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SPring-8 upgrade and nonlinear optimization

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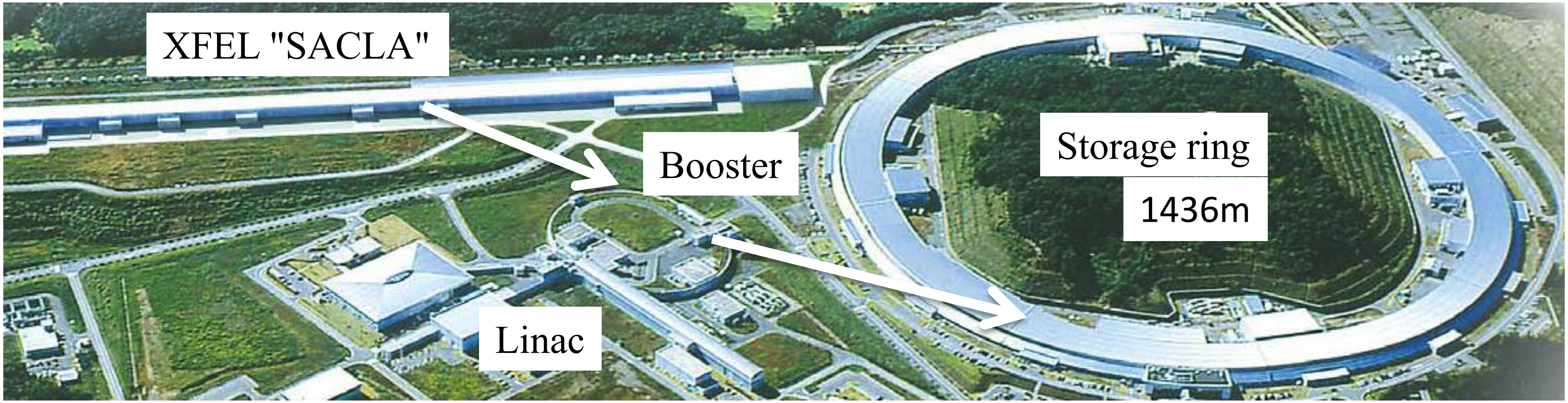
on behalf of
SPring-8-II working group

1. SPring-8 upgrade project
2. Key developments
3. Nonlinear optimization
4. Summary

SPring-8 upgrade, "SPring-8-II"

- Approx. one-year shutdown in early 2020's (not yet fixed)
- Replace the existing ring
- Take full advantage of existing resources, especially SACLA
  Injection from SACLA to SR will start *prior to* the upgrade
- Better performance, less energy
- Important: stability, reliability – *strong points of ring-based LS* –

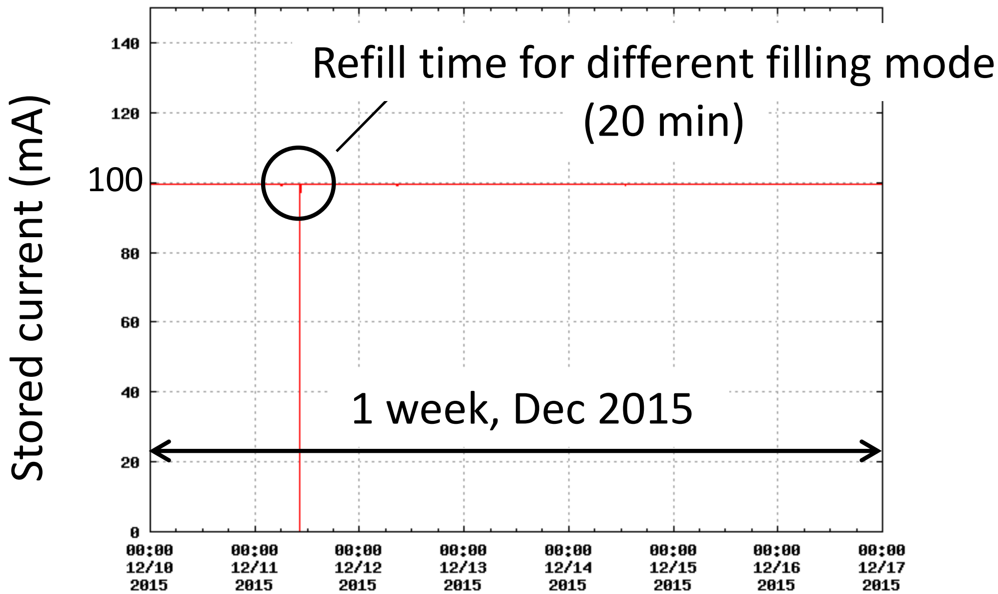


Reliability and stability of ring-based light sources

SPring-8
user time availability

Fiscal year	2013	2014	2015
User time (h)	3409	4058	4033
Down time (h)	20	17	17
Availability (%)	99.3	99.5	99.5

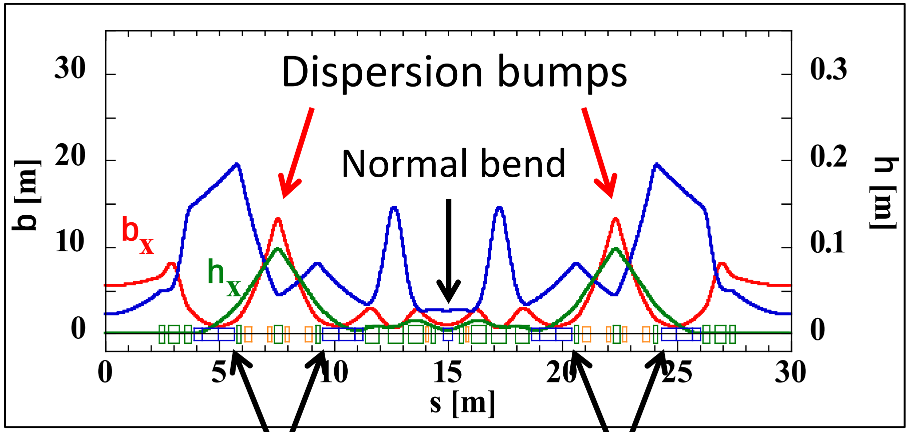
* Refill time is included in "down time".



Good reliability and stability are *the strong points of ring-based LS*.
We should keep it for SPring-8-II.

SPring-8-II linear lattice

5 bend achromat lattice



Longitudinal gradient bend (LGB)

> Lower energy, 6 GeV

> Lower hor.&vert. beta-functions

> Shorter & achromatic S.S. for IDs

> 4 longitudinal gradient bends (LGB)

> No very strong magnets

Q < 60 T/m, Sx < 3,000 T/m^2

(tentative)

	SPring-8-II	SPring-8
Energy (GeV)	6	8
Stored current (mA)	100	100
Circumference (m)	1435.45	1435.95
Effective emittance (nmrad)	0.157 ~0.10 w/ ID	2.8
Energy spread (%)	0.093	0.109
Betatron tune	(108.10, 45.58)	(41.14, 19.35)
Natl. chromaticity	(-143,-147)	(-117,-47)
Straight section (m)	4.6	6.6
βx, βy @ ID (m)	(5.5, 2.2)	(31.2, 5.0)
Dispersion @ ID (m)	0.0	0.146

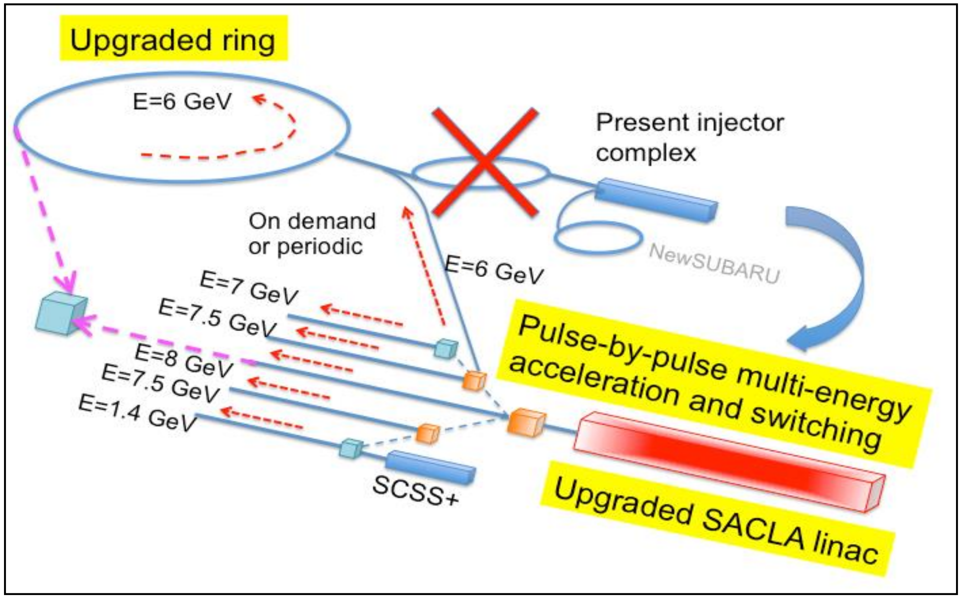
Two cutting-edge light sources – SACLA and SR – in the site

Accelerators

Share SACLA linac for two light sources.

1) On-demand pulse-by-pulse injection
   to SACLA and SR by revising LLRF
2) Timing system for SR and SACLA
are being developed*.

*H. Maesaka et al.



Experiments

Strengths of each LS should be taken into consideration in designing the SPring-8-II project.

XFEL: high peak current, short pulses
SR : high average current, high repetition rate, stability

➡ <u>Would not try to squeeze lots of electrons into small 6-dimensional volumes for generating short pulses at SPring-8-II.</u>
<u>Instead, focus on stable, reliable small emittance beams.</u>

Key developments

> Permanent dipole magnets
normal bends + longitudinal gradient bends + others (for injection)

> Narrow dimension SUS vacuum chambers

> Off-axis injection (today's talk by Shiro Takano)

> Short period undulators equipped with force cancellation function

> HOM dumped RF cavity without damping waveguide/pipe (phase-II)

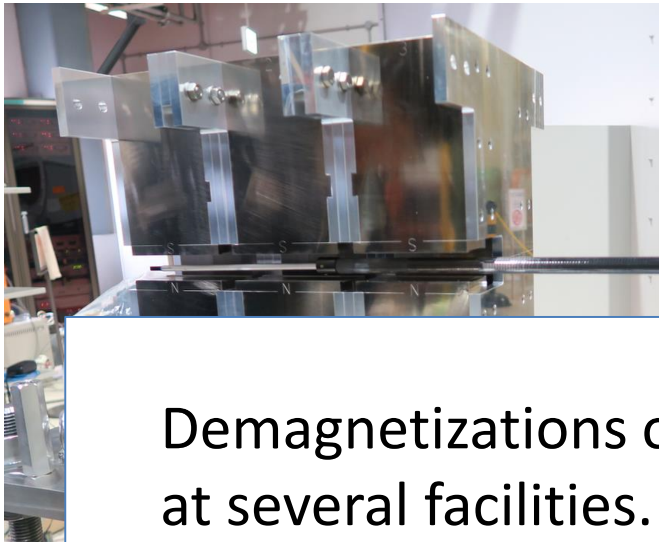
etc.

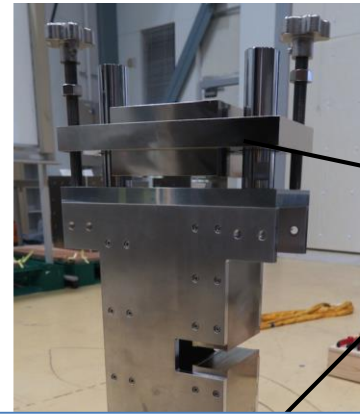
Integrated design and iteration between developments including lattice are essential in the optimization process.

Permanent magnet based dipoles

T. Watanabe et al., IPAC2016.

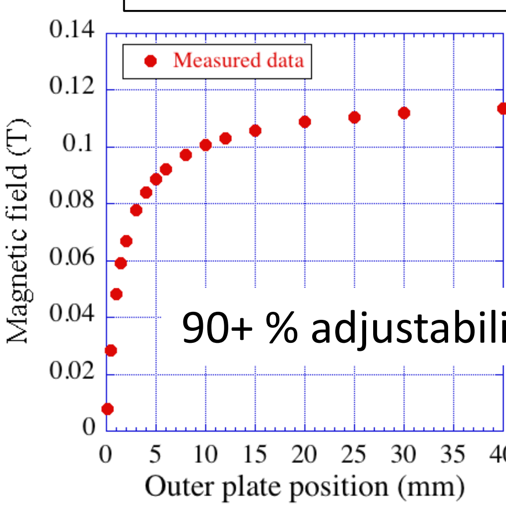
Test magnet, "Mini-LGB"





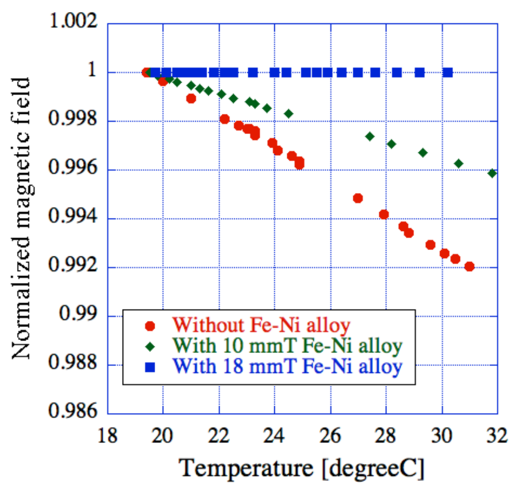
Demagnetizations of undulators have been observed at several facilities. Are dipoles OK?

Field adjustability

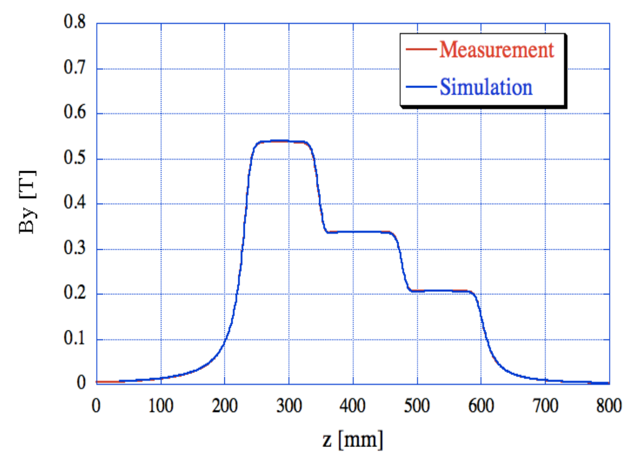


90+ % adjustability

Temperature dependence



LGB distribution



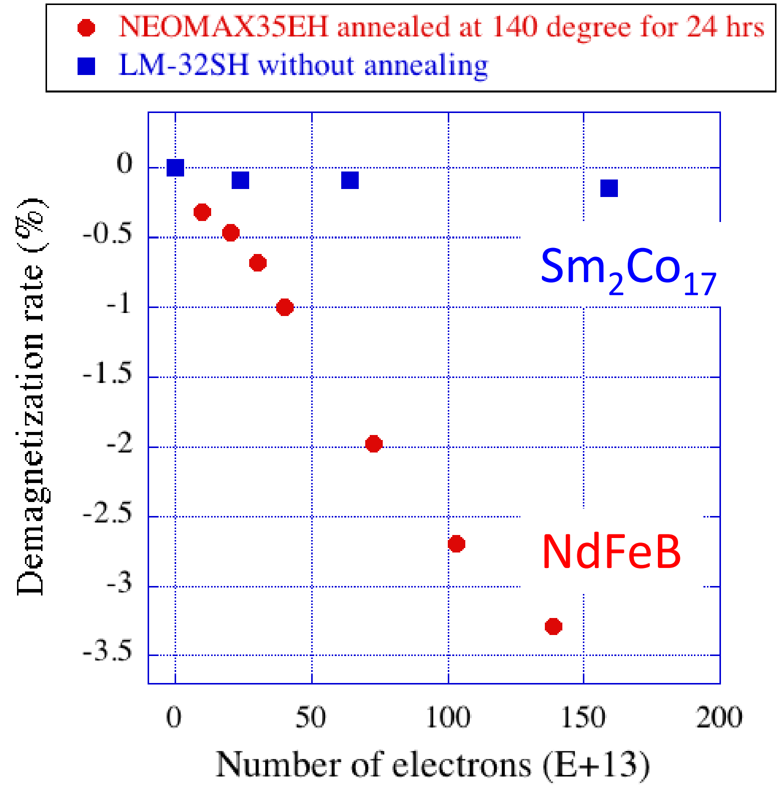
Demagnetization of permanent magnet due to radiation

	Undulator (in some cases)	Dipole (in some cases)
Magnet	NdFeB	Sm_2Co_{17}
Pc (typical)	0.1 – 1	2 - 7
Electrons	may directly hit magnet	hit thick iron yokes first

Permeance coefficient, Pc

$$P_c = -\frac{1}{\mu_0}\frac{B}{H}$$

Demag. in a long time range may be compensated by outer plates.



Blue: Sm_2Co_{17} (LS-32SH)

Red : NdFeB,

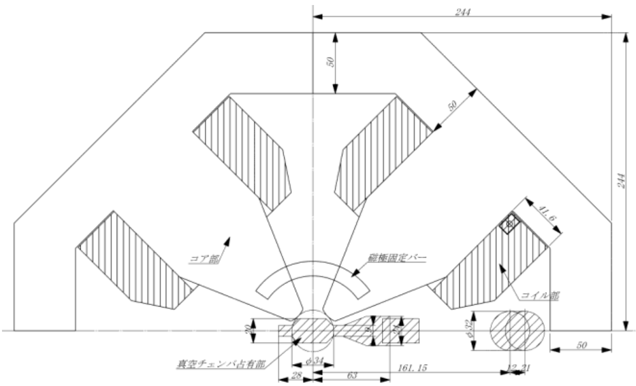
(T.Bizen et al., NIMA 574 (2007) 401.)

Demagnetization of currently provided NdFeB magnet will be tested soon.

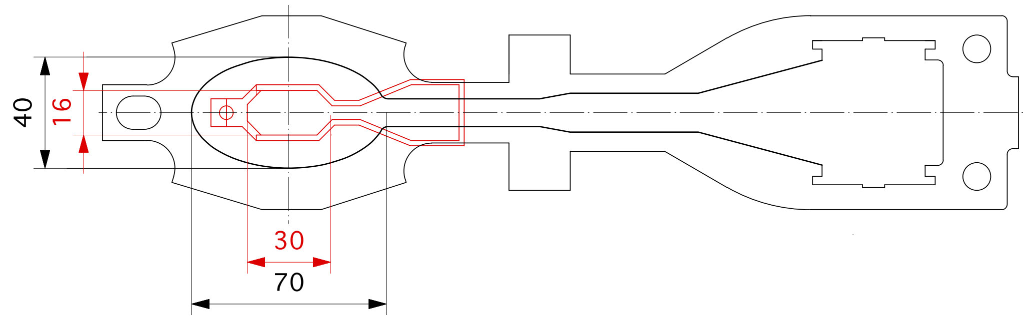
Vacuum chambers

M. Ohishi et al.

High gradient magnets impose small dimension vacuum chambers.



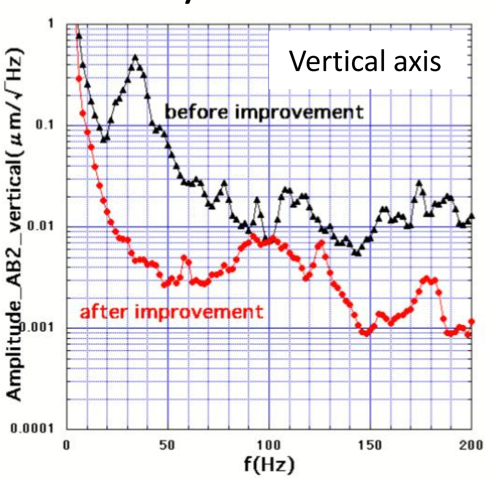
Bore diameters
Q: 34 mm Sx: 36 mm



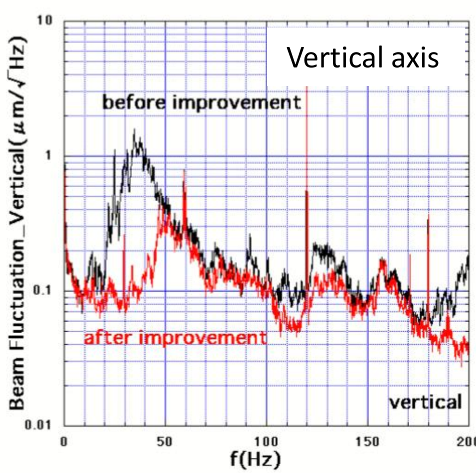
Red: SPring-8-II chamber(SUS)
Black: SPring-8 chamber (Al)

Based on experiences on beam vibrations at SPring-8, SUS is our choice.

Eddy current on chambers kicks e-beams



Vibration of vacuum chamber



Fluctuation of electron beam

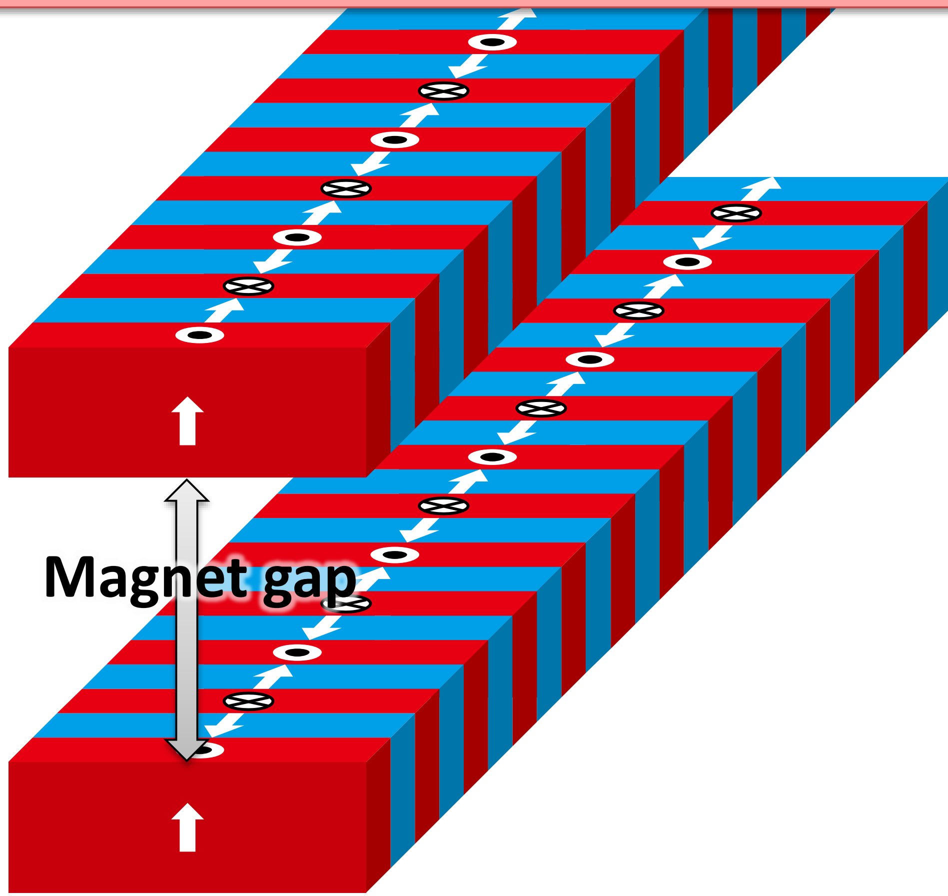
SUS:
Low conductivity-> Small eddy current
Can be mechanically thinner.

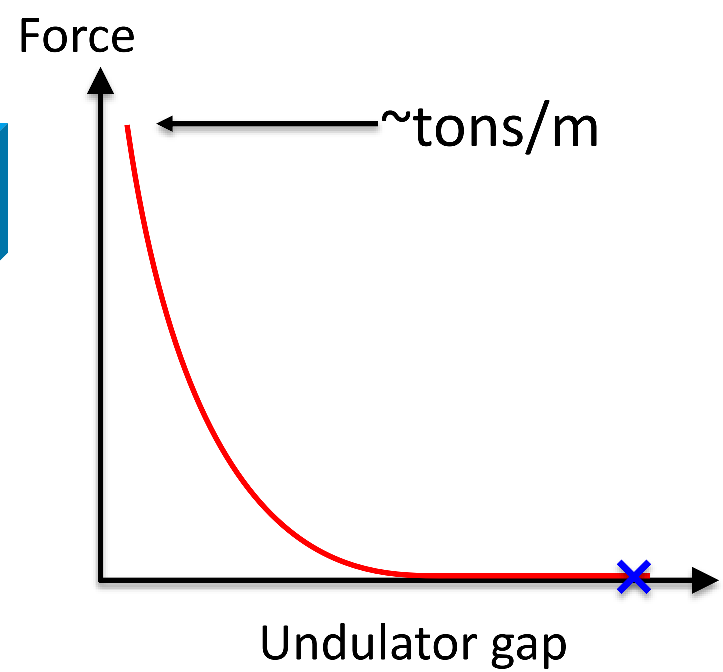
Resistive wall impedance will be suppressed by Cu coating.

New undulators equipped with force cancellation functtion

Magnetic force vs undulator gap

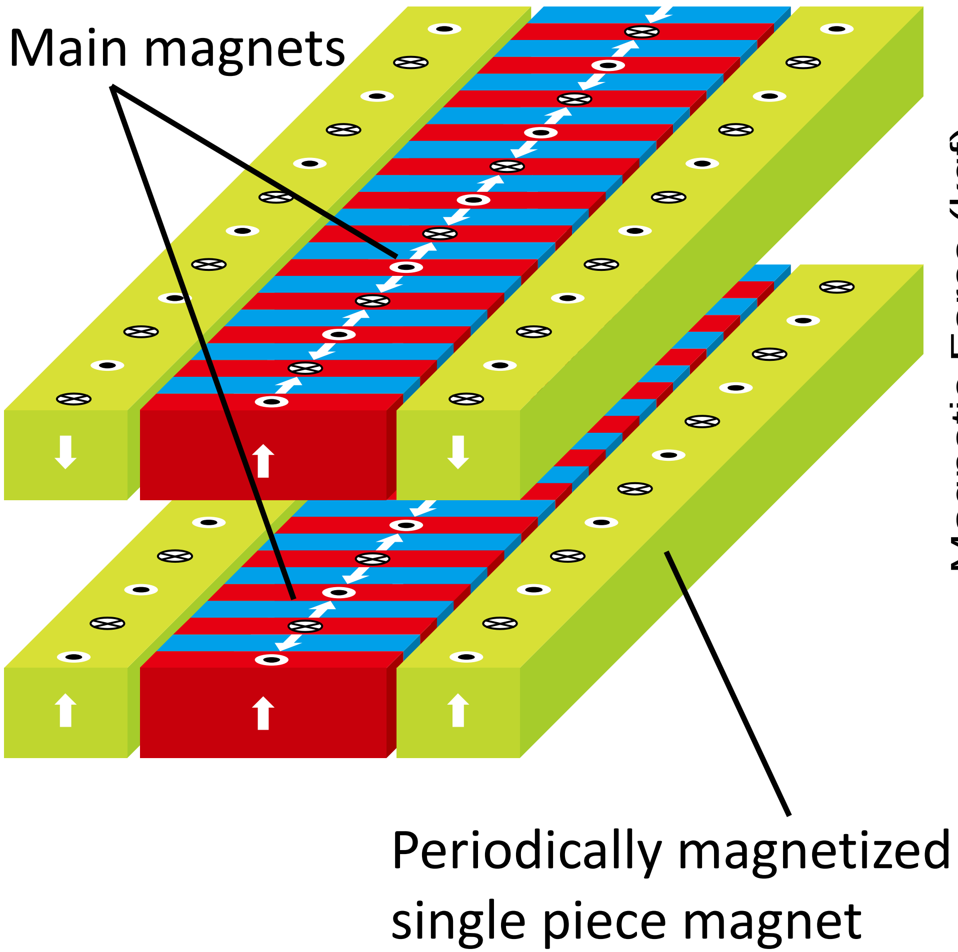
Mag force vs gap depends on the periodic structure.
-> Cancellation mechanics should also have a similar periodic structure, but it could cost much.

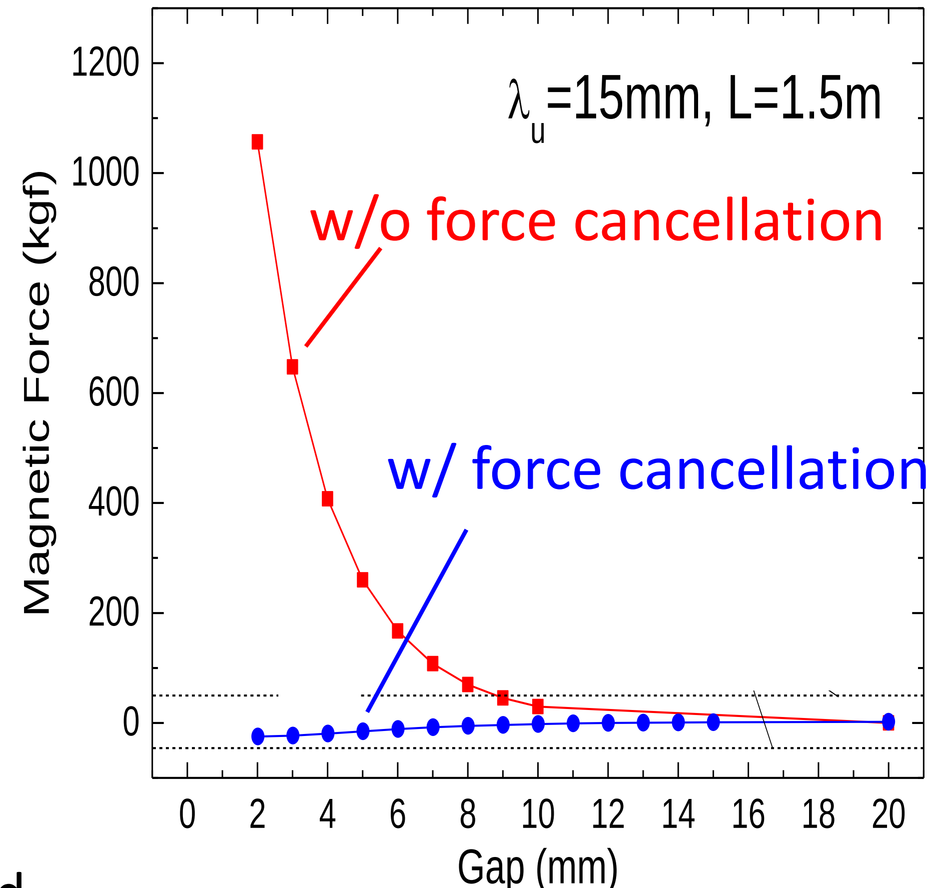




Takashi Tanaka et al

Periodically magnetized mono-structure for the force cancellation

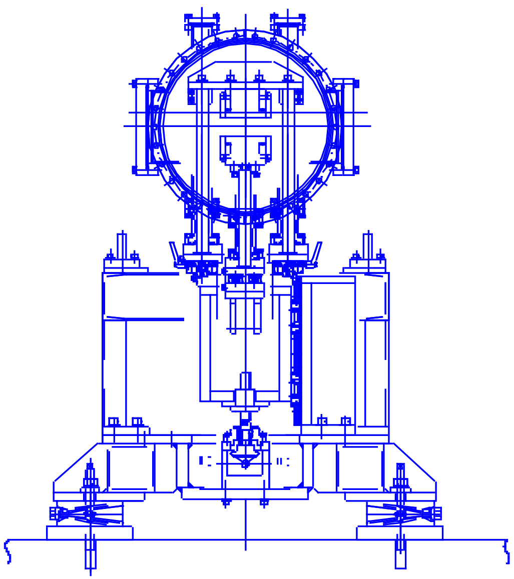




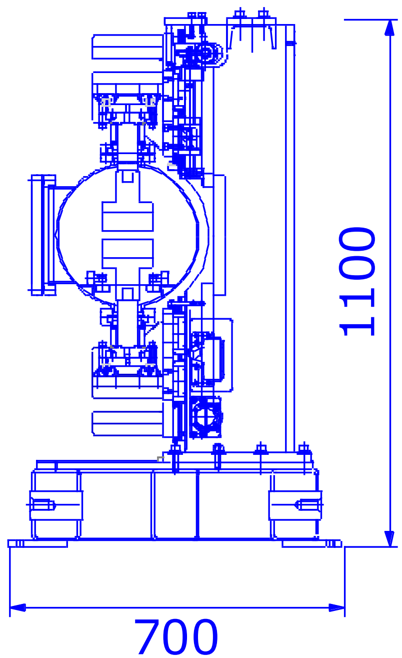
Takashi Tanaka, Shigeki Yamamoto et al

Less than 1/4 in size and weight.

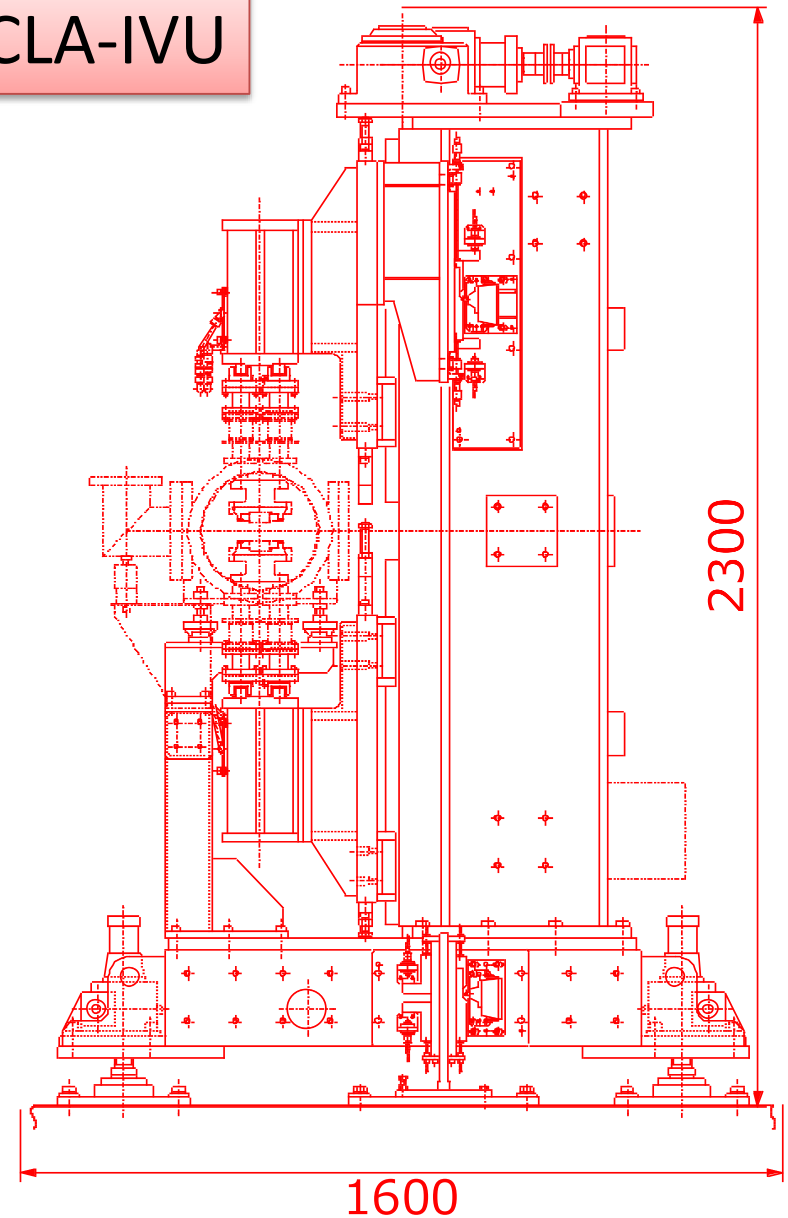
New type I



New type II

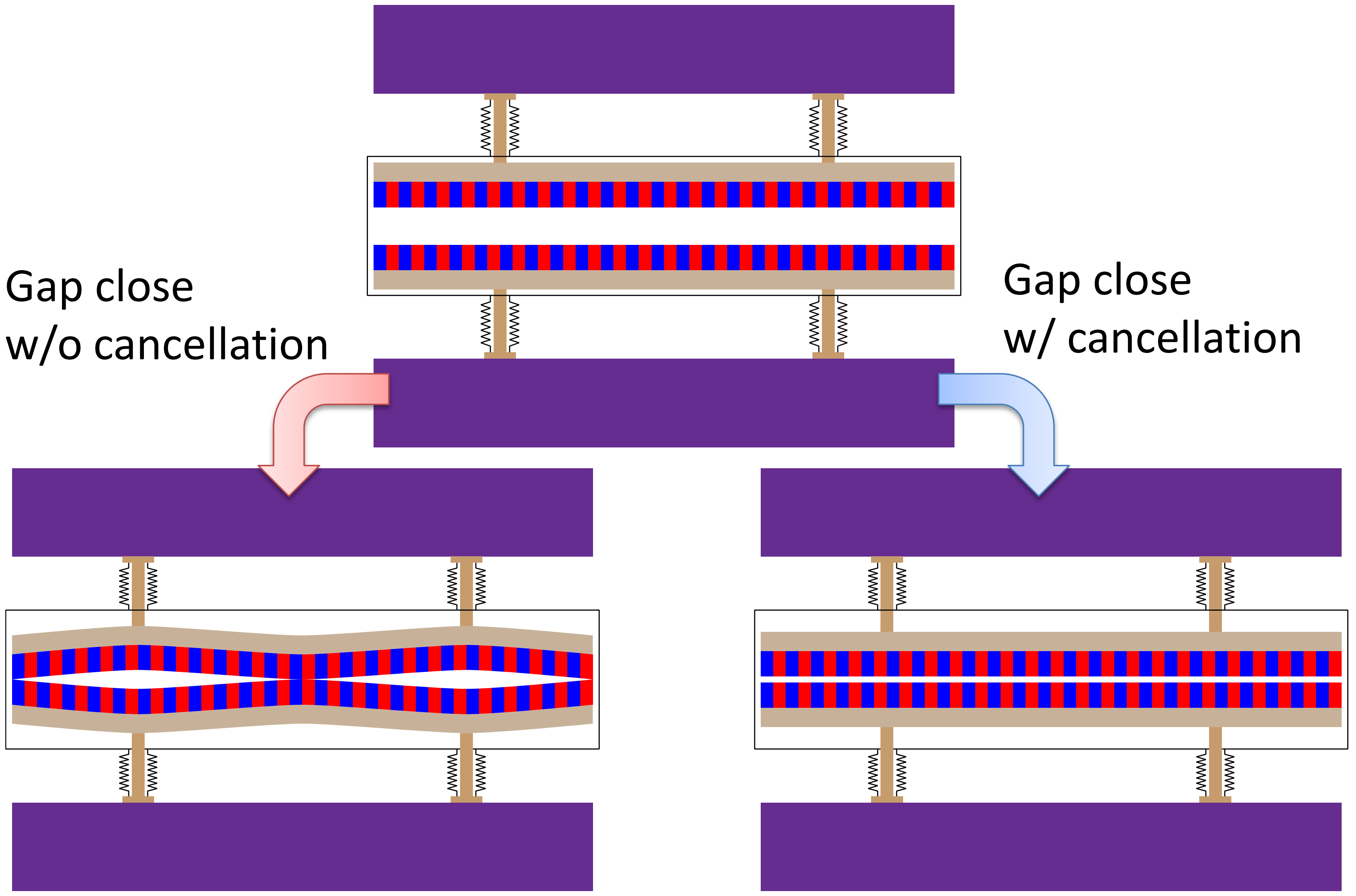


SACLA-IVU

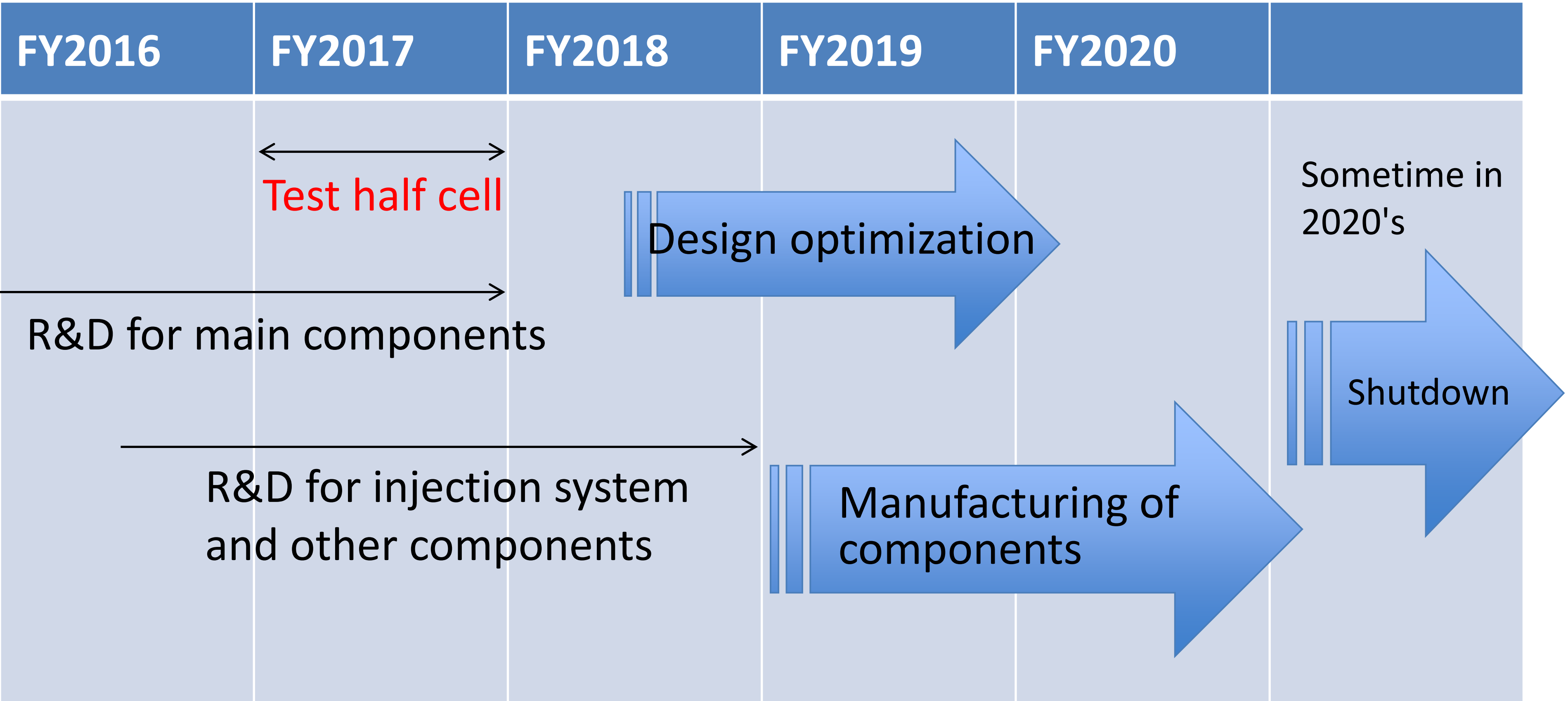


Takashi Tanaka et al

Force cancellation reduces phase errors in an undulator



Time schedule of R&D (as of now)



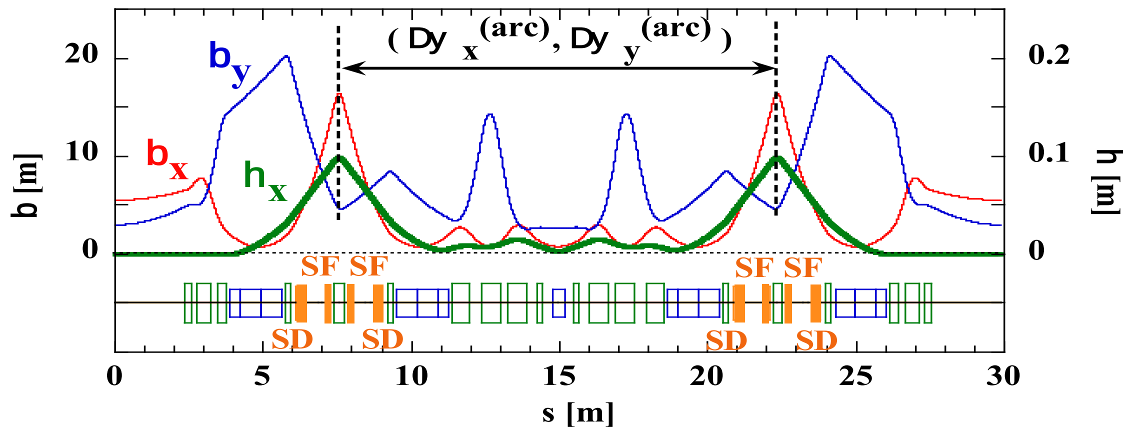
Detailed shutdown schedule is being discussed.

Nonlinear optimization

Kouichi Soutome
Hitoshi Tanaka

Basic idea:

1. Chromaticities are compensated by sextupoles at dispersion bumps.
2. Phase advance between bumps is set to Nπ to cancel nonlinear kicks.



But:

> The sextupole pairs are *nested* and cannot be cancelled enough for all the sextupole pairs.

> Tuning knobs are limited:

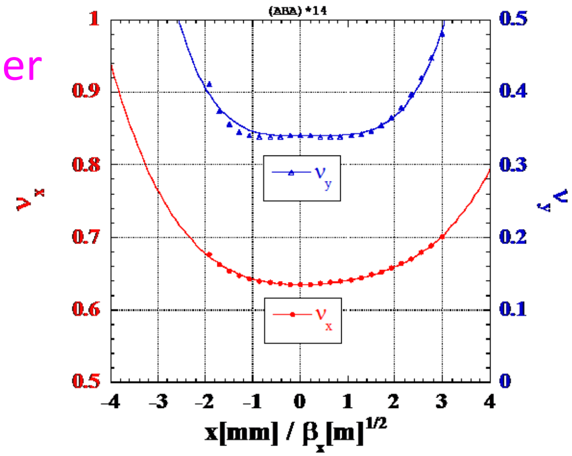
- A series of sextupoles are closely distributed with each other inside bumps.
- Phase advance between bumps should be fixed.
- Betatron functions at straight sections should be kept small.
- Tune at each cell cannot be changed a lot.

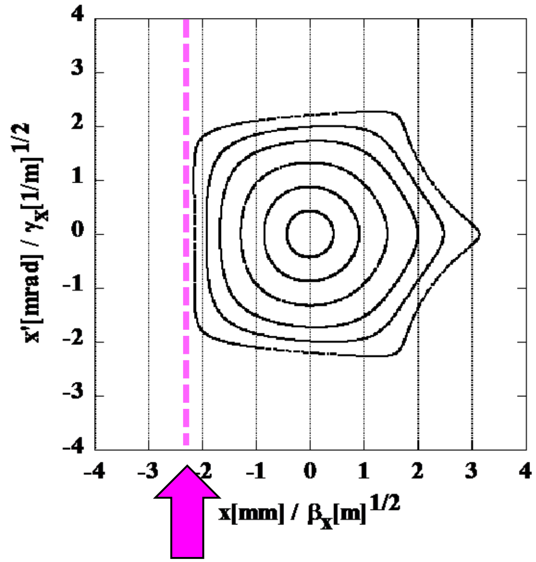
Example of amplitude dependent tune shift and Poincare map

Strong higher order ADTS ∝ x^4

y = 0.349+ m2 * ^2+m3...		
	値	エラー
m2	0.0064206	0.00019899
m3	-0.0011522	6.9545e-5
m4	0.000507913	4.2396e-5
カイ2乗	2.5431e-5	NA
R	0.99845	NA

y = 0.400+ m2 * ^2+m3...		
	値	エラー
m2	0.0019738	0.00095137
m3	-0.0024251	0.00033249
m4	0.0024332	0.00020269
カイ2乗	0.00058129	NA
R	0.99171	NA





DA is sharply limited by the higher-order field.

(1) Amplitude dependent tune shift is dominated by higher orders ∝ x^4 under practical conditions like nested sextupoles etc.

(2) To compensate it, we need to play with the higher order fields.

We have proposed two approaches to tackle the strong nonlinear problem.

Hitoshi Tanaka and Kouichi Soutome

First approach to suppress the nonlinearity

To formulate canonical perturbation up to $O(S^4)$ order

> ADTS is dominated by $O(S^4)$ or higher.

> We need large DA only in x.

> By neglecting $O(J_y^2)$, the number of terms in the formulation can be significantly reduced.

Hamiltonian

$$\tilde{H} = \frac{J_x}{\beta_x(s)} + \frac{J_y}{\beta_y(s)} + W_{xx}(s)J_x^2 + W_{xy}(s)J_xJ_y + W_{xxx}(s)J_x^3 + W_{xxy}(s)J_x^2J_y + \cdots$$

included

$$\Rightarrow \quad \tilde{\nu}_x = \frac{1}{2\pi}\int ds \frac{\partial\langle\tilde{H}\rangle}{\partial J_x} = \nu_x + C_{xx}J_x + C_{xxx}J_x^2 + \cdots \qquad (@J_y = 0)$$

$$\tilde{\nu}_y = \frac{1}{2\pi}\int ds \frac{\partial\langle\tilde{H}\rangle}{\partial J_y} = \nu_y + C_{xy}J_x + C_{xxy}J_x^2 + \cdots \qquad (@J_y = 0)$$

$O(S^2)$ $\quad$ $O(S^4)$ ← ***new formula***

$$x = \pm\sqrt{2\beta_x\left(J_x \mp AJ_x^{3/2} + BJ_x^2 \mp CJ_x^{5/2} + \cdots\right)} \qquad (@x' = 0, y = 0, y' = 0)$$

$O(S^1)$ $\quad$ $O(S^2)$ $\quad$ $O(S^3)$

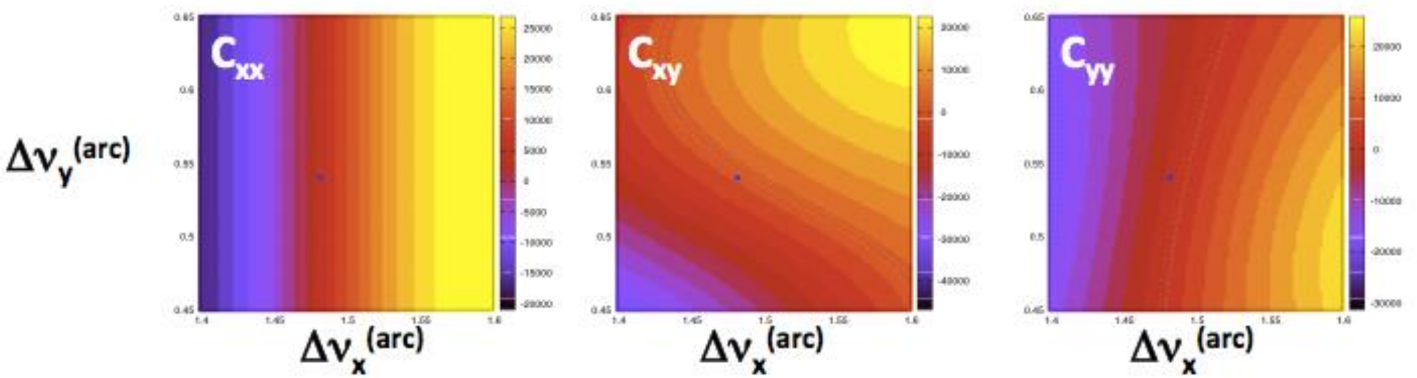
Objective function and tuning knobs

Tuning Knobs:

* SX excitation pattern under the constraint of fixed chrom.

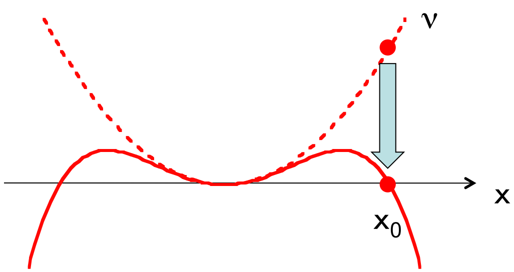
  5 families in a cell: { SD_1 SF_1 SF_2 SD_2 S_{aux} S_{aux} SD_2 SF_2 SF_1 SD_1 }
* detuning of phase between arcs: $(\Delta\nu_x^{(arc)}, \Delta\nu_y^{(arc)})$
* tune/cell

Response of lowest-order ADTS coef. ($O(S^2)$) to detuning (example)



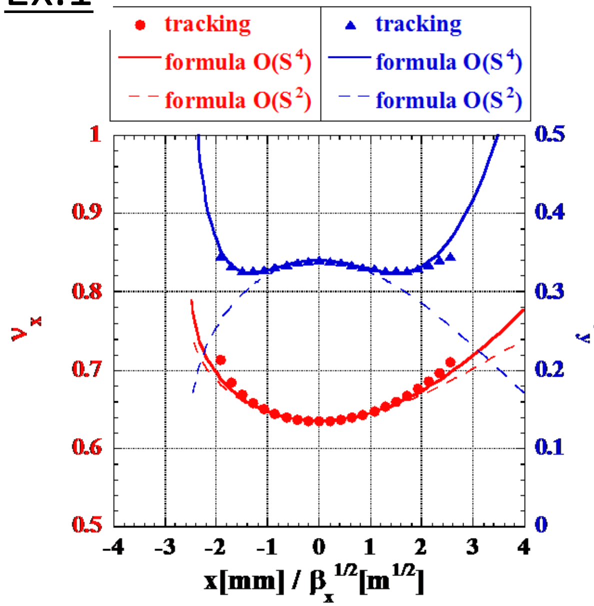
Objective Function:

* ADTS with the use of perturbation formula up to $O(S^4)$
* 1^{st} and 2^{nd} order terms of chromaticity
* resonance driving terms (when needed)

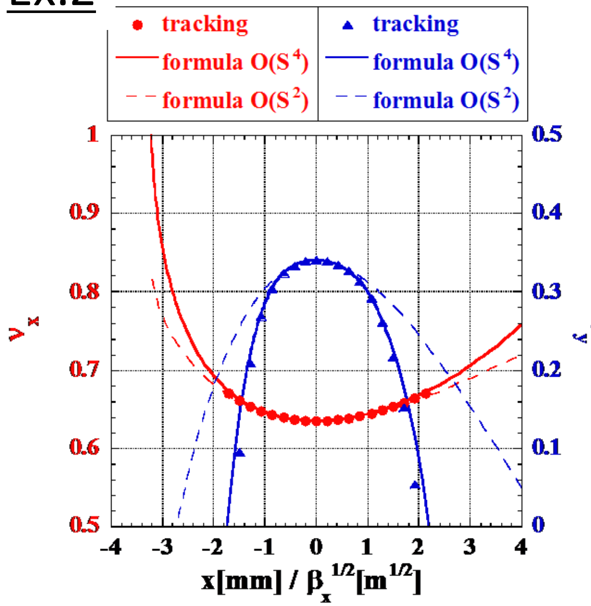


Canonical perturbation calculation up to O(S^4) vs particle tracking

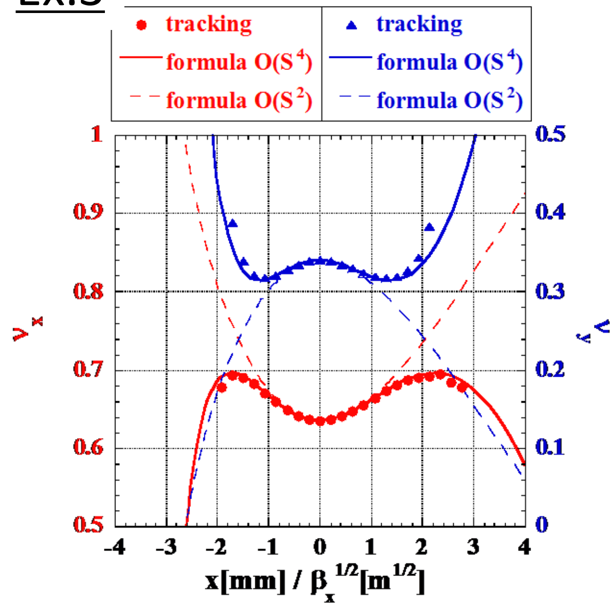
Ex.1

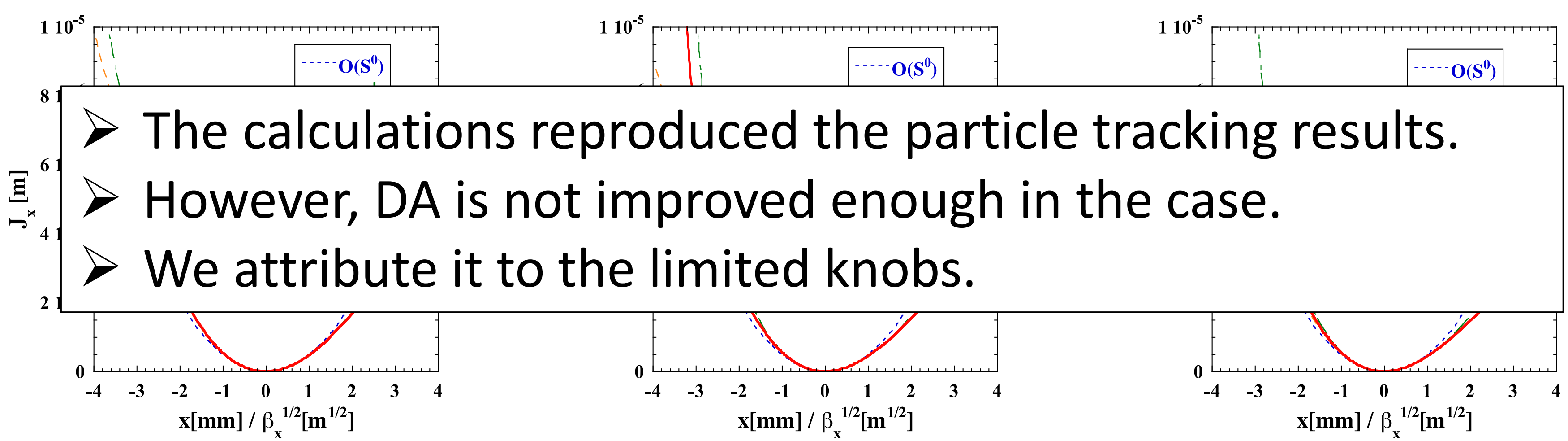


Ex.2



Ex.3



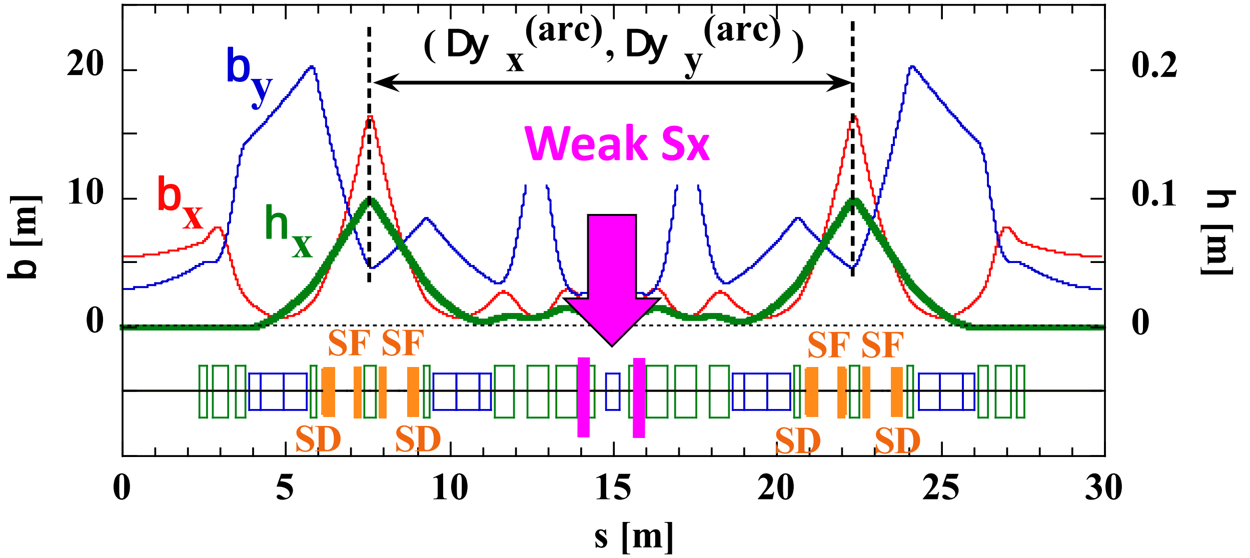


- The calculations reproduced the particle tracking results.
- However, DA is not improved enough in the case.
- We attribute it to the limited knobs.

Second approach to suppress the nonlinearity

To add *weak* sextupole singlets to compensate for the residual nonlinearities.

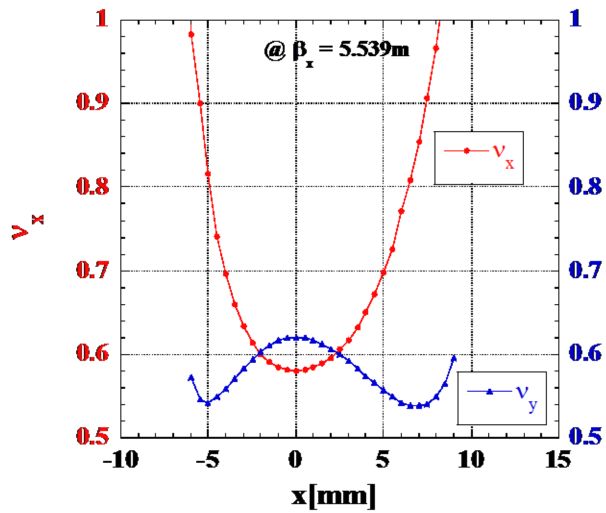
> The residual nonlinear kicks come from imperfect cancellation by sextupoles at bumps.
> Most of nonlinear kicks are already cancelled by sextupoles at bumps, so only a single (or two) sextupole with *weak* gradient should be enough.
> The magnet(s) may practically fit in the high packing factor lattice.

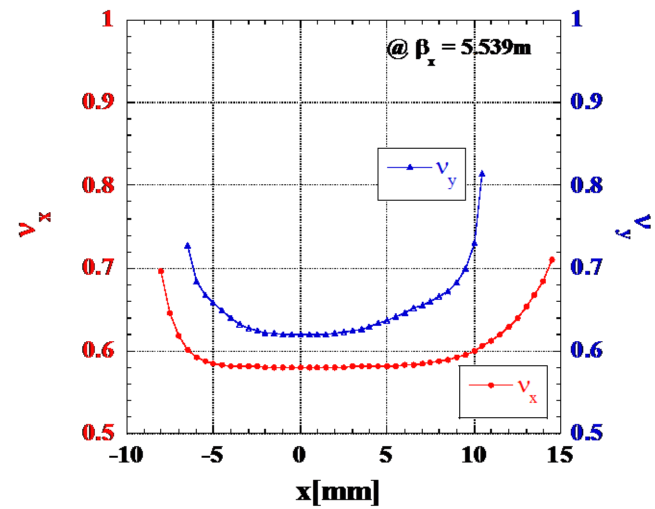


Improvement of amplitude dependent tune shift

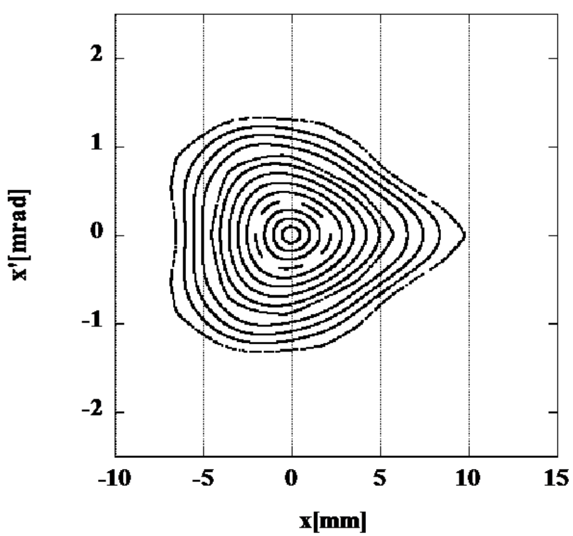
Without weak Sx | **With weak Sx**

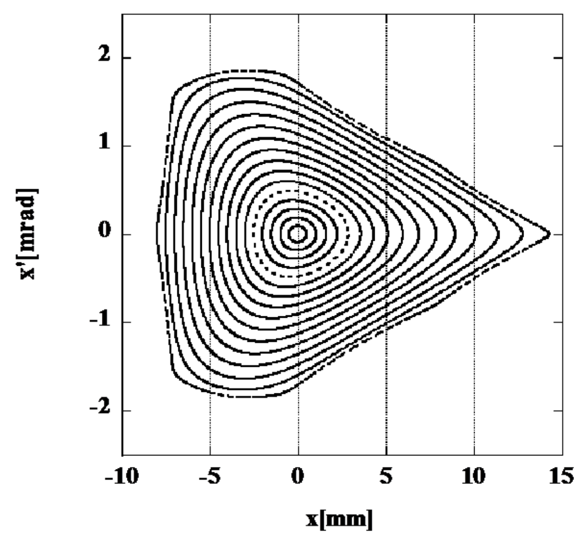
Amplitude dependent tune shift





Poincare map





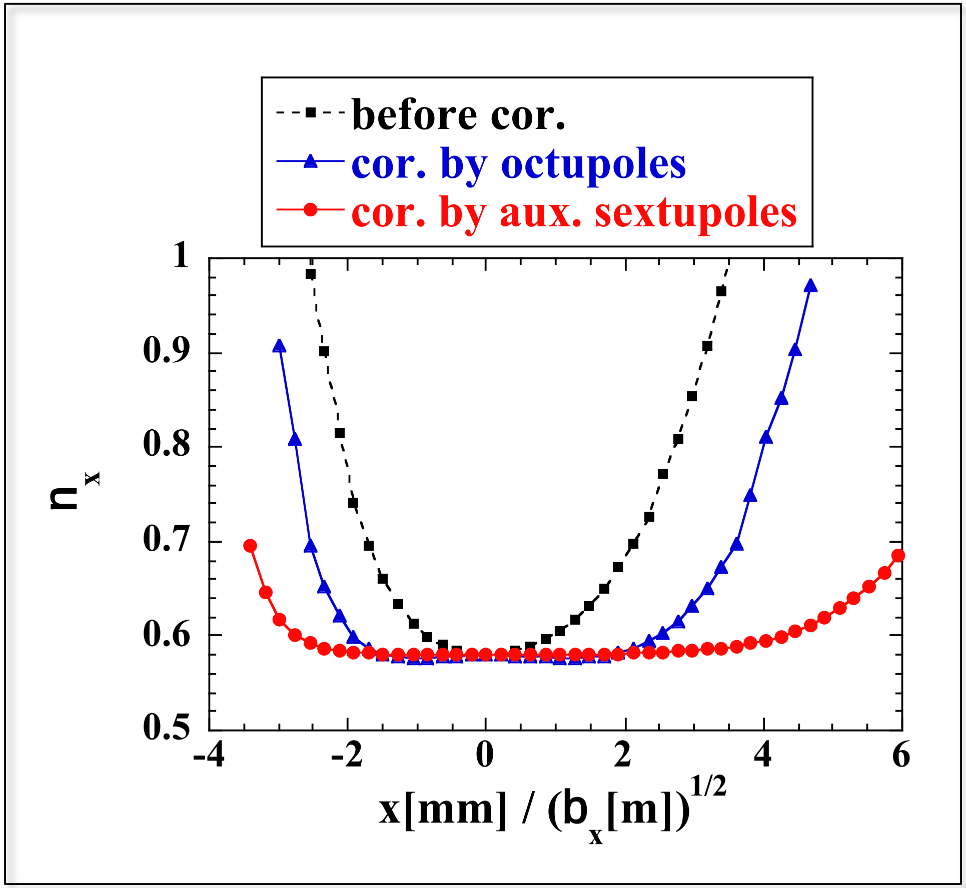
β_x = 5.5m

y = 0

Would be even better to rotate the Poincare map by 180 degree, but not so easy to do it for the current nonlinear lattice.

Comparison with octupoles

Horizontal ADTS



Higher order terms are well controlled to obtain small ADTS over the wide range of horizontal amplitude.

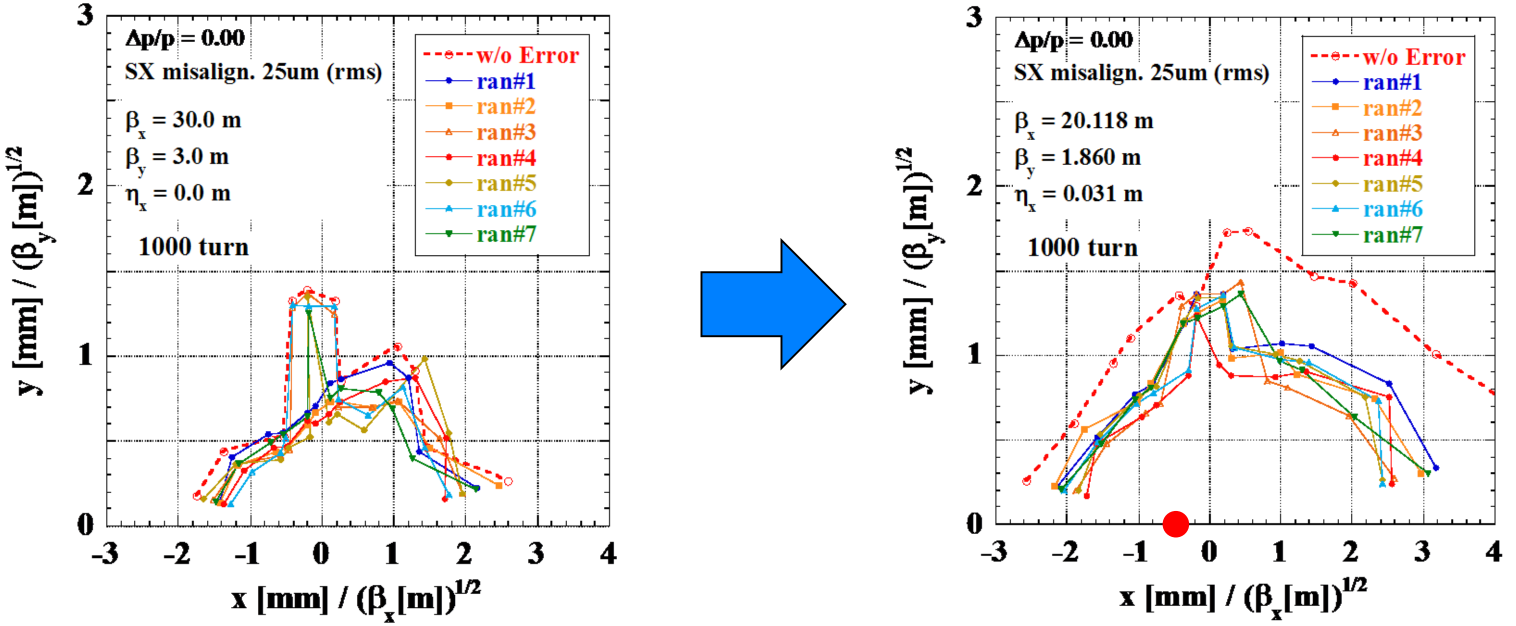
The weak Sx scheme is found to give better ADTS than octupoles.

One order of magnitude smaller SX field than chromatic SXs works, even though the SXs are placed where Betatron function is small.

* Octupoles may work as another knob for nonlinear chromaticity etc.

Improvement of dynamic aperture

CDR2014 **Current**



● Injection point
$x = 2$ [mm], $\beta_x = 20$ m

> The weak SX scheme works well to improve a dynamic aperture.

> Requirement on high β_x at the injection point can be relaxed.

$$b_{x,injection} = 30 \rightarrow 20\,m$$

Summary

- SPring-8-II project is on going aiming at major upgrade in the early 2020's.

- Stability, reliability and energy efficiency are also important.

- A combination with SACLA largely affects on the design in terms of accelerators and experiments.

- Key components, such as permanent magnets, vacuum system, and new IDs have been developed. A test half cell will be built in FY2017.

- Two new approaches for the nonlinear optimization have been proposed;
  - (i) canonical perturbation calculation up to $O(S^4)$
  - (ii) weak sextupole magnets to clean up residual nonlinearities

- Dynamic aperture has been successfully improved.
  Momentum aperture improvement will be tried soon.