Feasibility Study of Very Low-Emittance Storage Rings at SPring-8

K.Soutome (JASRI / SPring-8)

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Emittance of Ring-Based Light Sources

We set "ultimate" target of emittance to
"Fully Diffraction Limited" for 10keV Photon:
$\varepsilon_x \sim \varepsilon_y \sim 10$pmrad

2nd Generation

Far from Diffraction Limit

3rd Generation

Diffraction Limited in Vertical Direction

Small Emittance (~nmrad) and Small Coupling (~0.1%)

Next

Toward Diffraction Limited in Both H and V Directions

Toward "Fully Diffraction Limited"

"Is it possible?" ➔ Hopefully "Yes".

Since emittance scales as

$$\varepsilon = C_q \gamma^2 \theta^3 F(lattice) / J_x$$

proper choice of machine parameters will reduce the design value of ε.

Problem: Strong non-linearity of the machine

Large Nat. Chromaticity by Strong Q and Small Dispersion ➔ Strong SX ➔ Small Dynamic Apt.

Also, in reality, the design must be cost-effective as a light source: circumference, number and length of IDs, beam energy, construction cost, ...

Toward "Fully Diffraction Limited" (2)

Lattice Design:

Multi-Bend Lattice, TME-Structure, Combined B

ESRF*(study)*, APS*(study)*, MAX-IV, ...

D.Einfeld at al., EPAC96

A.Ropert at al., EPAC2000

L.Emery and M.Borland, PAC03; M.Borland, NIMA557 (2006)230

S.C.Leemann et al., PRST-AB 12(2009)120701 ...

Toward "Fully Diffraction Limited" (3)

Radiation Excitation and Damping Manipulations:

Combined B (Partition Control)

Robinson Wiggler (Partition Control)

T.Nakamura, unpublished note *(sufficient dispersion needed)*

Longitudinally Variable B (Optimized Radiation Integral)

R.Nagaoka and A.Wrulich, NIMA575(2007)292;

Y.Papaphilippou and P.Elleaume, PAC05, ...

Damping Wiggler : PETRA-III, PEP-X, NSLS-II, MAX IV ...

... Effects on the energy spread should also be considered.

Phase Space Manipulations:

Round Beam with Solenoid Field (at Special Straights)

A.Burov and V.Danilov, FERMILAB-TM-2043; R.Brinkmann, EPAC02;

H.Tanaka, unpublished note; K.Harada, K.Oide, private com.;

K.-J. Kim, PRST-AB 6(2003)104002

Lattice Design Work at SPring-8 for Upgrading Plan

Lattice Design Work

Proposal by K.Tsumaki and N.Kumagai (EPAC06)

Convert present two DB cells to one 10-Bend cell.

Energy: 8GeV ➔ 6GeV

Hard X-ray is covered by undulator upgrading.

ε_{nat} = ***0.083nmrad***

but ... Users demand: "Keep the number of ID-BL"

Working Group has been organized.

Convert one DB cell to one Multi-Bend cell.

Energy: 6GeV (or lower).

DB: 1.9nmrad (Non-Achomat)

➔ TB: 0.43nmrad

➔ QB: 0.16 nmrad

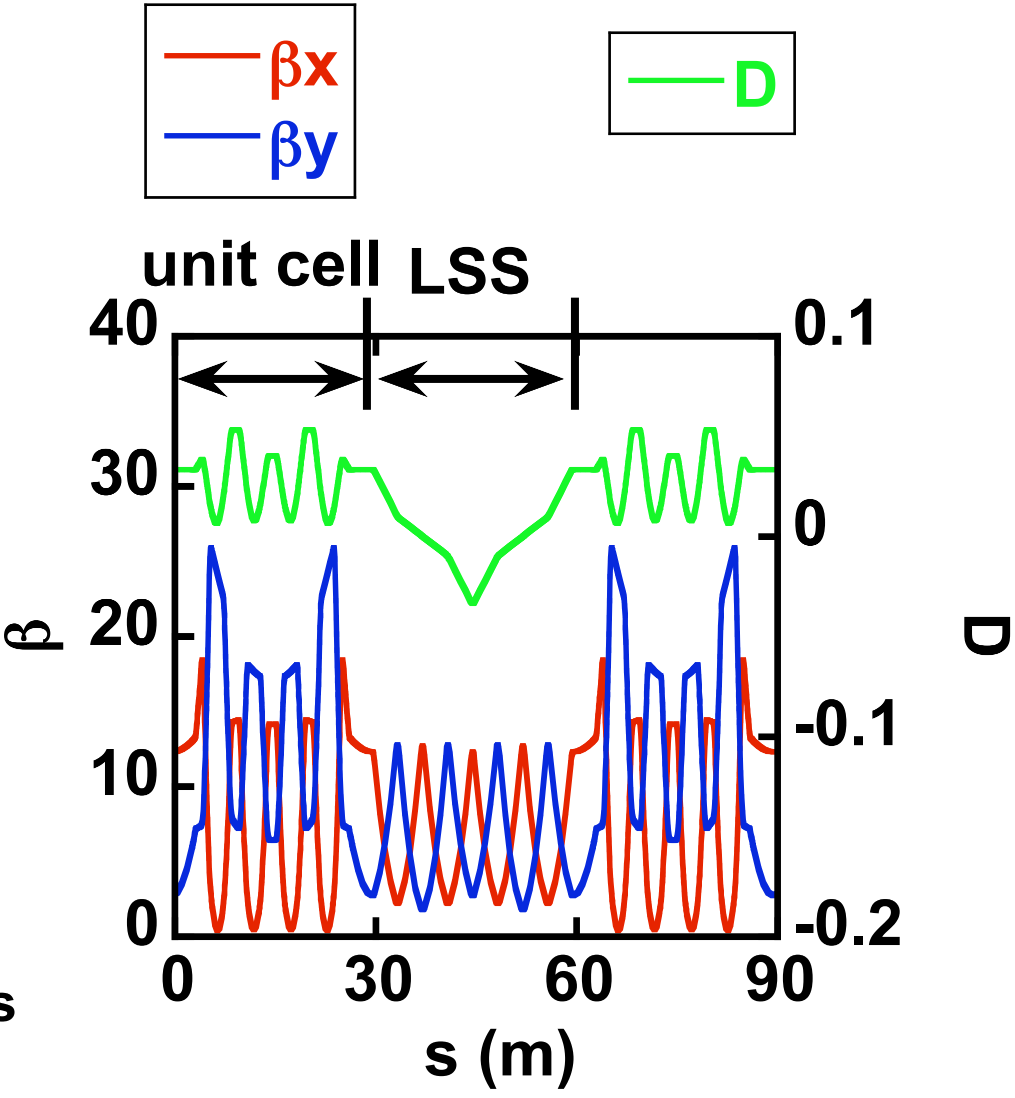
➔ Difficulty increases rapidly.

Strong Q
Large Nat. Chrom.
Small Dispersion
Strong SX
Small DA

"Chromaticity Wall": J.Bengtsson, EPAC08

Example: QB Lattice

$(\nu_x, \nu_y) = (85.15, 30.35)$
$(\xi_{x0}, \xi_{y0}) = (-206, -108)$
natural emittance
= 0.165 [nmrad]
effective emittance
= 0.193 [nmrad]
β_x = 12.3 [m]
β_y = 2.7 [m]
D = 0.03 [m] @ straights



4-bend lattice (QB)

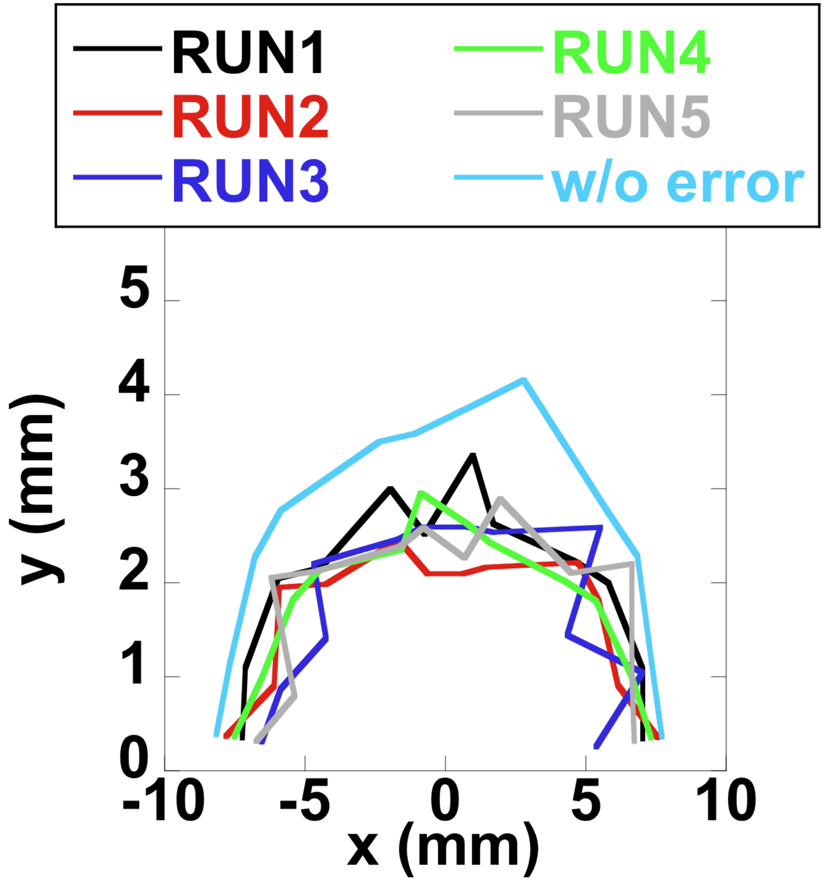
* A long straight section (LSS) is temporally connected using a FODO cell.

RING = 4 * (11 * UNIT-CELL + LSS)

Dynamic Aperture

Optimization of sextupoles (resonance suppression) for on- and off-momentum particles

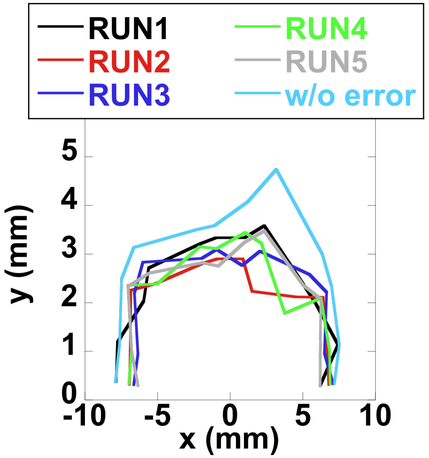
Y. Shimosaki,
2nd Workshop on Nonlinear Beam Dynamics in Storage Rings (2009)



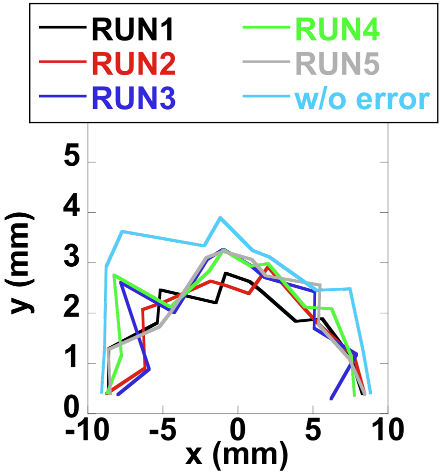
QB (ring) $\delta = 0\%$

(10um RMS Error for SX assumed)

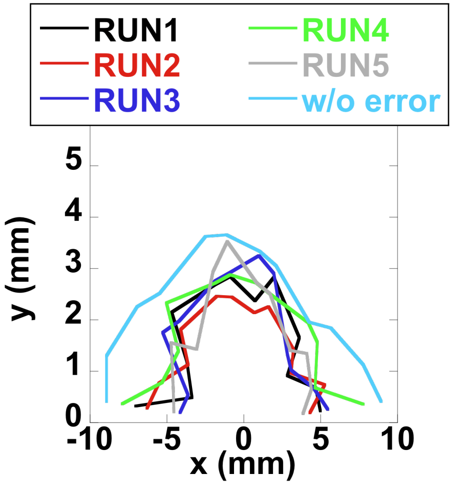
Momentum Acceptance



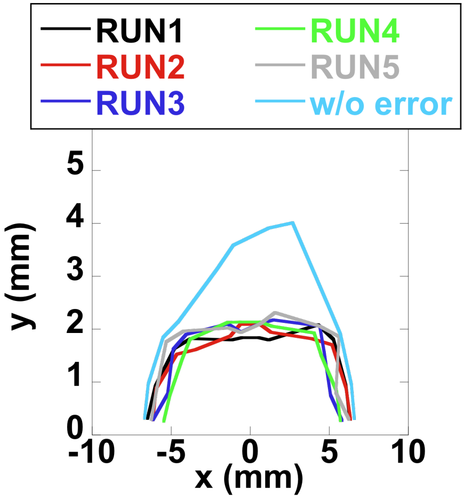
QB (ring) δ = +1%



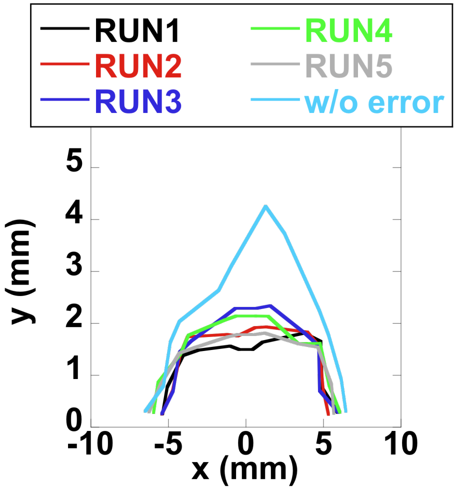
QB (ring) δ = +2%



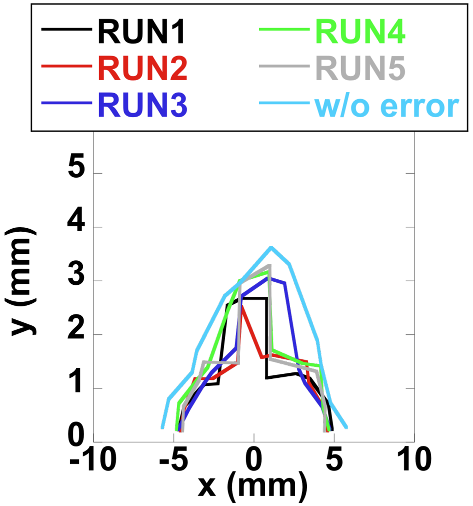
QB (ring) δ = +3%



QB (ring) δ = -1%



QB (ring) δ = -2%



QB (ring) δ = -3%

Issues

Optimization of sextupole strengths is still efficient to enlarge DA and MA, but it becomes harder as we go to smaller emittances.

To go further - toward "fully diffraction limited ring" - we think we should stop for a while and look for a way to manipulate nonlinearity of the machine.

Issues (2)

The first critical issue will be an injection process. Hurdles that must be cleared are:

(i) manipulation of non-linearity of the ring
to enlarge the dynamic aperture
and
(ii) realization of efficient injection scheme
to reduce the oscillation amplitued

Non-Linearity of the Ring

What we are thinking and trying is ...

*** sextupole optimization (resonance suppression) for on- and off-momentum particles**

*** octupole magnets (amplitude-dependent tune shift)**

*** modified (Gaussian) sextupole magnets**

*** cancellation of sextupole kicks**

Octupole Magnets

MAX IV *S.C.Leemann et al., PRST-AB 12(2009)120701*

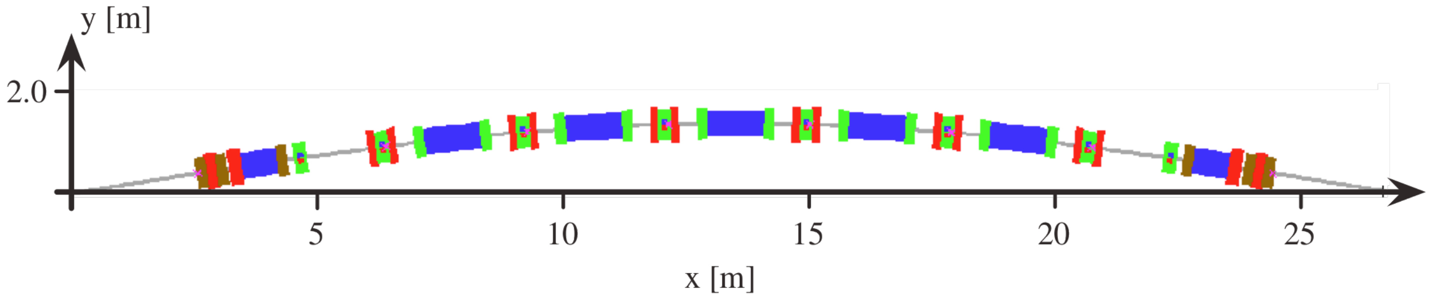


FIG. 1. (Color) Schematic of one of the 20 achromats in the 3 GeV storage ring. Magnets indicated are gradient dipoles (blue), focusing quadrupoles (red), sextupoles (green), and octupoles (brown).

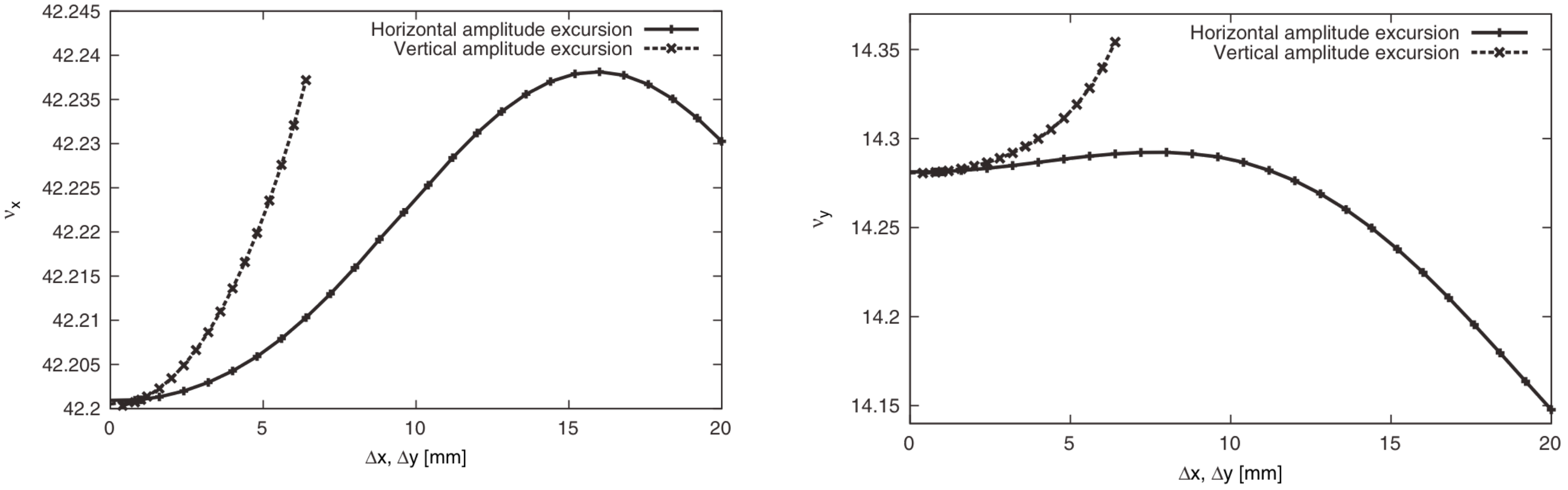


FIG. 3. Amplitude-dependent tune shifts for the 3 GeV storage-ring bare lattice. Sextupoles and octupoles have been included in this calculation.

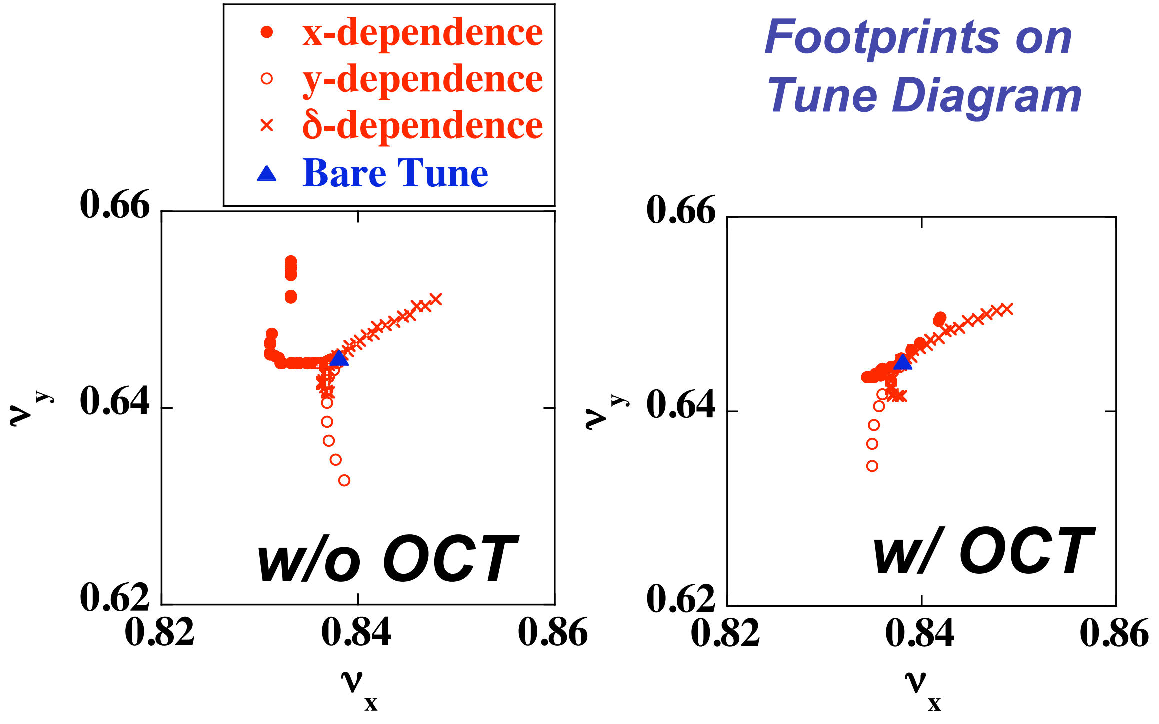
Octupole Magnets (2)

SPring-8 case

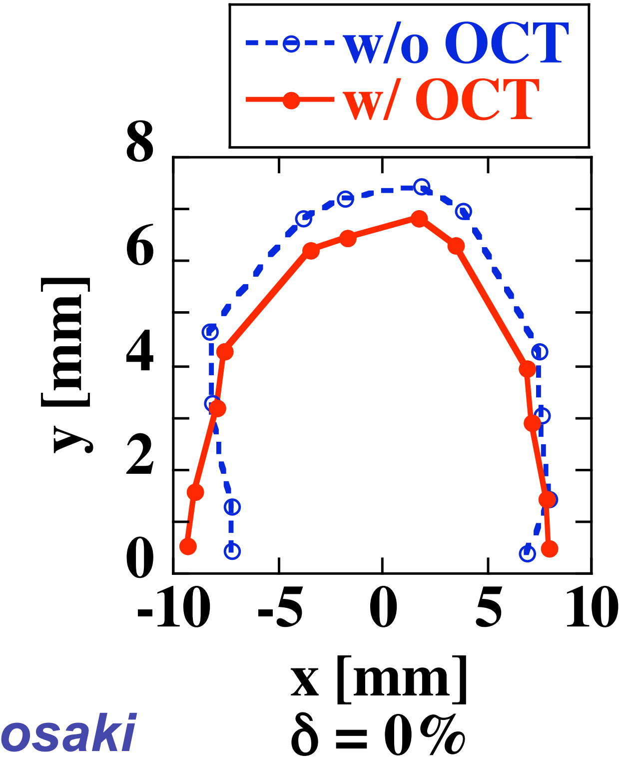
for a unit cell of QB lattice (preliminary cal.)

Amplitude-dependent tune shifts and resonances by octupoles are controlled (with 8 families).

Footprints on Tune Diagram



Dynamic Apt.



Y.Shimosaki

Modified Sextupoles (Gaussian Sextupoles)

Sextupole field is damped at large betatron oscillation.

$$B_x = Se^{K\left(x^2-y^2\right)}\left[\left(x^2-y^2\right)\sin\left(2Kxy\right)+2xy\cos\left(2Kxy\right)\right]$$

$$B_y = Se^{K\left(x^2-y^2\right)}\left[\left(x^2-y^2\right)\cos\left(2Kxy\right)-2xy\sin\left(2Kxy\right)\right]$$

M.Cornacchia and K.Halbach, NIM A290 (1990) 19

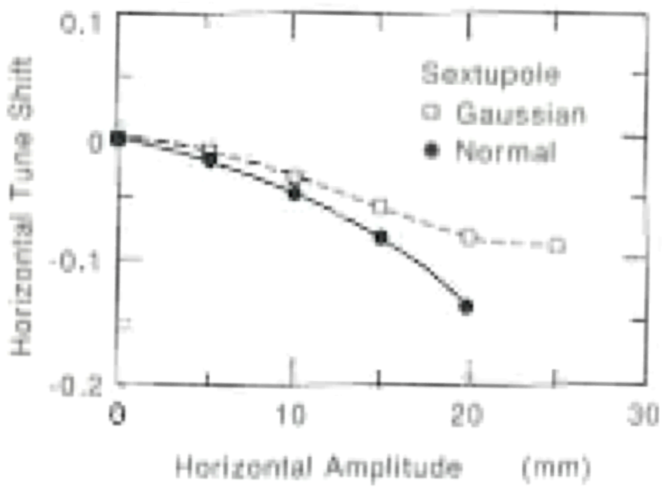


Fig. 4. Horizontal tune shift versus maximum betatron amplitude for normal and Gaussian sextupoles.

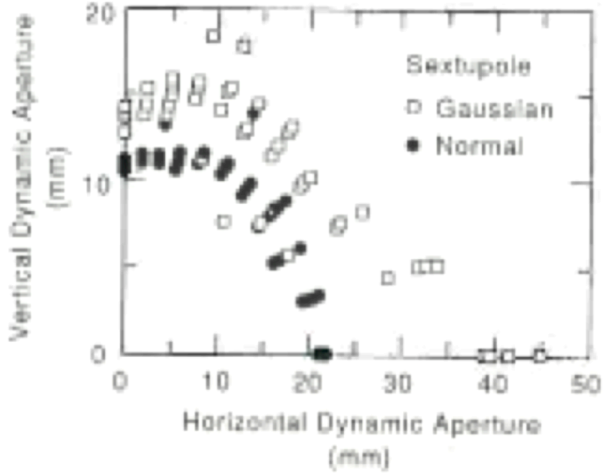
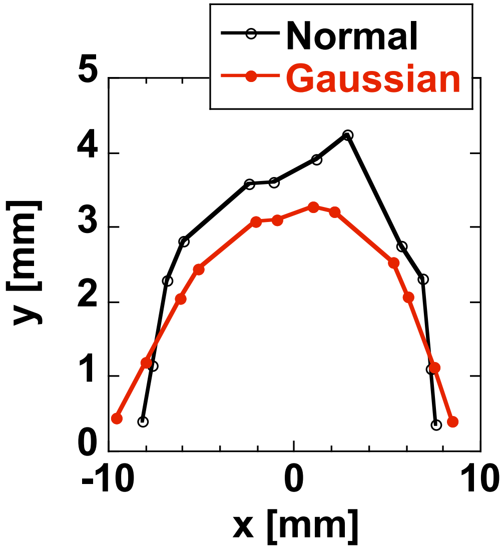


Fig. 6. Dynamic aperture of five different machines having magnetic field gradient errors randomly distributed in the quadrupoles. The rms value of the distribution of the relative gradient errors is 0.001.

J.C.Lee and W.Wiedemann, EPAC98
H.Tanaka, private com.

Modified Sextupoles (Gaussian Sextupoles) (2)

From preliminary calculations there seems to be some effects on DA.



QB ring w/o error, δ=0

Note: The simplest way of using the same Gaussian factor to all SXs did not work.

In addition to the strength, we have another knob of field shape for each sextupole, but ...

we do not know an established way of optimization, and so we have to develop it.

Studies are ongoing...

Cancellation of Sextupole Kicks

Use of "-*I* " Transformation between two SXs:

K.L.Brown, IEEE Trans. Nucl. Sci. NS-26 (1979) 3490.
L.Emery, in Proc. 1989 IEEE PAC (1989) p.1225.
K.Oide and H.Koiso, PR E47(1993) 2010.
K.Soutome et al., EPAC08

Is it possible to apply "noninterleaved sextupoles" scheme to very small emittance rings ?

K.Oide, private com.

Question:

We will need to put a set of sextupoles by considering betatron phase and amplitude in both H and V directions. Can we design such a ring?

SLS: A. Streun, "sextupole symmetrization", NLBD-WS (2009)

Injection Scheme

* pulsed bump magnets (std. scheme of off-axis inj.)

* pulsed multipole magnets

* synchrotron injection

... other schemes
... combination of these

Injection with Pulsed Multipole Magnets

Injection with a Pulsed Q (SX) at KEK

K.Harada et al., PRST-AB 10(2007)123501; EPAC06; PAC05

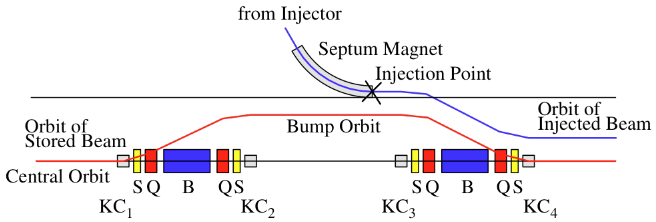


FIG. 1. (Color) Schematic drawing of a conventional injection scheme. After the injected beam is bent into the orbit by the septum magnet, the injected beam is perturbed by two kicker magnets KC_3 and KC_4; it then oscillates with a large amplitude in the ring. For the stored beam, the pulsed bump orbit is produced by four kicker magnets KC_1, KC_2, KC_3, and KC_4. B, Q, and S denote the bending, quadrupole, and sextupole magnets, respectively. The cross represents the injection point.

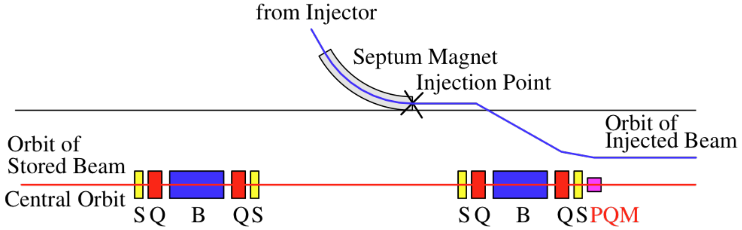


FIG. 2. (Color) Same as Fig. 1, but the injection scheme is using the PQM instead of the four kicker magnets. The injected beam is perturbed by the PQM; it then oscillates with a large amplitude in the ring. The stored beam passes through the central position of the PQM and its orbit is preserved on a central orbit.

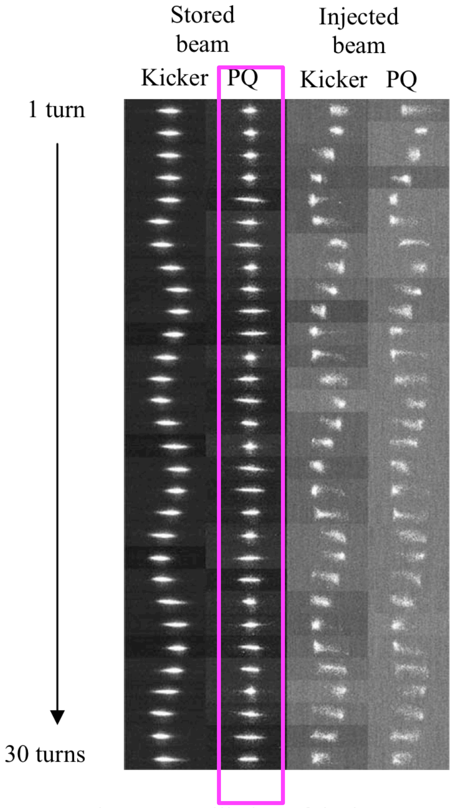


Figure 6 Oscillation of the beam.

repetition rate until the stored current reached at 10mA as shown in Fig. 4. As the stored current increased, the injection rate decreased. When the stored current reached about 30mA, the injection rate dropped to zero. Figure 5 shows the oscillation of the stored beam detected by the beam oscillation detector (BOD). Even after the COD correction, the small oscillation was remained. The

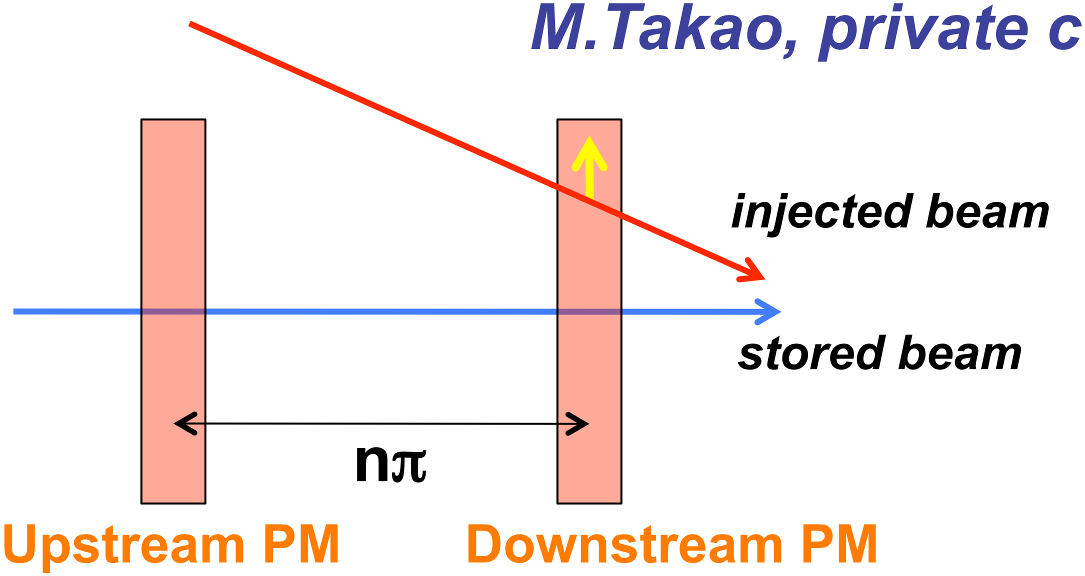
Successful in beam injection but ...

Quadrupole oscillation mode was induced in a stored beam.

Injection with Pulsed Multipole Magnets (2)

Additional upstream pulsed magnet separated by nπ in betatron phase will suppress the quadrupole oscillation mode of a stored beam.

M.Takao, private com.



It will be possible to combine the above scheme with a standard pulsed bump magnets.

➔ e.g. possibility of a scheme like

bump magnets and a series of pulsed SXs

Synchrotron Injection

Injection with Energy Offset at Dispersive Section

P.Collier, PAC95; Y.Onishi, private com.

Injection amplitude is shared in transverse and longitudinal phase spaces.

Large dispersion is needed.
➔ dispersion control at injection section
(*lattice, chicane, ...*)

100mm dispersion and 1% energy offset
➔ 1mm reduction of osc. amplitude

Other Schemes

in Top-Up WS (7-9 Oct. 2009, Melbourne)

Pulsed Non-Linear, In-Vacuum Magnet (P.Kuske)

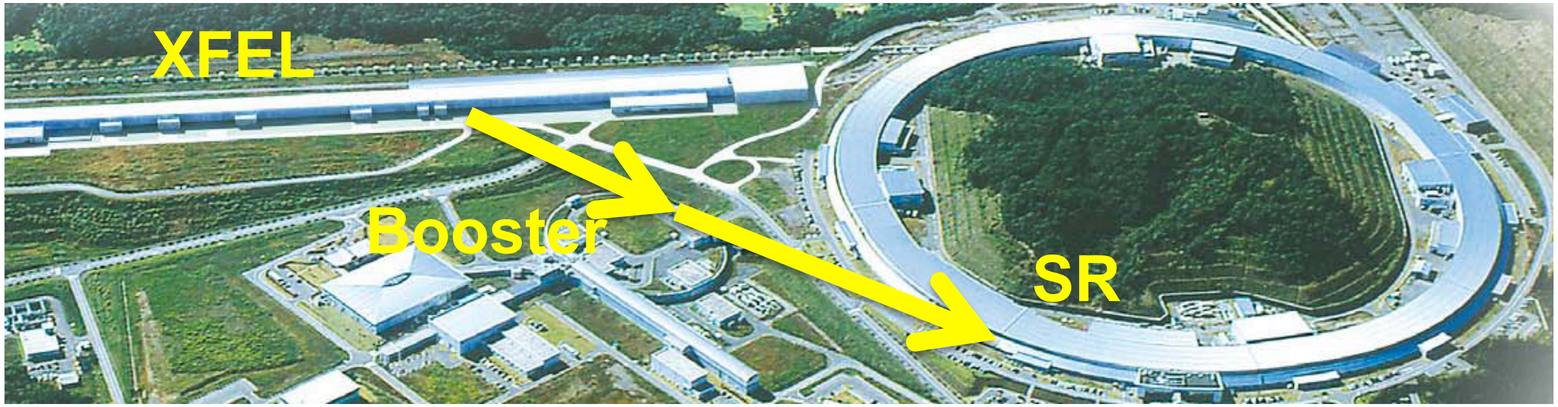
On-Axis Swap-Out Scheme with Accumulator (L.Emery)

http://www.synchrotron.org.au/index.php/news/events/australian-events/event/4-top-up-workshop

Injector

A high-quality injection beam is needed.

At SPring-8 we will have XFEL Linac that can be used as a full-energy injector to the ring.



Design Parameters (typical)

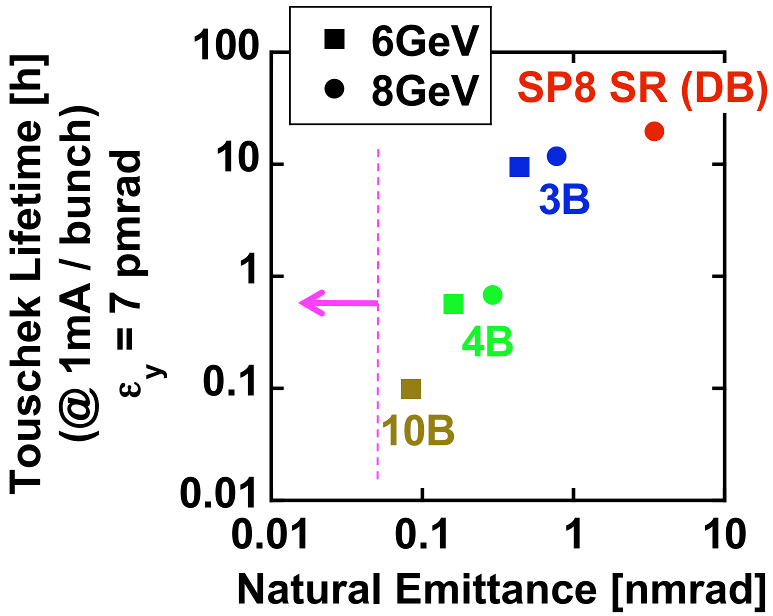
Energy: 8 GeV (max.)
Emittance: 40 pm.rad
Energy Spread: 0.01 %
Bunch Length: 30 fs (rms)
Electron Charge: 300 pC – 1 nC
Repetition Rate: 1 Hz

Touschek Effect
IBS
Round Beam

Touschek Beam Lifetime

Touschek lifetime will become long when the emittance is extremely small.

V.N.Litvinenko, ICFA WS(1999)
NSLS-II: CDR 4.2.2
MAX IV: S.C.Leemann et al., PRST-AB 12(2009)120701



Our case (at 6GeV) has not reached such a region yet.

$$\left(\frac{\Delta p}{p}\right)_c^2 >> \left(\gamma\sigma_{x'}\right)^2 \approx \frac{\gamma^2\varepsilon}{\langle\beta_x\rangle} \quad \text{i.e.} \quad \varepsilon << \frac{\langle\beta_x\rangle}{\gamma^2}\left(\frac{\Delta p}{p}\right)_c^2$$

For $\langle\beta_x\rangle \approx 10m$、 $\left|\frac{\Delta p}{p}\right|_c \approx 0.03$

E [GeV]	8	7	6	5	4	3
ε [nmrad]	0.037	0.048	0.065	0.094	0.147	0.261

Touschek Beam Lifetime (2)

... but at lower energies

E [GeV]	8	7	6	5	4	3
ε [nmrad]	0.037	0.048	0.065	0.094	0.147	0.261

NSLS-II: CDR, 4.2.2

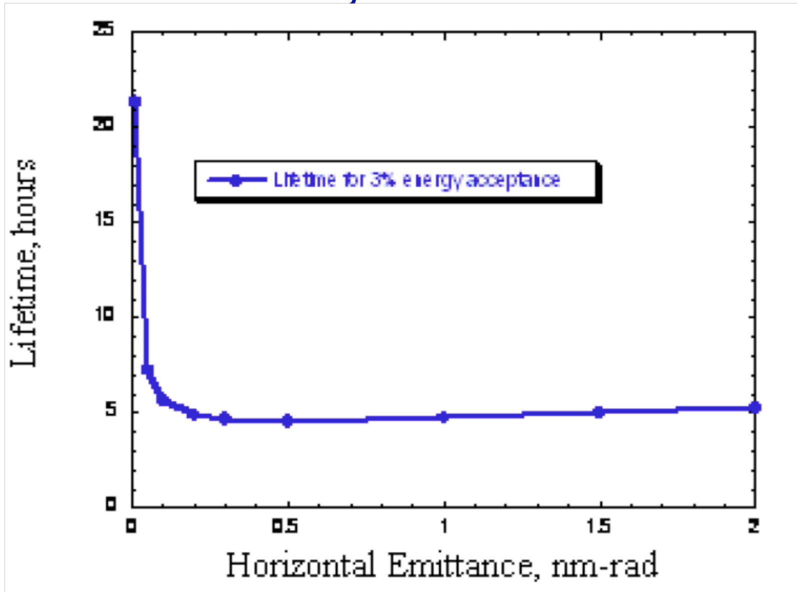


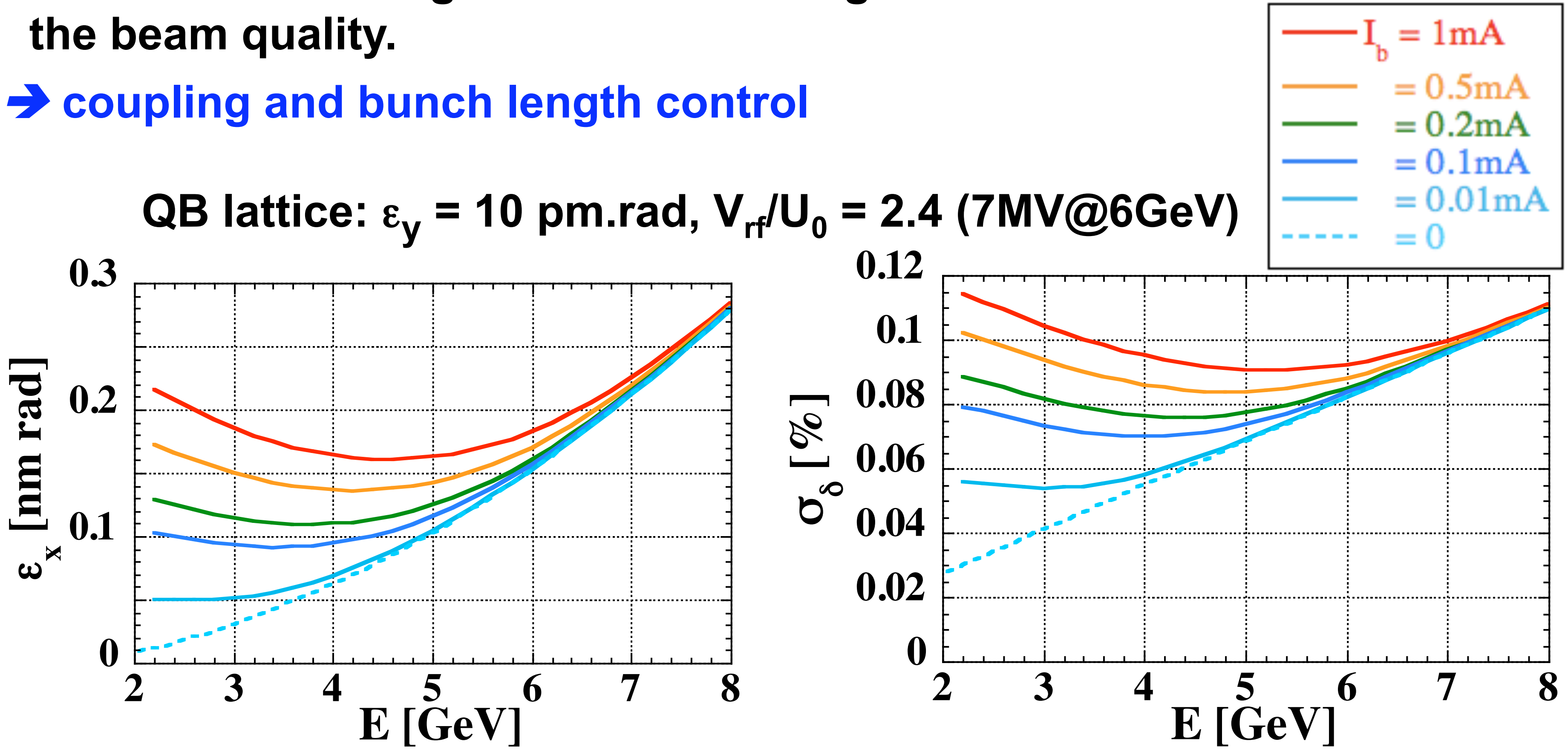
Figure 4.2.3 Dependence of the beam lifetime in NSLS-II on horizontal emittance for 0.008 nm-rad vertical emittance and fixed uniform 3% energy acceptance.

MAX IV: *S.C.Leemann et al., PRST-AB 12(2009)120701*

Intrabeam Effect

Expecting development of insertion device technologies (Mini-Pole U., Cryo-U., ...), we may lower beam energy to get lower emittance. Undulator length will be shorter and this also helps to increase the number of bend in a cell. At lower energies however strong IBS will affect the beam quality.

➔ coupling and bunch length control

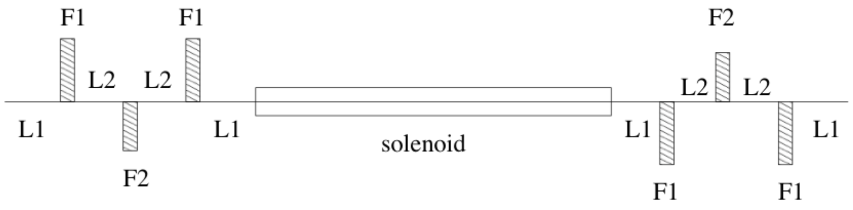


QB lattice: ε_y = 10 pm.rad, V_{rf}/U_0 = 2.4 (7MV@6GeV)

K.Bane, PRST-AB 5(2002)084403

Round Beam

A.Burov and V.Danilov, FERMILAB-TM-2043



skew Q **solenoid** **skew Q**

Figure 1: General scheme of the insertion.

Transformation between canonical and physical momentum in solenoid is

$$\pi_x = p_x + eA_x = p_x - (eB_z/2)y$$

$$\pi_y = p_y + eA_y = p_y + (eB_z/2)x$$

This is essential for manipulating emittance defined by (x, p_x, y, p_y) .

... K.Oide

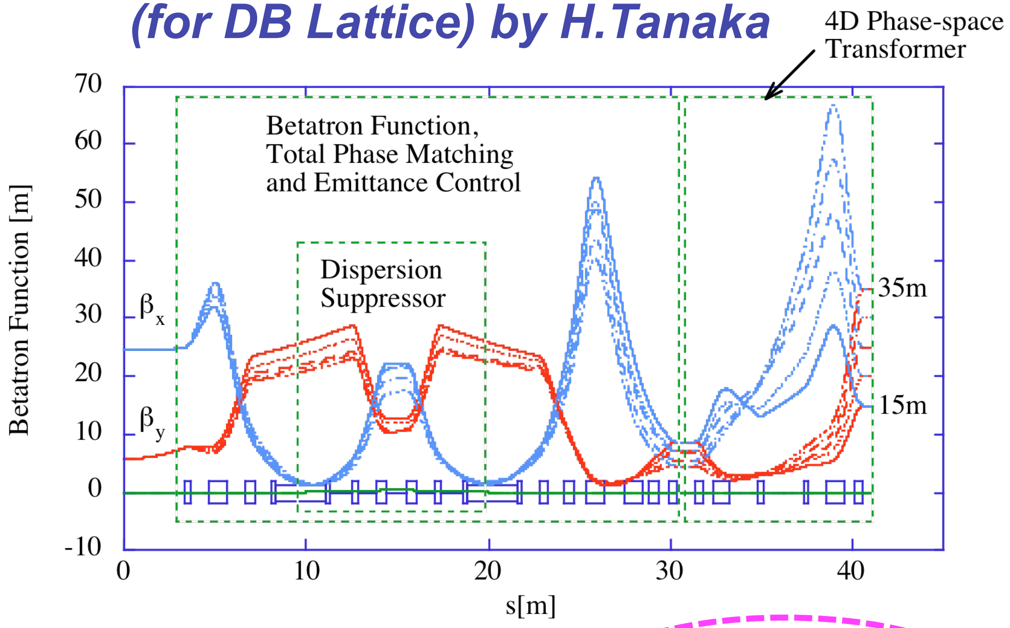
$$\beta = \frac{2[B\rho]}{B_z}$$

$$\sigma_x = \sigma_y = \sqrt{\frac{\beta\varepsilon_x}{2}}$$

$$\sigma_{x'} = \sigma_{y'} = \sqrt{\frac{2\varepsilon_y}{\beta}}$$

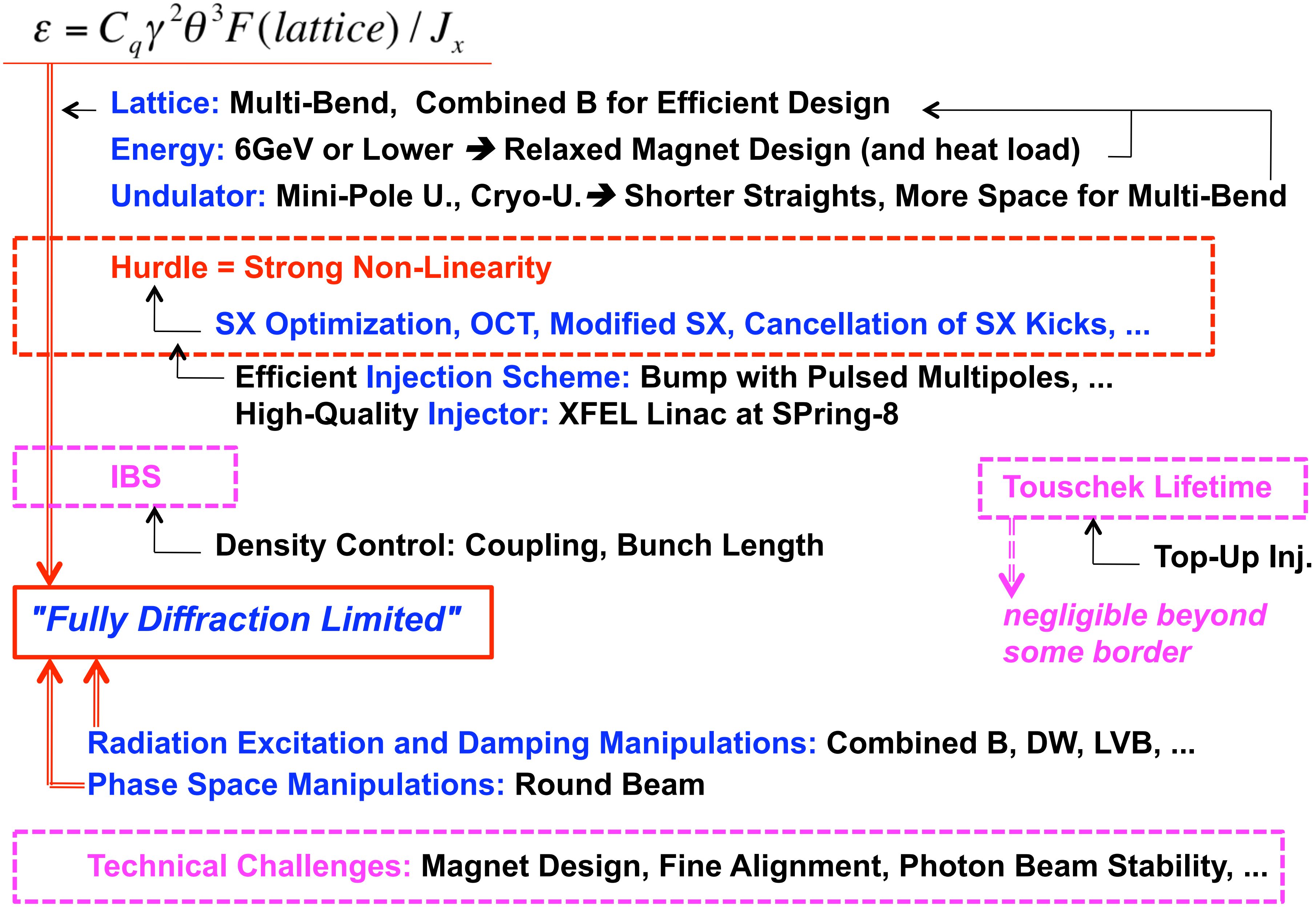
$$\sigma_x\sigma_{x'} = \sigma_y\sigma_{y'} = \sqrt{\varepsilon_x\varepsilon_y}$$

Example Design of Matching Section (for DB Lattice) by H.Tanaka



e.g. $B_z = 1.5T, E = 6GeV, \varepsilon_x = 0.2nmrad, \varepsilon_y = \varepsilon_x \times 0.003 \Rightarrow \sqrt{\varepsilon_x\varepsilon_y} = 11pmrad$

Summary



$$\varepsilon = C_q \gamma^2 \theta^3 F(lattice) / J_x$$

Lattice: Multi-Bend, Combined B for Efficient Design

Energy: 6GeV or Lower ➔ Relaxed Magnet Design (and heat load)

Undulator: Mini-Pole U., Cryo-U. ➔ Shorter Straights, More Space for Multi-Bend

Hurdle = Strong Non-Linearity

SX Optimization, OCT, Modified SX, Cancellation of SX Kicks, ...

Efficient Injection Scheme: Bump with Pulsed Multipoles, ...

High-Quality Injector: XFEL Linac at SPring-8

IBS

Density Control: Coupling, Bunch Length

Touschek Lifetime

Top-Up Inj.

negligible beyond some border

"Fully Diffraction Limited"

Radiation Excitation and Damping Manipulations: Combined B, DW, LVB, ...

Phase Space Manipulations: Round Beam

Technical Challenges: Magnet Design, Fine Alignment, Photon Beam Stability, ...

Summary (2)

There are many open questions, and we do not have definite answers yet.

We are looking for breakthrough to the "next-generation" ring-based light sources and want to exchange information and experience with other facilities to find a clue to a new methodology and/or technique in this WS. So we proposed a discussion session for brainstorming:

13 Jan. (Wed.) 18:05 – 19:00