Optimization of Sextupole Magnetic Fields at the SPring-8 Storage Ring

April 25th 2022

Yoshito Shimosaki (KEK)

Outline:

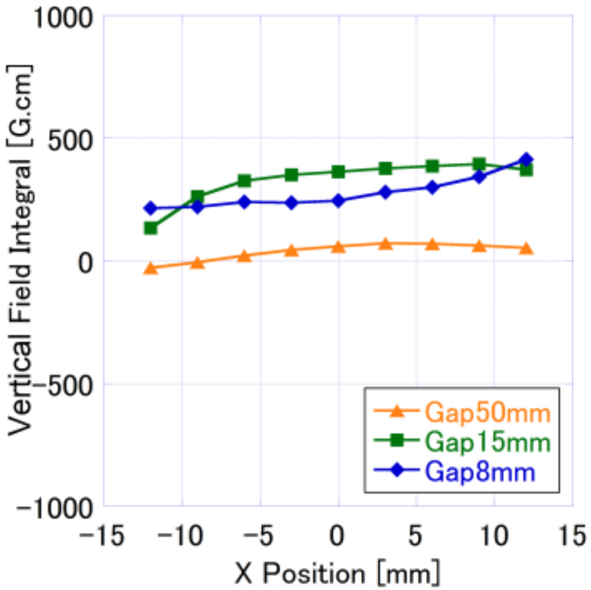
1. Introduction
2. Analyses to Manifest the Mechanism of Beam Loss
3. Strategy of Optimizing Sextupole Fields
4. Tracking Results after the Optimization
5. Experimental Results after the Optimization
6. Summary

Damage by Beam Loss

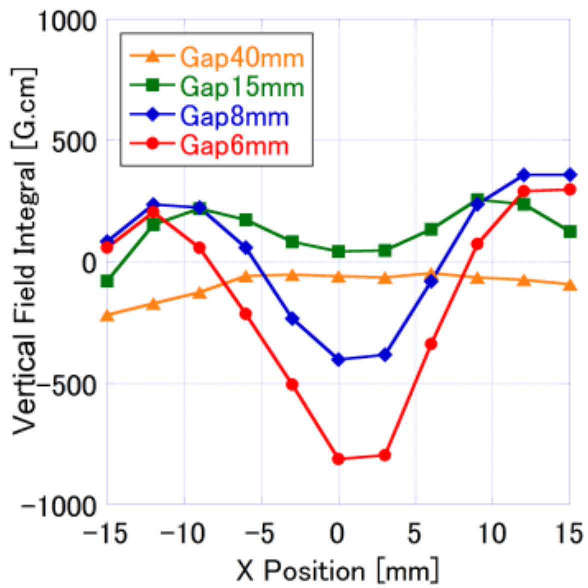
- **Beam loss** in an accelerator causes the the activation and the damage on the machine components.

Field Integral of permanent magnet of ID10 demagnetized at the SPring-8 [**].

Before demagnetization (1998)



After demagnetization (2015)



[**] T. Hasegawa et al., “Evaluation of permanent magnet demagnetization of the SPring-8 in-vacuum undulator by in-situ magnet measurements“, Proc. of PASJ2015, THP023.

Phenomena Induced by Sextupole Fields

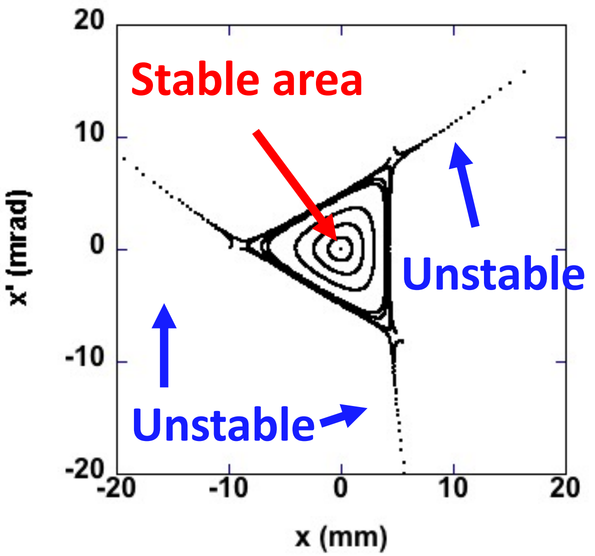
- In a ring, sextupole magnets are generally utilized for correcting the linear chromaticity.

- However, the nonlinear fields of the sextupole magnets also induce the various phenomena such as nonlinear resonances, the amplitude dependent tune and the amplitude dependent center shift, which can reduce the injection efficiency and the beam lifetime.

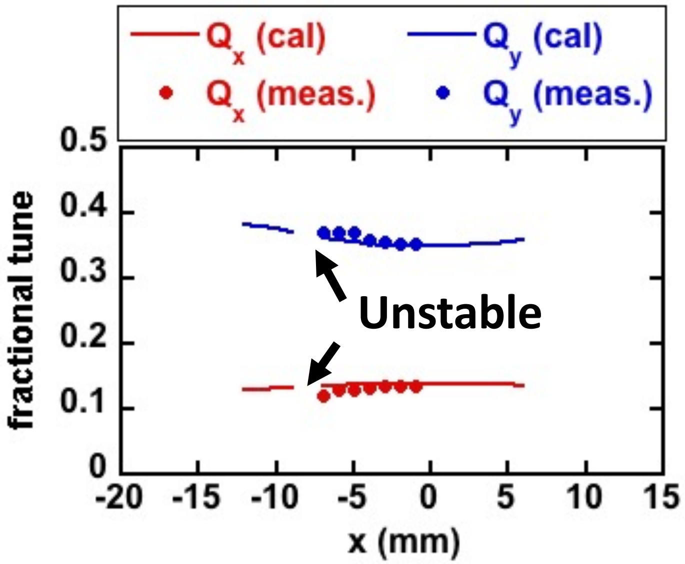
- So, an optimization of the sextupole fields to enrage the stable area as much as possible should be one of major concerns in a low emittance ring.

- At the SPring-8, the optimization of the sextupole fields was performed in 2015-2016.

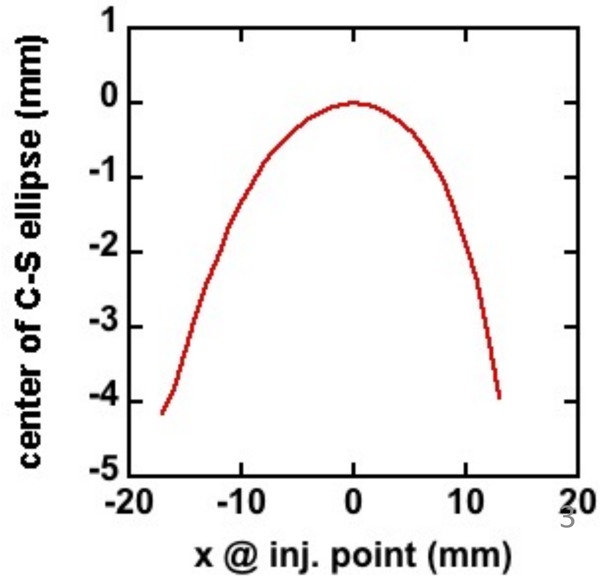
3rd integer resonance



Amplitude dependent tune



Amplitude dependent center shift

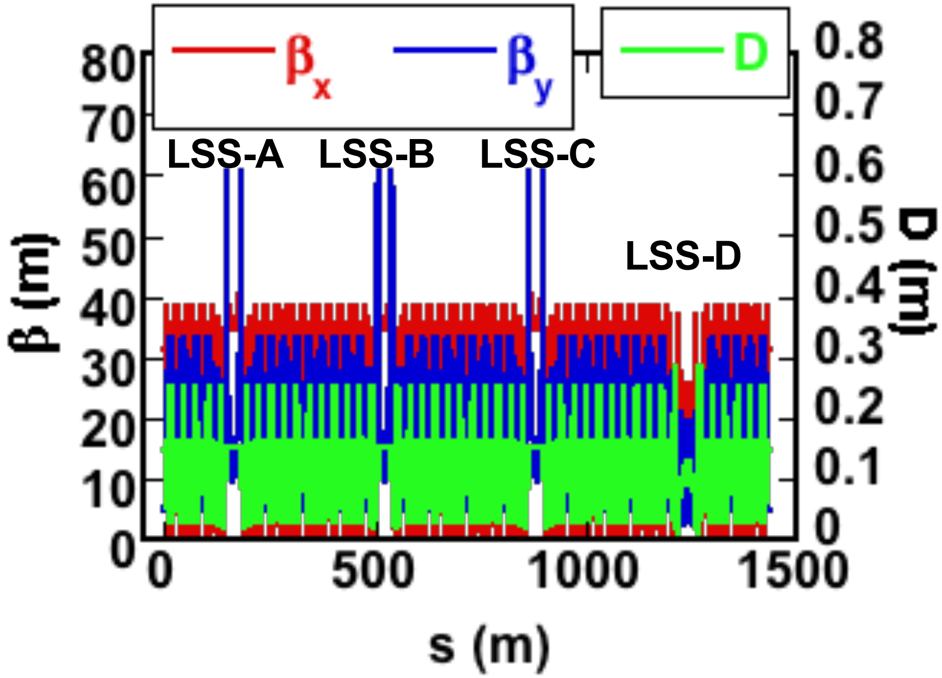


Parameters

Beam / machine parameters

Lattice Type	Double-bend
Circumference	1436 m
Energy	8 GeV
Stored Current	100 mA
Natural Emittance	2.41 nm.rad
Momentum deviation (RMS)	0.11 %
Betatron Tune	(41.14 , 19.325)
Natural Chromaticity	(-117 , -47)

Lattice function



"SPring-8" = 44 x "unit cell" + 4 x "30m long straight section (LSS)".

For installing the insertion devices (IDs), the symmetry of the lattice function is broken.
So, it becomes important to recover the stable area for electron beam to the sufficient level by optimizing the sextupole fields.

Number of sextupole families is 18.

6 families at unit cell.

3 families at LSS-A, 3 families at LSS-B, 3 families at LSS-C, and 3 families at LSS-D.

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Check of Simulation Model (1/3)

In order to manifest the mechanism of the injection beam loss, the 6D symplectic integrator code CETRA, which has been developed by Dr. H. Tanaka at SPring-8 [***], was utilized.

[***] J. Schimizu, et al., Proc. of 13th Symp. on Accel. Sci. and Tech. Osaka, Japan (2001), pp.80-82.

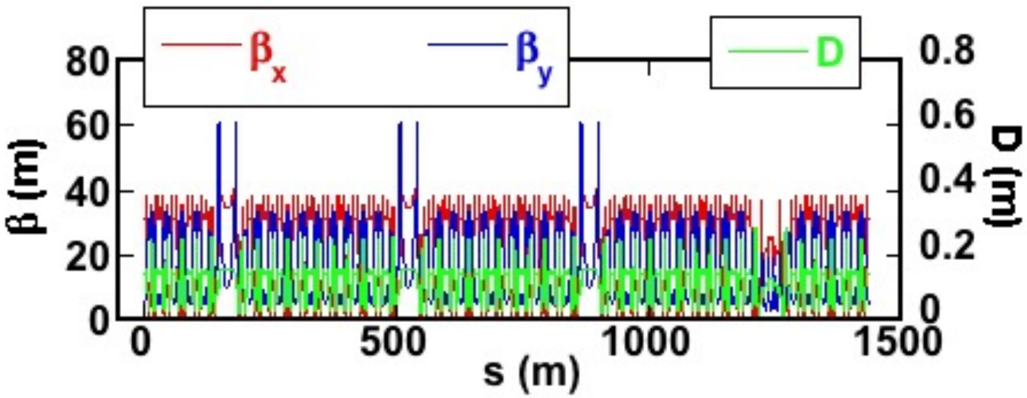
Simulation conditions:

1. Quadrupole errors and skew quadrupole errors evaluated by LOCO were included.
2. COD was not included, here.
3. ID model was included [*6].

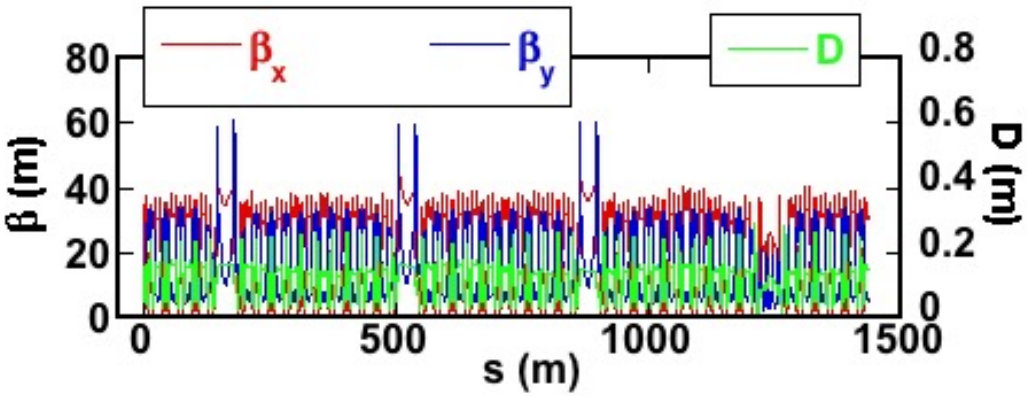
[*6] E.Forest and K.Ohmi, “Symplectic integrator for complex wiggler”, KEK Report 92-14, September 1992.

For checking the validity of simulation conditions, the tracking was performed for the comparison with the experimental results.

Lattice function (design)

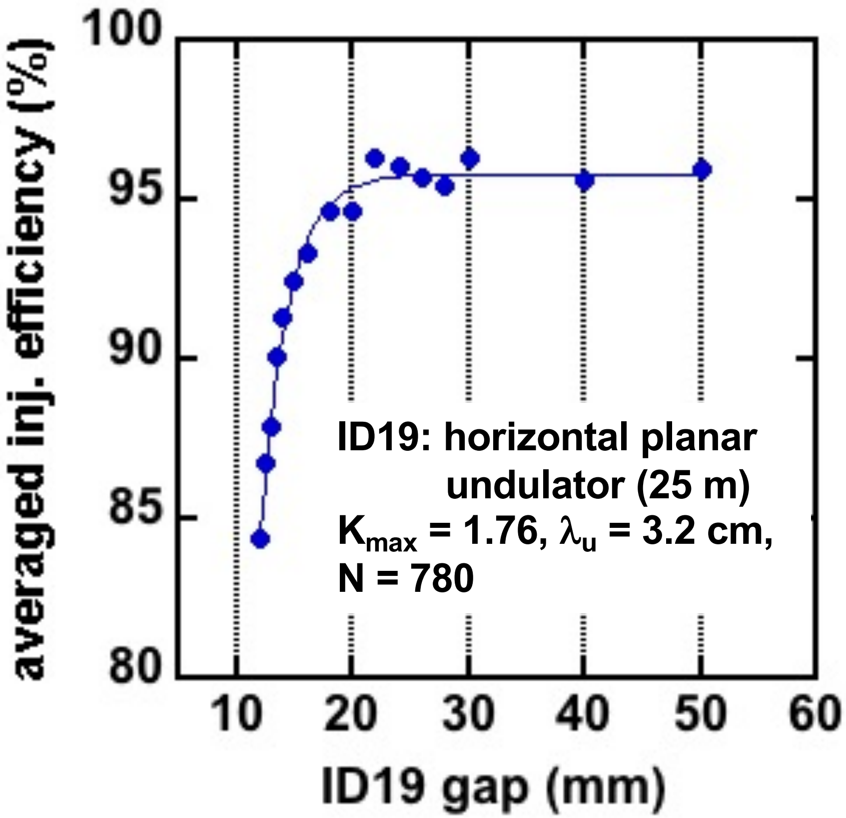


Lattice function w/ errors

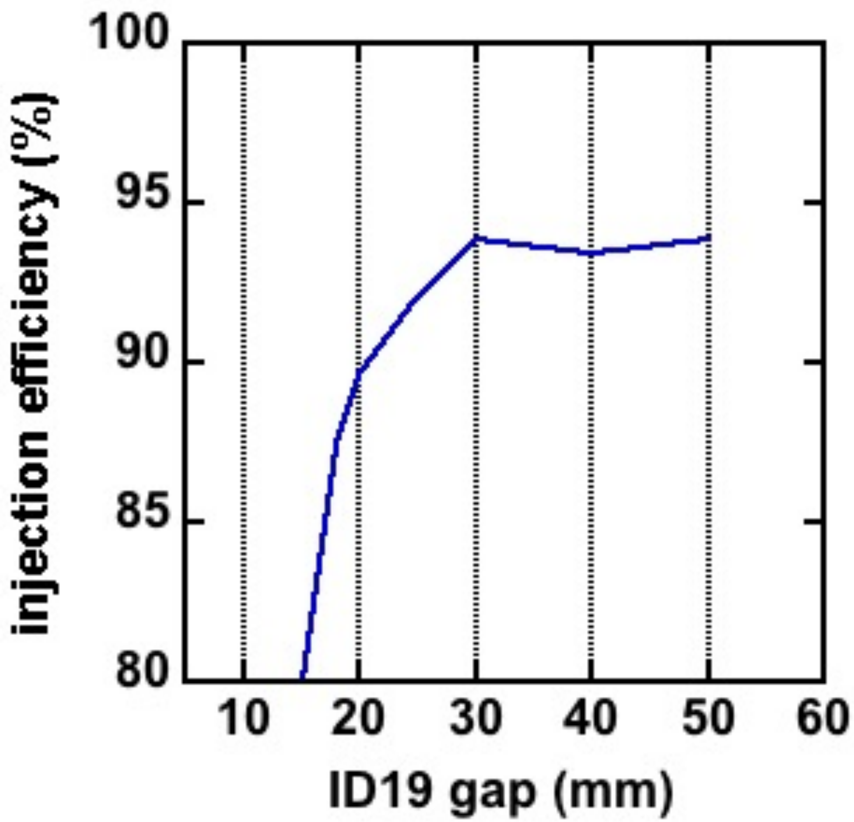


Check of Simulation Model (2/3)

(meas) Injection efficiency before optimization



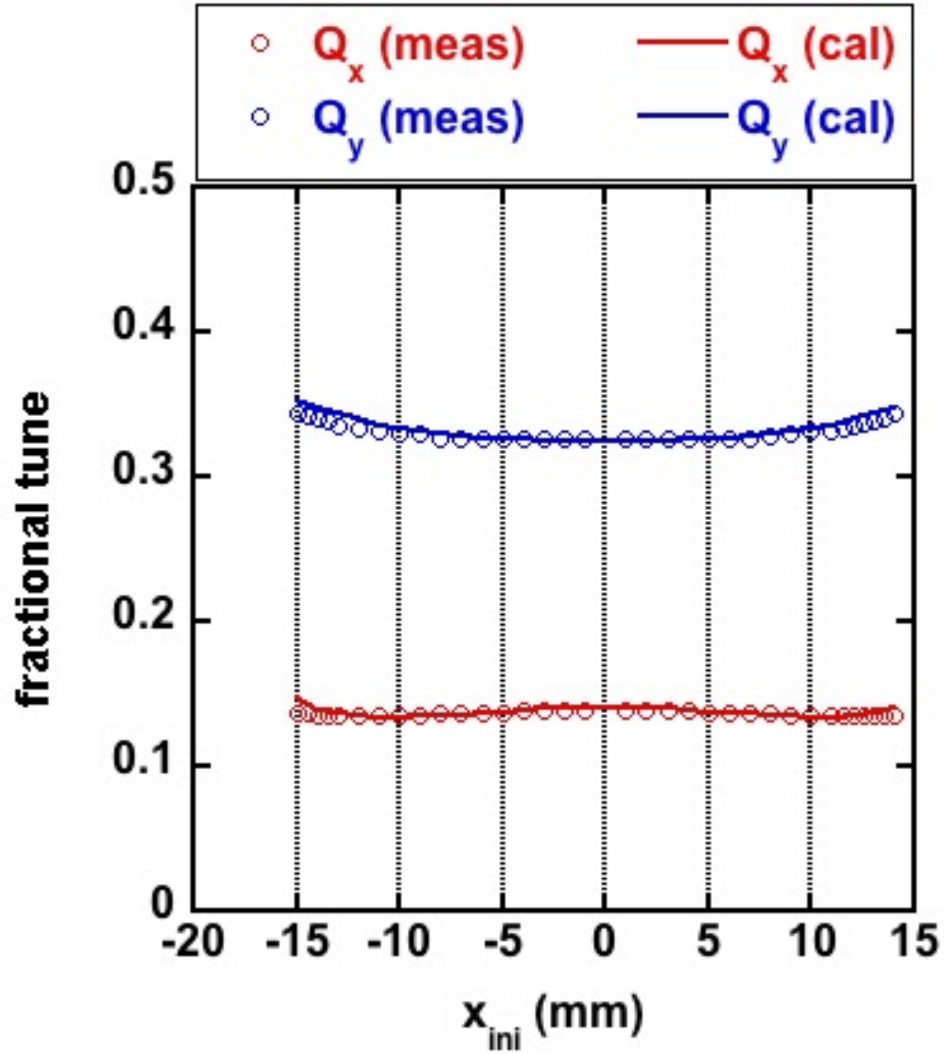
(cal) Tracking results with CETRA



The tune shift caused by closing the gap of ID19 was not corrected.

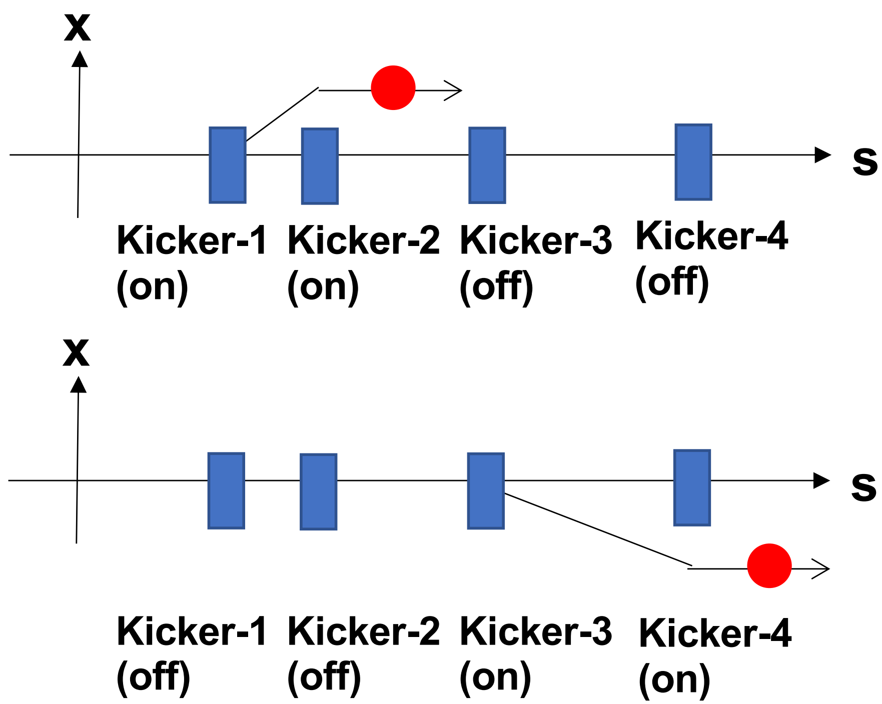
Check of Simulation Model (3/3)

Amplitude dependent tune in x



x' = 0 mrad
@ injection point

- 2 injection-kickers were turned on for setting the initial (x, x') @ injection point.

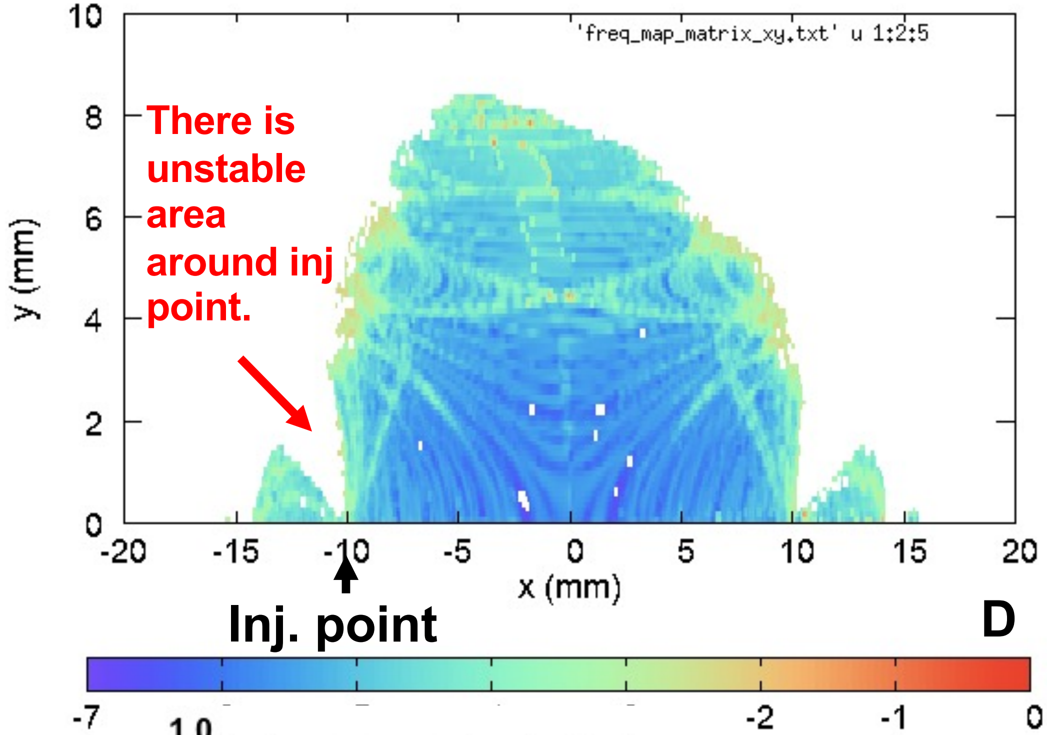


- ID gap was fully opened.

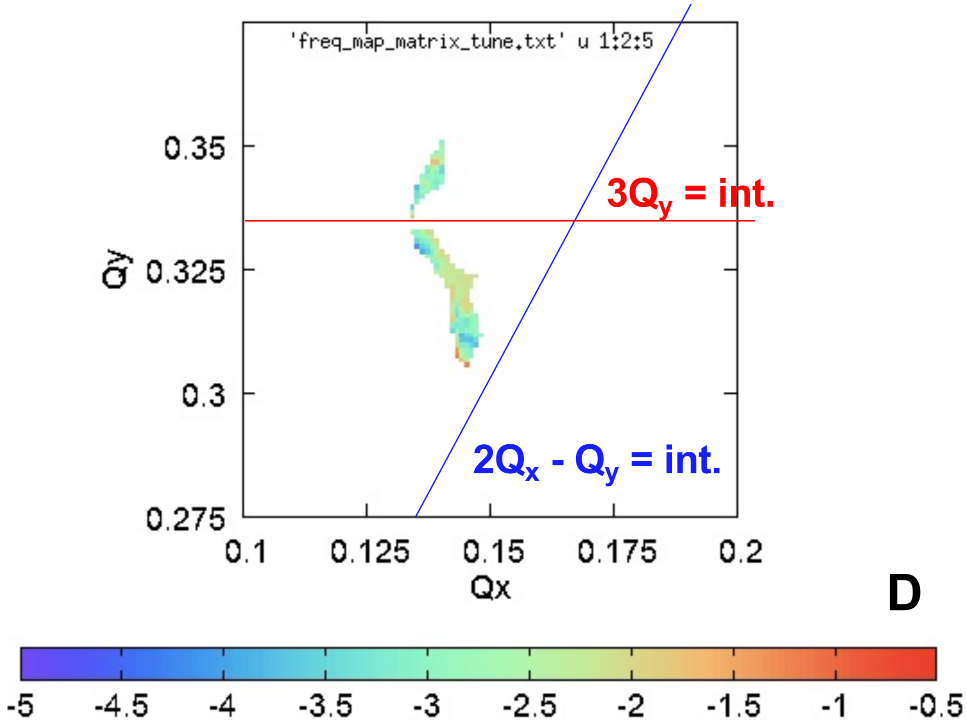
- There were no vertical kickers for beam diagnostic, so that there is no result concerning the amplitude dependent tune in y.

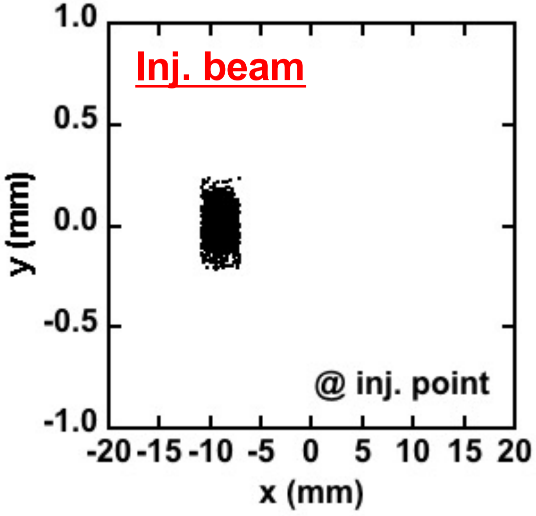
Analyses by Tracking (1/3): Frequency Map Analysis

Frequency map in (x, y) space



Frequency map in (Q_x, Q_y) space





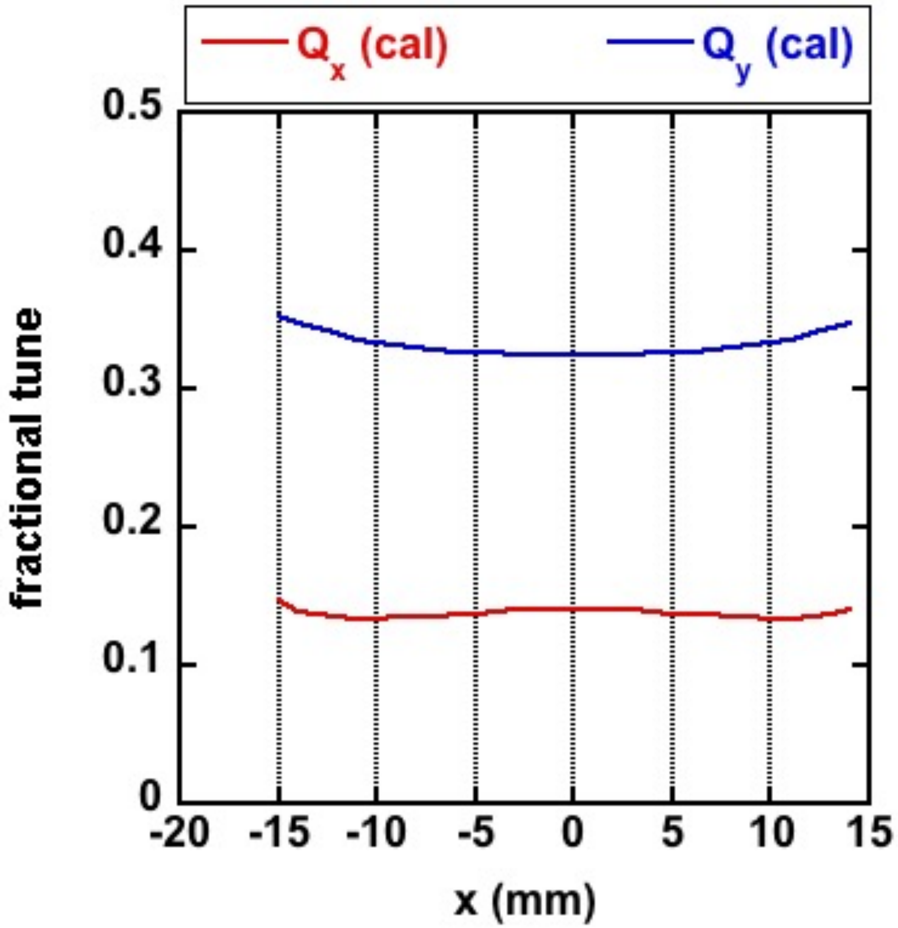
-11 mm < x < -7 mm
-0.2 mm < y < 0.2 mm

$$D = \log_{10}\sqrt{\left(Q_{x,1\sim1024} - Q_{x,1025\sim2048}\right)^2 + \left(Q_{y,1\sim1024} - Q_{y,1025\sim2048}\right)^2}$$

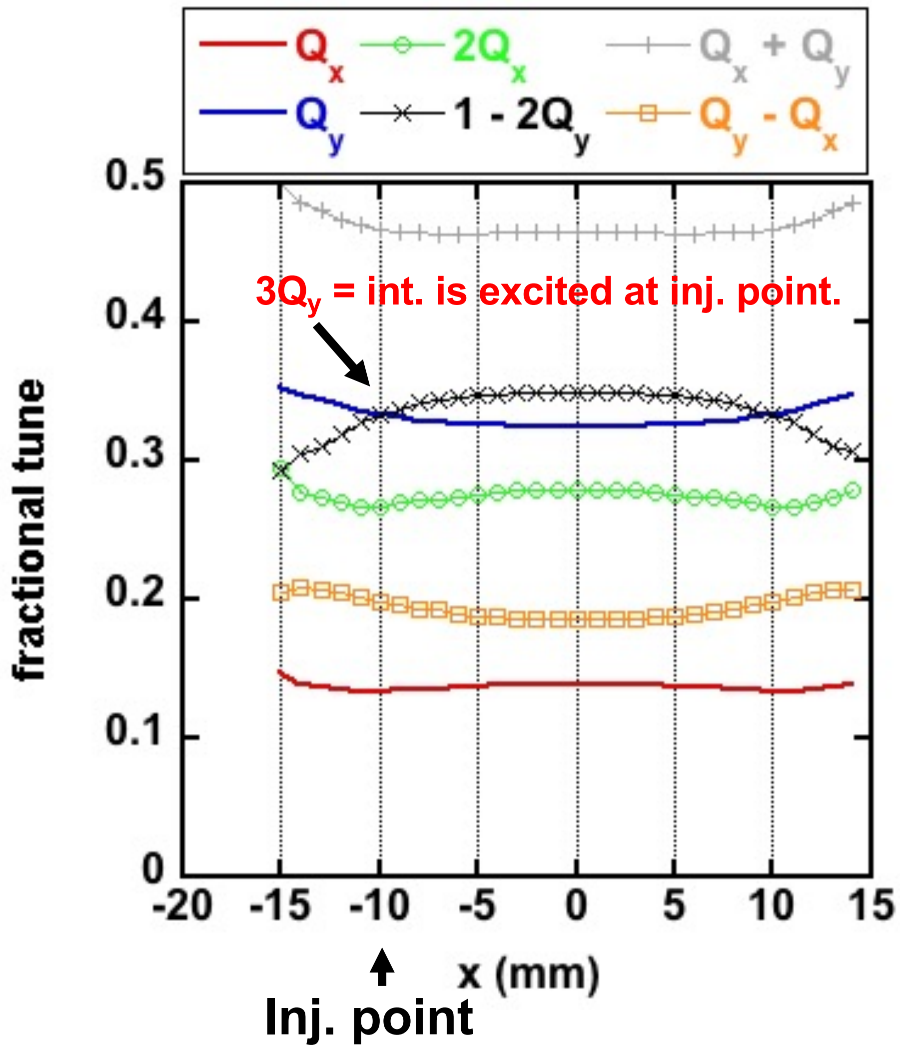
It seems that there is the unstable area around the injection point, and that a part of the initial beam is located at this unstable area.

Analyses by Tracking (2/3): Resonant Line

Amplitude dependent tune in x



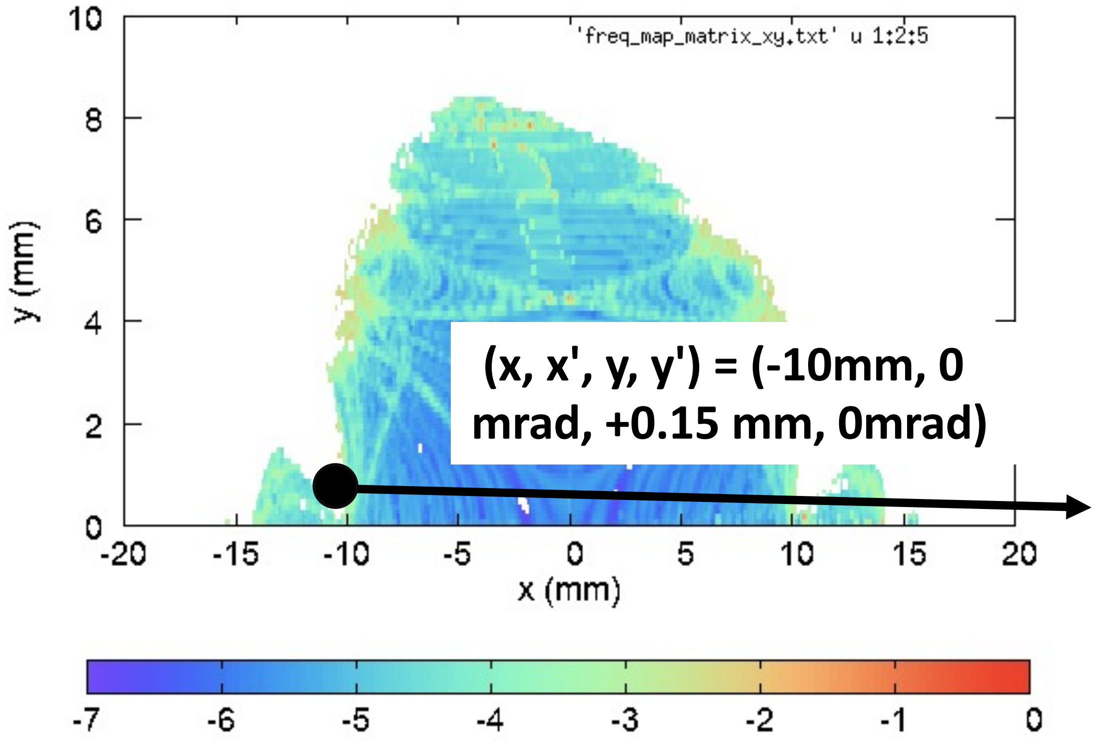
Resonant line estimated from amplitude dependent tune



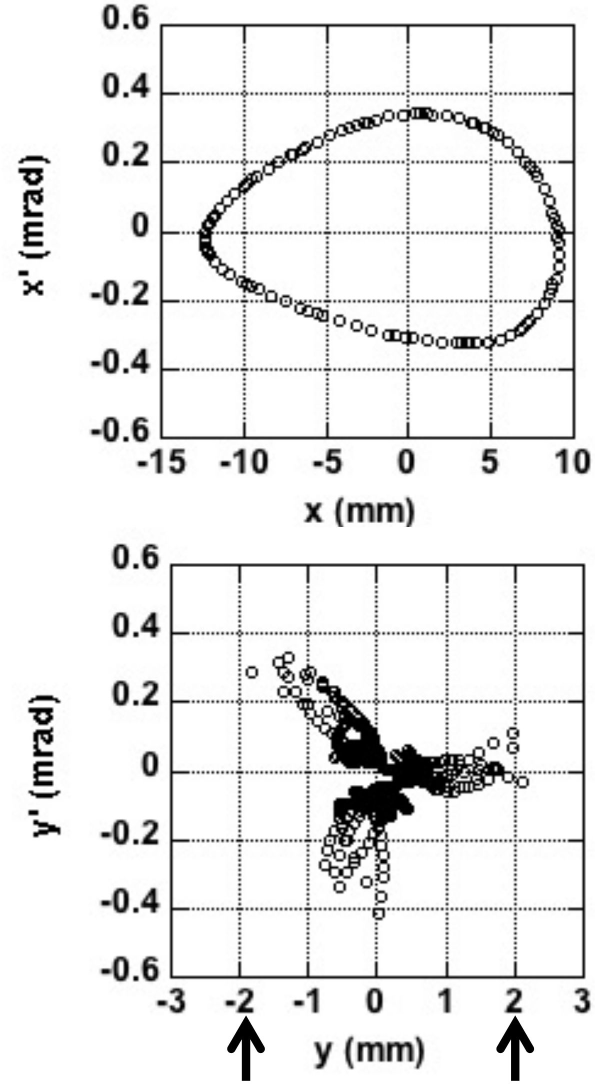
It seems that the resonance of $3Q_y$ = integer is excited at the injection point.

Analyses by Tracking (3/3): Single Particle Tracking

Frequency map in (x, y) space



Beam orbit in phase space @ scraper



It seems that there is the unstable area around the injection point, **which is caused by the resonance of $3Q_y$ ~ int.**, and that a part of the initial beam is located at this unstable area.

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Strategy to Improve Injection Efficiency

- There was no skew sextupole at the SPring-8, so that the correction of $3Q_y$ = int. by skew sextupoles was not possible.

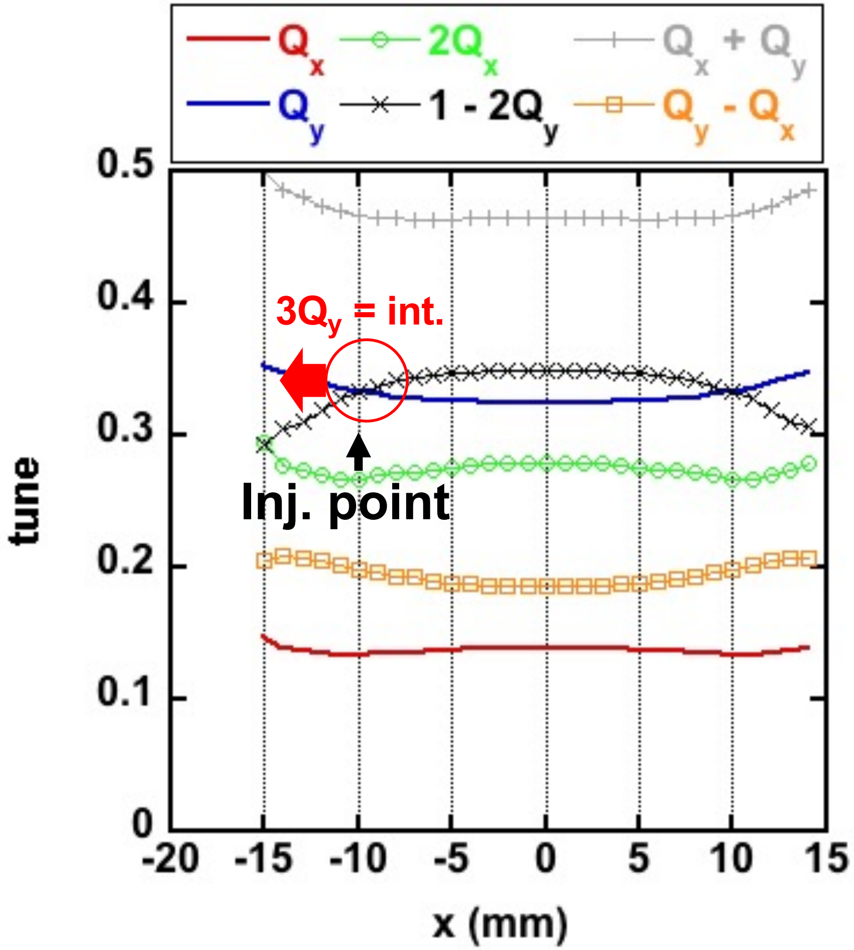
- The possible countermeasure is the separation of the resonant point of $3Q_y$ = int. from the injection point by modifying the amplitude dependent tune with the normal sextupole fields.

- The linear chromaticity should be fixed at $(\xi_x, \xi_y) = (3, 3)$.

- The resonance should not be excited by changing the sextupole fields.

- The amplitude dependent center shift should also be considered for suppressing the injection beam loss.

Resonant line evaluated from amplitude dependent tune



Set-Values for Optimizing Sextupole Fileds

Simultaneous equations

Mathematica[****] was utilized for solving.

[****] https://www.wolfram.com

$$\begin{pmatrix} \text{coef. of linear chromaticity} \\ \text{coef. of resonant terms} \\ \text{coef. of amp. dependent center shift} \\ \text{coef. of amp. dependent tune} \end{pmatrix} \begin{pmatrix} k_1 \\ \vdots \\ k_i \\ \vdots \\ k_n \\ k_1^2 \\ \vdots \\ k_i k_j \\ \vdots \\ k_n^2 \end{pmatrix} = \text{set}-\text{values}$$

Strength of nonlinear resonances

		before	after
$Q_x \sim$ int.	Re.	0.0	0.0
	Im.	0.1	0.1
$Q_x \sim$ int.	Re.	0.0	0.0
	Im.	0.0	0.0
$3Q_x \sim$ int.	Re.	-0.1	-0.1
	Im.	8.8	7.7
$Q_x + 2Q_y \sim$ int.	Re.	-7.4	-5.4
	Im.	-6.1	-4.5
$Q_x - 2Q_y \sim$ int.	Re.	-44.9	-39.5
	Im.	10.5	9.3

Linear chromaticity

	before	after
(ξ_x, ξ_y)	(3, 3)	(3, 3)

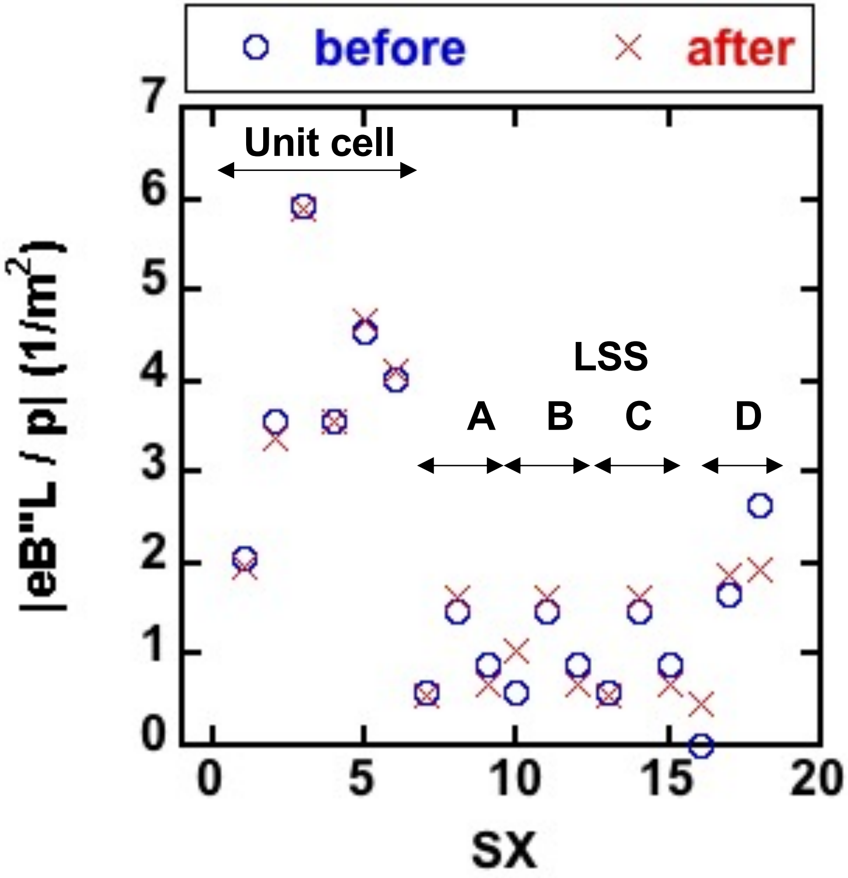
Coefficients of amplitude dependent tune

	before	after
α_{xx}	-7310	-7310
α_{xy}	1241	-1241
α_{yy}	-1553	0

Amplitude dependent center shift

	before	after
$\langle x \rangle$ (J_x)	-1049	-1237
$\langle x \rangle$ (J_y)	-183	-327

Solutions of Simultaneous Equations



The evaluated sextupole fields were adopted to both the tracking and the machine.

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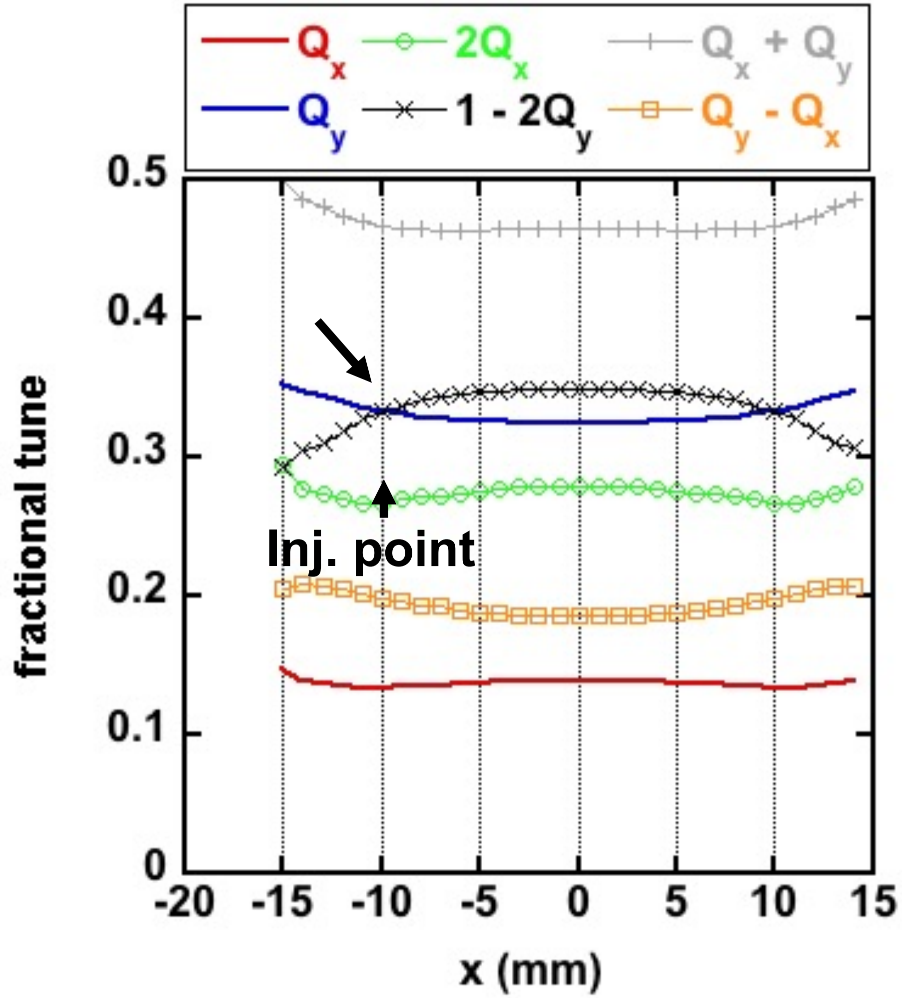
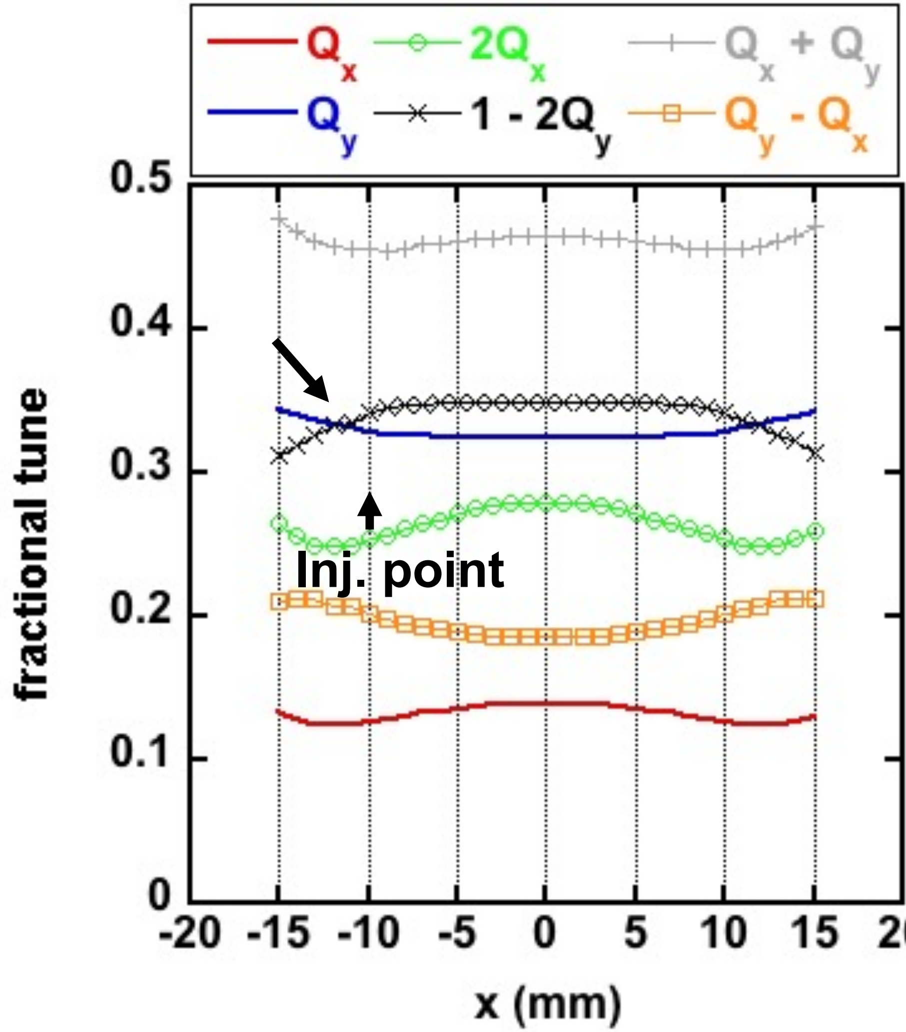
(cal) Resonant Line after Optimization

Before optimization



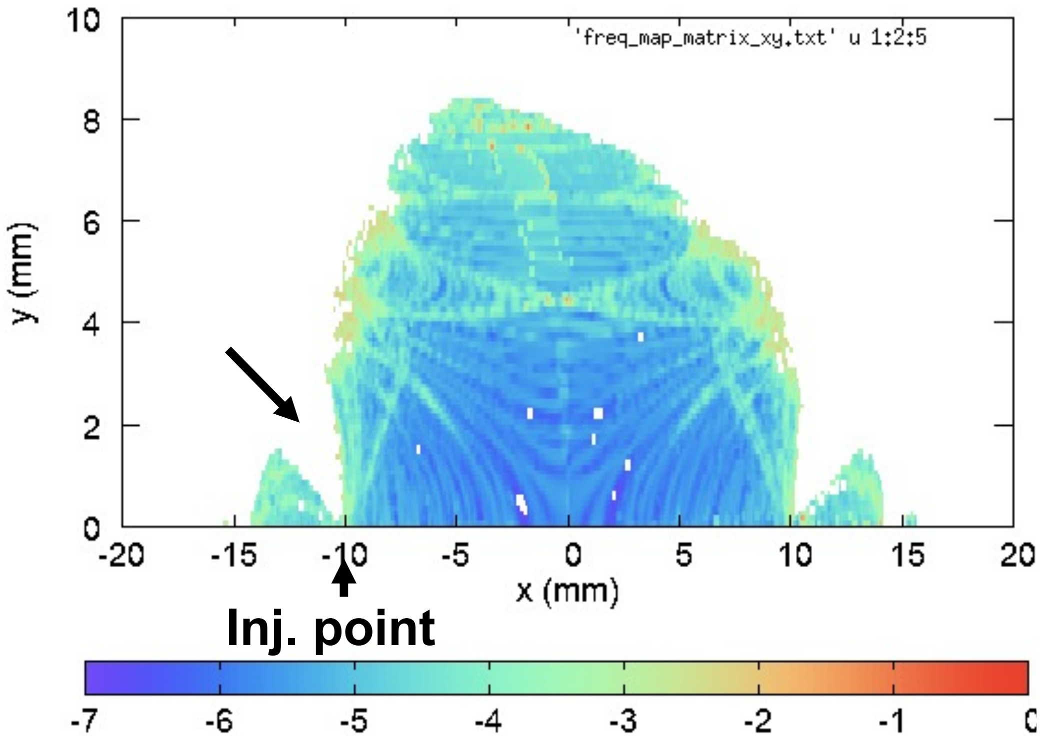
After optimization



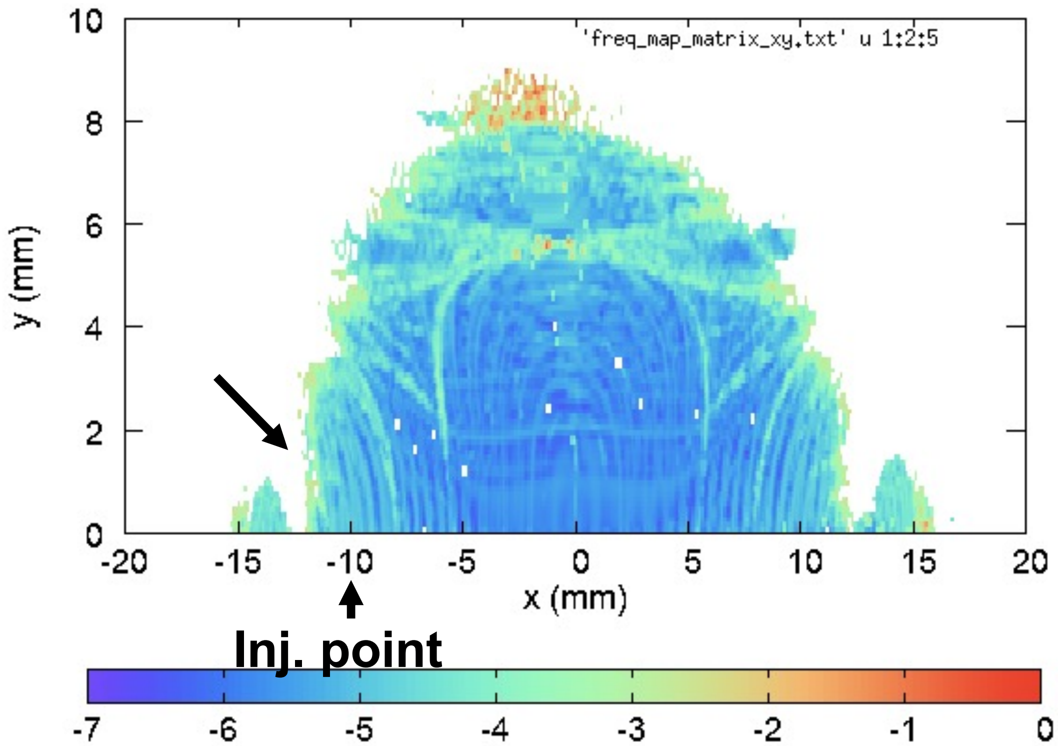
The resonance of $3Q_y$ = int. is away from the injection point.

Tracking Results: Frequency Map Analysis

Before optimization



After optimization

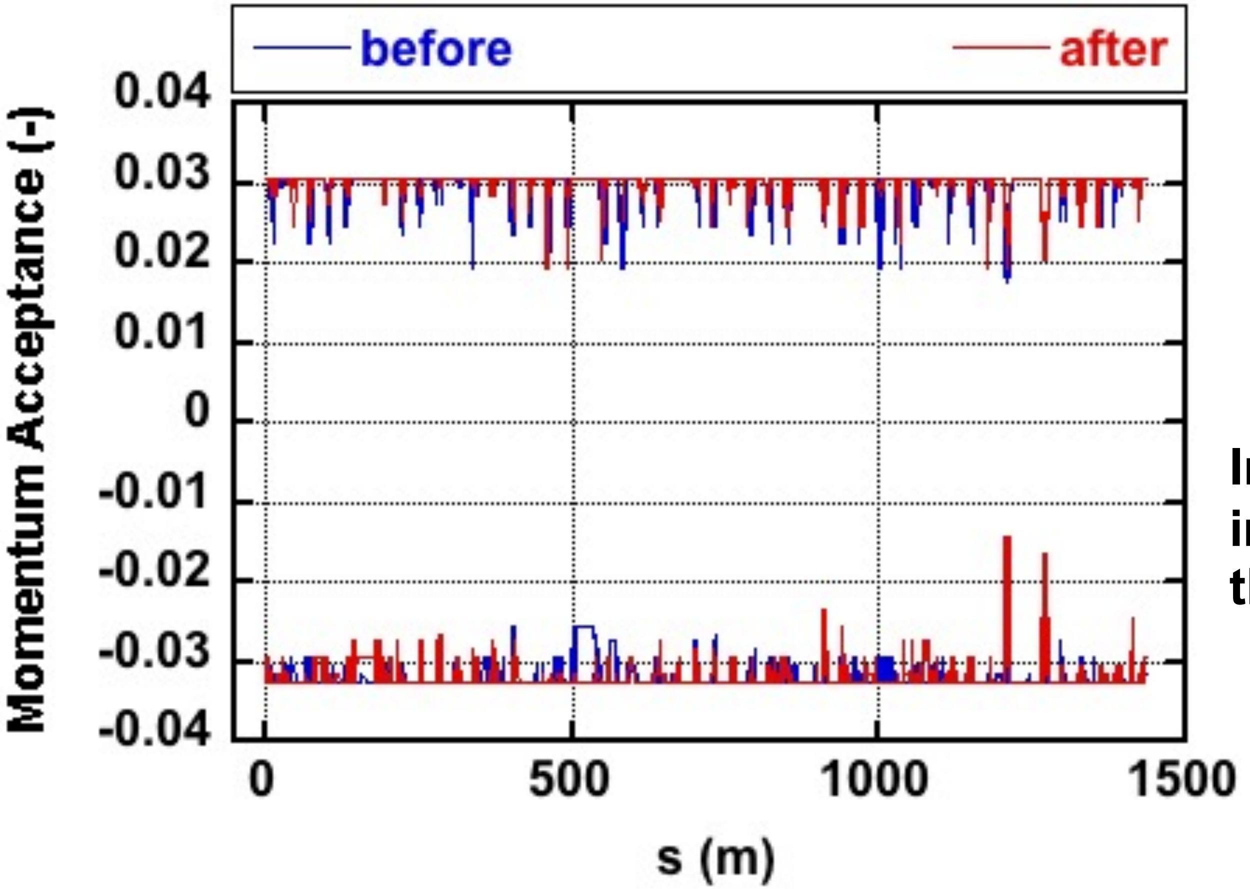


The unstable area induced by the resonance of $3Q_y$ ~ int. is away from the injection point.

-> Injection efficiency should be improved.

Tracking Results: Momentum Acceptance

Momentum Acceptance (RF voltage = 16 MV)



Momentum Acceptance

before opt.: 2.88 %

after opt.   : 2.92 %

Injection efficiency should be improved without the reduction of the beam lifetime.

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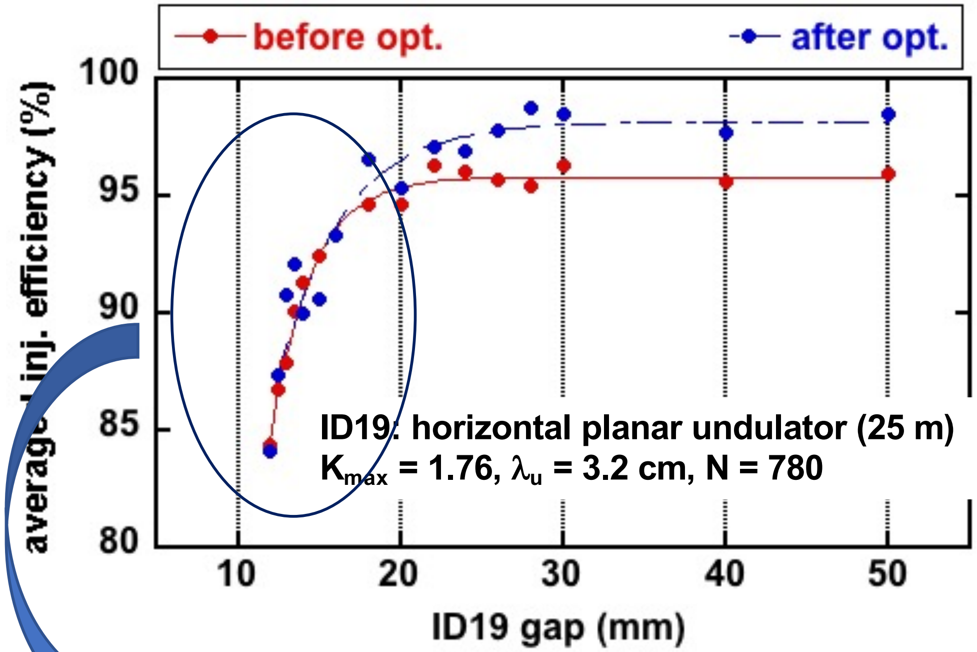
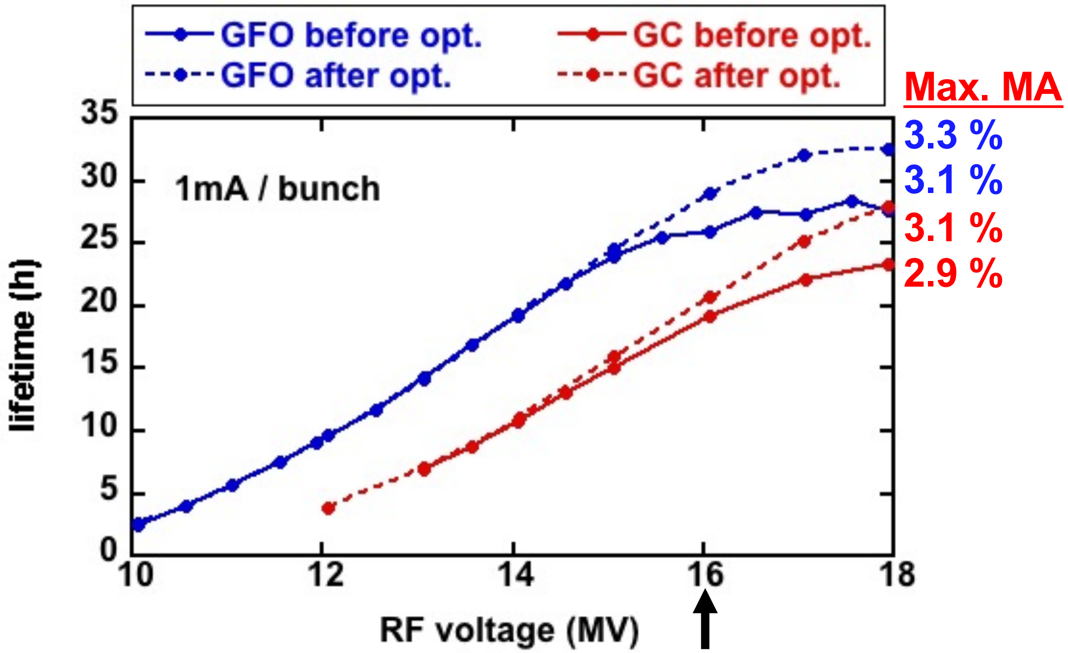
Experimental Results: Injection Efficiency and Beam LifeTime

(meas) Injection efficiency



(meas) Beam lifetime



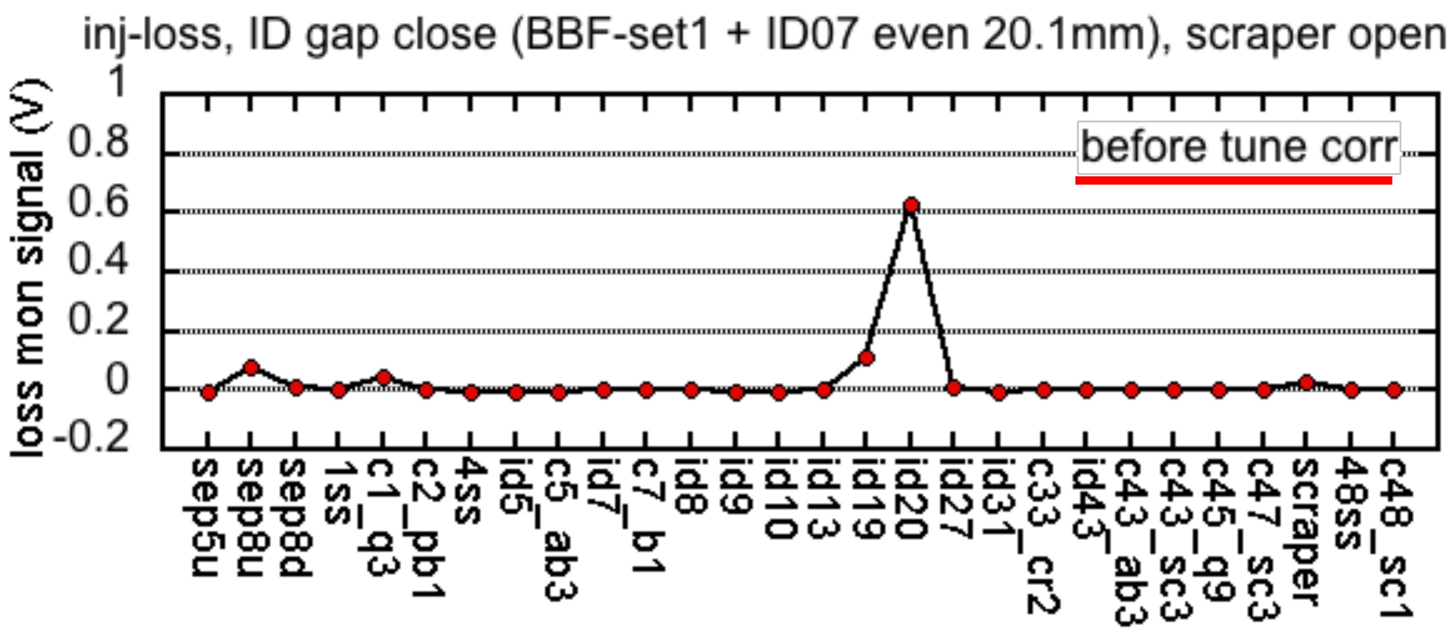
The tune shift induced by closing ID19 was not corrected.

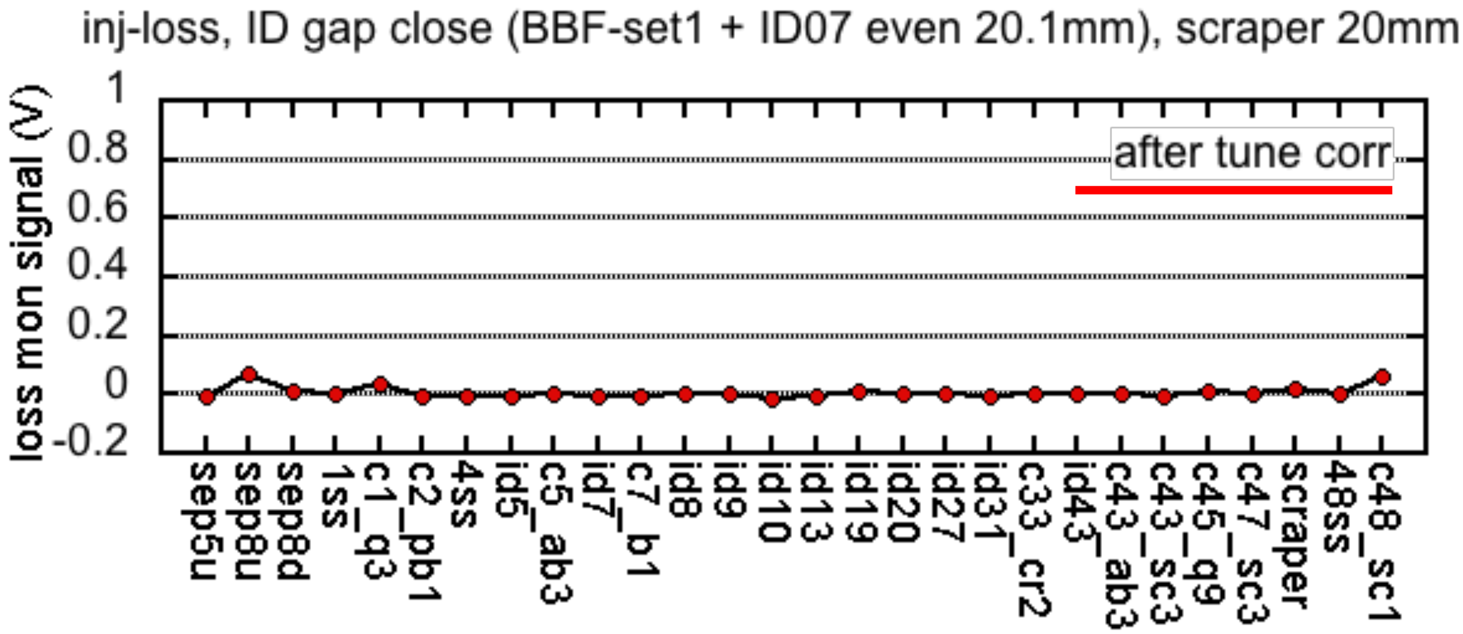
The injection efficiency should be improved by correcting the tune shift (next page).

GFO: All IDs were fully opened.

GC : All IDs were closed to the typical values of the user operation. Tune was not corrected.

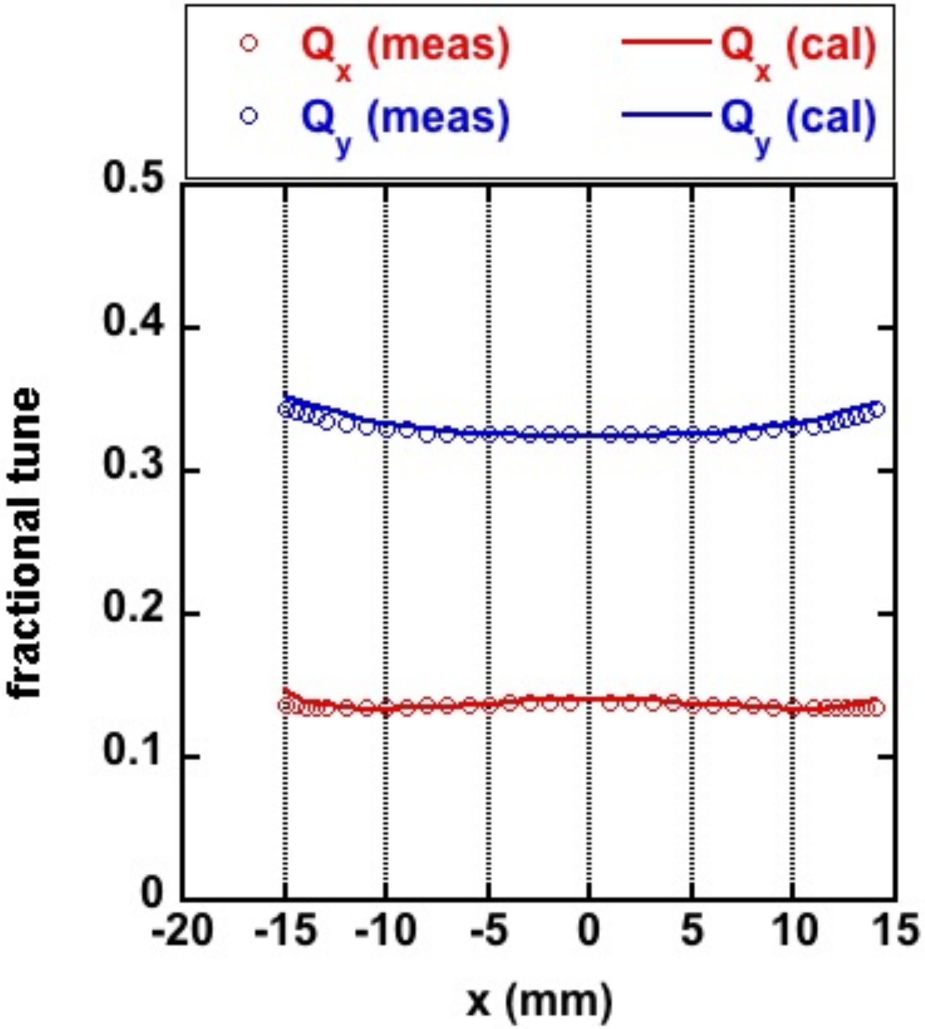
Injection Beam Loss Observed by Beam Loss Monitor





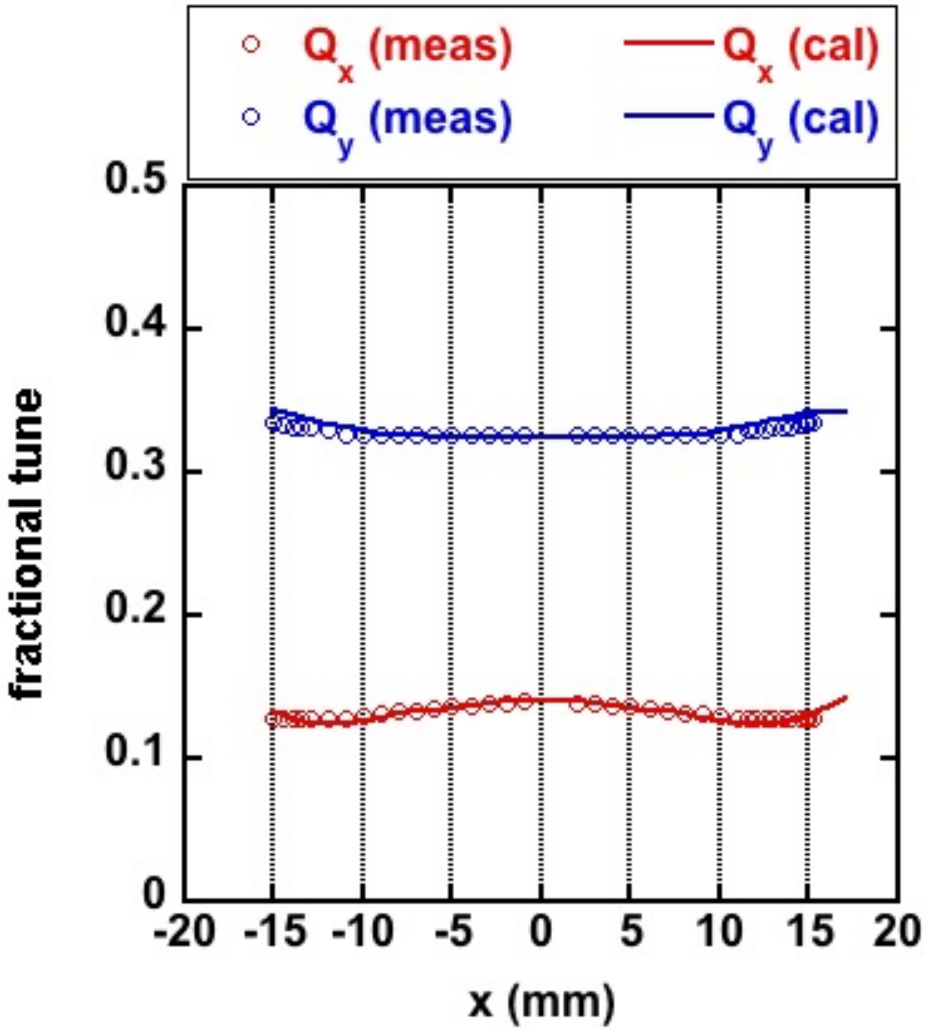
Experimental Results: Amplitude Dependent Tune

Before Optimization



x’ = 0 m.rad
@ injection point

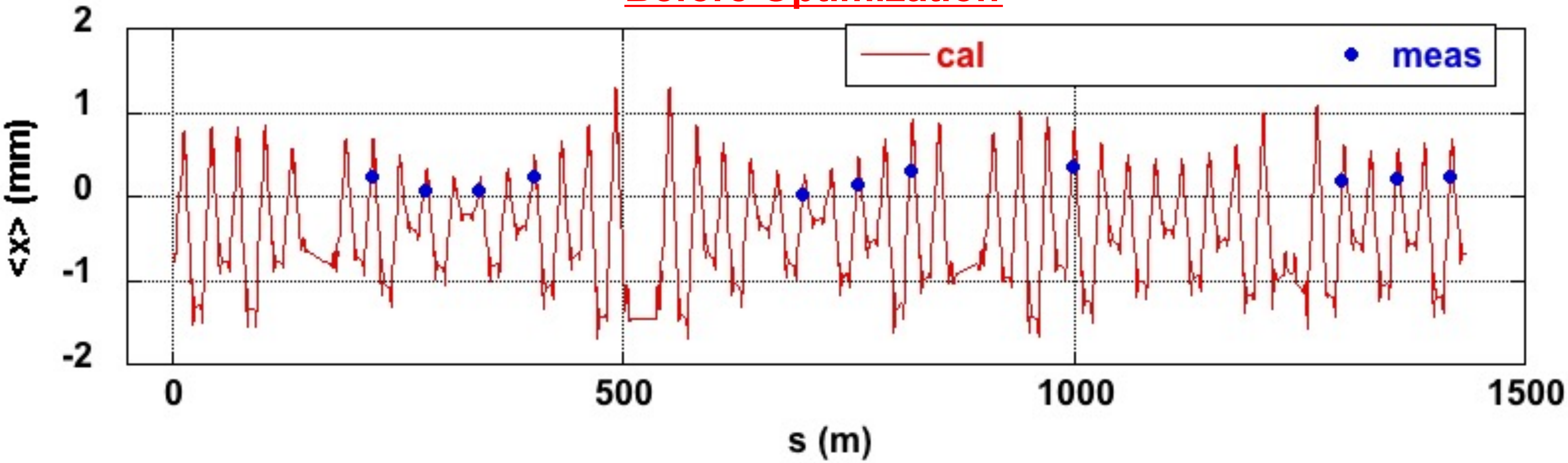
After Optimization



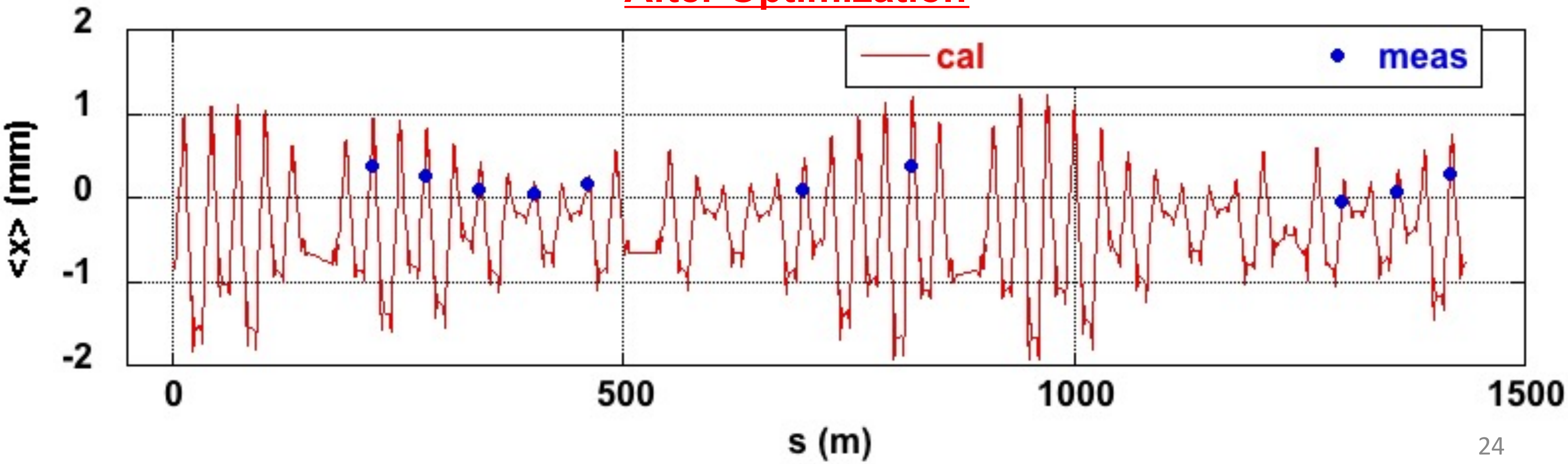
Experimental Results: Amplitude Dependent Center Shift

x_{ini} = -10 mm @ inj. point

Before Optimization



After Optimization



Summary

- **Beam loss should be suppressed for avoiding damage on machine components.**

- **Phenomena induced by sextupole magnetic fields can generate the beam loss, so that the optimization of sextupole fields is indispensable.**

- **At the SPring-8, the injection efficiency was improved by optimizing the sextupole fields, by separating the resonant point of $3Q_y$ ~ int. from the injection point.**

- **The reliable monitors and the reliable tracking code are powerful tools to manifest the mechanism of beam loss, to make the countermeasure, and to improve the performance of the low emittance ring.**

Amplitude Dependent Center Shift

Electron beam irradiation system

The aperture normalized by $\beta^{1/2}$ is narrowest in the horizontal.

Beam loss monitor