超伝導ウィグラーによる高エネルギー放射光の発生
Generation of High-Energy Synchrotron Radiation by SCW

早乙女光一 (K.Soutome)

SPring-8 加速器部門

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Abstract

Goal

High-Energy Electron Storage Ring (8GeV)
+ High Magnetic Field (10T Superconducting Wiggler : ＳＣＷ)
→ High-Energy Synchrotron Radiation (～MeV)

→ Production of Positrons
Use of High-Energy Synchrotron Radiation

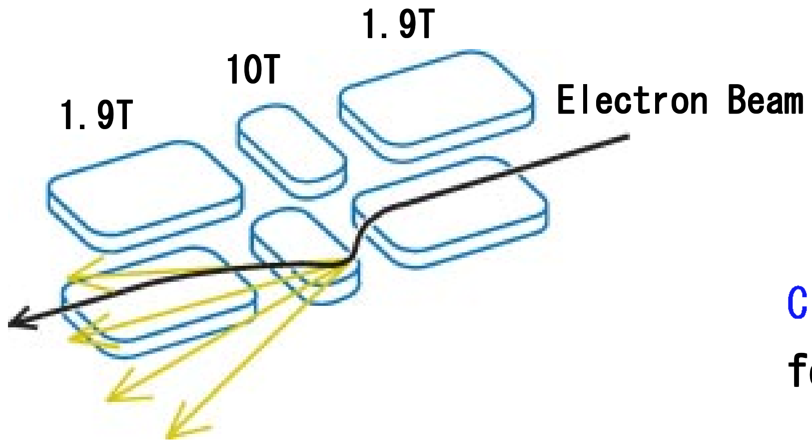
Contents

- 経緯／Brief History
- SCWからの放射光について／Synchrotron Radiation from SCW
- ビーム試験について／Beam Test

Brief History

１９９５年～	ＳＣＷ製作のための検討、設計、R&D (with Budker INP、Russia)
１９９９年	ＳＣＷ完成 *Fabricated*
２０００年１月	SPring-8 に搬入、励磁試験、磁場測定 *Transported to SP8, Field Meas.*
２００１年１１月～	冷却能力改善、設置に向けた検討と真空機器類の製作 *Cooling, Vac.Comp.*
２００２年８月	蓄積リング５セル直線部に設置。*Installed in Storage Ring*
２００２年９月	１回目のビーム試験 (0.1mA) *1st Beam Test*
	電子ビームに対する影響を見た。*Effects on Electron Beam*
２００２年１１月	２回目のビーム試験 (max.0.91mA @ 9.5T) *2nd Beam Test*
	放射線、熱負荷などの基礎データを取った。*Radiation Level, Heat Load*
	放射光スペクトルを測定した。*Spectrum Meas. of Synch. Rad.*
	・・・データ解析中 *data analysis in progress*
２００２年１２月	蓄積リングより撤去。組立調整実験棟に移設。*Moved to Test Bench*

Superconducting Wiggler

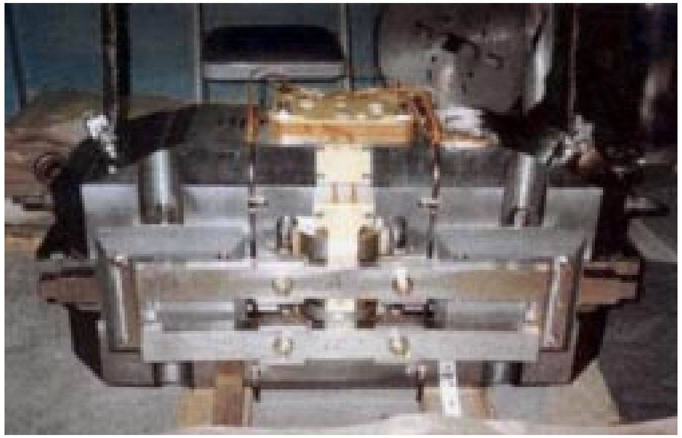


Critical Photon Energy = 0.43MeV

for E_e=8GeV, B=10T

Horizontal ~ ±25mrad

Vertical ~ ±25μrad for 1MeVγ

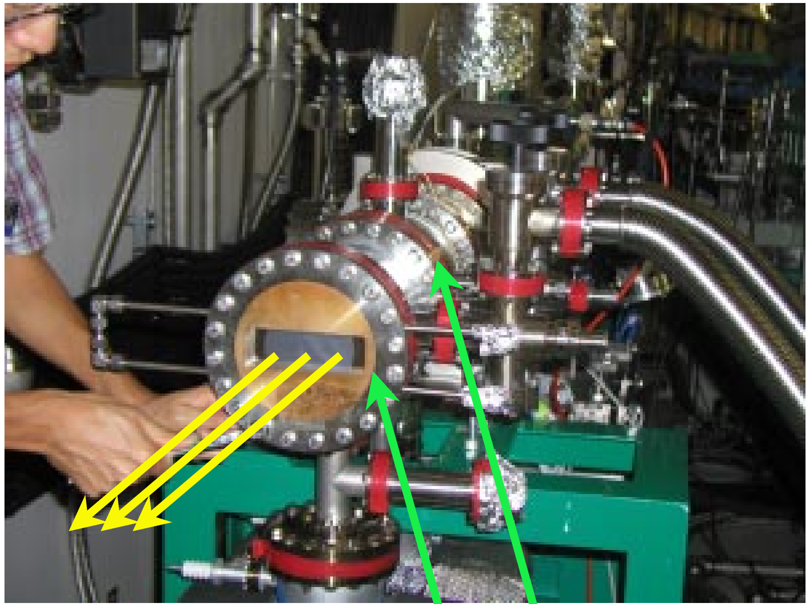


SCW Installed in the Storage Ring (August, 2002)

before

after

Photon Beamline in the Beam Test



Be t0.25mm

Al t3mm

Pb Shield

Critical Photon Energy

Bending Radius: $\rho = E_e/(ecB)$

$\rho[\mathrm{m}] = 3.336\, E_e[\mathrm{GeV}] / B[\mathrm{T}]$

e.g. E_e = 8GeV, B = 10T → ρ = 2.7m (SCW)

B = 0.68T → ρ = 39m (Bending Magnet)

Critical Photon Energy: $\varepsilon_c = \hbar\omega_c$

$\omega_c = 3\gamma^3 c/(2\rho)$

where $\gamma = E_e / m_e$

$\varepsilon_c\, [\mathrm{keV}] = 0.665\, E_e^2[\mathrm{GeV}]\, B[\mathrm{T}]$

e.g. E_e = 8GeV, B = 10T → ε_c = 426 keV (SCW)

B = 0.68T → ε_c = 29 keV (Bending Magnet)

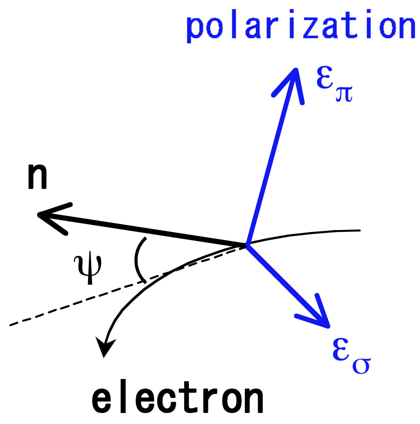
Most of the power is found in frequencies near ω_c.

Photon Flux Density

σ-component: $dF_\sigma / d\Omega = A\, (\omega / \omega_c)^2\, (1 + x^2)^2\, (K_{2/3}(\eta))^2$

π-component: $dF_\pi / d\Omega = A\, (\omega / \omega_c)^2\, (1 + x^2)\, x^2\, (K_{1/3}(\eta))^2$

Total: $dF/d\Omega = dF_\sigma / d\Omega + dF_\pi / d\Omega$



where

$A = 3/(4\pi^2)\, \alpha\, \gamma^2\, (\Delta\omega / \omega)\, (I/e)$

$\alpha = 1/137$, ω = photon energy, I = beam current

$x = \gamma \psi$

$\eta = (\omega / 2\omega_c)\, (1 + x^2)^{3/2}$

$dF_\sigma / d\Omega$ [photons / s / mrad² / 0.1% BW / mA]

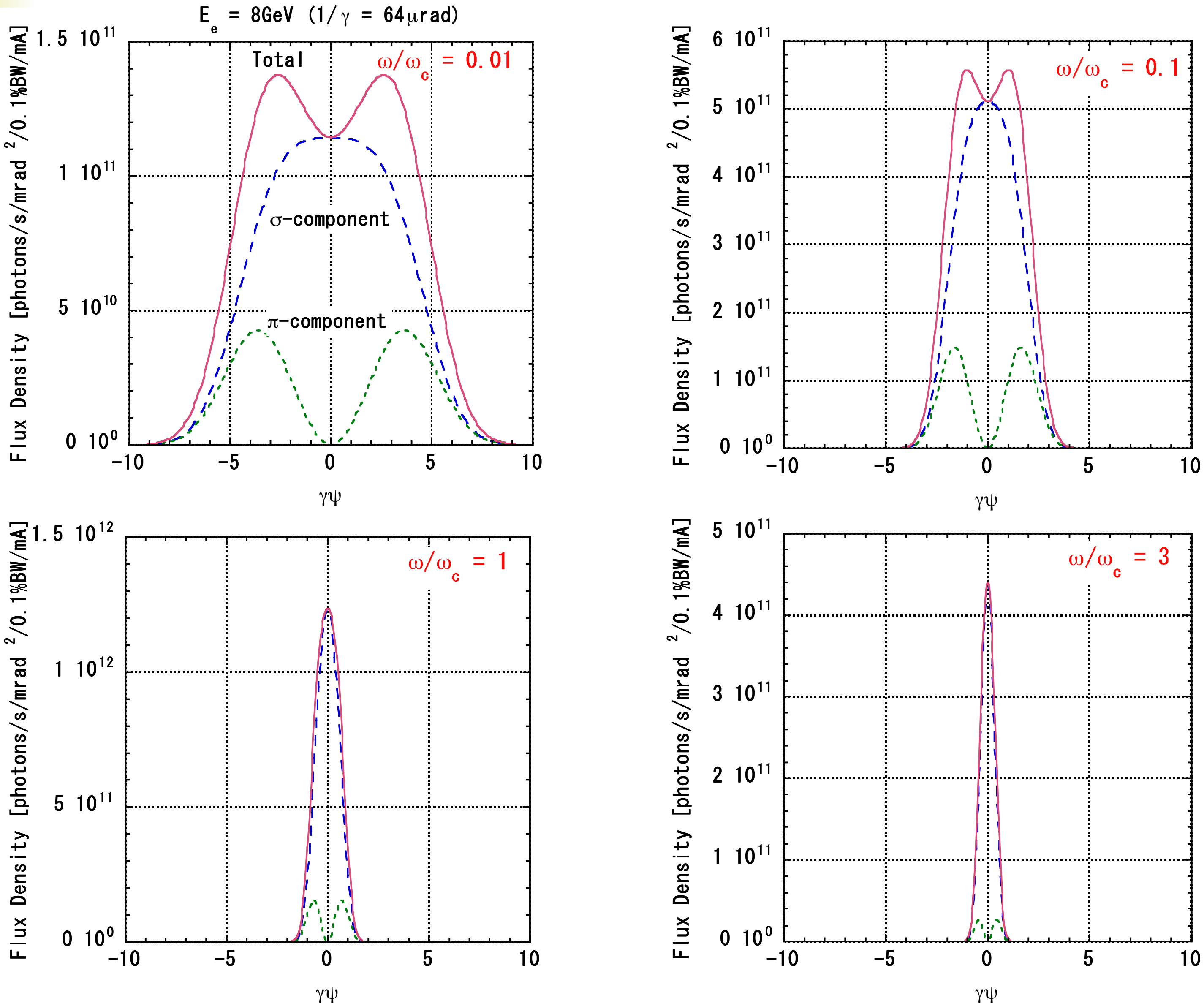
$= 1.325 \times 10^{10}\, E_e^2[\text{GeV}]\, (\omega / \omega_c)^2\, (1 + x^2)^2\, (K_{2/3}(\eta))^2$

$dF_\pi / d\Omega$ [photons / s / mrad² / 0.1% BW / mA]

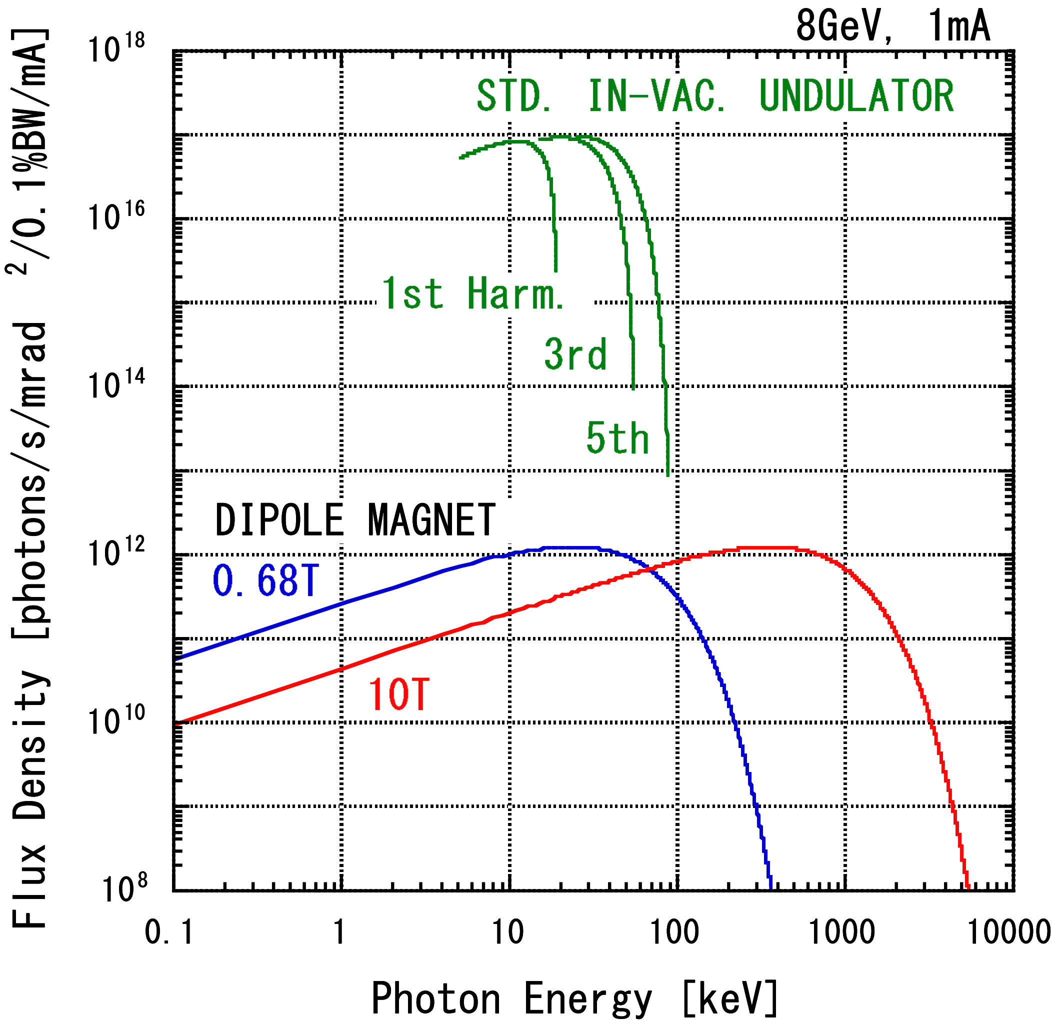
$= 1.325 \times 10^{10}\, E_e^2[\text{GeV}]\, (\omega / \omega_c)^2\, (1 + x^2)\, x^2\, (K_{1/3}(\eta))^2$

K.-J. Kim, AIP Conf. Proc. 184 (AIP, 1989) p.565.
J.D.Jackson, “Classical Electrodynamics”, (Wisley, 2nd ed.) sect.14.6.

Photon Flux Density (contd.)



Photon Flux Density (contd.)



Photon Flux

Integrating flux density over the vertical angle ψ, we have

$$dF_\sigma / d\theta = C\,(G(y) + y\,K_{2/3}(y))$$
$$dF_\pi / d\theta = C\,(G(y) - y\,K_{2/3}(y))$$
$$dF/d\theta = dF_\sigma / d\theta + dF_\pi / d\theta = 2\,C\,G(y)$$

where

$C = 3^{1/2} / (4\pi)\,\alpha\,\gamma\,(\Delta\omega / \omega)\,(I/e)$

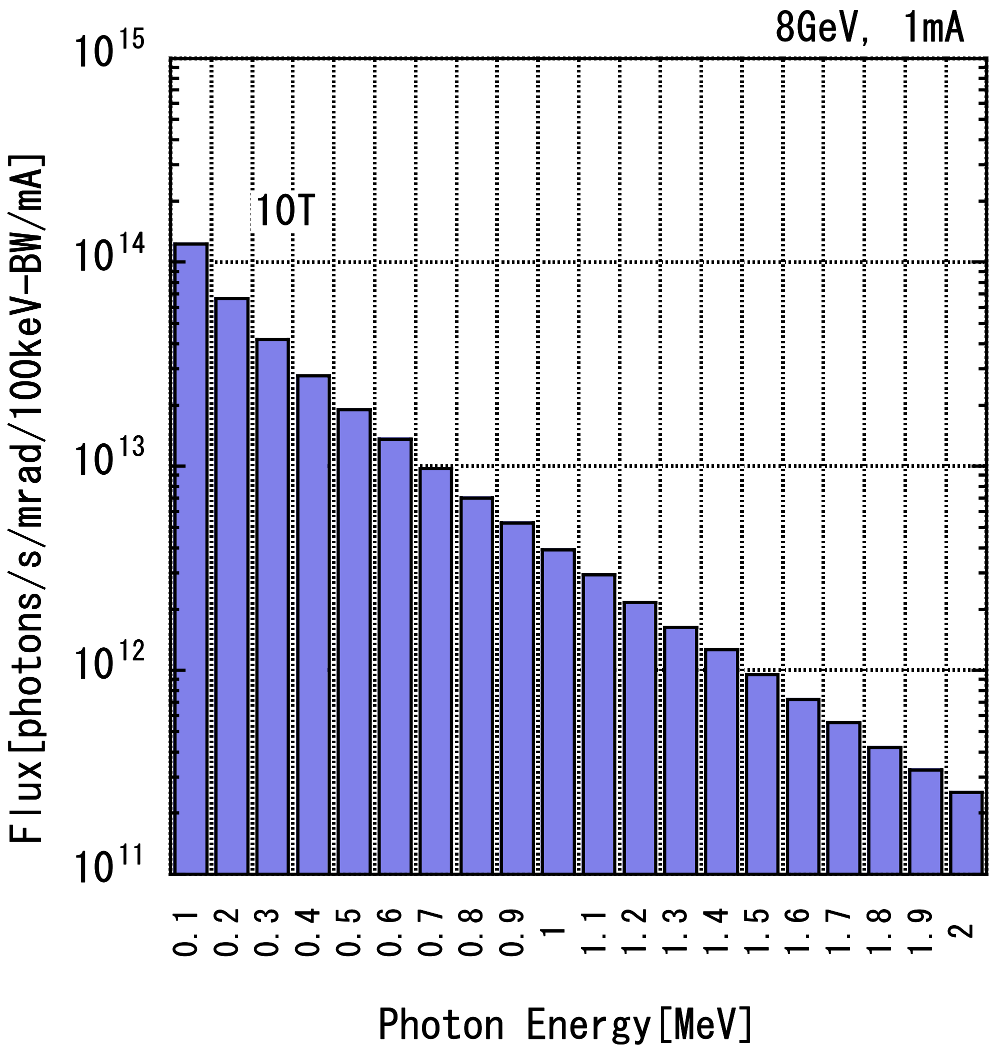
θ: orbital angle in the horizontal direction

$y = \omega / \omega_c$

$G(y) = y \int_y^\infty K_{5/3}(y')\,dy'$

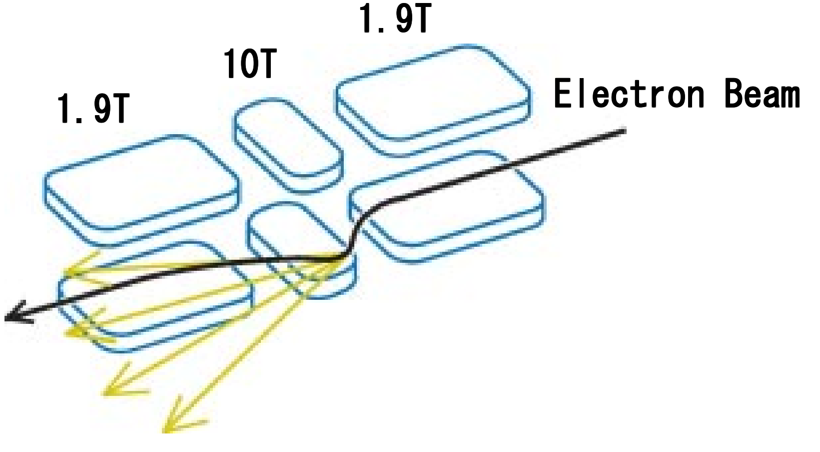
$$dF/d\theta\ [\text{photons / s / mrad / 0.1\% BW / mA}] = 2.460 \times 10^{10}\ E_e[\text{GeV}]\ G(y)$$

Photon Flux from 10T Field

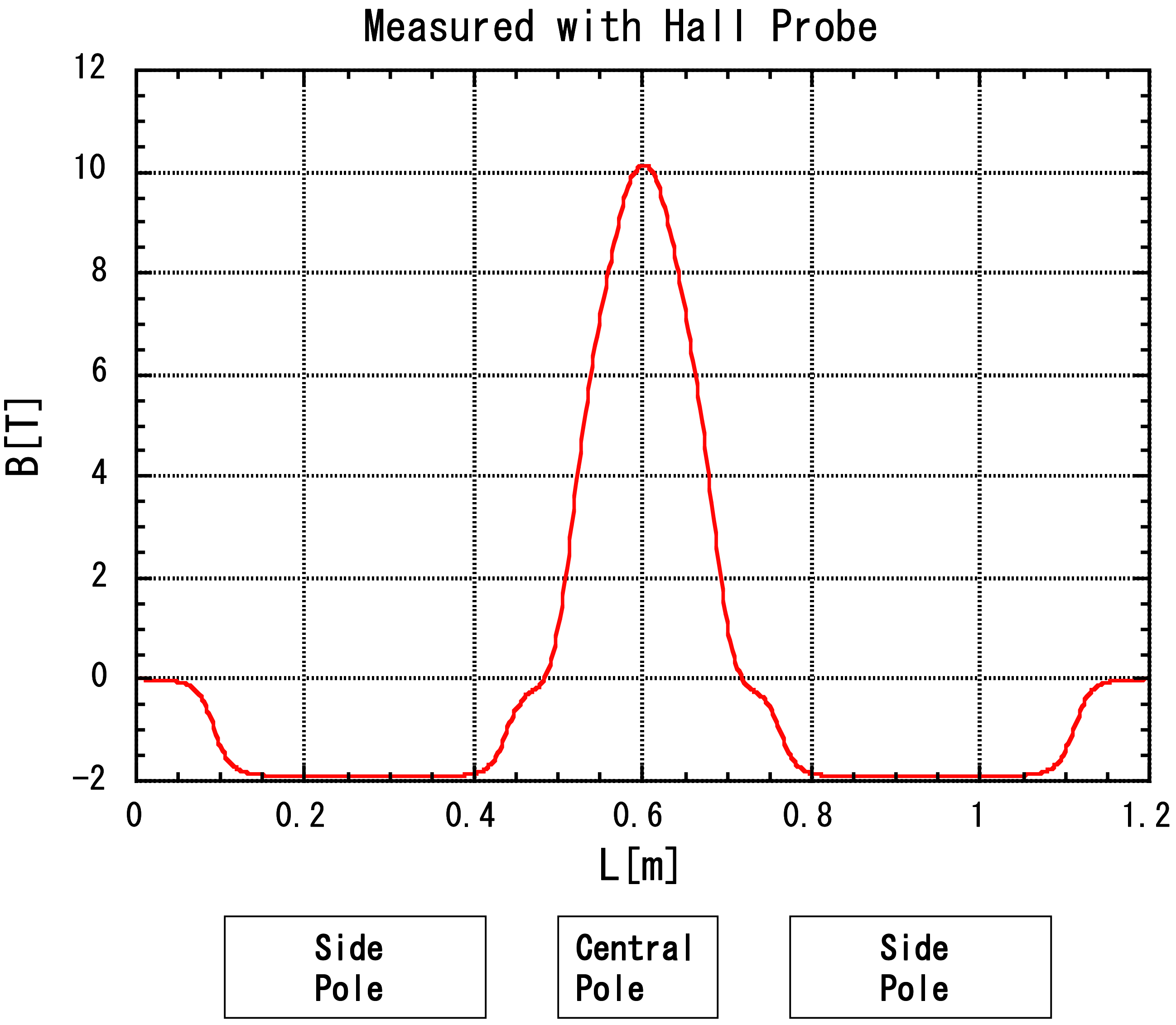


Number of Photons with Energies Higher than 1MeV $= 1.5\times10^{13}$/s/mrad/mA

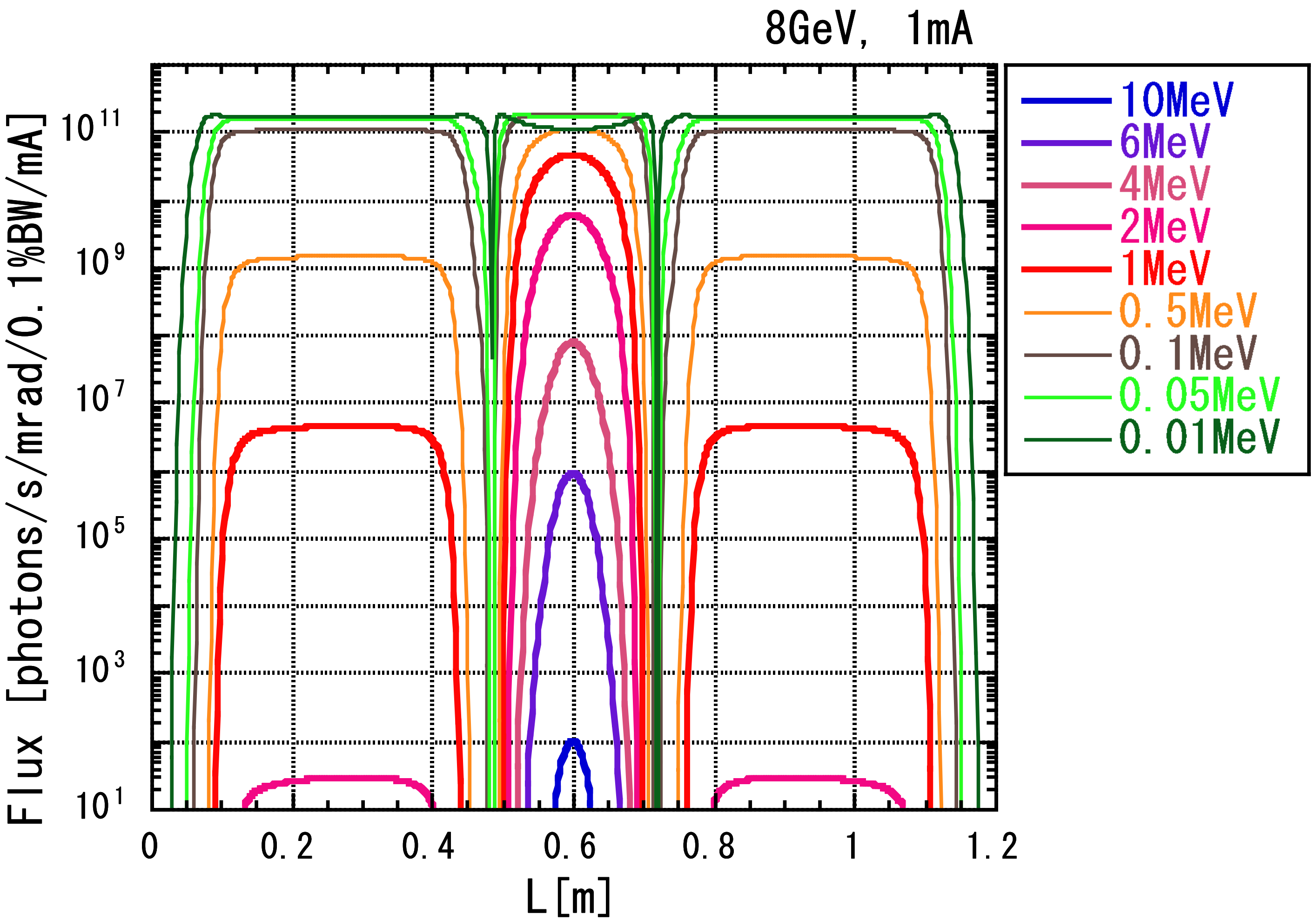
SCW



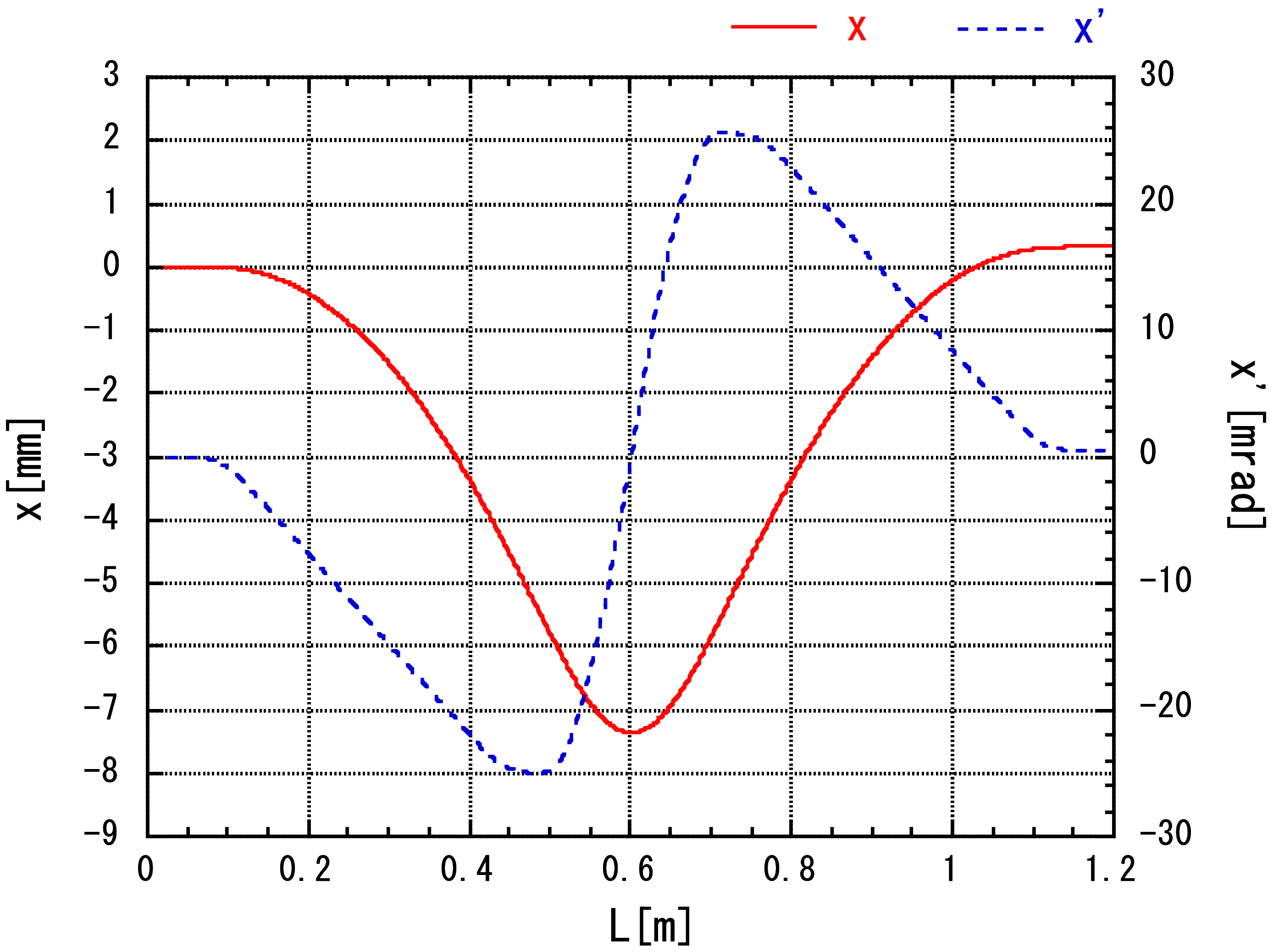
Dipole Field of SCW



Photon Flux from 10T SCW



Electron Orbit



Radiation Power and Power Density

$$d P_\sigma / d\Omega = (d P / d\Omega)_0 \, (1 + x^2)^{-5/2}$$
$$d P_\pi / d\Omega = (d P / d\Omega)_0 \, (5/7) \, x^2 \, (1 + x^2)^{-7/2}$$
$$d P / d\Omega = d P_\sigma / d\Omega + d P_\pi / d\Omega$$

where

$(d P / d\Omega)_0 = (7/16) \alpha (\hbar c) (\gamma^5 / \rho) (I/e)$ ... power in forward direction

$x = \gamma \psi$

$$(d P / d\Omega)_0 \, [W / mrad^2 / mA] = 5.420 \times 10^{-3} \, E_e^{\,4} [GeV] \, B[T]$$

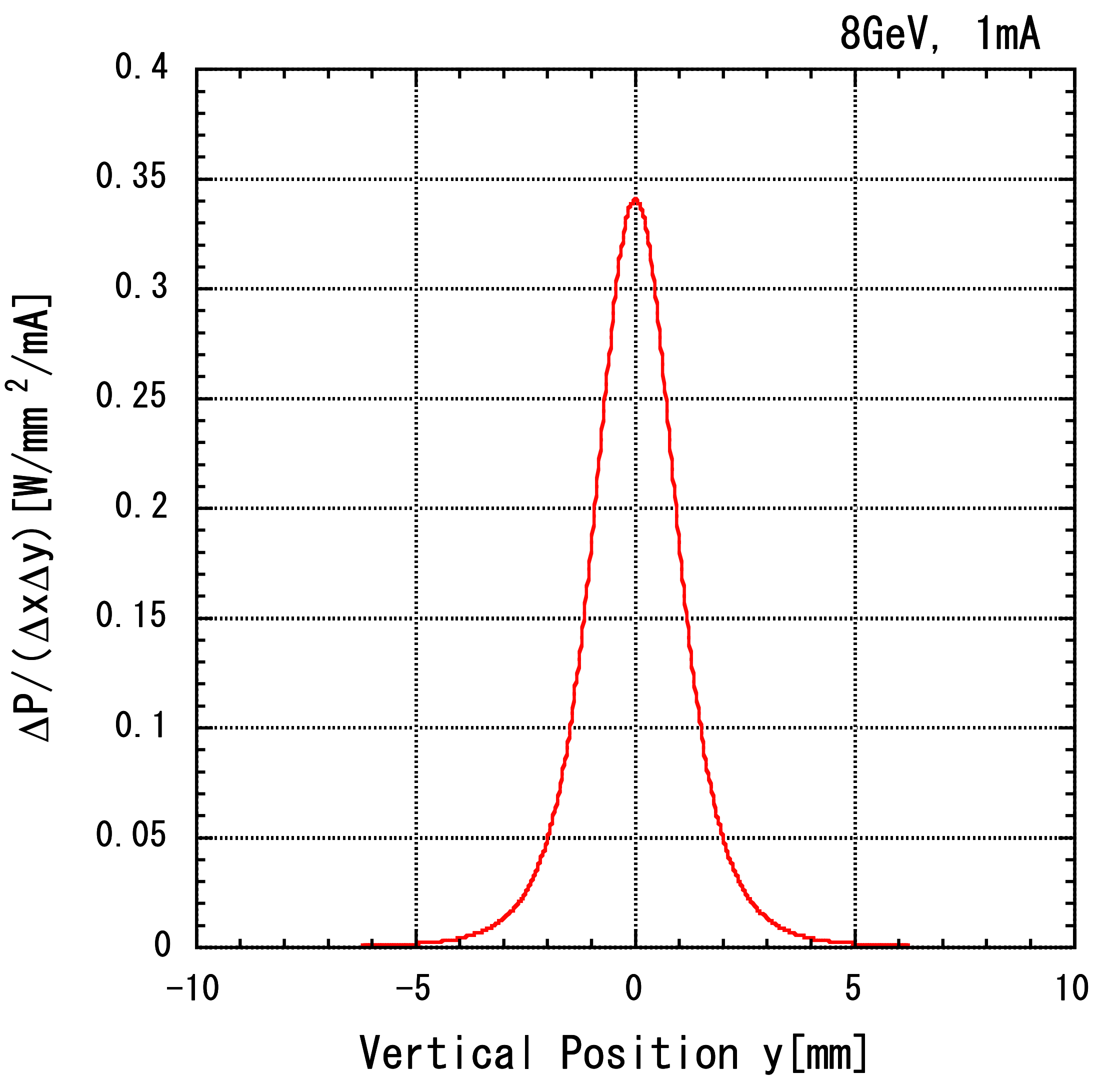
Integrating over the angles, we have

$$P = (2/3) \alpha (\hbar c) (\gamma^4 \Delta\theta / \rho) (I/e)$$
$$P \, [W / mrad / mA] = 4.220 \times 10^{-3} \, E_e^{\,3} [GeV] \, B[T]$$
$$P_\sigma : P_\pi = 7:1$$

e.g. E_e = 8GeV, B = 10T → P = 22 W/mrad/mA (SCW)

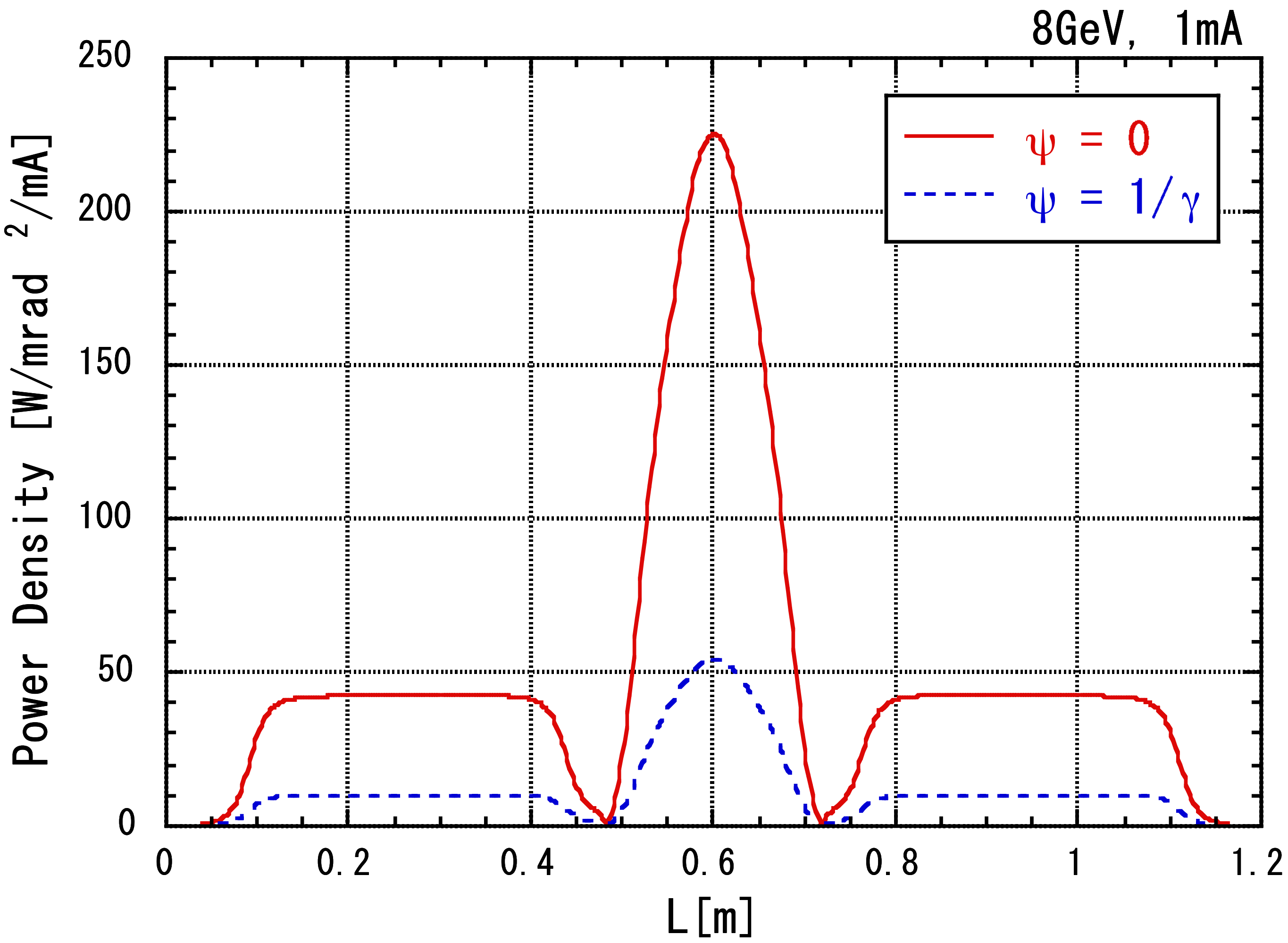
B = 0.68T → P = 1.5 W/mrad/mA (Bending Magnet)

Radiation Power Density from 10T field on Al-Window

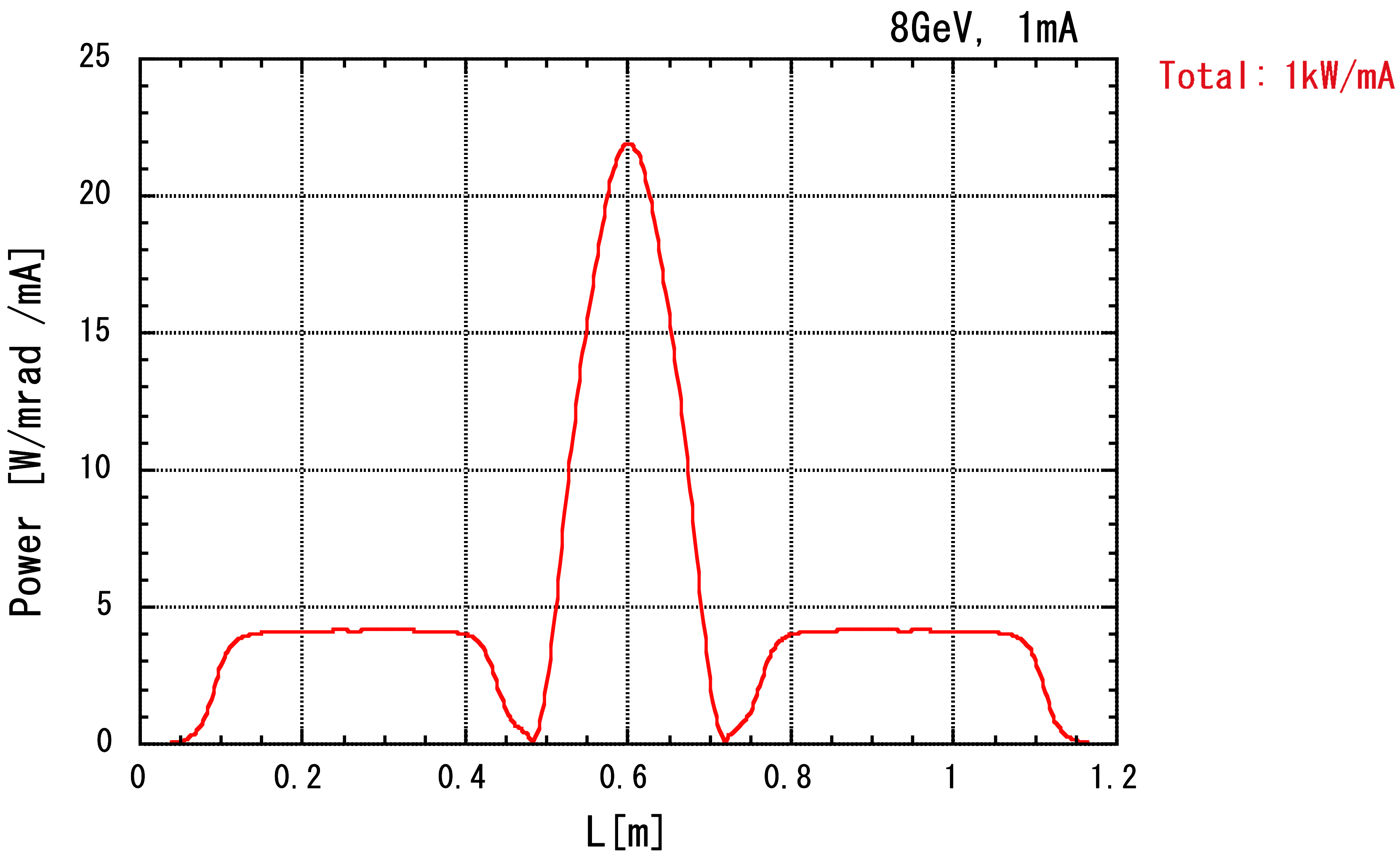


Al-Window:
26.2m downstream from SCW center

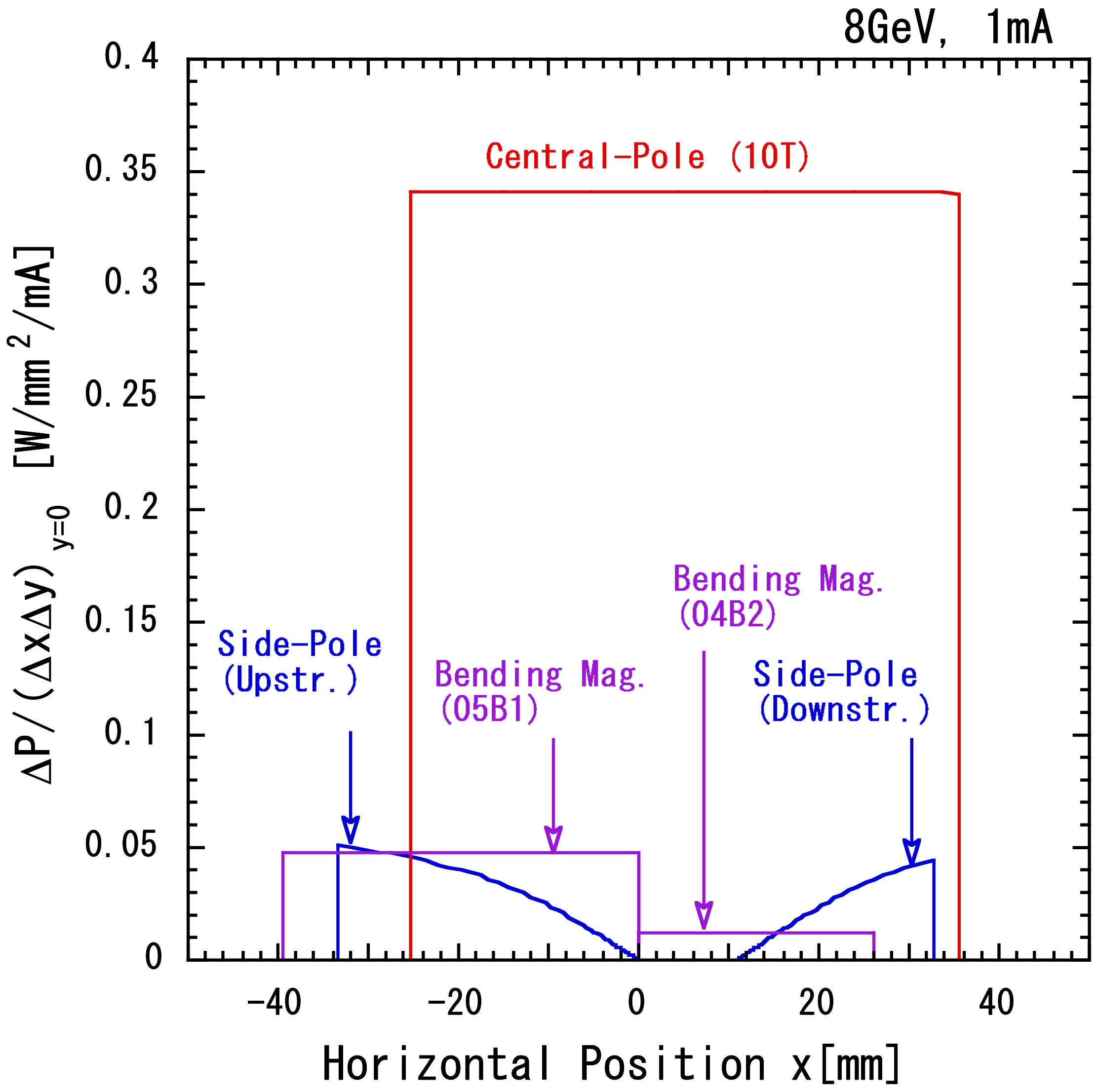
Radiation Power Density from 10T SCW



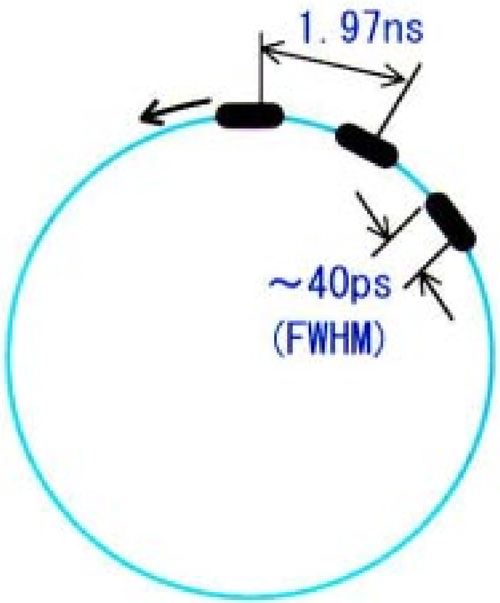
Radiation Power from 10T SCW



Radiation Power Density on Al-Window (Median Plane)



Time-Structure of Synchrotron Radiation



Ring Circumference : 1435.9488m
RF Accelerating Frequency : 508.58MHz

Total Number of RF Buckets : 2436
Time between Buckets : 1.97ns
Revolution Period : 4.79μs

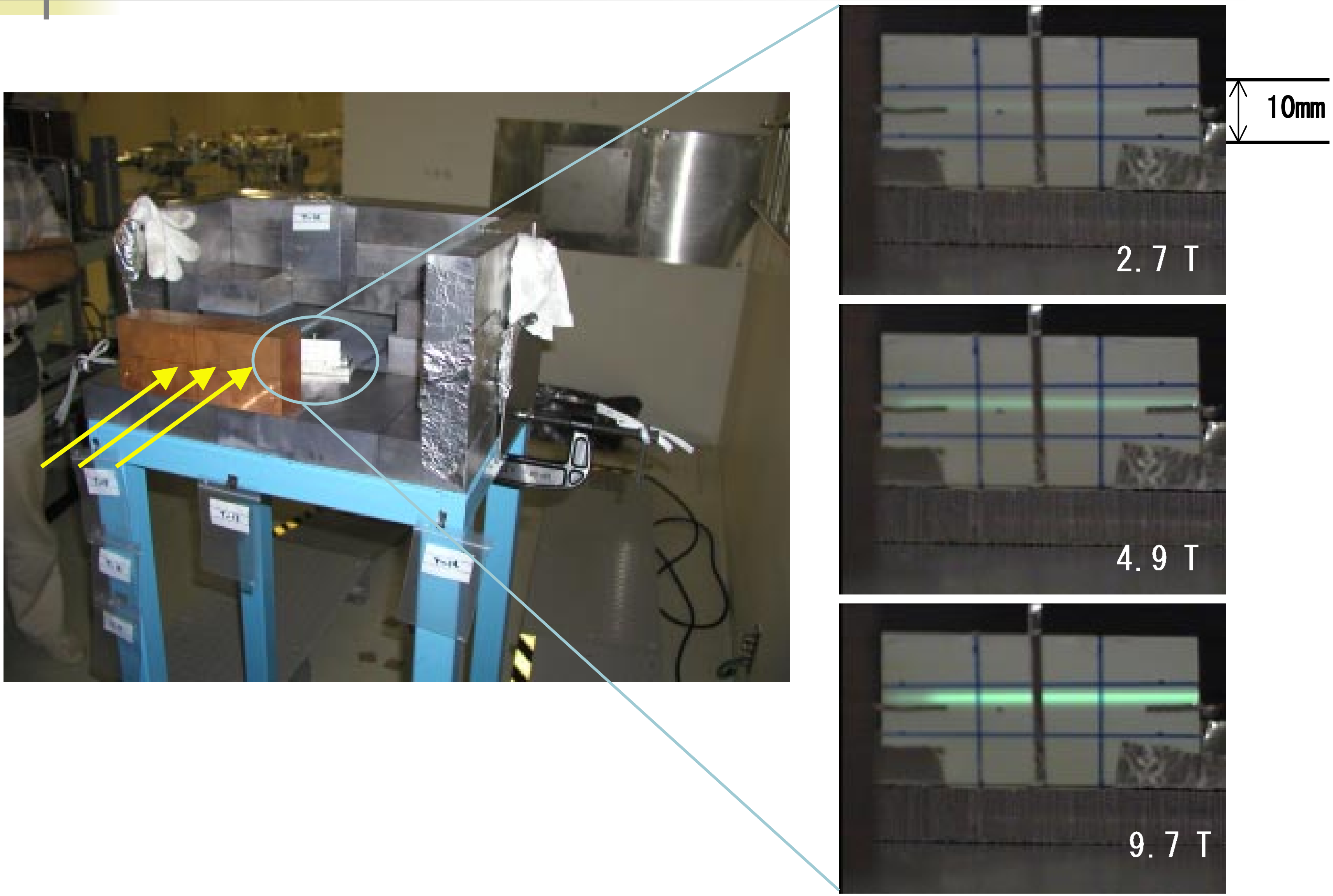
Beam Current without SCW

Multi-Bunch Operation : 100mA (User-Time／ユーザー運転時)

Single-Bunch Operation : ～ a few mA (Usual／通常)

～16mA (Maximum／過去の最大値)

Observed Synchrotron Radiation



Estimation of Positrons Produced at Al-Window (Cal.)

Field: 10T

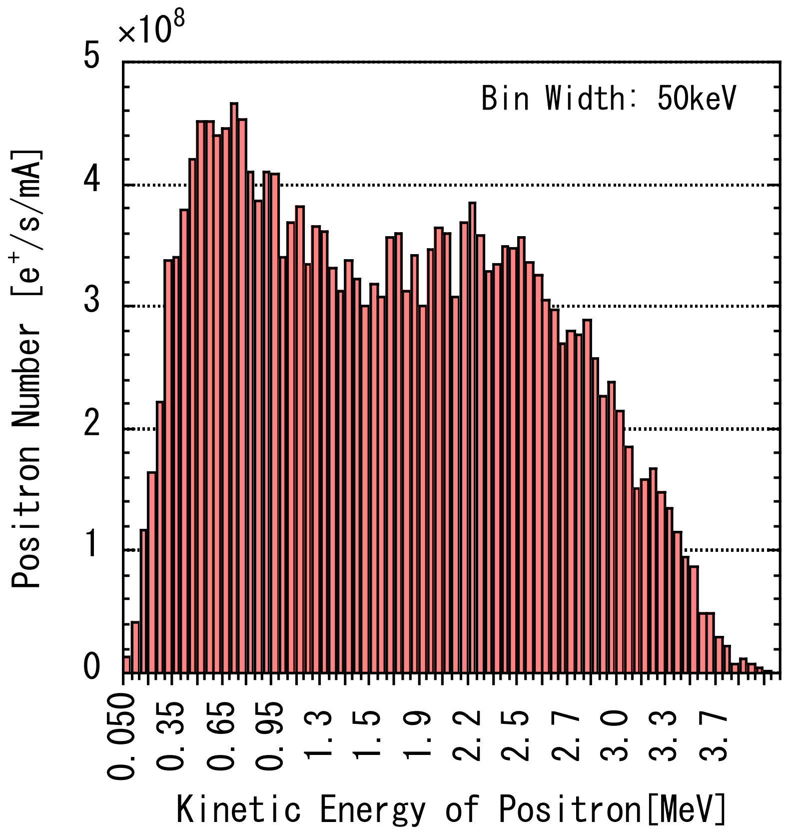
Material: Al t3mm (26.2m downstream)

Aperture for Photons: 2.38mrad

$$\frac{\text{No. of Produced Positrons}}{\text{No. of High-Ene. Photons}} = 7.1\times10^{-4}$$

$$\frac{\text{No. of Emitted Positrons}}{\text{No. of High-Ene. Photons}} = 4.4\times10^{-4}$$

→ Emitted Positrons:
1.6×10^{10} /s/mA (Cal.)

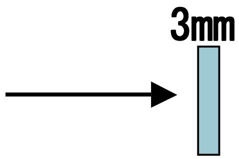


今回のビームラインは、陽電子生成用に最適化されていたわけではない。

The beamline was not optimized for positron production.

How to increase the number of positrons ... (estimation)

Al-Window



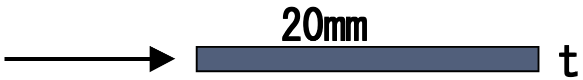
e^+/γ = 4.4×10^{-4}

Pb-Plate

e^+/γ = 6.3×10^{-4} (t=2.0mm)

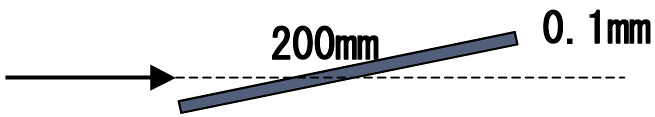
= 1.3×10^{-3} (t=1.0mm)

= 3.3×10^{-3} (t=0.5mm)



薄過ぎると照射領域で損。そこで...

プレートを傾ける。



e^+/γ = 1.0×10^{-2}
(t=0.1mm, 5mrad)

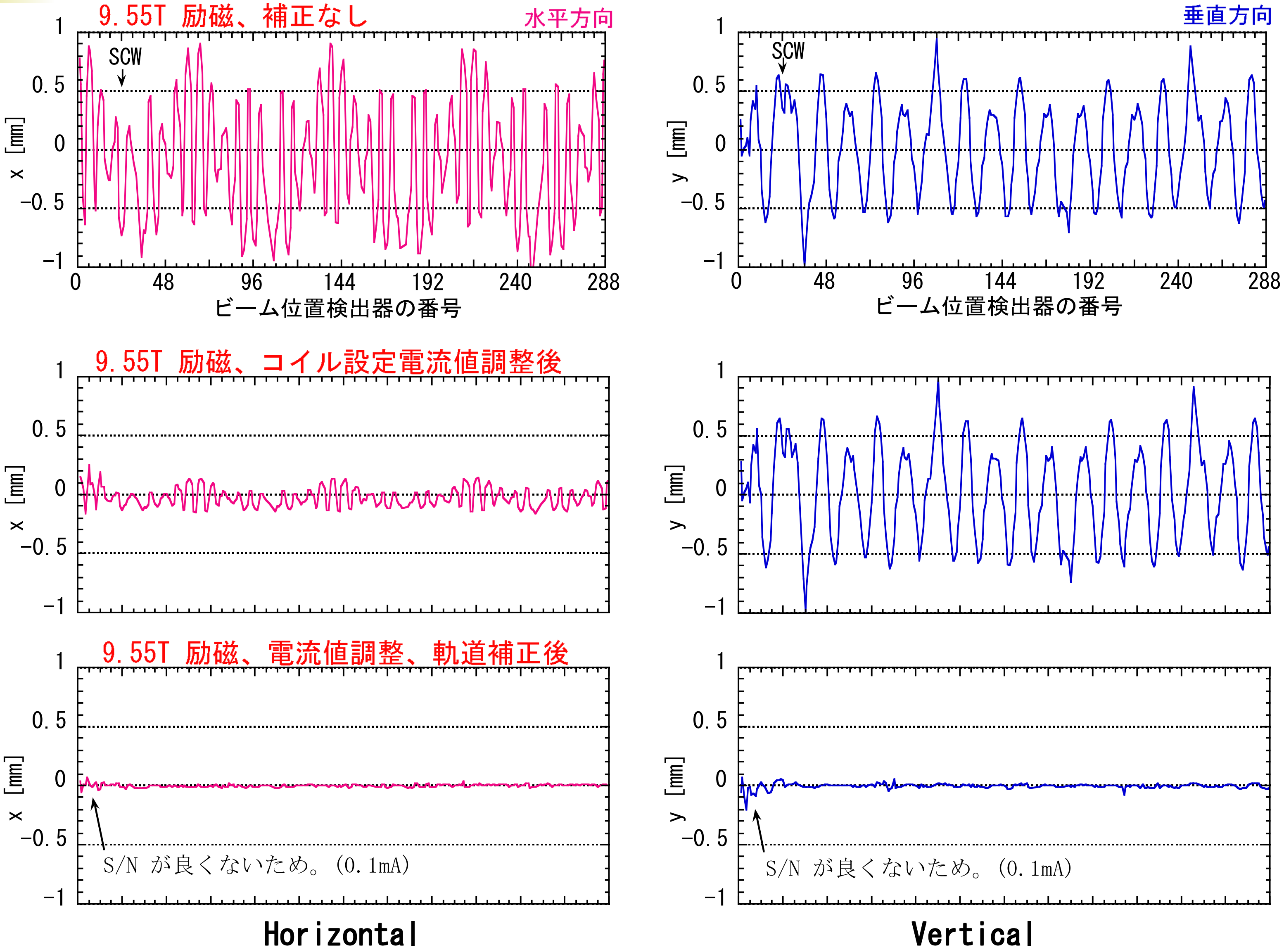
ただし、奥行きは大となる。

1MeV 以上の photon number 1.5×10^{13}/s/mrad/mA を単純にかけると

→ Emitted e^+ : 1.5×10^{11}/s/mrad/mA

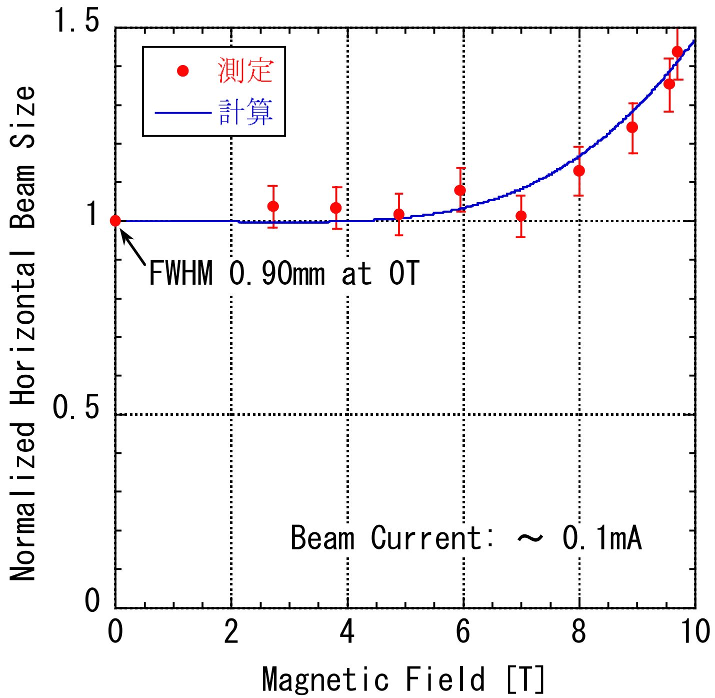
Moderator で $\times10^{-4}$ 倍になったとしても 1.5×10^{7}/s/mrad/mA ... too optimistic?

Effects on the Electron Beam: Closed Orbit Distortion

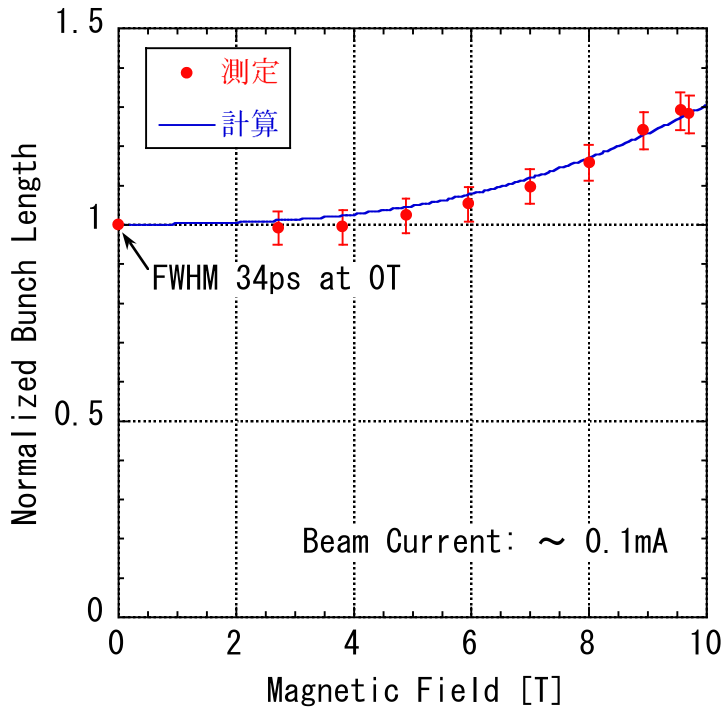


Effects on the Electron Beam: Beam Size

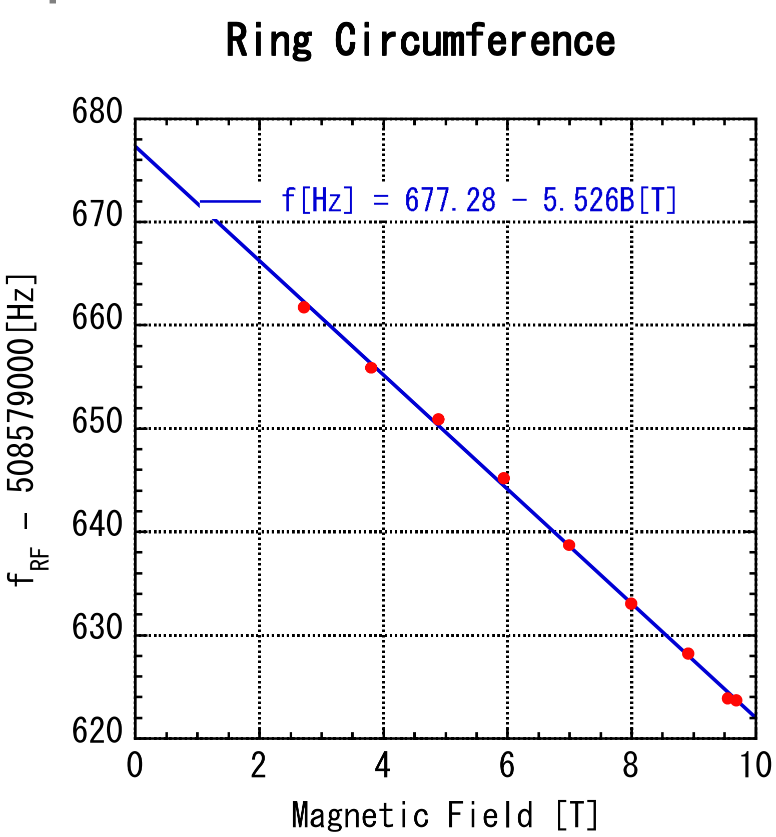
Horizontal Beam Size at Injection Point

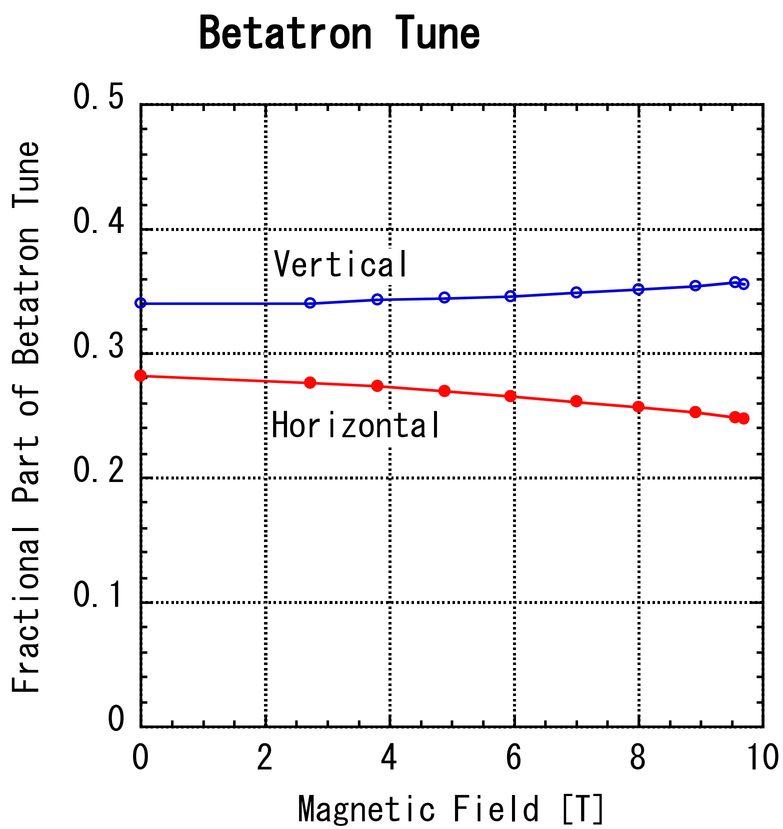


Bunch Length



Effects on the Electron Beam: Circumference and Betatron Tune



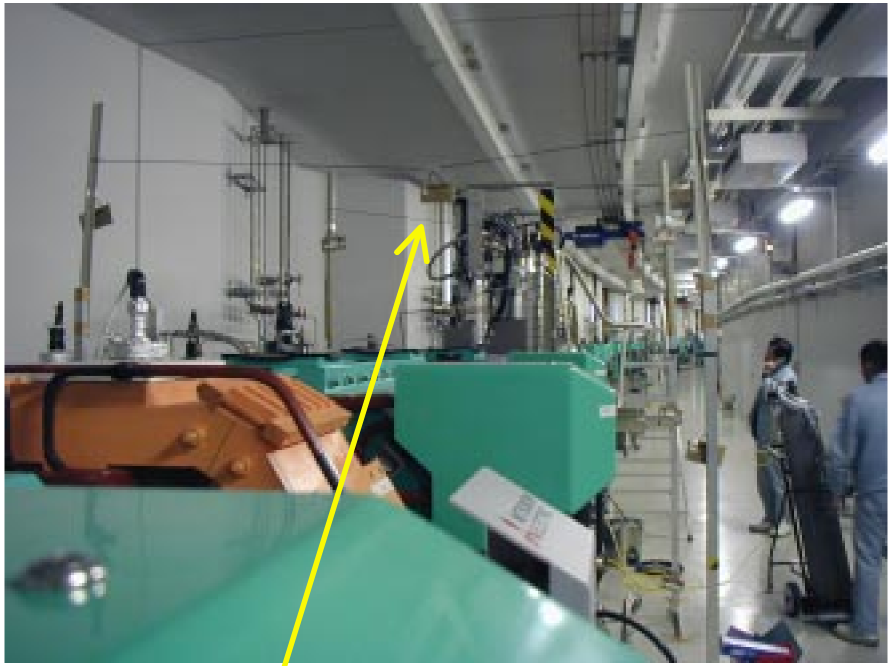


ΔB = 10T

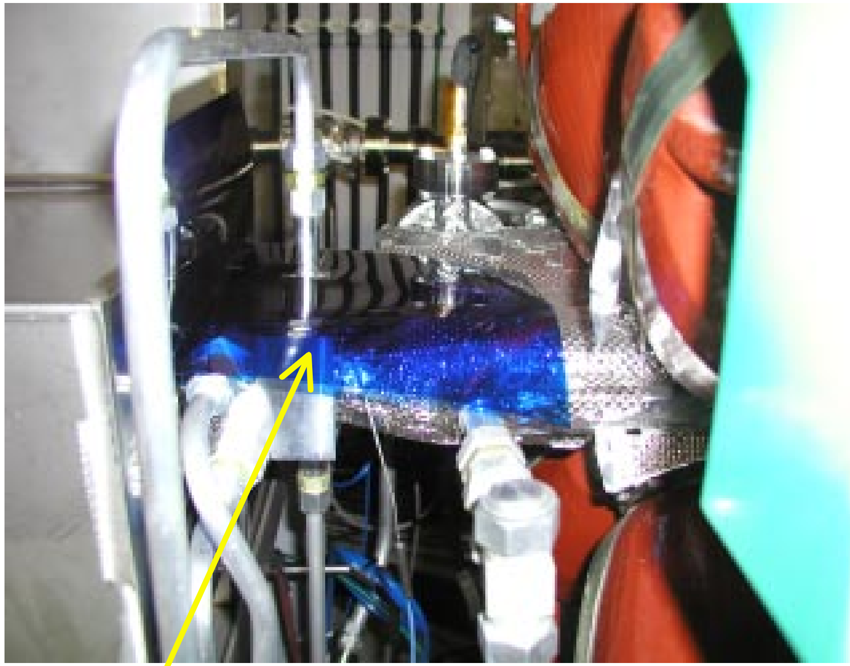
→ Δf_{RF} = –55Hz

→ ΔL = +0.155mm

Radiation Level Measurements



TLD



GAFCHROMIC Film

more than 10^4Gy
around photon absorber
(dose: 0.9mA×1h)

Summary

8GeV 電子蓄積リングに SCW を設置し、最大 9.7T まで励磁して高エネルギー放射光の発生試験を行った。現在、SCW は撤去され、テストベンチにおかれている。

SCW was installed in storage ring. Beam Test was carried out with max. field of 9.7T. SCW has now been removed and is in the test-bench.

蓄積電子ビームに対する影響 *Effects on Electron Beam*

・ほぼ予想通りの効果。　励磁状態での追加入射が可能。

・影響そのものは無視できない。→ 他の放射光ユーザーに影響。

Nothing special but non-negligible. Beam injection was possible with SCW ON.

放射線、熱負荷 *Radiation Level, Heat Load*

・かなり高い。本格設置のためには R&D が必要と思われる。

Very high. R&D will be neeed for permanent use in the future.

陽電子の観測 *detection of positrons*

・ポジトロニウムの 3γ崩壊の観測をシリカエアロジェルとNaI で試みたが、バックグラウンドの影響、NaI の放射線によるダメージなどでうまく測定できなかった。

We tried detection of 3γ-decay of positronium with Silica aerogels and NaI but could not due to high back-ground level and radiation damage of NaI.

高エネルギー放射光のスペクトル測定 *spectrum measurement of high-energy synchrotron radiation*

・蓄積電子数を 250 個程度に削り、NaI でスペクトルを測定した。1MeV 付近の強度（絶対値）は計算とよく合っている（解析中）。

We tried spectrum measurement of high-energy synchrotron radiation with NaI. Stored electrons were reduced to about 250. Absolute strength around 1MeV agrees well with calculation. ... analysis in progress