An intense terahertz radiation source at the Compact ERL

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Intense terahertz radiation source at the Compact ERL

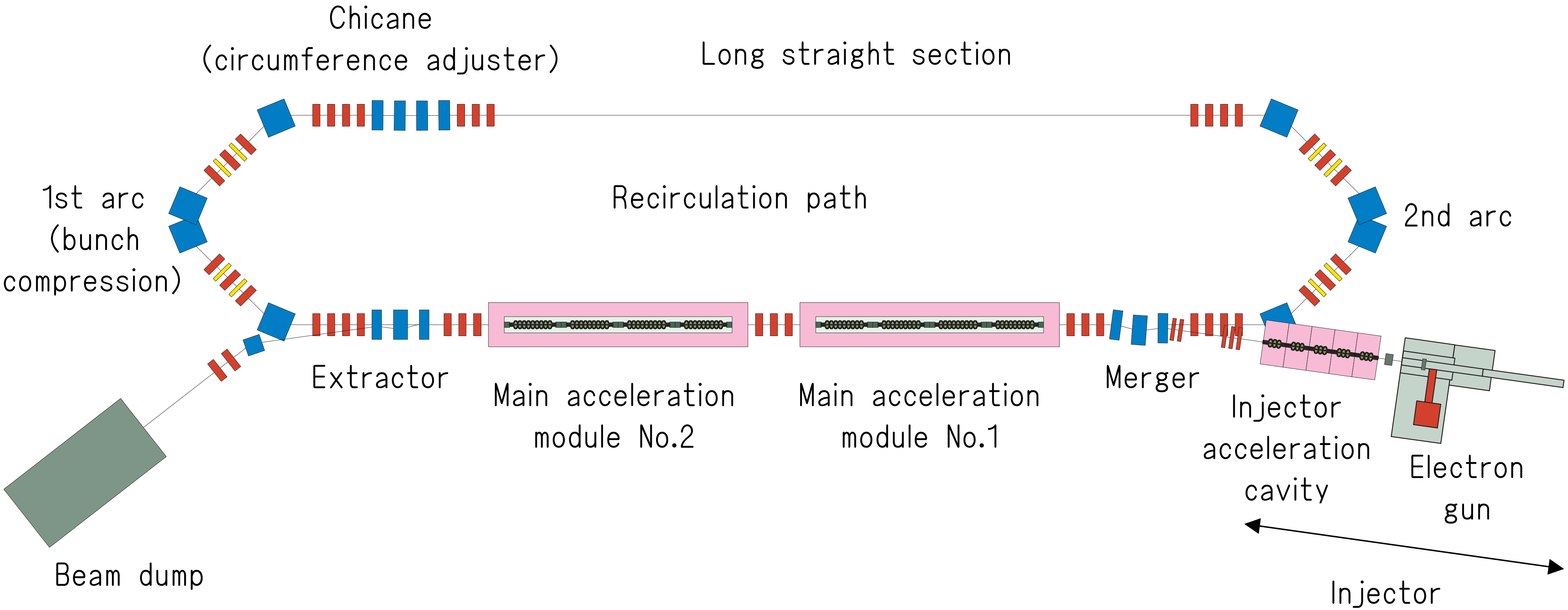
- Beam energy 65MeV, Beam current 77pC x 1.3GHz = 100mA
- Bunch length >0.1ps (～59fs r.m.s.)
- Bending curvature radius 1m
- Vertical aperture of vacuum duct ～5cm

- Terahertz radiation:
  ～0.16meV (cut-off of vacuum duct) < photons available < ～10meV (critical energy)
  including 4meV (1THz)
- Flux density is about 10^{16}～10^{18} [photons/s/mrad^2/0.1%b.w.]

- Integrated energy: a few μJ/pulse
  for the horizontal photon acceptance over 100mrad
- Peak electric field reaches the order of MV/cm
  for the focused spot size of 100μm x 100μm.

- Overview of ERL
- Review of CSR formulae
- Bunch compression
- Expected CSR spectrum calculation

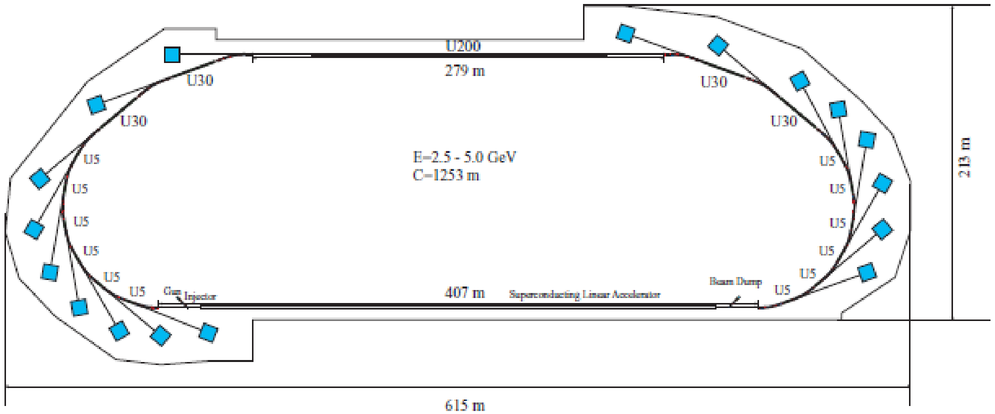
Lattice of the Compact ERL (ERL test facility)



Why ERL?

- The beam quality is determined by the equilibrium of the radiation excitation and damping at the synchrotron.
- The bigger the ring, the smaller the emittance. In order to achieve diffraction limit at the hard X-ray region, the circumference of the ring become huge. (10pmrad ～ 10keV)
- It is difficult to achieve the short bunch length at the synchrotron. (The large bunch charge is especially very hard.)
- The photocathode DC electron gun can make electron beam with ultra-small transverse (normalized) emittance and ultra-short bunch length. The beam passes the recirculation path only once and free from the radiation equilibrium.
- The beam power is huge (for example, 100mA x 5GeV = 500MW), and the energy recovery is inevitable for the RF system and the beam dump.

5-GeV ERL for the Future Light Source in Japan



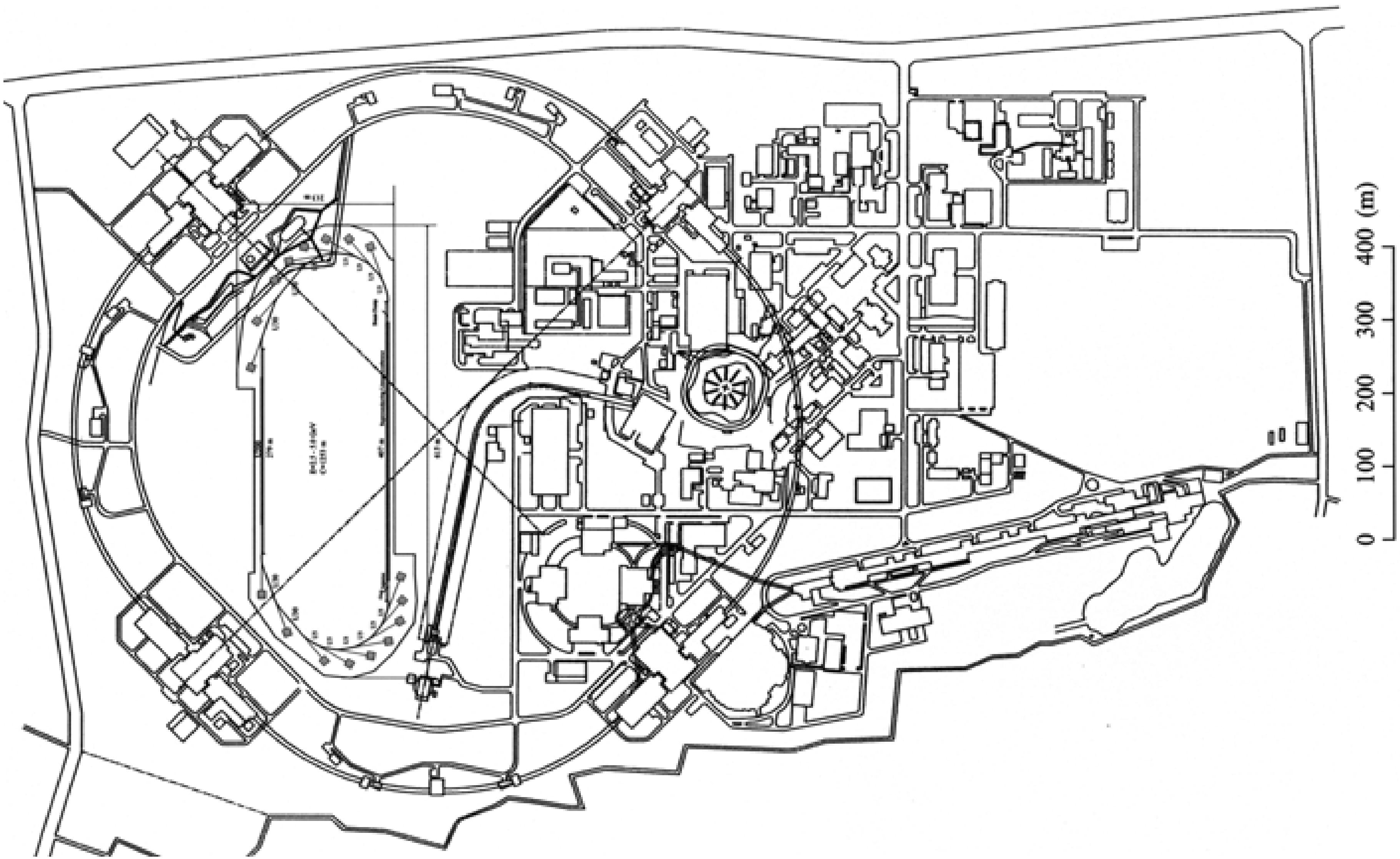
Machine parameters

Beam energy	5 GeV
Averaged beam current	100 mA
Circumference	1253 m
Normalized emittance ε_n	1 - 0.1 mm·mrad
Beam emittance at 5 GeV	100 - 10 pm·rad
Energy spread (r.m.s.)	4×10^{-5}
Bunch length (r.m.s.)	1 - 0.1 ps
RF frequency	1.3 GHz
Accelerating gradient	10 – 20 MV/m

Light source parameters

Spectrum range	30 eV – 30 keV
Brilliance from ID's (for 0.1 nm)	$10^{21} – 10^{23}$ ph/s/0.1%/mm^2/mrad^2
Averaged flux	> 10^{16} ph/s/0.1%
Bunch length (rms) (short pulse mode)	< 100 fs
Number of insertion devices	20 – 30

Plan of the 5-GeV ERL at KEK Tsukuba Campus



What’s difficult? -R&D plan-

Development of key components

- DC photocathode gun (ultra low emittance, large charge, long lifetime…)
- 1.3 GHz CW laser (high power, very stable, not too expensive…)
- Superconducting cavities & cryostats
  (HOM dumped, high power for injector…)

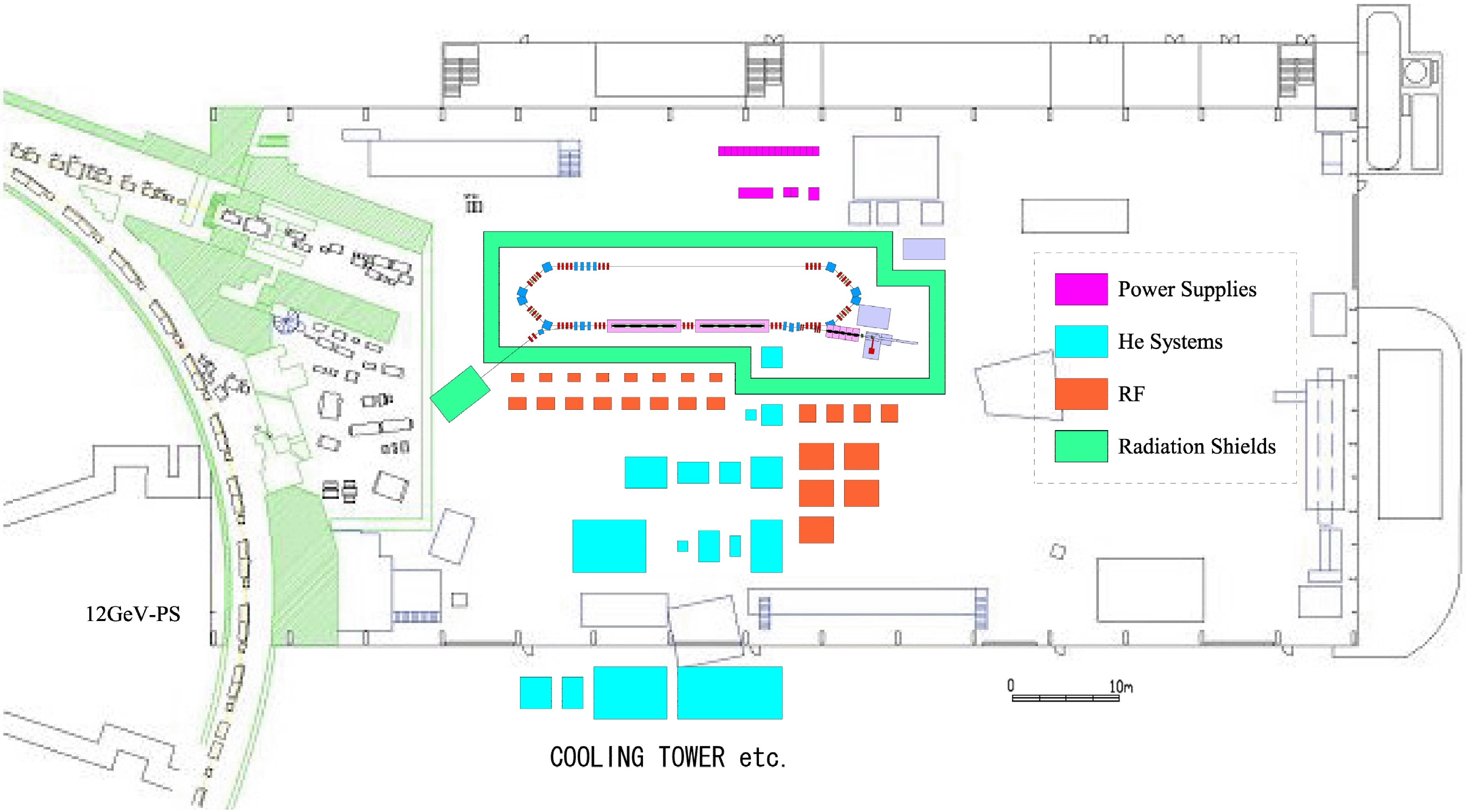
Construction of ERL test facility

- Testing critical components under beams
- Proof of predictions on accelerator physics issues
  - Space charge effects (especially for low energy)
  - CSR effects (impacts on emittance, energy spread, and bunch length)
  - Instabilities (ion trapping, RW-BBU, HOM-BBU)
  - Beam loss mechanism, *etc.*

Testing SC cavities for main linac, studying the instabilities, CSR, optimizing bunch compression. ⇒ Test facility with a return loop

Planned Compact ERL (ERL test facility)

In the East Counter Hall at KEK. Approved to use the building.



Tentative parameters

		Initial goal	Final goal
Circumference of recirculation path	m	69	
Lattice of recirculation path		TBA 2 cells	
Injection beam energy	MeV	5	10～15
Injection (=dumped) beam power	kW	500	1000～
Beam energy after acceleration	MeV	65	160～200
Number of Main acceleration module (1 module = 9cell cavity x 4)	modules	1	2
Normalized transverse emittance (r.m.s.)	mm·mrad	1	0.1
Beam current	mA	10	100
Bunch length (r.m.s.)	ps	1～2	～0.1
Insertion devices		no	1

Feasibility for the limited user operation

Main difference between test ERL and 5GeV ERL

• Beam energy	:	60MeV vs. 5GeV	
• Circumference	:	70m vs. 1.2km	
• Bunch length	:	1ps ～ >0.1ps	no difference!
• Normalized emittance	:	1mm·mrad	no difference!
• Averaged current	:	10mA～100mA	no difference!

Candidates for the user operation: **terahertz CSR and Inverse Compton Scattering**

CSR

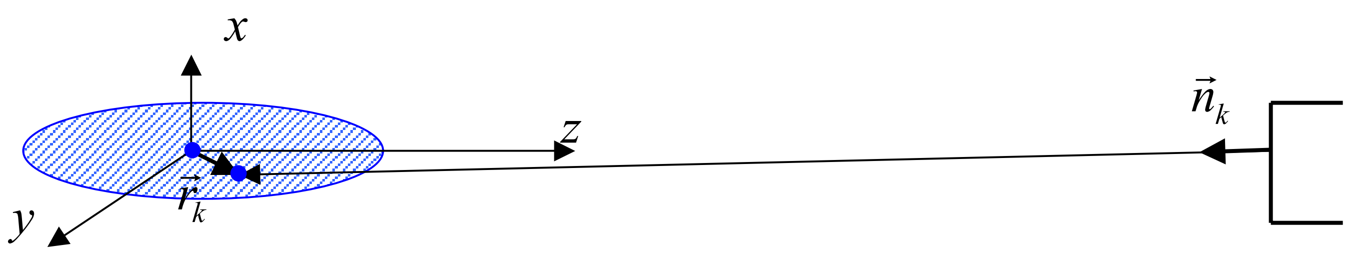
- For terahertz CSR, the bunch length is essential.
- The beam energy of 60MeV is sufficient without unnecessary higher energy photons.
- It is suitable for the test ERL to use intense terahertz radiation source.

Inverse Compton Scattering

- For 800nm laser with 60MeV electron beam, 90° inverse Compton scattering can generate short pulsed hard X-ray of the energy 42keV.
- For 5GeV ERL, however, the radiation from the undulator is short pulsed. The number of the photons is extremely large.

Review of CSR formulae

Formulation for the CSR



$\vec{E}(\lambda)$ is the electric field from the reference particle at the origin observed at the detector. The electric field from k-th particle can be written as

$$\vec{E}_k(\lambda) = \vec{E}(\lambda) e^{\frac{2\pi i}{\lambda} \vec{n}_k \cdot \vec{r}_k},$$

here $\vec{n}_k$ is the unit vector from detector to the particle, $\vec{r}_k$ the position of k-th particle in the bunch. The total field strength from N particles can be written as

$$\vec{E}_{total}(\lambda) = \vec{E}(\lambda) \sum_{k=1}^{N} e^{\frac{2\pi i}{\lambda} \vec{n}_k \cdot \vec{r}_k} \text{、} \quad P_{total}(\lambda) \propto \left| \vec{E}(\lambda) \right|^2 \left| \sum_{k=1}^{N} e^{\frac{2\pi i}{\lambda} \vec{n}_k \cdot \vec{r}_k} \right|^2$$

$$\left|\sum_{k=1}^{N} e^{\frac{2\pi i}{\lambda}\vec{n}_k\cdot\vec{r}_k}\right|^2 = \left|\sum_{j=1}^{N} e^{\frac{2\pi i}{\lambda}\vec{n}_j\cdot\vec{r}_j}\sum_{k=1}^{N} e^{\frac{2\pi i}{\lambda}\vec{n}_k\cdot\vec{r}_k}\right| = \left|N + \sum_{j\neq k}^{N} e^{\frac{2\pi i}{\lambda}\left(\vec{n}_k\cdot\vec{r}_k - \vec{n}_j\cdot\vec{r}_j\right)}\right|$$

Using the normalized distribution function of the particles of $\int S(r)dr = 1$, the number of the particles between r and $r+\Delta r$ is $NS(r)\Delta r$ (with zero transverse emittance and symmetrical distribution of $S(-r) = S(r)$).

$$\sum_{j\neq k}^{N} e^{\frac{2\pi i}{\lambda}\left(\vec{n}_k\cdot\vec{r}_k - \vec{n}_j\cdot\vec{r}_j\right)} = N(N-1)\int dr\int dr' e^{\frac{2\pi i}{\lambda}\vec{n}\cdot(\vec{r}-\vec{r}\,')} S(r)S(r') \approx N(N-1)\left|\int dr e^{\frac{2\pi i}{\lambda}z} S(z)\right|^2 .$$

Thus

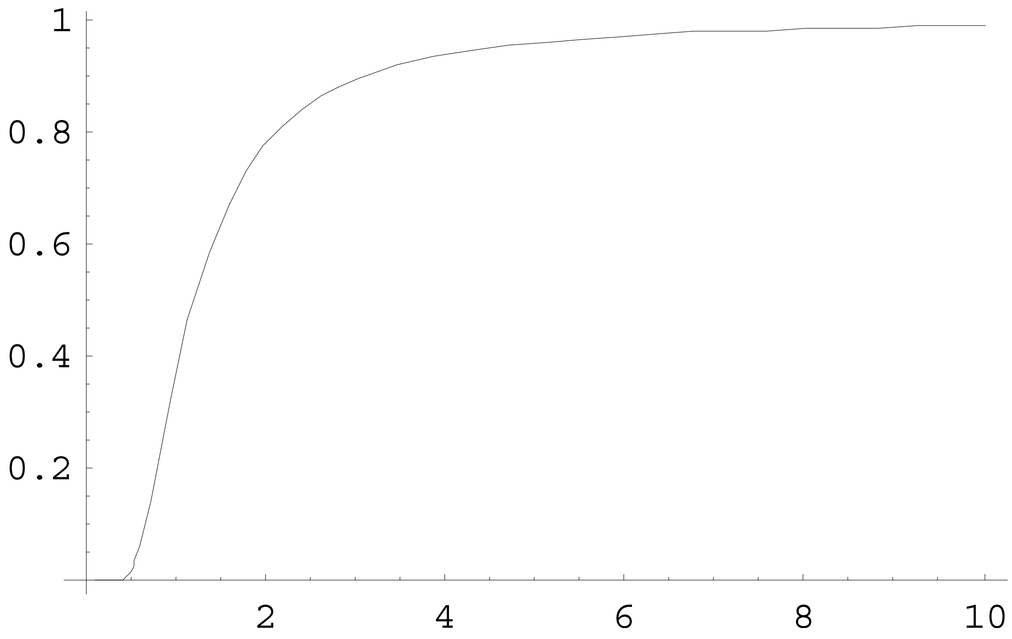
$$P_{total}(\lambda) = P_{incoh}(\lambda)\left(1+(N-1)f(\lambda)\right).$$

Here, $f(\lambda) = \left|\int dz e^{\frac{2\pi i}{\lambda}z} S(z)\right|^2$.

For the “Gaussian” distribution, $S(z) = \frac{1}{\sqrt{\pi}\sigma_z} e^{-\left(\frac{z}{\sigma_z}\right)^2}$ 、 $f(\lambda) = e^{-\left(\frac{\pi\sigma_z}{\lambda}\right)^2}$.

Reference : E.B.Blum,"Observation of coherent synchrotron radiation at the Cornell linac", NIM A307, (1991), pp568-576

$$f(x) = e^{-\left(\frac{1}{x}\right)^2}$$



0.37 for $x = 1$, and 0.99 for $x = 10$

For the bunch charge of 77pC, the number of the particles is 4.8×10^8 個. Thus if $\lambda = 2\pi\sigma_z$, the photon flux is increased by 10^8 times. ($\lambda = 2\sigma_z$ is used as a critical wavelength.)

Critical energy and critical angular divergence

Angular flux density of the synchrotron radiation can be written as

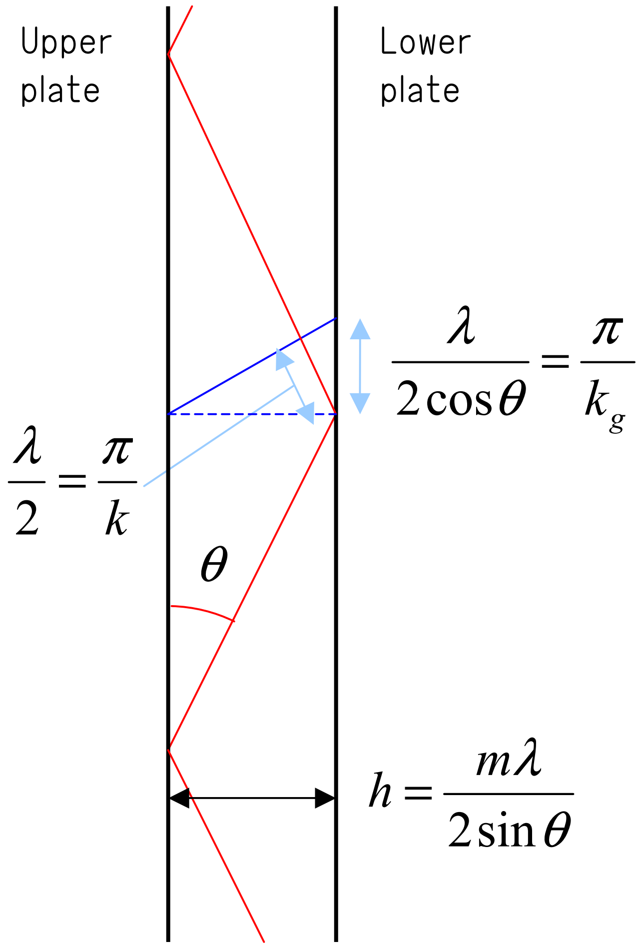
$$\frac{d^2P_{incoh}}{d\omega d\Omega}=\frac{3e^2\gamma^2}{16\pi^3\varepsilon_0 c}\left(\frac{\omega}{\omega_c}\right)^2\left(1+\gamma^2\theta^2\right)\left(BesselK_{\frac{2}{3}}(\xi)^2+\frac{\gamma^2\theta^2}{1+\gamma^2\theta^2}BesselK_{\frac{1}{3}}(\xi)^2\right).$$

Here, $\omega_c=\frac{3c\gamma^3}{2\rho}$, $\xi=\frac{\omega}{2\omega_c}\left(1+\gamma^2\theta^2\right)^{\frac{3}{2}}$, γ is the Lorentz factor, θ the observation angle, ε_0 the permittivity of vacuum, e the charge of an electron, and c the light speed.

From the argument of ξ, the critical frequency ω_c and critical angular divergence θ_c is calculated. ω_c is the frequency for $\xi=\frac{1}{2}$ on axis. θ_c is the divergence angle for $\xi\approx 1$ with the case with $\omega<<\omega_c$ and $\theta_c=\frac{1}{\gamma}\left(\frac{2\omega_c}{\omega}\right)^{\frac{1}{3}}=\left(\frac{3c}{\omega\rho}\right)^{\frac{1}{3}}$. (Usually, with $\omega>>\omega_c$, the divergence angle when the flux become $\frac{1}{e}$ is the critical angle, $\theta_c=\frac{1}{\gamma}\sqrt{\frac{2\omega_c}{3\omega}}$.)

Reference : J.D.Jackson “Classical Electrodynamics”

Shielding effect



TE wave is transmitting between two perfectly conducting parallel plate. The boundary condition is that the incident and reflected wave compensate the electric field on the surface.

When the mode number and gap of the plate are fixed, the incident angle is determined by the wavelength to satisfy the boundary condition. The shorter the wavelength, the larger the incident angle. When the incident wave perpendicular to the plate, the wave cannot transmit. The usual cut-off wavelength is $\lambda_c = 2h$ for the incident angle of 90 degree.

For the synchrotron radiation, the divergence angle is limited by the critical angle. Thus instead of 90 degree, we use critical angle for the calculation of the cut-off wave length.

$$\lambda_c = 2h\sin\theta_c \sim 2h\theta_c = 2\sqrt{\frac{3h^3}{\pi\rho}} \sim 2\sqrt{\frac{h^3}{\rho}}.$$

Reference : S.Heifets, A.Michailichenko, "On the Impedance Due to Synchrotron Radiation", Proc. of PAC 1991, p458

Parameters

- Intensity

$$P_{total}(\lambda) = P_{incoh}(\lambda)\left(1 + (N-1) f(\lambda)\right)、\quad f(\lambda) = e^{-\left(\frac{2\pi\sigma_z}{\lambda}\right)^2}$$

- Critical angular frequency of the photon

$$\omega_c = \frac{3c\gamma^3}{2\rho}$$

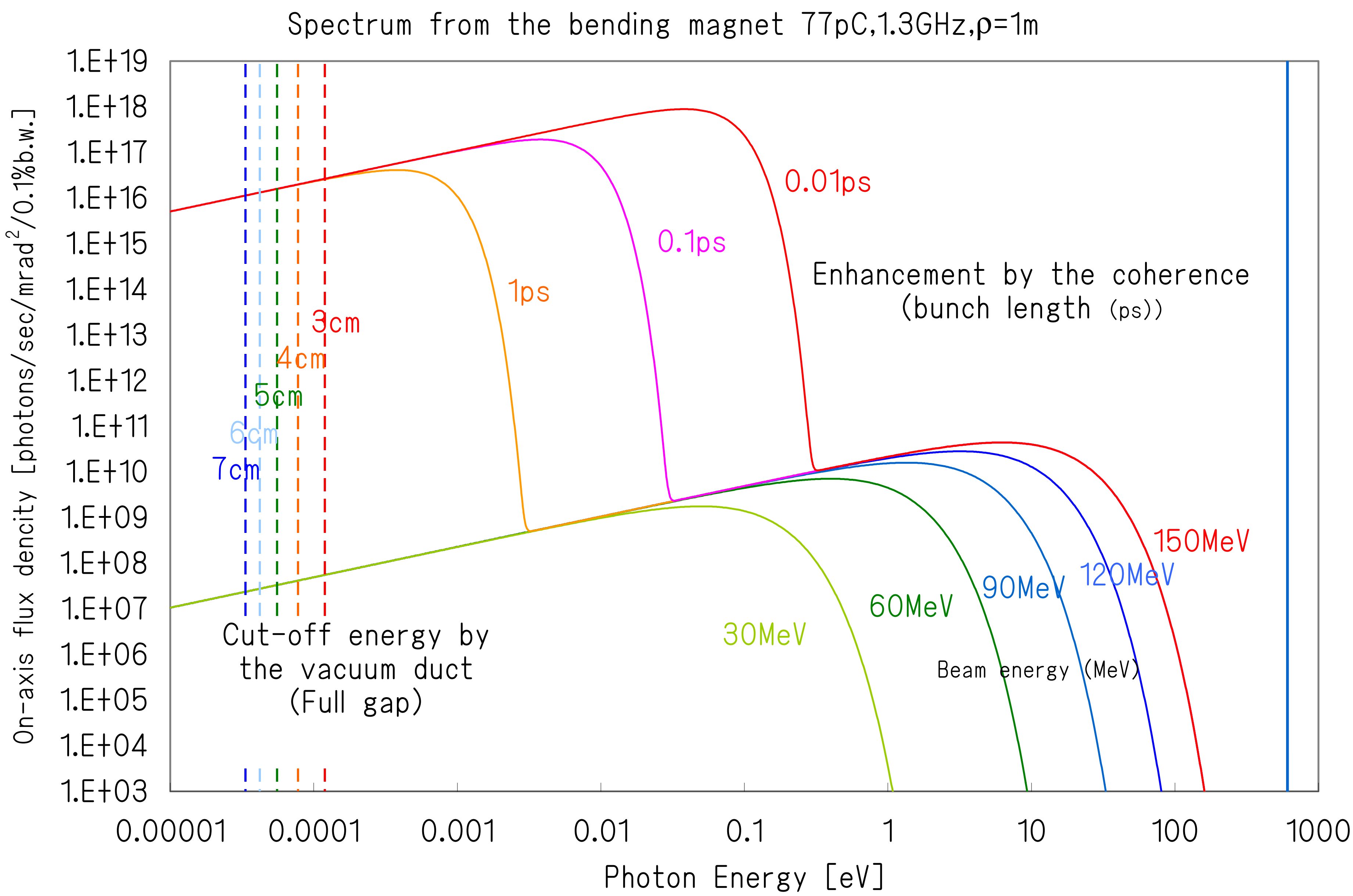
- Critical angular frequency for CSR

$$\omega_{c-csr} = \frac{\pi c}{\sigma_z} \qquad \left(\lambda_{c-csr} = 2\sigma_z\right)$$

- Shielded angular frequency for CSR

$$\omega_{cut-off} = \pi c \sqrt{\frac{\rho}{h^3}} \qquad \left(\lambda_{cut-off} = 2\sqrt{\frac{h^3}{\rho}}\right)$$

- Thus CSR is generated between $\omega_{cut-off} < \omega < \omega_{c-csr} (< \omega_c)$.


Spectrum from the bending magnet 77pC,1.3GHz,ρ=1m
On-axis flux dencity [photons/sec/mrad2/0.1%b.w.]
1.E+19
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
1.E+12
1.E+11
1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
Photon Energy [eV]
0.01ps
0.1ps
1ps
Enhancement by the coherence
(bunch length (ps))
3cm
4cm
5cm
6cm
7cm
Cut-off energy by
the vacuum duct
(Full gap)
150MeV
120MeV
90MeV
60MeV
30MeV
Beam energy (MeV)

Angular divergence and polarization

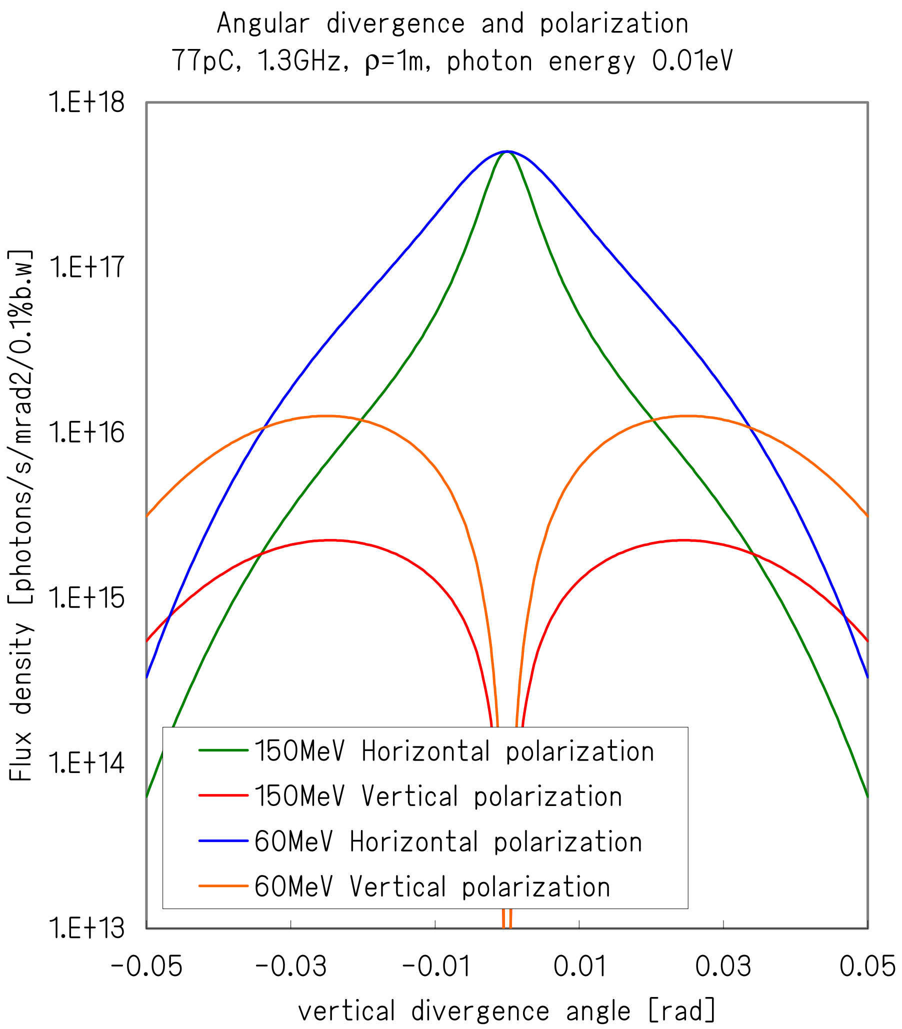
$$\frac{d^2 P_{incoh}}{d\omega d\Omega} = \frac{3e^2\gamma^2}{16\pi^3\varepsilon_0 c}\left(\frac{\omega}{\omega_c}\right)^2 \left(1+\gamma^2\theta^2\right)\left(BesselK_{\frac{2}{3}}(\xi)^2 + \frac{\gamma^2\theta^2}{1+\gamma^2\theta^2} BesselK_{\frac{1}{3}}(\xi)^2\right)$$

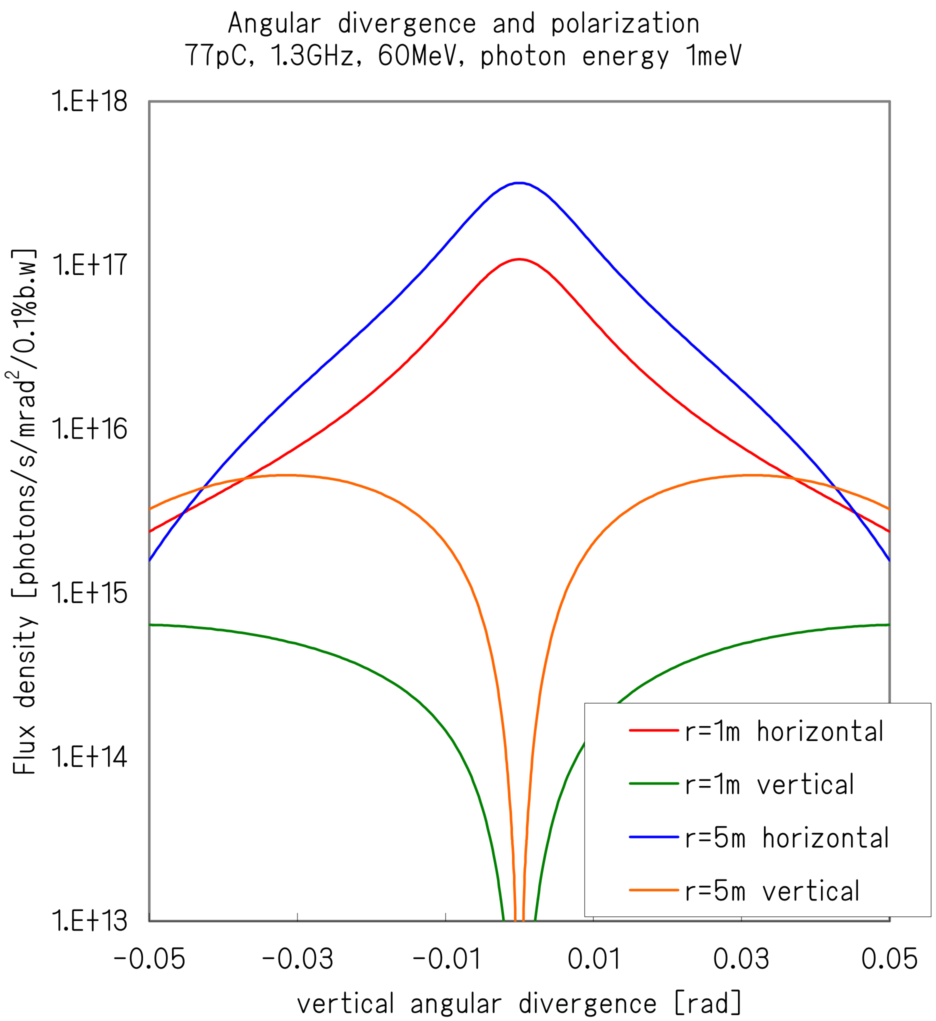
Horizontally polarized

Vertically polarized

- Terahertz radiation has large angular divergence due to the low energy.
- Of-axis vertically polarizing photons has some intensity and available for the users.

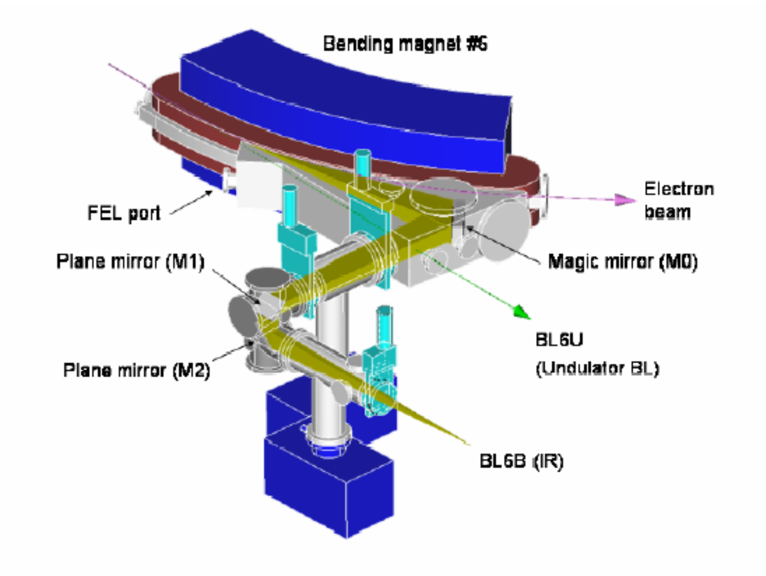
Vertical angular divergence and polarity of the photons

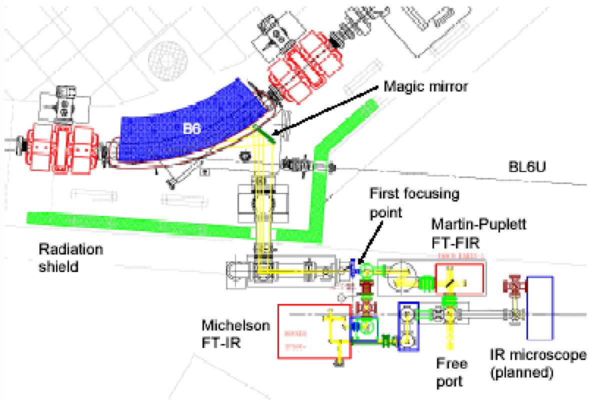


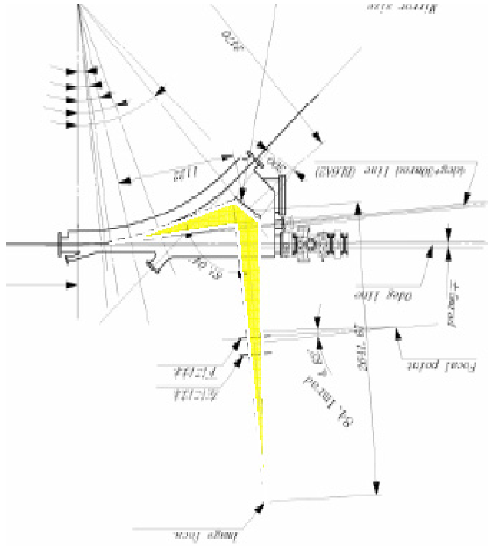


Acceptance of the photons

- Because the terahertz radiation has small γ, the aperture angle of the beam line is important in order to capture the large number of the photons.
- At the BL6B of the UVSOR, the first mirror is fixed in the vacuum duct of the bending magnet.
- The effect of the wake field may be severe.







Reference: UVSOR BL6B Introduction pdf(left), IMS meeting ”赤外放射光の現状と将来計画”, S.Kimura(right)

Bunch compression

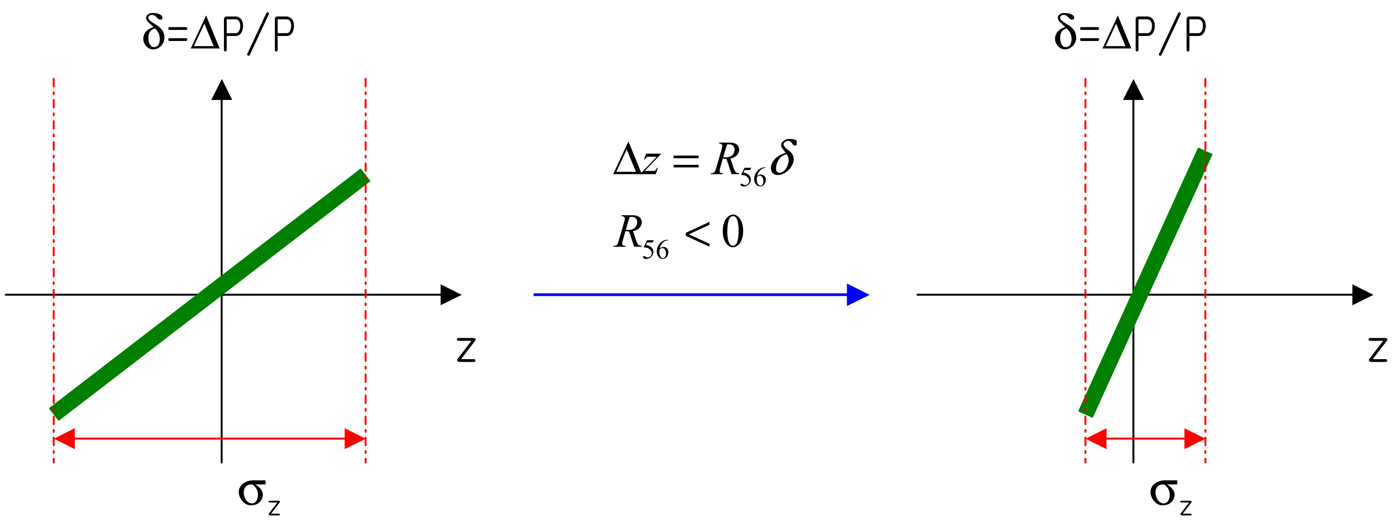
Bunch compression

- Even if the ultra-short bunch could be generated at the electron gun, the bunch length is rapidly lengthened because of the velocity spread, space charge, and CSR effect.
- The higher the beam energy, the weaker the bunch lengthening effect.
- In order to make the bunch length smaller than about 1ps, the bunch compression after the acceleration is inevitable.

- For the bunch compression, we use the RF curvature effect.
- The momentum deviation $\delta = \Delta P/P$ makes the difference of the orbit length as

$$\Delta z = R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 .$$

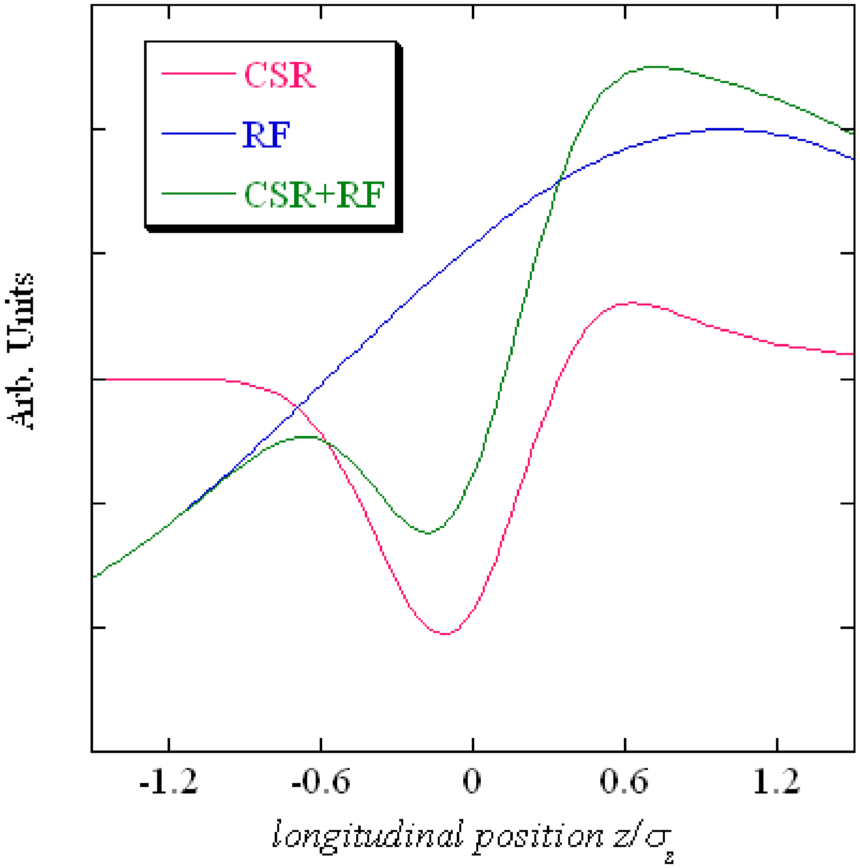
- Off-crest acceleration at the main linac generate the energy correlation in the bunch.

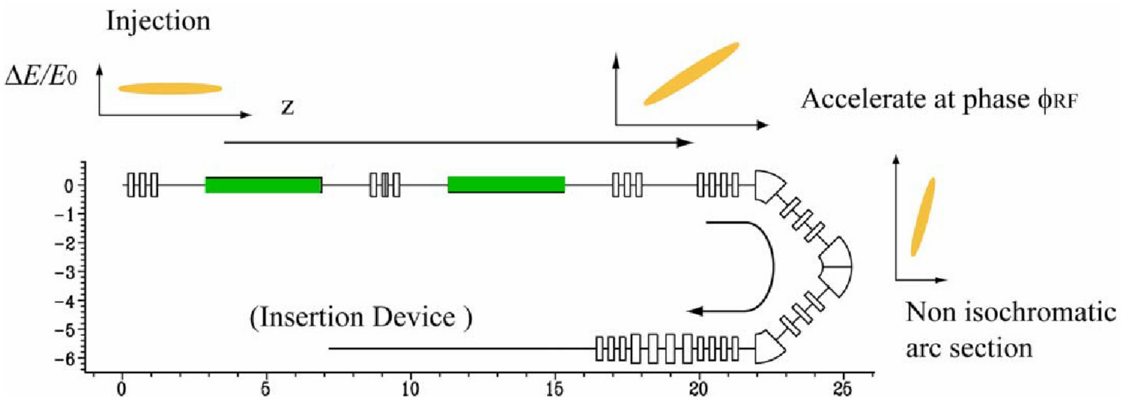


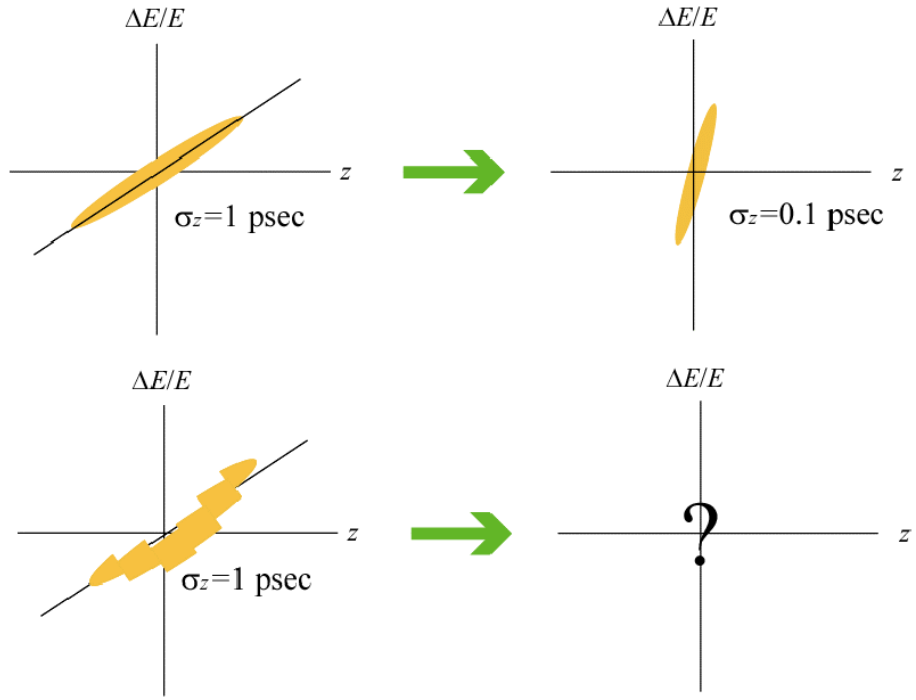
Emittance growth and the bunch lengthening

- The energy spread is the cause of the emittance growth, the bunch lengthening and the beam loss.
- While the random energy spread (as the initial energy spread from the electron gun) cannot be corrected, the energy spread from the RF curvature and the CSR effect can be suppressed by the optics optimization.
- The betatron tune shift and higher order optics distortion from the chromaticity cause the vertical emittance growth. For the horizontal direction, the distortion of the dispersion function (higher order dispersion) is another cause for the emittance growth.
- The distorted dispersion also brings about the bunch lengthening.
- Thus the correction of the chromatic effect is the cure for both the emittance growth and the bunch lengthening.

CSR wake potential

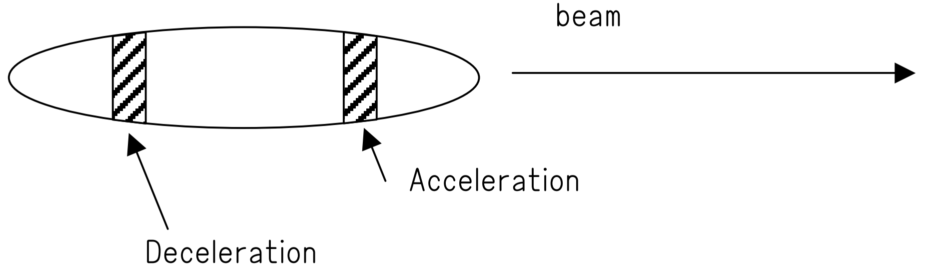


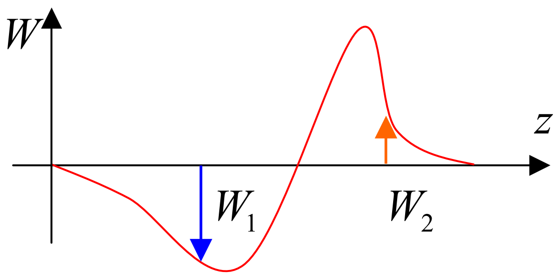




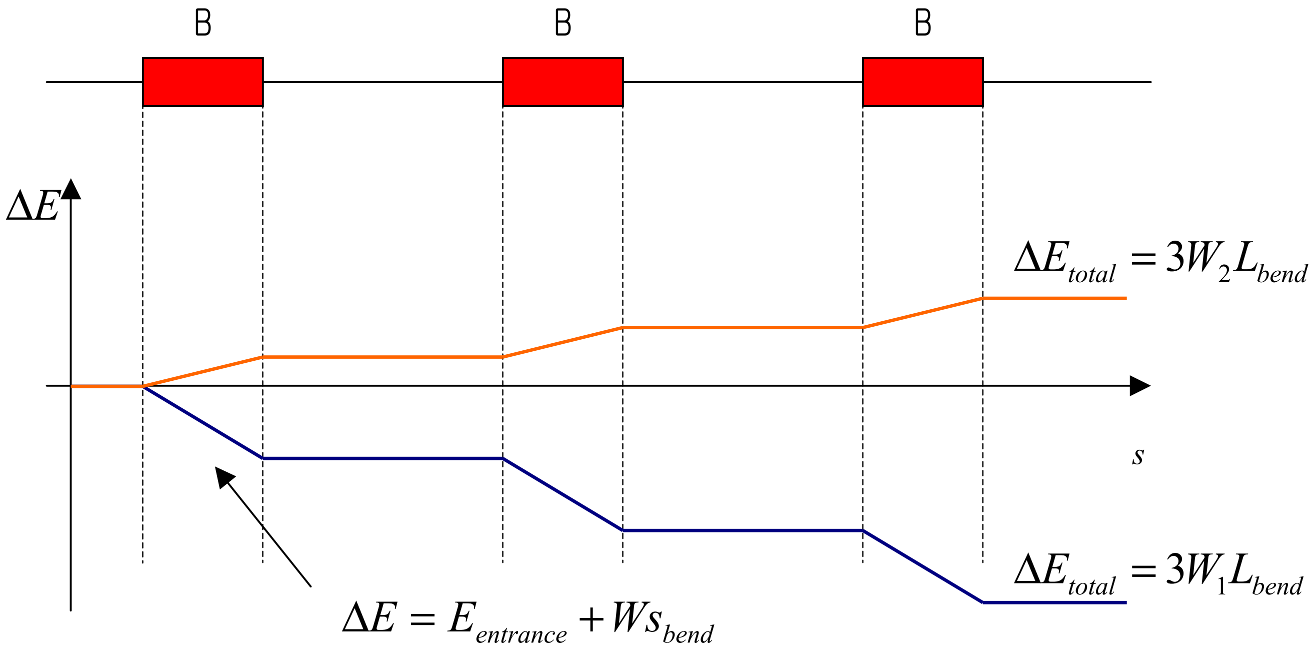
“Linear part” of the CSR

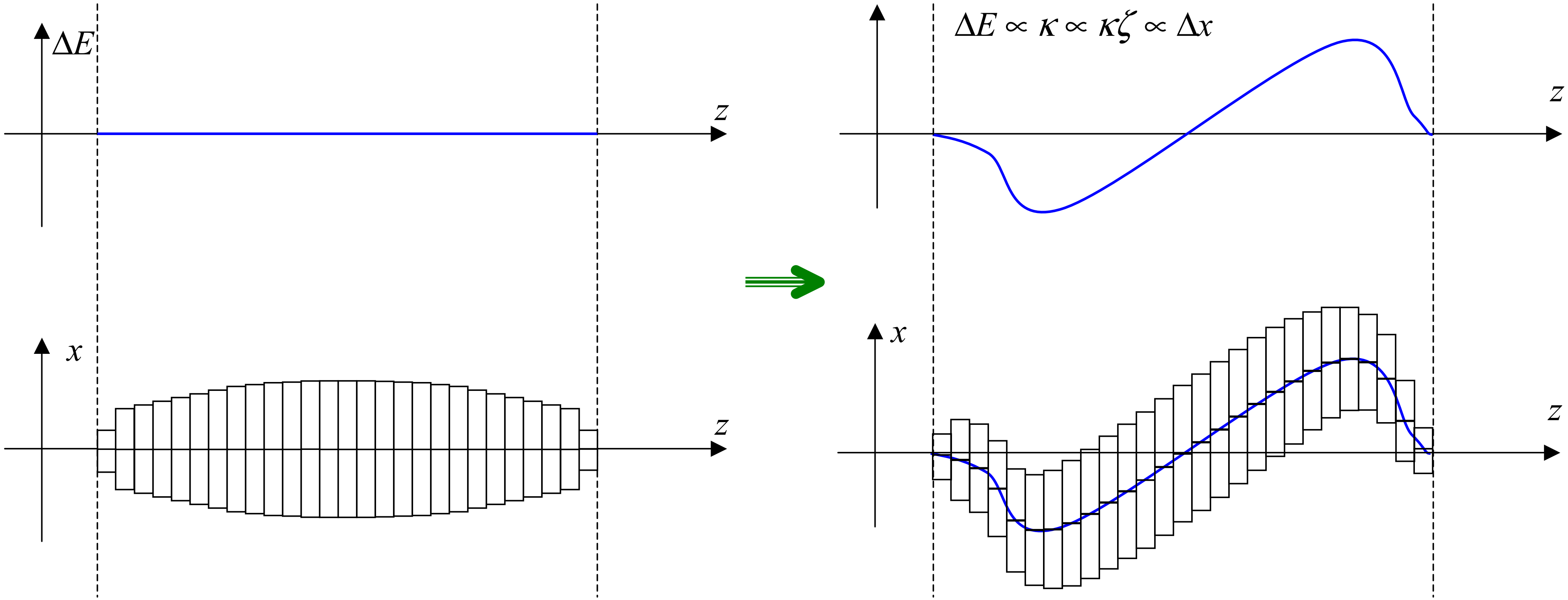
→ Energy change proportional to the orbit length in the bending magnets





Acceleration depending on the longitudinal position





ΔE
z
x
z
ΔE ∝ κ ∝ κζ ∝ Δx
z
x
z

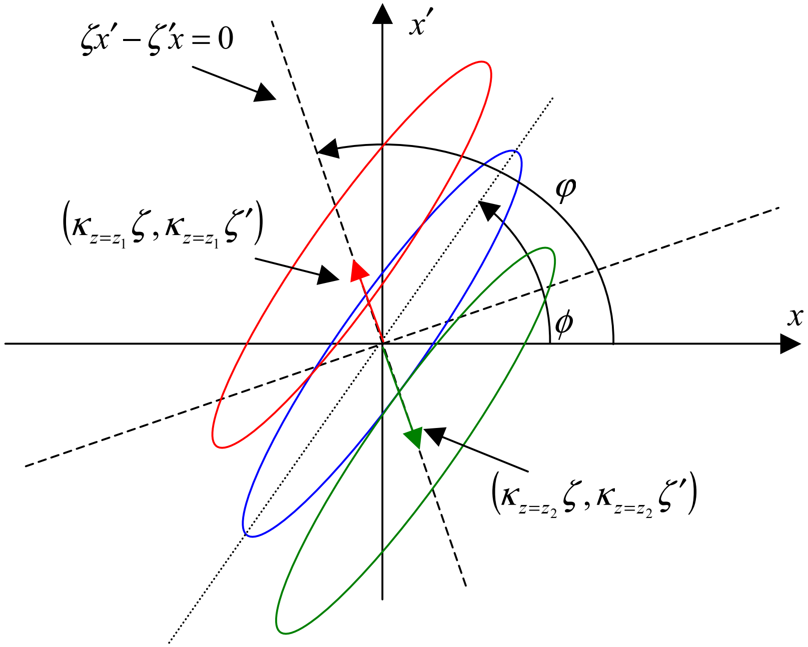
$$x'' = -\frac{x}{\rho^2} + \frac{\delta_0 + \kappa s}{\rho}, \quad \kappa = \frac{W}{E_0}, \quad \delta = \delta_0 + \kappa s$$

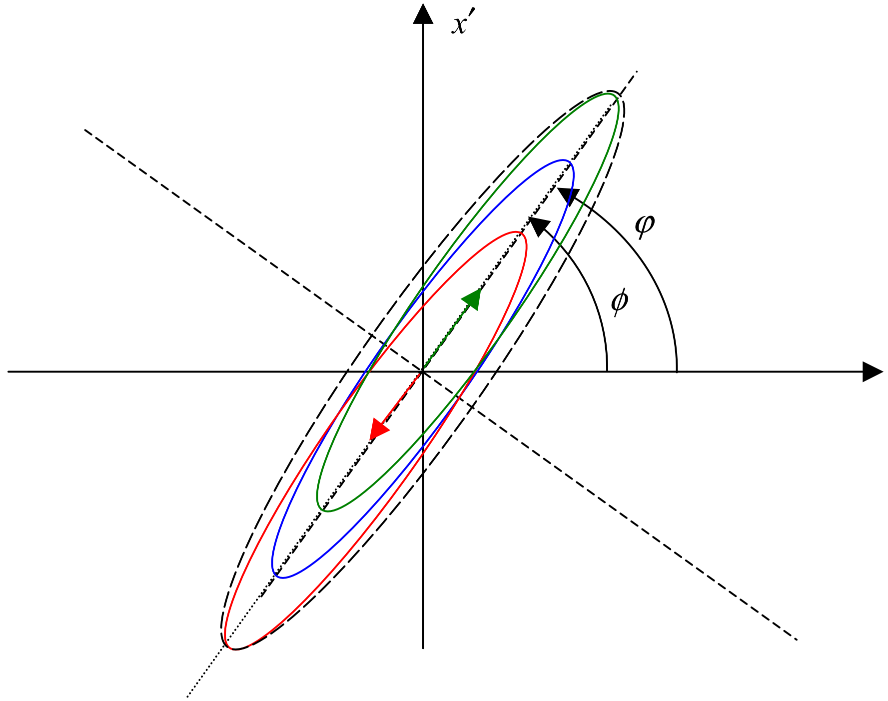
$$x = x_0 \cos\frac{s}{\rho} + x_0'\rho \sin\frac{s}{\rho} + \rho\left(1 - \cos\frac{s}{\rho}\right)\delta_0 + \rho^2\left(\frac{s}{\rho} - \sin\frac{s}{\rho}\right)\kappa$$

$$x' = -\frac{x_0}{\rho}\sin\frac{s}{\rho} + x_0' \cos\frac{s}{\rho} + \delta_0 \sin\frac{s}{\rho} + \rho\left(1 - \cos\frac{s}{\rho}\right)\kappa$$

$$\begin{pmatrix} x \\ x' \\ \delta_0 \\ \delta_{CSR} \\ \kappa \end{pmatrix} = \begin{pmatrix} \cos\frac{s}{\rho} & \rho\sin\frac{s}{\rho} & \rho\left(1-\cos\frac{s}{\rho}\right) & \rho\left(1-\cos\frac{s}{\rho}\right) & \rho^2\left(\frac{s}{\rho} - \sin\frac{s}{\rho}\right) \\ -\frac{1}{\rho}\sin\frac{s}{\rho} & \cos\frac{s}{\rho} & \sin\frac{s}{\rho} & \sin\frac{s}{\rho} & \rho\left(1-\cos\frac{s}{\rho}\right) \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & s \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ \delta_0 \\ \delta_{CSR} \\ \kappa \end{pmatrix}$$

Envelope matching technique for horizontal emittance compensation





Optimizations with CSR wake potential

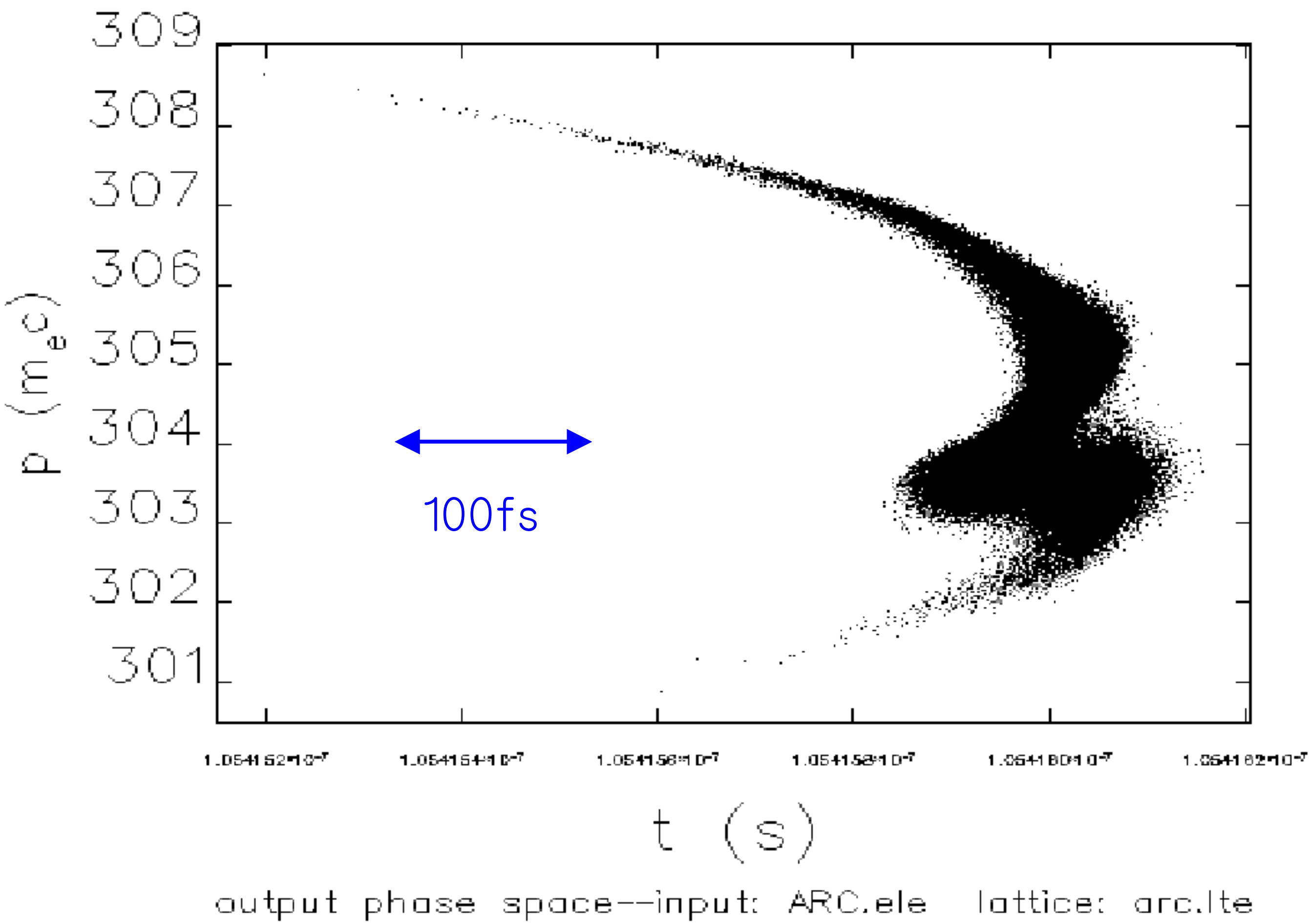
- The initial beam parameters at the merger is the injected beam energy of 5MeV, the bunch charge of 77pC, the bunch length of 1ps r.m.s., the transverse beam emittance 0.1mm·mrad r.m.s., and the energy spread 0.01MeV r.m.s.
- Optimizing RF phase, R_{56} by the linear optics and T_{566} by the sextupoles.
- The effect of the horizontal emittance growth is not severe for the terahertz radiation. For example, the diffraction limit emittance for the photons of 10meV (λ=120mm) is about 10mm·mrad at 65MeV that is the normalized emittance of 1215 mm·mrad.

- By the optiomization,

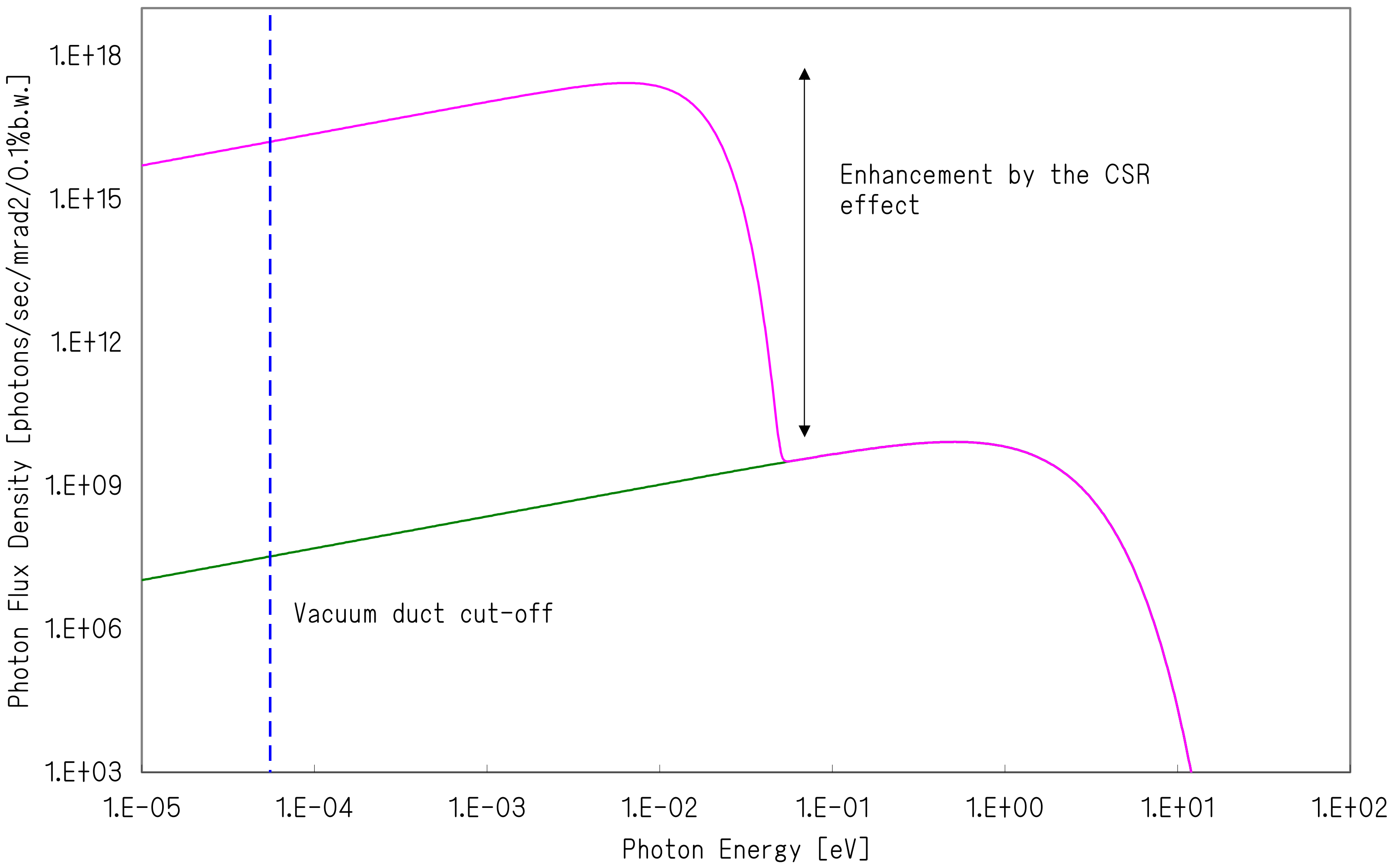
  RF phase : 109.6 degree
  R56 : -0.1m
  T566 : -0.97m.

  Bunch length : 59fs r.m.s.
  Horizontal projected emittance : 5.6mm·mrad

The longitudinal phase space distribution



Estimated flux density



Cconclusion

- Beam energy 65MeV, Beam current 77pC x 1.3GHz = 100mA
- Bunch length >0.1ps (∼59fs r.m.s.)
- Bending curvature radius 1m
- Vertical aperture of vacuum duct ∼5cm

- Terahertz radiation:
  ∼0.16meV (cut-off of vacuum duct) < photons available < ∼10meV (critical energy)
  including 4meV (1THz)
- Flux density is about 10^{16}∼10^{18} [photons/s/mrad^2/0.1%b.w.]

- integrated energy : 4μJ/pulse
  for the horizontal photon acceptance over 100mrad
- Peak electric field is about 1 MV/cm
  for the focused spot size of 100μm x 100μm.

Thank you very much.