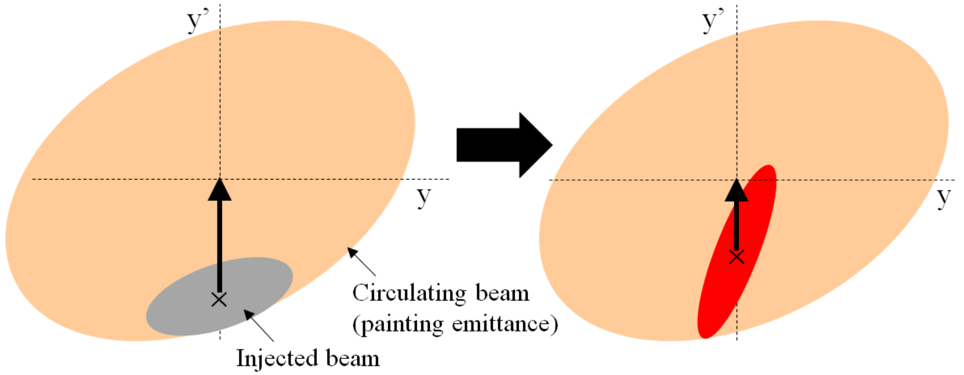


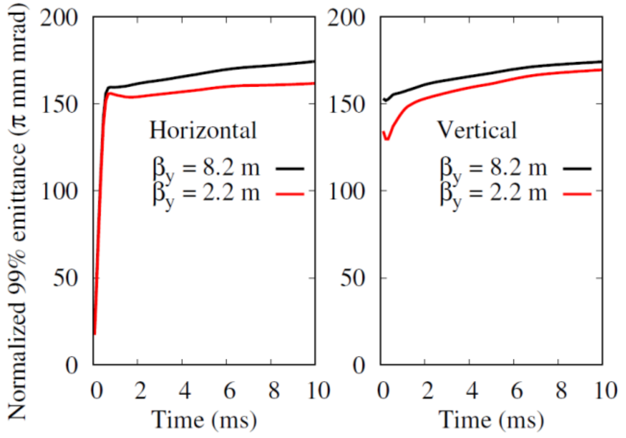
Vert. beam profile at the foil



Optimization of the vertical painting

Y' adjusted keeping painting area unchanged for a smaller size inj. beam as α_y = ~0.

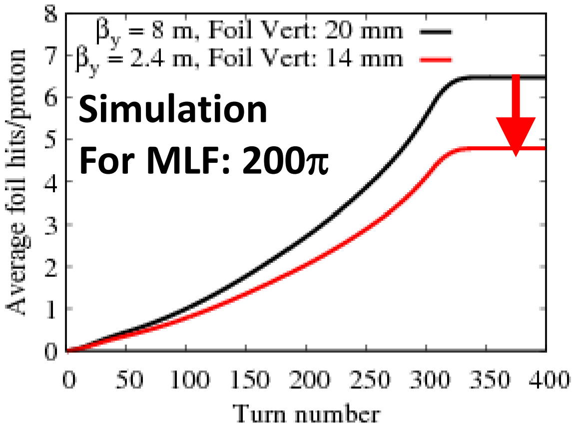


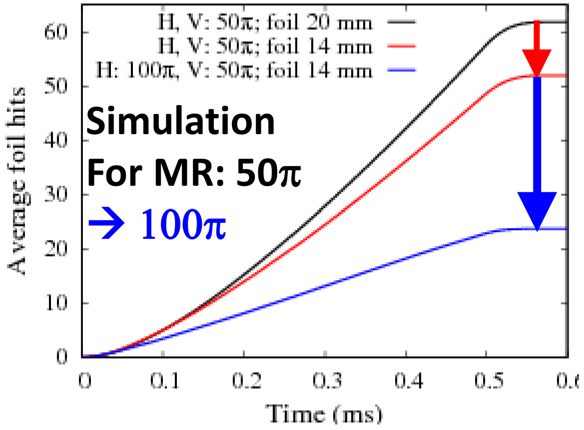


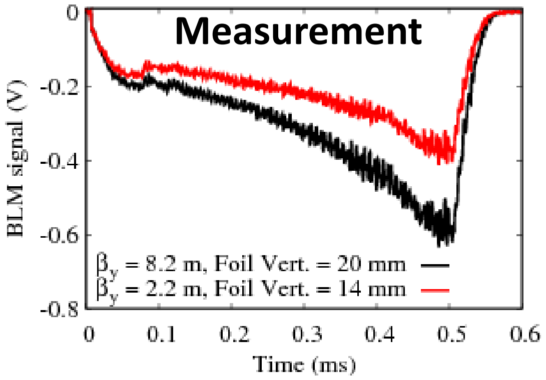
Simulation: Large emittance particles reduced.

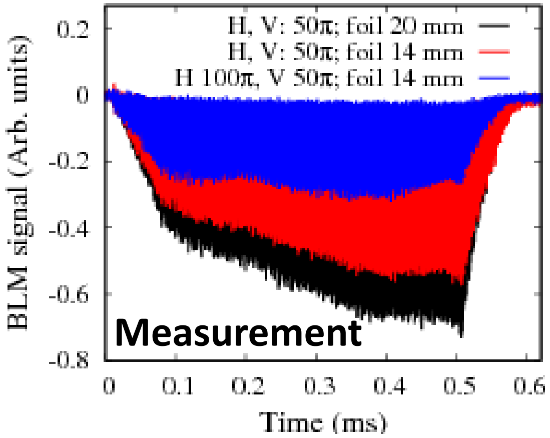
➢ Beam loss is also accordingly reduced.

Measurement results of foil hitting and foil scattering beam loss reduction



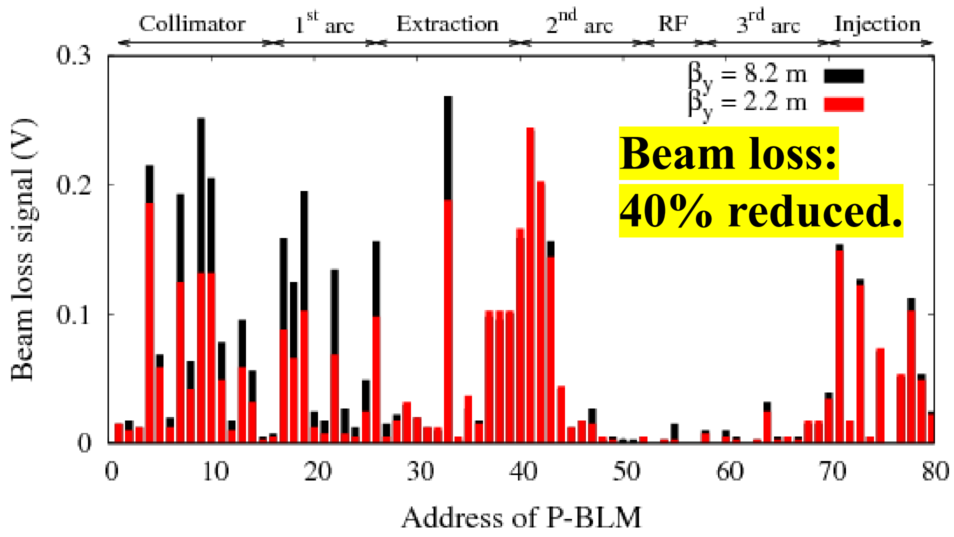


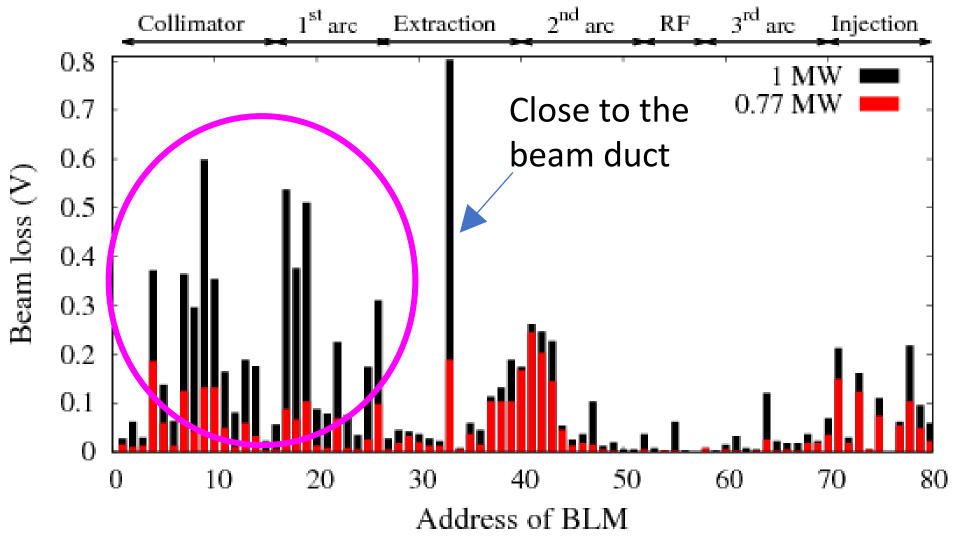




- ✓ Average foil hits (foil scattering beam loss) is significantly reduced:
- ➢ **30% for the MLF, 60% for the MR**
- ✓ Cosistent with with simulation results.

Measured beam loss at 0.77 MW and SC effect at 1 MW



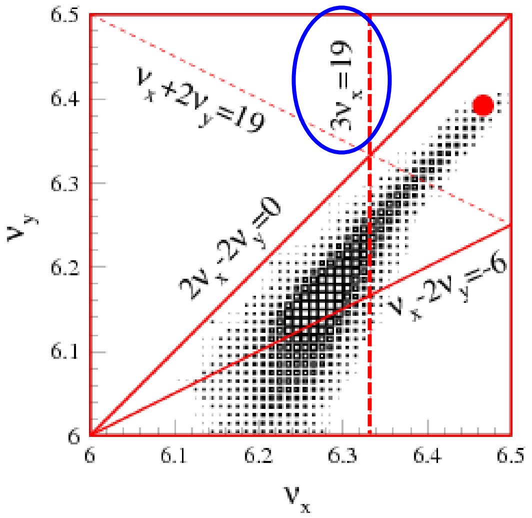


- The SC effect at 1 MW is rather serious.
- Beam loss 4 times higher for only 30% beam intensity increase from 0.77 MW.

➢ ***Further SC mitigation at 1 MW is necessary!***

Beam loss minimization at 1 MW

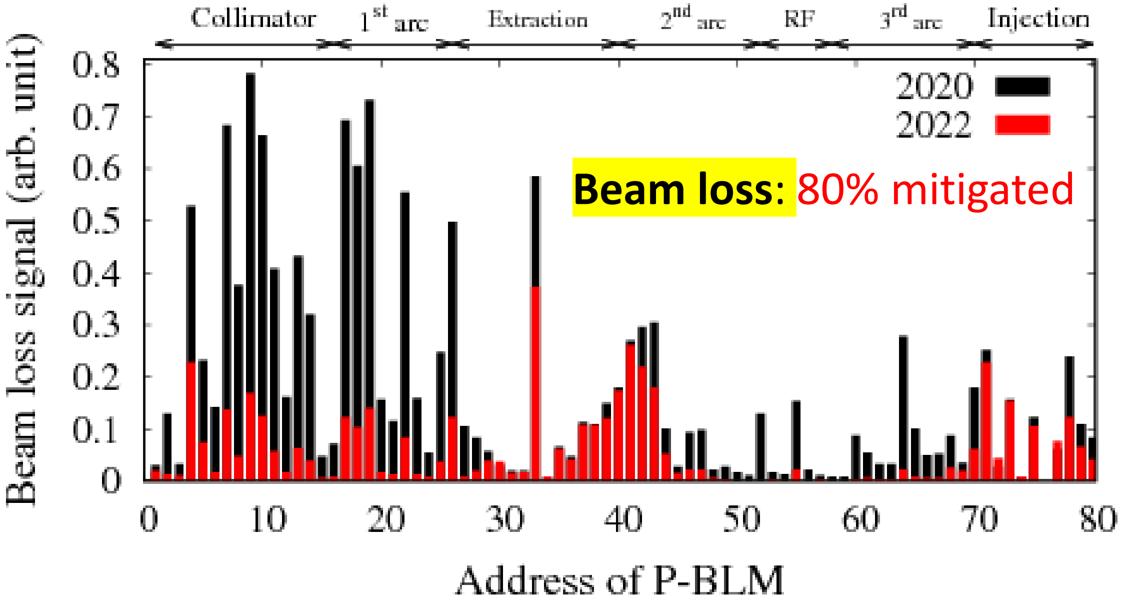
Identified SC driven individual beam loss sources/mechanisms based on simulation and systematic beam tests and compensated by implemented realistic approaches.
(see backup slides for more details)



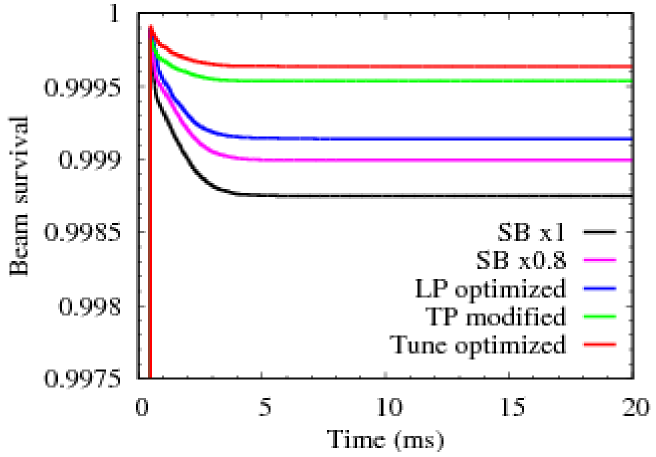
ID	Optimizations/Modifications
1	Tune optimization: (6.46, 6.32) → (6.45, 6.36) LP optimization: Δf RF → Inj. energy offset ($\Delta p/p$ = -0.15%)
2	Foil hitting rate minimization: **Foil Vert size : 20 mm → 14 mm ; Inj. β_y : 8.2 m → 2.2 m**
3	Partial correction of $3\nu_x$ = 19 resonance excited by Sextupole fields intrinsic in the injection Chicane bump (SB). **Reduced SB height: ×0.8.** **→ Reduced hori. Beam emittance growth reduced.**
4	Longitudinal painting (LP) optimization: **$\Delta p/p$ offset + Δf RF** **→ Reduce longitudinal beam halos**
5	Transverse painting (TP) modification by **slowly varying painting functions**: **→ Reduced spatial charge concentration, emittance growth.**
6	Tune optimization: (6.45, 6.36) → **(6.46, 6.36)** **→ Separation from the Montague resonance…..**

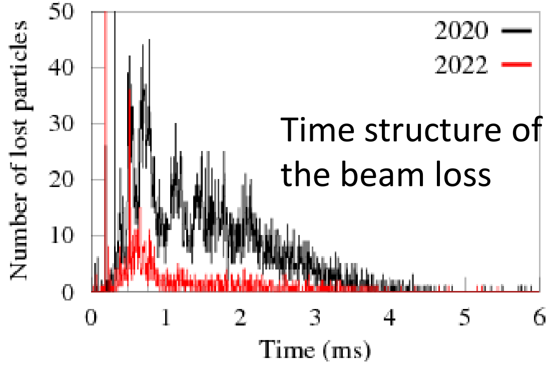
Beam loss mitigation result at for MLF 1 MW

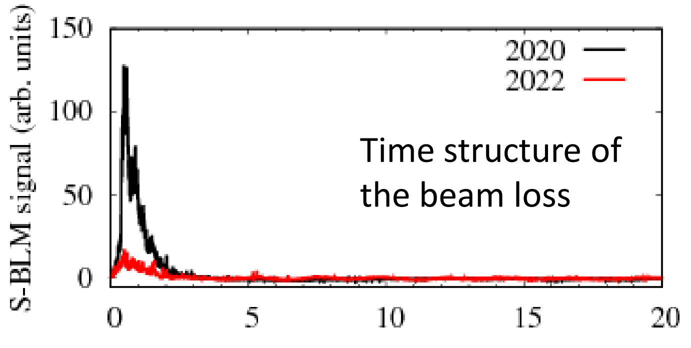
Measurement results:



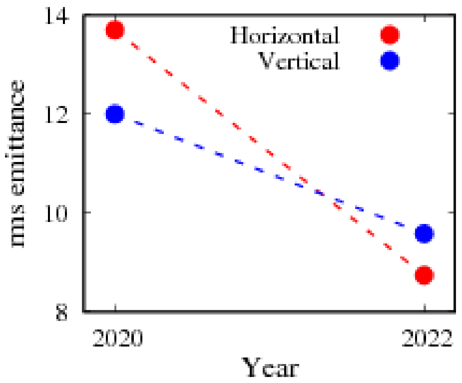
Simulation results:







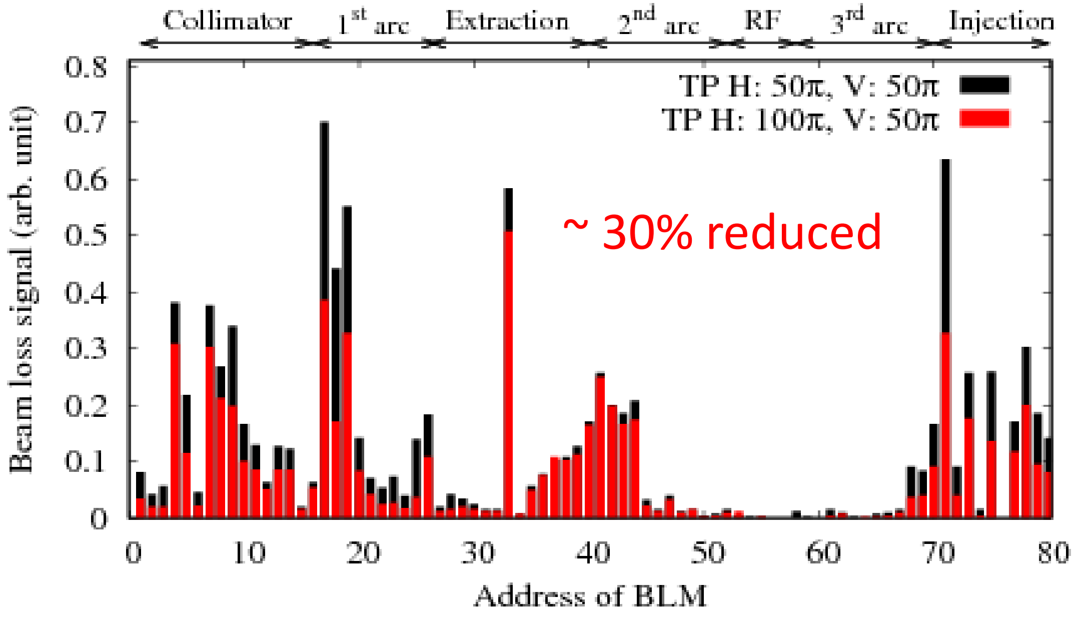
Time structure of the beam loss



Extracted beam emittance (rms)
40% reduced at maximum.

- ✓ The SC effect is well mitigated to minimize the beam loss and beam emittance at 1 MW for operation to the MLF.
- ✓ **Beam loss occurs only at the injection energy localizing well at the collimator section.**
- ✓ The residual **beam loss is << 0.1%,** ~1/2 due to foil scattering.
- ✓ **The beam loss power is ~0.1 kW << Collimator capacity (4 kW)**
- ✓ The simulation results are consistent with measurements.

Beam loss and beam emittance mitigations for the MR

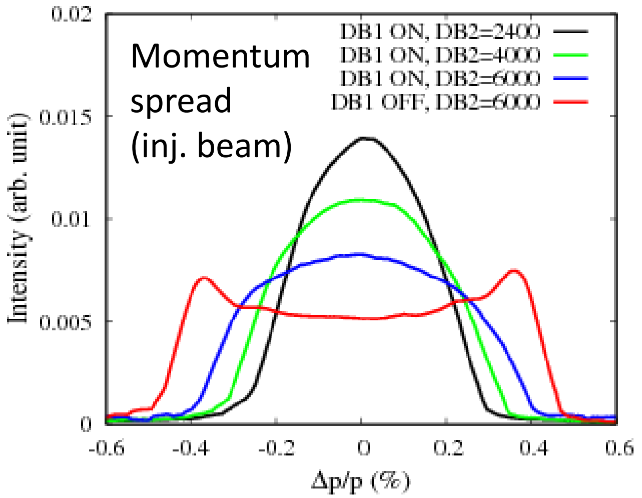


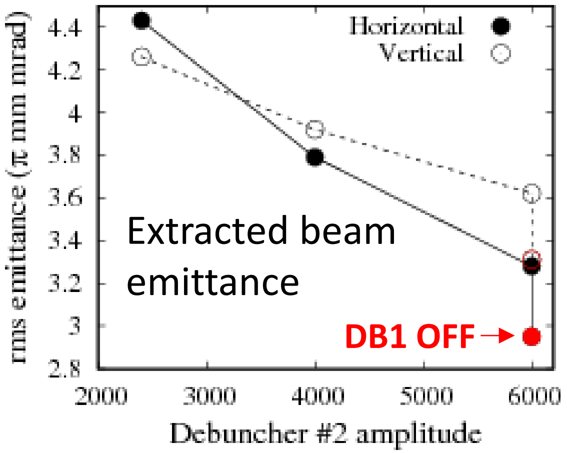
- ✓ As compared to 2020 data, the beam loss is 30% reduced .
- ✓ In addition, transverse rms emittance is also ~15% reduced.

◆ Recent efforts for further beam emittance mitigation

- ✓ Applying a higher amplitude of Linac 2nd debuncher (DB2) for a higher momentum spread of the injection beam.
- ✓ Keeping DB1 OFF and DB2 maximum gives a maximum spread.

➢ **Δp/p spread (rms): 0.15% → > 0.3%**

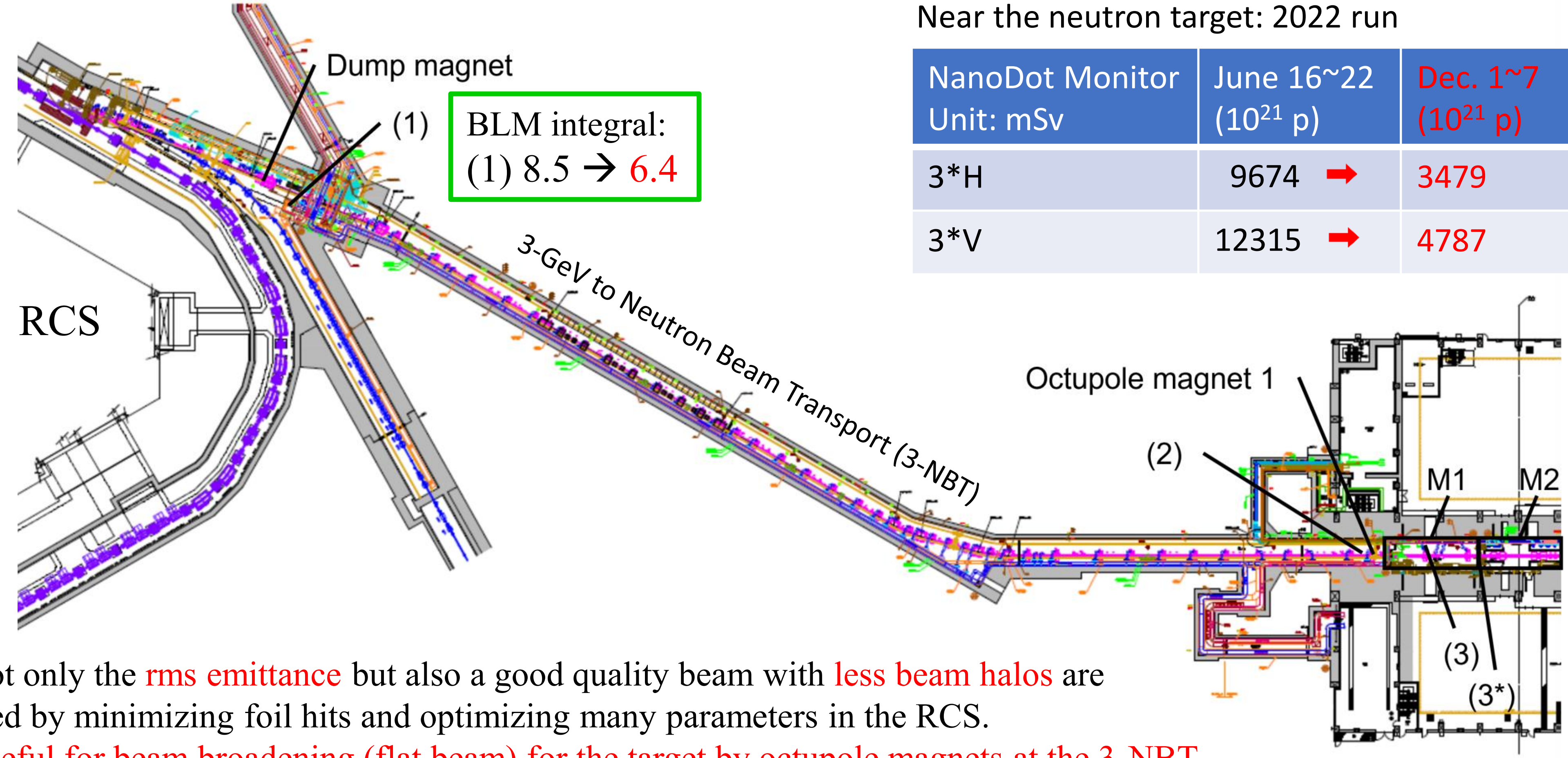




✓ The SC effect is further mitigated to achieve **a nearly 30% reduction** of the rms emittance of the extracted beam.

User confirmation of improvement of beam emittance and beam halos

Courtesy: Y. Yamaguchi, S. Meigo



Near the neutron target: 2022 run

NanoDot Monitor Unit: mSv	June 16~22 (10^{21} p)		Dec. 1~7 (10^{21} p)
3*H	9674	➡	3479
3*V	12315	➡	4787

✓ Not only the rms emittance but also a good quality beam with less beam halos are ensured by minimizing foil hits and optimizing many parameters in the RCS.

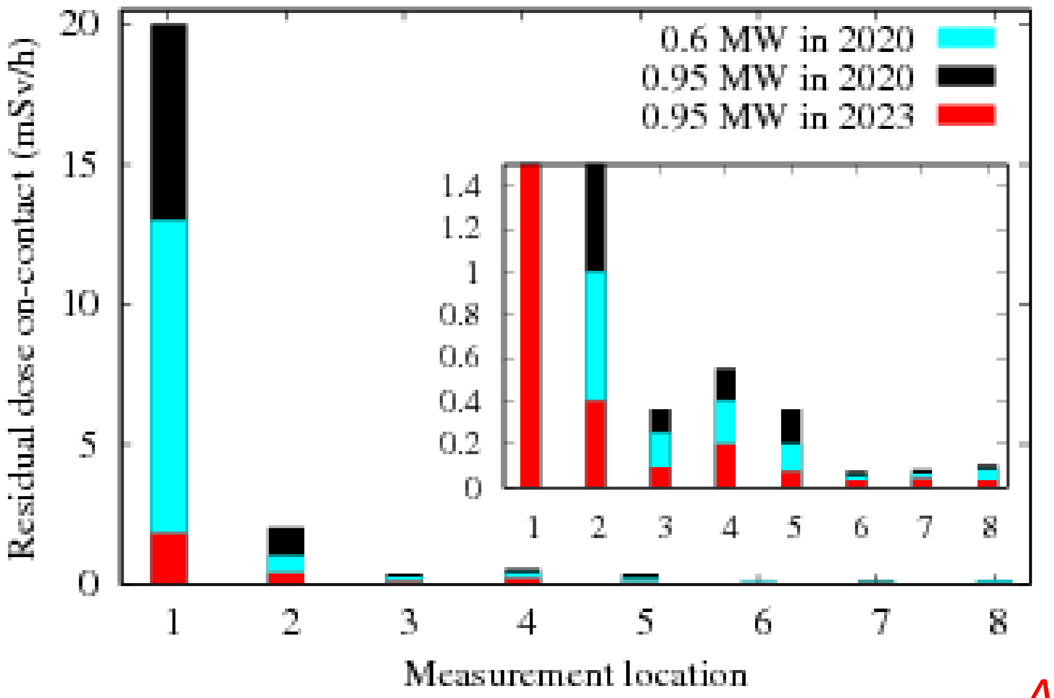
➢ Useful for beam broadening (flat beam) for the target by octupole magnets at the 3-NBT.

✓ Beam emittance and beam halo reduction at the 3-50BT have also been confirmed.

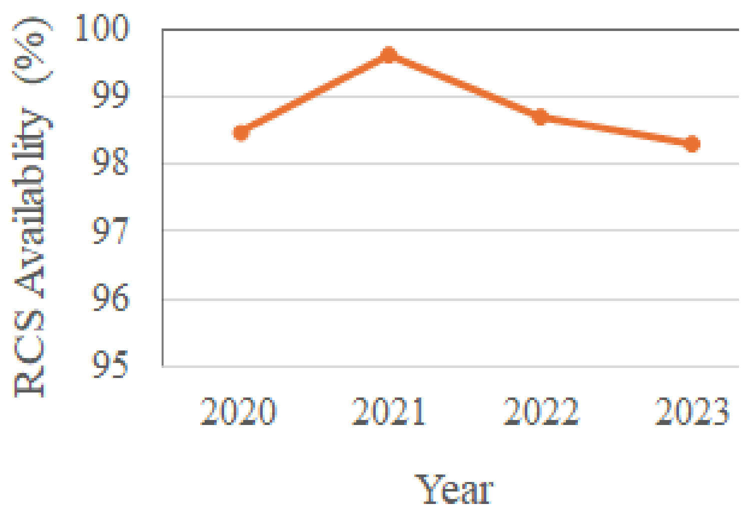
➢ Useful for MR beam power ramp up

Suppression of RCS machine activation and operational performance

Measured residual does



Recent availability chart



Accepted for publication to the PRAB (Editors' suggestion)

Measurement locations:
#1 Collimator max
#2 Collimator exit
#3~6 Dispersion peaks

- ✓ RCS machine activation at present with ~1MW routine operation is significantly reduced as compared to 1 MW trail operation and even 0.6 MW operation in 2020.
- ✓ **We have achieved sustainable operation with more than 98% availability.**
- ■ The downtime mainly caused by the hardware failures/replacement.

Summary and outlook:

✓ Recently in the J-PARC RCS, we have first minimized the uncontrolled foil scattering beam loss by reducing both foil and injection beam sizes.

✓ The SC effect at 1 MW has also been sufficiently mitigated by clearly identifying all possible sources and implementing realistic measures.

- Beam loss and the beam emittance for both MLF and MR have been significantly reduced.
- The residual beam loss 1 MW is <<0.1% and well localized at the collimator section.
- The residual beam loss is dominated by the remaining foil scattering of the circulating beam.
- **The beam loss power is only less than 0.1 kW << 4 kW collimator capacity.**

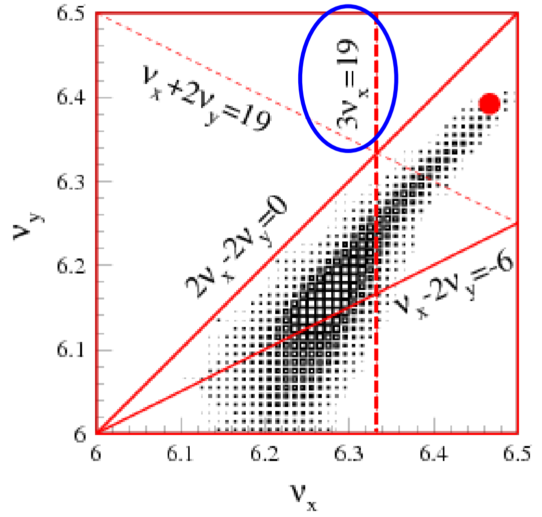
→ *(Developing laser stripping to eliminate the foil scattering beam loss, foil issues.)*

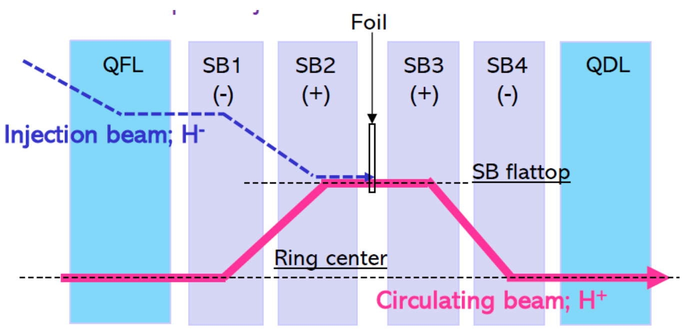
✓ The simulations results are well consistent with measurement ones.

✓ **RCS beam quality improvement has also been well recognized at the downstream facilities.**
✓ **Achieved sustainable operation with > 98% availability with extremely low machine activation.**

■ *Further effort for beam loss and beam emittance mitigations are continuing including to* ***achieve 1.5 MW and even more*** *keeping a beam loss sufficiently low level.*

Partial correction of 3nx = 19 resonance



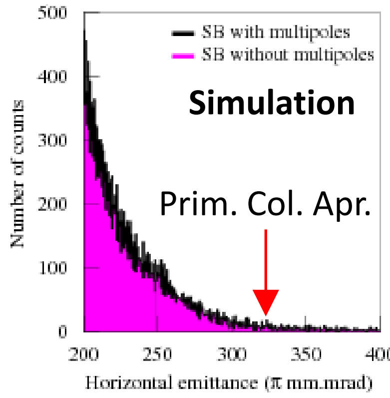


Chicane bump (SB1~4) for injection

◆ $3\nu_x = 19$ resonance is driven by sextupole fields intrinsic in the SB.

- ➢ Hori. beam emittance growth and beam loss.
- ➢ No additional sextupoles exist for correction.
- ➢ **SB fields reduced as much as possible (20%)**

(Further reduction is impossible due to beam injection)



Horizontal beam halos
w/ and w/o SB multiples

Measurement results:

- Beam loss: 30% reduced.
- Hori. rms emittance:20% reduced.

Additional advantages:

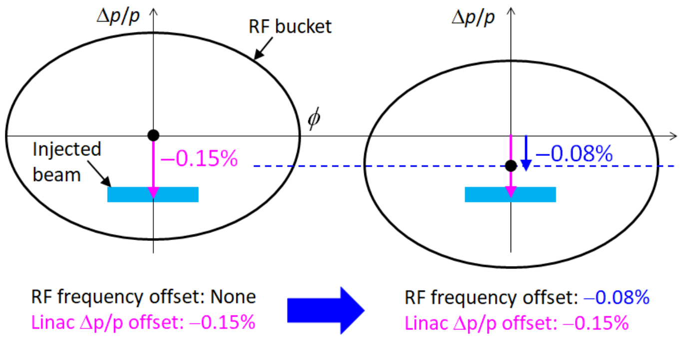
- Vert. beta beating reduction: 40%

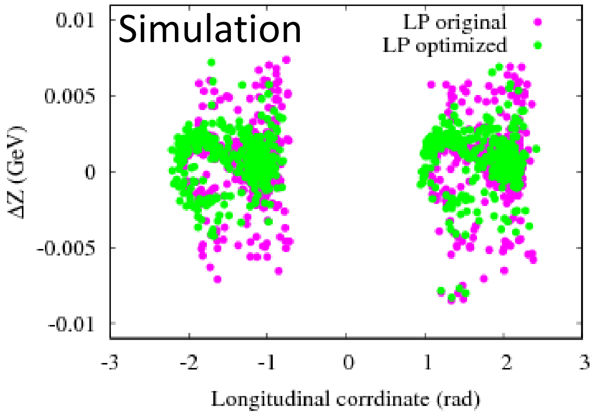
→ Partial mitigation of $\nu_x + 2\nu_y = 19$ resonance.

- Reduction of the excited H^0 decay loss.

LP and TP optimization schemes

LP optimization:

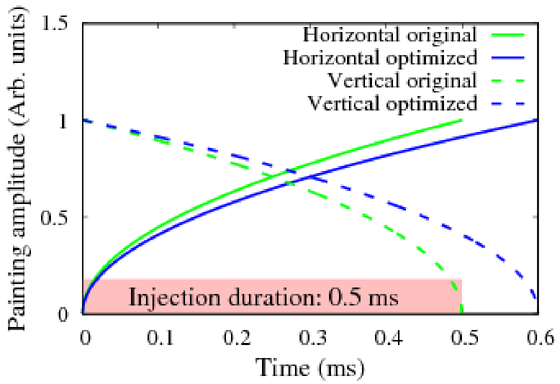




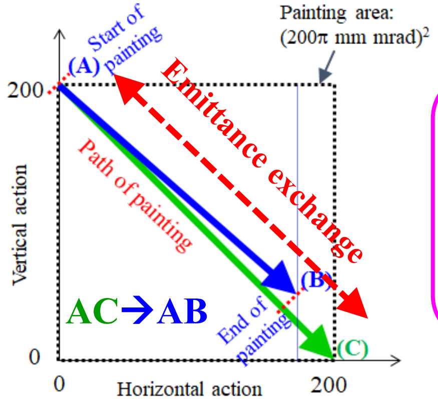
Beam loss occurred due to large Δp/p.

➢ Reduced by LP optimization

TP optimization:



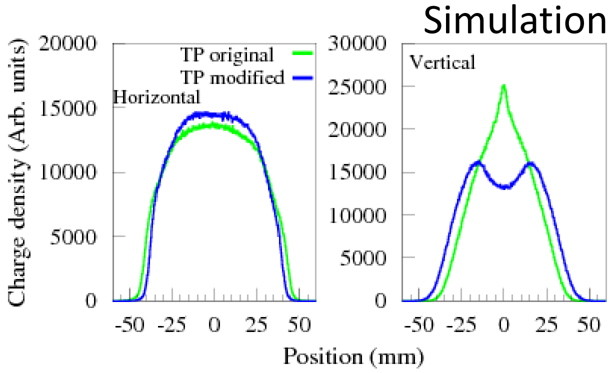
Slow variation of painting

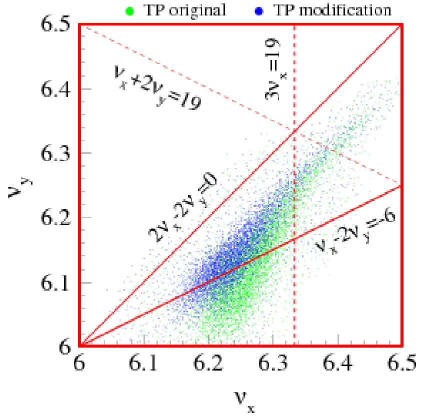


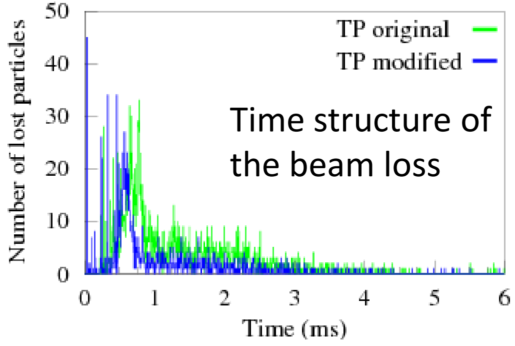
The unpainted area is filled by the SC effect and emittance exchange

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

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







・High spatial charge concentration. ・Asymmetric tune distribution.

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

➢ **Well optimized by TP modification.**