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

Light Source in East Japan

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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 is obtained in accelerator technology and science

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

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

- **In-vacuum undulator**

$$\begin{array}{l} \lambda_u = 15\ mm \\ B_0 = 0.7\ T \\ E_e = 3\left(2.5\right)\ GeV \end{array} \Rightarrow \begin{array}{l} \varepsilon_{\text{photon}}^{\text{1st}} = 3.8\left(2.6\right)\ keV \\ \varepsilon_{\text{photon}}^{\text{7st}} = 27\left(18\right)\ keV \end{array}$$

⇒ X-ray region up to ~ 20 keV can be covered by 3 GeV class light source.

- **Low emittance beam**

⇒ extremely long straight section is not required any longer.

⇒ small aperture quad and sextupoles

⇒ compact devices and ring itself.

- **Recent generic technology in Japan**

⇒ Progress of information and communication technologies may bring flexible control of accelerators.

⇒ Fine processing technology can produce high-performance combined function magnets

High brilliance beam based on low-energy and low-emittance ring is directly linked with low-cost, saving-energy and earth conscious.

Target of Light Source Performance

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

Target of Machine Performance

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

Some additional points to keep in mind

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

Recent medium energy class light sources

Ring	Energy (GeV)	Circumference (m)	Cell number	Beam current (mA)	Emittance (nmrad)	Brilliance @ 2-10 keV
DIAMOND	3	561.6	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	0.33	10^{21}
NSLS II	3	792	30	500	0.9	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 ($N_{\mathrm{cell}} \geq 12$)
- 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 $(\mathrm{n_B} = 20)$ // $2.2 - 3.3$ nmrad $(\mathrm{n_B} = 40)$ // $0.65 - 0.98$ nmrad $(\mathrm{n_B} = 60)$

$\mathrm{n_B}$; number of identical bending magnets

- Multi-bend lattice

  Lattice of many dipoles in arc such as MX-IV requires dispersion suppressor at the edge of the arc.

  => half-bend is efficient but complicate design.

  Longer arc section as lower emittance.

- Conventional Double-Bend Achromat (DBA) lattice

  Many straight sections, but limited emittance for given ring.

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

At least 1-set of quad and 2-set of sext have to be inserted between bends for any type of lattice.

⇒ 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.

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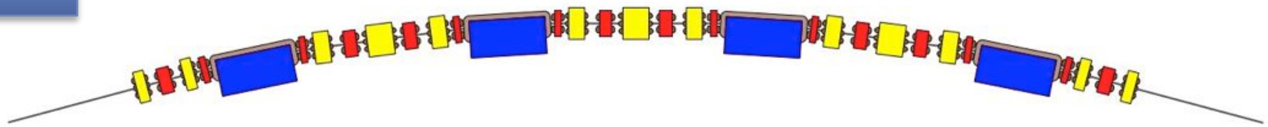
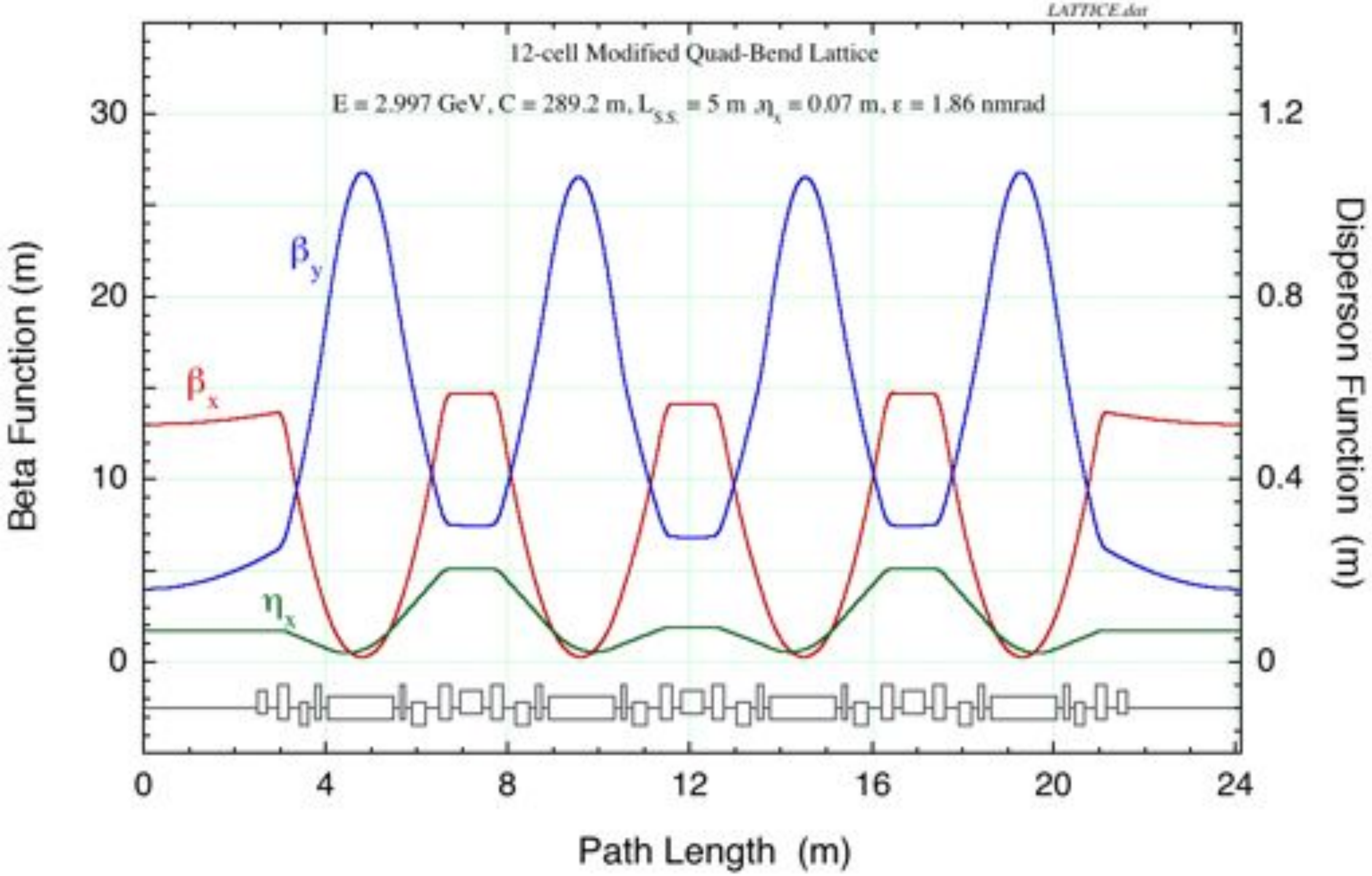
Springboard is 12-cell of quad-bend lattice.
Non-achromat is being default toward less than 2 nmrad.

Lattice function in a normal cell

TENTATIVE DESIGN



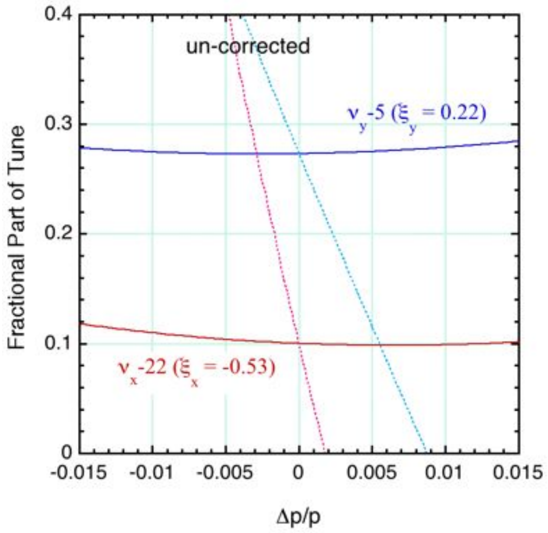


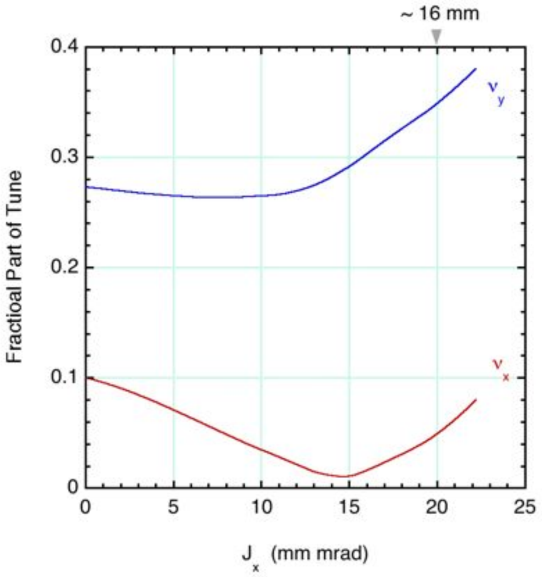
Major machine parameters

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. verticalbeta 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

Nonlinearity correction by 6-family sextupoles

Nonlinear chromaticity

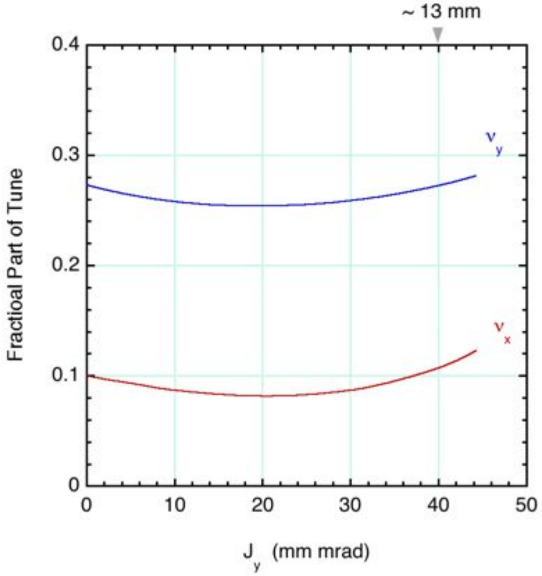


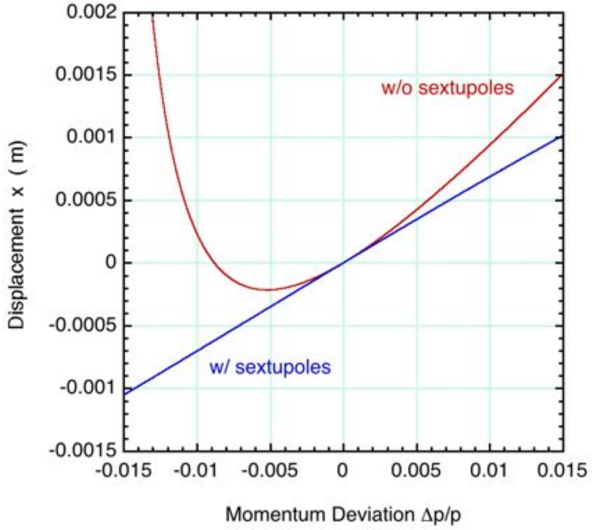


Amplitude (V) dependent tune shift

Next correction
ν_x: ↑ ν_y: ↓

Amplitude (H) dependent tune shift



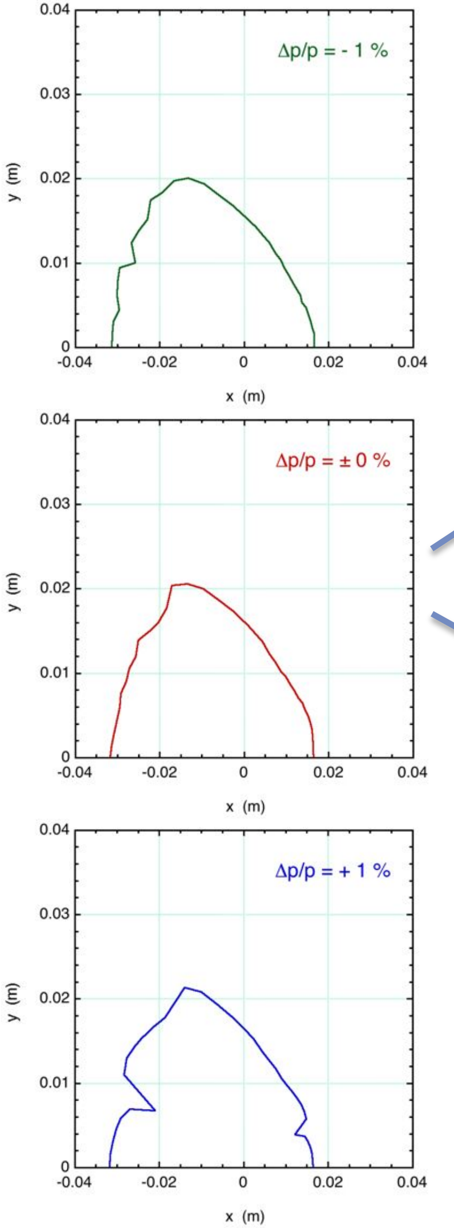


Nonlinear dispersion@s.s.

Dynamic aperture

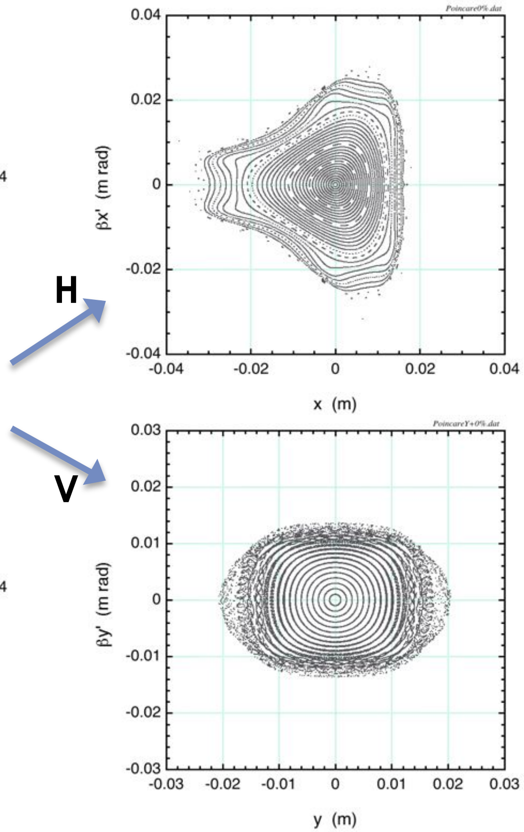
It 's original !

TRaCKDuCT (no RF)

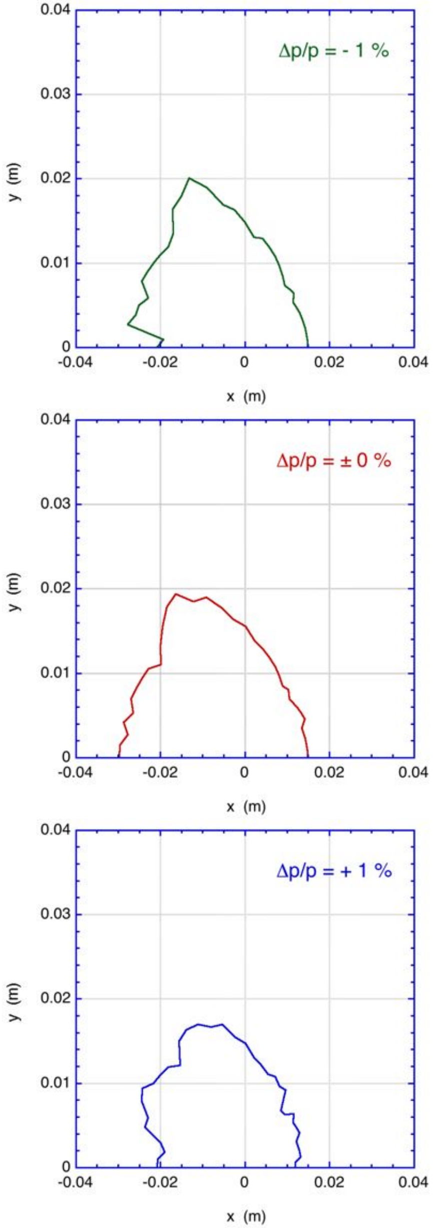


Rather stable for large amplitude particles

Poincaré plot



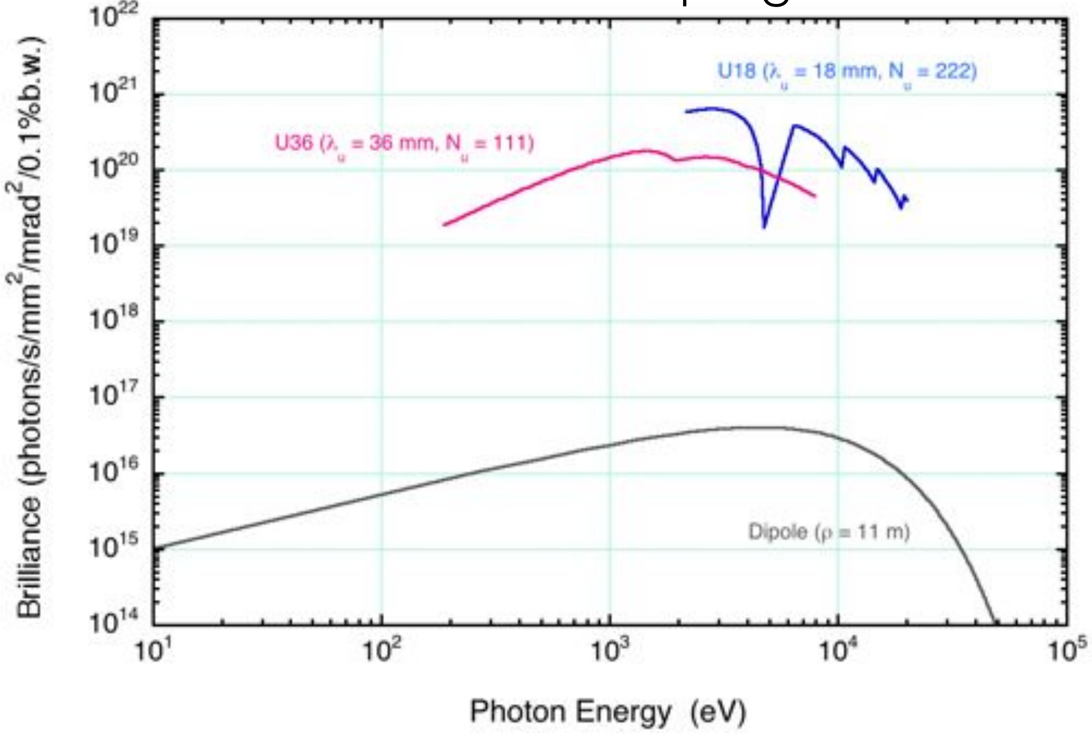
SAD (V_{RF} = 3 MV)



☞ **No serious defect in lattice**

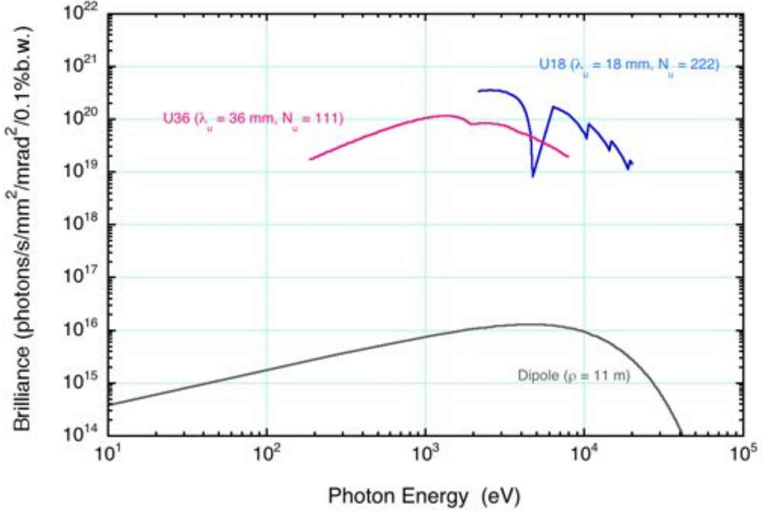
Brilliance@300mA

0.1 % coupling



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

1 % coupling



- **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)

  $\varepsilon_{\mathrm{photon}} < 3$ keV (~ 0.4 nm), $P_{\mathrm{peak}} > 1$ 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 (tentative plan)