# Project “SLiT-J”

## Synchrotron Light in Tohoku, Japan

Outline
Conceptual Design of Accelerator Complex V1.0
April, 2014

SLiT-J Design Team

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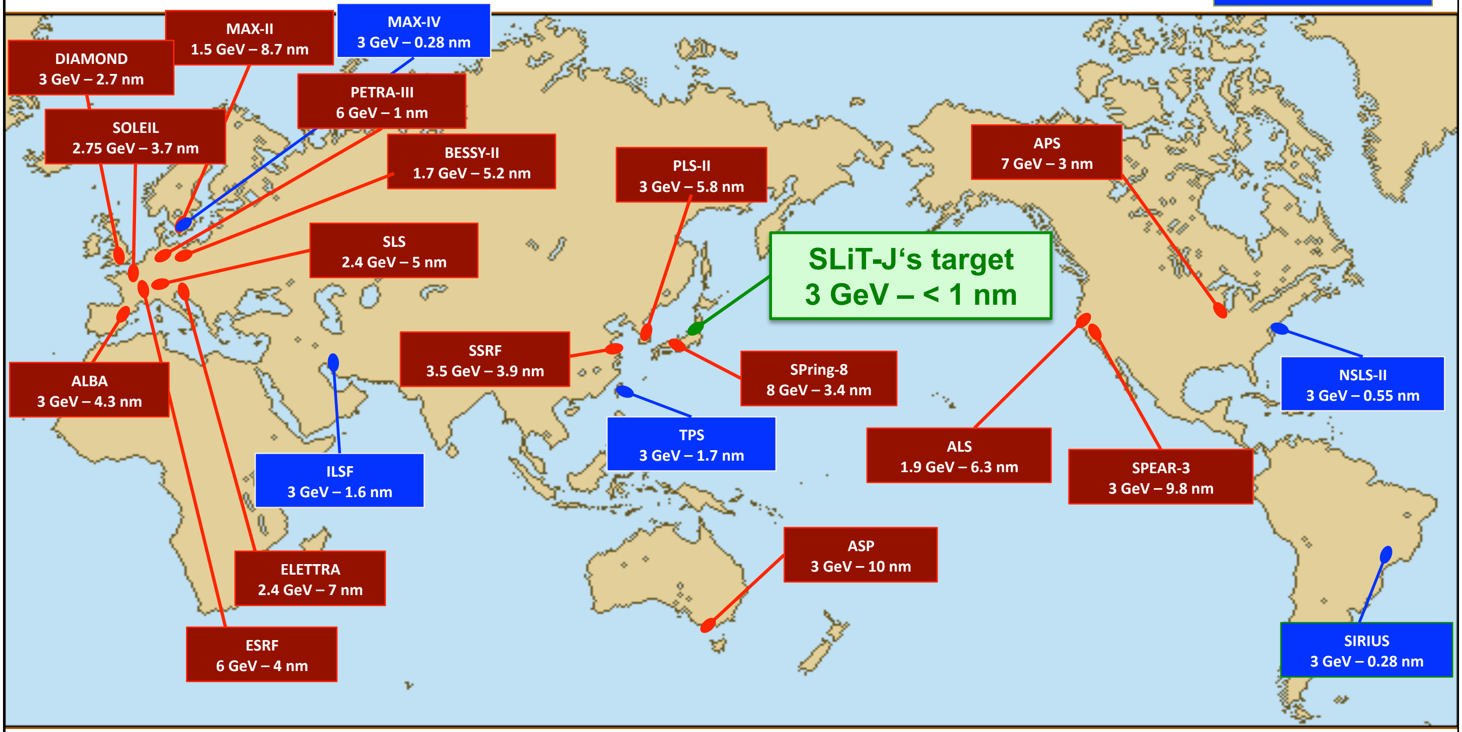
# High Brilliant Light Source in the World

horizontal emittance $\mathcal{E}_x$ < 10 nmrad

🟥 Operational
🟦 Under constructing



## STORAGE RING 1. Low emittance strategy

### Synchrotron integrals

$$I_1 = \oint \frac{\eta_x}{\rho} ds$$

$$I_2 = \oint \frac{1}{\rho^2} ds$$

$$I_3 = \oint \frac{1}{|\rho|^3} ds$$

$$I_4 = \oint \frac{\eta_x}{\rho}\left(\frac{1}{\rho^2} + 2K\right) ds$$

$$I_5 = \oint \frac{H}{|\rho|^3} ds \quad \text{where } H(s) = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

Important function of quantum excitation in bends

1. Momentum compaction factor $\alpha = \frac{I_1}{2\pi R}$
2. Horizontal emittance $\varepsilon_x = \frac{C_q \gamma^2 I_5}{(I_2 - I_4)}$ where $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} = 3.83 \times 10^{-13}$
3. Energy spread $\left(\frac{\sigma_E}{E}\right)^2 = \frac{C_q \gamma^2 I_3}{(2I_2 + I_4)}$
4. Energy loss $U_0 \approx \frac{C_\gamma E^4 I_2}{2\pi}$ where $C_\gamma = \frac{4\pi}{3(mc^2)^3} = 8.85 \times 10^{-5} \frac{m}{(GeV)^3}$
5. Damping partition $J_x = 1 - \frac{I_4}{I_2}$, $J_E = 2 + \frac{I_4}{I_2}$, $D = \frac{I_4}{I_2}$

### How to achieve low emittance lattice

Theoretical minimum emittance

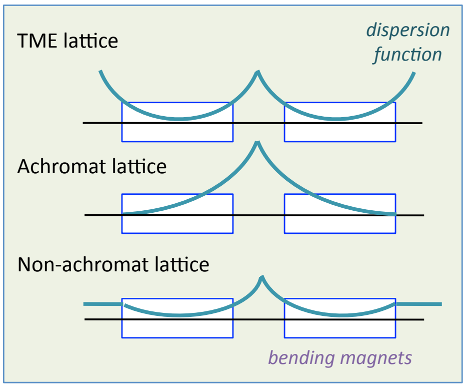
$$\varepsilon_x^{\min} = \frac{1}{4\sqrt{15}} \frac{C_q \gamma^2 \theta^3}{J_x} (achromat), \qquad \varepsilon_x^{\min} = \frac{1}{12\sqrt{15}} \frac{C_q \gamma^2 \theta^3}{J_x} (non-achromat)$$

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

$\theta$ ; bending angle (rad)

$J_x$ ; horizontal damping partition ($\sim 1.5$)

$$J_x = 1 - \frac{\oint (1-2n)\eta/\rho^3 ds}{\oint 1/\rho^2 ds}$$



- Smaller $\theta$ means increase of **number of bending magnets**.
- **Non-achromat lattice** reduces the emittance significantly.

  ☞ Be careful, energy spread increases the effective emittance.

$$\varepsilon_{x\text{-}effective} = \varepsilon_x \sqrt{1 + \frac{\left(\eta_x \frac{\sigma_E}{E}\right)^2}{\varepsilon_x \beta_x}}$$

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## STORAGE RING 1. Low emittance strategy

### Reducing emittance further

$\varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4}$ - for radiation damping on bending magnets only

$\varepsilon_{xW} = C_q \gamma^2 \frac{I_5 + I_{5W}}{I_2 - I_4 + I_{2W} - I_{4W}}$ - for radiation damping in bending magnets and wigglers ($_W$ denotes S.I. in wigglers)

- Strong **damping wiggler** is employed in NSLS-II ( 2.1 nmrad -> 0.55 nmrad)

when $\frac{\langle H_{dipole} \rangle}{H_W} >> 1$ $\quad \varepsilon_{xW} \approx \varepsilon_x \frac{U_0}{U_0 + U_W}$ where

$U_0$; Radiated power from dipoles

$U_W$; Radiated power from wigglers

$$\boxed{U_0 \text{ [MW]} = 8.846 \times 10^{-2} E^4 \text{ [GeV]}/\rho \text{ [m]} I \text{ [A]}}$$

$$\boxed{U_W \text{ [MW]} = 6.336 \times 10^{-6} E^2 \text{ [GeV]} B_0^2 \text{ [kG]} L_u \text{ [m]} I \text{ [A]}}$$

$\varepsilon_{xW} \approx \frac{1}{4} \varepsilon_x$ ➡ $U_0 \approx 3U_W$ Bends; $E$ = 3 GeV, $\rho$ = 25 m
$U_0$ ~ 0.3 MW/A

➡ Wigglers; $E$ = 3 GeV, $B_0$ = 1.5 T, $L_u$ = 70 m
$U_0$ ~ 0.9 MW/A

It is possible !

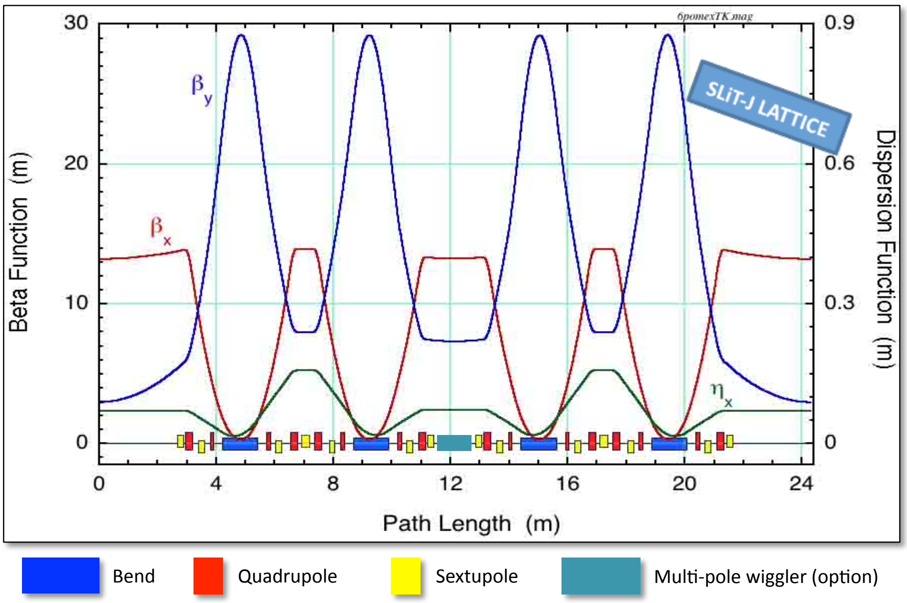
**SLiT-J's solution: Multi-bend lattice structure + high-field multi-pole wiggler (MPW)**

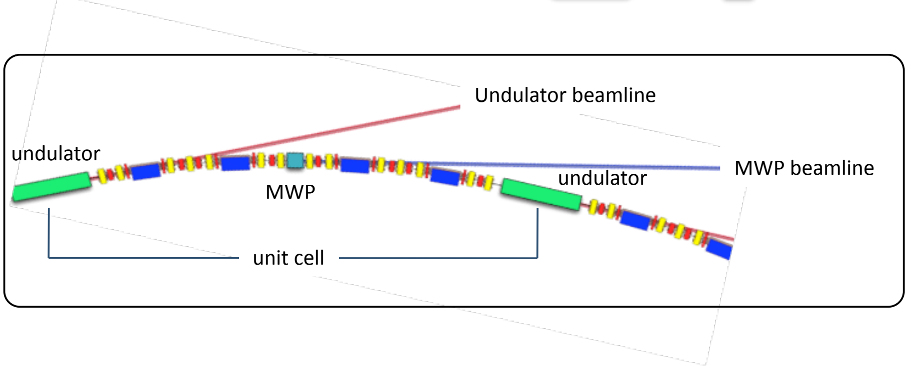
**•SLiT-J 's Targets**

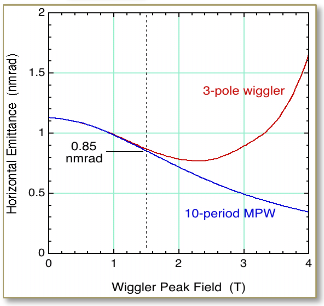
1. **$\varepsilon_{effective}$ ~ 1 nmrad or below for world class high brilliant light source**
2. **C ~ 300 – 400 m for compactness and low construction and operation costs**
3. **More then 10 straight sections for sufficient number of the beam-lines**

## 4-bend non-achromat lattice

| | |
|---|---|
| •beam energy | 2.998 GeV |
| •number of cells | 14 |
| •circumference | 340 m |
| •number of bends | 56 (combined)<br>B = 0.923455 T<br>K = 6.2 T/m |
| •number of quads | 224 (5-family) |
| •number of sexts | 196 (6-family) |
| •natural emittance | 1.13 nmrad |
| ( with MPW | 0.85 nmrad) |
| •straight section | 1.43 m × 14<br>5.33 m × 14 |







Additional damping effect by wiggler in short straight section

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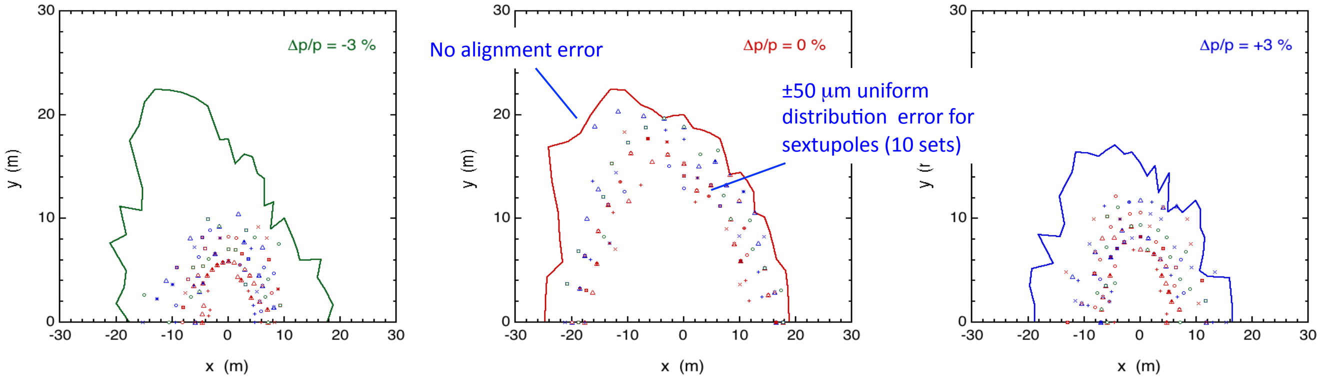
## Dynamic aperture optimized by "Genetic Algorism"

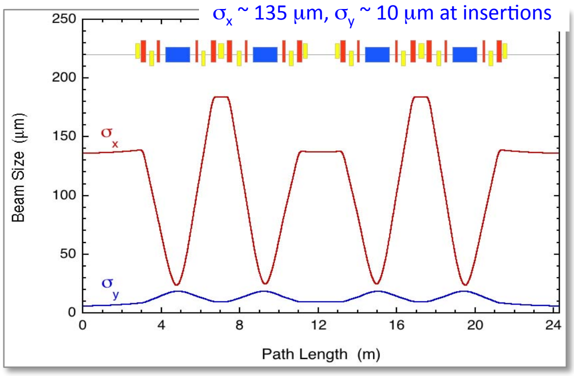


No alignment error

±50 μm uniform distribution error for sextupoles (10 sets)

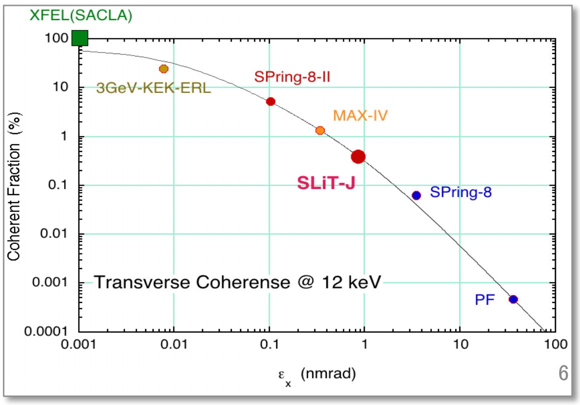
- **Sufficiently wider dynamic aperture with reasonable sextupole strengths.**

## Beam size in a cell



$\sigma_x$ ~ 135 μm, $\sigma_y$ ~ 10 μm at insertions

## Coherent fraction



STORAGE RING 2. Lattice

## Basic Parameters of SLiT-J Storage Ring

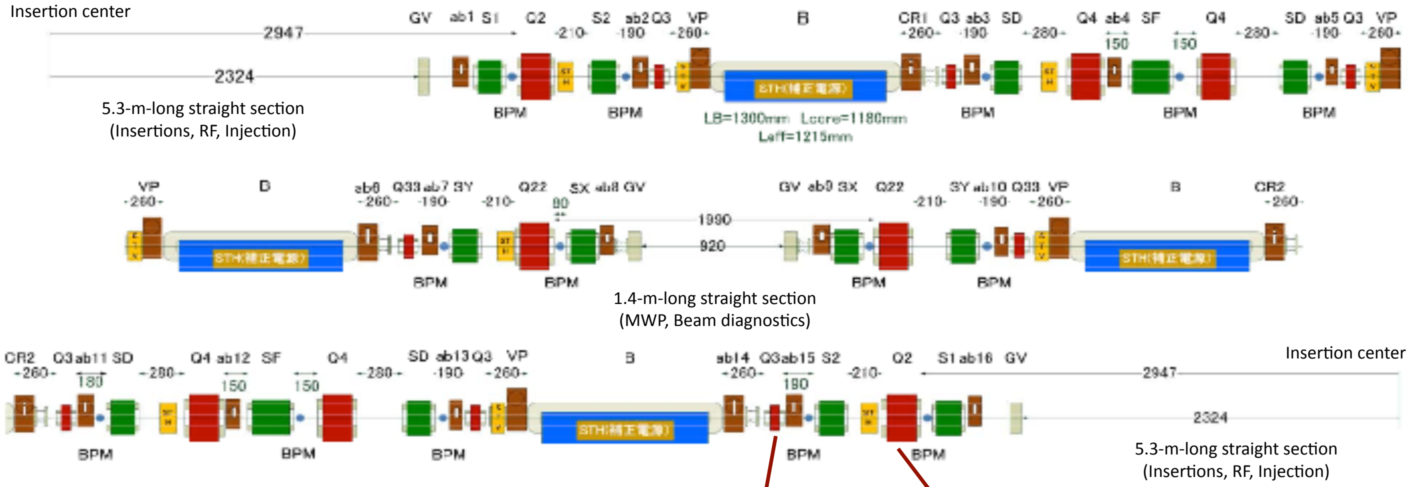
| | | *(14-cell lattice)* | *(16-cell option)* |
|---|---|---|---|
| Beam energy | $E$ | 2.998 GeV | 2.998 GeV |
| Lattice structure | | 4-bend cell | 4-bend cell |
| Circumference | $C$ | 339.92 m | 388.480m |
| Number of cells (bends) | $N_c$ | 14 (56) | 16 (64) |
| Long straight section | LSS | 5.33 m × 14 | 5.33 m × 14 |
| Short straight section | SSS | 1.43 m × 14 | 1.43 m × 14 |
| Betatron tune | $(\nu_x, \nu_y)$ | (25.85, 6.75) | (29.15, 7.25) |
| Natural chromaticity | $(\xi_x, \xi_y)$ | (-64.8, -44.7) | (-65.2, -47.5) |
| Natural horizontal emittance | $\varepsilon_x$ | 1.129 (0.85*) nmrad | 0.78 (0.55*) nmrad |
| Momentum compaction factor | $\alpha$ | 0.00047 | 0.00037 |
| Natural energy spread | $\sigma_E/E$ | 0.0858 % | 0.0805 % |
| Lattice functions at LSS | $(\beta_x, \beta_y, \eta_x)$ | (13.2, 2.96, 0.07) m | (11.9, 3.73, 0.06) m |
| Damping partition number | $(D, J_x, J_s)$ | (-0.341, 1.341, 1.659) | (-0.349, 1.349, 1.651) |
| Damping time | $(\text{v}_x, \tau_y, \tau_s)$ | (7.7, 10.3, 6.2) ms | (9.9, 13.4, 8.1) ms |
| Energy loss in bends | $U_0$ | 0.662 MeV/turn | 0.579 MeV/turn |
| RF frequency | $f_{RF}$ | 508 MHz | 508 MHz |
| RF voltage | $V_{RF}$ | 3 MV | 3 MV |
| Harmonic number | $h$ | 576 | 658 |
| Natural bunch length | $\sigma_B$ | 3.43 mm (11.1 ps) | 2.95 mm (9.85 ps) |

* with MPWs in all short straight section

STORAGE RING 3. Magnet

🟦 Bending magnet
🟥 Quadrupole magnet
🟩 Sextupole magnet
🟨 Steering magnet

## Magnet configuration (1 cell)



Insertion center

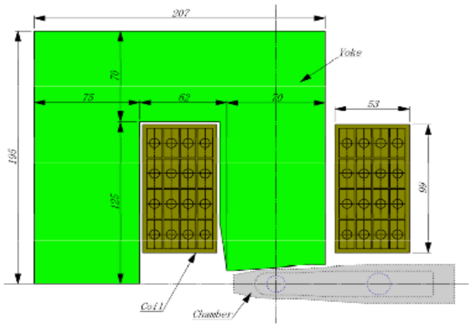
5.3-m-long straight section
(Insertions, RF, Injection)

1.4-m-long straight section
(MWP, Beam diagnostics)

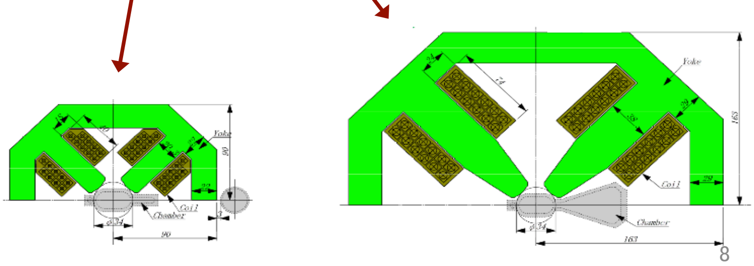
Insertion center

5.3-m-long straight section
(Insertions, RF, Injection)

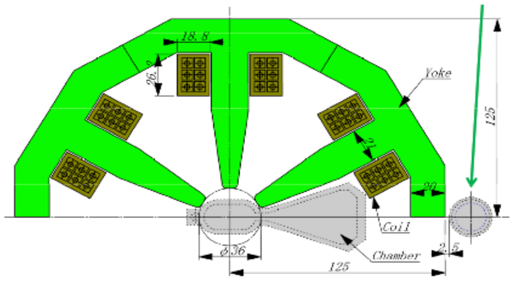
## Bending magnet



## Quadrupole magnet

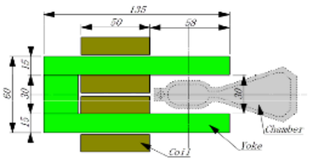


## Sextupole magnet

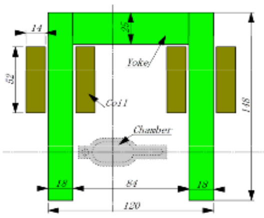


## Steering magnet

Horizontal



Vertical



## Power supply maximum rating

| | Name | Magnet (number) | $I_{max}$ (A) | Cable size sq, Length (m) | Total resistance (Ω) | Total voltage (V) | Power (kW) | Number of PS |
|---|---|---|---|---|---|---|---|---|
| Bend. | PS-B | B (56) | 583 | 250 × 2, 1620 | 0.44 + 0.06 = 0.50 | 292 | 170.2 | 1 |
| Quad. | PS-QA | QA (28) | 306 | 250, 1200 | 0.15 + 0.10 = 0.25 | 77 | 23.4 | 2 |
| | PS-QB | QB (56) | 306 | 250, 1620 | 0.30 + 0.13 = 0.43 | 132 | 40.3 | 1 |
| | PS-QC | QC (28) | 192 | 150, 1200 | 0.11 + 0.16 = 0.27 | 51.8 | 10.0 | 1 |
| | PS-QD | QD (84) | 115 | 150, 2040 | 0.62 + 0.27 = 0.89 | 102.4 | 11.8 | 1 |
| Sext. | PS-SXA | SXA (28) | 129 | 100, 1200 | 0.23 + 0.24 = 0.47 | 60.0 | 7.8 | 6 |
| | PS-SXB | SXB (28) | 129 | 100, 1200 | 0.33 + 0.24 = 0.57 | 73.5 | 9.5 | 1 |

Sum 0.28 MW

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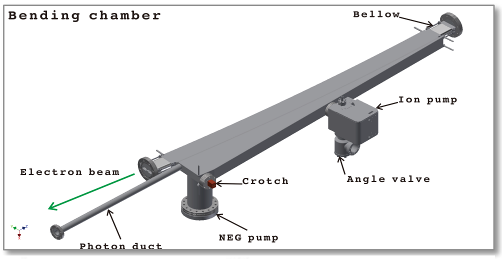
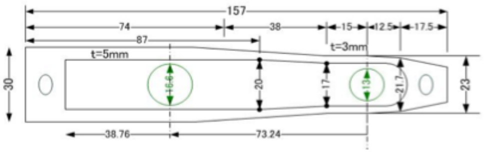
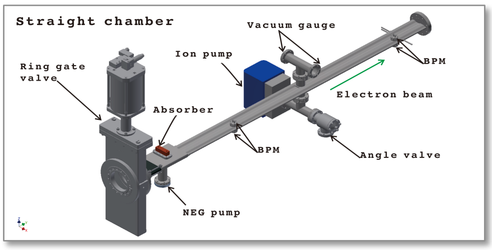
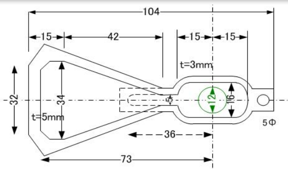
## Bending magnet section



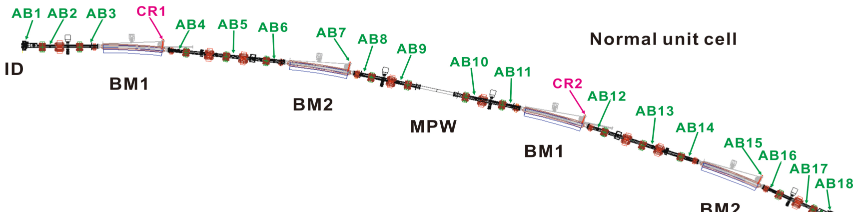


## Straight section





## Absorber and pumping speed in a cell

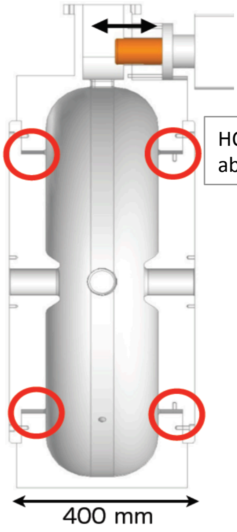


| Absorber | SR Power @ 400 mA (W) | PSD (Pa/Ls) | Required Pumping Speed* (L/s) |
|---|---|---|---|
| AB1 | 337 | 5.1E-6 | 51 |
| AB2 | 5 | 8.0E-8 | 1 |
| AB3 | 11 | 1.7E-7 | 2 |
| CR1 | 2619 | 4.0E-5 | 395 |
| AB4 | 1069 | 1.6E-5 | 161 |
| AB5 | 659 | 1.0E-5 | 100 |
| AB6 | 231 | 3.5E-6 | 35 |
| AB7 | 2755 | 4.2E-5 | 416 |
| AB8 | 956 | 1.4E-5 | 144 |
| AB9 | 748 | 1.1E-5 | 113 |
| AB10 | 287 | 4.3E-6 | 43 |
| AB11 | 44 | 6.6E-7 | 7 |
| CR2 | 2679 | 4.0E-5 | 405 |
| AB12 | 1067 | 1.6E-5 | 161 |
| AB13 | 661 | 1.0E-5 | 100 |
| AB14 | 231 | 3.5E-6 | 35 |
| AB15 | 2755 | 4.2E-5 | 416 |
| AB16 | 956 | 1.4E-5 | 144 |
| AB17 | 772 | 1.2E-5 | 117 |
| AB18 | 30 | 4.6E-7 | 5 |
| Total | 18873 | 2.850E-4 | 2850 |

* target pressure is 1e-7 Pa

## STORAGE RING 5. RF cavity

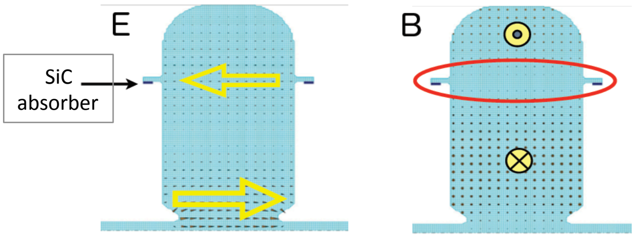
### TM020 cavity (under developing)



Coupling tuner
$\beta = 1 \sim 3$

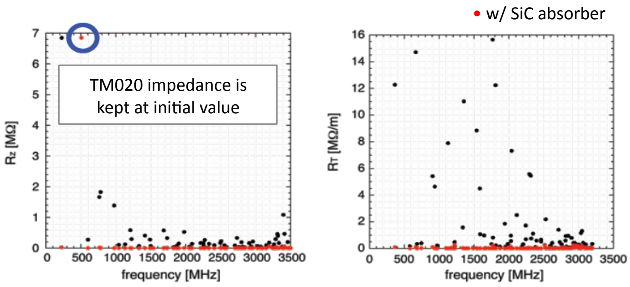
HOM•LOM
absorber SiC slot

| | Calculated (MAFIA) |
|---|---|
| f (MHz) | 508.58 |
| Mode | TM020 |
| $Q_0$ | 60300 |
| $R_z$ (MΩ) | 6.8 |
| $R_z/Q_0$ | 113 |
| $V_a$ (MV) | 0.75@83kW |

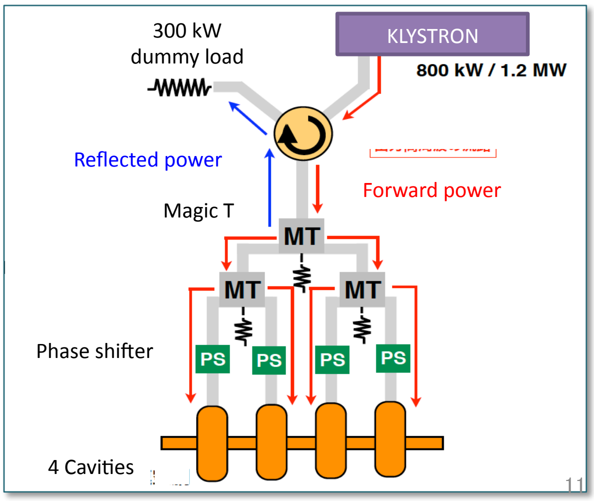


TM020 mode is not absorbed

### Parasitic modes impedance



### RF system



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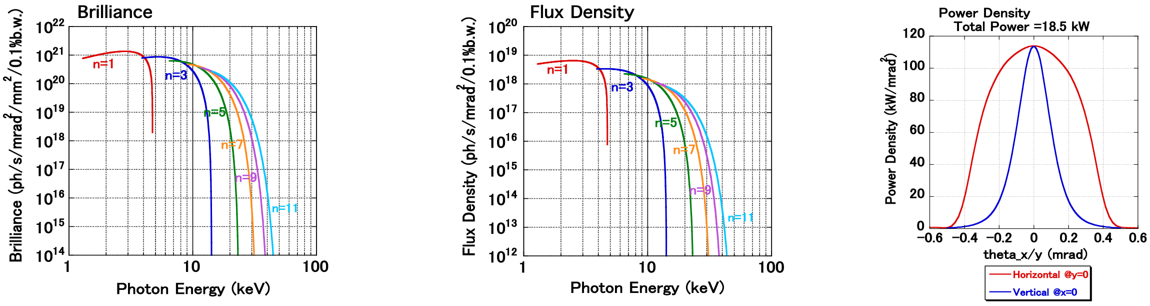
## STORAGE RING 6. Insertion devices

Lifetime due to residual gas scattering is more than 20 hours @ < 1× $10^{-7}$ Pa

### Hard X-ray

| | $\lambda_u$ (mm) | $N_u$ | $K_{max}$ | $gap_{min}$ (mm) | $\varepsilon_{photon}$ (keV) | Brilliance | Type, polarization |
|---|---|---|---|---|---|---|---|
| HXU | 18 | 241 | 2.3 | 3.1 | 1 - 20 | ~ $10^{21}$@several keV | In-vacuum, Linear |

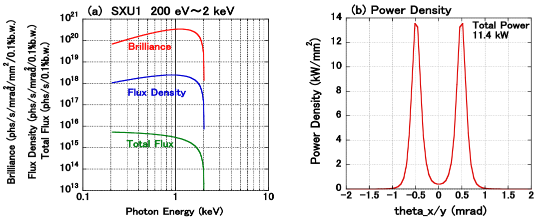


@$gap_{min}$

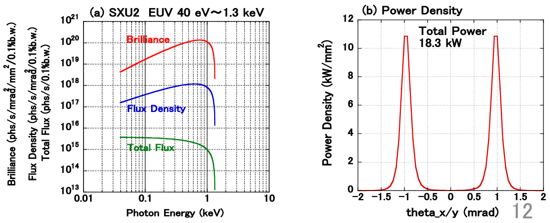
### Soft X-ray

| | $\lambda_u$ (mm) | $N_u$ | $K_{max}$ | $gap_{min}$ (mm) | $\varepsilon_{photon}$ (keV) | Brilliance | Type, polarization |
|---|---|---|---|---|---|---|---|
| SXU1 | 42 | 104 | 2.97 | 15 | 0.2 - 2 | ~ $10^{20}$@1keV | Helical |
| SXU2 | 64 | 68 | 5.74 | 18 | 0.04 – 1.3 | ~ $10^{20}$@1keV | Helical |

SXU1



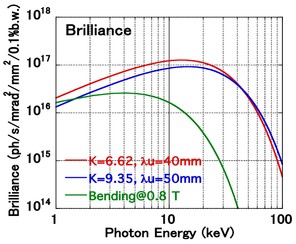
SXU2

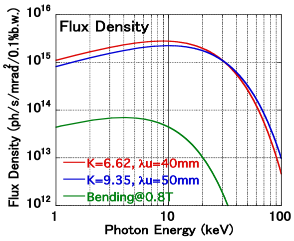


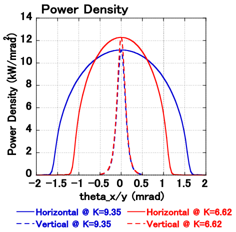
## STORAGE RING | 6. Insertion devices

### MPW for hard-X continuum

| | $\lambda_u$ (mm) | $N_u$ | $K_{max}$ | $gap_{min}$ (mm) | $\varepsilon_{photon}$ (keV) | Brilliance | Type, polarization |
|---|---|---|---|---|---|---|---|
| MPW | 40 | 20 | 6.62 | 4.8 | - 100 | ~ $10^{17}$@several 10s keV | In-vacuum, Linear |
| MPW* | 50 | 16 | 9.35 | 4.8 | - 100 | ~ $10^{17}$@several 10s keV | In-vacuum, Linear |
| MPW* | 80 | 10 | 11.205 | fixed 15 | - 100 | ~ $10^{16}$@several 10s keV | Damping W., Linear |



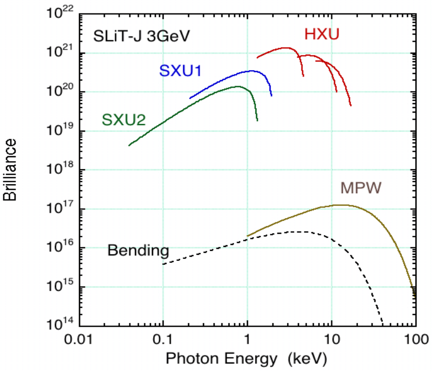


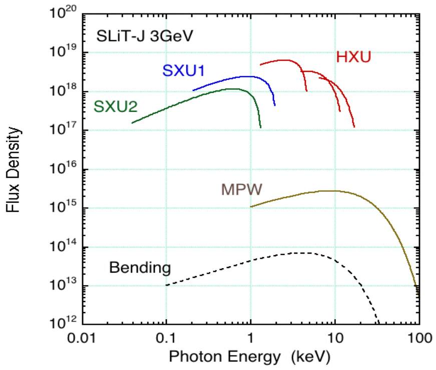


*not yet confirmed

### Summary

- Typical insertion devices are proposed. Details may change due to beamline applications.
- MPW will be used as substitute for bending magnet. Though damping effect to reduce the emittance is expected, MPW's parameter is not yet confirmed.





@400mA

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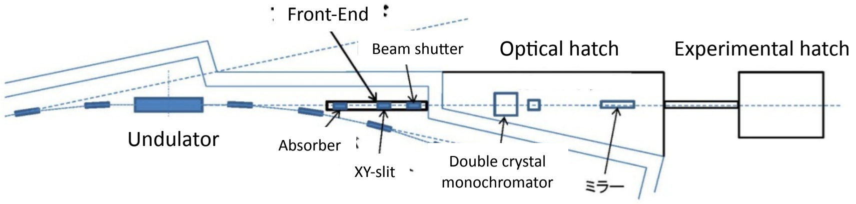
## BEAMLINE

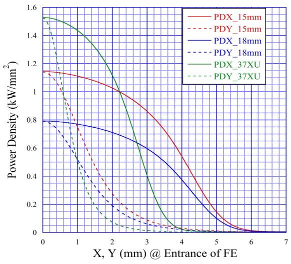


### Front-End

- Expected maximum heat load is 10 kW/m.
  ex. in SPring-8: Power density of short period undulator ~ 800 kW/mrad²

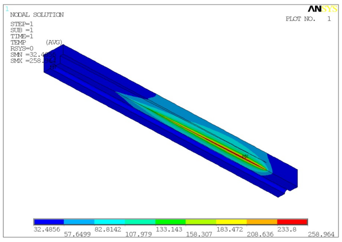
**Virtual undulator**
$\lambda_u$: 15 mm
$N_u$: 290
$K_{max}$: 2.3

Total power: 26.7 kW
Power density: 164.3 kW/mrad²



**Absorber analysis**
Model: SP8 standard
Location: 10 m from source
Irradiated power: 26.4 kW
=>
Light receiving surface: 259 °C
Cooling surface: 89.6 °C
=>
SP8 standard absorber can receive radiation power of SLiT-J insertions

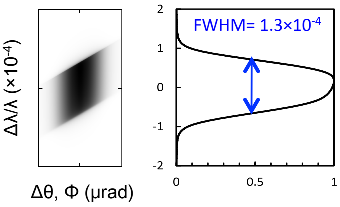
Temperature distribution

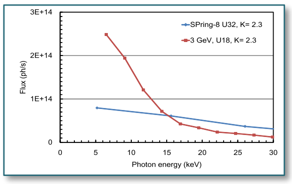


### Double-crystal monochromator

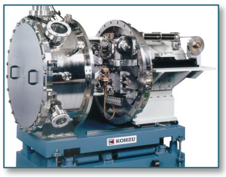
**Si111 crystal**
$h\nu$: 3 – 30 keV
$\theta_B$: 4 – 45 °
=>
Band width (energy resolution)
$\Delta E/E$ ~ $1.3\times10^{-4}$

DuMond plot

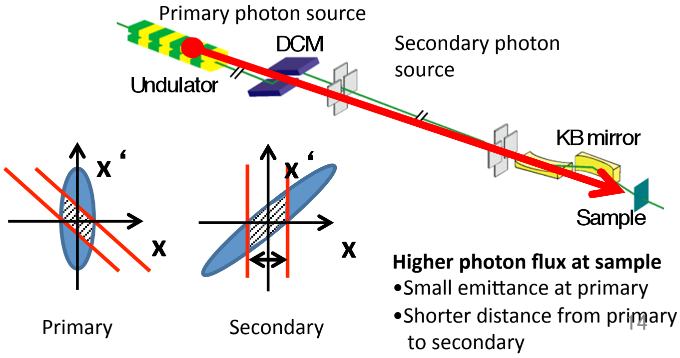




After Si111 monochromator



### Condenser mirror



**Higher photon flux at sample**
- Small emittance at primary
- Shorter distance from primary to secondary

## INJECTOR

### Strategy

- Injector's beam should be very low emittance for efficient injection to the ring.
- Achievement of XFEL machine, "**SACLA**", allows us to construct a compact **full-energy injector linac**.
  (c-band technology, high brilliant thermionic gun . . .)
- **Soft-XFEL** will be considered to be a next step of SLiT-J as the advanced light source facility.

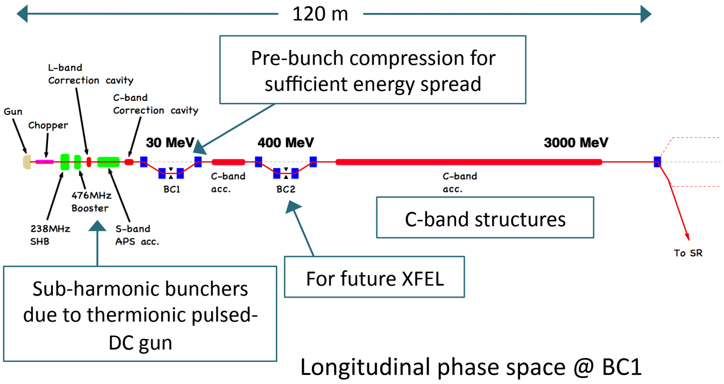
### Target of injector linac

| | | |
|---|---|---|
| Beam energy | $E$ | 3 GeV |
| Energy spread | $\Delta E/E$ | < 0.1 % (rms) |
| Energy stability | $\delta E$ | < 0.1 % (rms) |
| Bunch charge | $Q$ | ~ 1 nC (max.) |
| Charge stability | $\delta Q$ | ~ 1 % |
| Transverse emittance | $\varepsilon$ | < 5 mm.mrad* (normlized) |
| Bunch length | $\sigma_\tau$ | < 5 ps |
| Repetition rate | $f_{rep}$ | 25 Hz (max.) |

* 1 mm.mrad required for FEL

- Expected power consumption:
  0.2 MW@1Hz, 1 MW@25H

### Layout



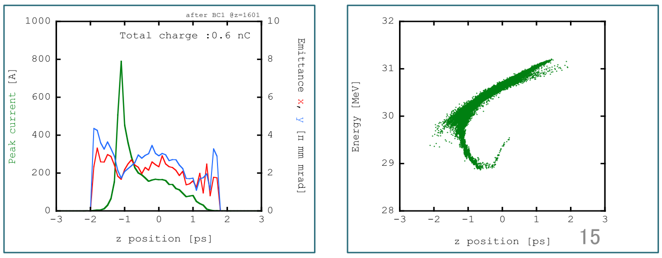
Pre-bunch compression for sufficient energy spread

C-band structures

For future XFEL

Sub-harmonic bunchers due to thermionic pulsed-DC gun

Longitudinal phase space @ BC1



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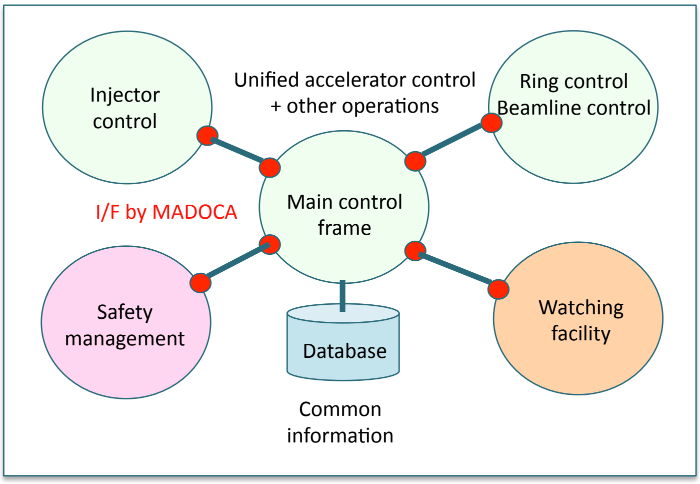
## CONTROL and NETWORK

### Mission

- Rapid construction of the system.
- Stable support for machine commissioning and tuning.
- Saving energy in operation.
- Reliable framework "MADOCA II" will be employed.

### Integrated control system



Injector control

Unified accelerator control + other operations

Ring control
Beamline control

I/F by MADOCA

Main control frame

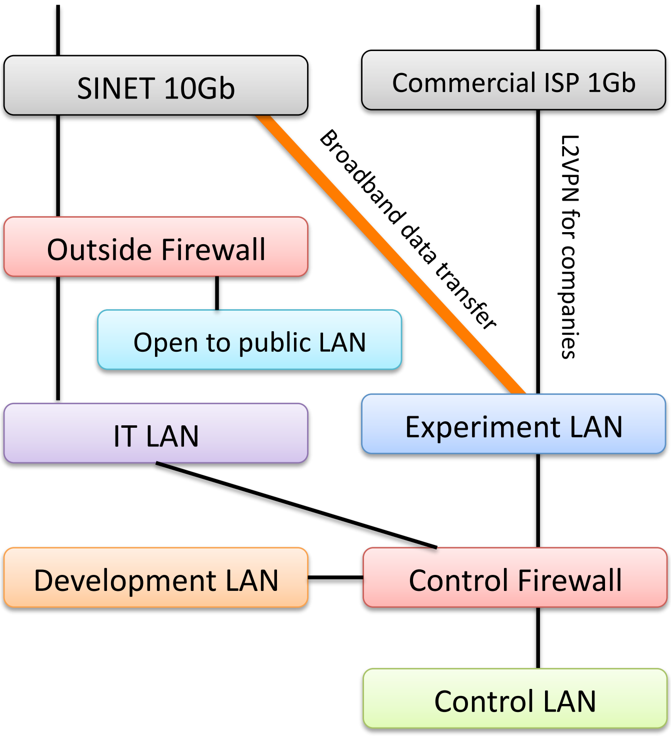
Safety management

Database

Watching facility

Common information

### Network structure



SINET 10Gb

Commercial ISP 1Gb

Broadband data transfer

L2VPN for companies

Outside Firewall

Open to public LAN

IT LAN

Experiment LAN

Development LAN

Control Firewall

Control LAN