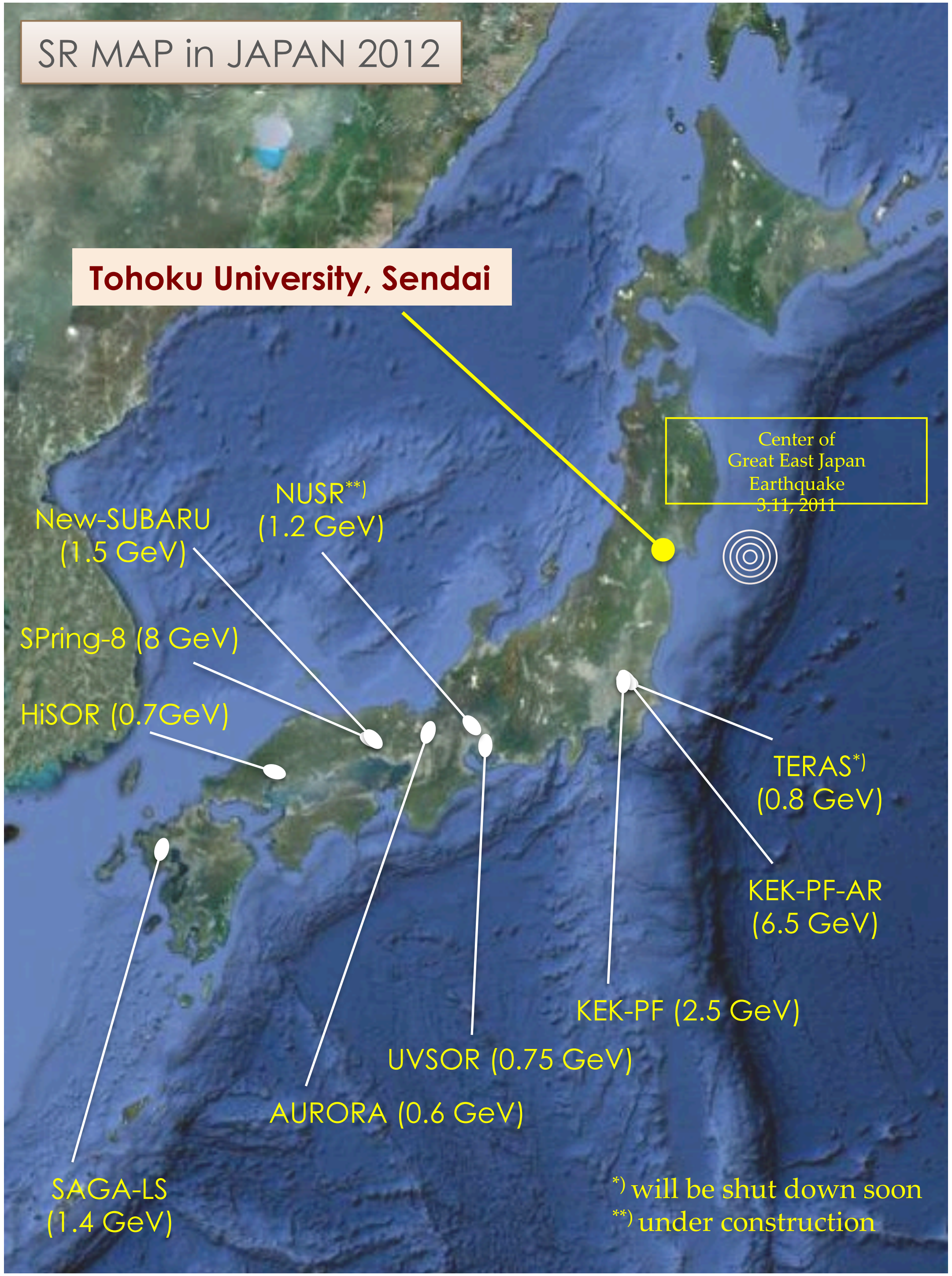
Ground design of the 3 GeV accelerator-complex for synchrotron radiation facility in East Japan

LSEJAPAN

Light Source in East Japan

Presented @ FLS2012, J-Lab, Newport News
2012.3.7

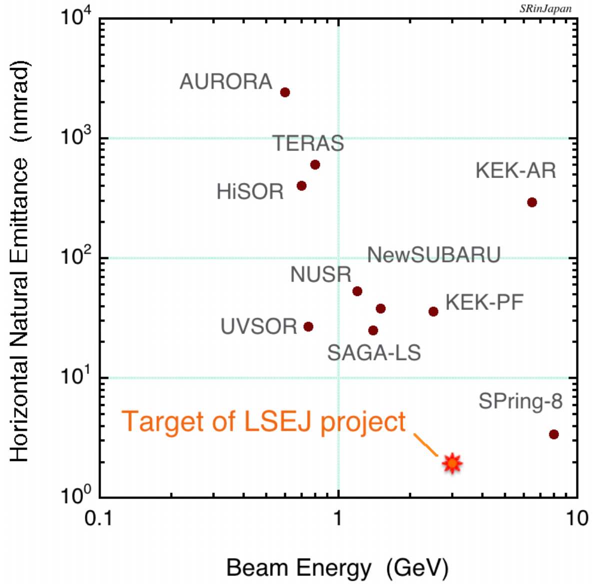
Hiroyuki Hama
with Beam Physics G.
Electron Light Science Centre
Tohoku University



L S E Japan

Particular incentive

We are aware that the role of East Japan (Tohoku area) for basic science, technology and industry has been very much significant because the Japanese activities of many scientific fields was getting paralyzed and atrophied after the disaster of the Great East Japan Earthquake and Tsunami, March 11, 2011. Nevertheless there has been no light source in East Japan (Tohoku area) so far.



An advanced low emittance 3 GeV machine for X-ray should be established in East Japan.

Requirements and target performance

1. X-ray analysis for elements with relatively small atomic numbers, which will be important material to substitute rare-earth elements.
2. Low emittance beam for complete control of polarization for radiation from insertions, and ultra-high resolution X ray spectroscopy by nano-beam confinement.
3. Clear observation of material function and structure in nano-region.
4. Short pulse X ray for real-time analysis of chemical reaction and phase transition in matter.
5. Proper operation to derive maximum performance of the light source.
6. Low cost and energy saving light source facility.

On the other hand, rapid progress in accelerator technology and science

1. Well understanding of nonlinear dynamics for the low emittance ring
2. Ultra-short period in-vacuum undulator
3. Topping-up operation
4. C-band linac technology for XFEL (SACLA)

• • • • •

Advanced light source facility but high reliability and stability based on recent established accelerator science and technology

Target of Light Source Performance

Wavelength	0.1 ~ 20 keV
Brilliance	10^{21} phs/s/mm^2/mrad^2/0.1%b.w.@ 1~10 keV

Target of Machine Performance

Beam energy	~ 3 GeV
Horizontal emittance	< 2 nmrad
Circumference	**< 300 m**

Things to keep in mind

- Laser slicing / low alpha operation toward short-pulse production
- Topping up operation
- Seeded soft X-ray FEL driven by a C-band injector

L S E Japan

Recent 3 GeV class light sources

Ring	Energy (GeV)	Circumference (m)	Number of cells	Beam current (mA)	Emittance (nmrad)	Brilliance @ 2-10 keV
DIAMOND	3	562.6	24	300	2.7	10^{20}
ALBA	3	268.8	16	400	4.3	10^{20}
TPS	3	518.4	24	400	1.6	10^{21}
MAX-IV	3	528	20	500	0.24	10^{21}
NSLS II	3	792	30	500	0.55	10^{21}
SPring-8	8	1436	44	100	3.4	10^{20}

It seems to be very difficult to realize < 2 nmrad emittance
with a circumference less than 300 m

Memorandum in designing lattice

- Proper and rational length of straight section
- Smaller cell number and many bends
- At least 10 straight section for insertions ($N_{cell} \geq 12$)
- No super long straight section, simple lattice without technical difficulty
- Introduce combined function magnets to make compact
- Employ pulse quad (or sext) beam injection

Storage ring lattice design

Lattice design strategy

Theoretical minimum emittance

$$\varepsilon_x^{\min} = \frac{1}{4\sqrt{15}} \frac{C_q \gamma^2 \theta^3}{J_x} (achromat), \qquad \varepsilon_x^{\min} = \frac{1}{12\sqrt{15}} \frac{C_q \gamma^2 \theta^3}{J_x} (non-achromat)$$

$C_q = 3.83 \times 10^{-13}$ (mrad)

θ ; bending angle (rad)

J_x ; horizontal damping partition (1 ~ 1.5)

$\Rightarrow$

18 - 27 nmrad $(n_B = 20)$ // 2.2 - 3.3 nmrad $(n_B = 40)$ // 0.65 - 0.98 nmrad $(n_B = 60)$

n_B; number of identical bending magnets

- Conventional Double-Bend Achromat (DBA) lattice

  Many straight sections, but limited emittance for given ring.

  ex. ALBA (C=270 m, 16 cells): <u>ε ~ 4 nmrad</u>

  Many dipoles ???????

  => However, we do not want difficult and complicate lattice !
  Moreover construction and commissioning should be quick.

Number of cells and number of bends

From theoretical limit of emittance, ~ 50 bends are at least required toward 2 nmrad at 3 GeV, practically.

• Consider the distance between bends in an arc . . . . . .

$$C \approx 2\pi\rho + N\ell_{ss} + N(n-1)S$$

ρ ; bending radius

N ; number of cells

ℓ_{ss} ; length of straight section + ~3 m

n ; number of bending mag in a cell

S ; length between bending mags

for example,

$C = 300$ m

$\rho = 12$ m $(B = 0.83\ T)$

$N \times n = 48$

$\ell_{ss} = 5$ m

N	n	S (m)
24	2	1.4
16	3	3.0
12	4	3.6
8	6	4.0

$\Rightarrow$ For a 300 m ring, 24-cell DBA seems impossible, maybe 16-cell TBA too.

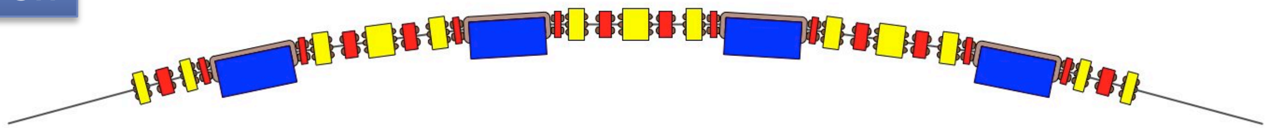
No trade-off and compromise between number of beam lines, the low emittance should be 1st priority.

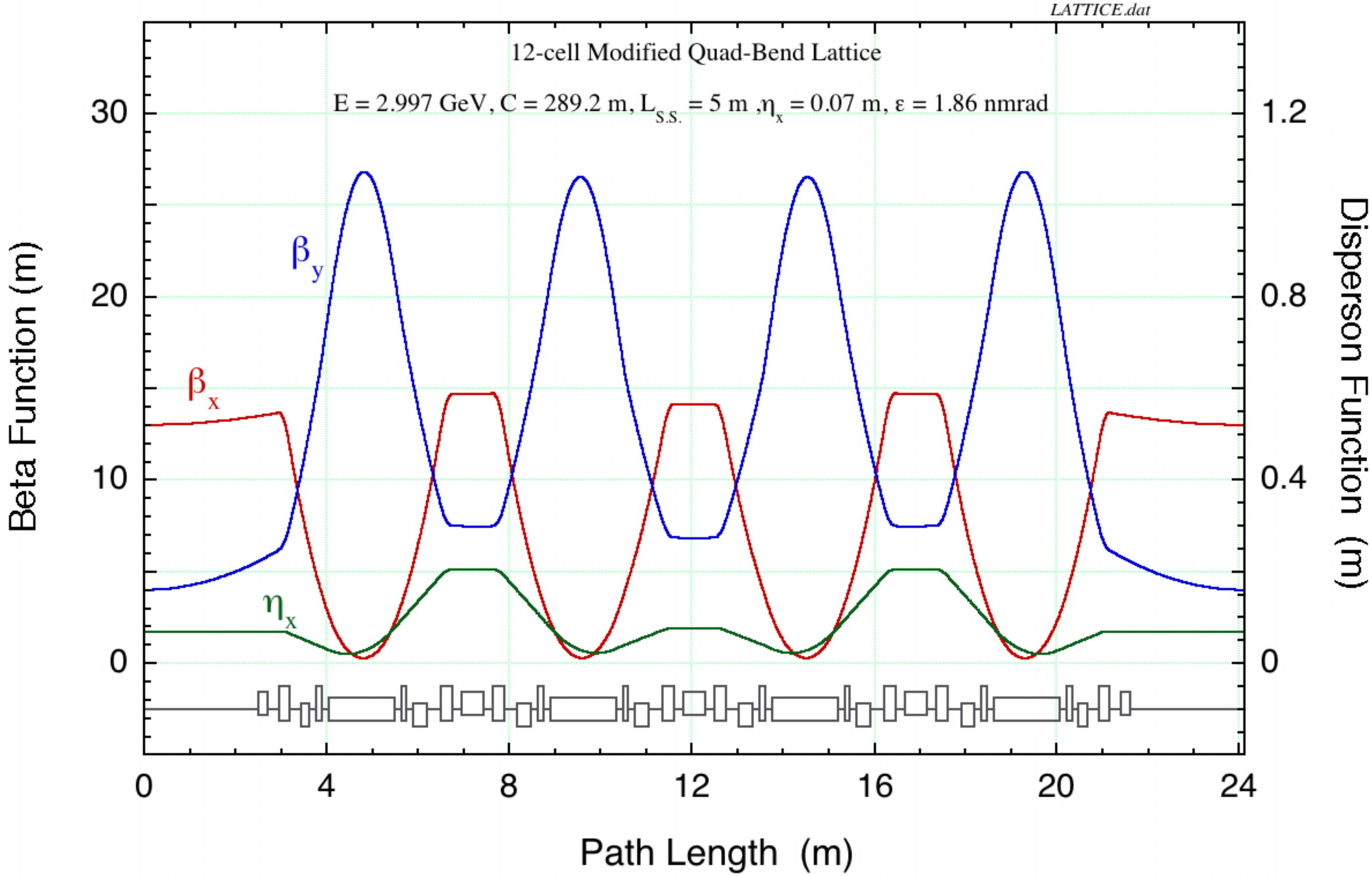
Springboard is 12-cell of quad-bend lattice.
Non-achromat is being default toward less than 2 nmrad.

L S E J apan

Lattice function in a normal cell

TENTATIVE DESIGN





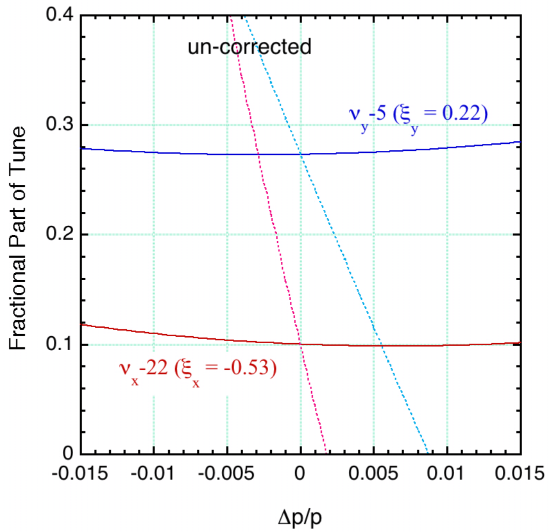
Major machine parameters

Energy	E	2.997 GeV ($B\rho = 10$)
Circumference	C	289.2 m
Betatron tune	(ν_x, ν_y)	(22.10, 5.27)
Natural chromaticity	(ξ_x, ξ_y)	(- 56.99, - 33.58)
Natural horizontal emittance*)	ε_x	1.862 nmrad
Momentum compaction factor	α	0.00076
Damping time*)	$(\tau_x, \tau_y, \tau_\varepsilon)$	(6.32, 8.88, 5.56) ms
Natural energy spread*)	σ_E/E	8.69×10^{-4}
Synchrotron energy loss*)	ΔE	0.652 MeV/turn
Min. and max. horizontal beta function	$(\beta_x^{min}, \beta_x^{max})$	(0.28, 14.71) m
Min. and max. vertical beta function	$(\beta_y^{min}, \beta_y^{max})$	(4.00, 26.80) m
Min. and max. dispersion function	$(\eta_x^{min}, \eta_x^{max})$	(0.02, 0.21) m
Length (number) of straight section	L_{ss}	5 m (12)
Lattice functions at straight section	$(\beta_x, \beta_y, \eta_x)$	(13, 4, 0.07) m

*)Only dipoles are taken into account

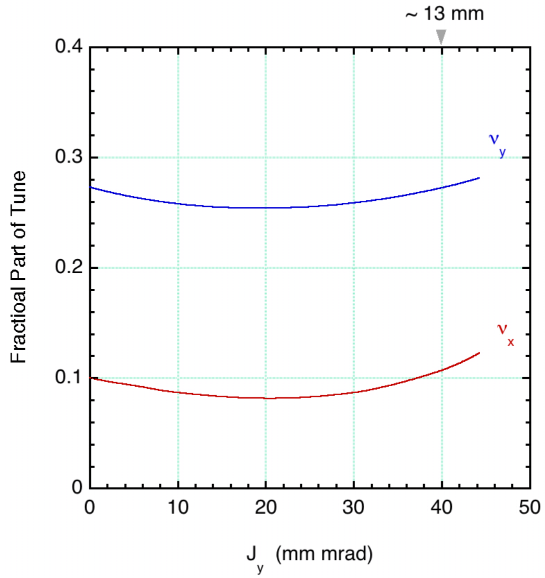
Nonlinearity correction

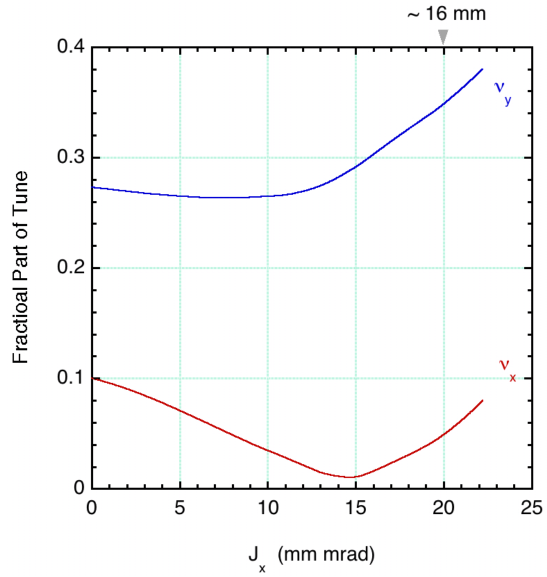
Nonlinear chromaticity



- Iterative minimization of $d\nu_{x,y}/dp$, $d\nu_{x,y}/dJ_x$, $d\nu_{x,y}/J_y$ by using 6-family sextupoles (no dispersion free sextupole)
- Tune is not optimized yet

Amplitude (H) dependent tune shift



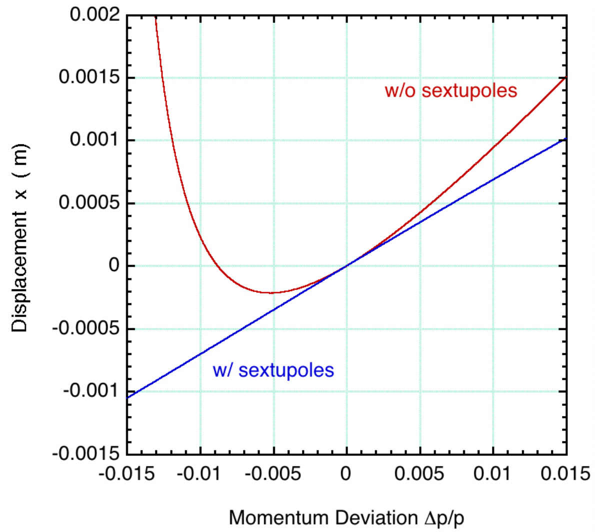


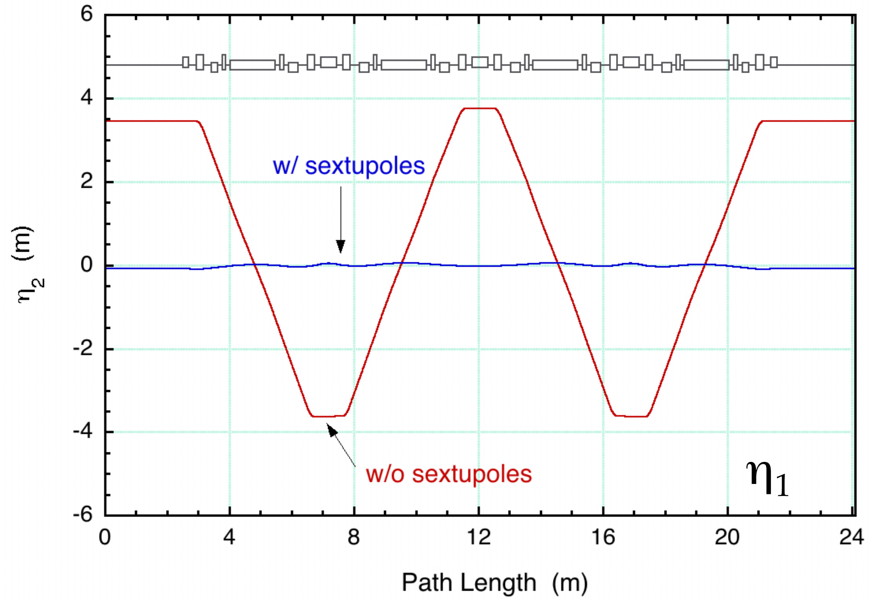
Amplitude (V) dependent tune shift

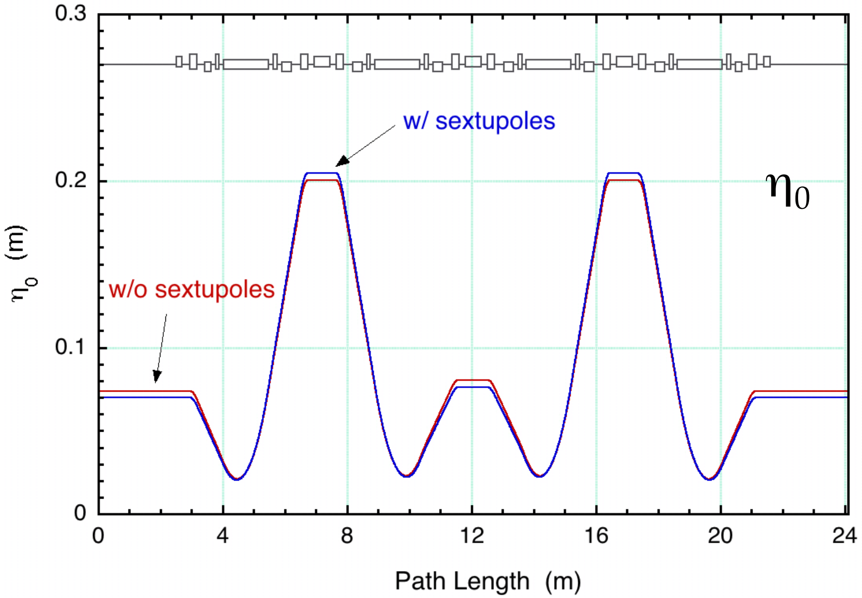
Next correction
ν_x: ↑ ν_y: ↓

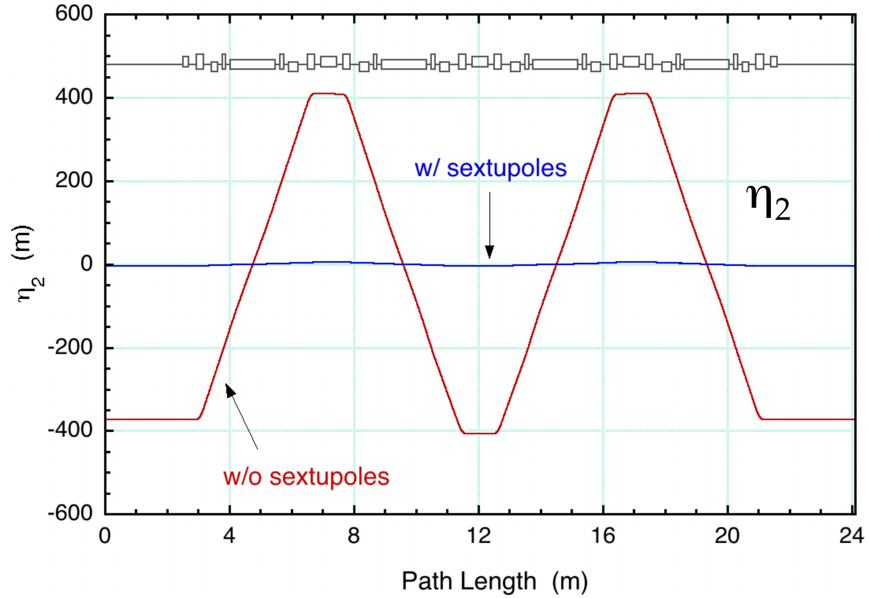
Nonlinear dispersions

@S.S







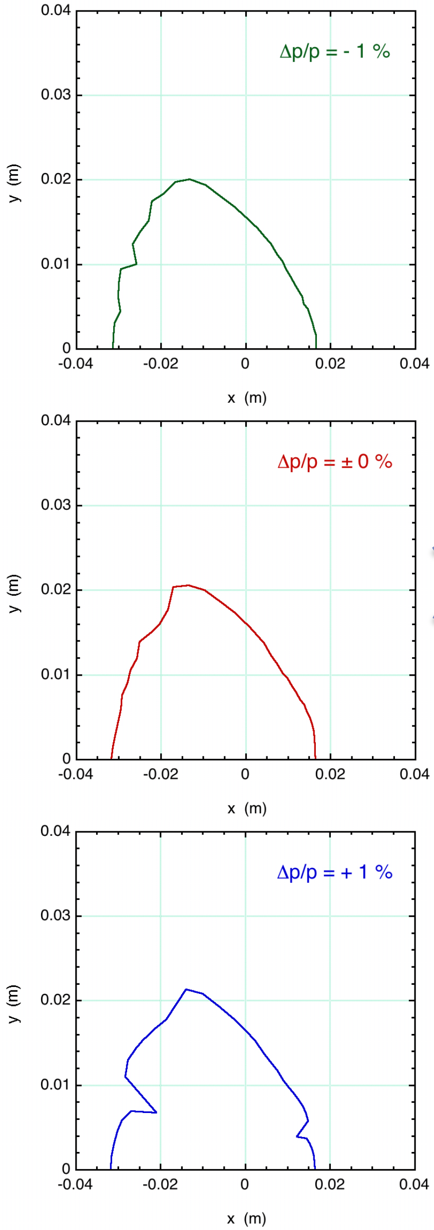


- No idea for advantage of linearized dispersion (may be not bad)

Dynamic aperture

It 's original !

TRaCKDuCT (no RF)

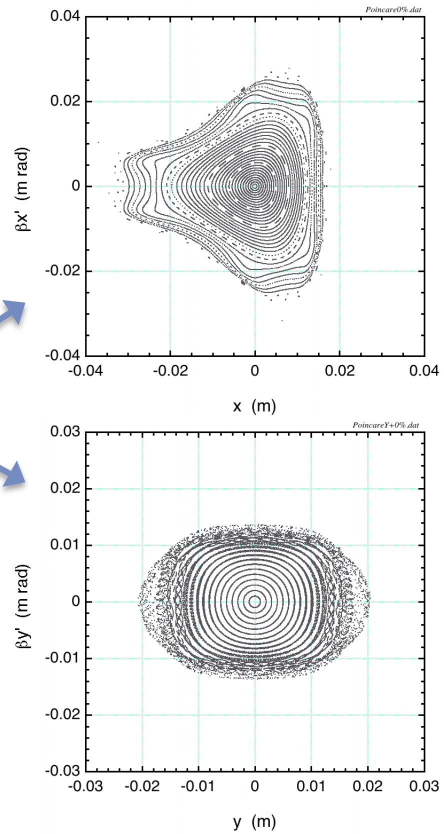


Rather stable for large amplitude particles

Poincaré plot

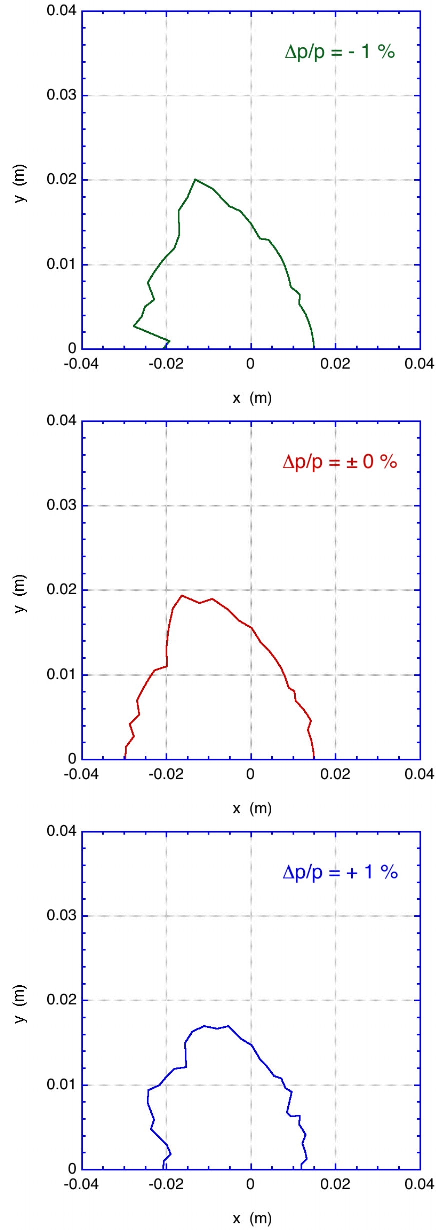
H

V



☞ **No serious defect in lattice**

SAD (V_{RF} = 3 MV)

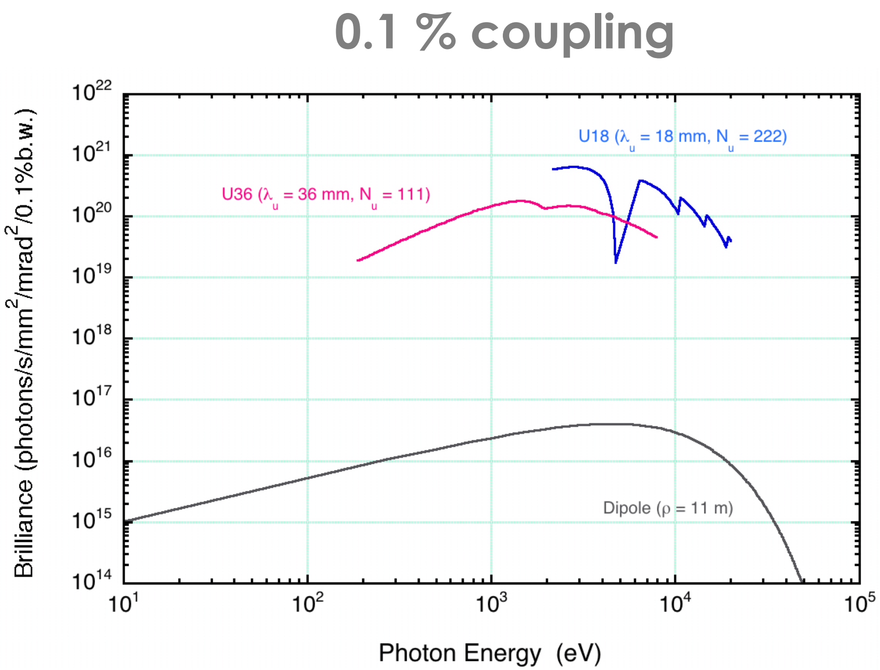


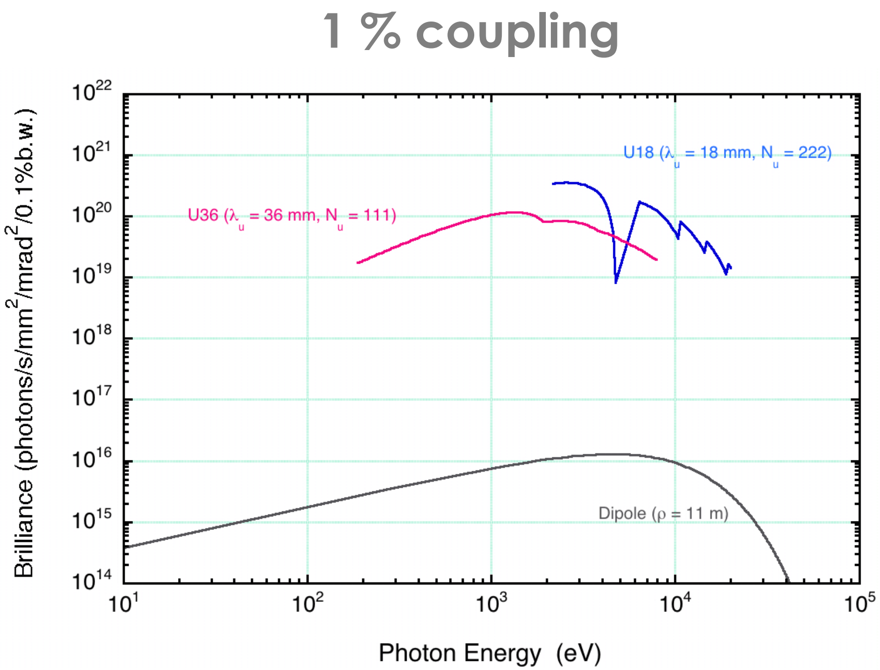
Synchro-beta coupling resonance maybe not severe

LSEJapan

Brilliance@300mA

$Gap^{und.}_{min}$ = 5 mm





- **Still below 10^{21}, but favorably comparable with recent 3 GeV class machines**
- **Require more brightness in lower energy region**

  => optimization of undulator parameters

Injector

- Less future progress for booster synchrotron
- Employing recent advanced linac technology to secure potential ability

  ⇒ Seeded soft X-ray free electron laser (s-SXFEL) for high quality laser (longitudinal single mode)

  ε_{photon} < 3 keV (~ 0.4 nm)

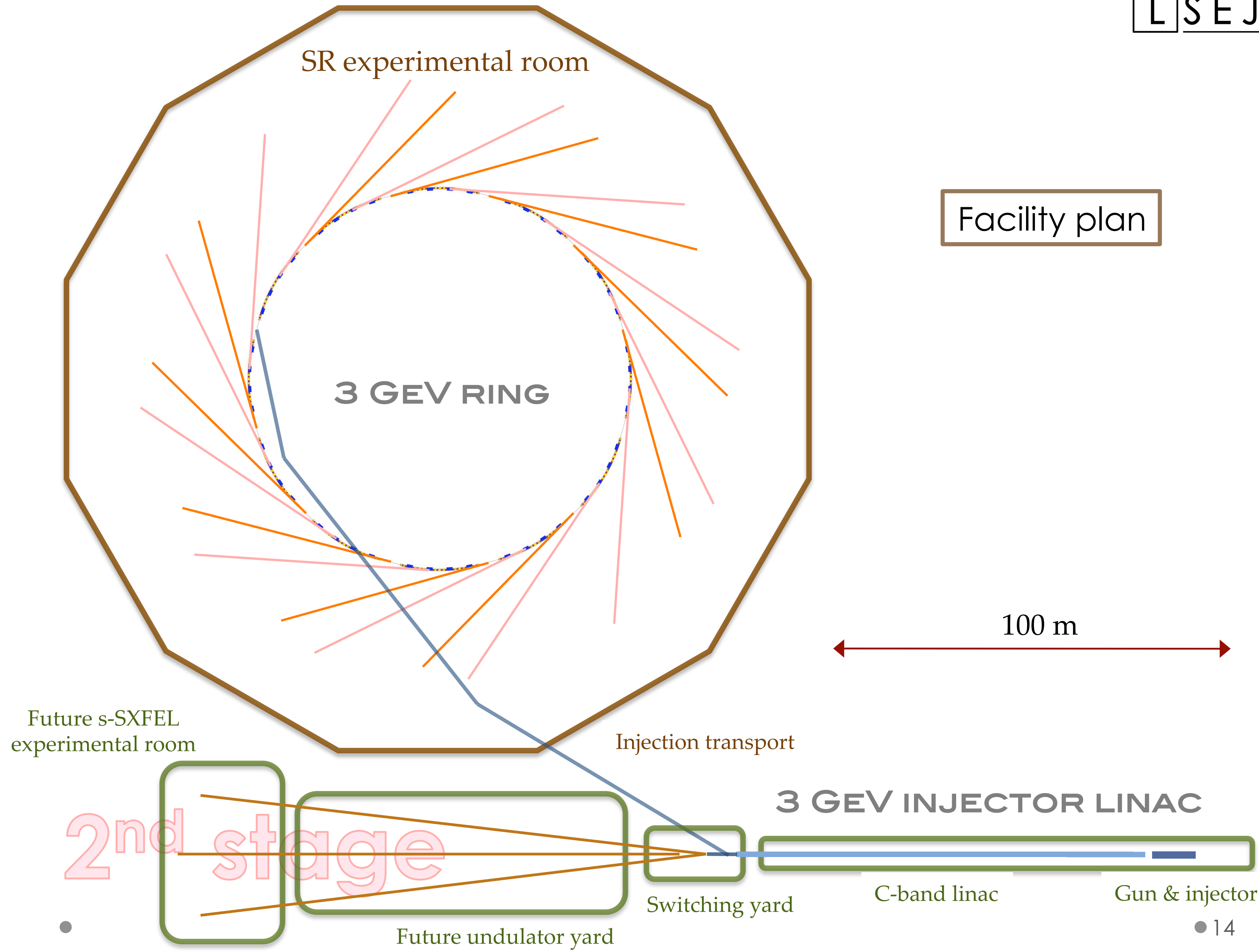
  P_{peak} > 1 GW
- Independently developed C-band technology in SACLA has to be succeeded.

Expected characteristics of C-band injector

Beam energy	3 GeV
Normalized emittance	1 πmm mrad (0.17 nm rad @ 3GeV)
Maximum bunch charge	1 nC
Bunch length	2 ps
Energy spread	0.06%
Maximum repetition rate	50 Hz (1 ~ 10 Hz @ topping up)

- Bunch compressors have to be equipped in advance of s-SXFEL, but the total length is still ~ 100 m.
- Choke structure is not necessary, conventional style of the accelerating structure to reduce cost.

Facility plan



Things to be considered

10-insertion is sufficient ? (Biggest question to be discussed)

If the ring circumference can be extended to ~ 350 m,

Does the emittance reach around 1 nmrad, then **the brilliance exceeds 10^{21} ?**

=> How about 14 cells ?

=> How about 3-bend 20 cells ?

=> Further short period undulator such as λ_u = 15 mm

Still rare earth elements are important, need high energy photons above 20 keV.

Higher field bends such as B = 1.5 T is sufficient (presently B = 0.91 T) ?

=> Increase the energy loss/turn, load of the RF cavity becomes serious

=> Insert short straight sections (~ 0.5 m) and put strong mini-undulator

=> How about a superconducting multipole wiggler ?

Other stuff

Injection scheme

Pulsed-multipole injection is a solution because of limited number of s.s.

RF cavity

Considering a standard superconducting one developed at KEK

Allowable alignment error

C-band linac spec

LSEJapan

Other stuff

Injection scheme

Pulsed-multipole injection is a solution because of limited number of s.s.

RF cavity

Considering a standard superconducting one developed at KEK

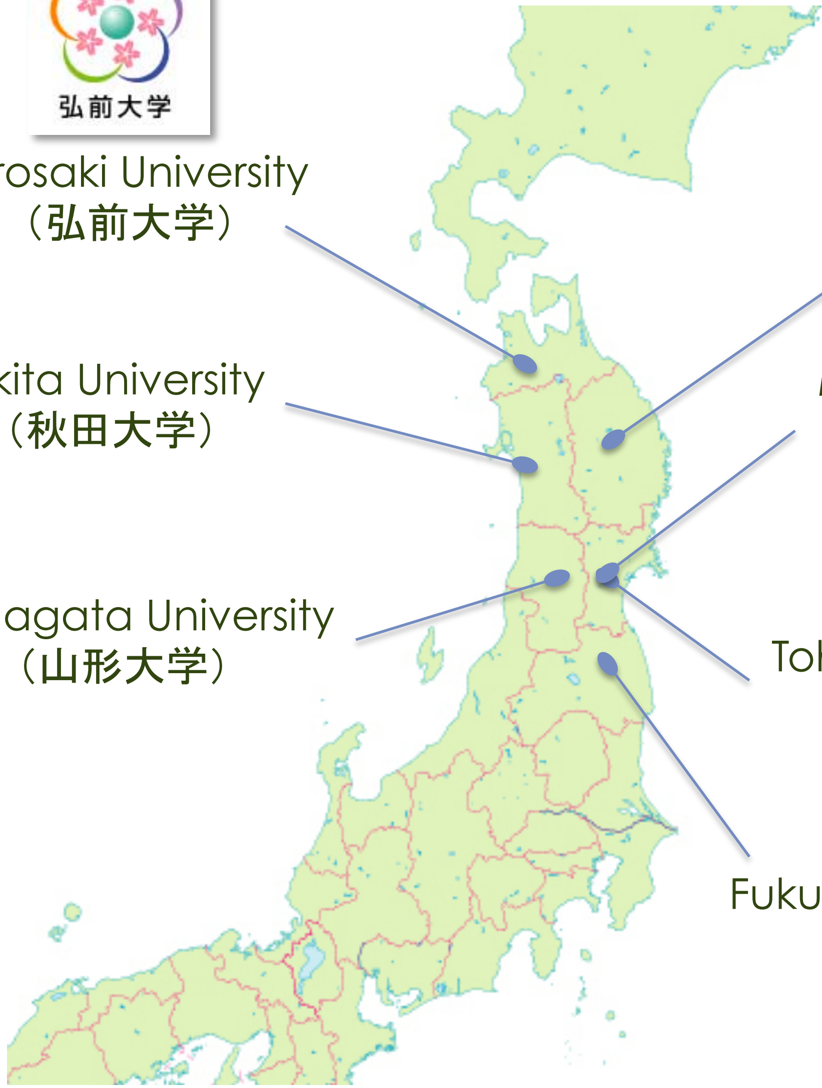
Allowable alignment error and COD correction scheme

Higher field bends such as B = 1.5 T is sufficient (presently B = 0.91 T) ?

=> Increase the energy loss/turn, load of the RF cavity becomes serious
=> Insert short straight sections (~ 0.5 m) and put strong mini-undulator
=> How about a superconducting wiggler ?

The LSEJ project is now supported by a collaboration of 7 national universities and industries in Tohoku area.

Prof. Yoshio Waseda @ Tohoku University (project leader)



Hirosaki University
（弘前大学）

Akita University
（秋田大学）

Yamagata University
（山形大学）

Iwate University
（岩手大学）

Miyagi University of Education
（宮城教育大学）

Tohoku University
（東北大学）

Fukushima University
（福島大学）

Expected budget 250 M$

Our basic policy

We will quit the project if the budget is not approved within 2 years because of upcoming projects of SPring-8 II and PF-ERL.

L S E JAPAN