High Intensity Synchrotron Radiation Effects

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Introduction

- Recent high-power (that is, high-currents and high-energies) accelerators generate intense synchrotron radiation (SR).
- It is a good photon source, but, on the other hand, it has potentially harmful effects on the accelerator performance;
  - Heat load ⇒ Damage of beam pipes or instruments
  - Gas load ⇒ Short lifetime, Noise to particle detectors
  - Electron emission ⇒ Beam instabilities, Gas load
  - ……
- In this lecture, basic and practical matters to understand above three effects, and how to treat these problems, that is, to protect the machine in a broad sense, are presented.
- These problems are especially important for the vacuum system of accelerators, but they have widespread effects on machine performances. The understanding of those should be also useful in designing and constructing accelerators.

Contents

- About synchrotron radiation (SR)

  Basic concepts and some important formula

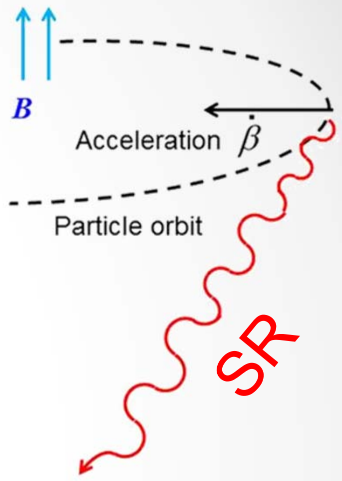
- Effects of SR
  - Heat load
  - Gas load
  - Electron emission

    Mechanism, properties and countermeasures

- Summary

Synchrotron radiation

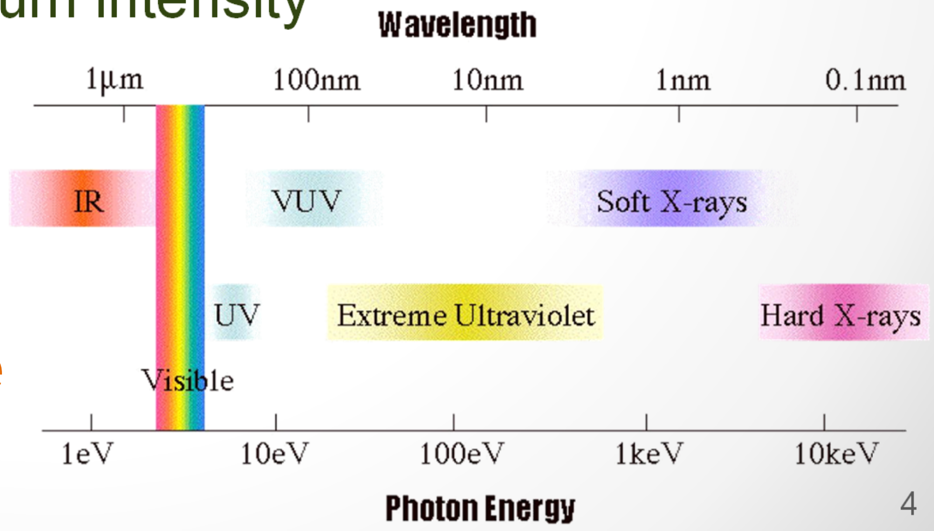
- What is the synchrotron radiation (SR)?
  - Electro-magnetic wave emitted when a high-energy charged particle is accelerated to the orthogonal direction to the velocity, such as a case in a magnetic field.



- General features of SR
  - High intensity, high photon flux
  - Wide range in wave lengths, from infrared to hard X-ray
  - Well understood spectrum intensity
  - High brightness
  - High polarization ratio

and so on

Useful as a photon source



Synchrotron radiation

- An accelerated charged particle emits electro-magnetic radiation.
  - The radiation fields are given by

$$\vec{E} = -\frac{\partial}{\partial t}\vec{A} - \nabla\phi \quad \vec{B} = \nabla \times \vec{A}$$

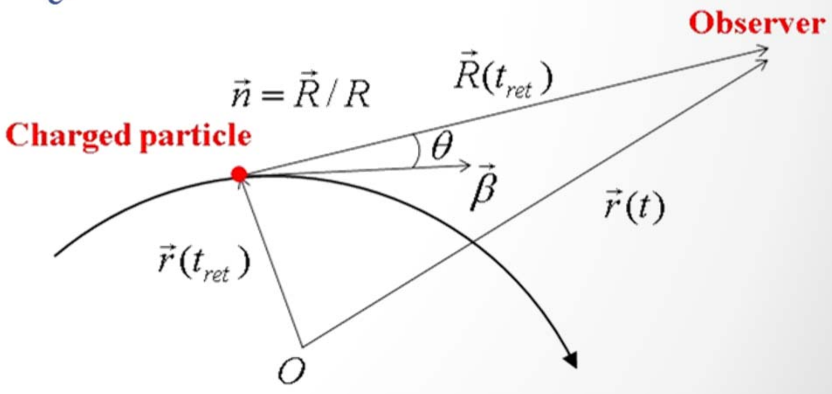
ϕ: Scalar potential
A: Vector potential

Here the retarded Lienard-Wiechert potentials are given by

$$\vec{A}(t) = \frac{e}{4\pi\varepsilon_0 c}\left[\frac{\vec{\beta}}{R(1-\vec{n}\cdot\vec{\beta})}\right]_{ret}$$

$$\phi(t) = \frac{e}{4\pi\varepsilon_0}\left[\frac{1}{R(1-\vec{n}\cdot\vec{\beta})}\right]_{ret}$$

$\beta = \frac{v}{c}$, v : velocity, c : speed of light



where $\vec{R}(t_{ret})$ is the distance vector form source to observer, and t_{ret} is the retarded time $ct_{ret} = ct - R(t_{ret})$

Synchrotron radiation

- Electric and magnetic fields are finally given by

$$\vec{B} = \frac{1}{c}\left[\vec{n}\times\vec{E}\right]_{ret}$$

$$\vec{E} = \boxed{\frac{e}{4\pi\varepsilon_0}\left[\frac{\left(1-\beta^2\right)\left(\vec{n}-\vec{\beta}\right)}{R^2\left(1-\vec{n}\cdot\vec{\beta}\right)^3}\right]_{ret}} + \boxed{\frac{e}{4\pi\varepsilon_0 c}\left[\frac{\vec{n}\times\left(\vec{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}}{R\left(1-\vec{n}\cdot\vec{\beta}\right)^3}\right]_{ret}}$$

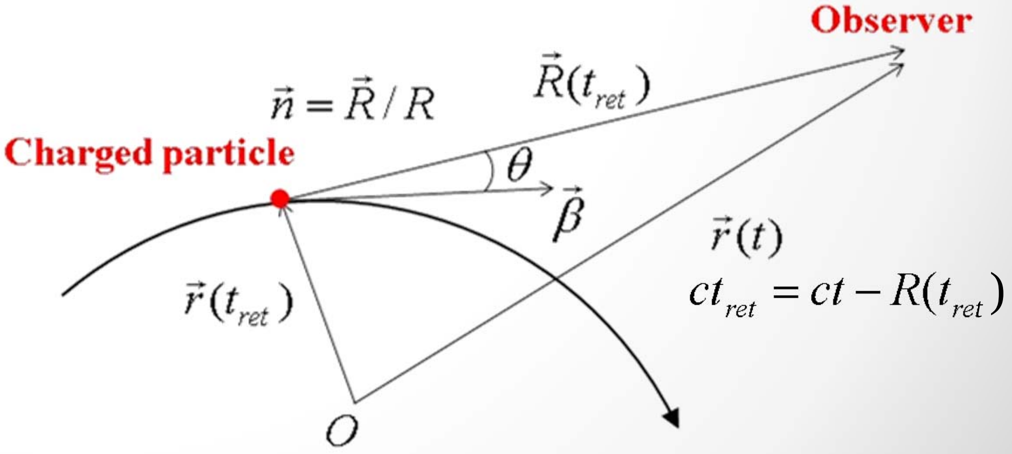
Coulomb field

$\propto 1/R^2$

Radiation field

$\propto 1/R$

- At points far from emitting point, the radiation field ($\propto 1/R$) is more important.



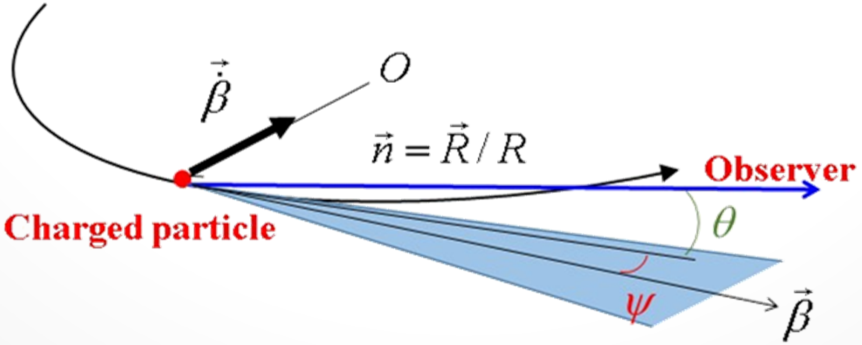
Synchrotron radiation

- Power of radiation per unit solid angle
  - Pointing vector = Radiation energy flow toward R per unit area.

$$\vec{S}_r(t) = \frac{1}{\mu_0}\vec{E}\times\vec{B} = \frac{1}{\mu_0 c}E^2\left(1-\vec{\beta}\cdot\vec{n}\right)\vec{n}\Big|_{ret} = \varepsilon_0 c E^2\left(1-\vec{\beta}\cdot\vec{n}\right)\vec{n}\Big|_{ret}$$

Then, the instantaneous differential radiation power per unit solid angle is

$$\frac{dP}{d\Omega} = \vec{n}\cdot\vec{S}R^2\Big|_{ret} = \varepsilon_0 c E^2\left(1-\vec{n}\cdot\vec{\beta}\right)R^2\Big|_{ret} = \frac{e^2}{16\pi^2\varepsilon_0 c}\frac{\left|\vec{n}\times\left\{\left(\vec{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right\}\right|^2}{\left(1-\vec{n}\cdot\vec{\beta}\right)^5}\Bigg|_{ret}$$



Synchrotron radiation

- Beaming
  - If β is parallel to $\dot{\beta}$

$$\frac{dP}{d\Omega}=\frac{e^2\dot{\beta}^2}{16\pi^2\varepsilon_0 c}\frac{\sin^2\theta}{(1-\beta\cos\theta)^5}$$

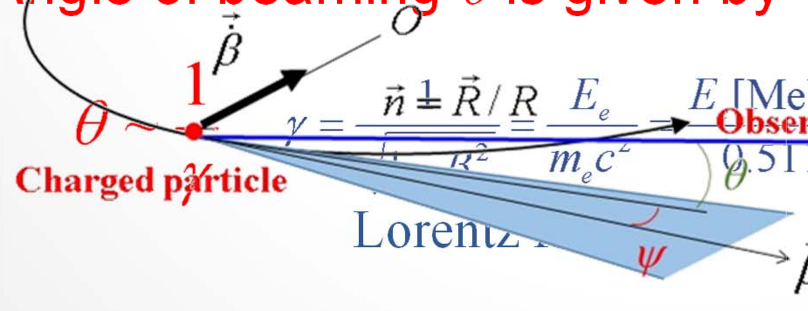
  - If β is orthogonal to $\dot{\beta}$

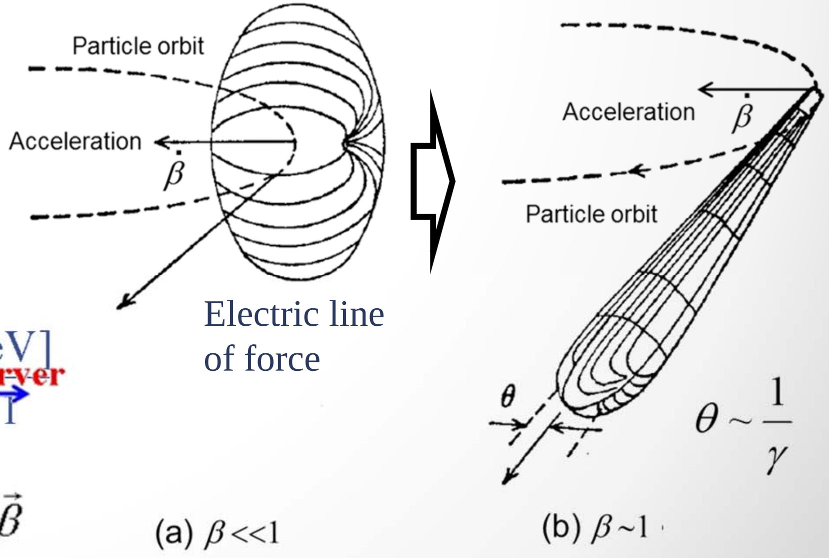
$$\frac{dP}{d\Omega}=\frac{e^2\dot{\beta}^2}{16\pi^2\varepsilon_0 c}\frac{(1-\beta\cos\theta)^2-(1-\beta^2)\sin^2\theta}{(1-\beta\cos\theta)^5}$$

When $\beta\sim 1$, $(1-\beta\cos\theta)^5\rightarrow 0$ for $\theta\rightarrow 0$, then the power beams to the front of orbit.

$\Rightarrow$ Beaming

  - Angle of beaming θ is given by



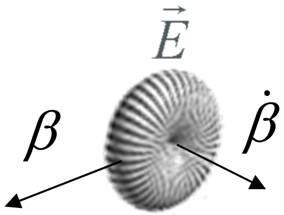


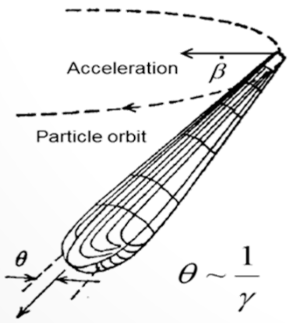
Synchrotron radiation

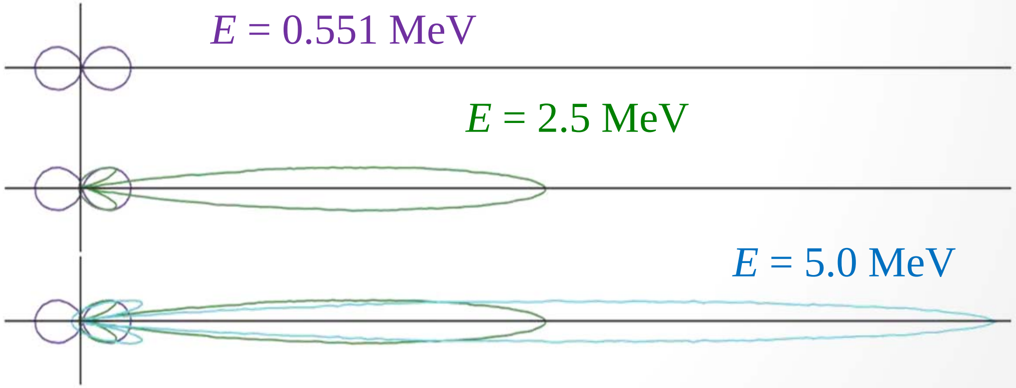
- Beaming
  - $\beta \,//\, \dot{\beta}$

$\gamma = 1,\ \beta = 0$ $\gamma = 1.5,\ \beta = 0.75$ $\gamma = 2,\ \beta = 0.87$ $\gamma = 3,\ \beta = 0.94$

  - $\beta \perp \dot{\beta}$







Synchrotron radiation

- Now, consider a charged particle in homogeneous field B.
  - The acceleration in B is given by

$$\dot{\vec{\beta}}_{\perp} = \frac{\beta^2 c}{\rho} \qquad m\dot{v} = \frac{mv^2}{\rho}$$

Centripetal force

where the bending radius of charged particle, ρ, at energy E_e is

$$\frac{1}{\rho\,[\mathrm{m}]} = \frac{eBc}{\beta E_e} = 0.2998\frac{B\,[\mathrm{T}]}{\beta E_e\,[\mathrm{GeV}]} \qquad \rho = \frac{mv}{eB} = \frac{mc^2 v}{eBc^2} = \frac{E_e \beta}{eBc}$$

Larmor radius

Then the instantaneous radiation power becomes

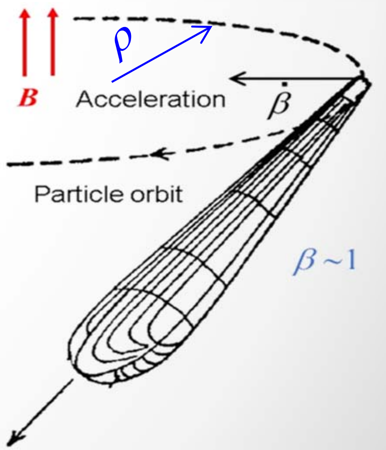
$$P = \frac{2cr_e m_e c^2}{3}\frac{\beta^4\gamma^4}{\rho^2} = \frac{cC_\gamma}{2\pi}\frac{E_e^4}{\rho^2}$$

(For electrons)

$$C_\gamma \equiv \frac{4\pi}{3}\frac{r_e}{\left(m_e c^2\right)^3} = 8.85\times10^{-5}\,\frac{\mathrm{m}}{\mathrm{GeV}^3}$$

$$r_e = \frac{e}{4\pi\varepsilon_0 m_e c^2}$$

Classical electron radius



Synchrotron radiation

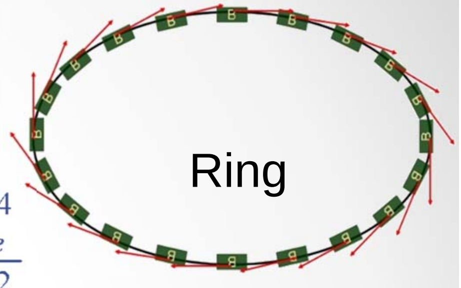
- Mass dependence of power
  - Radiation power depends on the mass of the radiating particle like $1/m^4$. For protons and electrons of the same total energy.

$$\frac{P_p}{P_e} = \left(\frac{m_e}{m_p}\right)^4 = 8.8 \times 10^{-14}$$

  - Synchrotron radiation is much more important for electron and positron ring.
  - Note that, for superconducting system, such as LHC, the SR is important even proton beams, since the heating might have a significant effect to the cryogenics system.
  - Hereafter, we consider the case of an electron or a positron deflected by a dipole magnet.

Synchrotron radiation

- Total power
  - The radiation along a ring per electron is



$$U_0 = \oint P dt = \frac{C_\gamma}{2\pi} E_e^4 \oint \left(\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2} \right) ds$$

$$P = \frac{cC_\gamma}{2\pi} \frac{E_e^4}{\rho^2}$$

$$cdt = ds$$

For an isomagnetic magnetic field ($\rho = \text{const.}$),

$$U_0 = C_\gamma \frac{E_e^4}{\rho}$$

$$\oint ds = 2\pi\rho$$

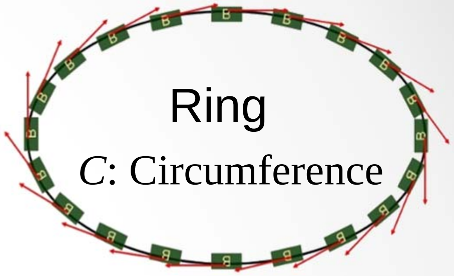
For a circulating beam current I_e, the total radiation power P_{Ie} is

$$P_{Ie} = U_0 \times \frac{I_e}{e} = C_\gamma \frac{E_e^4}{\rho} \times \frac{I_e}{e}$$

$$P_{Ie}[W] = 8.85 \times 10^4 \frac{E\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I\,[\mathrm{A}] = 2.65 \times 10^4 E[\mathrm{GeV}]^3 B[\mathrm{T}] I_e[\mathrm{A}]$$

Synchrotron radiation

- Total power
  - The total radiation power



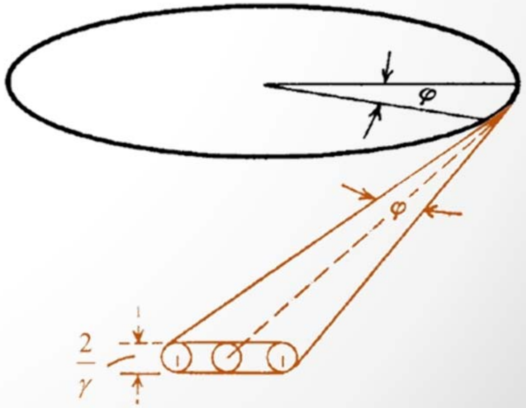
$$P_{Ie} = U_0 \times \frac{I_e}{e} = C_\gamma \frac{E_e^4}{\rho} \times \frac{I_e}{e}$$

$$P_{Ie}[W] = 8.85\times 10^4 \frac{E\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I\,[\mathrm{A}] = 2.65\times 10^4 E[\mathrm{GeV}]^3 B[\mathrm{T}] I_e[\mathrm{A}]$$

  - The average power line density along the ring is obtained by

$$\left\langle P_{Ie,line} \right\rangle = P_{Ie} / C$$

  - The power in an angle of φ



$$P_{Ie}(\varphi) = P_{Ie} \frac{\varphi}{2\pi}$$

Synchrotron radiation

- Frequency spectrum of power
  - Frequency spectrum is obtained by Furrier transform of $E(t)$.

$$\tilde{E}(\omega)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}E(t)e^{i\omega t}\,dt$$

$$\frac{dP}{d\Omega}=\varepsilon_0 cE^2R^2\Big|_{ret}$$

$$\frac{dW}{d\Omega}=\int\frac{dP(t)}{d\Omega}dt=\frac{1}{\mu_0 c}\int_{-\infty}^{+\infty}(RE)^2\,dt=\frac{1}{\mu_0 c}\int_{-\infty}^{+\infty}\left|R\tilde{E}(\omega)\right|^2 d\omega$$

  - The frequency spectrum of power is given by

$$\frac{d^2W}{d\Omega d\omega}=\frac{1}{\mu_0 c}\left(R\tilde{E}(\omega)\right)^2=\frac{1}{2\pi\mu_0 c}\left|\int_{-\infty}^{+\infty}(RE)e^{i\omega t}dt\right|^2$$

$$=\frac{e^2}{16\pi^3\varepsilon_0 c}\left|\int_{-\infty}^{+\infty}\left[\frac{\left|\vec{n}\times\left\{\left(\vec{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right\}\right|^2}{\left(1-\vec{n}\cdot\vec{\beta}\right)^5}\right]_{ret}e^{i\omega\left(t'+\frac{R(t')}{c}\right)}dt'\right|^2$$

Synchrotron radiation

- The spatial and spectral energy distribution per unit frequency and solid angle is

$$\frac{d^2W}{d\Omega d\omega}=\frac{e^2}{16\pi^3\varepsilon_0 c}\gamma^2\frac{\omega^2}{\omega_c^2}K_{2/3}^2(\xi)F(\xi,\theta)$$

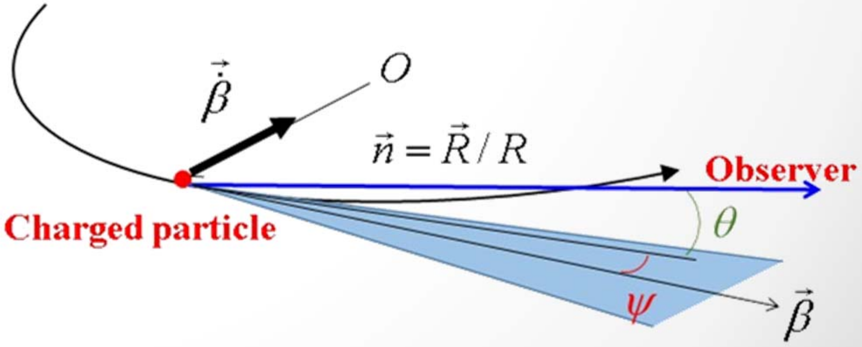
$$\xi\equiv\frac{1}{2}\frac{\omega}{\omega_c}\left(1+\gamma^2\theta^2\right)^{3/2}\qquad F(\xi,\theta)\equiv\left(1+\gamma^2\theta^2\right)^2\left[1+\frac{\gamma^2\theta^2}{1+\gamma^2\theta^2}\frac{K_{1/3}^2(\xi)}{K_{2/3}^2(\xi)}\right]$$

where $K_i(\xi)$ is the modified Bessel function,

and $\boxed{\omega_c\equiv\frac{3}{2}\frac{c\gamma^3}{\rho}}$ is the critical frequency.

⇩

The frequency that halves the total energy



Synchrotron radiation

- The photon number (photon flux) with a beam current I_e per unit solid angle and frequency is given by

$$\frac{d^2\dot{N}_{ph,Ie}}{d\Omega(d\omega/\omega)} = \frac{d^2P_{Ie}}{d\Omega d\omega}\frac{1}{\hbar} = \frac{d^2W}{d\Omega d\omega}\frac{I_e}{e}\frac{1}{\hbar}$$

Plank's constant

$$\dot{N}_{ph}\hbar\omega = P \quad \hbar = \frac{h}{2\pi}$$

- The spatial and spectral photon flux distribution per unit solid angle and band width (Brightness) is given

$$\frac{d^3\dot{N}_{ph,Ie}}{d\theta d\psi(d\omega/\omega)} = C_\omega E^2 I_e \frac{\omega^2}{\omega_c^2} K_{2/3}^2(\xi) F(\xi,\theta)$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = 7.297\times10^{-3}$$

Fine-structure constant

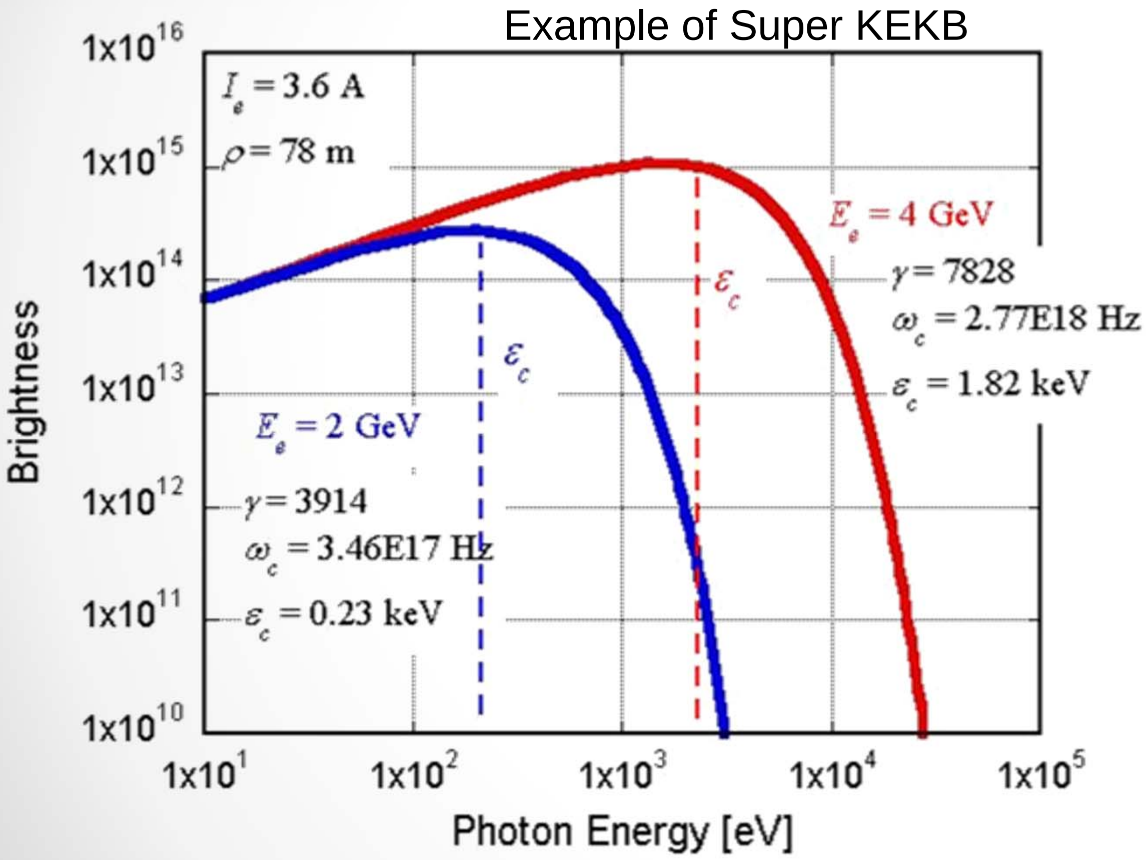
$$C_\omega \equiv \frac{3\alpha}{4\pi^2 e(m_e c^2)^2} = 1.3255\times10^{22}\,\frac{\text{photons}}{\text{s rad}^2\ \text{GeV}^2\ \text{A}}$$

$$= 1.3255\times10^{13}\,\frac{\text{photons}}{\text{s mrad}^2\ \text{GeV}^2\ \text{A 0.1\%bandwidth}}$$

  - A key parameter of light (photon) sources.

Synchrotron radiation

- Example of Brightness



Example of Super KEKB

- Critical energy

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

$$\varepsilon_c[\text{eV}] = 2.218 \times 10^3 \times \frac{E_e\,[\text{GeV}]^3}{\rho\,[\text{m}]}$$

$$= 0.665 \times 10^3 \times E_e\,[\text{GeV}]^2 B\,[\text{T}]$$

- Mean photon energy

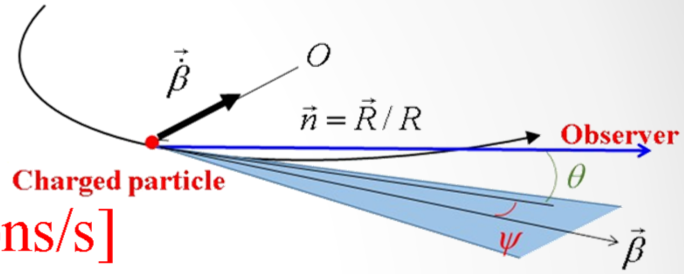
$$\langle \varepsilon \rangle = \frac{8}{15\sqrt{3}} \varepsilon_c$$

- Total photon flux

$$\dot{N}_{ph} = \frac{15\sqrt{3}}{8} \frac{P_{tot}}{\varepsilon_c}$$

Synchrotron radiation

- Total photon numbers
  - Integration over θ, ψ (that is, whole of the ring) and ω gives

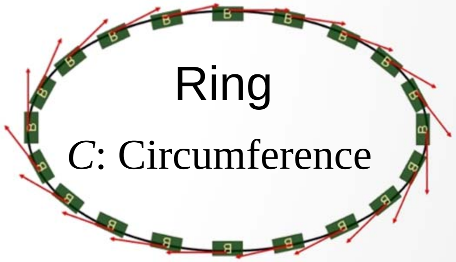


$$\dot{N}_{ph,Ie}=\frac{15\sqrt{3}\pi}{4}C_{\psi}I_eE_e$$

$$=8.08\times10^{20}\,I[\mathrm{A}]E_e[\mathrm{GeV}]\quad[\mathrm{photons/s}]$$

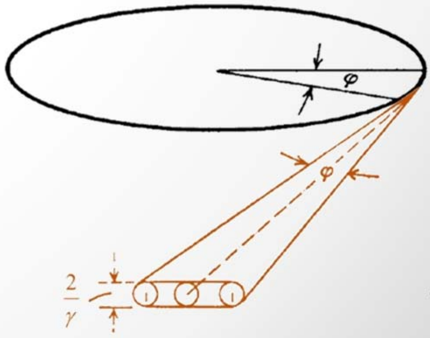
$$C_{\psi}\equiv\frac{4\alpha}{9em_ec^2}=3.9614\times10^{19}\,\frac{\mathrm{photons}}{\mathrm{s\ rad\ GeV\ A}}$$

  - The average photon numbers per unit length along the ring is obtained by



$$\left\langle\dot{N}_{Ph,Ie,line}\right\rangle=\dot{N}_{Ph,Ie}/C$$

  - The photon numbers in an angle of φ



$$\dot{N}_{ph,Ie}(\varphi)=\dot{N}_{ph,Ie}\frac{\varphi}{2\pi}$$

Synchrotron radiation

- Important formula from practical view point as a summary
  - Total power along a ring:

$$P_{Ie}[W] = 8.85\times10^4 \frac{E_e\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I_e\,[\mathrm{A}] = 2.65\times10^4\, E[\mathrm{GeV}]^3\, B[\mathrm{T}] I_e[\mathrm{A}]$$

  - Total photon numbers along a ring:

$$\dot{N}_{ph,Ie} = 8.08\times10^{20}\, I_e[\mathrm{A}] E_e[\mathrm{GeV}] \quad [\mathrm{photons/s}]$$

  - Critical energy:

$$\varepsilon_c[\mathrm{eV}] = 2.218\times10^3 \times \frac{E_e\,[\mathrm{GeV}]^3}{\rho\,[\mathrm{m}]} = 0.665\times10^3 \times E_e\,[\mathrm{GeV}]^2 B\,[\mathrm{T}]$$

  - Beaming angle:

$$\theta \sim \frac{1}{\gamma} = \sqrt{1-\beta^2}$$

Synchrotron radiation

- Exercise

  Calculate

  (1) total SR power along the ring P_{Ie}

  (2) total photon numbers along the ring $\dot{N}_{ph,Ie}$

  (3) critical energy of photon ε_c

  for a ring with $E_e = 7\ \mathrm{GeV}$, $I_e = 2\ \mathrm{A}$, $\rho = 100\ \mathrm{m}$.

- Solution

(1) $$P_{Ie} = 8.85\times 10^4 \frac{E_e\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]} I\,[\mathrm{A}]$$

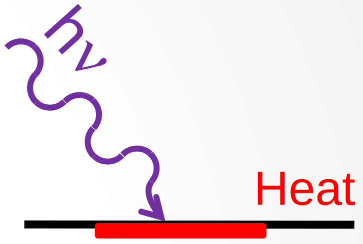
(2) $$\dot{N}_{ph,Ie} = 8.08\times 10^{20} I[\mathrm{A}] E_e[\mathrm{GeV}]$$

(3) $$\varepsilon_c = 2.218\times 10^3 \times \frac{E_e\,[\mathrm{GeV}]^3}{\rho\,[\mathrm{m}]}$$

Effect of SR

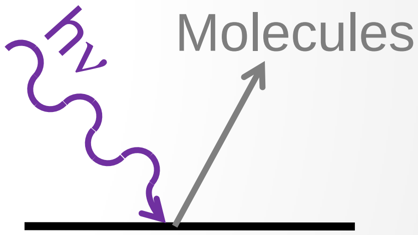
- Effects of SR on vacuum system
  - Thermal load
    - When the SR hit the surface, it deposits the power on it.

    ⇒ Heat up beam pipe, damage beam pipes by heating and thermal stress.



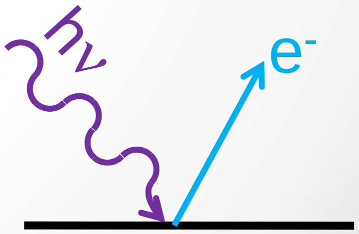
  - Gas load
    - When the SR hit the surface, it desorbs the gas molecules on it.

    ⇒ Increase pressure, reduce beam lifetime, increase background noise.



  - Emission of electrons
    - When the SR hit the surface, it emits electrons (photoelectrons) from it.

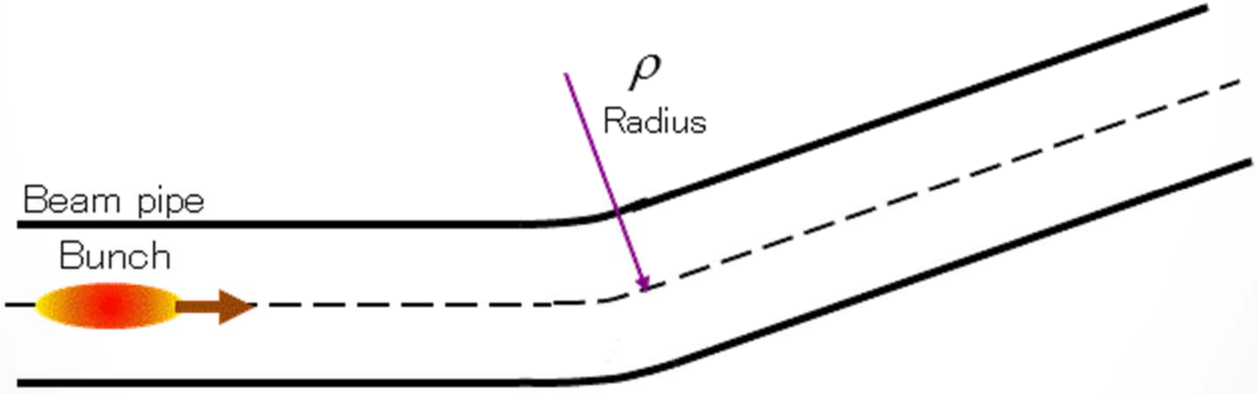
    ⇒ Enhance the forming of the electron cloud, leads to the electron cloud instabilities.



Effect 1: Heat load

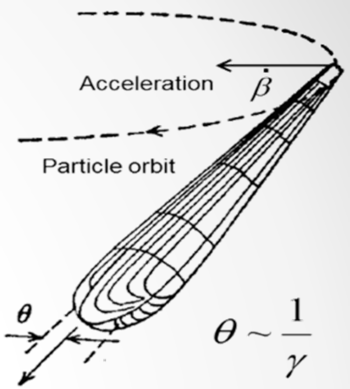
- Heat load due to SR
  - SR hit the inner wall

    ⇒ SR deposits energy on the surface ⇒ Heating.
  - Careful cares should be paid for high-intensity SR, since it can damage components or beam pipes.



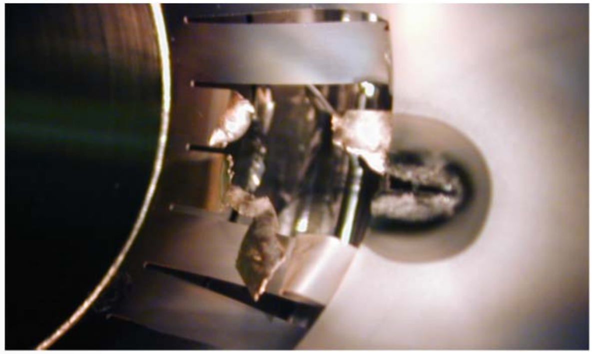
Effect 1: Heat load

- The SR beams (concentrates) in the front.
  - If the irradiated area is not properly cooled, the surface is easily damaged.



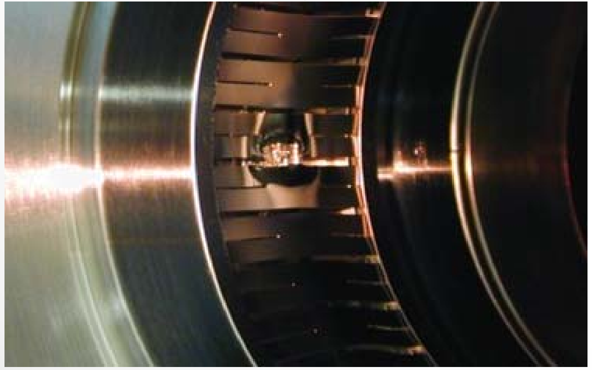
- Examples of damages experienced in KEKB

RF-shield fingers of bellows



⇒Air leak

RF-shield fingers of gate valve



⇒Excess heating

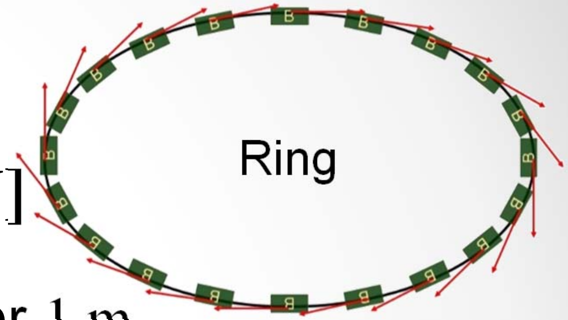
Helicoflex-delta seal
(a gasket for vacuum seal)

⇒Air leak

Effect 1: Heat load

- Estimation of heat load
  - Total power along the ring

$$P_{Ie} = 88.4\times10^{3} E_e[\mathrm{GeV}]^4 \times I_e[\mathrm{A}]/\rho[\mathrm{m}] \quad [\mathrm{W}]$$



  - Average power line density (SR power per 1 m along the ring)

$$\langle P_{Ie,line}\rangle = 88.4\times10^{3} E_e[\mathrm{GeV}]^4 \times I_e[\mathrm{A}]/\rho[\mathrm{m}]/C[\mathrm{m}] \quad [\mathrm{W/m}]$$

For example, if $E_e = 4$ GeV, $I_e = 3.6$ A, $\rho = 74$ m, $C = 2000$ m (arc)

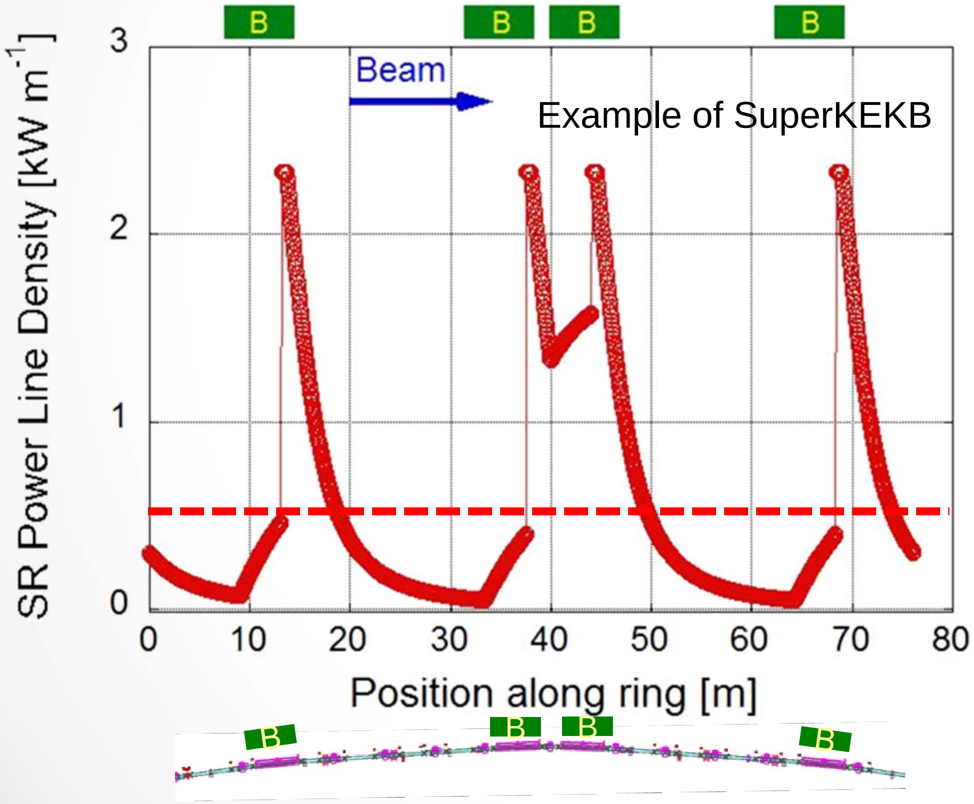
SuperKEKB positron ring

$$\langle P_{Ie,line}\rangle = 88.4\times10^{3}\times4^{4}\times2.6/74/2000 = 550 \quad \mathrm{W/m}$$

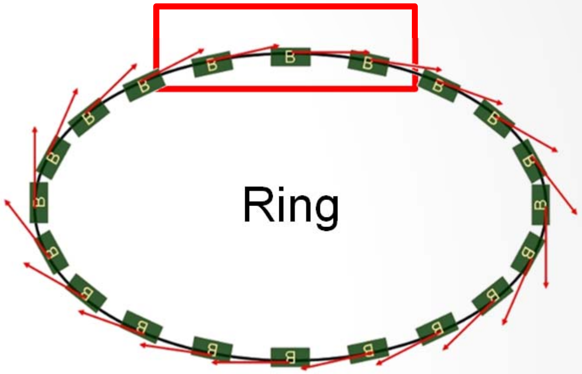
The power density is sufficiently high to melt metals if no cooling is prepared in vacuum.

Effect 1: Heat load

- The heat load has actually a distribution along the ring.
  - The sources (emitting points) are in bending magnets.
- Then the maximum power density is more important than the average one.



Most of power are deposited at the directly irradiated points



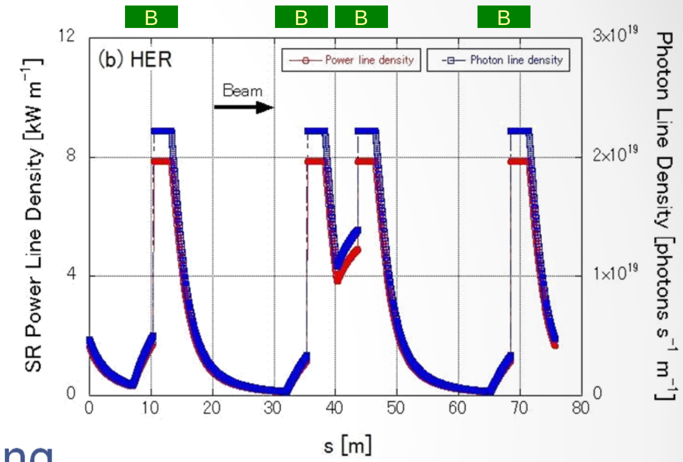
Average power line density ~0.6 kW m^{-1}

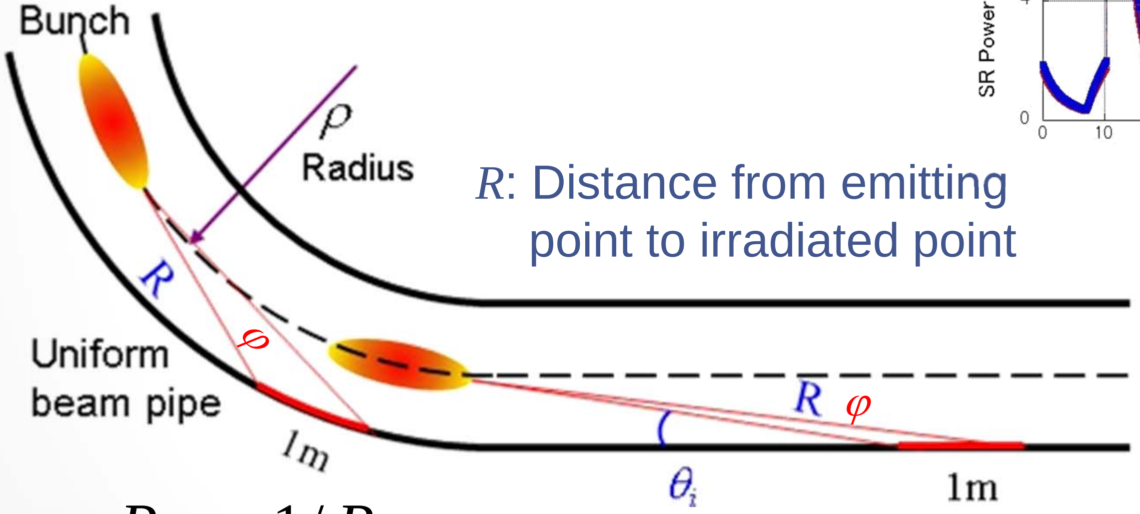
Peak power line density ~2.3 kW m^{-1}

For a uniform beam pipe, the heat load has maximum in the bending magnets, and decrease gradually at down stream side.

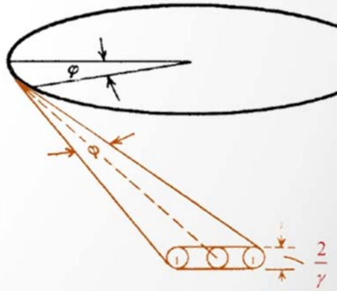
Effect 1: Heat load

- Dependence of the SR power line density on the distance from the emitting point to the hitting point, R, and the incident angle, θ_i, to the surface.
  - Power line density, P_{line} [W mm^{-1}], is important in evaluating temperature and thermal stress.





R: Distance from emitting point to irradiated point



$$P_{line} \propto 1/R$$

(inside of magnet)

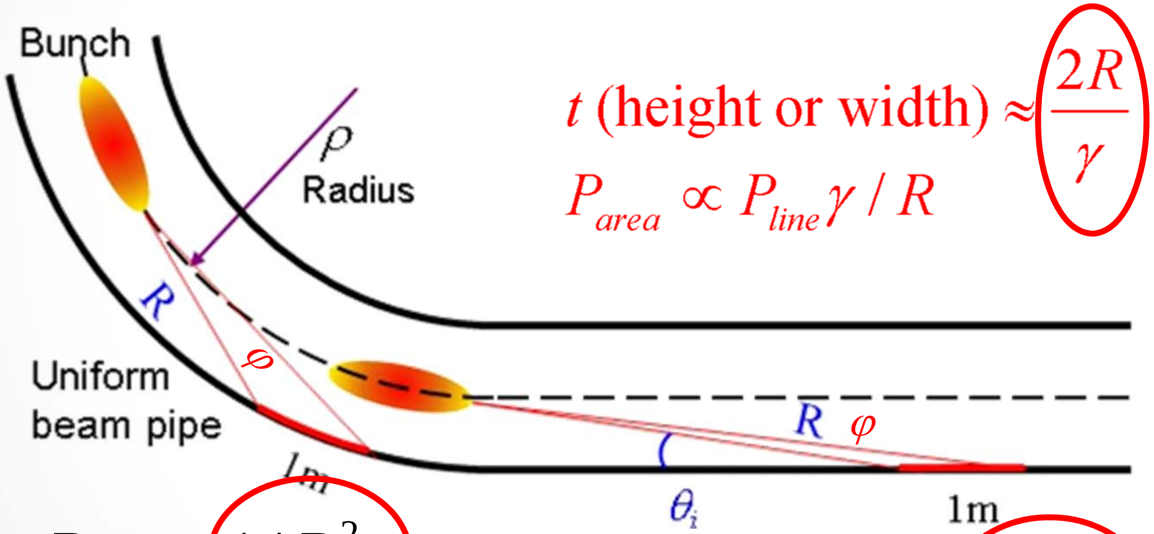
$$P_{line} \propto 1/R \times \theta_i \propto 1/R^2$$

(outside of magnet)

Almost constant in a magnet for SR emitted in the same magnet (θ_i, R~const.)

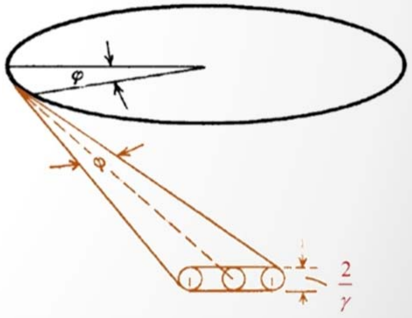
Effect 1: Heat load

- For the power area density, the vertical spread angle of $2/\gamma$ should be taken into account.
  - Power area density, P_{area} [W mm^{-2}], is key especially in evaluating thermal stress..



t (height or width) $\approx \boxed{\dfrac{2R}{\gamma}}$

$P_{area} \propto P_{line}\gamma / R$



$P_{area} \propto \boxed{1/R^2}$

(inside of magnet)

Almost constant in a magnet for SR emitted in the same magnet (θ_i, R~const.)

$P_{area} \propto \boxed{1/R^3}$

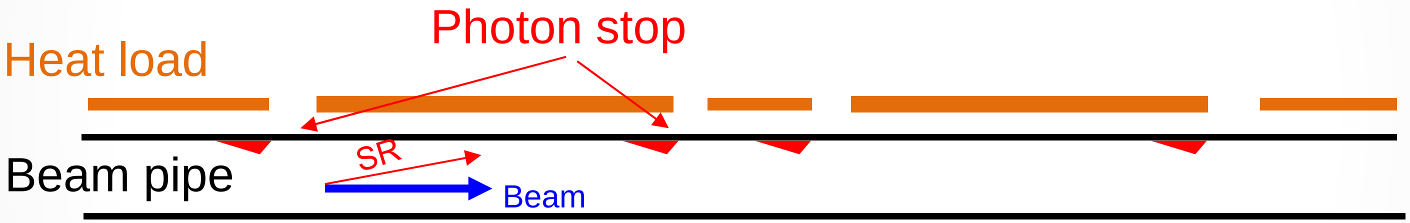
(outside of magnet)

How to treat heat load

- Basic principle: Receive SR at specific places (photon stops) with cooling system at large R and small θ_i.
- There are two ways.

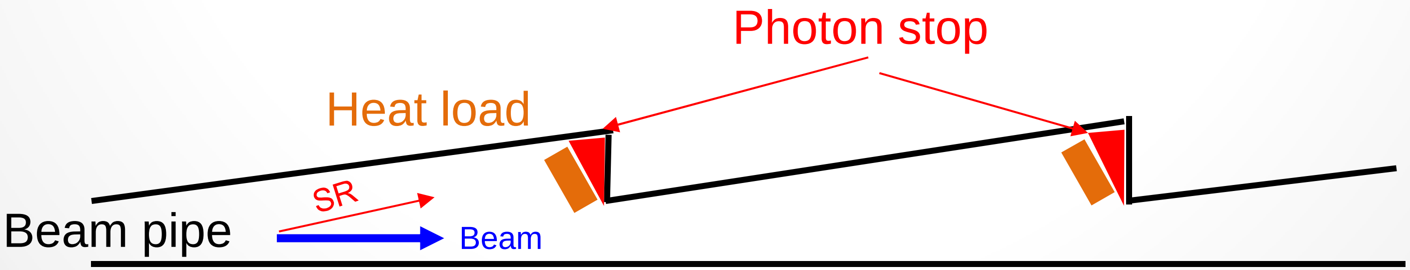
(1) Distributed photon stops (photon masks)

  - Small photon stops enough to make short shadow



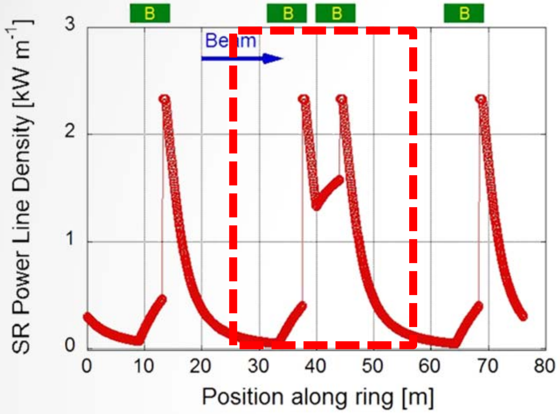
(2) Localized photon stops

  - Large photon stops to make long shadow, and localize loads

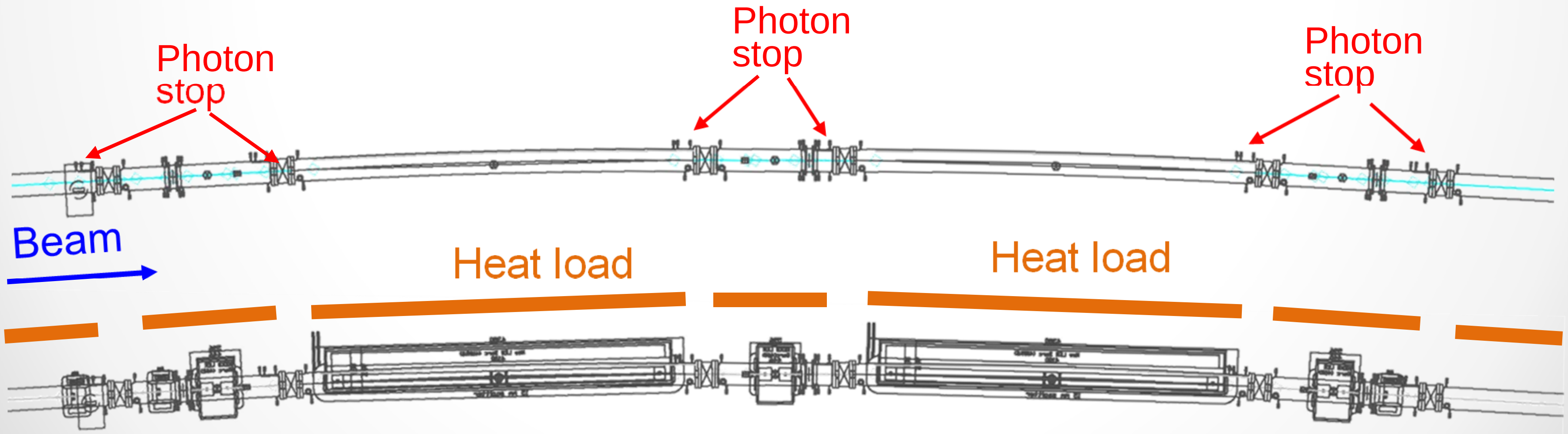


How to treat heat load

- Distributed photon stops (photon masks)



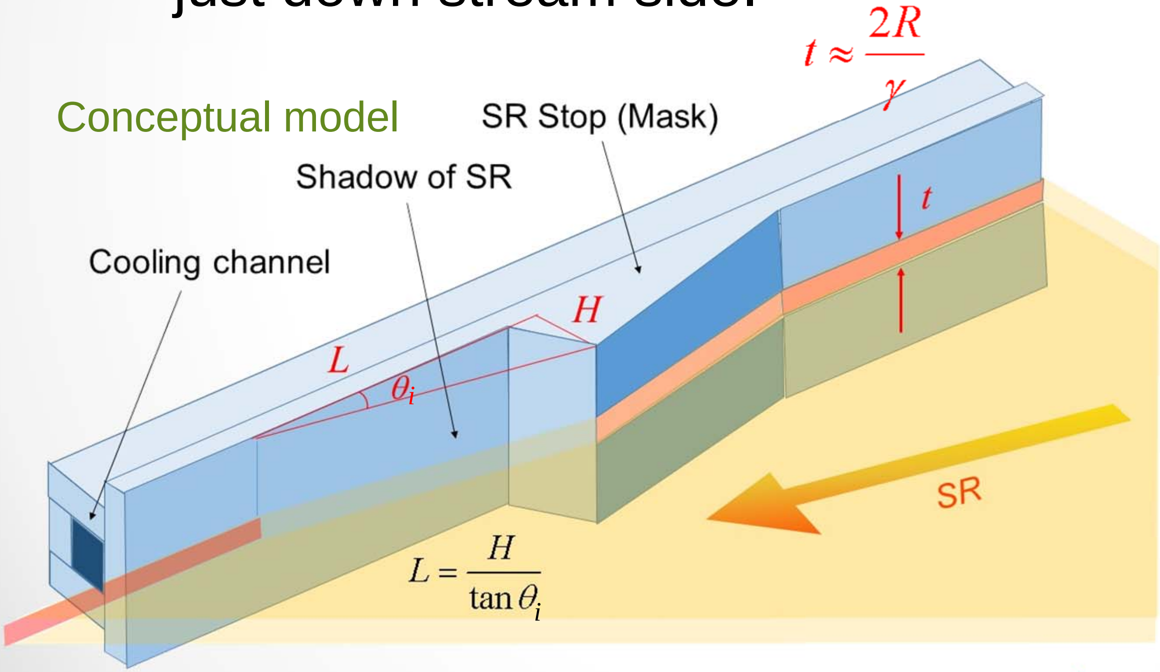
  - Small photon masks enough to make shadows only for bellows chambers or flanged at just down stream side.
  - Shadow length 200 ~ 400 mm.
  - Most of heat load distribute along the ring.
  - Heat load at photon stops are relatively small (θ_i is also small).



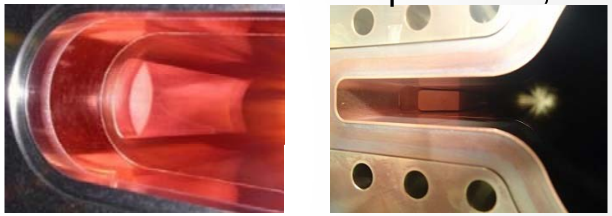
SuperKEKB, KEK

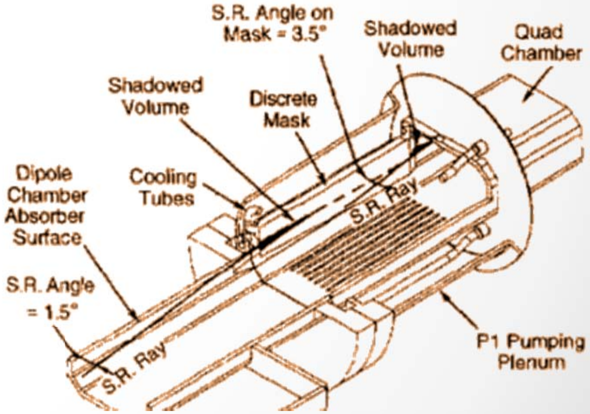
How to treat heat load

- Distributed photon stops
  - Relativity low mask height (H): ~10 mm
  - Shadow length $L = H/\tan\theta_i$, where θ_i is the incident angle of SR, H is the height of photon stop.
  - The shadow protects only flanges and bellows chambers at just down stream side.

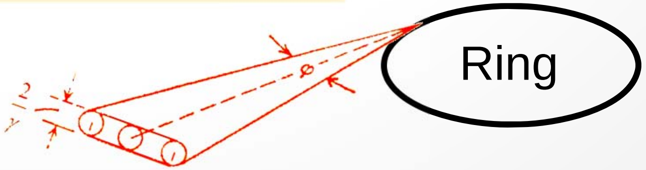


SuperKEKB, KEK





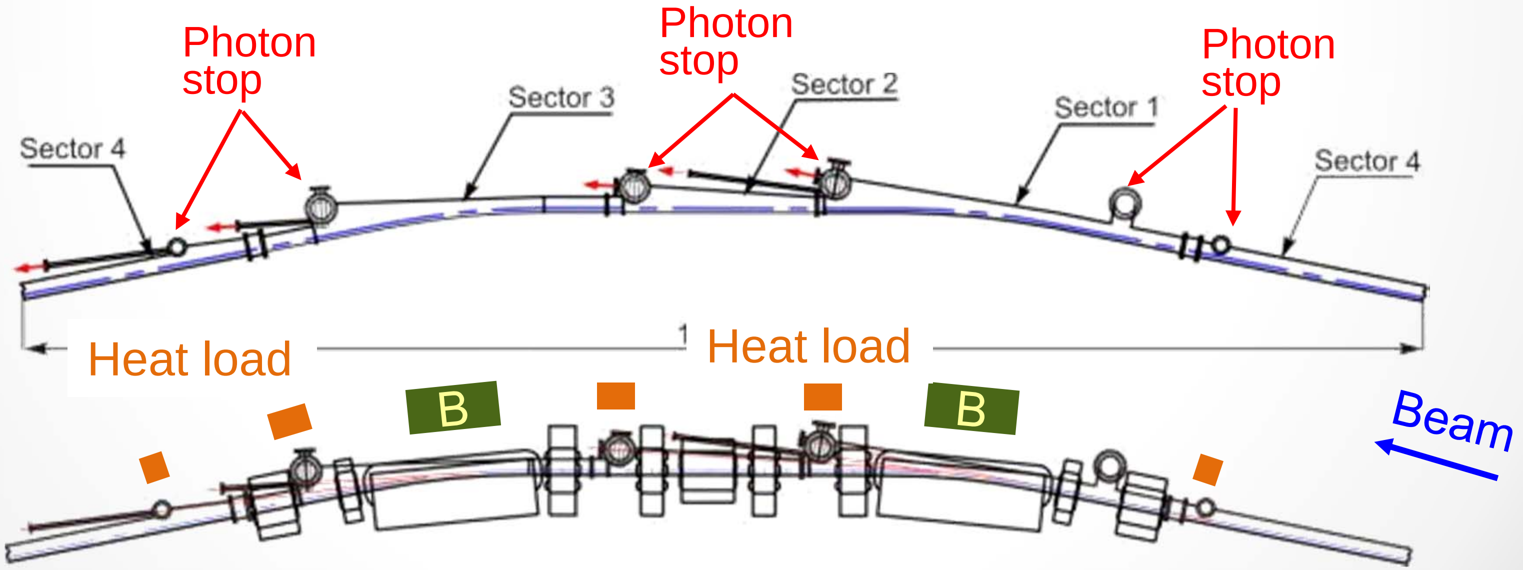
M. Nordby et al., EPAC94, p.2500



How to treat heat load

- Localized photon stops
  - Shadow length $L = \text{a few m}$, i.e., photon stops receive the SR power corresponding to that of ~a few m.
  - Most of heat load concentrate to the photon stops, usually much higher power density than the case of distributed photon stops.

  ⇒One of the criterion to decide the photon stop scheme, i.e., distributed, or localized.



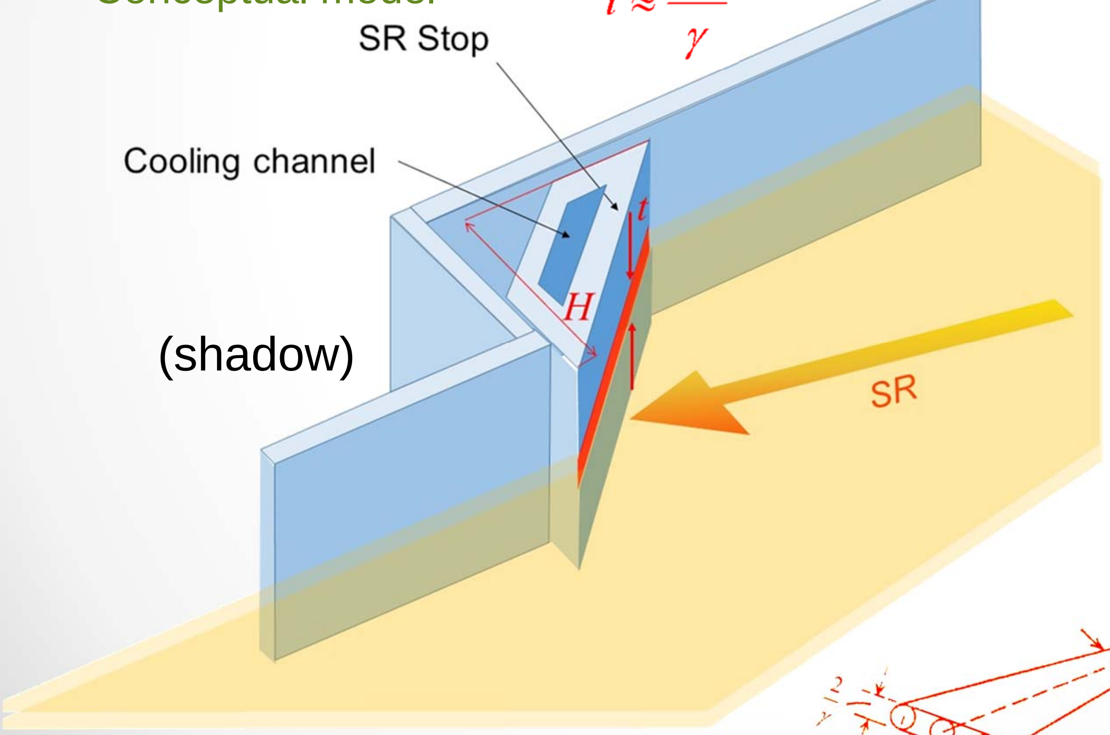
V. Avagyan, EPAC 2002, p.2532

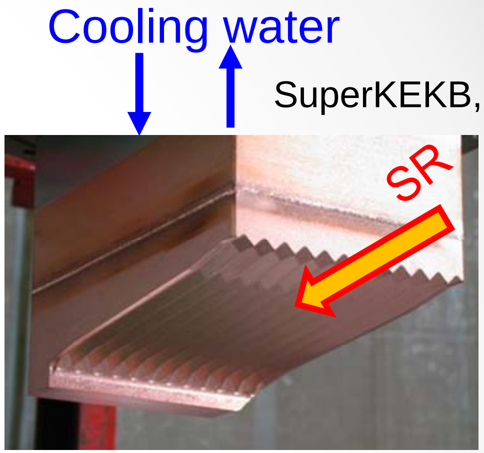
How to treat heat load

- Localized photon stops
  - Mask height (H): 100~200 mm
  - Shadow length L =a few ~ 20 m
  - Sometime called as “crotch absorber” in light sources

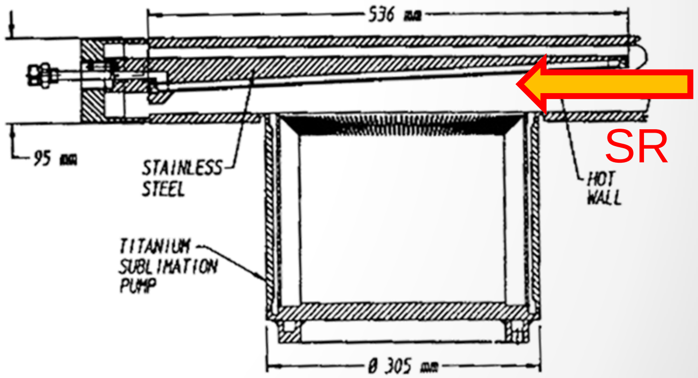
Conceptual model

$$t \approx \frac{2R}{\gamma}$$





SuperKEKB, KEK



M.S.Zisman, PEP-II

How to treat heat load

- Various types of SR stops (masks) have been designed in various accelerators.
- In designing, simulation codes using FEM are very usable in evaluating the temperature and stress distribution.
- Key points in designing:
  - To make slant slope at hitting surface (i,e, small θ_i as much as possible) to reduce power density
  - To design effective cooling structure
  - To use materials with high thermal conductivity, and high thermal strength

SuperKEKB, KEK

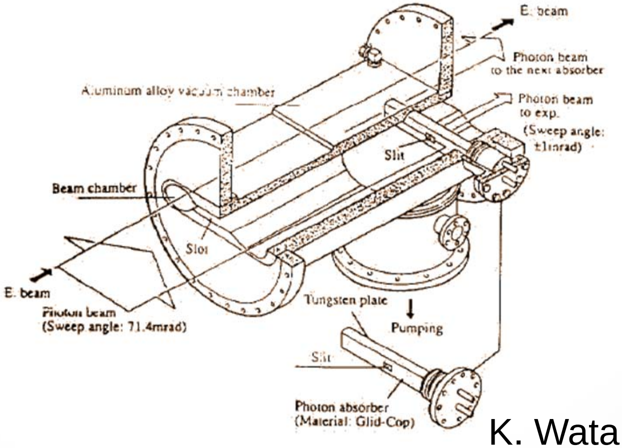
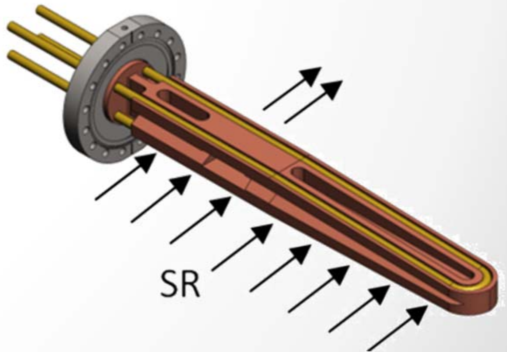


Fig1. Isometric view of the crotch

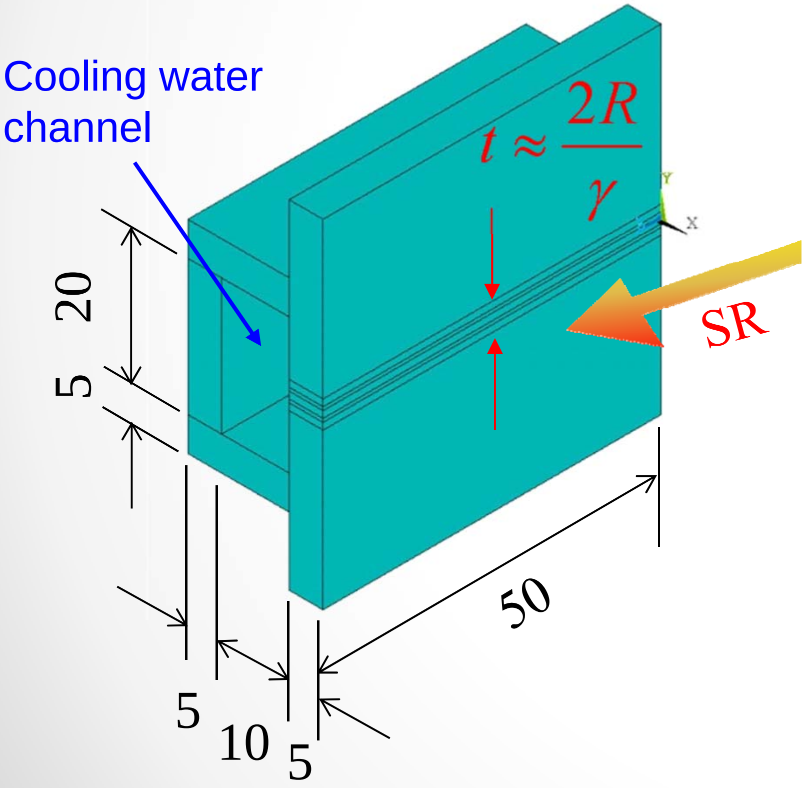
K. Watanabe et al., PAC1993, p.3845



Y. T. Cheng et al., IPAC2011, p.1692

Model calculation

- Here some simulation results are presented using a simple model.



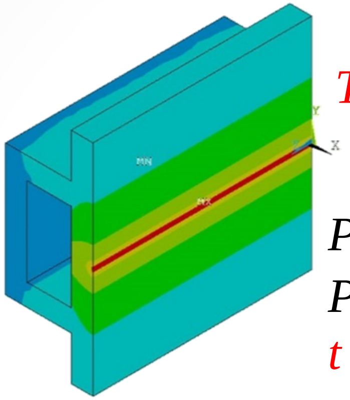
Calculation Model

	Copper (C1011)	**Aluminum alloy (A6063)**	**Unit**
Thermal conductivity	0.4	0.22	W mm^{-1}
Young modulus	118000	69000	N mm^{-2}
Poisson ratio	0.3	0.3	
Thermal expansion rate	1.7×10^{-5}	2.4×10^{-5}	
Reference temperature	25	25	°C
Thermal transfer to water	0.008	0.008	W mm^{-2}
Tensile strength	245 (1/2H) 195 (O)	185 (T5) 90 (O)	W mm^{-2}
Annealing temperature	~250	~200	°C

Model calculation

- Effect of line density and area density (copper)

Temperature

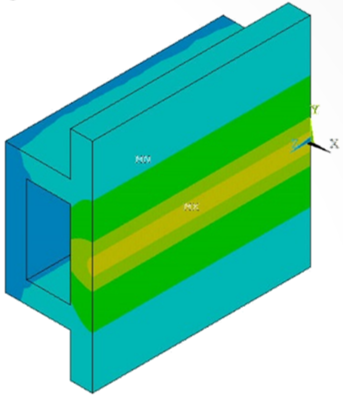


T_{max} = 87 °C

$P_{line} = 10\ \mathrm{W\ mm^{-1}}$

$P_{area} = 10\ \mathrm{W\ mm^{-2}}$

$t = 1$ mm



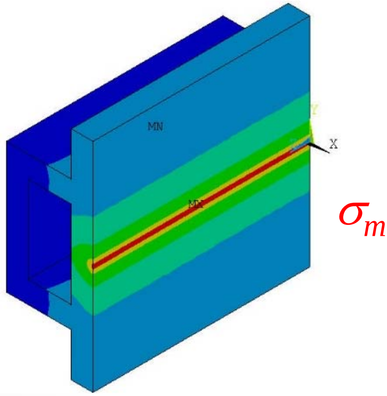
T_{max} = 76 °C

$P_{line} = 10\ \mathrm{W\ mm^{-1}}$

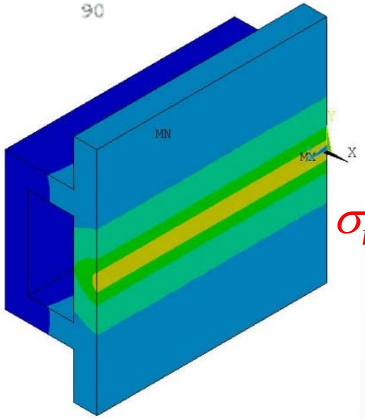
$P_{area} = 2.5\ \mathrm{W\ mm^{-2}}$

$t = 4$ mm

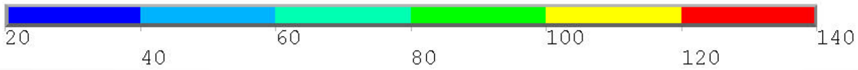
Stress
(Von mises)



$\sigma_{max} = 123\ \mathrm{N\ mm^{-2}}$



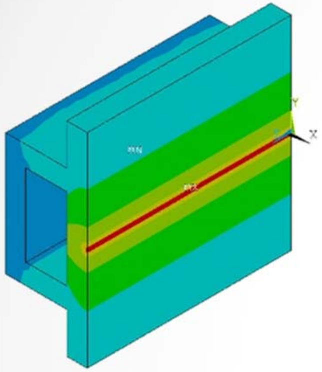
$\sigma_{max} = 102\ \mathrm{N\ mm^{-2}}$



- The narrow area increase stress as well as temperature.

Model calculation

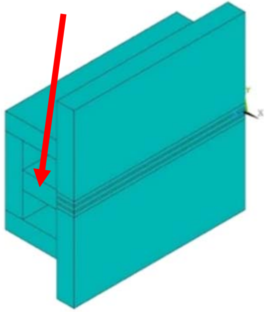
- Structure of cooling channel (copper)

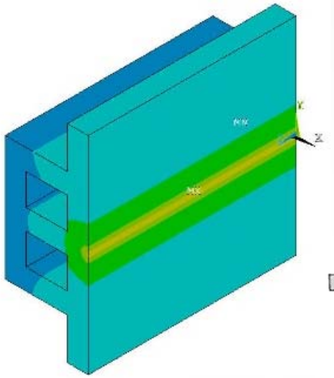


T_{max} = 87 °C
σ_{max} = 123 N mm^{-2}

P_{line} = 10 W mm^{-1}
P_{area} = 10 W mm^{-2}
t = 1 mm

Add a plate





T_{max} = 78 °C

σ_{max} = 104 N mm^{-2}

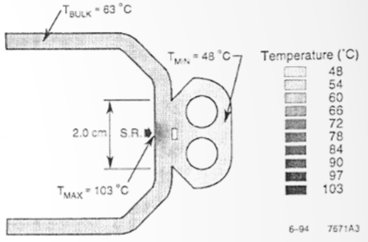


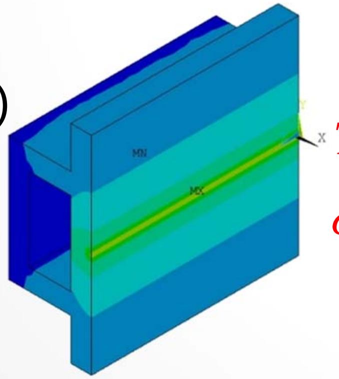
Figure 3. Temperature profile in a dipole chamber cross-section.

- Increase in the contact area between metal and water is effective.

- Material: Copper or Aluminum alloy

M. Nordby et al., EPAC94, p.2500

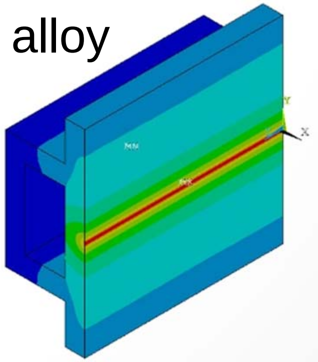
Copper (C1011)



T_{max} = 87 °C

σ_{max} = 123 N mm^{-2}

Aluminum alloy (A6063)



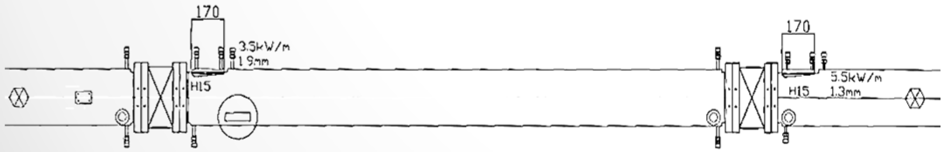
T_{max} = 116 °C

σ_{max} = 149 N mm^{-2}

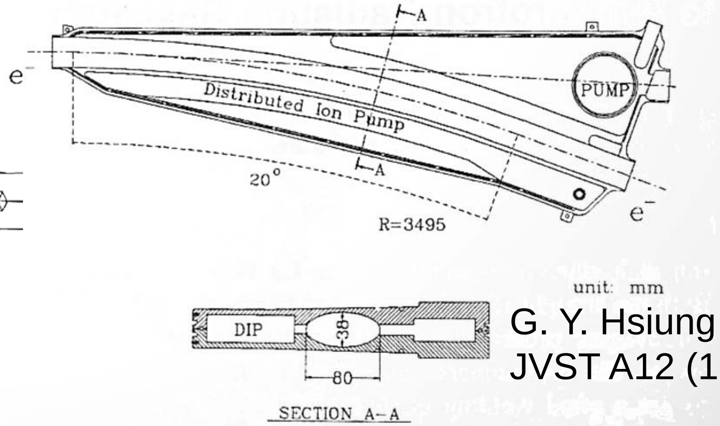
- High thermal conductivity is preferable, of course.

How to treat heat load

- Comparison
  - Distributed photon stops
    - Relatively low heat load at the photon stop
    - Simple structure of beam pipe
    - No choice if the power density at the localized photon stop is too high
  - Lumped photon stops
    - Relatively high heat load at the photon stop
    - Complicated structure of beam pipe
    - Effective pumping is realized by putting pumps at the same places (next topic)



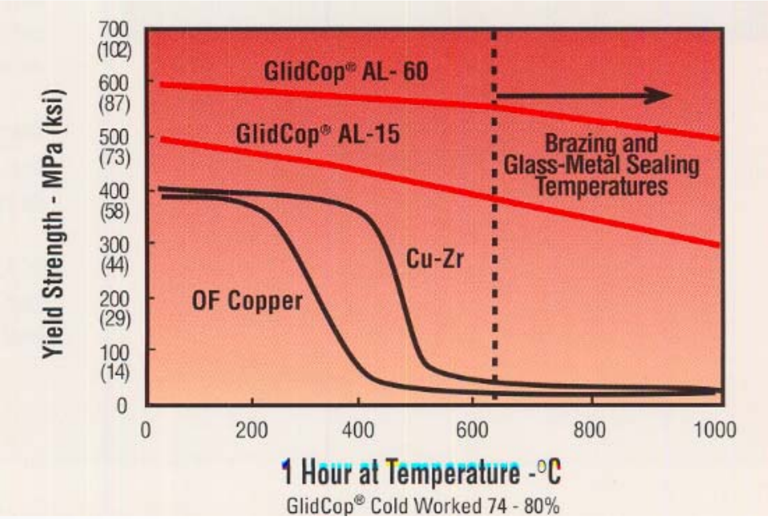
SuperKEKB, KEK

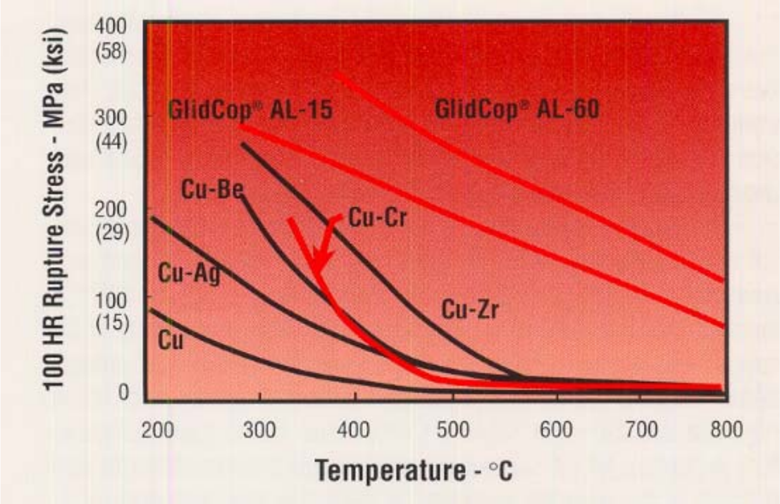


G. Y. Hsiung et al.,
JVST A12 (1994) 1639.

How to treat heat load

- Other countermeasure
  - Use materials with high thermal conductivity and high thermal strength.
    - Copper, copper-chromium alloys, glidcop



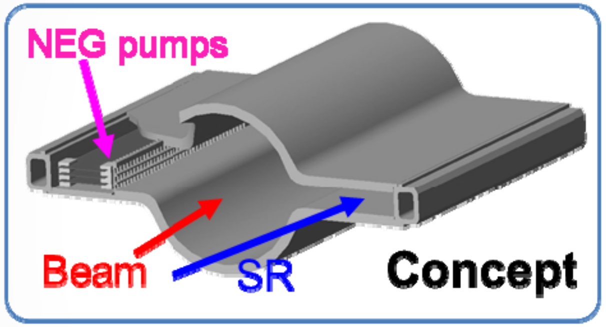


http://www.aps.anl.gov/APS_Engineering_Support_Division/Mechanical_Operations_and_Maintenance/Miscellaneous/tech_info/Glidcop/SCM_Glidcop_product_info.pdf

- GLIDCOP: The registered trademark name of North American Hoganas, Inc. that refers to afamily of copper-based metal matrix composite (MMC) alloys mixed primarily with aluminum oxide ceramic particles. (Wikipedia)

How to treat heat load

- Other countermeasure
  - Use beam pipes with an antechamber
    - SR hit at far point from emission point. ⇒ Decrease in power area density



Y. Suetsugu, SuperKEKB

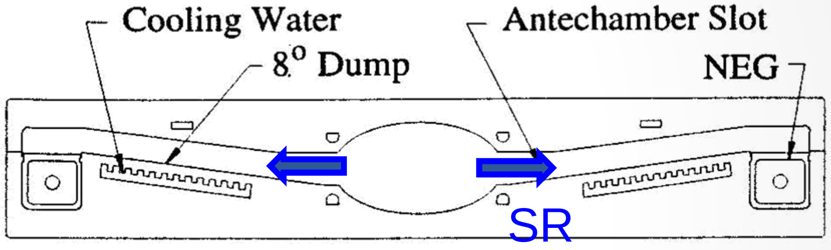


Fig. 3 Wiggler Vacuum Chamber Cross-Section

J. Heim, PEP-II

  - Secure interlocking system
    - Trigger for alarm for beam abort: Temperature of components, flow rate of cooling water
  - Alignment of beam pipes (photon stops)
    - Avoid unnecessary irradiation

Effect 1: Heat load

- Exercise

  Calculate

  (1) average power line density along the ring

  (2) width of SR (t) at the irradiated point of 10 m from the emitting point (use $2/\gamma$ as a spread angle)

  for a ring with $E_e = 7$ GeV, $I_e = 2$ A, $\rho = 100$ m, C = 2000 m.

- Solution

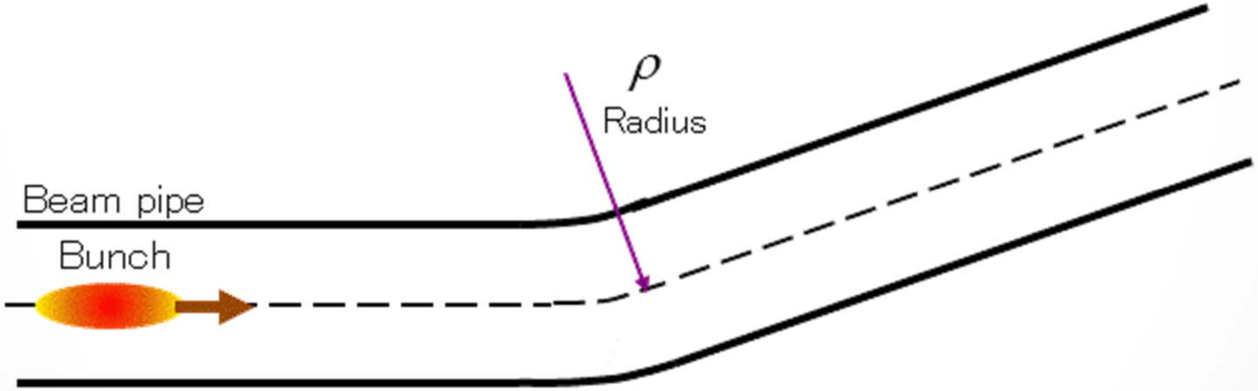
  (1) $\left\langle P_{Ie,line} \right\rangle = 88.4 \times 10^3 E[\mathrm{GeV}]^4 \times I[\mathrm{A}] / \rho[\mathrm{m}] / C[\mathrm{m}] \quad [\mathrm{W/m}]$

  (2) $\gamma = \dfrac{1}{\sqrt{1-\beta^2}} = \dfrac{E_e}{m_e c^2} = \dfrac{E_e[\mathrm{MeV}]}{0.511}$

  $\therefore t = \dfrac{2}{\gamma} R$

Effect 2: Gas load

- Gas desorption from surface
  - SR hitting on the inner surface desorbs the gas molecules adsorbed on it
    = photon stimulated gas desorption (PSD)
  - Residual gases in beam pipes during beam operation mainly come from the PSD.



Effect 2: Gas load

- Effect of the gas load
  - Energy loss due to the scattering with the residual gases
    ⇒ Particle loss ⇒ Shorten life time.
  - Lost particles also increase in the background noise of detectors and can be a cause of radiation.
  - Beam life time, τ, is defined as $I_e = I_{e0} e^{-\frac{t}{\tau}}$

$$\frac{1}{\tau} = \sum_i \left(\sigma_B(Z_i) + Z_i\sigma_M + \sigma_R(Z_i)\right)\boxed{p_i}$$

I_e : Beam current
I_{e0} : Initial beam current
τ : Life time

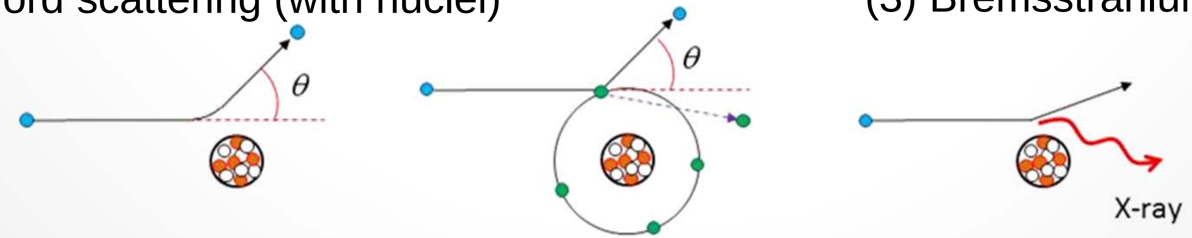
Here, σ_B, σ_M and σ_R are the cross sections of major three interaction processes with gas molecules.

  - The life time is in proportion to the pressure, p_i, i.e., gas load.

(2)Möller scattering (with electrons outside nuclei)

(1)Rutherford scattering (with nuclei)

(3) Bremsstrahlung by nuclei



Property of PSD

- Energy of photon
  - Critical energy of photon

$$\varepsilon_c = 2.22\times10^3 \times \frac{E_e\,[\mathrm{GeV}]^3}{\rho\,[\mathrm{m}]} \quad [\mathrm{eV}]$$

For example, if $E_e = 4\ \mathrm{GeV},\ \rho = 75\ \mathrm{m}$

$$\varepsilon_c = 2.22\times 4^3 / 75 = 1.9 \quad \mathrm{keV}$$

  - Temperature equivalent to $1\ \mathrm{eV}$ is, therefore

$$1\,\mathrm{eV} = \frac{kT}{e} \qquad \therefore T = \frac{e}{k} = \frac{1.6\times10^{-19}}{1.38\times10^{-23}} \approx 12000^\circ\mathrm{C} \quad \text{at 1eV}$$

  - $1\ \mathrm{keV}$ photon is enough to cut the chemical bonding between adsorbed molecule and surface molecules (a few eV). And also much more effective than baking.

    ⇒Considerable gas desorption compared to thermal gas desorption for large photon numbers.

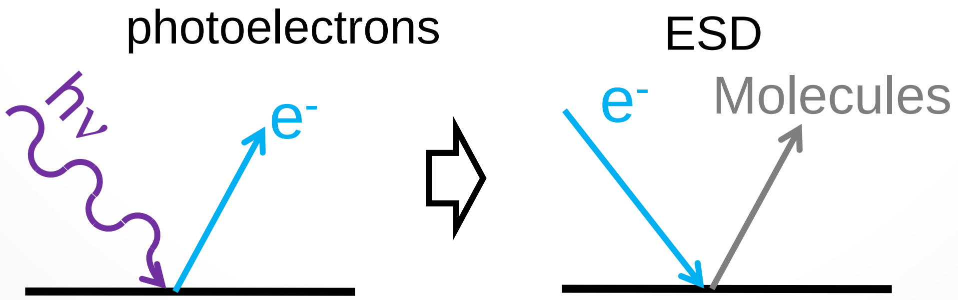
Property of PSD

- Effect of photoelectrons
  - The SR hitting on the inner surface emits electrons

    = Photoelectrons (touched later again)

    The photon energy is sufficiently high to emit electrons (photoelectrons) from material surfaces, where the work functions are a few eV.
  - The electrons hitting the surface desorb the molecules from the surface, since they have also sufficiently high energies.

    = Electron stimulated gas desorption, ESD
  - It is said that most of PSD come from ESD.



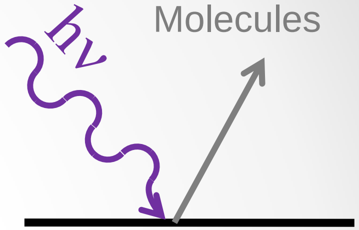
Property of PSD

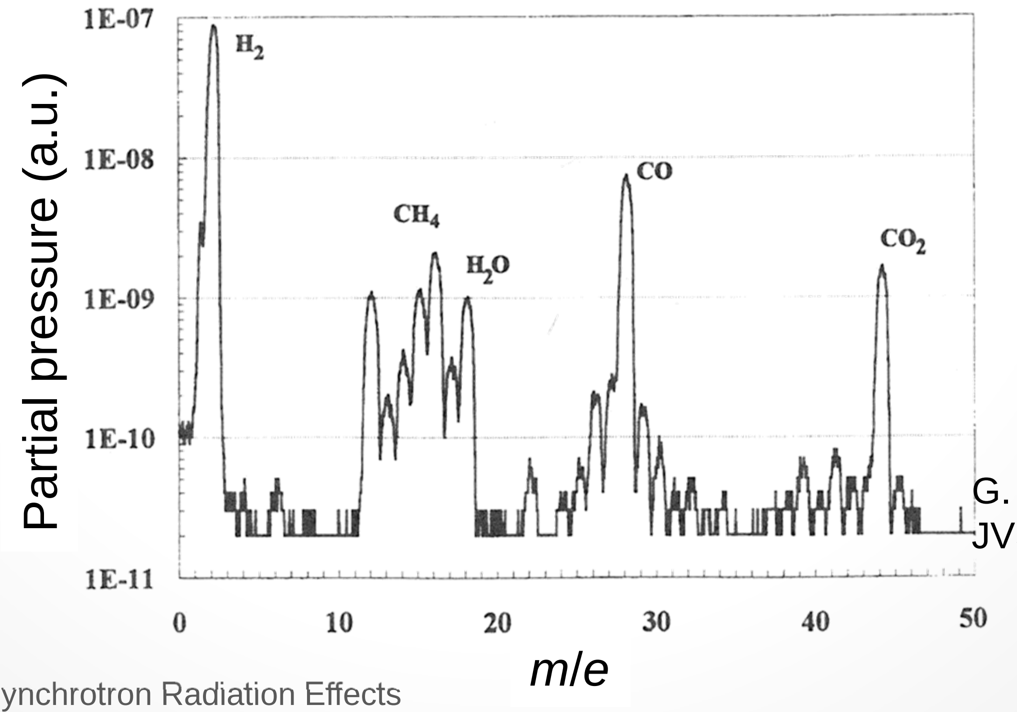
- Number of gas molecules emitted by one photon

  = Photon stimulated gas desorption rate

  (η [molecules photon^{-1}])

  - Major gases are Hydrogen (H_2)、Carbon mono-oxide (CO)、carbon double-oxide (CO_2), after usual baking.





G. Y. Hsiung et al.
JVST A12 (1994) 1631

Property of PSD

- Energy dependence

  η increase with the incident photon energy (critical energy) since the deposit energy increases.

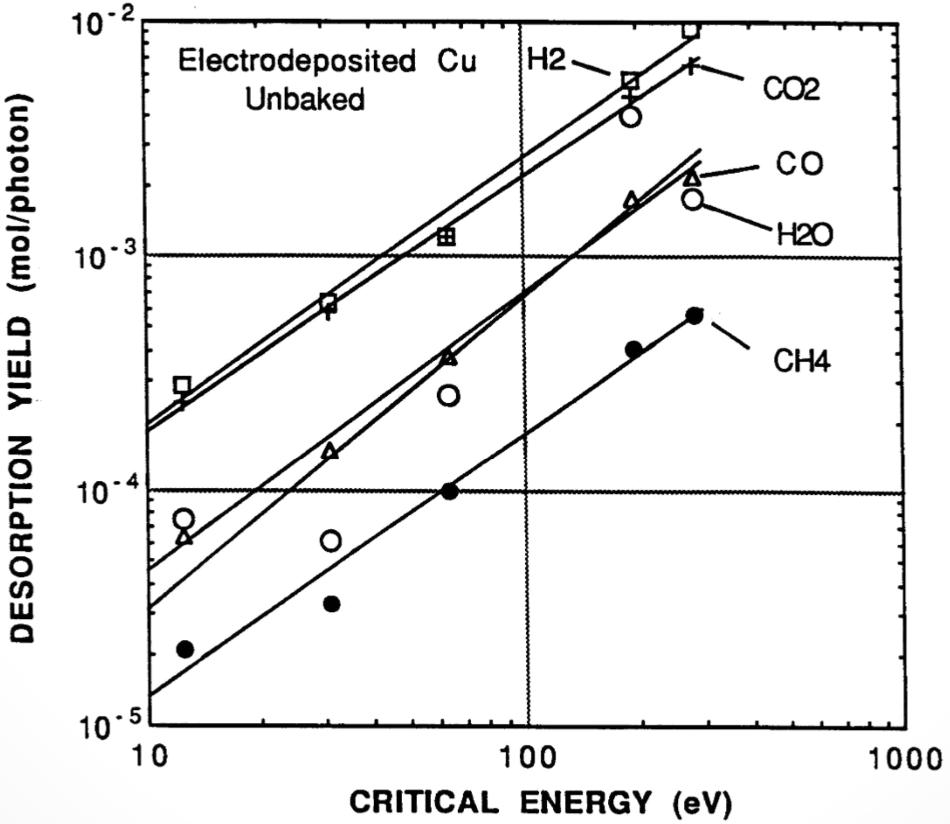
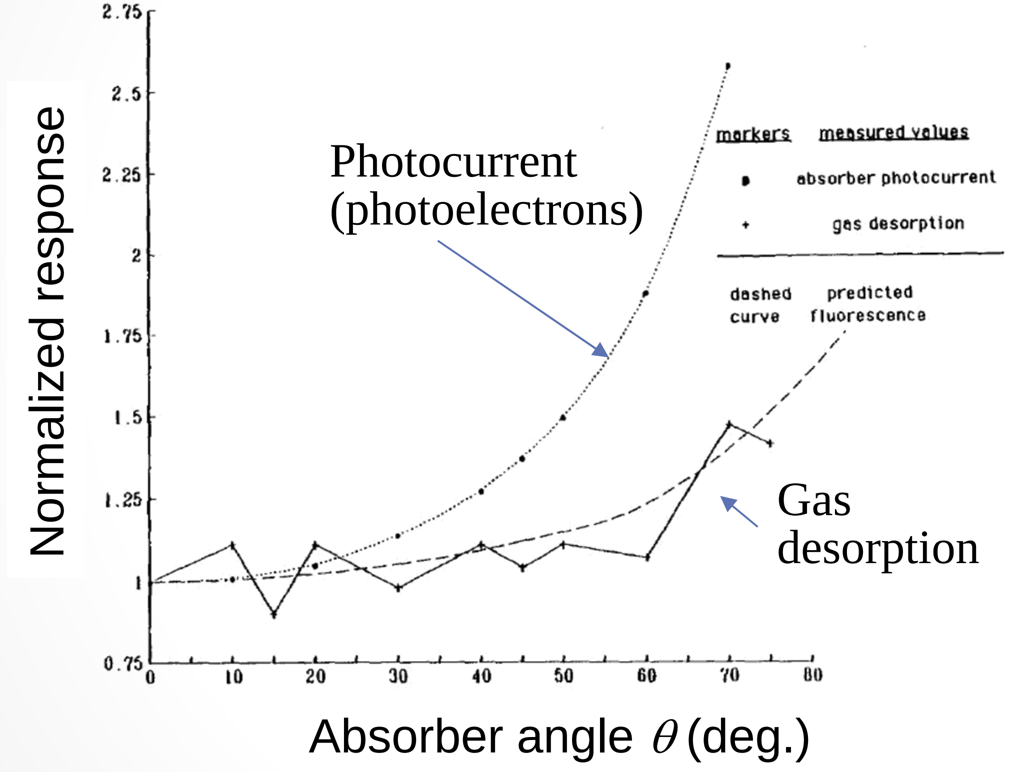


Fig. 10 Fits of the photon induced desorption yields as a function of the photon critical energy for electrodeposited Copper.

J. Gomez-Goni, et al.,
VT Note 93-1, CERN

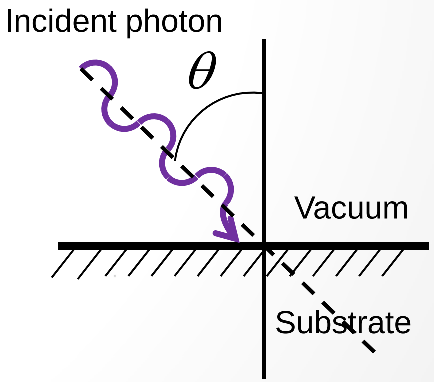
Property of PSD

- Angle dependence
  The shallower the incident angle is, the larger the η is.
  A rough surface can decrease η.



B. A. Trickett et al.,
JVST A10 (1992) 217

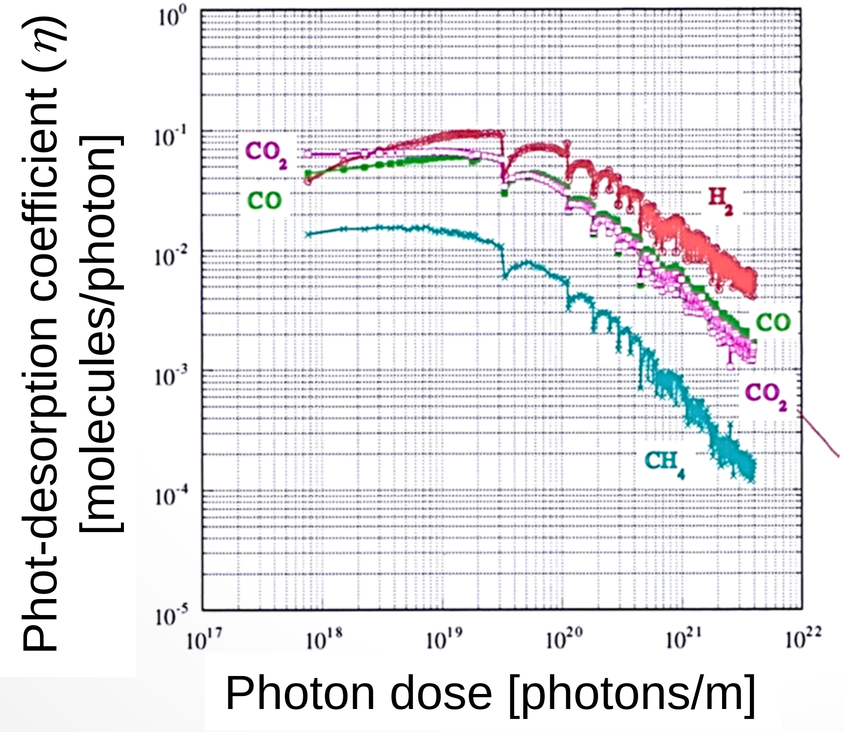
FIG. 4. The effect of absorber angle on gas desorption, shown along with the simultaneous recording of the photoelectron current. The dashed curve illustrates the predicted photon flux arising from fluorescence. All data normalized to the response at normal incidence.



- Note: If the surface is smooth and the incident angle is shallow, the reflection of SR should be taken into account.

Property of PSD

- Aging (Scrubbing)
  - η decreases with integrated photon number (photon dose, D) = Beam aging or scrubbing
  - Typical values of η at the beginning (before SR irradiation are $10^{-3} \sim 10^{-2}$ molecules/photon. η decreases down to $\sim 10^{-7}$ after sufficient aging.



Y. Suetsugu, KEK

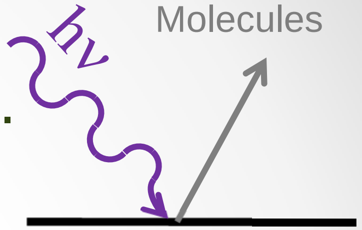
- η decreases as

$$\eta \propto D^{-1\sim-0.6}$$

- In designing the vacuum system, the η of $1\times10^{-5} \sim 1\times10^{-6}$ molecules photon^{-1} are assumed expecting the aging effect.

Property of PSD

- Dependence on surface conditions, materials
  - η also strongly depends on the surface condition.



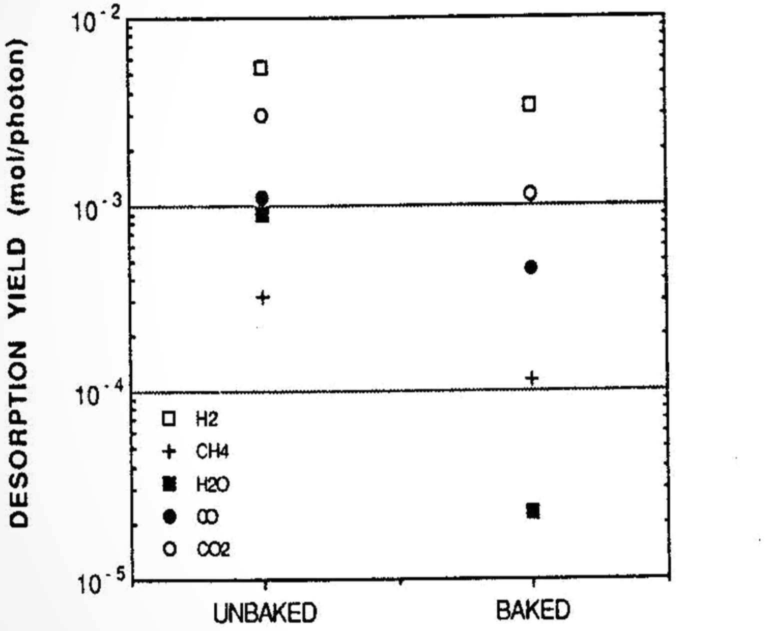
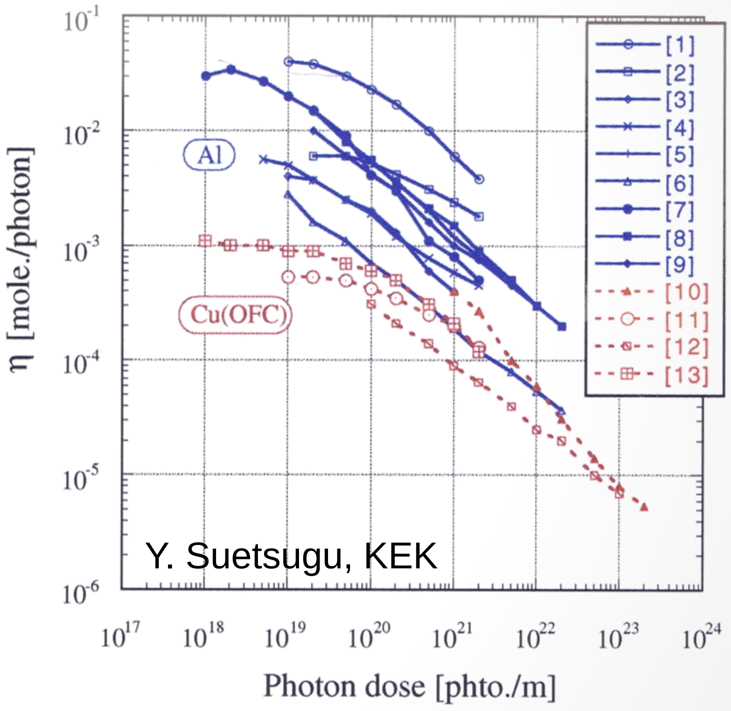


Figure 5. The photon induced desorption yields at 194 eV critical energy from Cu before and after a 150°C, 24 h bakeout.

A.G. Mathewson,
Vacuum (1993) 479

η measurement experiments summary



Y. Suetsugu, KEK

θ_i: 8.7 ~ 100 mrad
Energy: 0.5 ~ 26.3 keV
Surface treatment: Baking, Acid clearning

Effect 2: Gas load

- Estimation of gas load
  - Photon linear density (photon numbers per $1\ \mathrm{m}$ along a ring)

$$\left\langle \dot{N}_{ph,Ie,line} \right\rangle = 8.08\times10^{20}\, E_e[\mathrm{GeV}]\times I_e[\mathrm{A}]/C\,[\mathrm{m}] \quad [\mathrm{photons\ s^{-1}m^{-1}}]$$

For example, if $E_e = 4\ \mathrm{GeV},\ I_e = 2.6\ \mathrm{A},\ C = 3000\ \mathrm{m}$

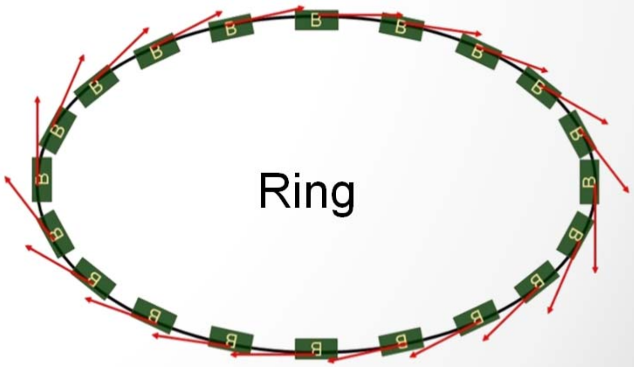
$$\left\langle \dot{N}_{ph,Ie,line} \right\rangle = 8.08\times10^{20}\times4\times2.6/3000$$

$$= 2.8\times10^{18}\ \ \mathrm{photons\ s^{-1}m^{-1}}$$

If $\eta = 1\times10^{-6}$ molecules photon^{-1}

$$\left\langle \dot{N}_{mol,Ie,line} \right\rangle = 2.8\times10^{18}\times1\times10^{-6}$$

$$= 2.8\times10^{12}\ \ \mathrm{molecules\ s^{-1}m^{-1}}$$



Effect 2: Gas load

- Estimation of gas load (contd.)
  - The average line gas desorption rate (gas load) along the ring, $Q_{av,line}$, is (T = 25 °C = 298 K)

$$Q_{av,line} = \left\langle \dot{N}_{mol,Ie,line} \right\rangle \times k_B T = 2.8\times10^{12} \times 1.38\times10^{-23} \times 298$$
$$= 1.1\times10^{-8} \boxed{\mathrm{Pa\ m^3 s^{-1} m^{-1}}}$$

Here we used the equation of ideal gas:

$$PV = N_{mol} k_B T$$

P: Pressure, V: Volume,
k_B: Boltzmann constant, T: Temperature

This expression is convenient in designing vacuum system.

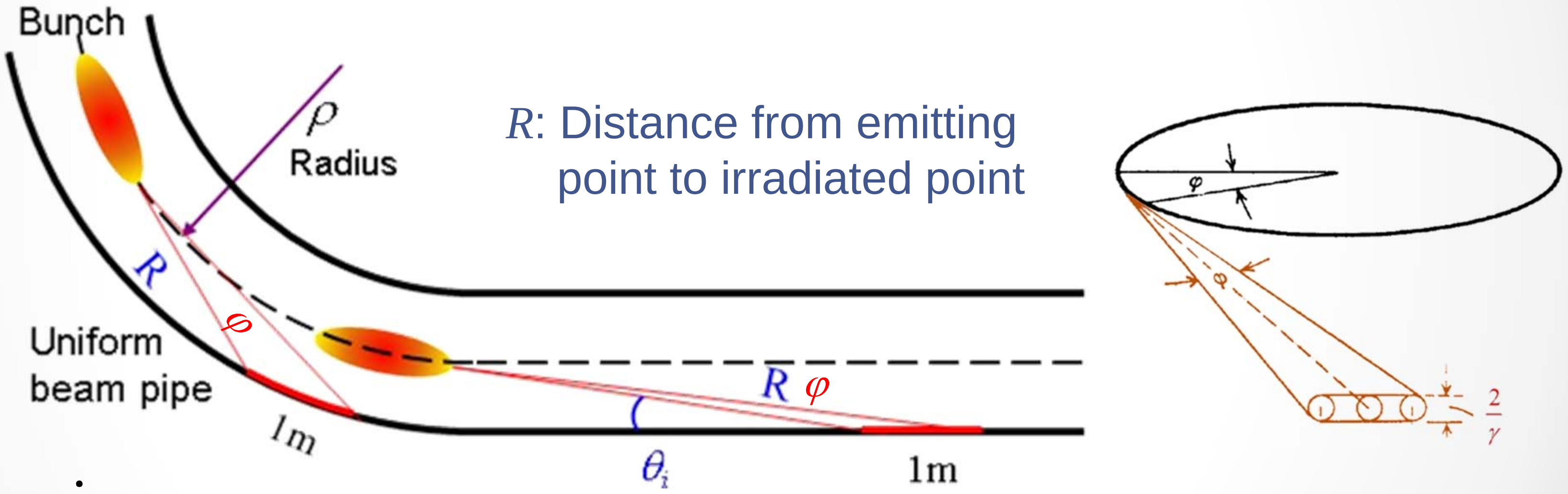
- If an average linear pumping speed is, $S_{av,line}$ [$\mathrm{m^3\ s^{-1}\ m^{-1}}$], along the ring, the obtained average pressure, P_{av} [Pa], is

$$P_{av} = \frac{Q_{av,line}}{S_{av,line}}$$

$$Q_{av,line} = P_{av} S_{av,line}$$

Effect 2: Gas load

- Actually, the photon line density depends on the distance from the emitting point of SR to the irradiated point, R, and the incident angle, θ_i, as in the case of SR power density.
  - Vertical spread of SR, $\sim 2/\gamma$, is not so important in this case.



R: Distance from emitting point to irradiated point

$$\dot{N}_{ph,Ie,line} \propto 1/R$$

(inside of magnet)

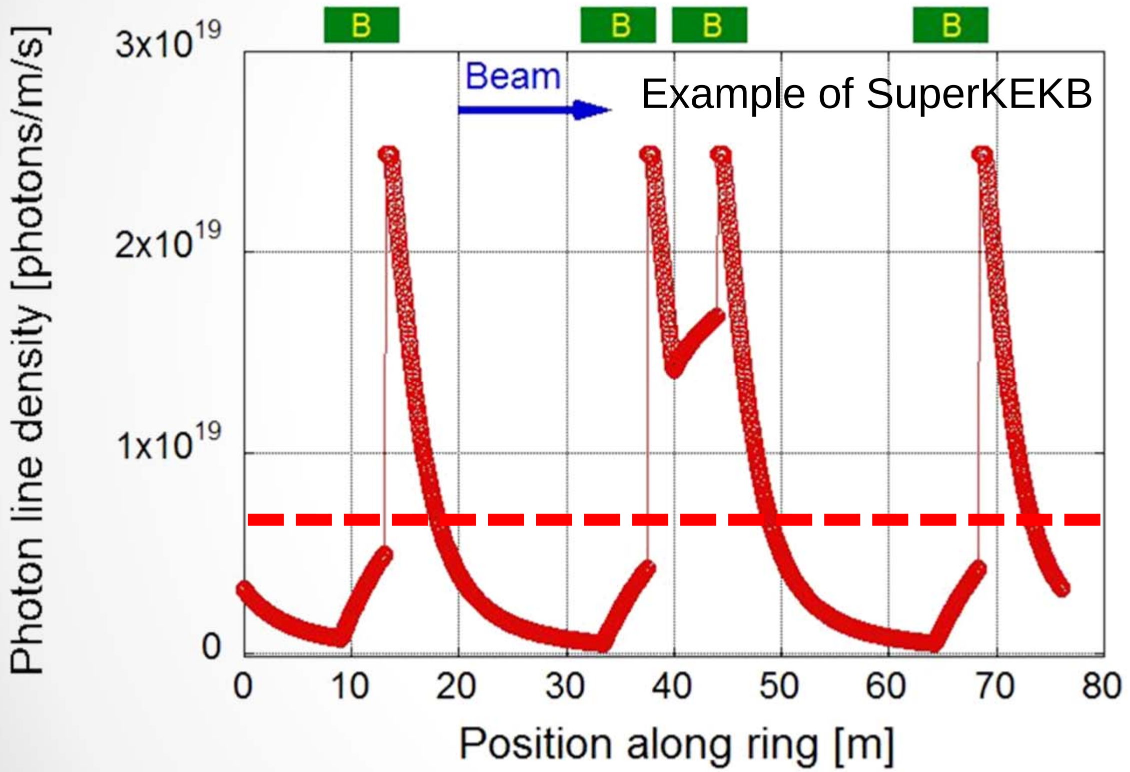
$$\dot{N}_{ph,Ie,line} \propto 1/R \times \theta_i \propto 1/R^2$$

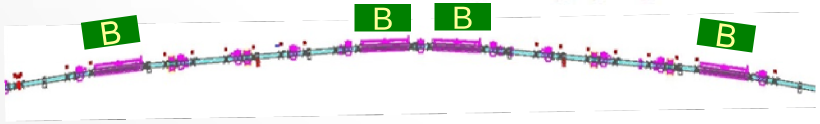
(outside of magnet)

Almost constant in a magnet for SR emitted in the same magnet (θ_i, R~const.)

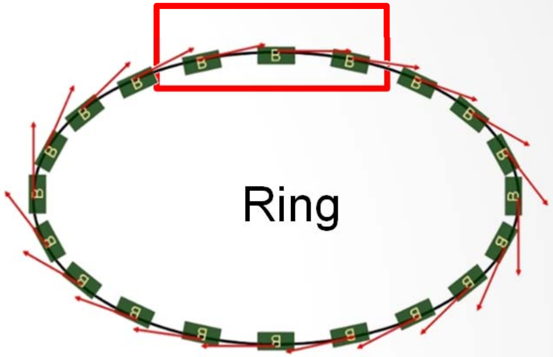
Effect 2: Gas load

- Distribution of gas load ~ Distribution of photons
  - Basically gas load is high at downstream of bending magnets, as in the case of heat load.





(Direct photons, and the reflection is neglected.)



Average photon line density

~5.5×10^{18} photons s^{-1} m^{-1}

Maximum photon line density

~3×10^{19} photons s^{-1} m^{-1}

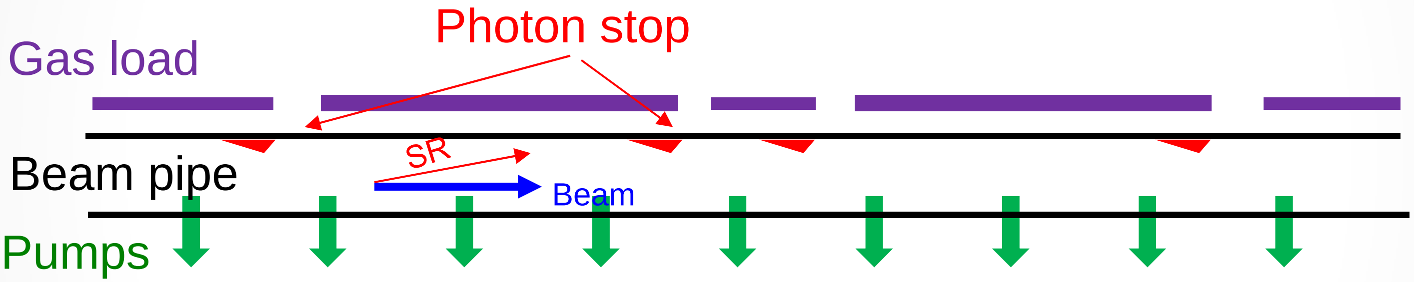
Note: Actually, the distribution of gas load is NOT that of photons due to PSD dependence on the beam dose and θ_i. The difference is reduced with time.

How to treat gas load

- Basic principle: Prepare pumps at places where photons are irradiated.
- There are two ways to treat gas load:

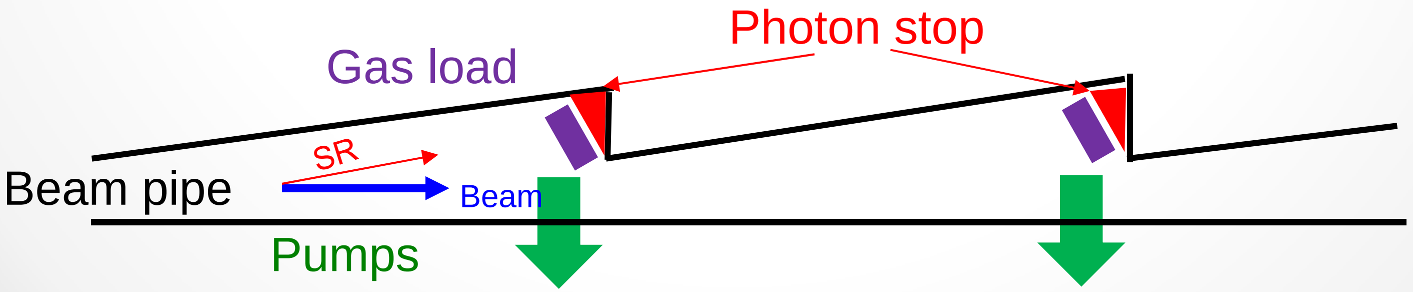
(1) Distributed pumping

- Works well with the distributed photon stops.



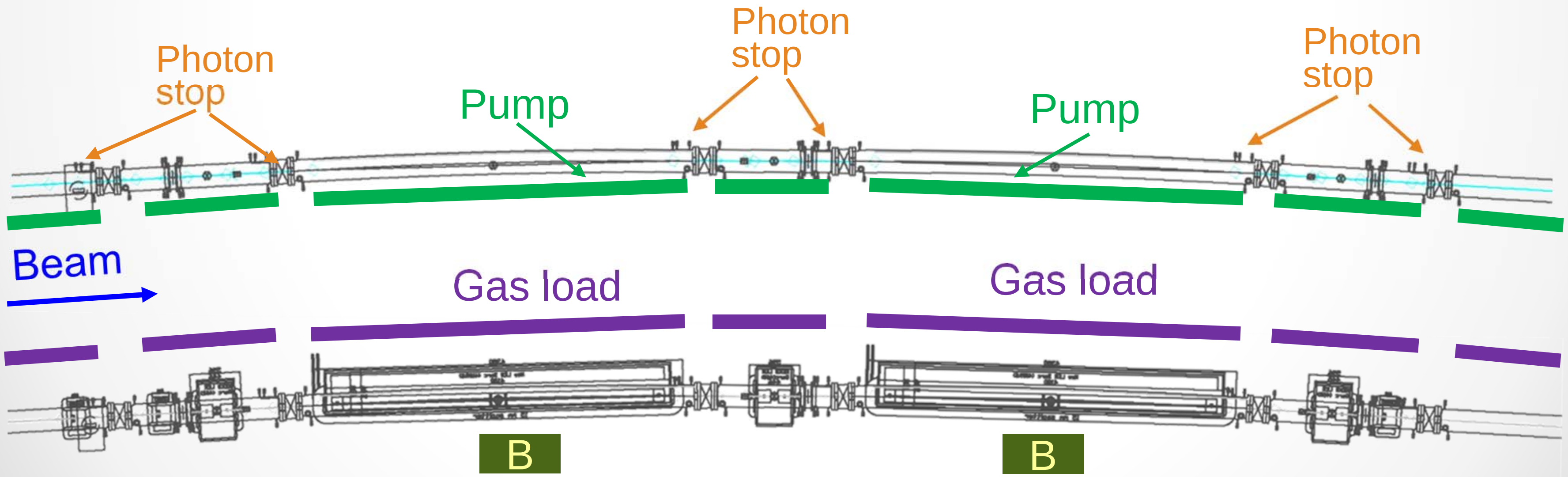
(2) Localized pumping

- Works well with the localized photon stops (reasonable way)



How to treat gas load

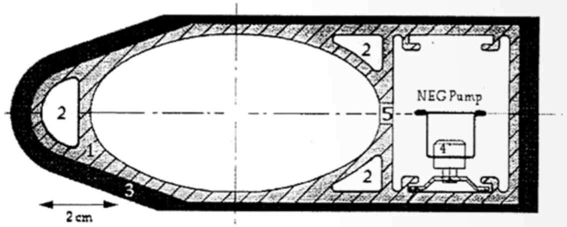
- Distributed pumping
  - Usually, the beam pipes are very narrow and long. So the conductance of them is small, typically < 0.1 $m^3 s^{-1} m^{-1}$.
  - Pumps are located along the beam pipe, just side of the beam channel. The beam pipe is effectively evacuated, if the gas load is distributed along the ring.
  - Relatively simple beam pipe, smooth inner surface.



SuperKEKB, KEK

How to treat gas load

- Distributed pumping
  - Distributed pumps
    - Distributed sputter-ion pump(DIP)：
      Sputter-ion pump using the magnetic filed of bending magnet
      Popular until ~1990.
    - NEG(Non evaporable getter pump)
      NEG strips along the beam pipe
      Coating inside is popular now

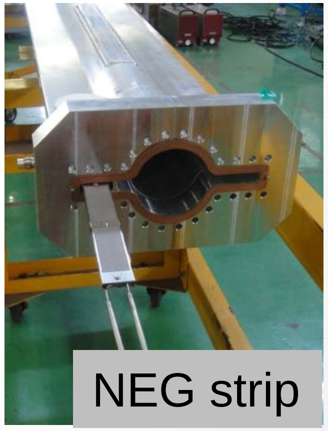


(LEP, CERN)

DIP (TRISTAN, KEK)

http://indico.cern.ch/getFile.py/access?contribId=29&resId=1&materialId=slides&confId=169352

NEG strip

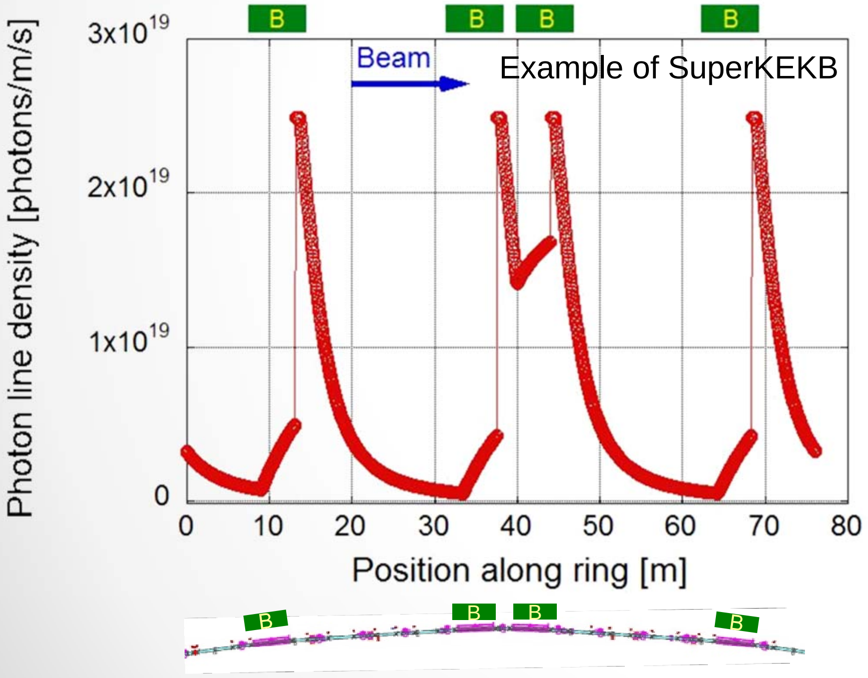


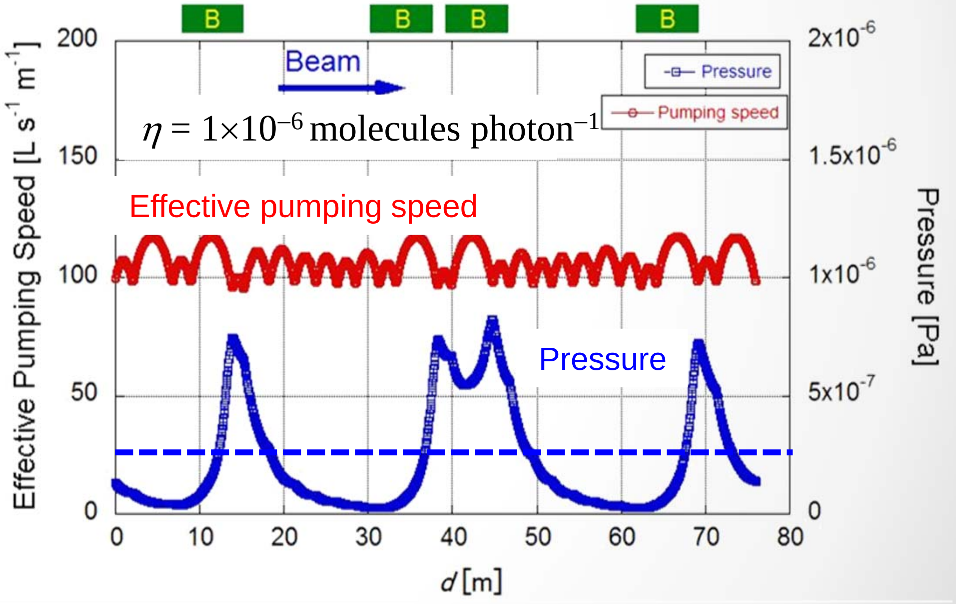
NEG strip

(SuperKEKB, KEK)

How to treat gas load

- In the case of the previous example, if we use a distributed pumping system with an average pumping speed of ~0.11 $\mathrm{m^3\ s^{-1}\ m^{-1}}$, the average pressure of 2.3×10^{-7} Pa is obtained. (for $\eta = 1\times10^{-6}$ molecules photon^{-1})
  - The similar profile to that of photon line density is obtained.



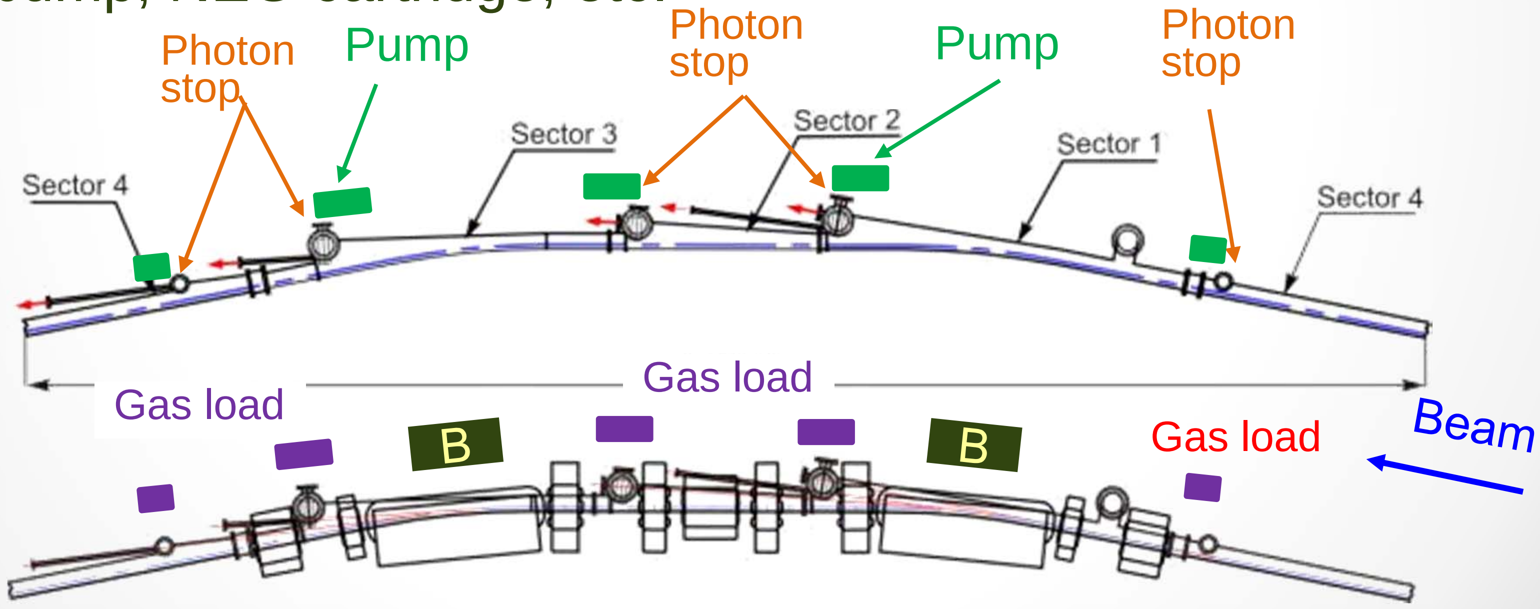


Average pressure = 2.3×10^{-7} Pa

(Direct photons, and the reflection is neglected.)

How to treat gas load

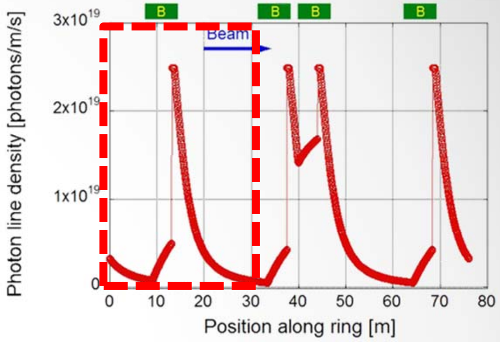
- Localized pumping
  - Place photon stops locally, usually at downstream of bending magnets.
  - Localize photons = Localize gas load
  - Concentrate pumps where the gas load is large.
    ⇒ Reasonable approach
  - Turbo-molecular pump, Sputter ion pump, Ti-sublimation pump, NEG cartridge, etc.



V. Avagyan, EPAC 2002, p.2532

How to treat gas load

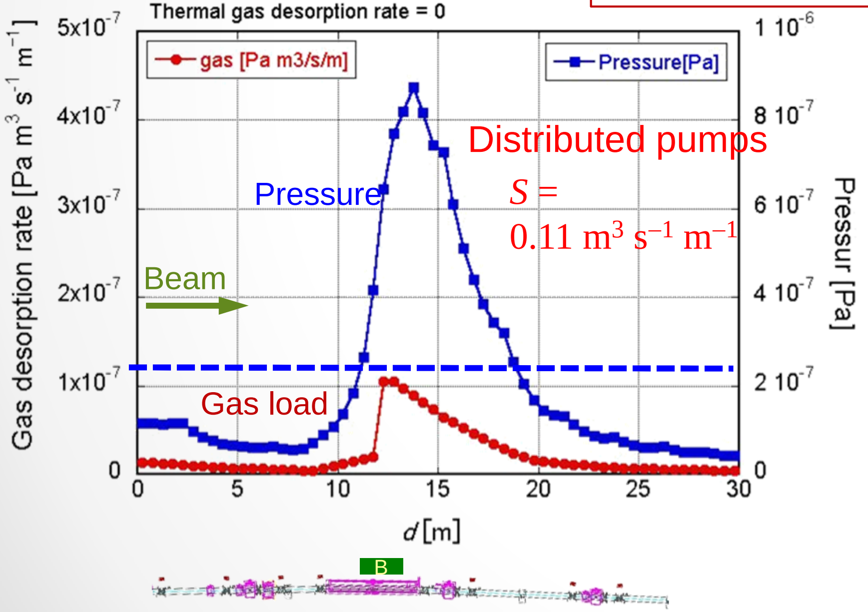
- Consider again the previous case.
  - If localized pumps are used as below, and the thermal gas desorption is ignored, a lower average pressure is obtained compared to the case of distributed pumping with smaller pumping speeds.

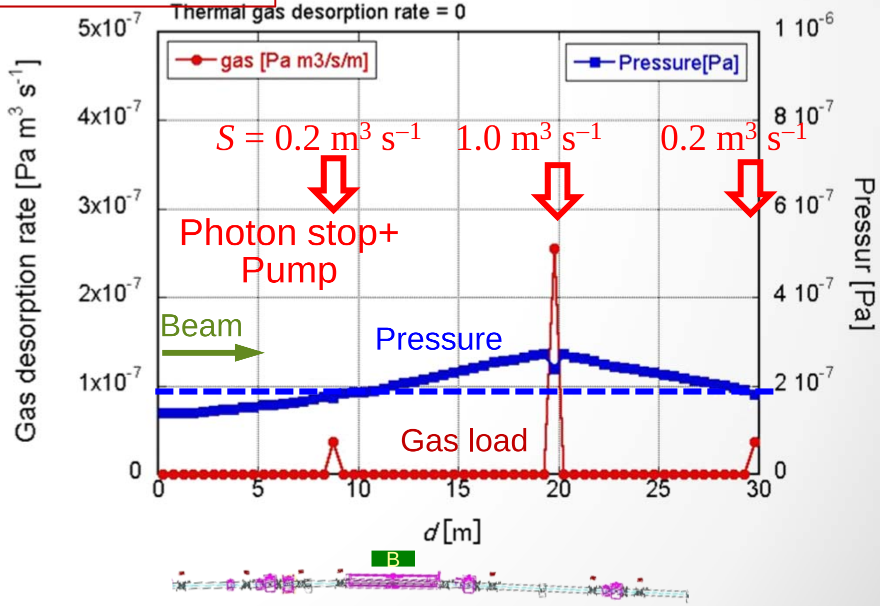


Distributed pumping

No thermal gas desorption

Localized pumping





Average pressure = 2.3×10^{-7} Pa

Average pressure = 2.0×10^{-7} Pa

How to treat gas load

- Comparison between distributed and lumped pumps
  - Distributed pumping system
    - Work with distributed photon stops
    - Relatively simple structure of beam pipes
    - Uniform pumping speed along the ring
    - Similar pressure profile to the photon distribution
  - Localized pumping system
    - Work with localized photon stops
    - Relatively complicated structure of beam pipes
    - Reasonable approach to realize ultra high vacuum, and adopted for recent photon sources.
    - Low thermal gas desorption is essential.

(Distributed photon stops)

SuperKEKB, KEK

(Localized photon stops)

TPS, NSRRC

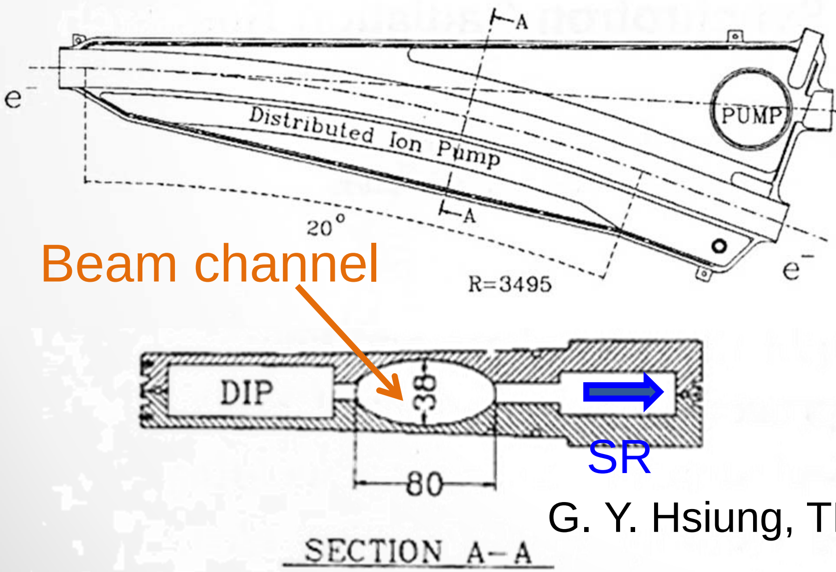
How to treat gas load

- Other effective countermeasures
  - To avoid contamination during the manufacturing and assembling processes of beam pipes is essential .
    - Clean environment during assembling
    - Surface treatment:
      - Chemical cleaning
      - Argon grow discharge
    - Pre-baking is effective to reduce thermal gas desorption.

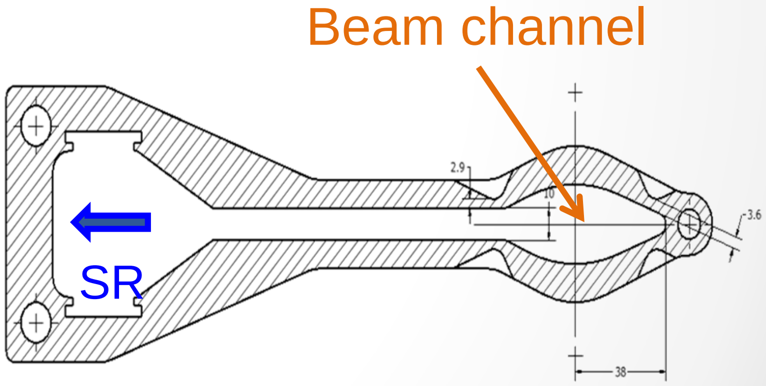
SuperKEKB,
KEK

How to treat gas load

- Other effective countermeasures (contd.)
  - Antechamber scheme
    - Photons hit photon stops in the antechamber which is separated from beam channel.
    - Desorbed gas is confined in the antechamber.
    - Usually adopted for the localized photon stop scheme.
    - Relatively smooth beam channel ⇒ low beam impedance.



G. Y. Hsiung, TPS



H. C. Hseuh, NSLS-II

Effect 2: Gas load

- Exercise

  Calculate

  (1) average photon line density along the ring

  (2) average gas load in the unit of [Pa m^3 s^{-1} m^{-1}]

  for a ring with $E_e = 7$ GeV, $I_e = 2$ A, $\rho = 100$ m, C = 2000 m, where $\eta = 1\times10^{-5}$ molecules photon^{-1} and $T = 25$ °C (298 K) .

- Solution

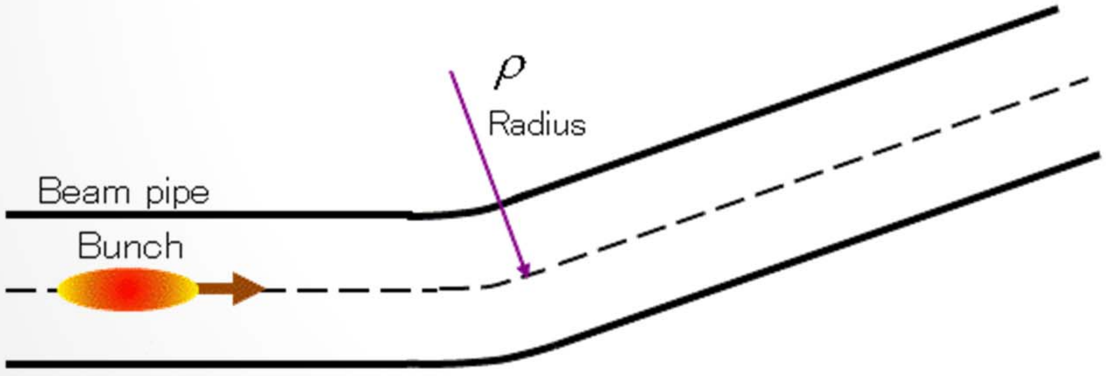
  (1) $\left\langle \dot{N}_{ph,Ie,line} \right\rangle = 8.08\times10^{20}\, I[\mathrm{A}] E_e[\mathrm{GeV}]/\mathrm{C[m]}$

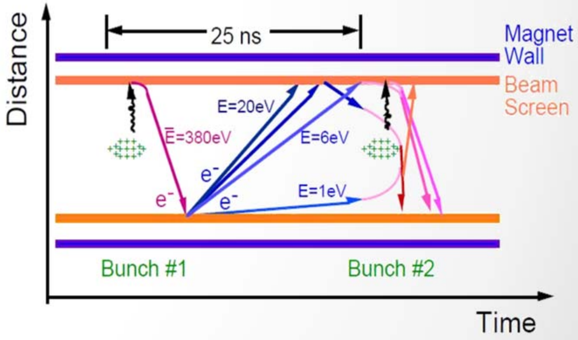
  (2) $\left\langle \dot{N}_{mol,Ie,line} \right\rangle = \left\langle \dot{N}_{ph,Ie,line} \right\rangle \times \eta$

  $$Q_{ave,line} = \left\langle \dot{N}_{mol,Ie,line} \right\rangle \times k_B T$$

Effect 3: Electron emission

- Electron emission from surface - 1
  - The SR hitting on the surface emits photoelectrons, as described before.
    - Quantum efficiency η_e ~0.1 electrons photon^{-1}
  - If the beams are positively charged (i.e., positrons or protons), they attract the electrons.
  - The electrons accelerated by the beam's electric field hit the surface, and emit electrons ⇒ secondary electrons

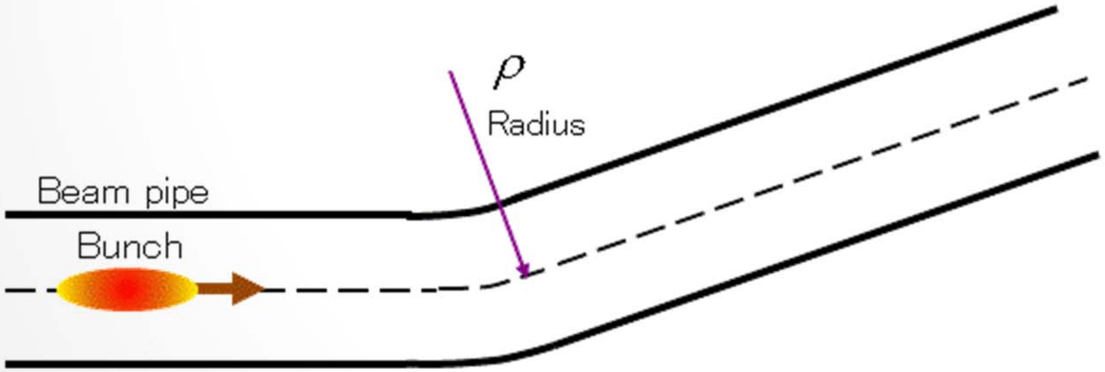


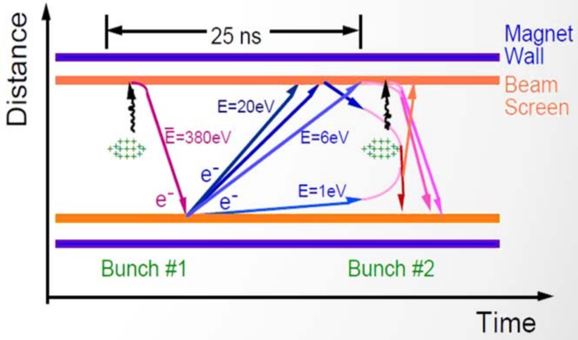


“EXPERIMENTAL INVESTIGATIONS OF THE ELECTRON CLOUD KEY PARAMETERS”, V. Baglin et al.

Effect 3: Electron emission

- Electron emission from surface - 2
  - If the secondary electron yield (SEY) is larger than 1, the enhancement of electrons (multipactoring) occurs.
  - This positive feedback leads to the accumulation of electrons around the beams.
  - The electrons forms “electron cloud” around the beam orbit.

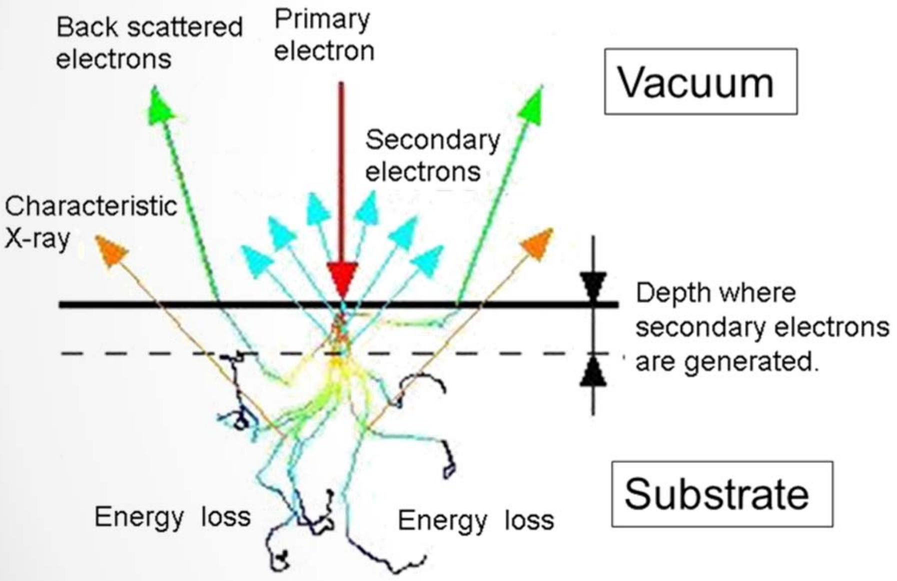


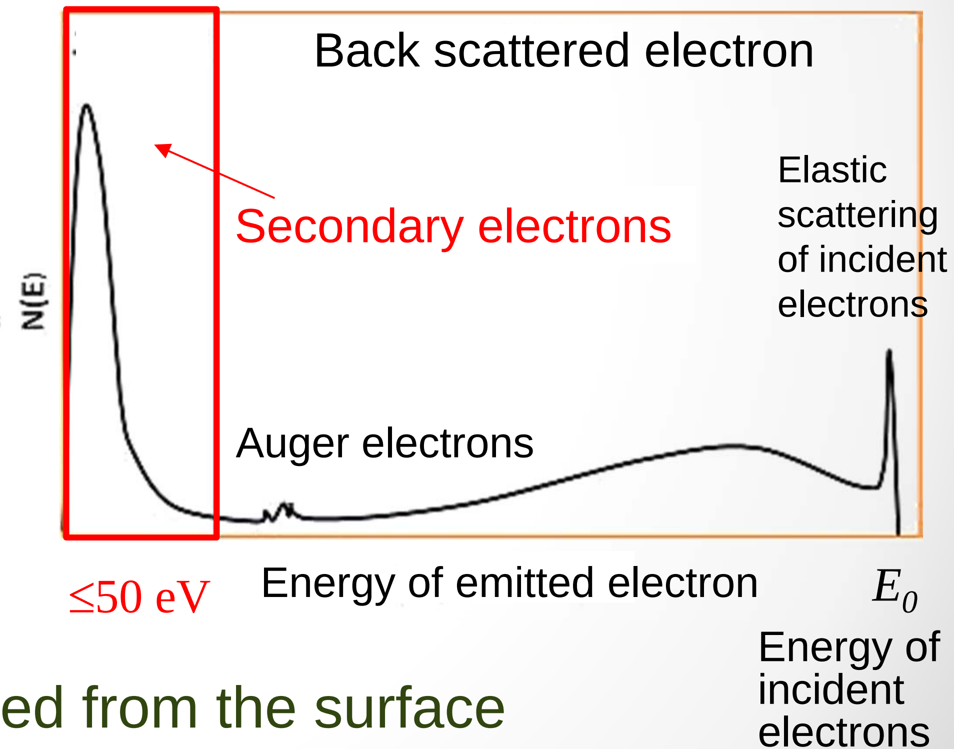


“EXPERIMENTAL INVESTIGATIONS OF THE ELECTRON CLOUD KEY PARAMETERS”, V. Baglin et al.

Property of SEY

- Process of SEY and energy spectrum of secondary electrons
  - Process of SEY
  - Energy spectrum of emitted electrons





- Secondary electrons are emitted from the surface following the cosine law, i.e., uniformly.

Property of SEY

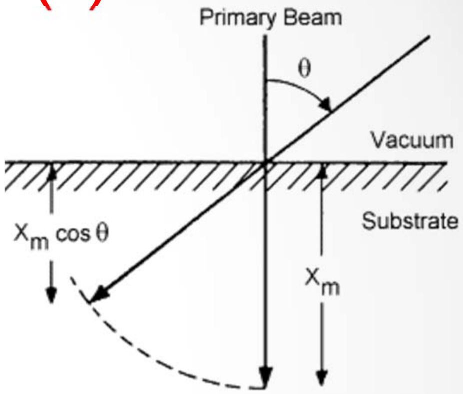
- Dependence on the angle of incident electrons
  SEY (δ) increases for large incident angle (θ).
  - For shallow incidence, generated electrons along the path of incident electron can easily escape to vacuum.
  - For $\theta \sim 0°$

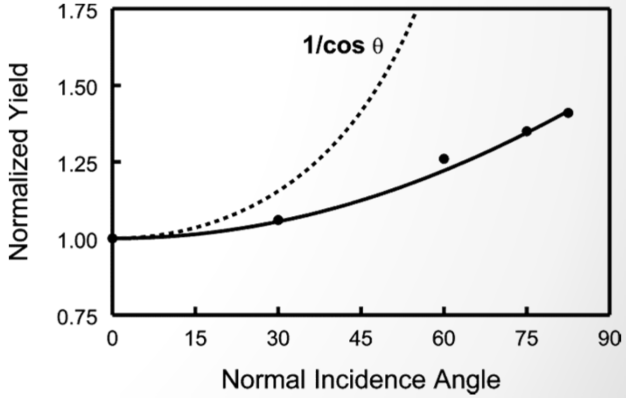
$$\delta \approx \frac{\delta_{\max}}{\cos\theta}$$

  - For $\theta \to 90°$

$$\delta \approx \delta_{\max} e^{\alpha X_m (1-\cos\theta)}$$

X_m: Depth at which secondary electros are generated at normal incidence
α: Absorption rate





$\alpha X_m \sim 0.4$

R. E. Kirby et al.,
NIM-A 469 (2001) 1

Property of SEY

- Dependence on the energy of incident electron
  SEY (δ) has a maximum at the incident electron energy of 200~400 eV, and decreases gradually with the energy.
- Two formula of δ are usually used for the simulation.

$$\delta(E_r) \approx \delta_{\max} \times 1.11 E_r^{-0.35}\left(1-e^{-2.3E_r^{1.35}}\right)$$

δ_{max} : Maximum yield for perpendicular incident
$E_r \equiv E_p / E_p{}^m$
E_p : Energy of incident electron
$E_p{}^m$: Primary energy at which the yield is maximum. Usually, 200~400 eV.

$$\delta(E_r) \approx \delta_{\max} \frac{s \times \frac{E_p}{E_p^m}}{s-1+\left(\frac{E_p}{E_p^m}\right)^s}$$

s ~ 1.4.

F. Zimmermann, SLAC-PUB-7664 (1997)

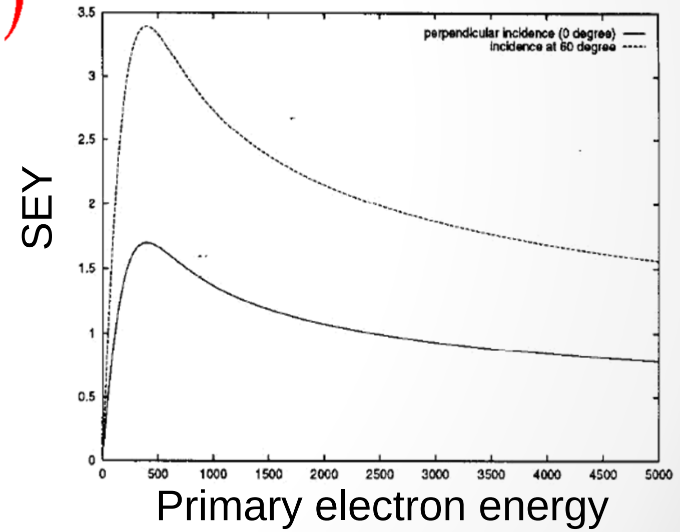


Figure 1: Secondary emission yield, Eq. (6), as a function of the primary electron energy (in eV), for 0° and 60° incident angle with respect to the surface normal; the maximum emission yield for perpendicular incidence was chosen as $\delta_{max} = 1.7$.

Property of SEY

- Decrease in SEY with electron dose (integrated electrons per unit area) : Aging or conditioning
- SEY also strongly depends on the surface conditions.

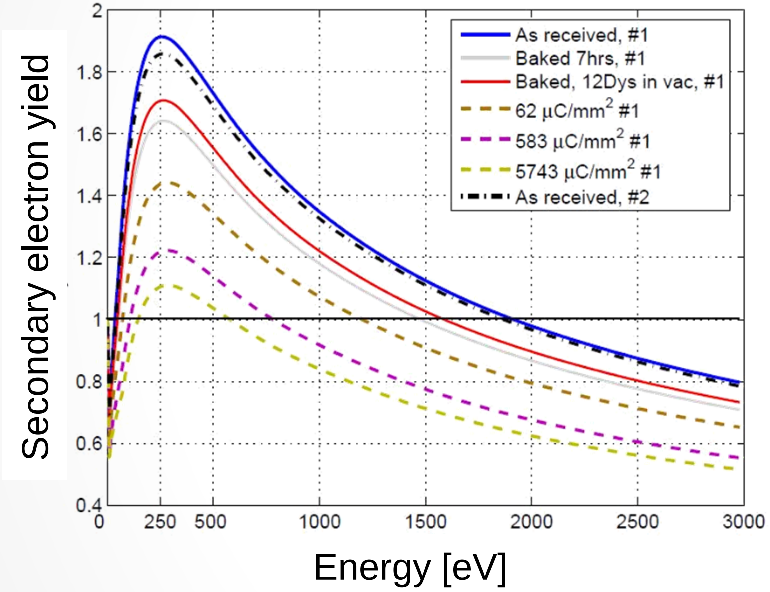


Figure 2: SEY of TiN/Al under different conditions. As-received (#1 and #2), baked at 150°C, vacuum recontamination after 12 days at 5.10^{-10} Torr and conditioning by 130 eV electrons. Measurement performed at 23° primary incidence.

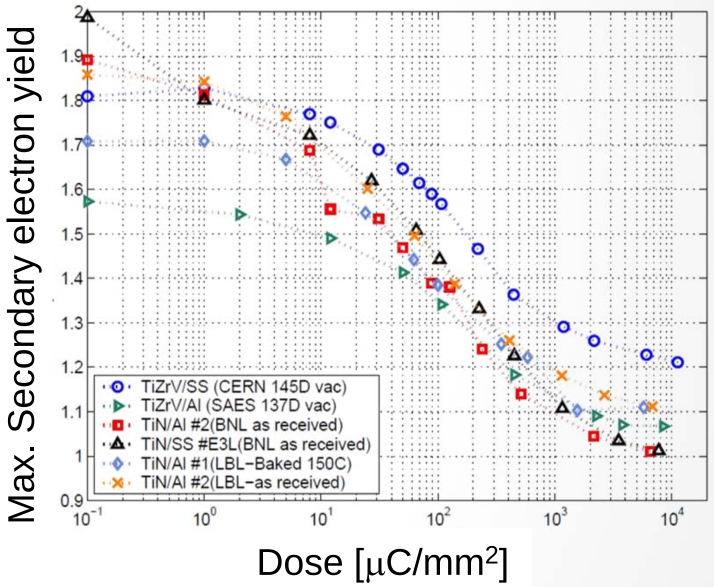


Figure 3: SEY of TiN and TiZrV getter under exposure by 130 eV electrons. Measurement performed at 23° primary incidence.

“Summary of SLAC’S SEY Measurement On Flat Accelerator Wall Materials”, F. Le Pimpec

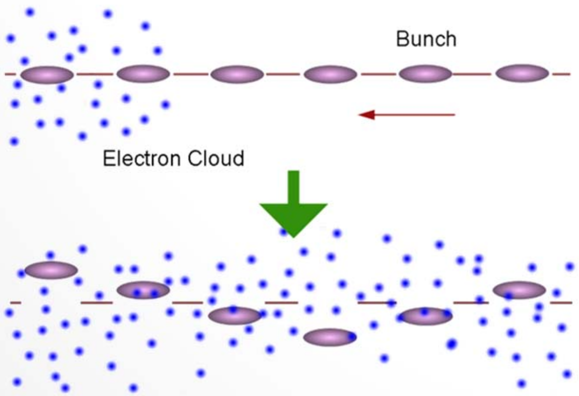
Electron cloud effect

- If the electron density around the beam exceeds a threshold value, the electron cloud excites an beam instability.
  ⇒ Electron cloud instability
  - Displacement of bunch effects the following bunches via electron cloud.

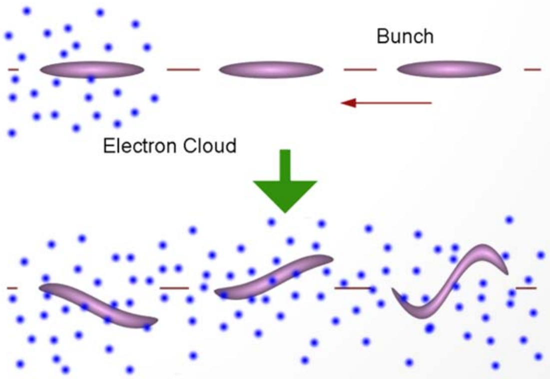
    Displacement of the top bunch ➡ Perturbation of electron cloud (Wake Field)

  - Two types of instabilities: Head-tail instability is serious.

Coupled bunch instability



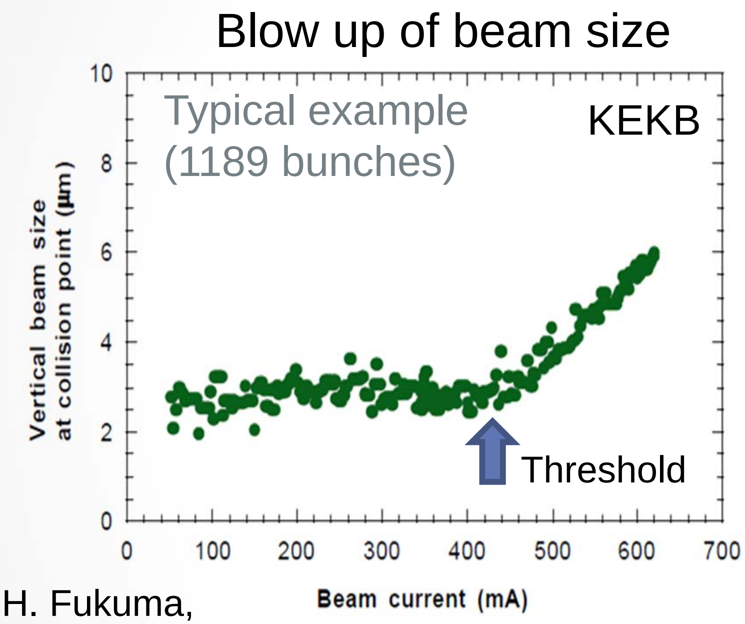
Head-tail instability



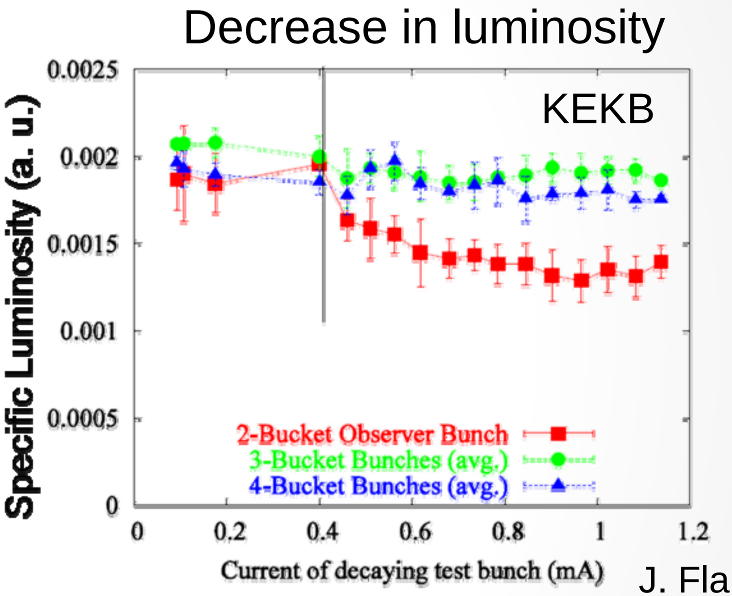
Electron cloud effect

- Electron cloud instability leads to the blow up of beam size.

  ⇒ Decrease in the luminosity in colliders



H. Fukuma,
KEK



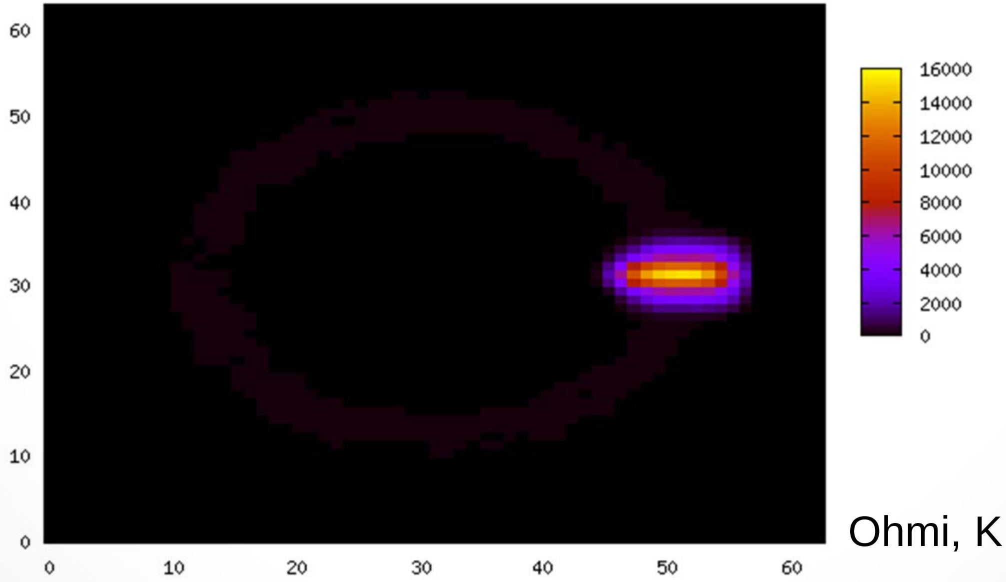
J. Flanagan,
KEK

- Critical issue in the recent high-intensity proton and positron storage rings.

Electron cloud effect

- Lots of studies have been done in various accelerators
  - Formation of electron cloud
  - Simulation of beam instability
  - Countermeasures against ECE
- Results are presented in many workshops, such as ECLOUD’10 , 12 etc..

Simulation of electron cloud formation



Ohmi, KEK

Electron cloud effect

- Threshold of electron density to excite instability

K. Ohmi , KEK Preprint 2005-100 (2006)

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_{e,y}\sigma_z/c}{\sqrt{3}KQr_e\beta L}.$$

$$\omega_{e,y} = \sqrt{\frac{\lambda_+ r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

E [GeV]	= 4.0			
γ	= 7828	N_b	= 6.25E+10	
ν_s	= 0.026	Q_b[C]	= 1.4E-08	(1.4 mA/bunch)
		S_b [m]	= 1.2	(4ns)
σ_z [m]	= 6.E-03	λ [C/m]	= 5.2E+12	($Q_b/2/\sigma_z$)
c [m/s]	= 3.E+08	σ_y [m]	= 2.E-05	
K	= 11	σ_x [m]	= 2.E-04	
Q	= 7			
r_e [m]	= 2.80E-15	ω_e	= 5.46E+11	$K = \omega_e\ \sigma_z/c$
β_y [m]	= 25	$\omega_e\ \sigma_z/c$	= 10.9	$Q = \mathrm{Min}(Q_{nl},\ \omega_e\ \sigma_z/c)$
L [m]	= 3016			Q_{nl} ~7

For example, in the case of SuperKEKB

$$(\ E_e = 4\ \mathrm{GeV},\ I_e = 3.6\ \mathrm{A})$$

$$\rho_{e,th} = 2\times10^{11}\ [\mathrm{electrons\ m^{-3}}]$$

Electron cloud effect

- Rough estimation of photoelectron numbers
  - For E_e = 4 GeV, I_e = 3.6 A, C = 3000 m, the average photon linear density along the ring is

$$\left\langle \dot{N}_{ph,Ie,line} \right\rangle = 8.08\times 10^{20}\, E_e[\mathrm{GeV}]\times I_e[\mathrm{A}]/C[\mathrm{m}]$$

$$= 8.08\times 10^{20} \times 4 \times 3.6/3000 = 3.9\times 10^{18} \quad \text{photons s}^{-1}\text{m}^{-1}$$

If the quantum efficiency (η_e) is 0.1, the emitted photoelectron number is

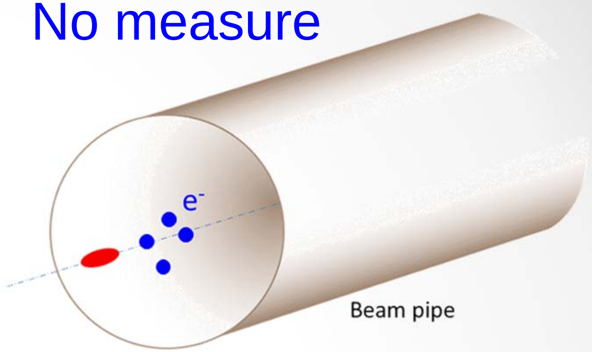
$$\left\langle \dot{N}_{ele,Ie,line} \right\rangle = \eta_e \times \left\langle \dot{N}_{ph,Ie,line} \right\rangle = 3.9\times 10^{17} \quad \text{electrons s}^{-1}\ \text{m}^{-1}$$

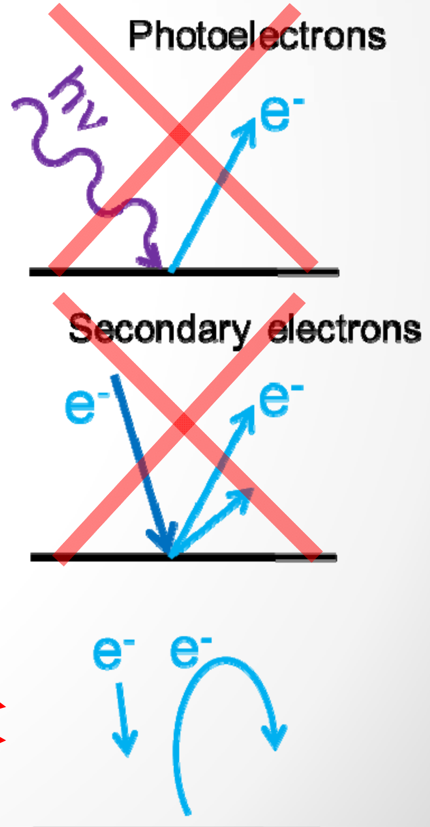
  - The density of ~2×10^{11} electrons m^{-3} is easily achieved if no countermeasure are not adopted.

How to treat ECE

- Countermeasures against ECE
  - Suppress electron emissions
  - Remove electrons around beams
- Various countermeasures have been proposed and studied, and some have been applied actually.
  - Beam pipe with antechamber
  - Rough surface
  - Coating with low secondary electron yield
  - Grooved surface
  - Solenoid field
  - Clearing electrode

No measure



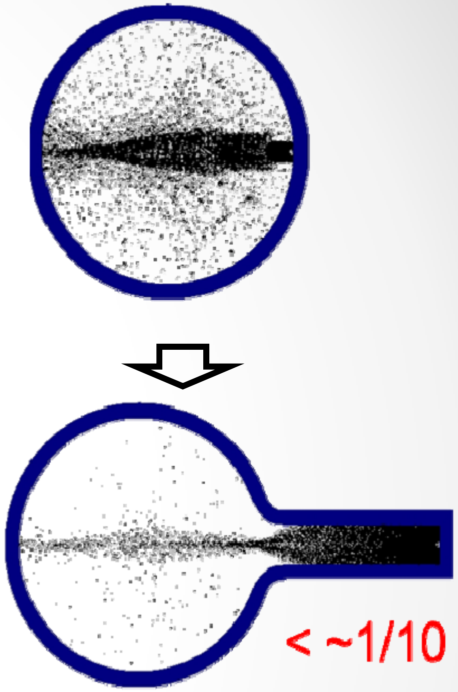


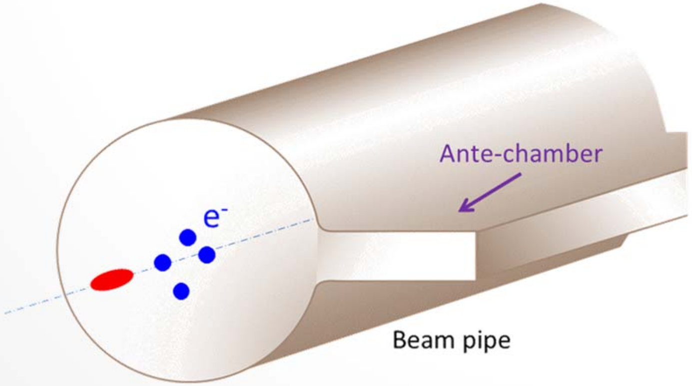
How to treat ECE

- Beam pipe with antechambers
  - SR is irradiated at the side wall of antechamber, far from the beam.

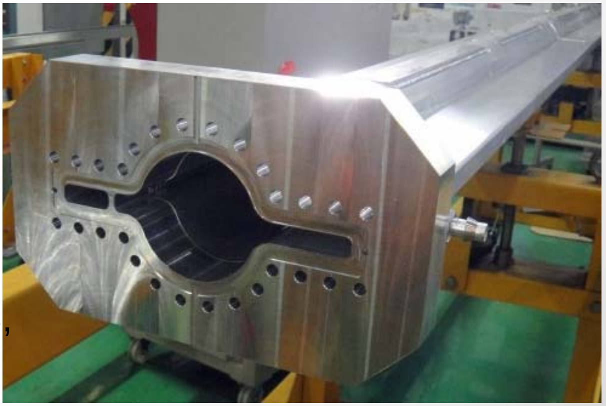
    ⇒Photoelectrons are difficult to approach to the beam.
  - Note that the some photons hit out side of antechamber at far from the photon source due to the vertical spread of ~$2/\gamma$.
  - Furthermore, multipactoring of secondary electrons becomes more significant for large beam current.

    ⇒Effective at low beam currents





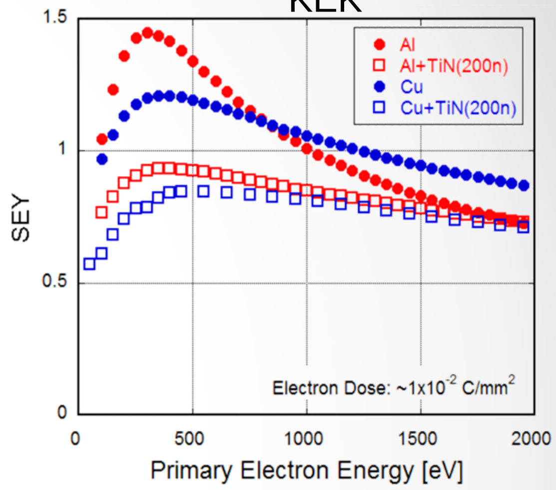
SuperKEKB, KEK

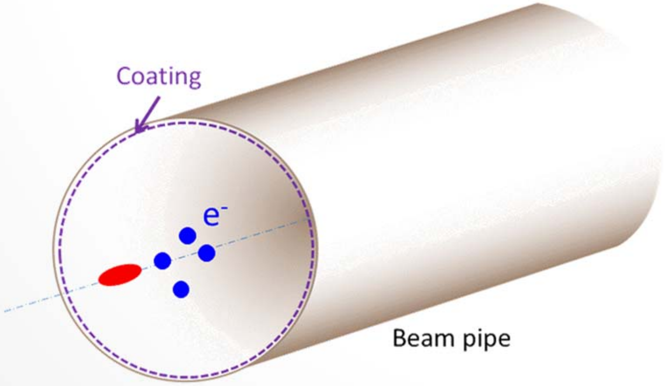


Electron cloud issue

- Inner coating with a low SEY
  - At high beam currents, the main mechanism of forming the electron cloud is the multipactoring of secondary electros.
  - In this point of view, some inner coatings with low SEY are effective to suppress the electron cloud forming.
  - Possible candidates: TiN, Graphite, NEG (non-evaporable getters)

K. Shibata, KEK





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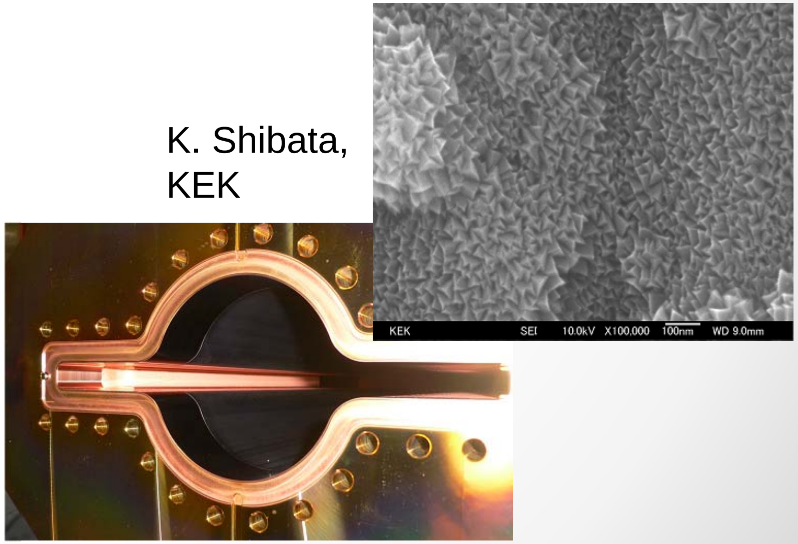
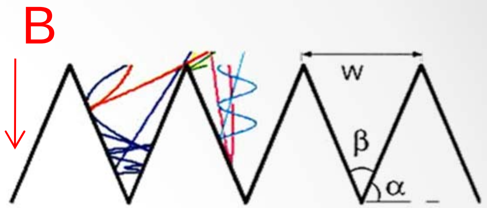
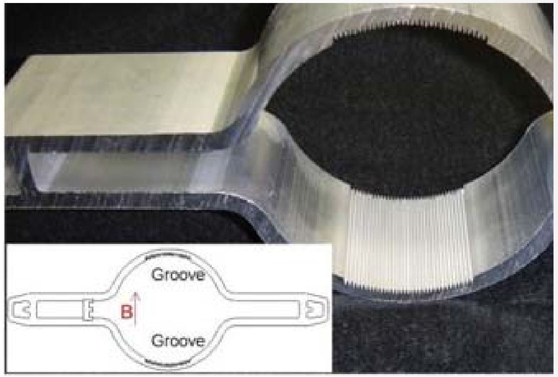


Electron cloud issue

- Groove surface
  - A surface with groove structure is found to have a low SEY.
  - The SEY structurally reduces, especially in magnetic field.
  - Coating on the groove enhanced the reduction of SEY.
  - One concern is the impedance.



by L. Wang et al., EPAC2006, p.897



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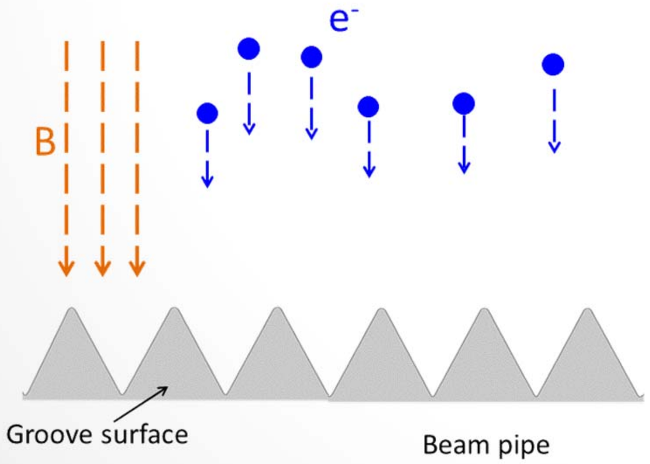
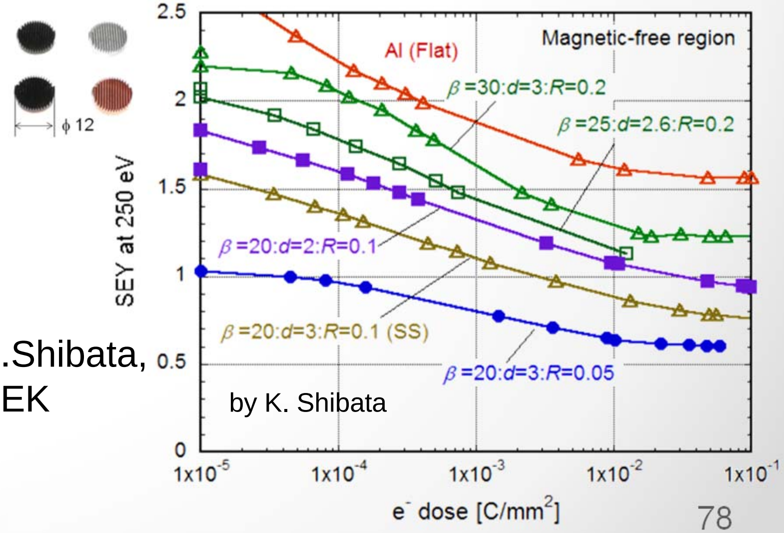
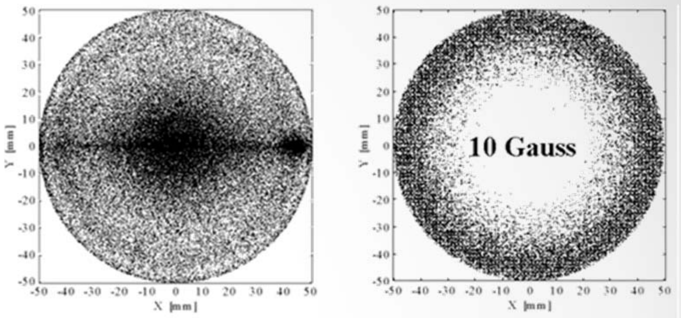




K.Shibata, KEK

How to treat ECE

- Solenoid filed
  - Magnetic filed along the beam pipe.
  - Electrons emitted from the surface return to the surface due to the Larmor motion.
  - Emitted photoelectrons or secondary electrons have an energy of several tens eV. So, several tens gausses are enough.
  - Drastic effects were observed in PEP-II and KEKB B-factory.



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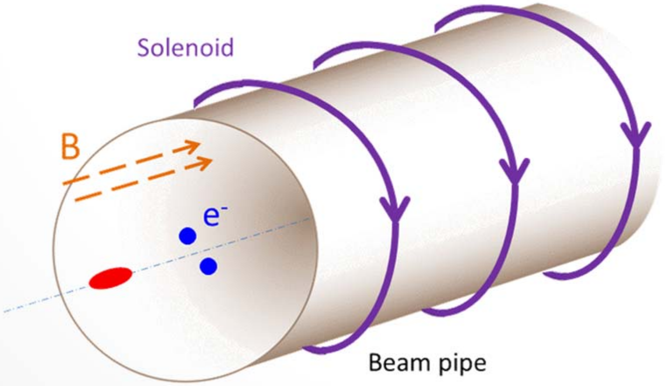
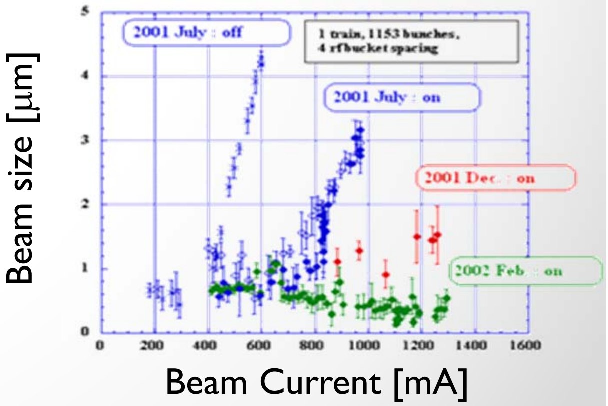


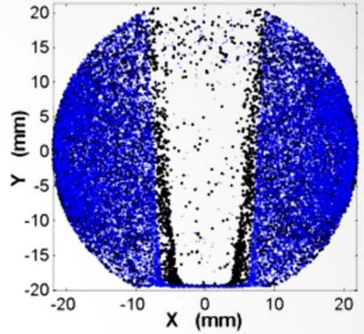


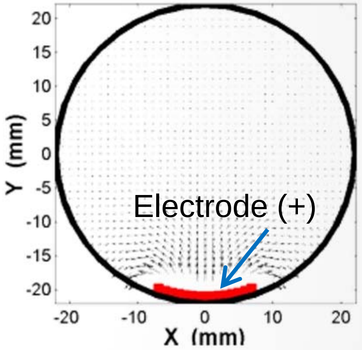
H. Fukuma,
KEK

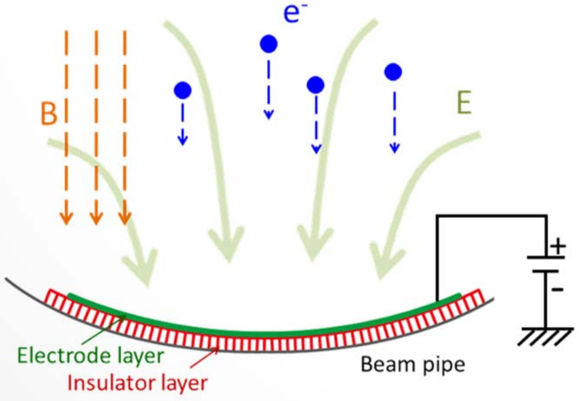
Electron cloud issue

- Clearing electrode
  - An electrode in a beam pipe with a high positive potential attracts the electrons around the beam orbit.
  - A drastic effect is expected and was actually observed in experiments.
  - Demonstrated at DAFNE, Italy (D. Alesini, IPAC2012 p.1107)
  - One concern is again its impedance effect on the beam.

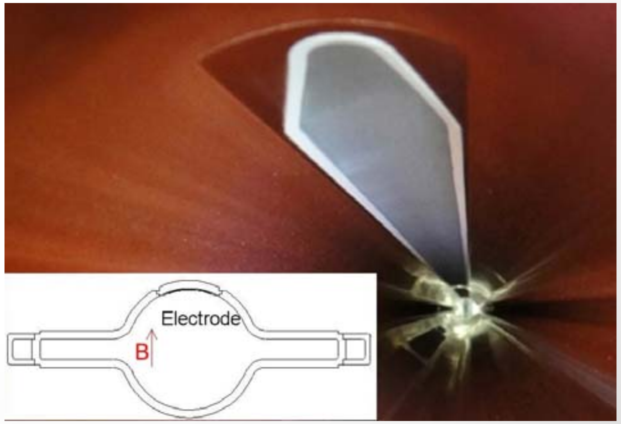
by L. Wang et al., EPAC2006, p.1491







SuperKEKB, KEK



Effect 3: Electron emission

- Exercise

  Calculate

  (1) average emitted photoelectrons per meter per second along the ring assuming η_e of 0.1

  for a ring with $E_e = 7$ GeV, $I_e = 2$ A, $\rho = 100$ m, C = 2000 m.

- Solution

(1) $$\left\langle \dot{N}_{ele,Ie,line} \right\rangle = \eta_e \times \left\langle \dot{N}_{ph,Ie,line} \right\rangle$$

$$= \eta_e \times 8.08 \times 10^{20} E_e[\mathrm{GeV}] \times I_e[\mathrm{A}] / C[\mathrm{m}] \quad [\mathrm{electrons\ s^{-1} m^{-1}}]$$

Summary

- Basic and practical matters to understand the effect of the synchrotron radiation to the accelerator performance, and how to treat these problems were presented.
  - Heat load
  - Gas load
  - Electron emission
- Effect of SR on the performance of accelerator
  - Heat load
    - Heat up beam pipe, damage beam pipes by heating and stress.
    - Install proper photon stops at proper locations. Design to decrease power density. Use materials for the photon stops with high thermal strength.

Summary

- Effect of SR on the performance of accelerator
  - Gas load
    - Increase pressure, reduce beam lifetime, increase background noise.
    - Install vacuum pumps at proper locations and prepare sufficient pumping speed, following the photon stops scheme.
      Decrease contamination on the surface of beam pipes.
  - Electron emission
    - Enhance forming of electron cloud, leads instabilities.
    - Prepare proper countermeasures in order to suppress secondary electrons as well as photoelectrons, such as TiN coating, solenoid field and groove surface.

Thank you!

and wish you continued success

in the work.

Home work

(1) The synchrotron radiation induce the following three process in accelerators;

  a. Power deposition at irradiated area
  b. Gas desorption
  c. Photoelectron emission

- How do they affect on the accelerator performance?
- What type of countermeasures are available to deal with the problems?

Home work

(1) Solution (example)

a. Power deposition at irradiated area

- Heat up beam pipe, damage beam pipes by heating and stress.
- Install distributed or localized photon stops cooled by water along the ring, taking into account the SR power absorbed to the photon stops.
- Use materials with high thermal strength for these photon stops.

b. Gas desorption

- Increase pressure, reduce beam lifetime.
- Place distributed or localized pumps following the photon stops arrangement along the ring.
- Decrease contamination on the surface of beam pipes.

Home work

(1) Solution (example) contd.

c. Photoelectron emission

- Enhance forming of electron cloud, which leads to beam instabilities and deteriorate the performance.
- Prepare proper countermeasures in order to suppress secondary electrons as well as photoelectrons, such as TiN coating, solenoid field, groove surface etc.

Home work

(2) Calculate the followings related to the synchrotron radiation (SR) from the bending magnets.

a. Spread angle of SR ($2/\gamma$)
b. Critical energy of photons
c. Total power in the ring
d. Average photon line density along the ring

for a electron ring with

Beam energy: $E_e = 3\ \mathrm{GeV}$
Beam current: $I_e = 1\ \mathrm{A}$
Bending radius: $\rho = 80\ \mathrm{m}$
Circumference: $C = 500\ \mathrm{m}$.

Home work

(2) Solution

a. Spread angle of SR ($2/\gamma$)

$$\gamma = \frac{E_e}{m_e c^2} = \frac{E_e[\mathrm{MeV}]}{0.511} = 5.87\times10^3 \quad \therefore \frac{2}{\gamma} = \frac{2}{5.87\times10^3}\times10000 = 3.4\times10^{-4} \ \ \mathrm{rad}$$

b. Critical energy of photons

$$\varepsilon_c = 2.218\times10^3\times\frac{E_e\,[\mathrm{GeV}]^3}{\rho\,[\mathrm{m}]} \quad = 2.218\times10^3\times\frac{3^3}{80} = 750 \quad \mathrm{eV}$$

c. Total power in the ring

$$P_{Ie} = 8.85\times10^4\,\frac{E_e\,[\mathrm{GeV}]^4}{\rho\,[\mathrm{m}]}\,I\,[\mathrm{A}] \quad = 8.85\times10^4\times\frac{3^4}{80}\times1 = 9.0\times10^4 \quad \mathrm{W}$$

d. Average photon line density along the ring

$$\left\langle \dot{N}_{ph,Ie,line} \right\rangle = 8.08\times10^{20}\,I[\mathrm{A}]E_e[\mathrm{GeV}]/\mathrm{C}[\mathrm{m}]$$

$$= 8.08\times10^{20}\times1\times3/500 = 4.9\times10^{18} \quad \mathrm{Photons\ s^{-1}m^{-1}}$$