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

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J-PARC, Japan

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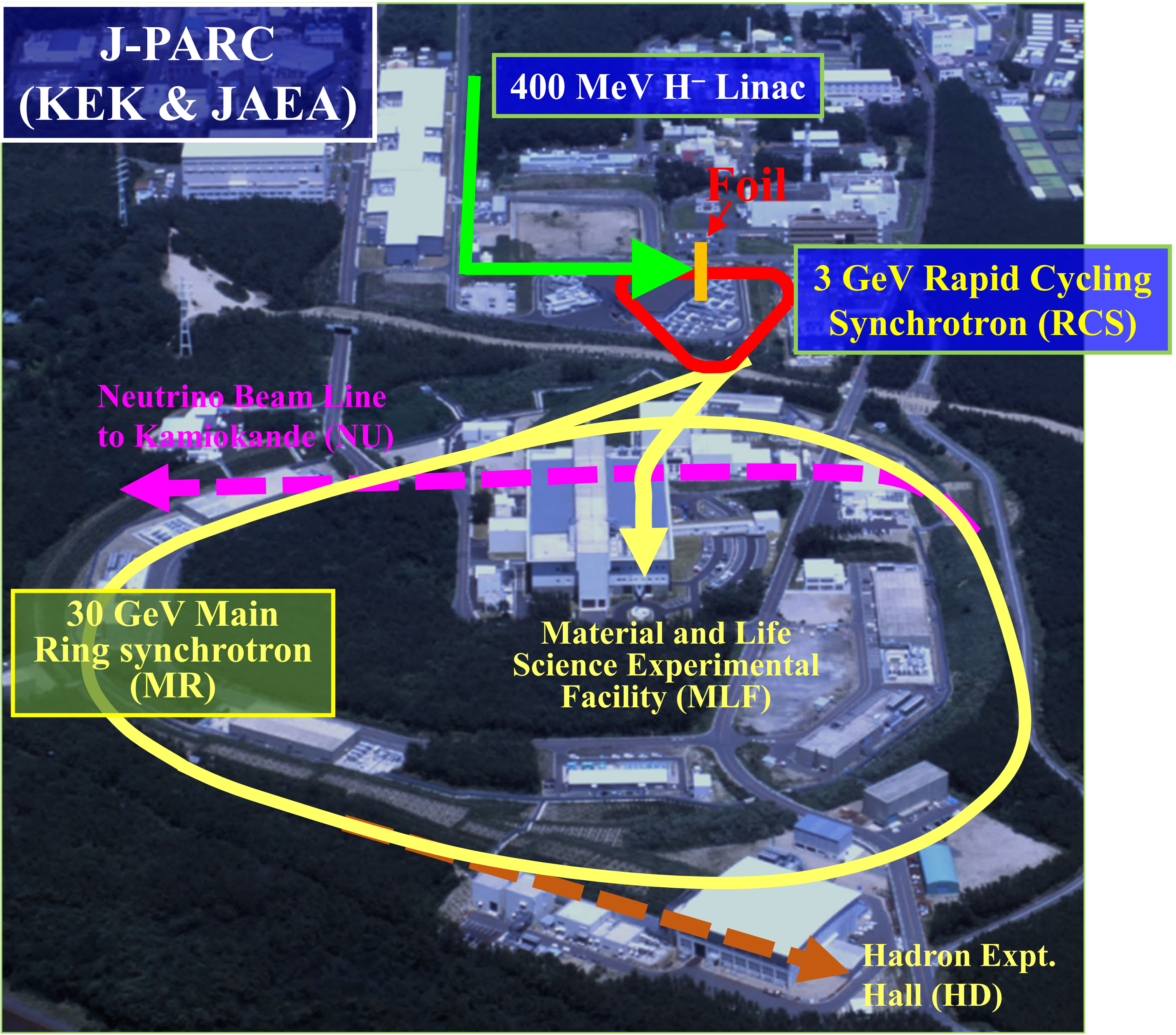
Accelerators at J-PARC



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:

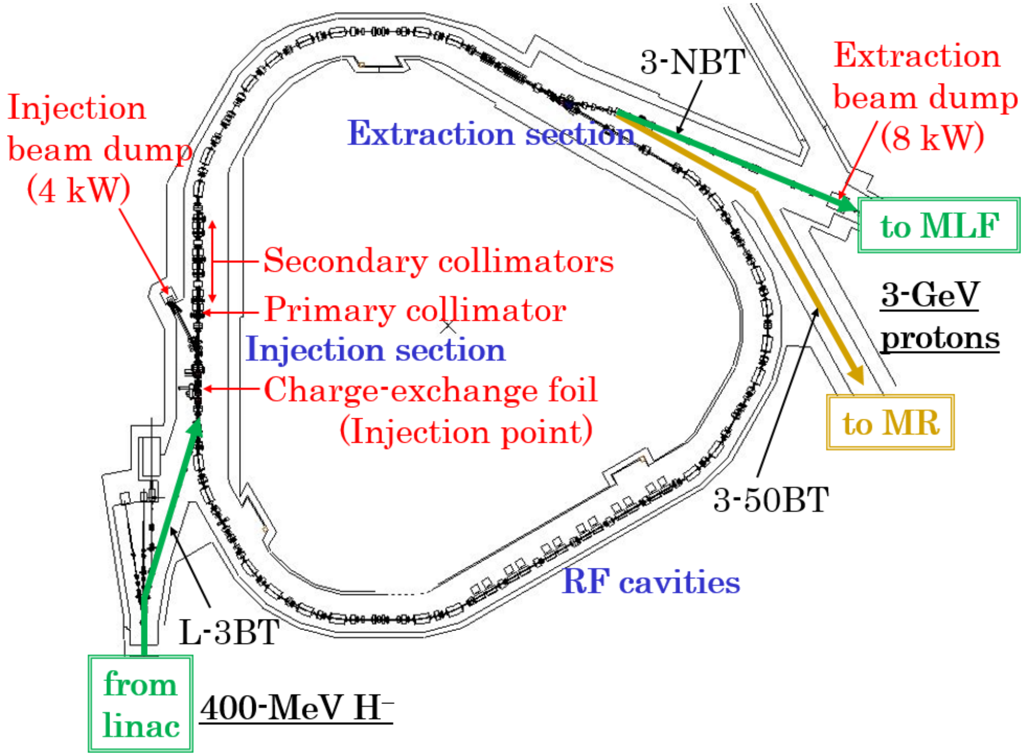
- Brief overview of the 3-GeV RCS of J-PARC
- Beam loss minimization at 0.7 MW and SC effect at higher intensity
- **Beam loss mitigation at 1 MW by**
  - Resonance correction
  - Optimization of longitudinal painting
  - Optimization of transverse painting
  - Optimization of betatron tune at injection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

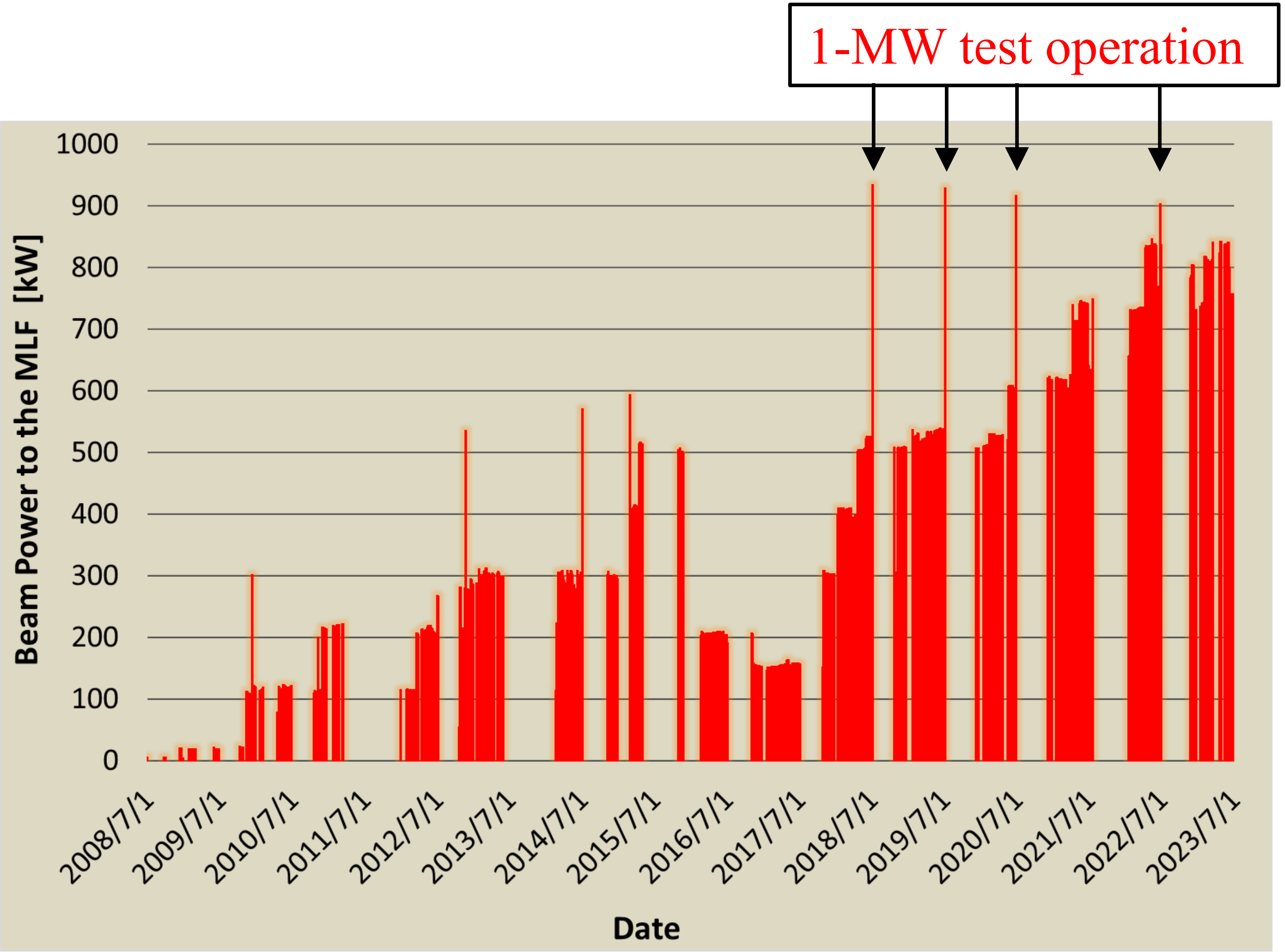
Beam power : 1 MW



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.

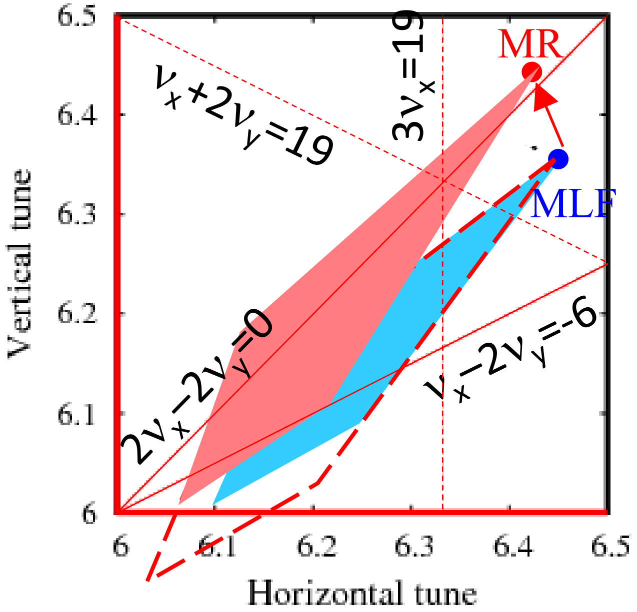
Operational strategy of the RCS

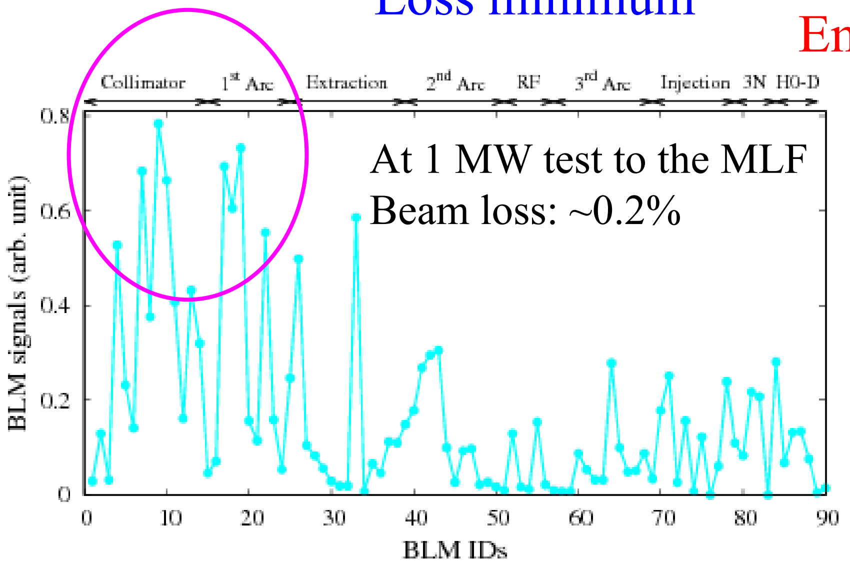
Optimization of many parameters and their switching pulse-by-pulse to the MLF and MR is done according to the demand.

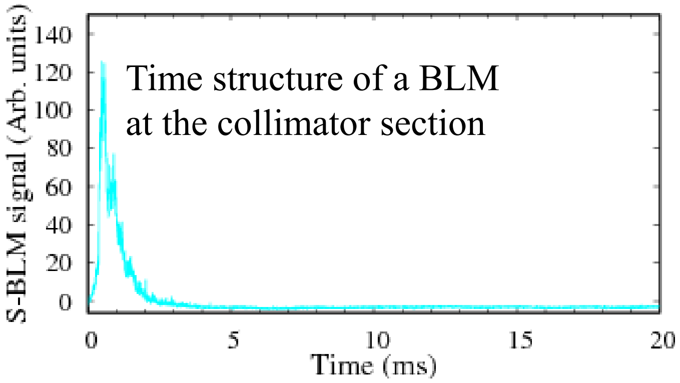
Parameter	For MLF	For MR
Beam power	~1 MW	800 kW-eq. (FX), ~200 kW-eq.(SX)
Tune@ inj. → ext.	(6.46, 6.36) → (6.37, 6.35)	(6.417, 6.447) → (6.37, 6.35)
Transverse painting & type	200π mm mrad (anti-correlated)	50π mm mrad (correlated)
Longitudinal painting	V_2 duration: 6 ms Δp/p offset: -0.15% + RF freq. 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



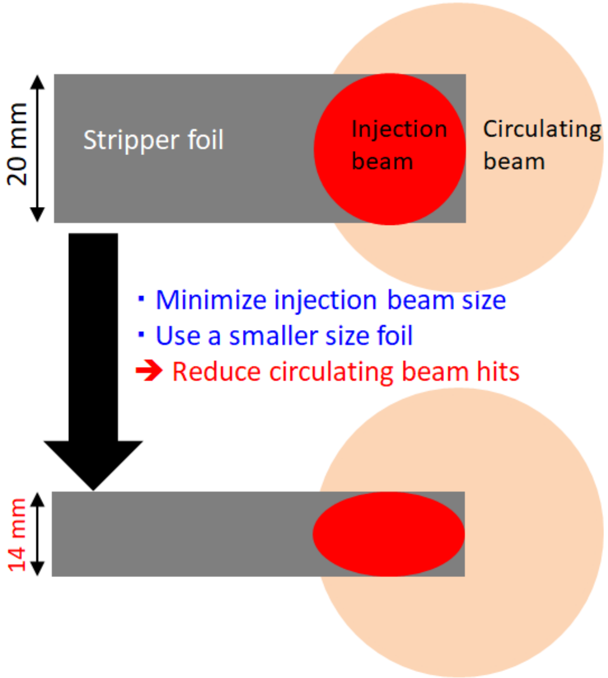


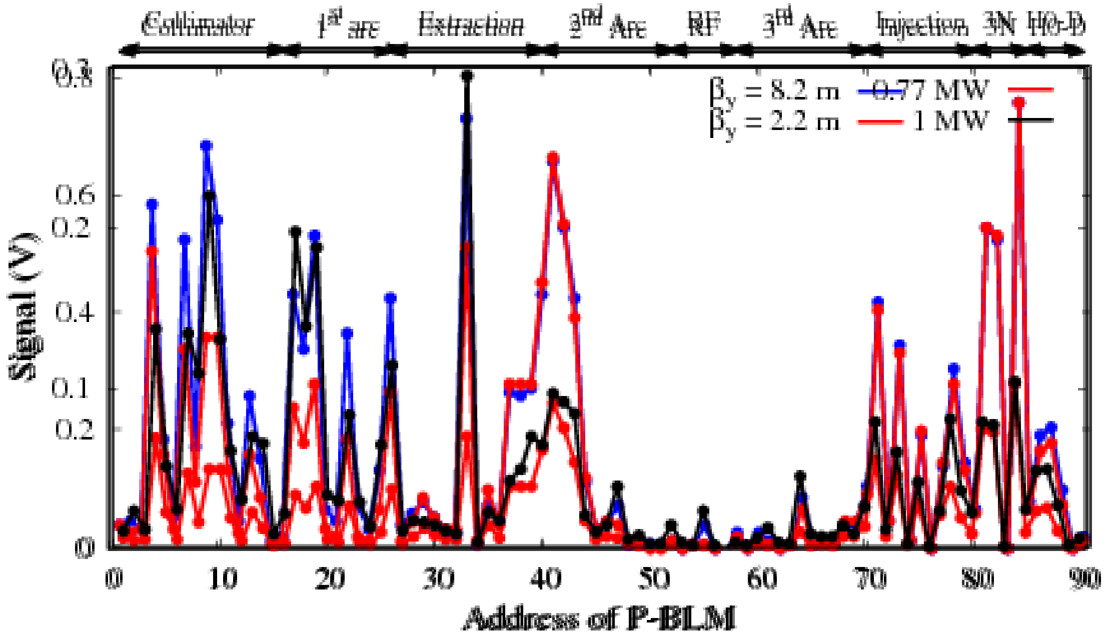


- Beam loss is well mitigated and controlled to occur only at inj. energy and localized mostly at the collimator section.
- However, the residual radiation at the injection, collimator and at the 1st arc sections are still high.
- Further beam loss mitigation is necessary.

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.





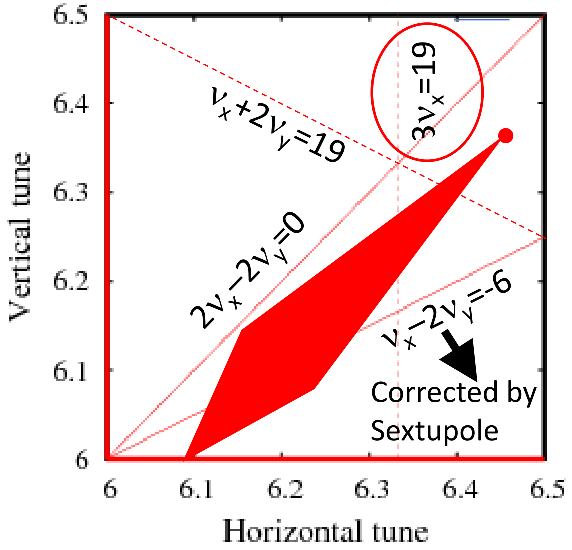
- **However, due to the SC effect, the beam loss at 1 MW was 4 times higher than that at 0.7 MW.**
- ➢ We continued systematic experimental and simulations studies for minimizing the beam loss at 1 MW.

Beam loss mitigation measures at 1 MW:

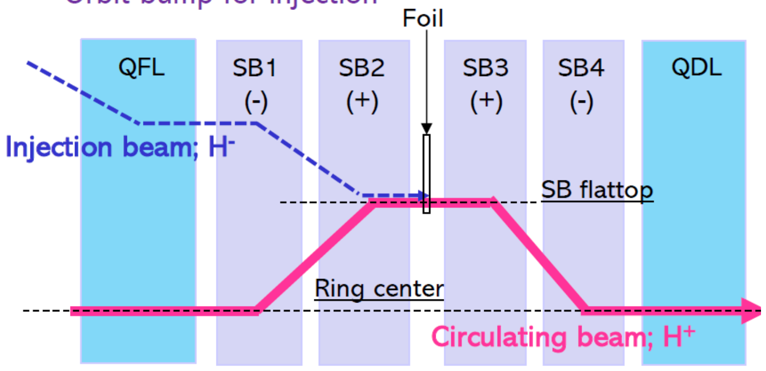
- Partial correction of the $3\nu_x = 19$ resonance
- Optimization of the LP
- Modification of the TP
- Optimization of tune at injection

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

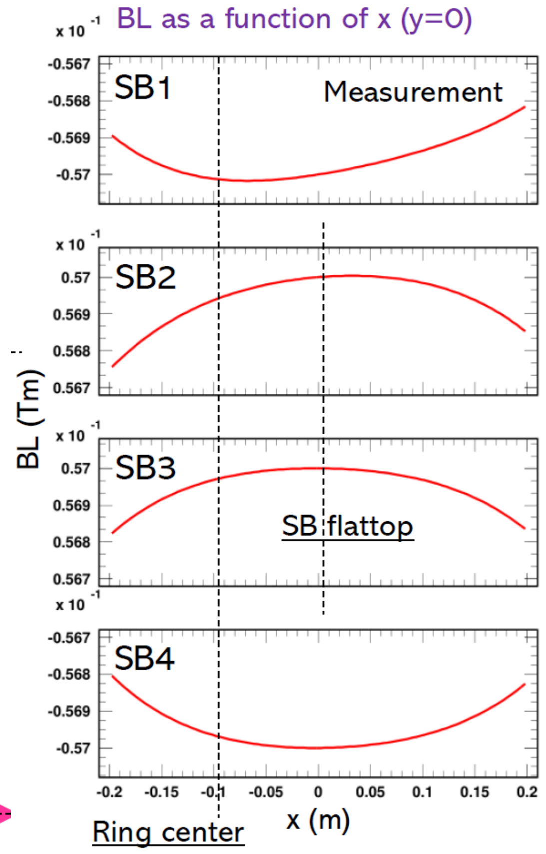
The $3\nu_x = 19$ resonance is driven by the sextupole field component intrinsic in the injection chicane bumps (**SB**).



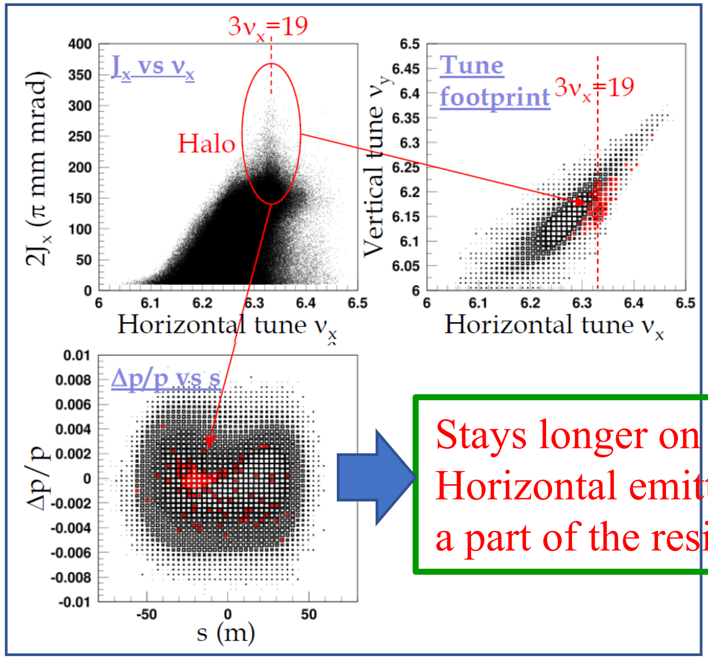
Orbit bump for injection



H. Hotchi, HB 2021



Simulation results:



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

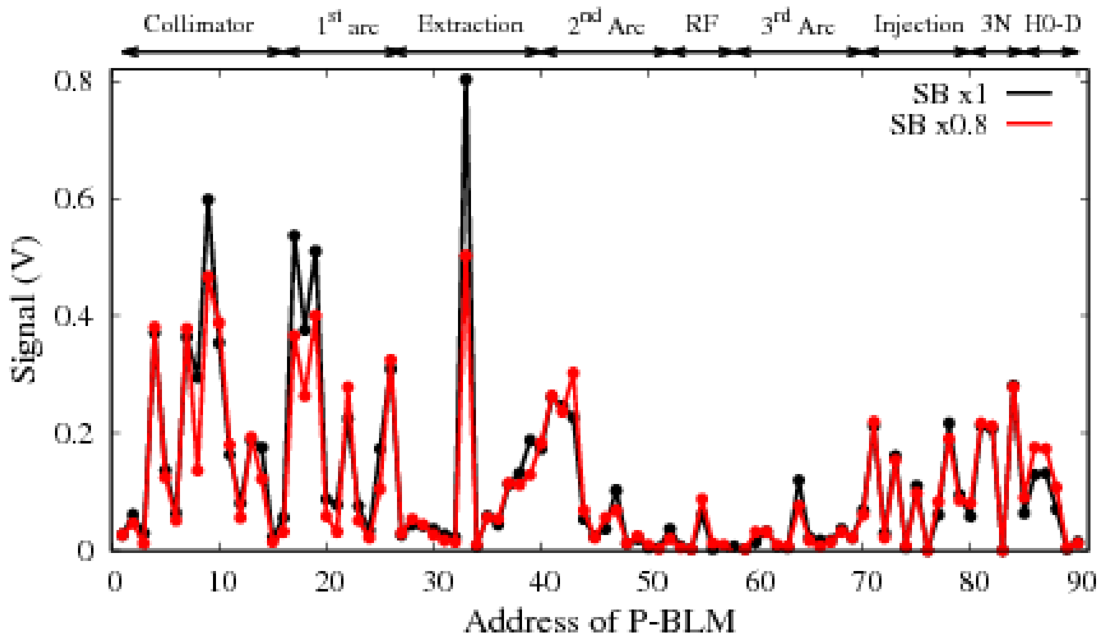
— Dipole fields of SBs are compensated through integration over SB 1-4
— But for higher order field components, such a compensation is incomplete due to magnetic interferences in reality.

◆ **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)

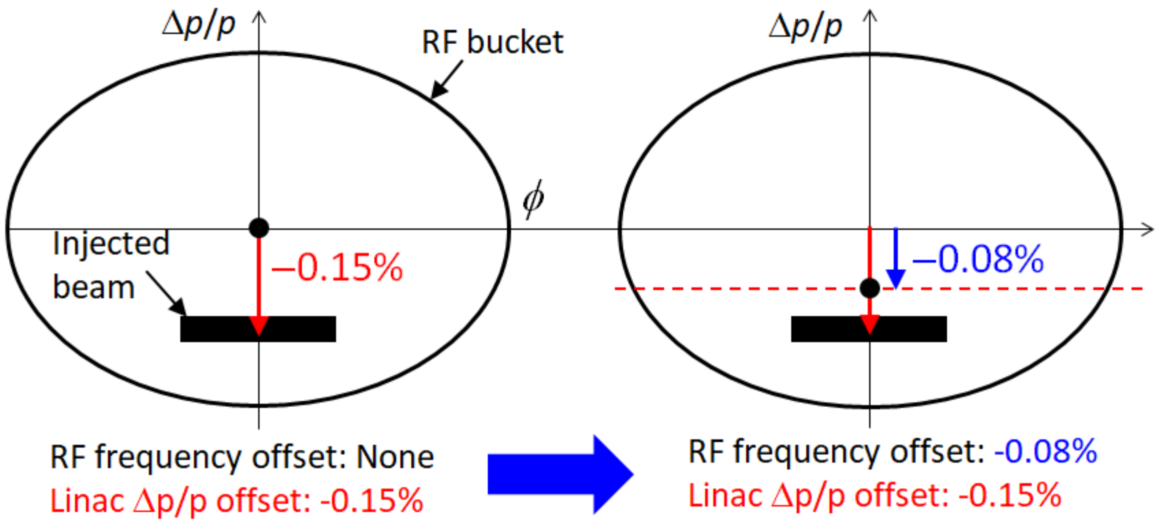


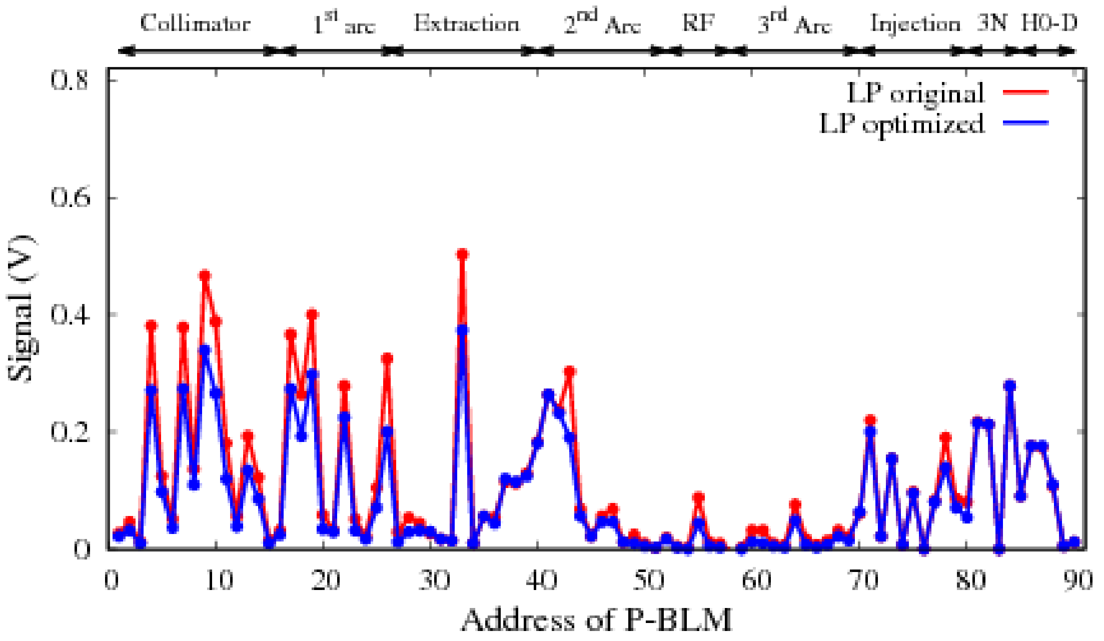
- ✓ The SB with ×0.8 gives ~**20% beam loss mitigation** at the collimator and 1st arc sections.
- ✓ The hori. rms beam **emittance also 10% reduced**.

-- 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.**

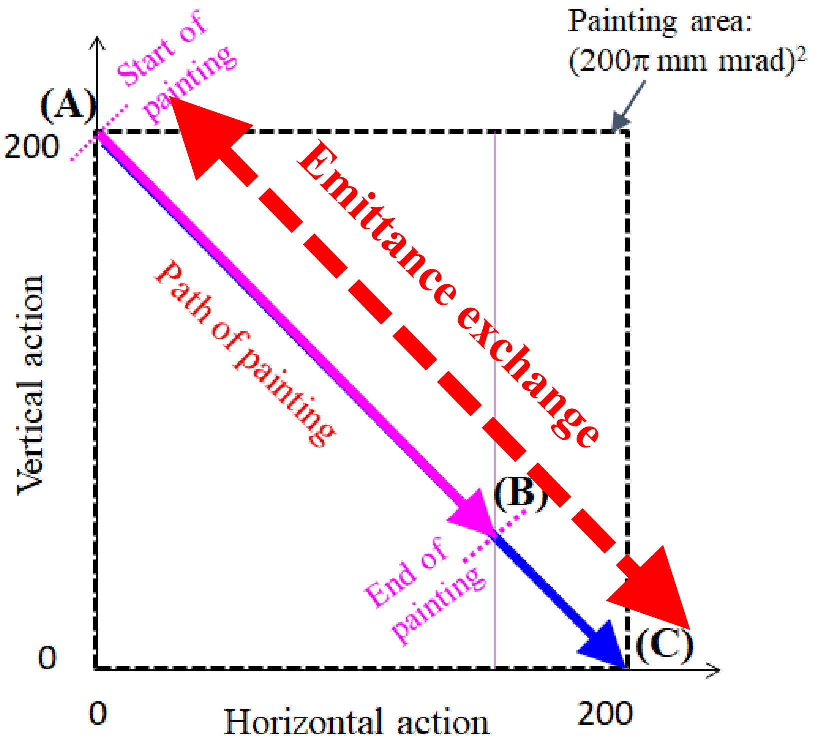
◆ However, the beam emittances remain unchanged.

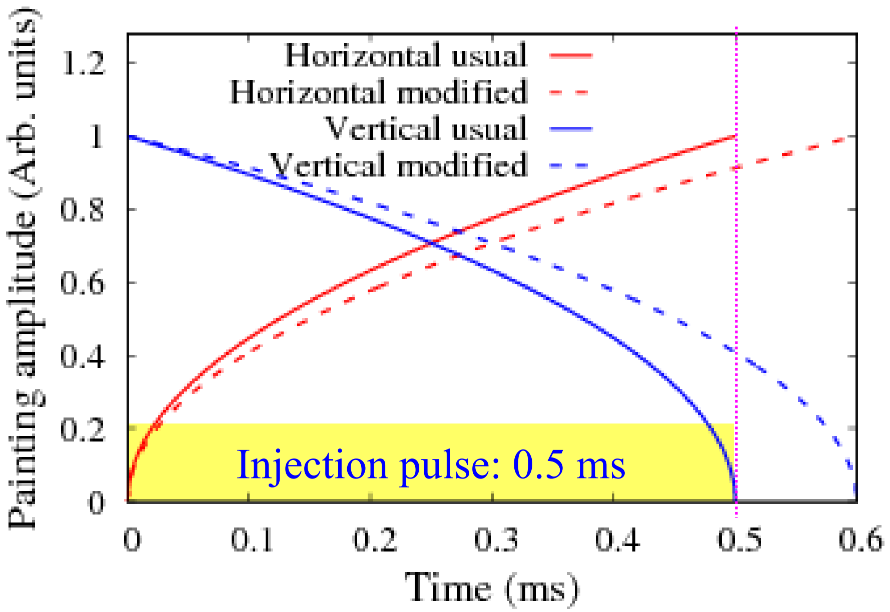
✓ Therefore, the longitudinal beam motion improved and reduced the longitudinal beam halos lost by the chromaticity effects.

➢ 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.

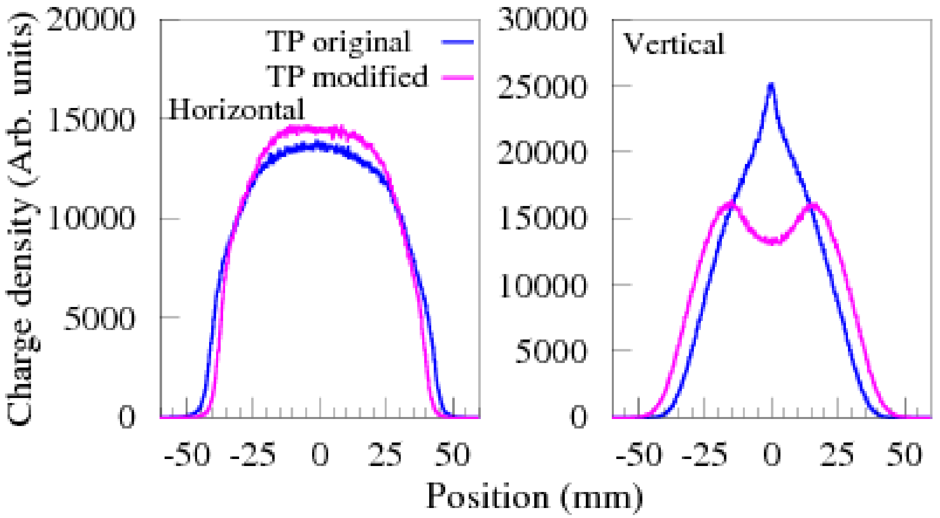


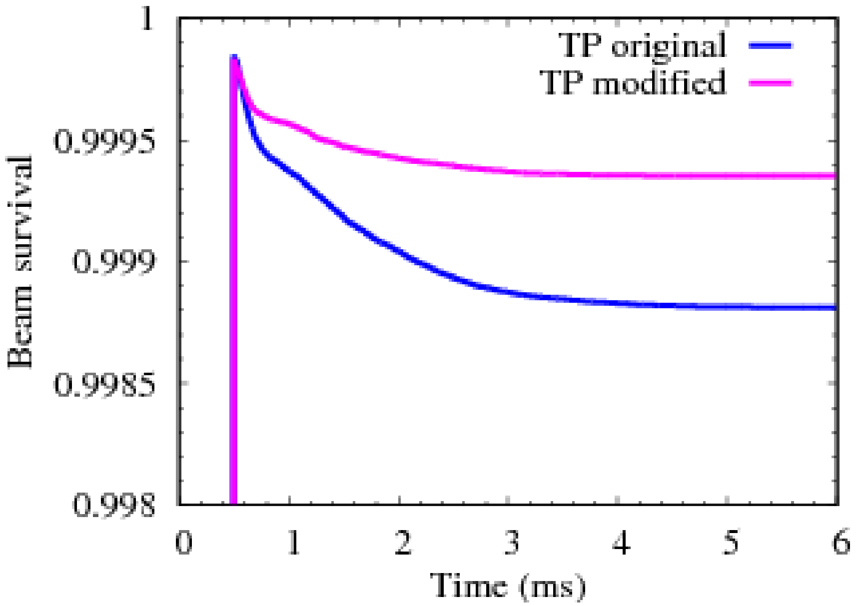


Simulation results by optimizing the TP

Beam profiles at the end of injection.

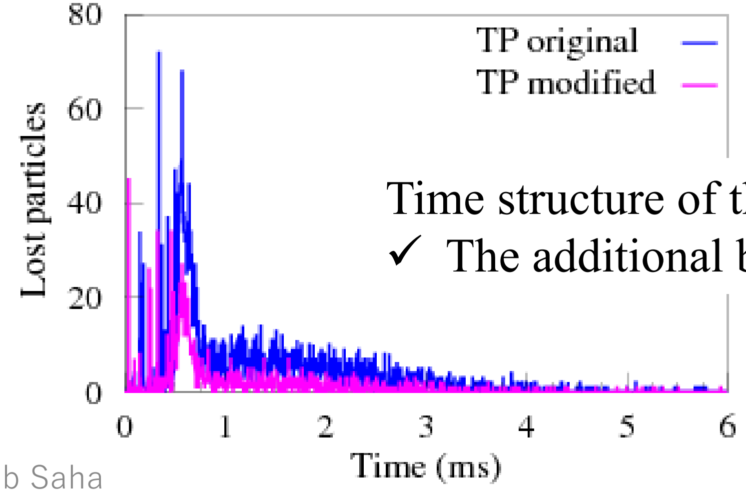
✓ Minimized vertical spatial charge concentration.





Beam survival at 1 MW.

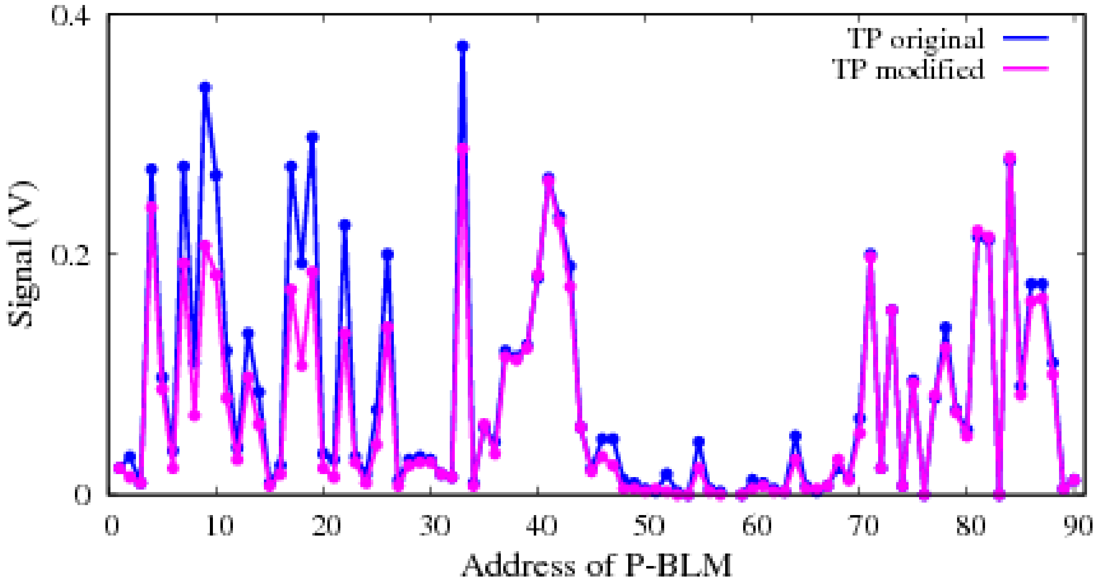
✓ Beam survival is more than 40% improved by applying a modified TP.



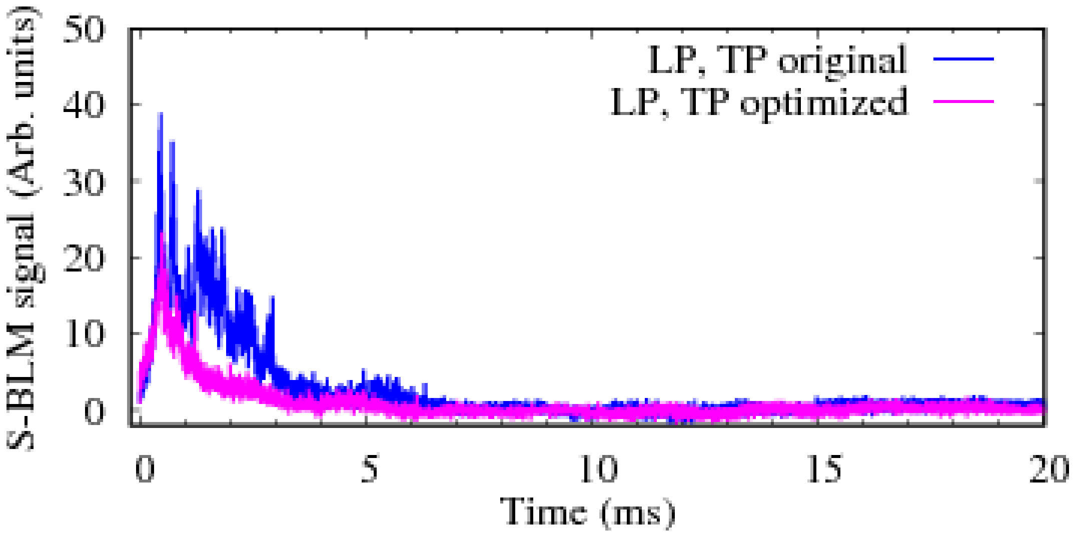
Time structure of the beam loss.

✓ The additional beam losses have almost mitigated.

Measurement results by modifying the TP



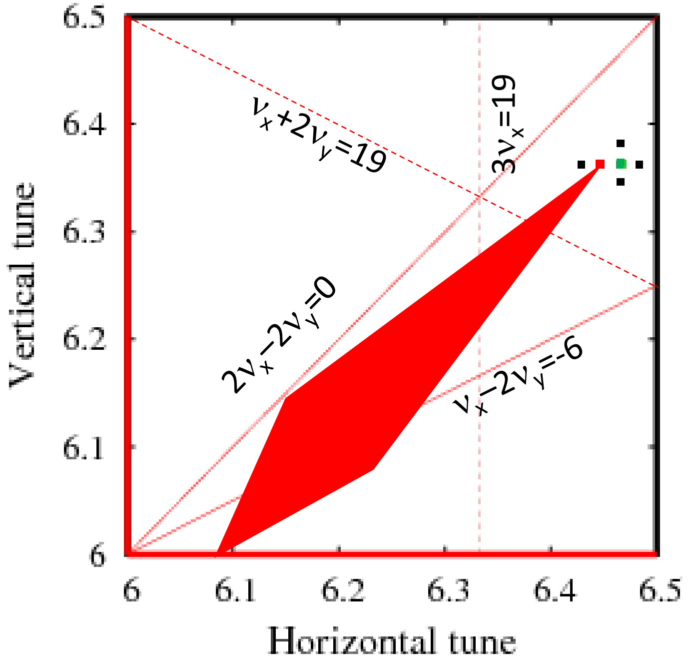
Time structure of the beam loss measured by a plastic scintillator at the collimator section.

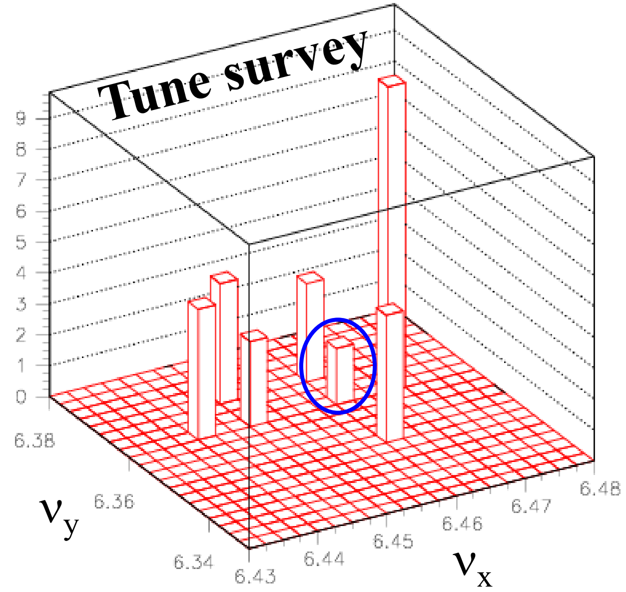


- ✓ As expected, the beam loss at 1 MW is further ~35% mitigated by applying a modified TP.
- ✓ The rms emittance of the extracted beam (horizontal) is also ~20% improved.

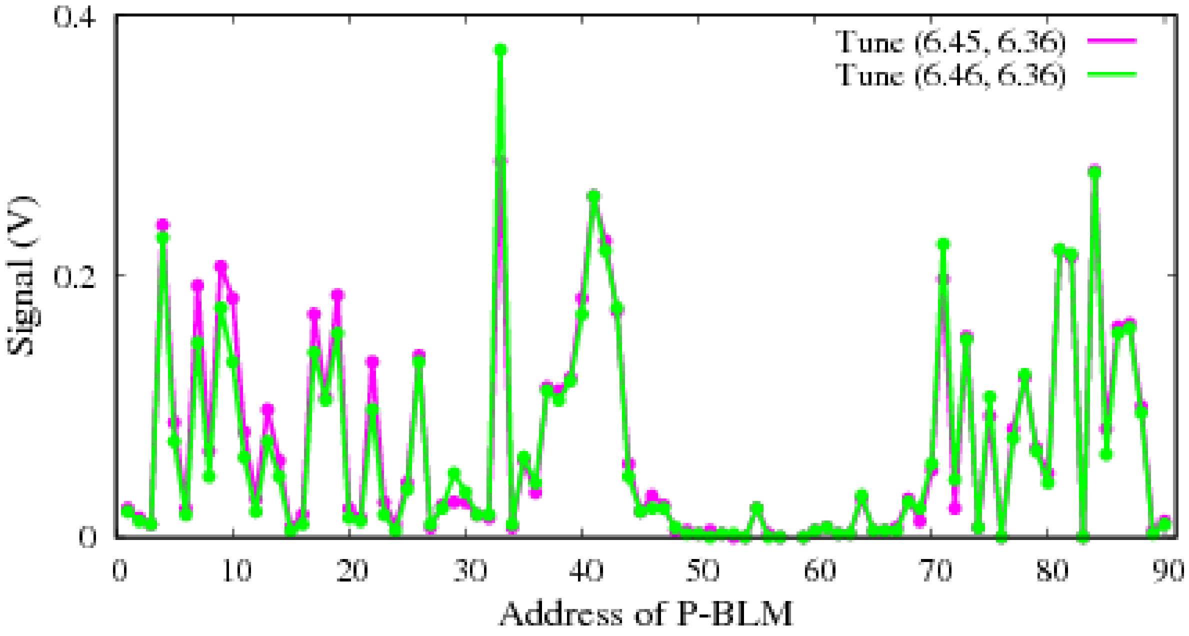
- ✓ The beam loss remains only around injection period caused by the foil scattering.

Optimization of the betaron tune at injection





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

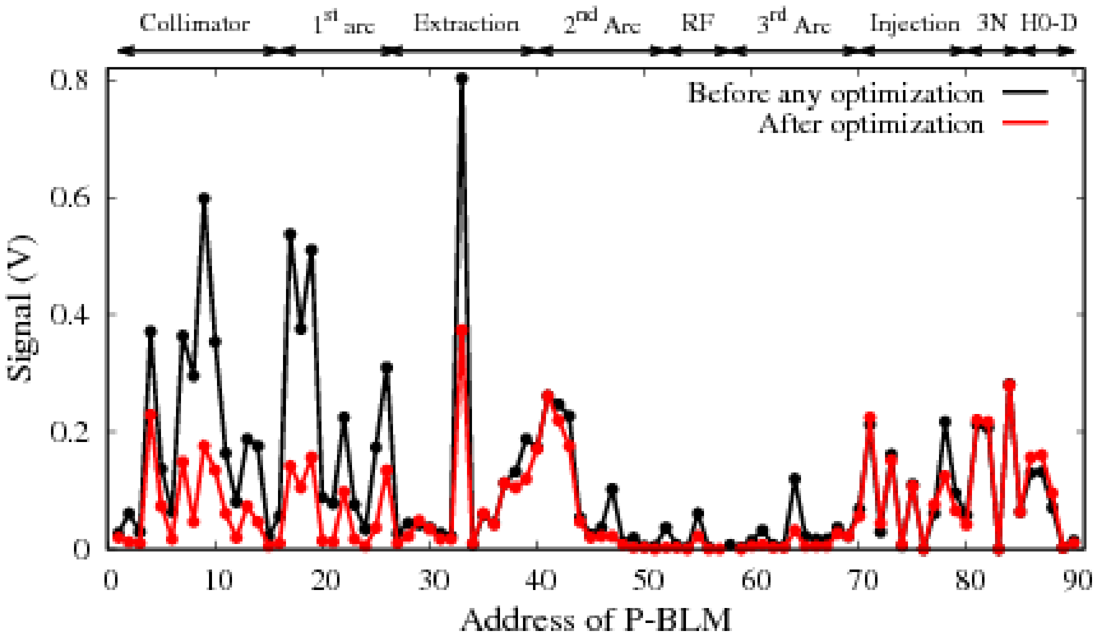


- ✓ Obtained another ~20% beam loss mitigation by tune optimization.
- ✓ Extracted beam emittance was also slightly improved.

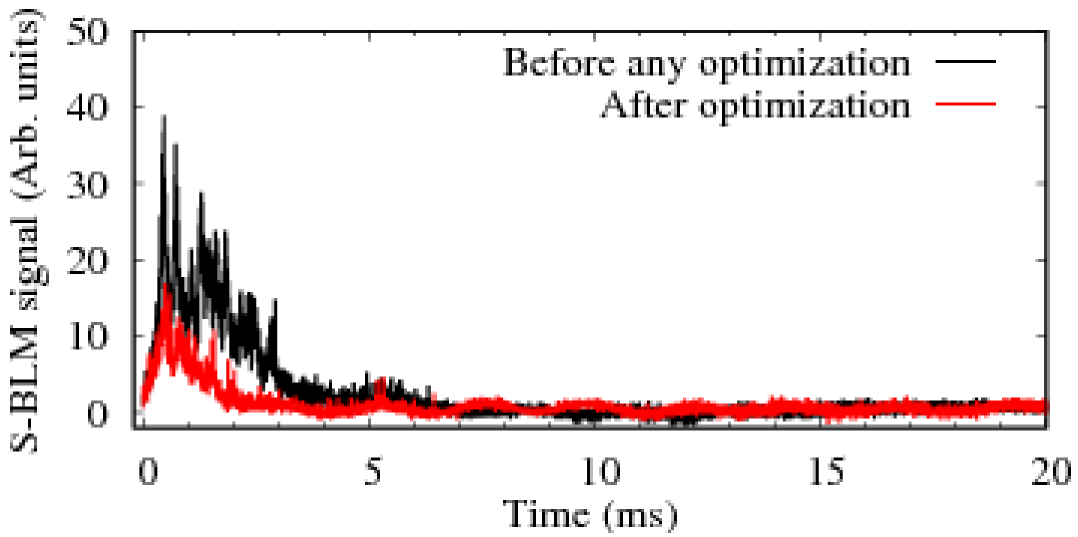
- ✓ Based on the tune survey, the present optimized one (6.46, 6.36) gives a minimum beam loss.

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.



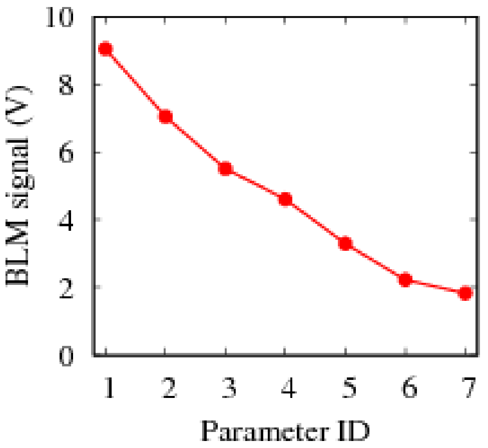
✓ We have obtained ~70% beam loss reduction at 1 MW by using a smaller injection β_y with a smaller size foil and implementing some important optimizations of the machine parameters by sufficient mitigation of the SC.

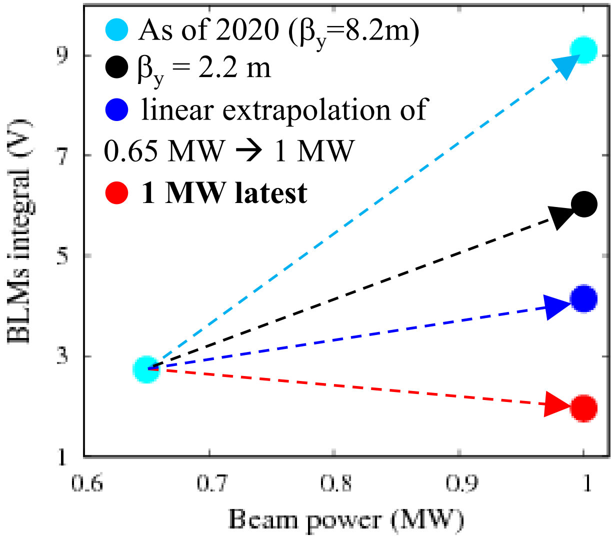
✓ The residual beam loss is mainly due to the foil scattering of the circulating beam.

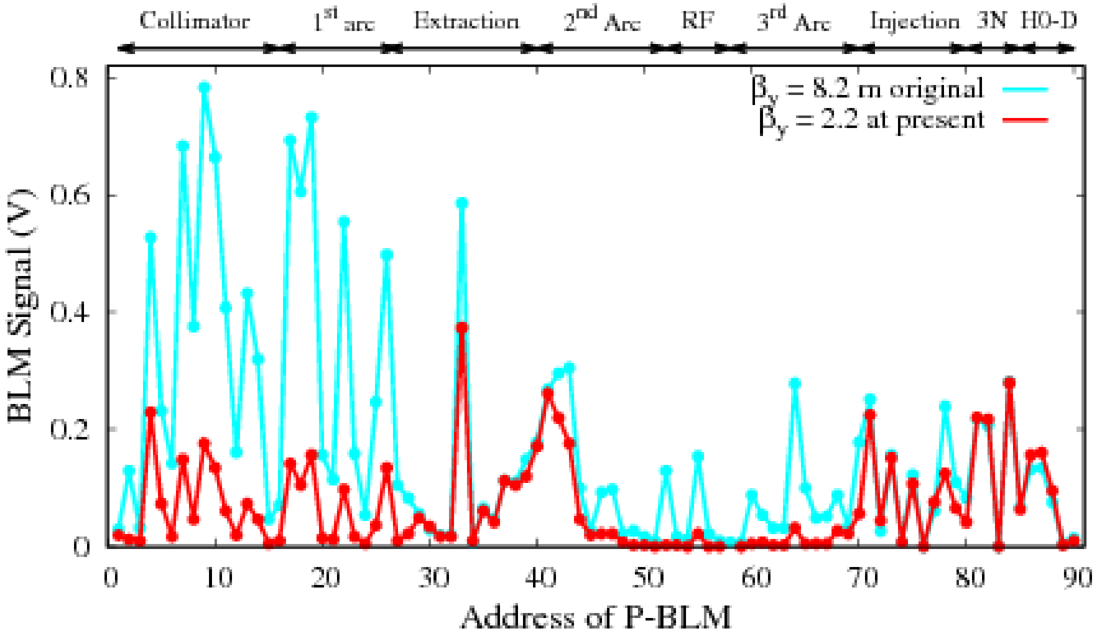
✓ The rms emittance of the extracted beam is also ~25% improved.

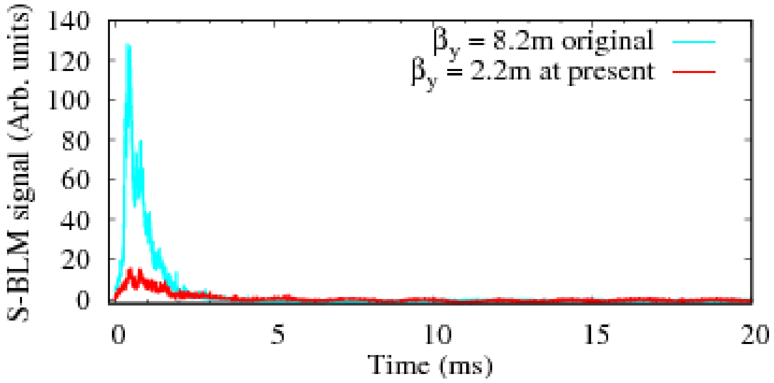
Beam loss mitigation as compared to previous 1 MW operation

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









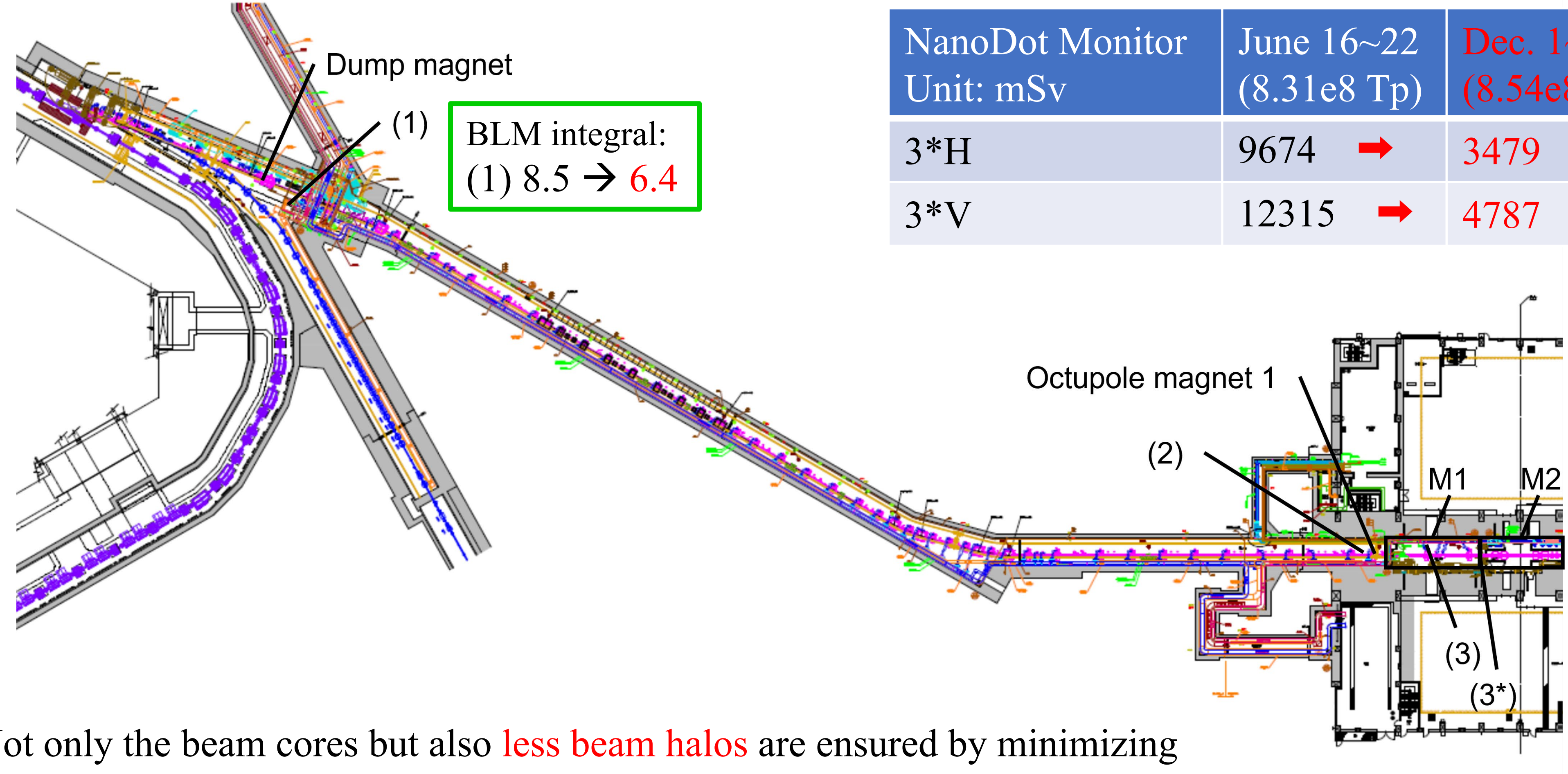
- The residual beam loss is <<0.1%, caused by the foil scattering.
- The SC effect has sufficiently been mitigated.
- *A laser stripping can thus give almost no beam loss at 1MW!*

- ✓ 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.