第1回放射光基礎講習会
2009年9月7日　東京大学本郷キャンパス

光の特性
シンクロトロン放射とその特性

自然科学研究機構分子科学研究所
総合研究大学院大学物理科学研究科

加藤政博

Contents

- What is Synchrotron Light Source?
- Characteristics of Synchrotron Radiation
- Advanced Technologies
  - Towards High Brightness
  - Towards Coherence

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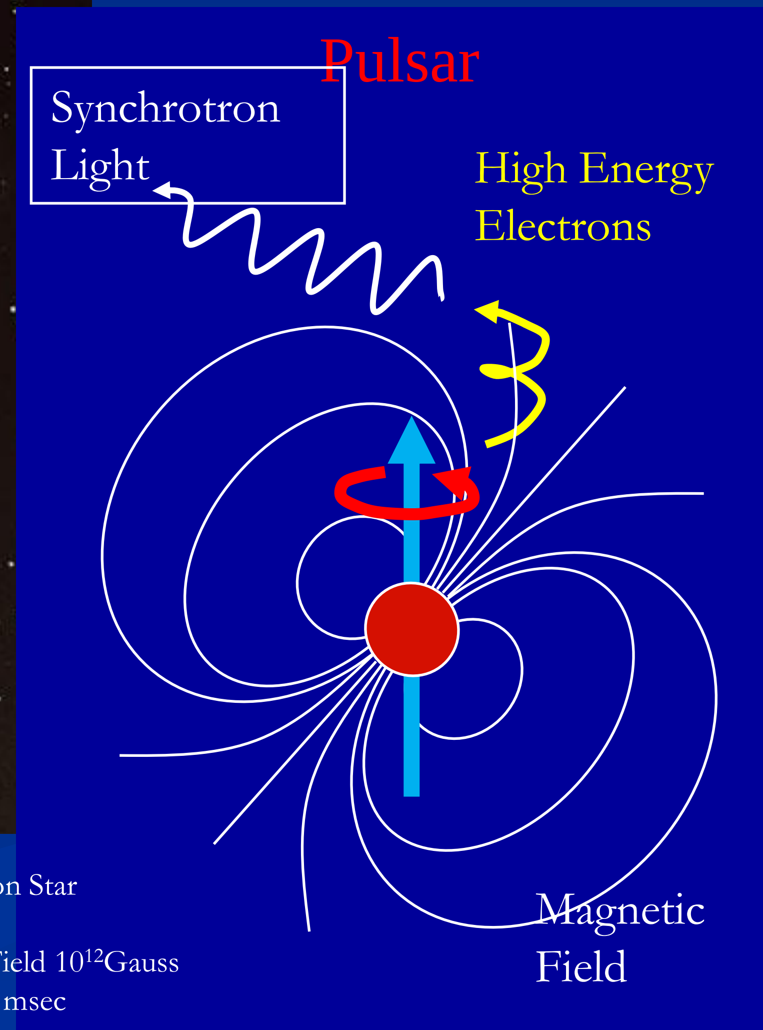
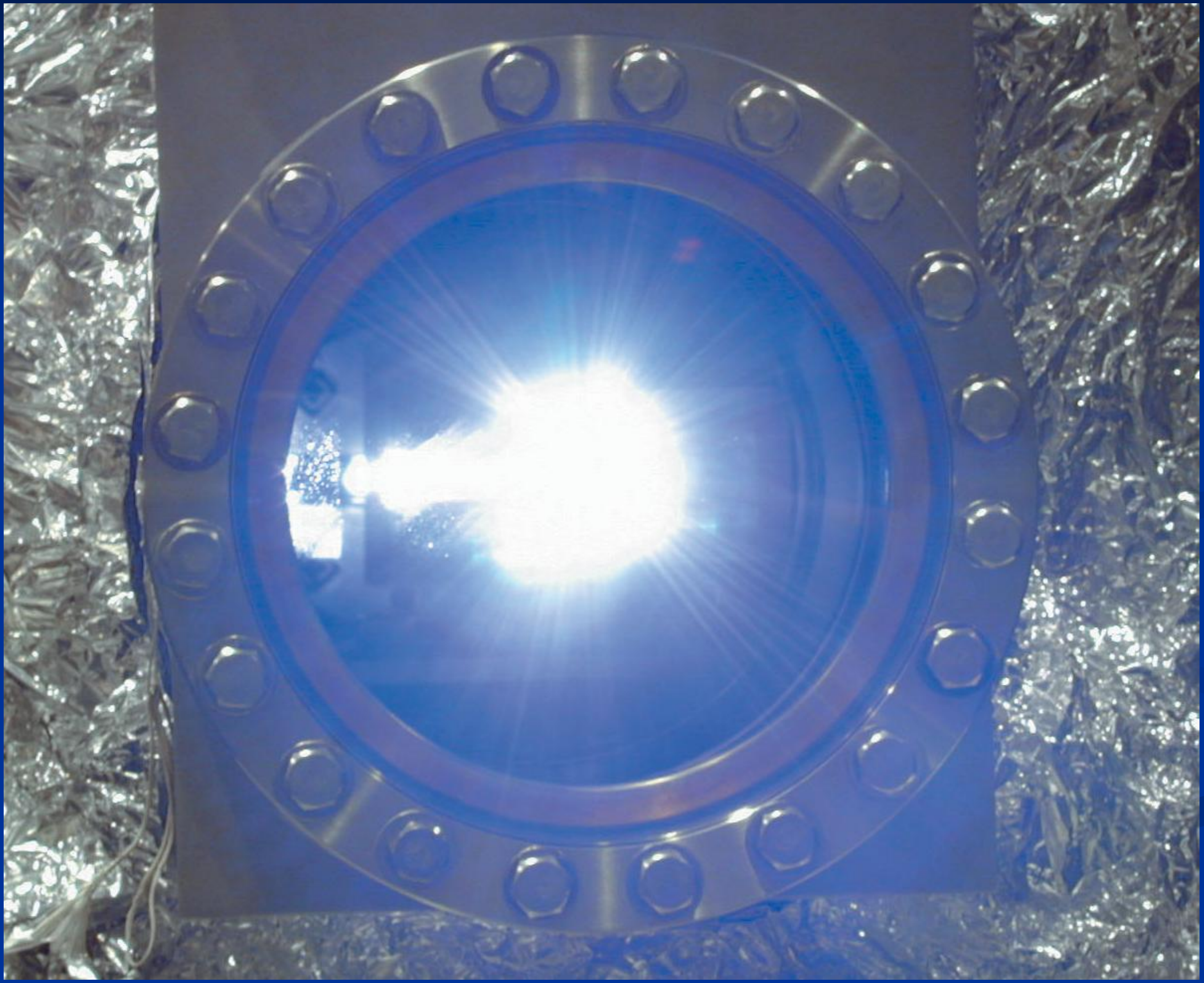
Synchrotron Light Source in the Sky

http://www.nasa.gov/multimedia/imagegallery/

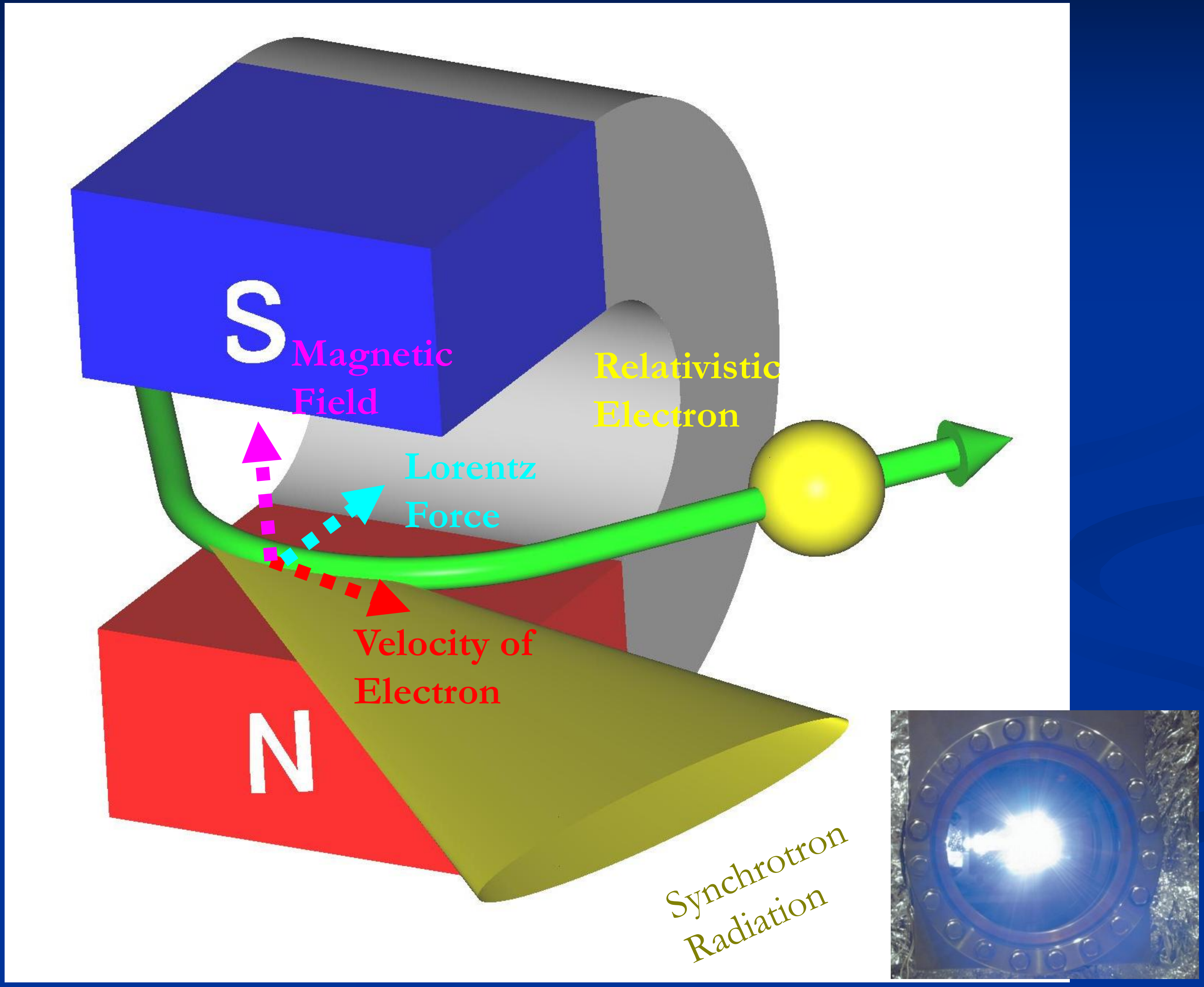


What is Pulser?
Magnetized Neutron Star
Diameter 10 km
Surface Magnetic Field 10^{12}Gauss
Rotating Period 33 msec

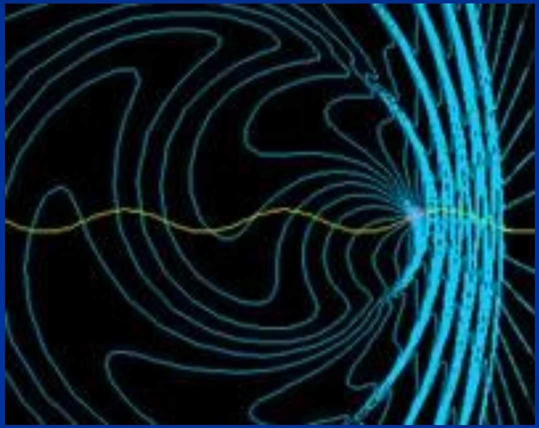
Synchrotron Light Source on the Earth



Synchrotron Radiation



Radiation Simulator



http://www-xfel.spring8.or.jp/dlmonitor.html

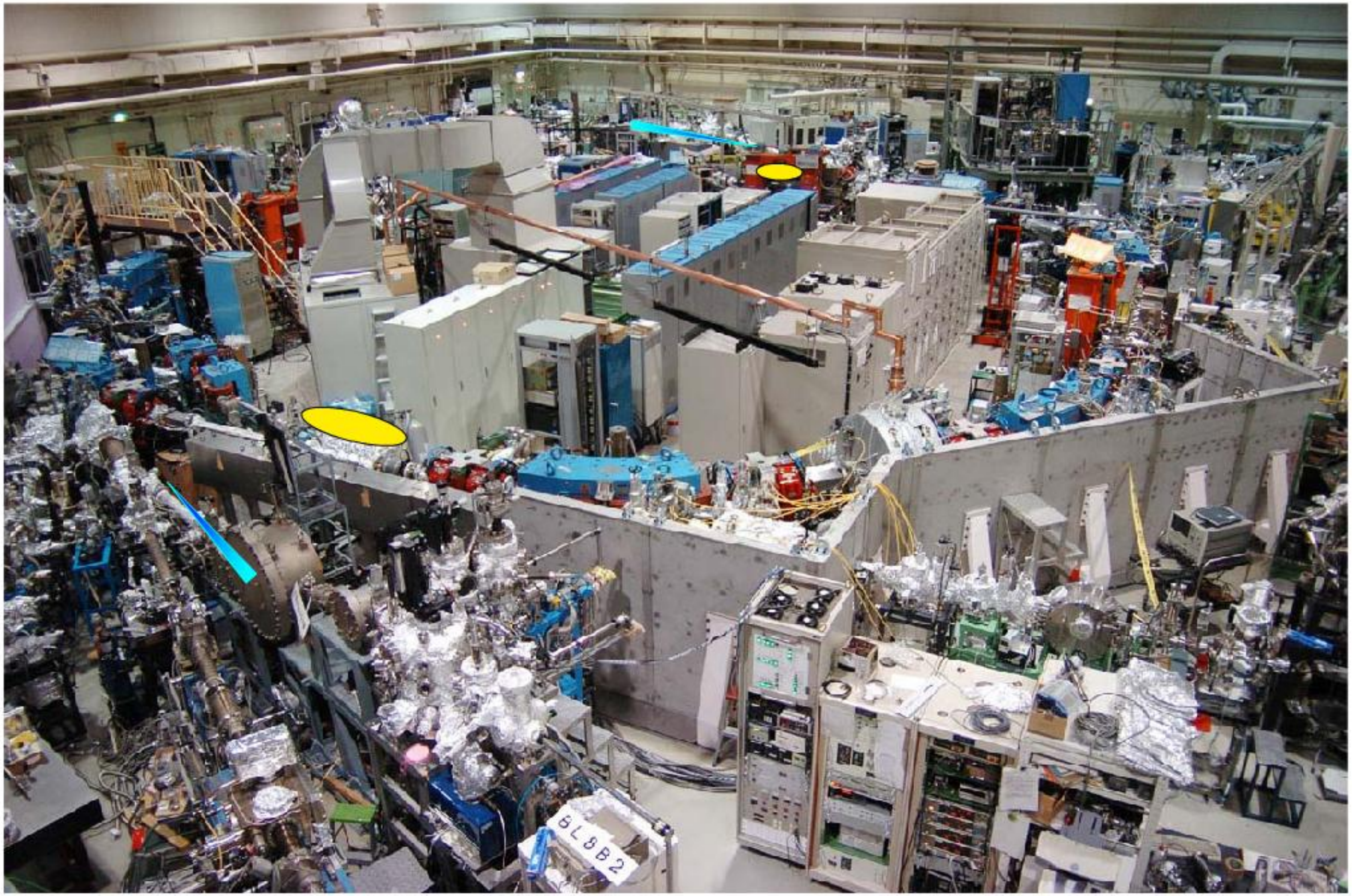
What are needed to produce synchrotron light?

- High Energy Electrons
  - ~0.5 to ~10 GeV
- Strong Magnetic Field
  - ~1 to ~10Tesla (=$10^{4\sim5}$ Gauss)
- Ultra-high Vacuum
  - $10^{-7\sim-8}$Pa

UVSOR-II

Institute for Molecular Science, Okazaki, Japan

Circumference 53m, Electron Energy 750MeV

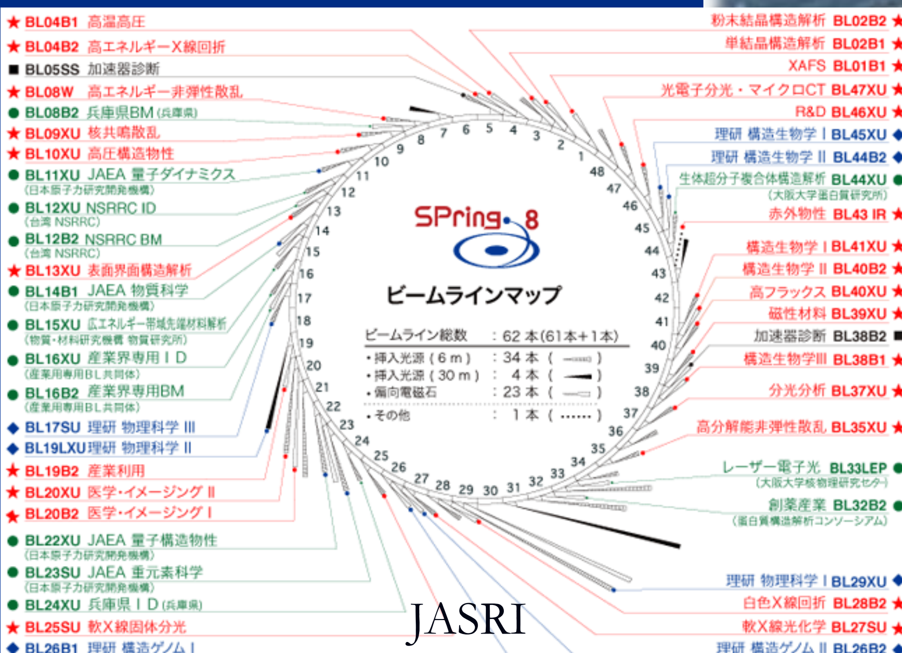


SPring-8 (Nishi-Harima, Japan)

http://www.spring8.or.jp

Circumference; 1436 m

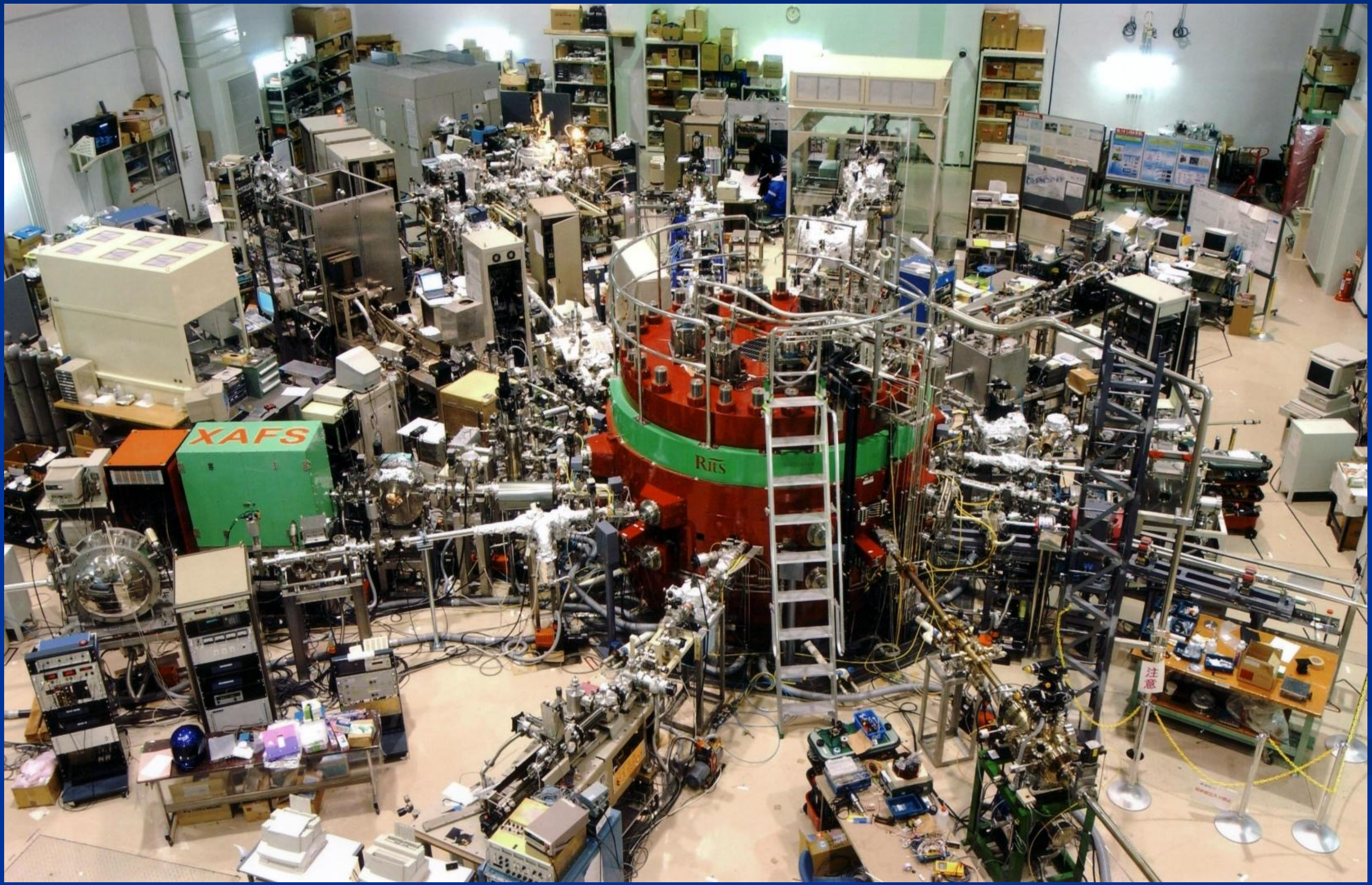
Electron Energy; 8 GeV



AURORA (Ritsumeikan Univ.)

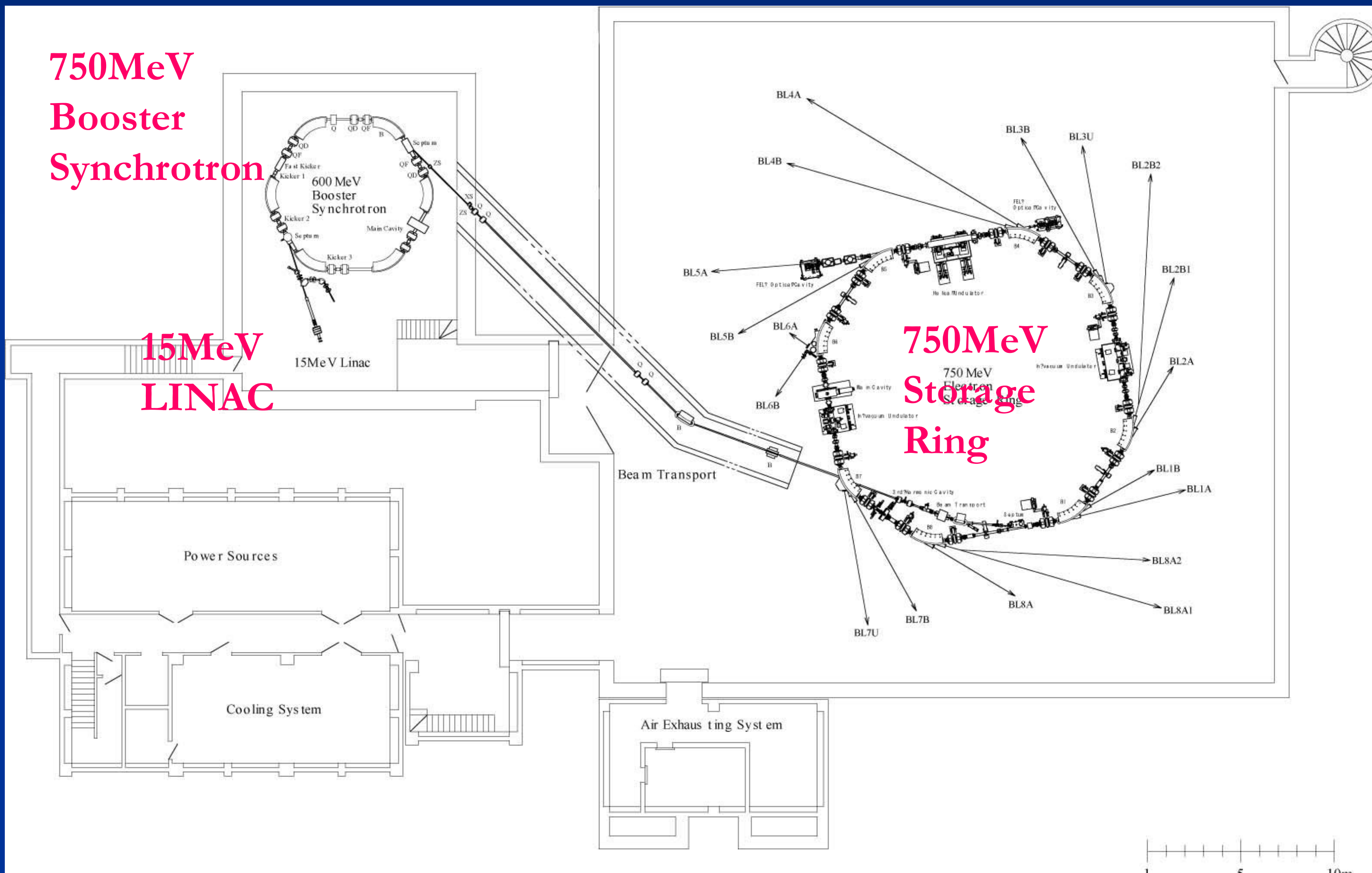
http://www.ritsumei.ac.jp/acd/re/src/index.htm

Circumference; 3 m, Electron Energy; 575 MeV

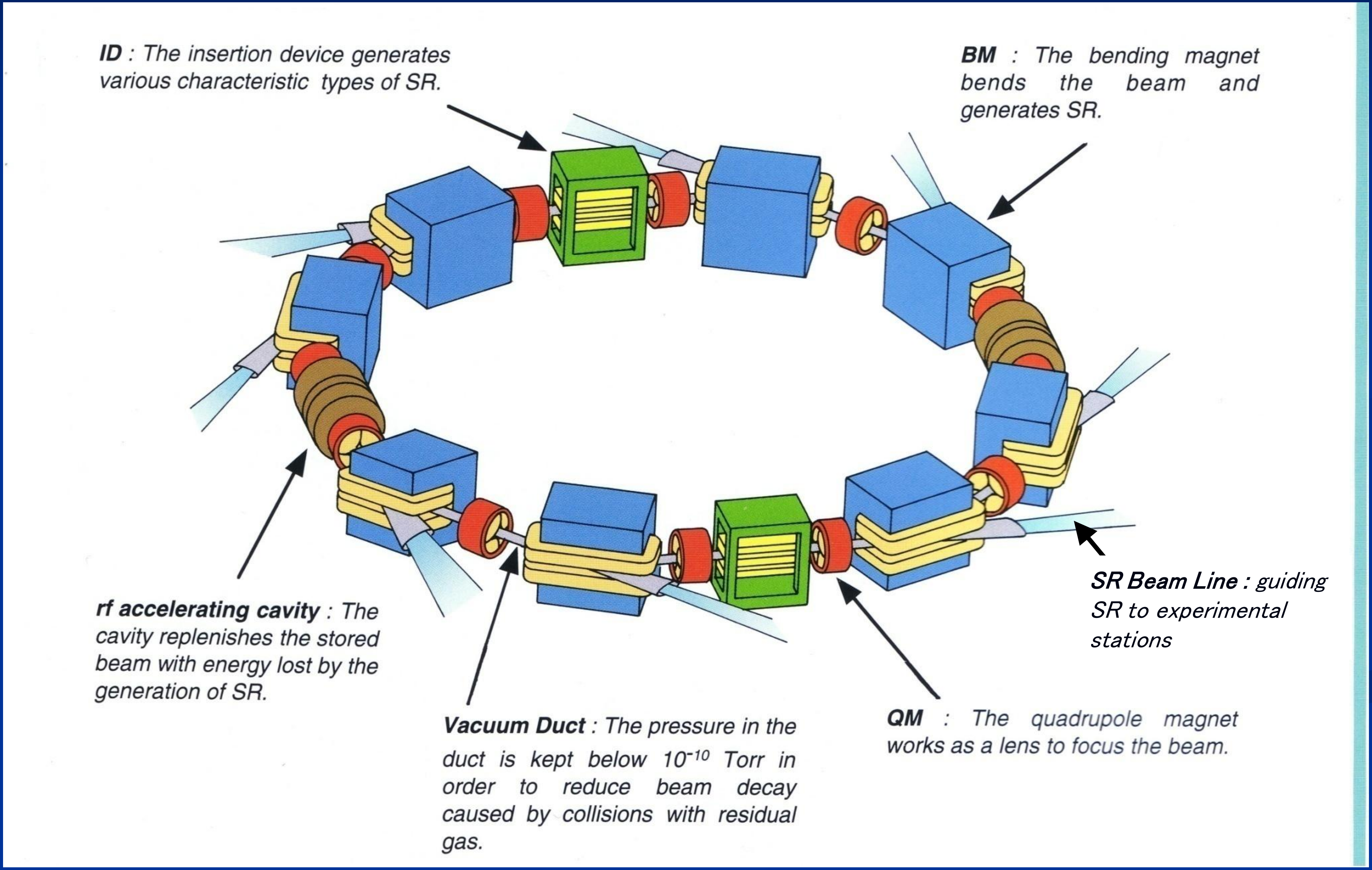


Layout of Synchrotron Light Source

UVSOR-II at Institute for Molecular Science

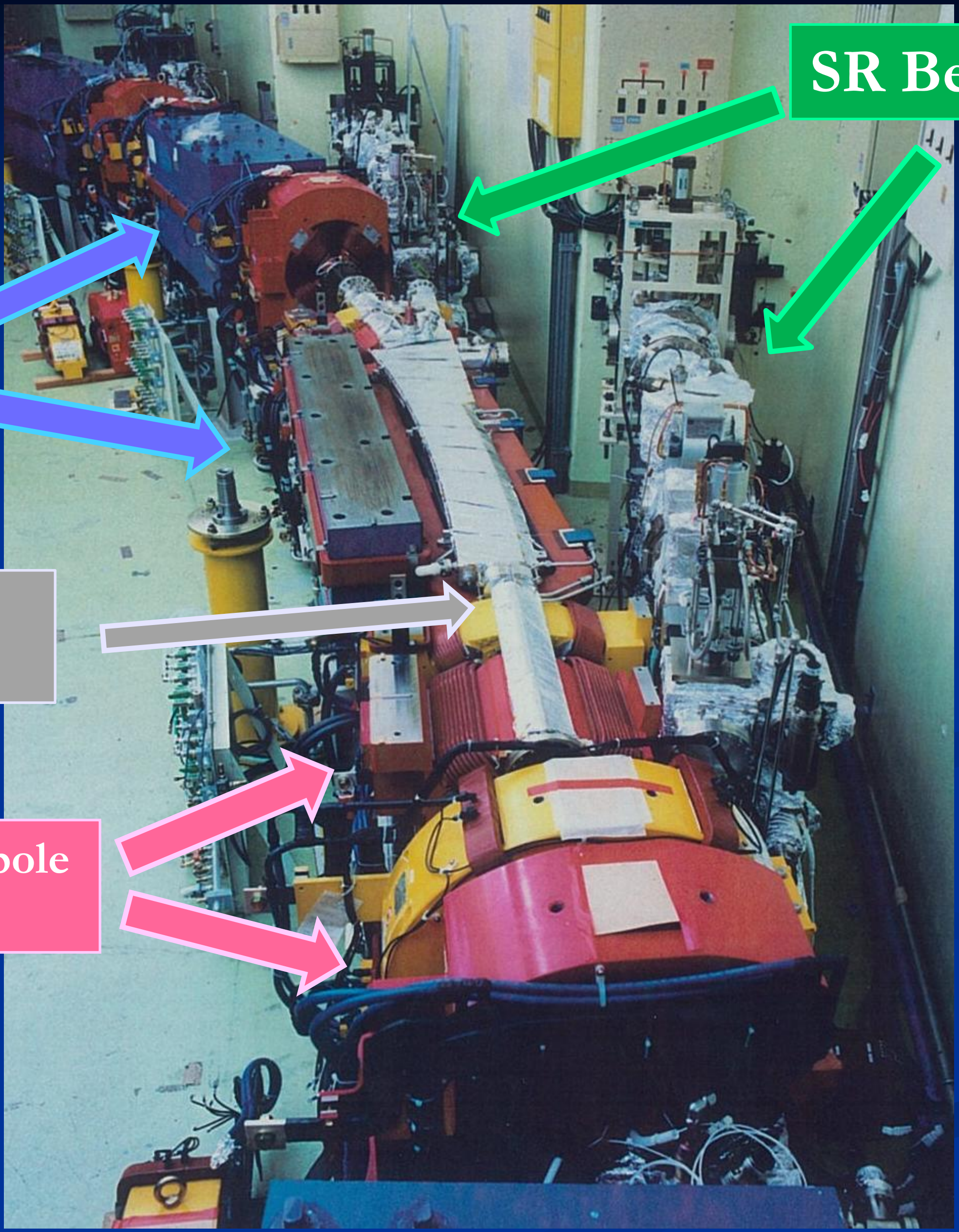


Configuration of Electron Storage Ring



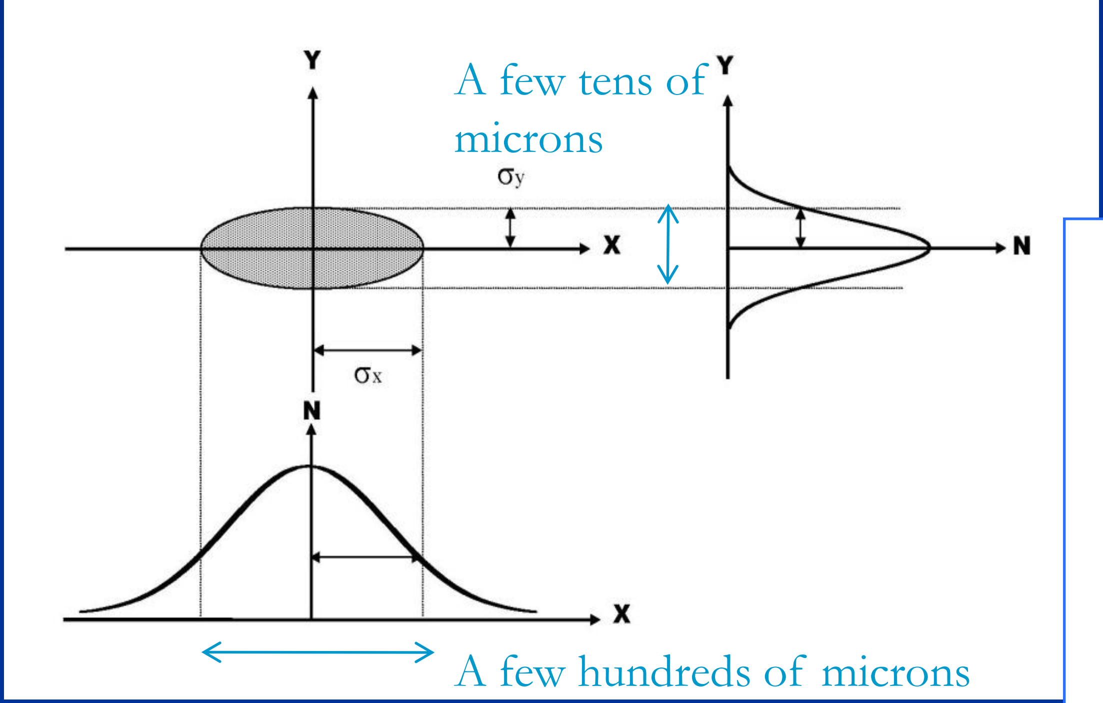
http://www.kek.jp/kids/accelerator/system.html

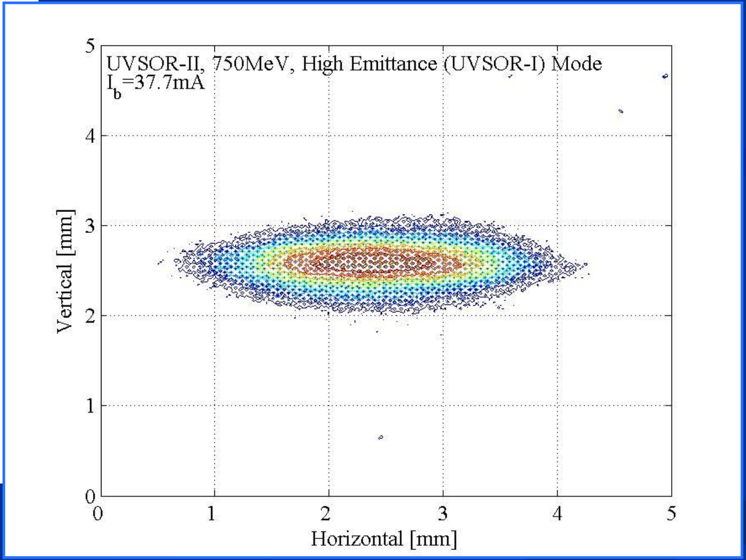
Electron Storage Ring



KEK Photon Factory (Tsukuba, Japan)

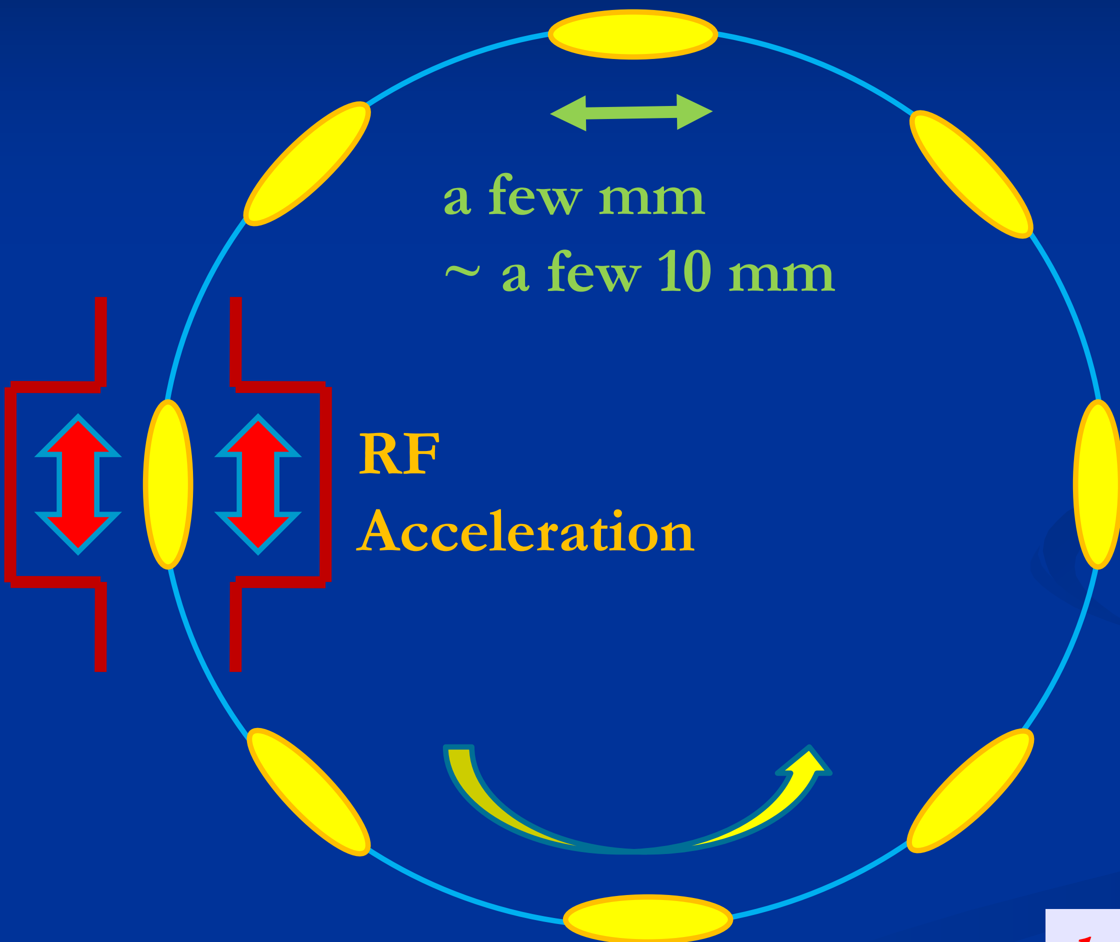
Transverse Profile of Electron Beam in Storage Rings





Observed cross-section of the electron beam in UVSOR-II

Bunched Electron Beam



Harmonic Number

$$h = \frac{f_{RF}}{f_{rev}} = \text{integer}$$

UVSOR-II
f_{RF}=90.1 MHz
f_{rev}=5.6 MHz
h=16

***h* = Number of RF buckets**

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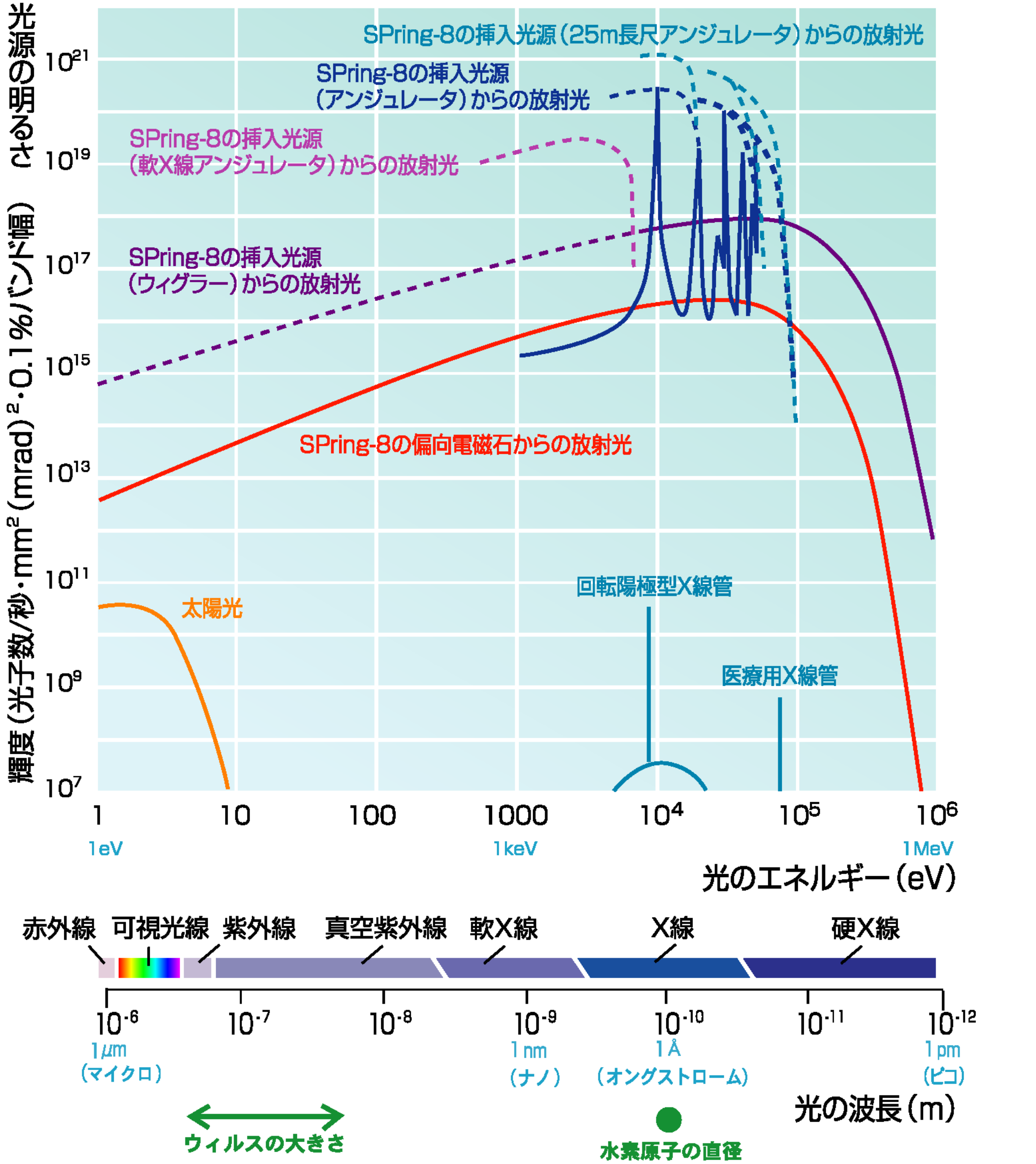
Characteristics of Synchrotron Radiation

- Intense
- Collimated
- Broadband
- Polarized
- Pulsed

Brightness of SR from SPring-8

http://www.spring8.or.jp/ja/



Why intense?

Larmor Formula for Circular Orbit

$$P = \frac{e^2 c}{6\pi\varepsilon_0} \frac{\beta^4}{\rho^2} \gamma^4$$

$$\left(\beta = \frac{v}{c} \approx 1 \right)$$

Lorentz Factor; $\gamma = E/mc^2$

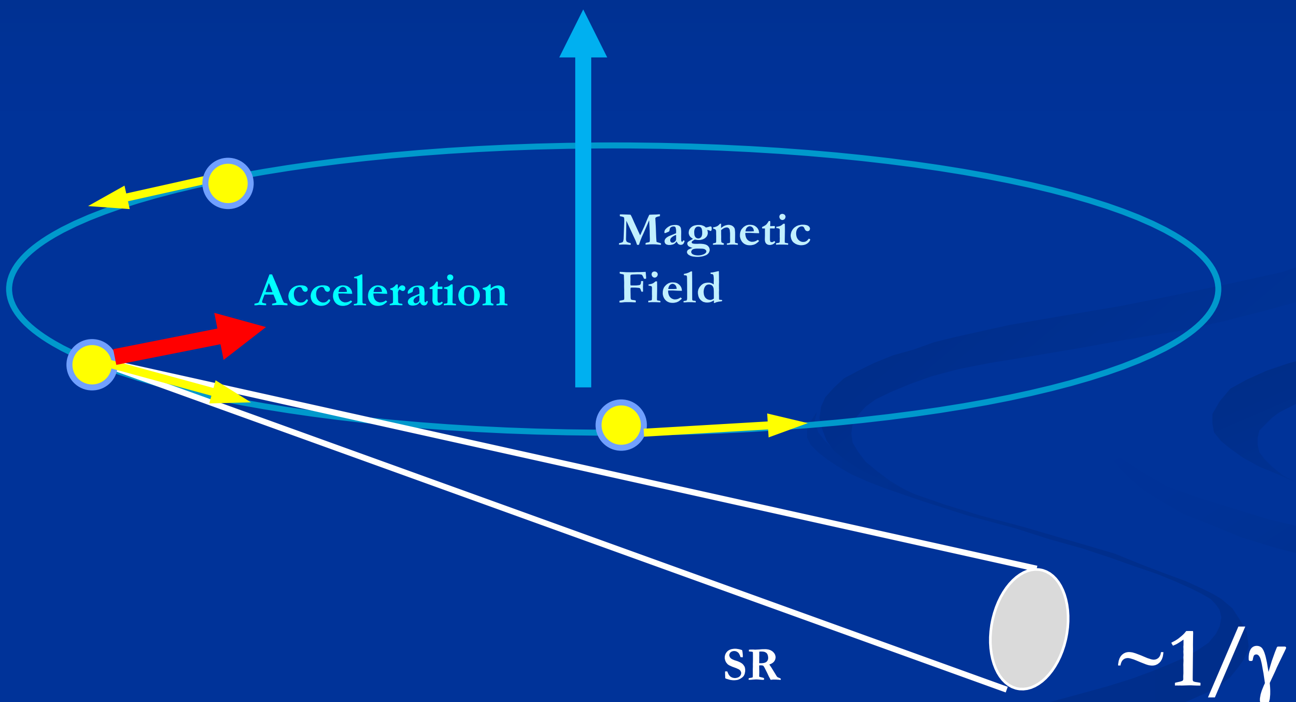
E=0.75 GeV => γ~1500
E=2.5 GeV => γ~5000
E=8.0 GeV => γ~16000

Example; E=2.5GeV, B=1T, ρ=8.3m

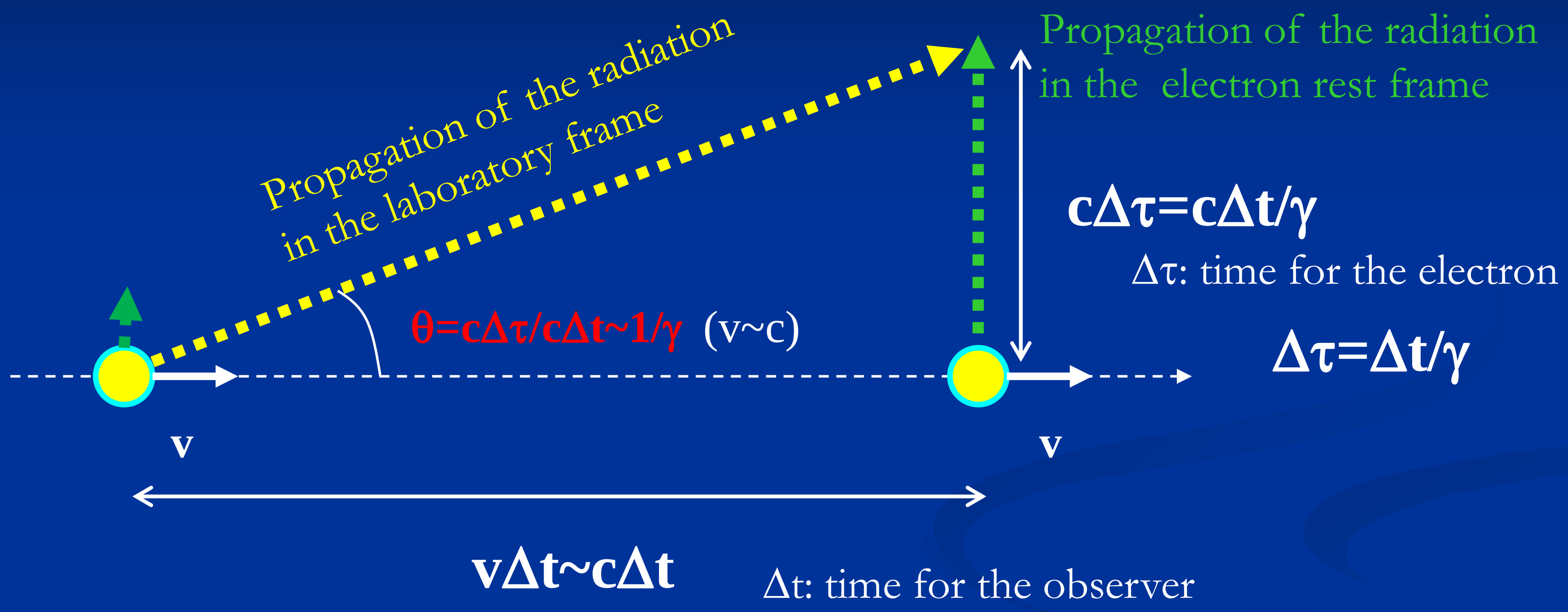
$\Rightarrow$ $t_d = E/P = \sim$ 4msec

(An electron loses most of its energy within 4msec.)

Why collimated?



Relativistic Beaming



In case of SPring-8 (E=8GeV);

$\gamma \sim 16000$

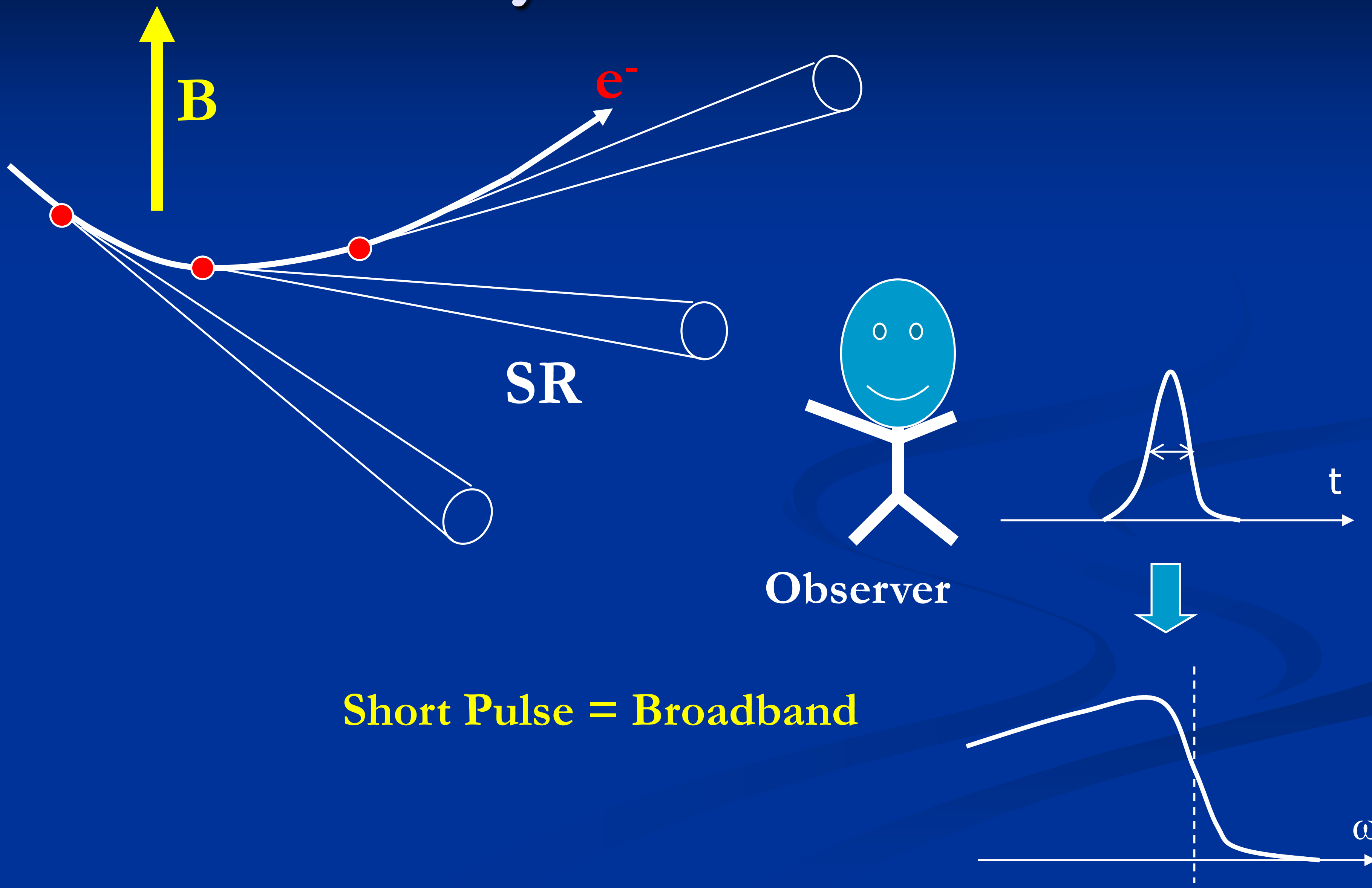
$1/\gamma \sim 1/16000 = 1\ \text{mm}/16\ \text{m} = 0.06\text{mrad}$

In case of UVSOR-II (E=0.75GeV);

$\gamma \sim 1500$

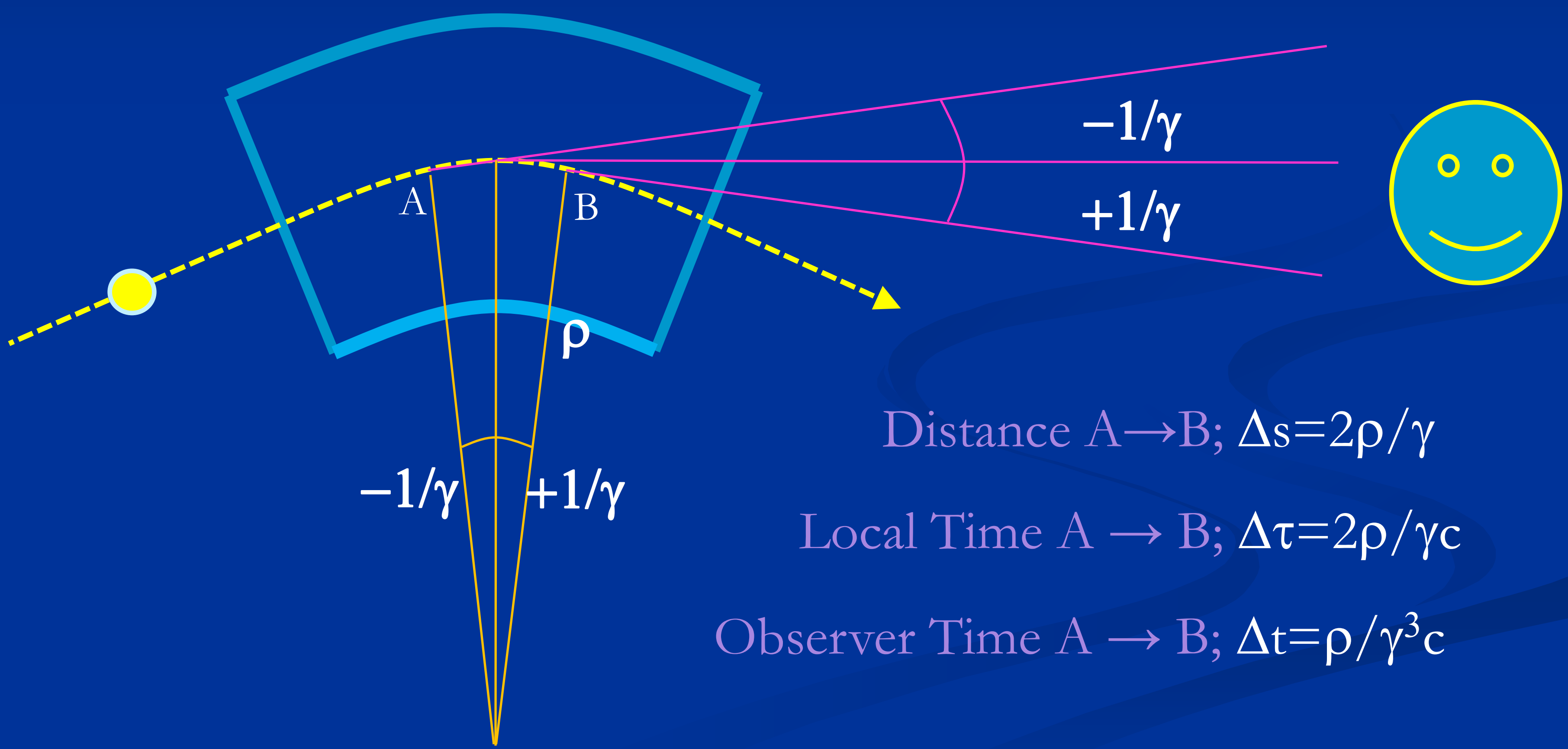
$1/\gamma \sim 1/1500 = 1\text{mm}/1.5\text{m} = 0.7\text{mrad}$

Why broadband?



Short Pulse = Broadband

Why broadband? (cont.)

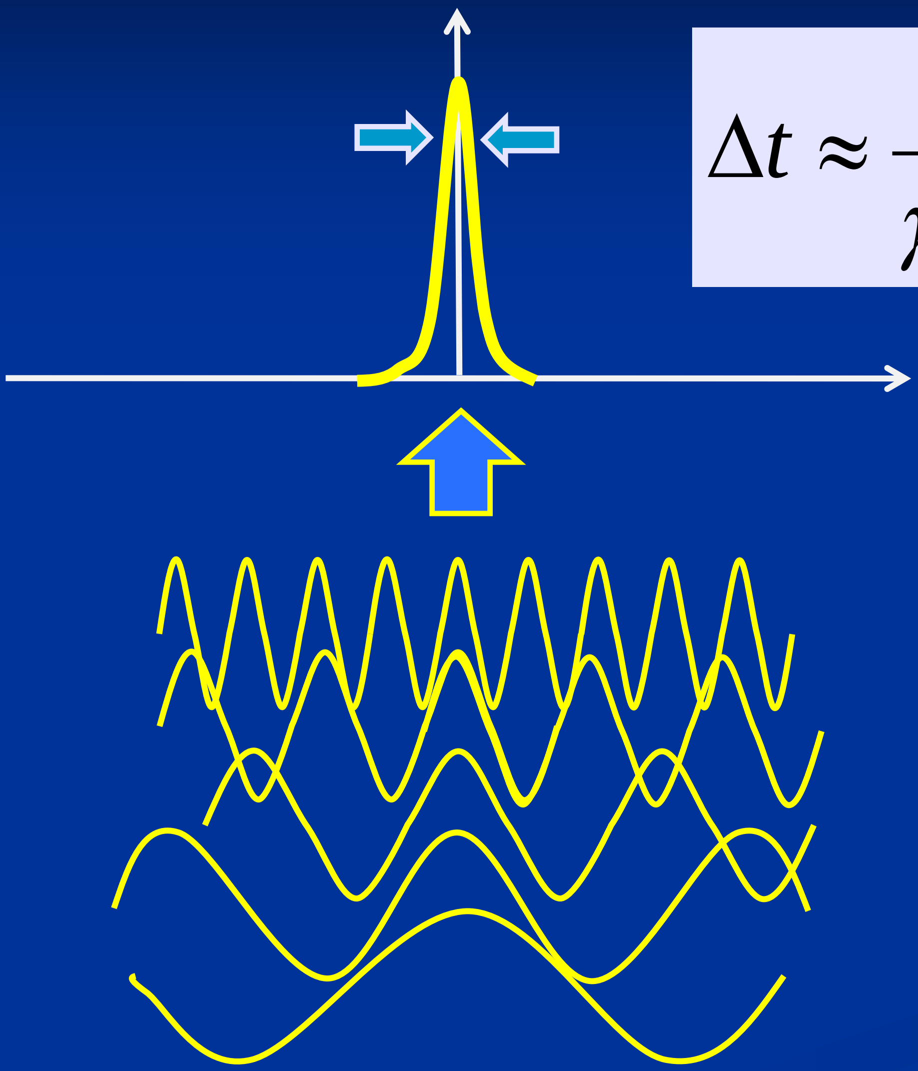


Distance A→B; $\Delta s=2\rho/\gamma$

Local Time A → B; $\Delta\tau=2\rho/\gamma c$

Observer Time A → B; $\Delta t=\rho/\gamma^3 c$

Why broadband? (cont.)



$$\Delta t \approx \frac{\rho}{\gamma^3 c}$$

A short pulse contains frequency components in wide range.

The highest frequency is given by

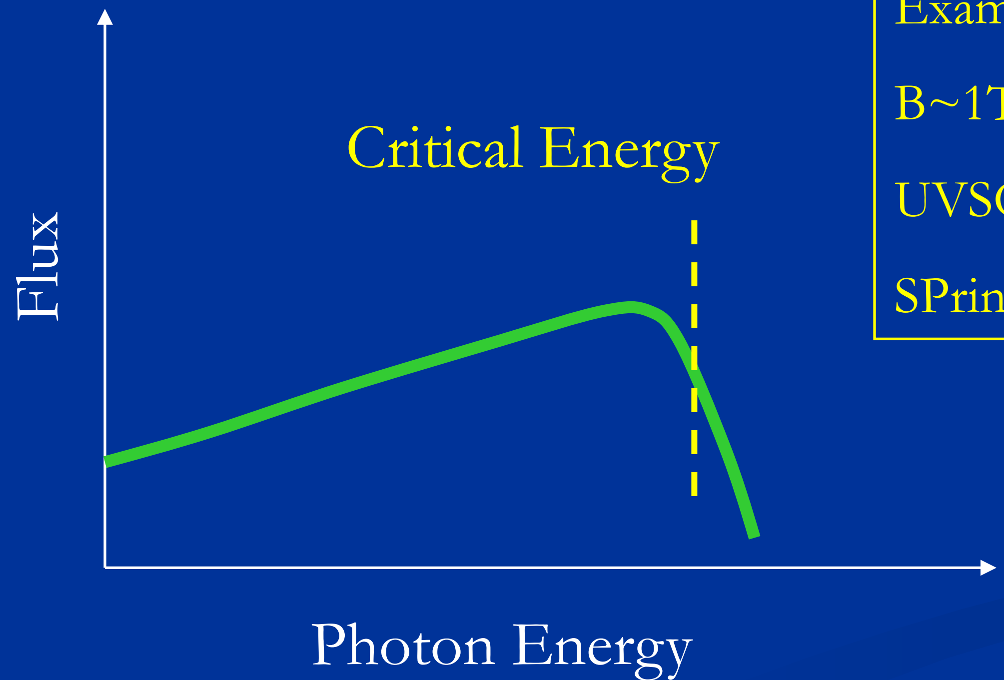
$$\omega_c \approx \frac{1}{\Delta t}$$

In case of UVSOR-II, $\rho \sim 2$ m, $c = 3\text{x}10^8$ m/s, $\gamma \sim 1500$

$\Rightarrow \Delta t \sim 10^{-18}$ s, $\varepsilon_c = h/2\pi\omega_c \sim 600$ eV

Critical Energy of Synchrotron Radiation

$$h\nu_c[keV] = 0.665E_e^2[GeV]B[T]$$



Example;

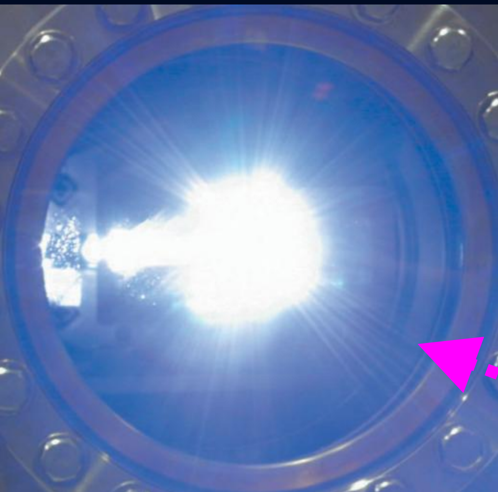
B~1T for normal conducting magnets.

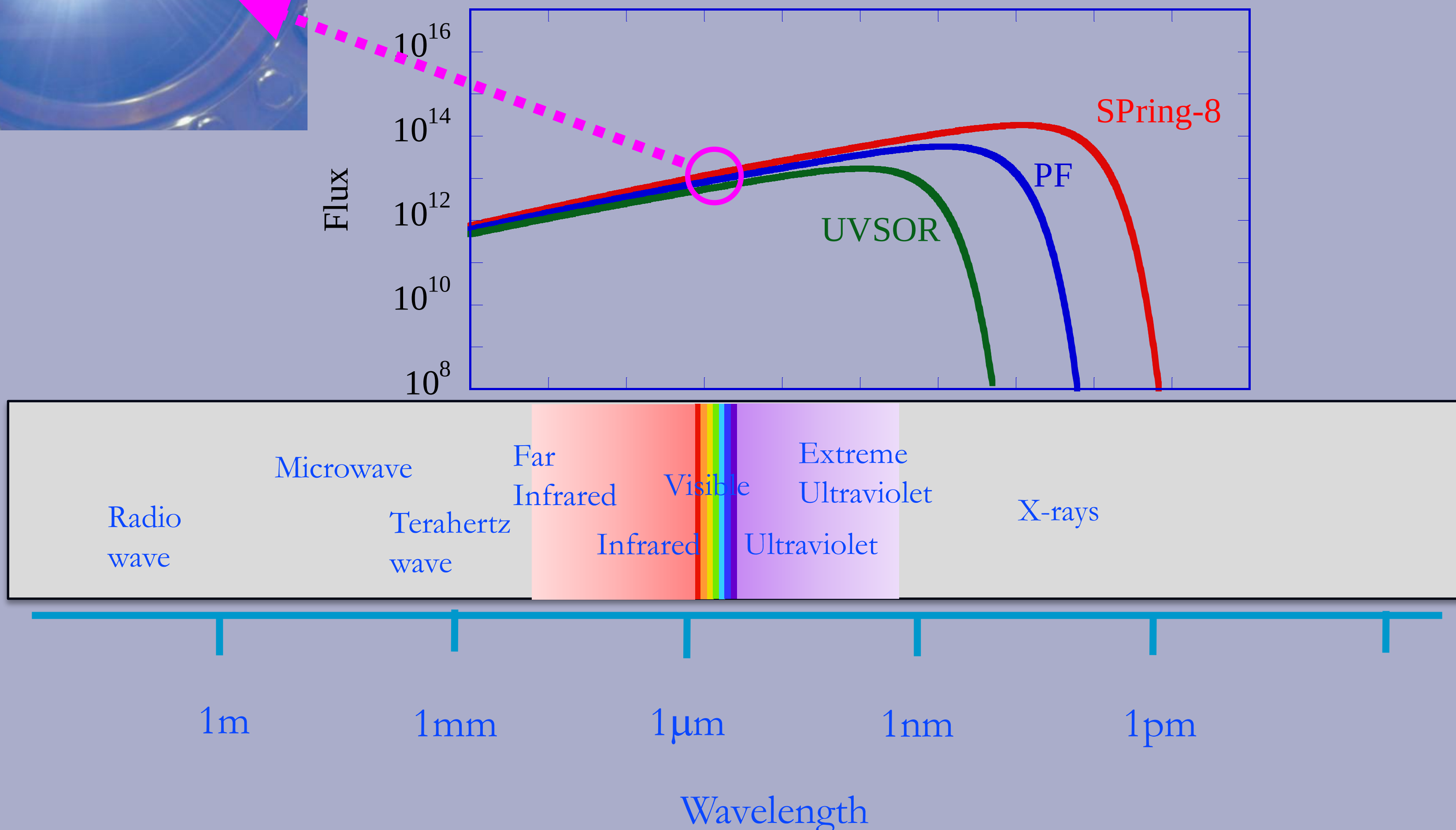
UVSOR-II; E_e=0.75 GeV => ε_c~0.4 keV

SPring-8; E_e=8.0 GeV => ε_c~40 keV

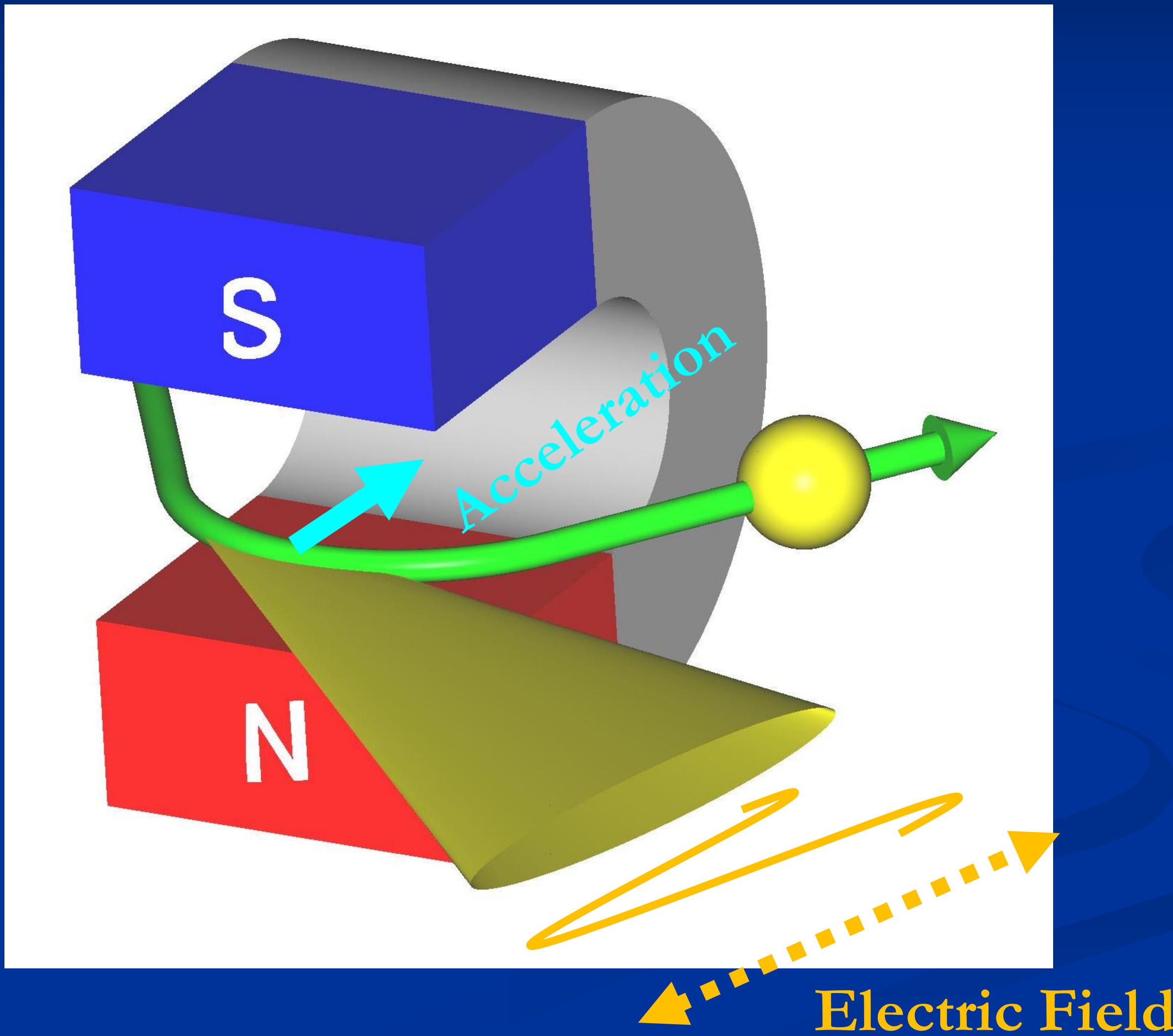
Extremely Broadband

from millimeter wave to X-rays

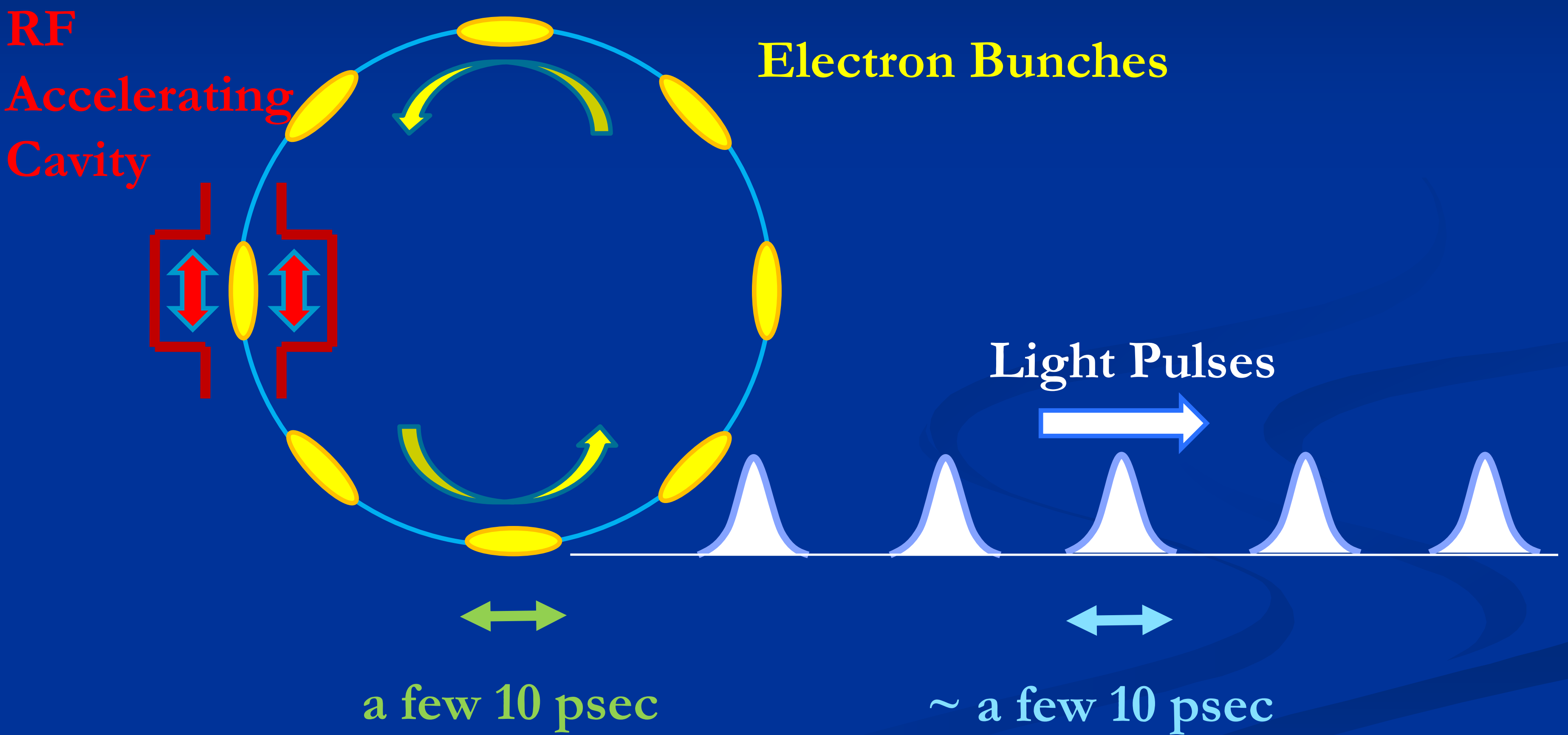




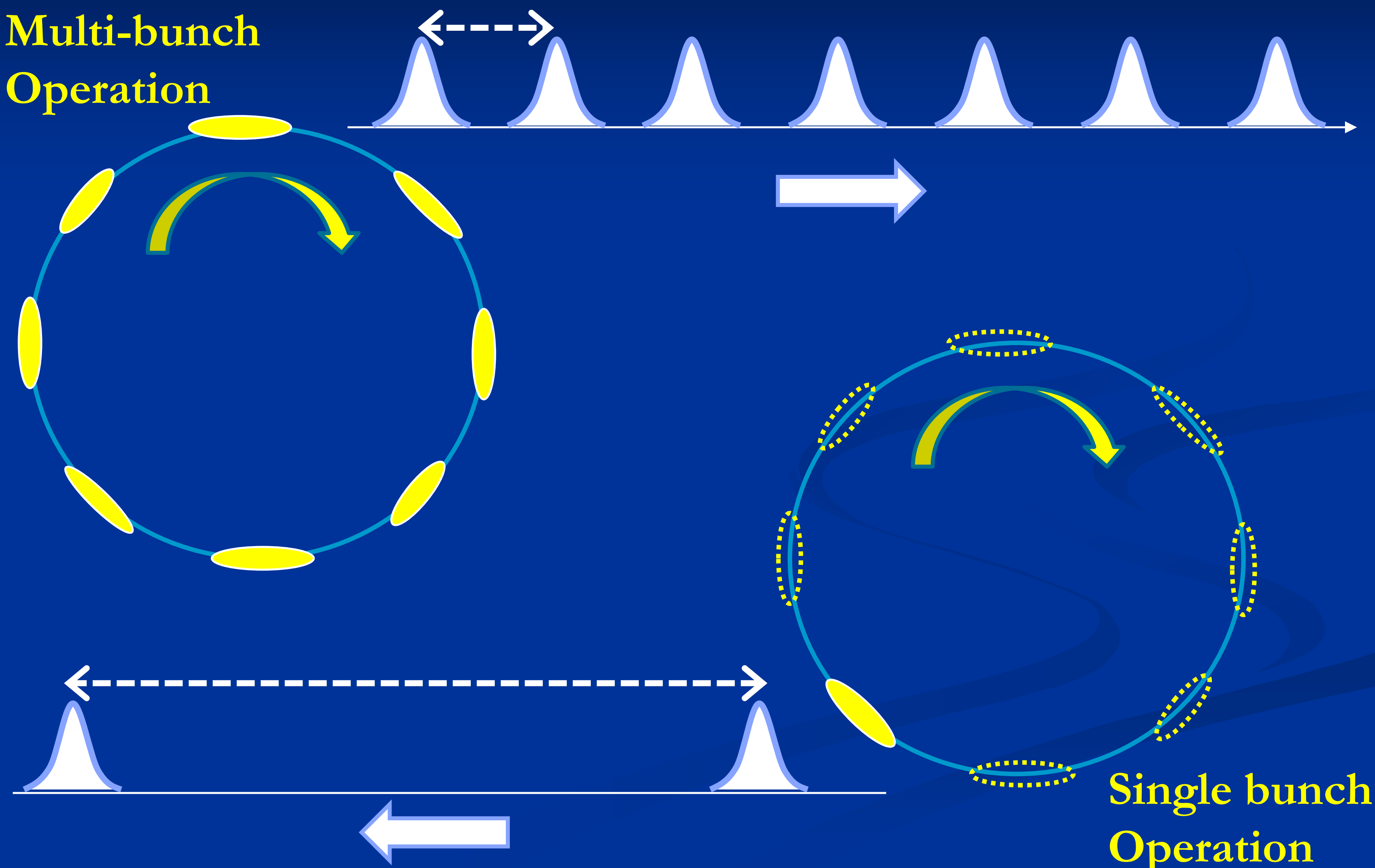
Why highly polarized?



Why pulsed?


RF
Accelerating
Cavity
Electron Bunches
Light Pulses
a few 10 psec
~ a few 10 psec

Time Structure of SR



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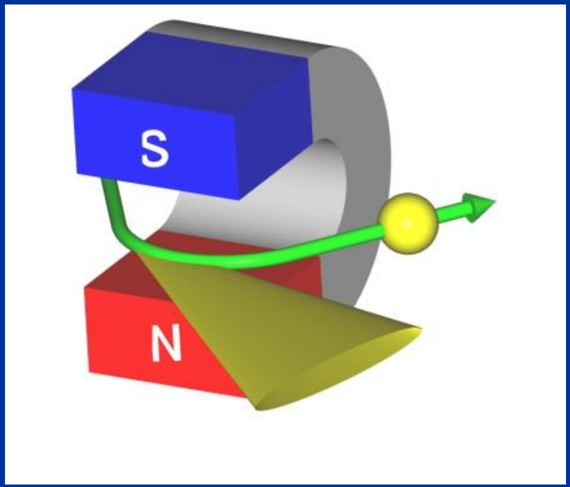
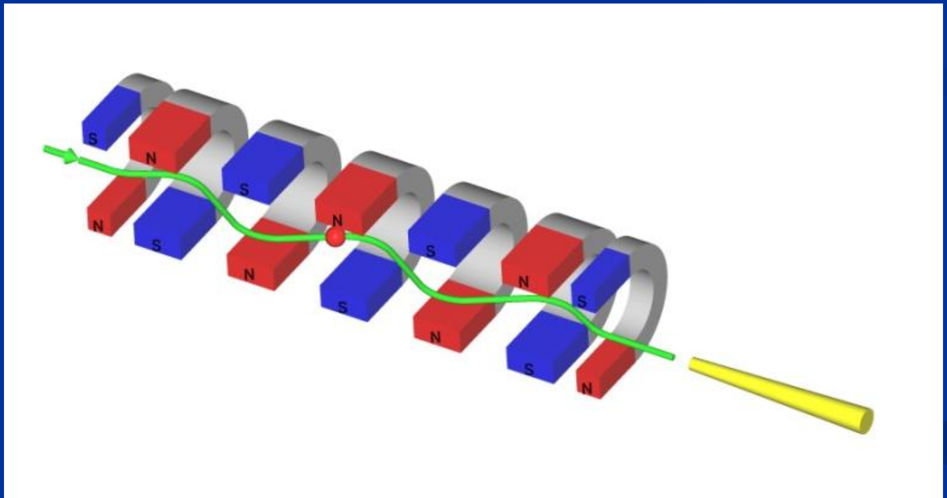
Towards Higher Brightness

Bending Magnet ⇒ Undulator



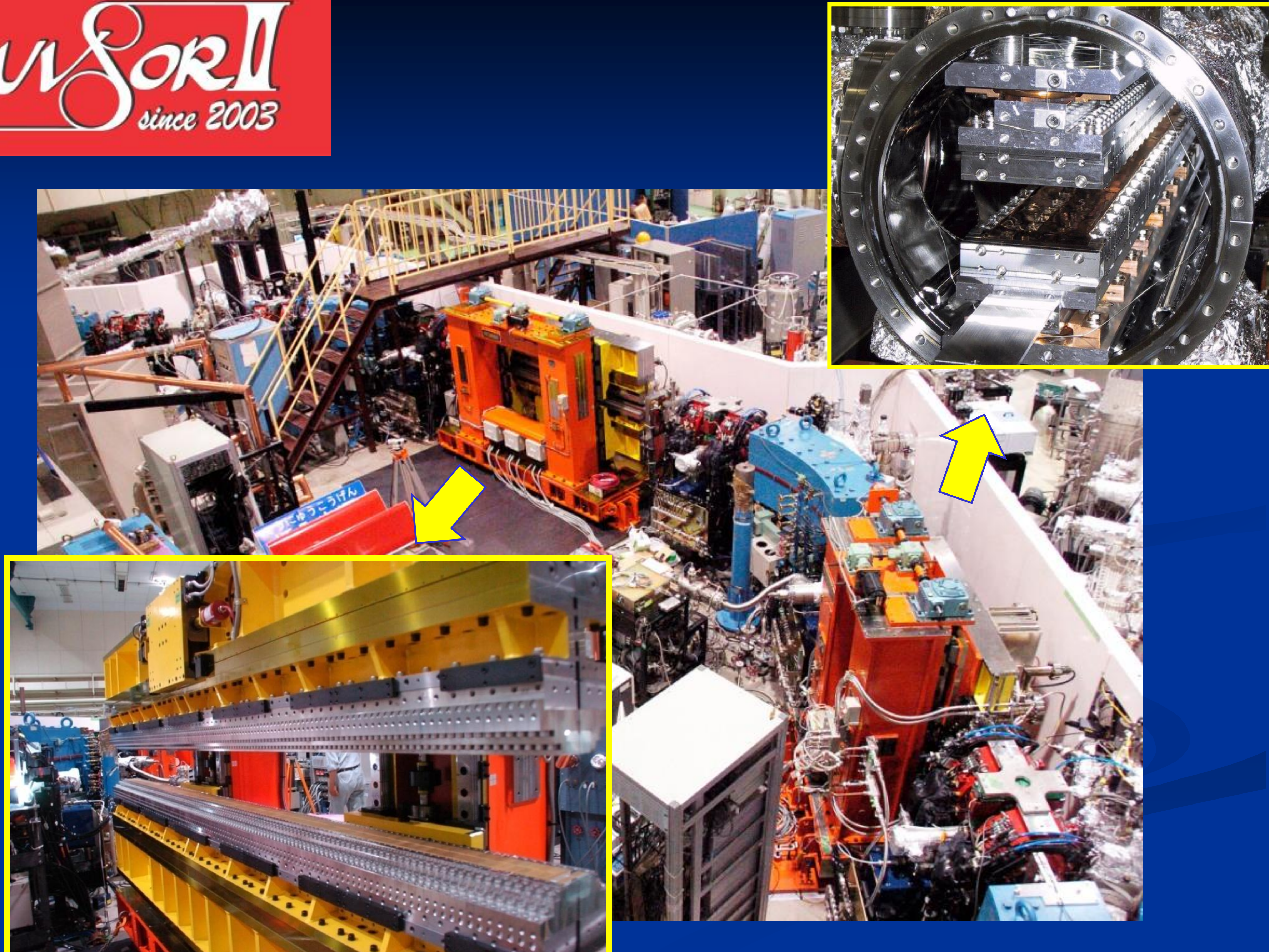


Undulator

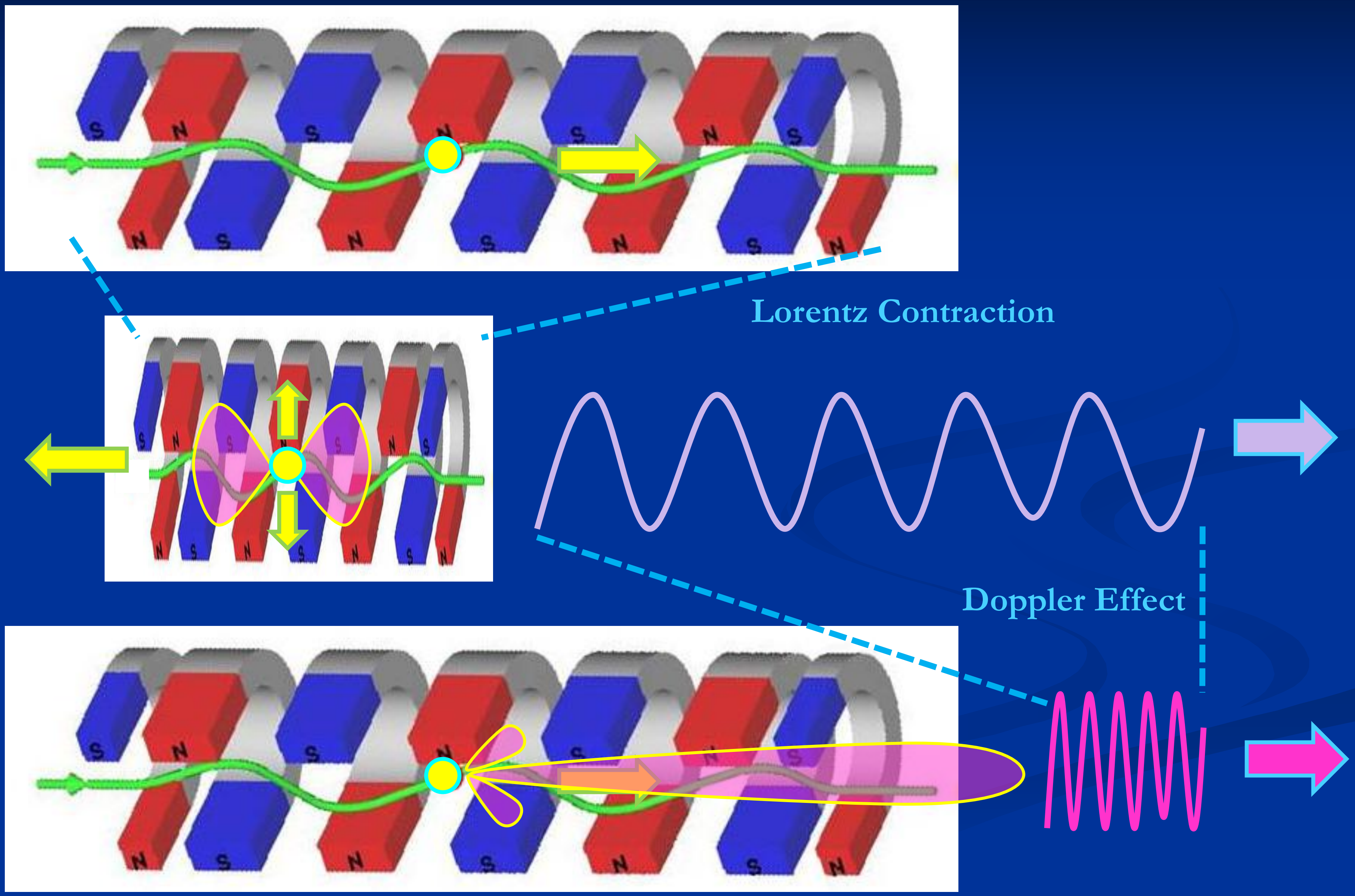
Configuration	APPLE-II
Polarization	Hor/Ver/Helical
Number of periods	40
Period length	76 mm
Total Length	3040 mm
Remanent field	1.3 T
Magnetic gap	24 – 200 mm
Deflection parameter (K)	
(horizontal mode)	max. 5.4
(vertical mode)	max. 3.6
(helical mode)	max. 3.0

Variable Polarization Undulator at UVSOR-II BL7U
Institute for Molecular Science, Okazaki, Japan

UVSOR II
since 2003



Principle of Undulator



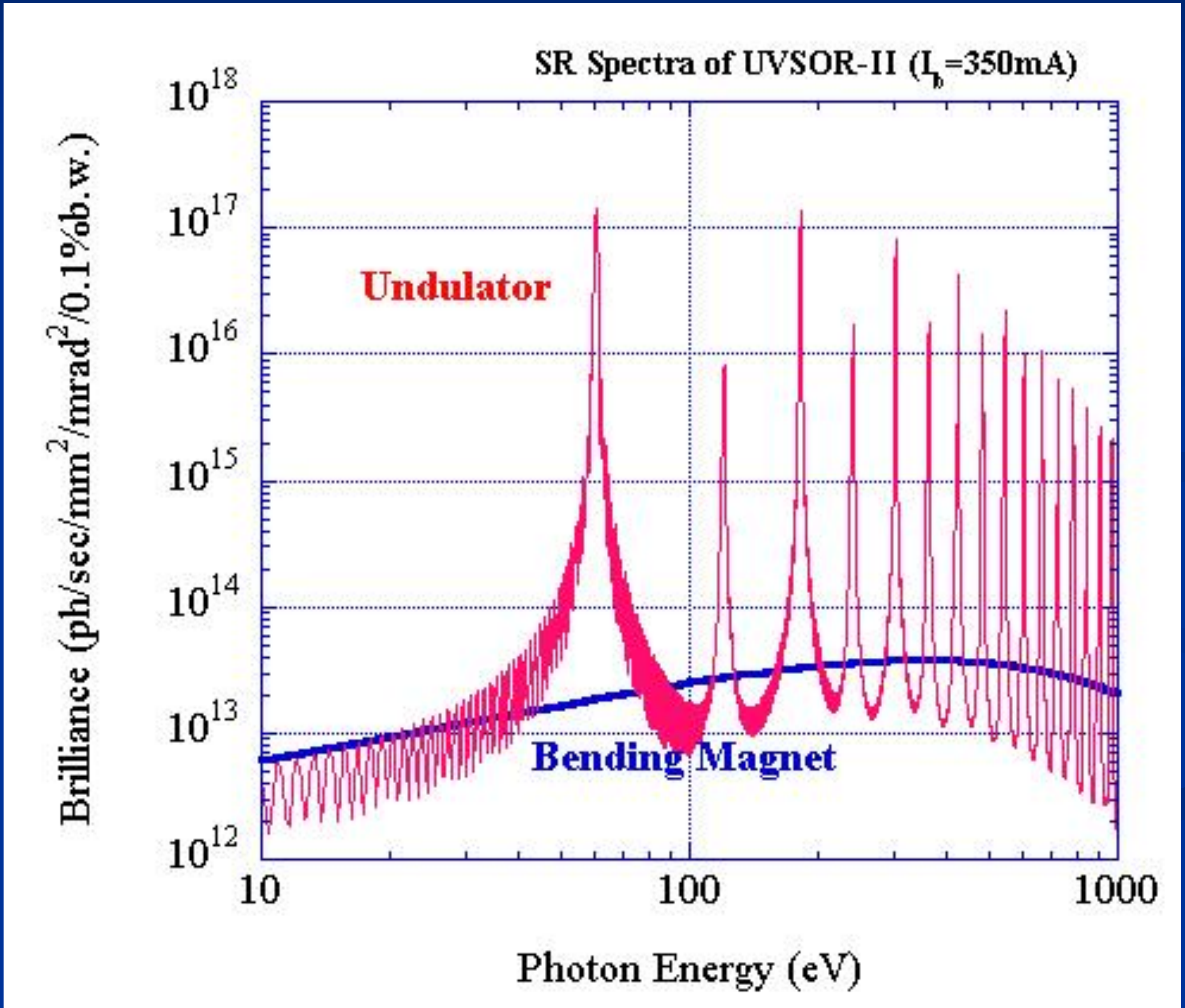
Undulator Radiation Spectrum (cont.)

$$h\nu[keV] = \frac{0.95E_e^2[GeV]}{(1+K^2/2)\lambda_u[cm]}$$

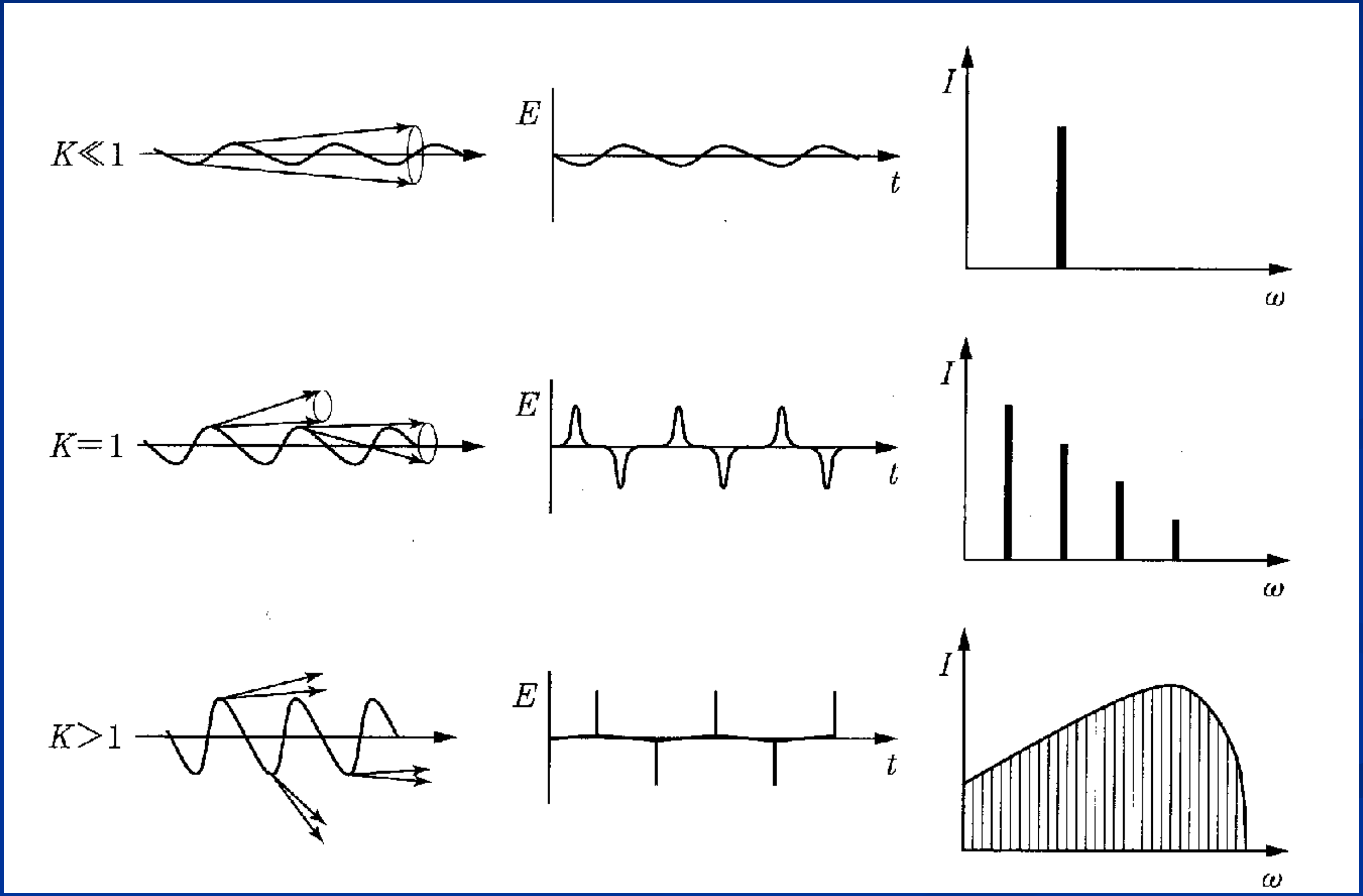
$$K = 0.934\lambda_u[cm]B_0[T]$$

Example;
E_e=8 [GeV], λ_u=3.2 [cm], B_0=0.5 [T]
$\Rightarrow$ hν~9 [keV]

Undulator Radiation Spectrum (cont.)

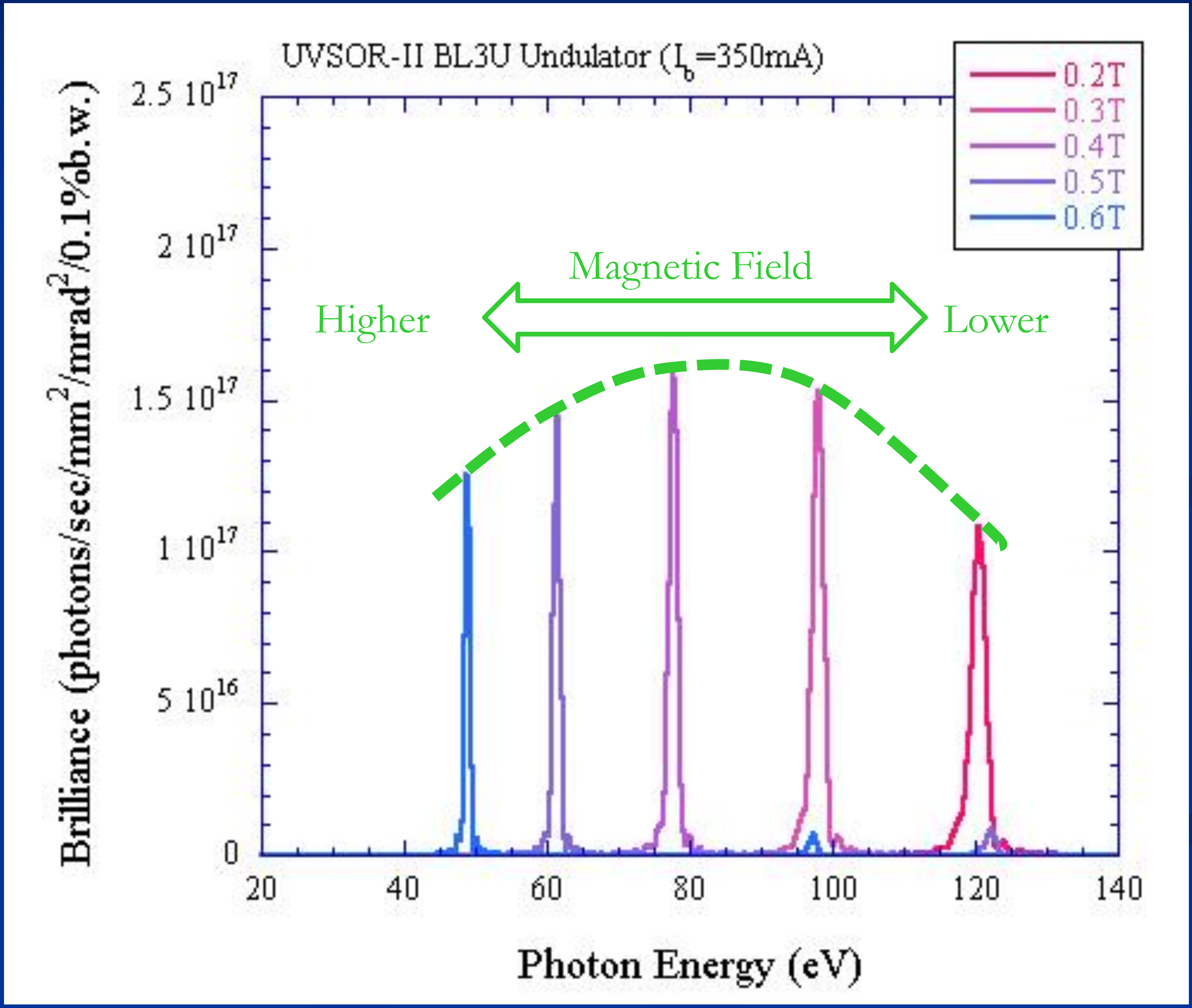


Why Higher Harmonics?



H. Kamitubo, T. Ohta, “シンクロトロン放射光” (2005)

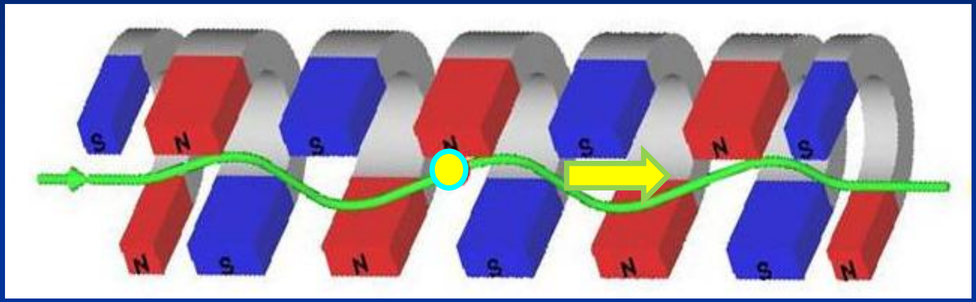
Tunability



UVSOR-II BL3U Undulator (I_b=350mA)
0.2T
0.3T
0.4T
0.5T
0.6T
Magnetic Field
Higher
Lower
2.5 10^17
2 10^17
1.5 10^17
1 10^17
5 10^16
0
20
40
60
80
100
120
140
Brilliance (photons/sec/mm^2/mrad^2/0.1%b.w.)
Photon Energy (eV)

Why Tunable?

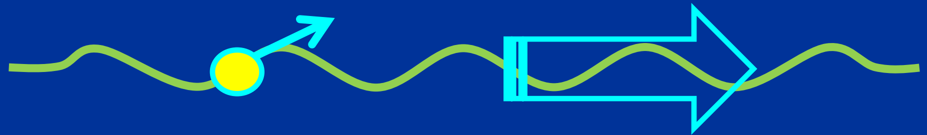
Average Velocity of Electron in Undulator

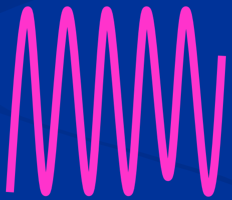


$$\bar{v}_z = v\left(1 - \frac{K^2}{4\gamma^2}\right)$$

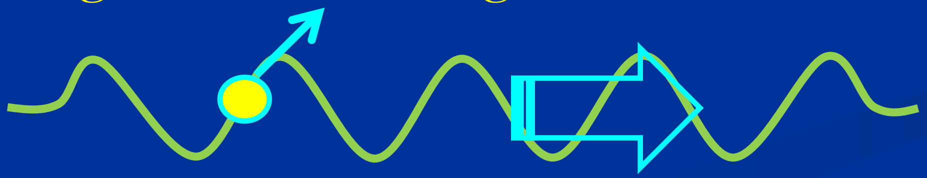
$$K = \frac{eB_0\lambda_u}{2\pi mc}$$

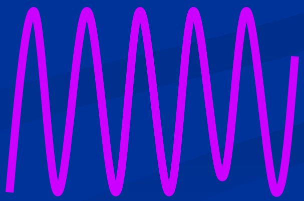
Small K; Electrons go fast.



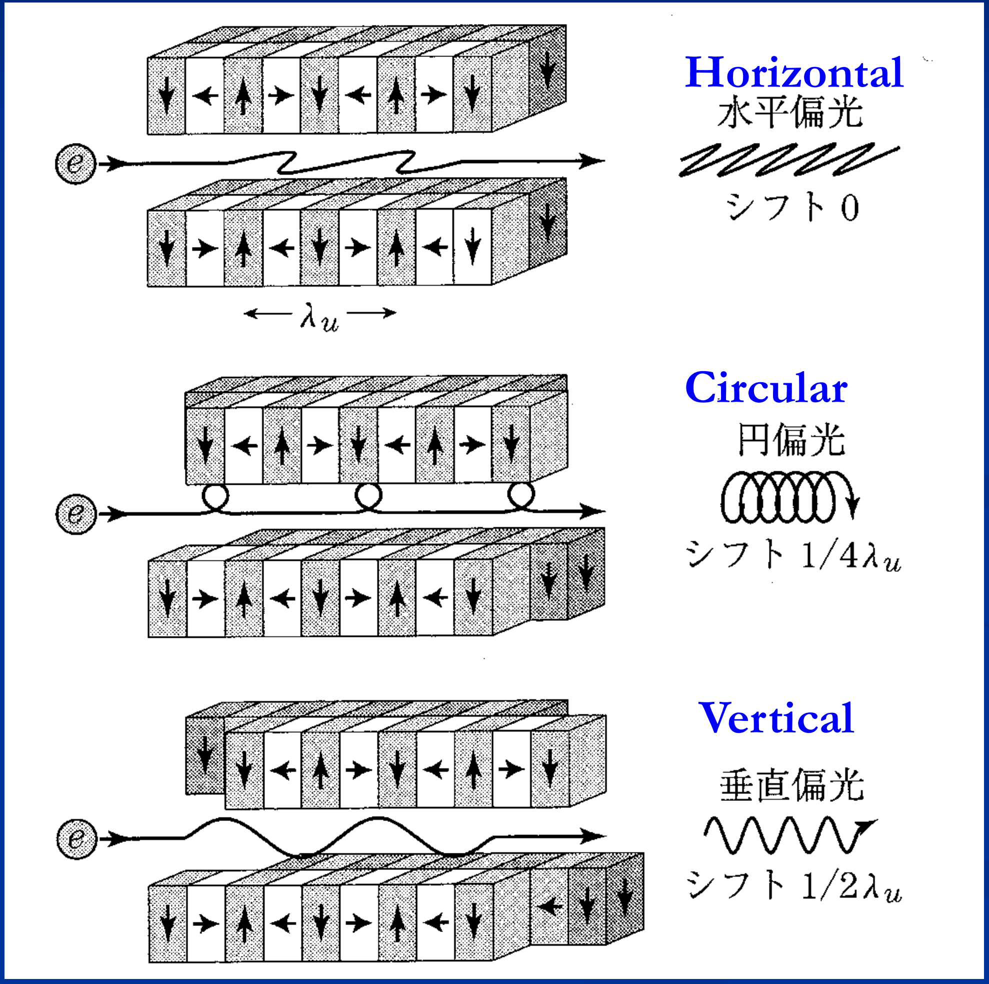


Large K; Electrons go slow.





Variable Polarization Undulator



S. Sasaki, NIM A347 (1994) 83

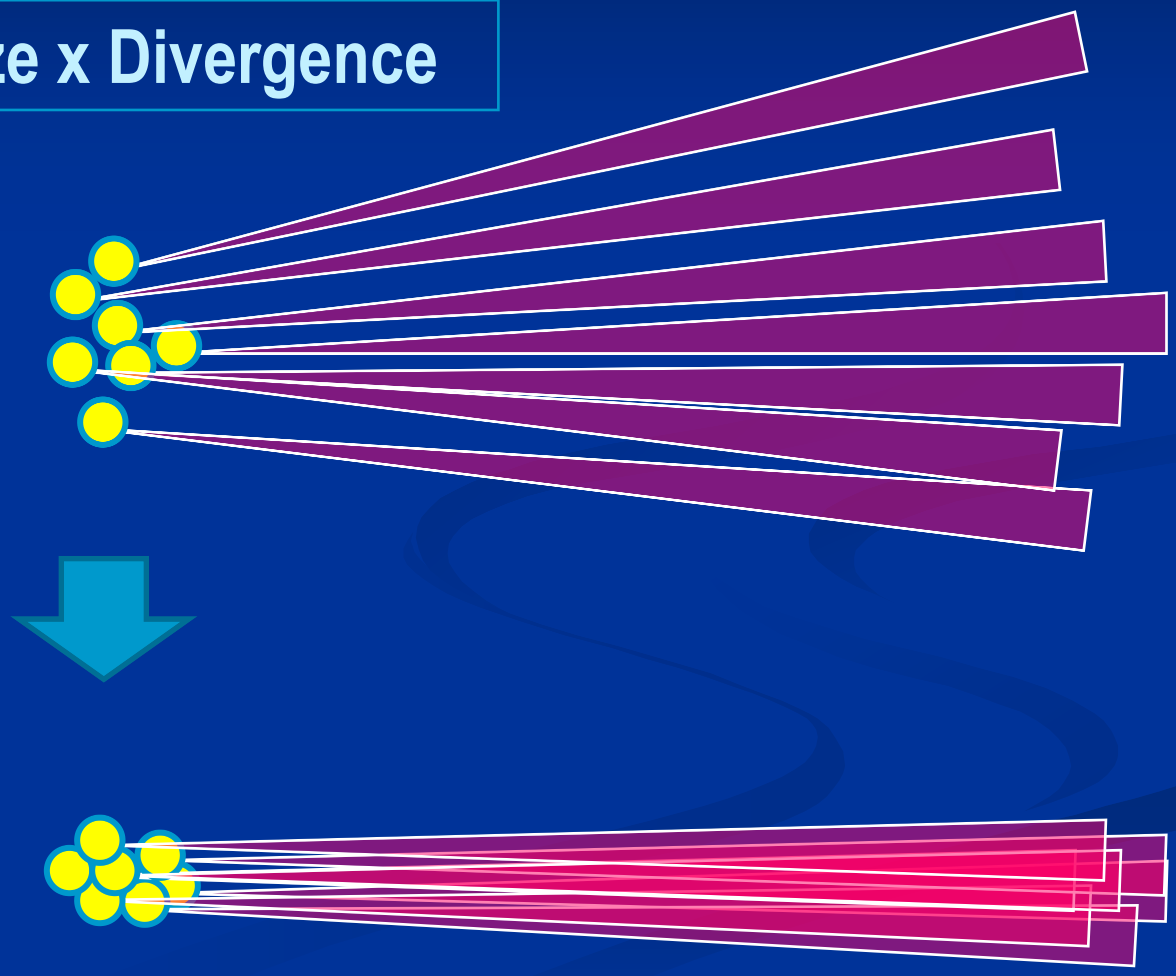
H. Kamitsubo and S. Ohta, “シンクロトロン放射光”、2005

Towards Higher Brightness
Low Emittance Electron Beam

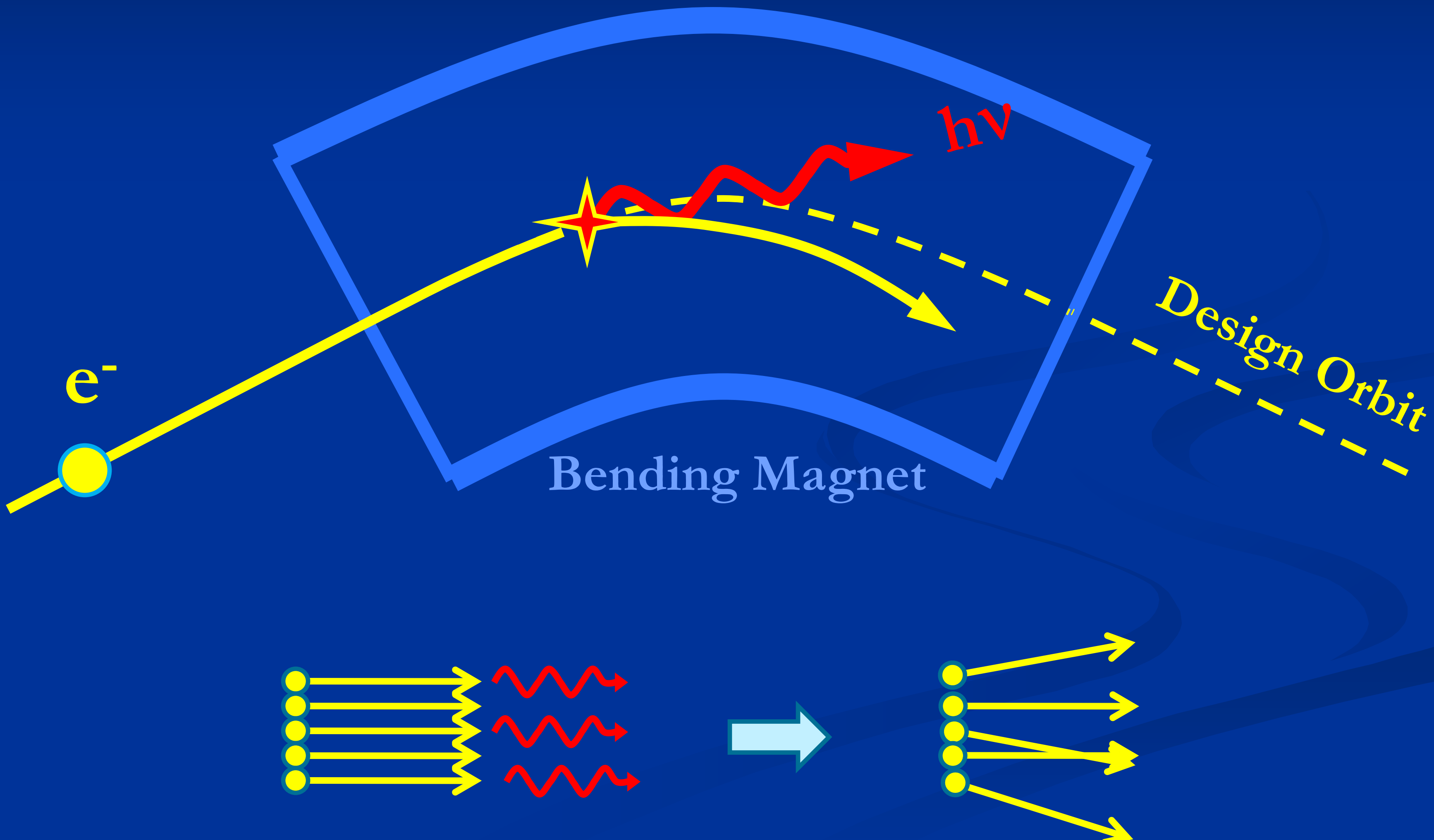
Emittance = Size x Divergence

High emittance electron beam

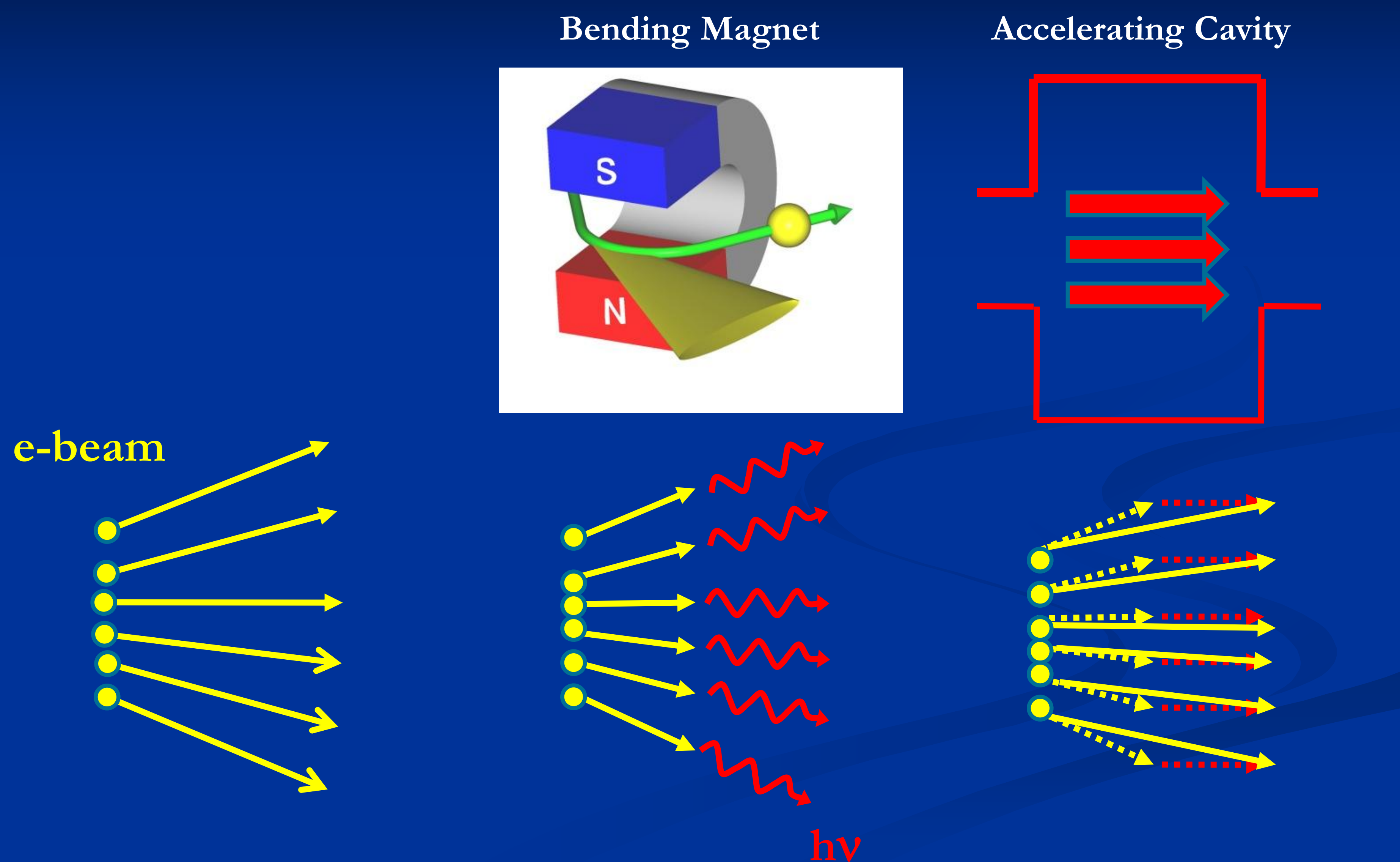
Low emittance electron beam



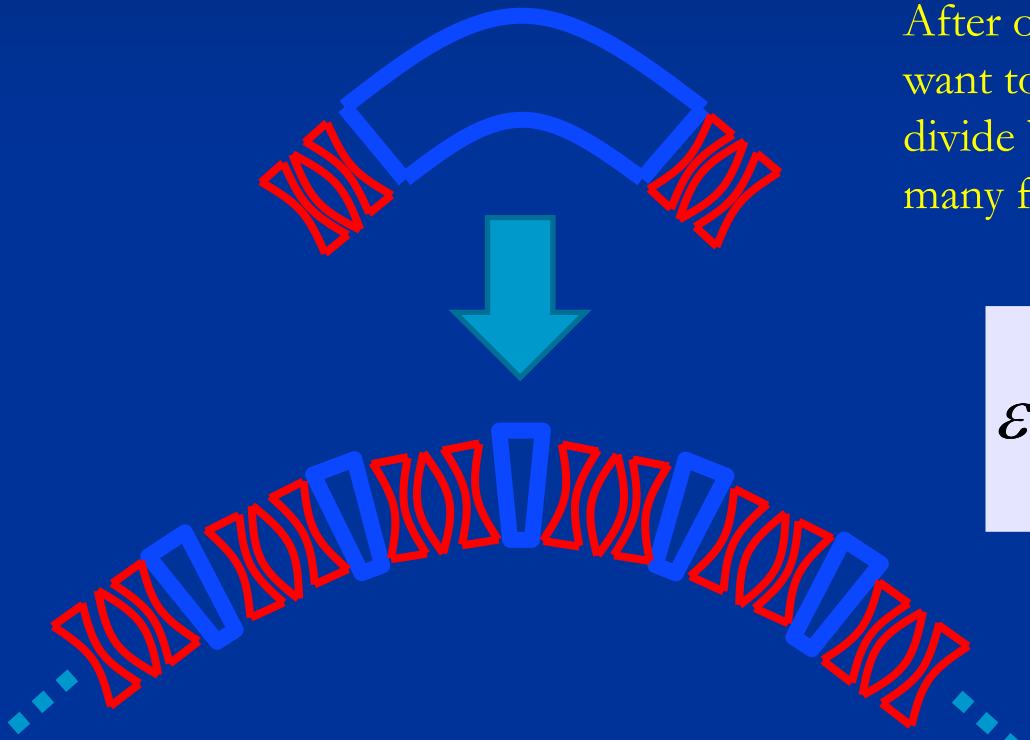
Radiation Excitation



Radiation Damping



Low Emittance Lattice



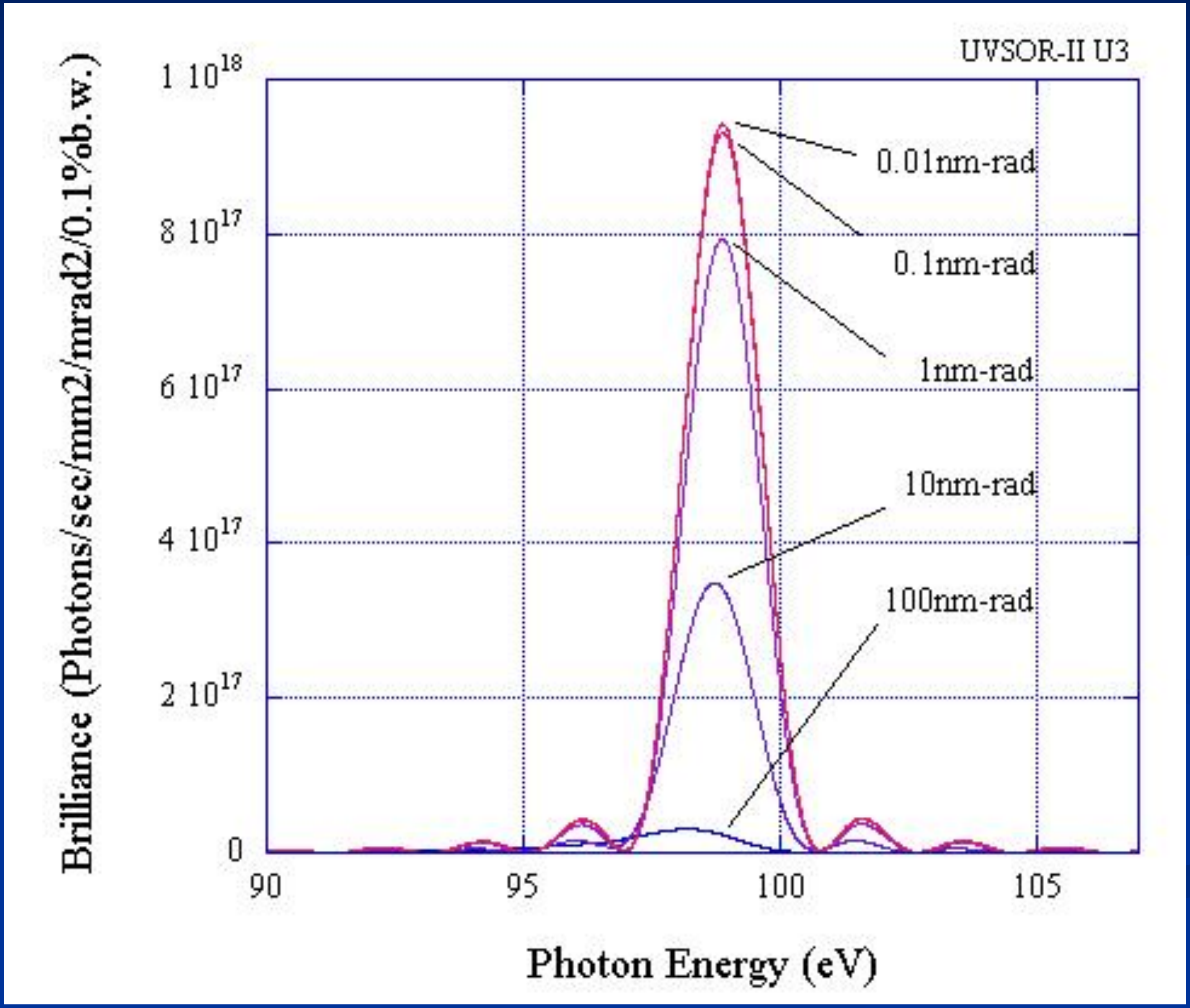
After optimizing the focusing magnets, if we want to reduce the emittance more, we must divide bending magnets in small peaces and put many focusing magnets between them.

$$\varepsilon = F(\nu_x, \text{lattice}) \frac{E^2[\text{GeV}]}{J_x N_d^3}$$

N_d; Number of Bending Magnets

J. B. Murphy, BNL 42333 (1996)

Diffraction Limit on Brilliance



Effect of Emittance on Brilliance

Brilliance of Undulator Radiation

$$B = \frac{F}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

Flux into the central cone

$$F = \frac{\pi}{2}\alpha N \frac{\Delta\omega}{\omega}\frac{I}{e}Q_n(K)$$

Effective Source Size and Divergence

$$\Sigma_x = \sqrt{\sigma_r^2 + \sigma_x^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{r'}^2 + \sigma_{x'}^2}$$

$$\Sigma_y = \sqrt{\sigma_r^2 + \sigma_y^2}$$

$$\Sigma_{y'} = \sqrt{\sigma_{r'}^2 + \sigma_{y'}^2}$$

Size and Divergence of e-Beam

$$\varepsilon_x = \sigma_x \sigma_{x'}$$

$$\varepsilon_y = \sigma_y \sigma_{y'}$$

Size and Divergence of Undulator Radiation

$$\sigma_r = \sqrt{2\lambda L} / 4\pi$$

$$\sigma_{r'} = \sqrt{\lambda / 2L}$$

$$\varepsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{4\pi}$$

e.g. K. J. Kim, AIP Conf. Proc. 184 (1989), 565

Diffraction Limit

$$B = \frac{F}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

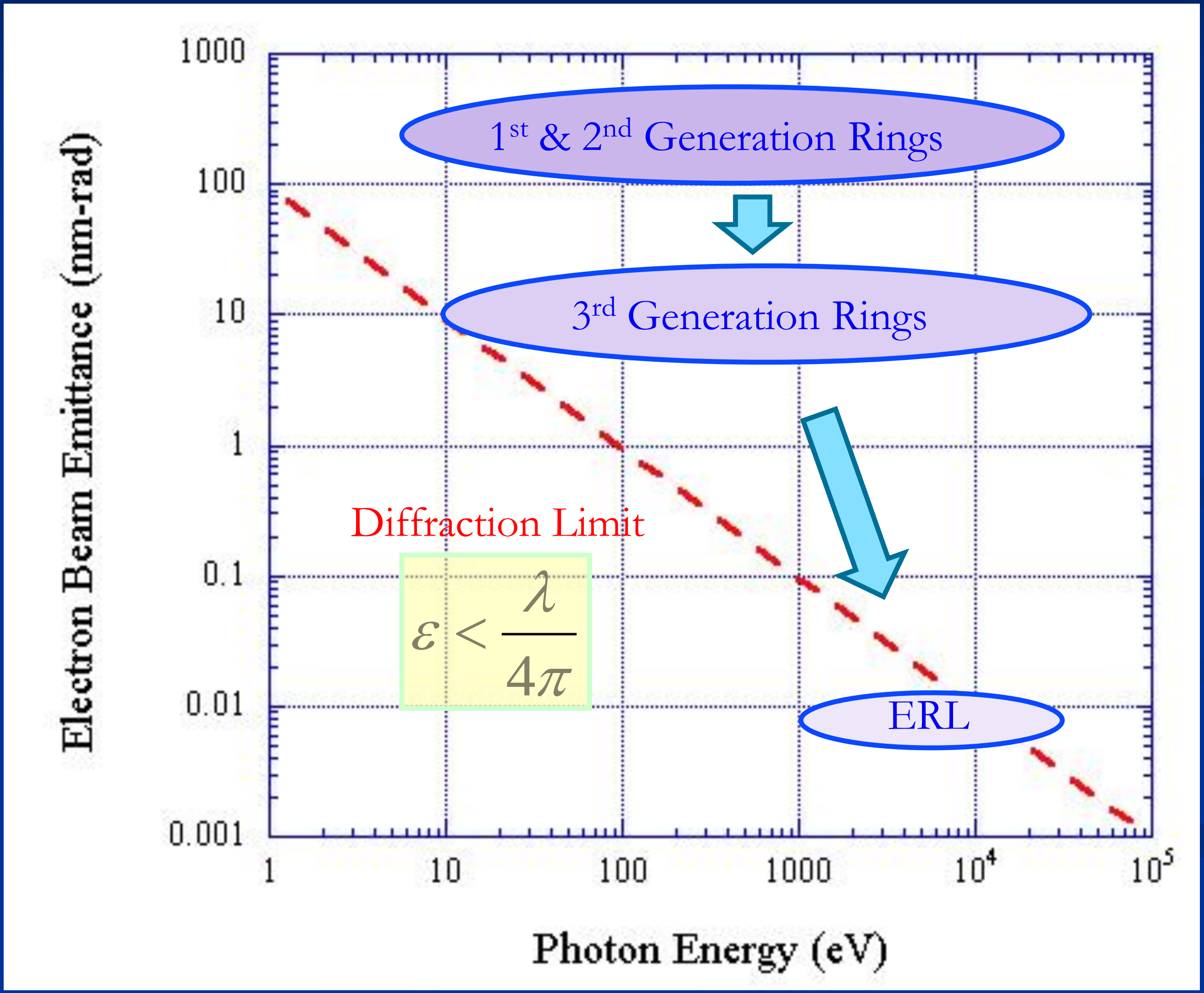
$$\sigma_x, \sigma_y << \sigma_r$$

$$\sigma_{x'}, \sigma_{y'} << \sigma_{r'}$$

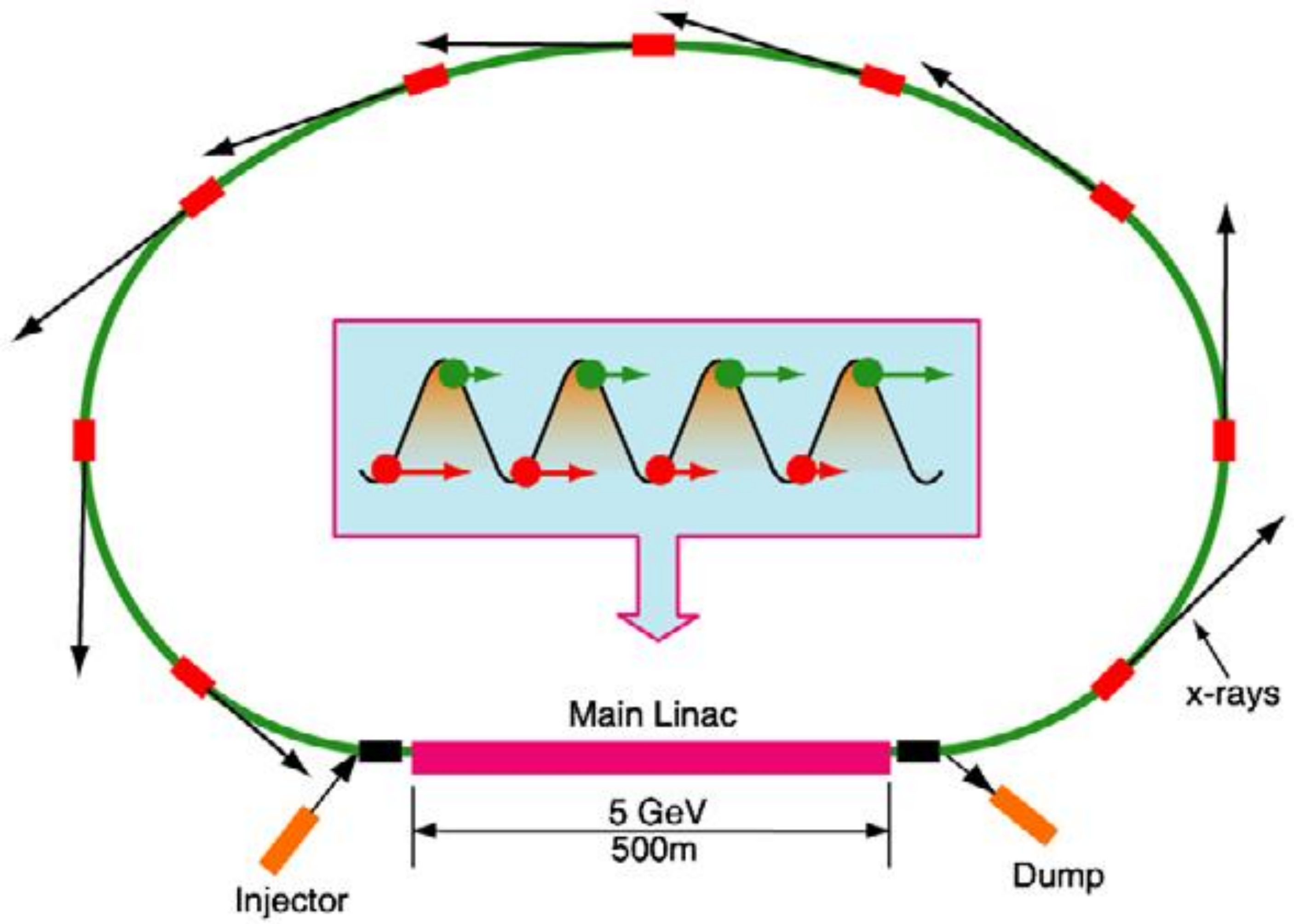
$$\varepsilon_r = \sigma_r \sigma_{r'} = \frac{\lambda}{4\pi}$$

$$B = \frac{F}{(2\pi)^2 \sigma_r^2 \sigma_{r'}^2} = \frac{F}{(\lambda/2)^2}$$

Towards Diffraction Limit

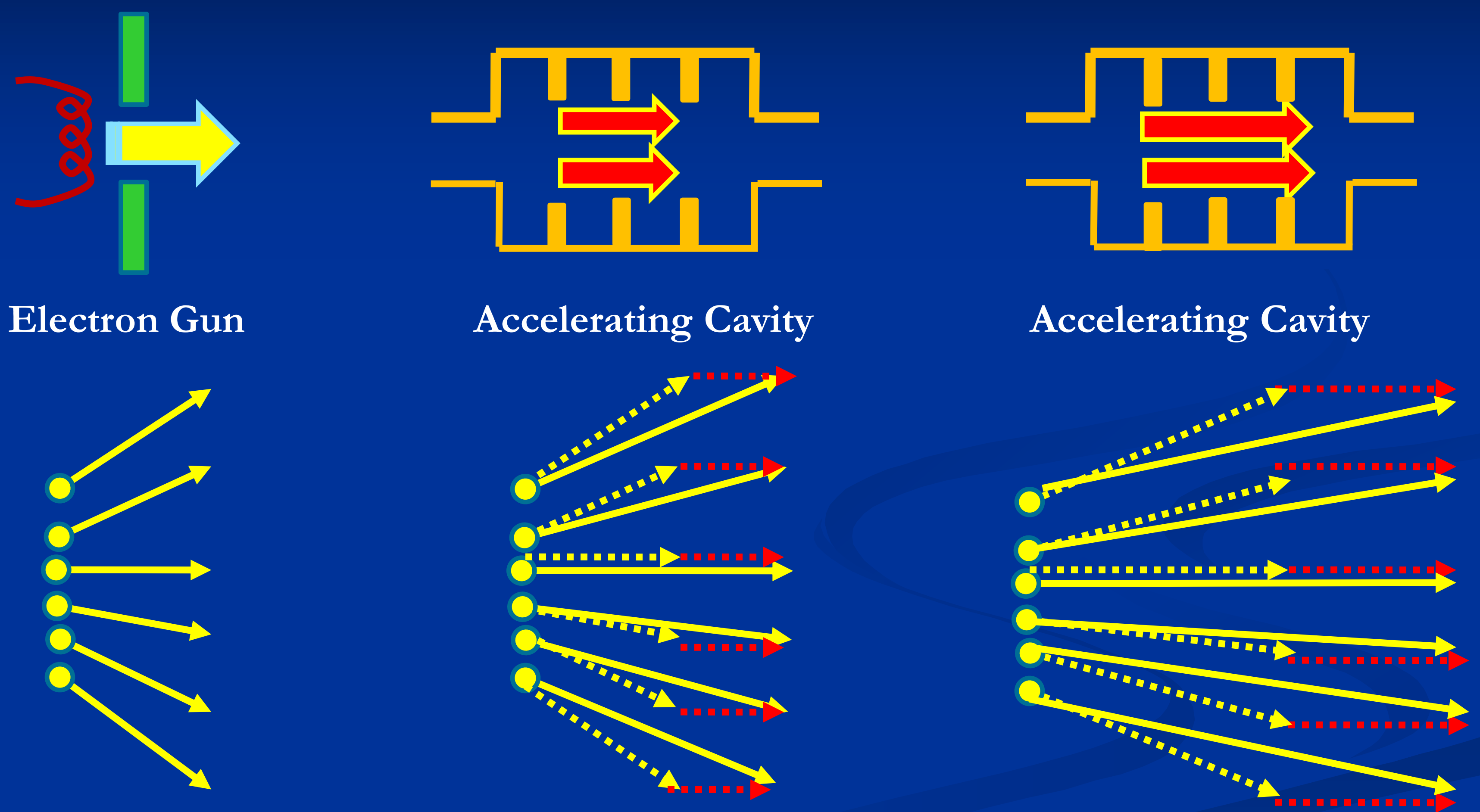


Energy Recovery Linac



D.H. Bilderback, P. Elleaume, E. Weckert, J. Phys. B: At. Mol. Opt. Phys. 38 (2005) S773–S797

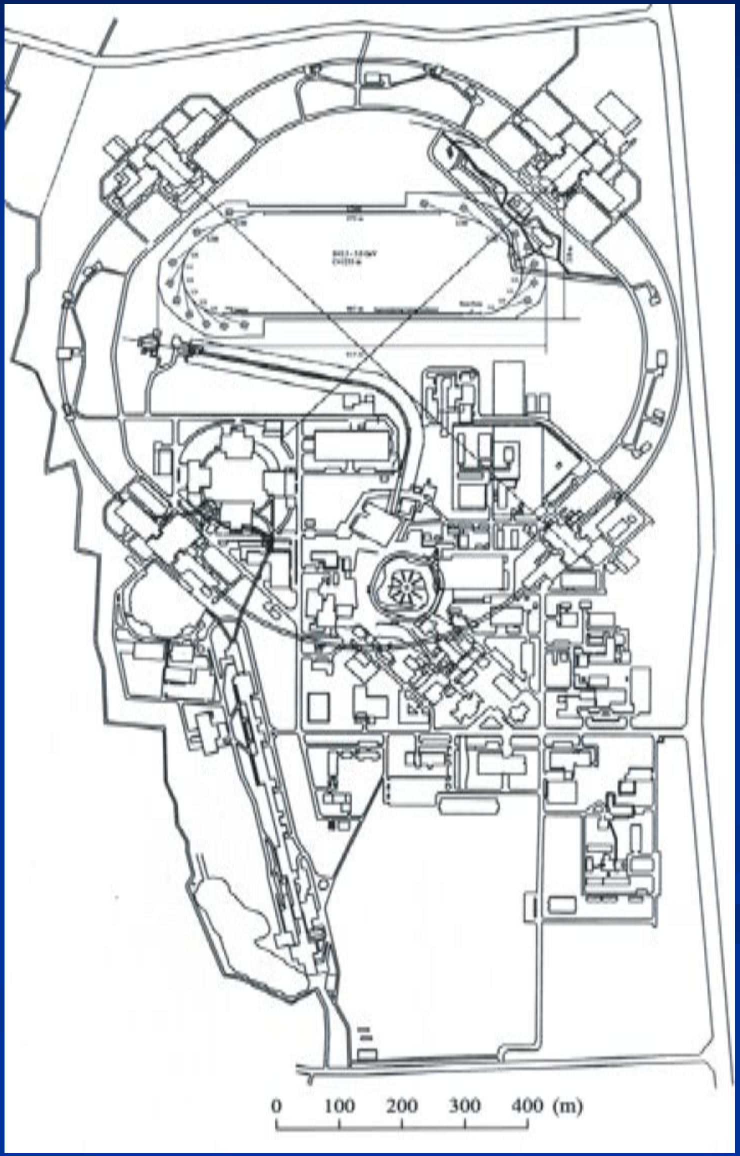
Adiabatic Damping in Linear Accelerator



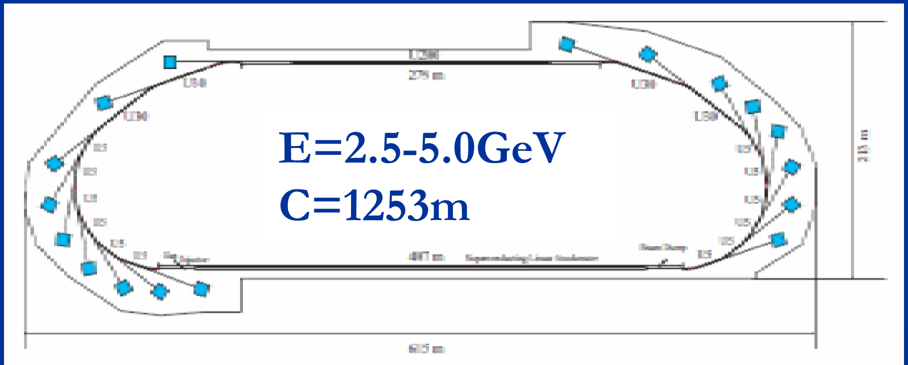
Low emittance e-gun + Acceleration = Ultra-low emittance

ERL Plan at KEK

http://pfiqst.kek.jp/ERLoffice/index.html



Energy region :VUV-X (30eV-30keV)
Brilliance: 10^{21}-10^{23}
photons/sec/mrad^2/mm^2/0.1%B.W. @1~10 keV
Coherent fraction: 10~20%@10keV
Emittance: 10pmrad~λ /4π@ 10keV
Short pulse: ~100 fs
Number of ID beamlines: ~30 lines

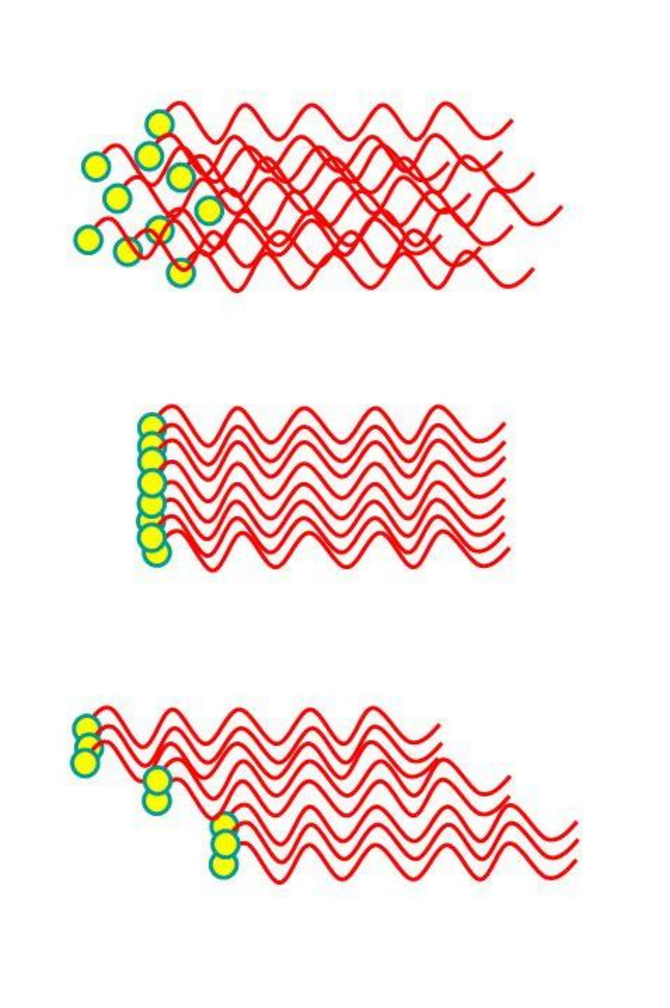


Towards Coherence

Incoherent Radiation
(Normal SR)

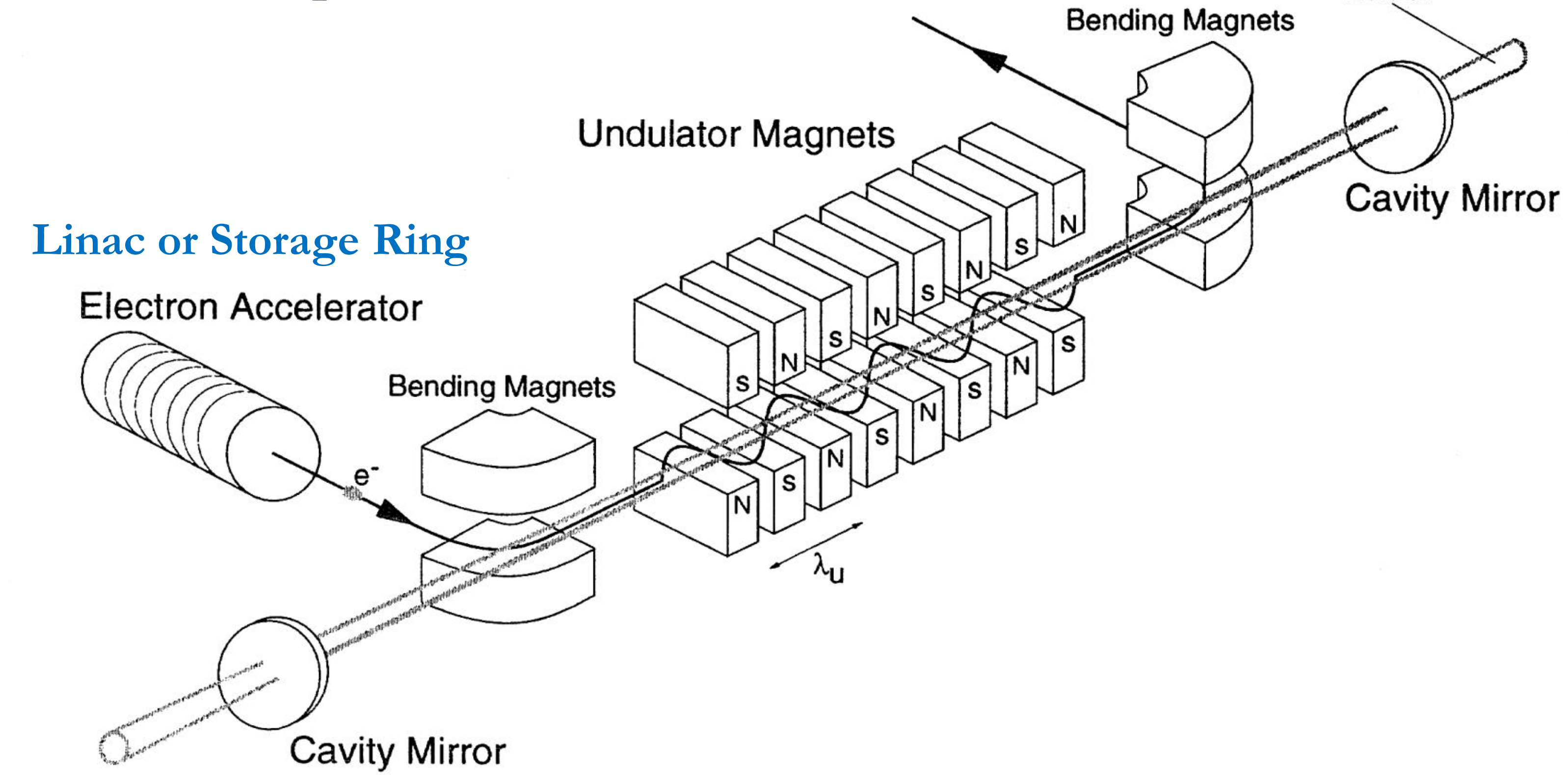
Coherent Radiation from
Ultra-short Electron Bunch

Coherent Radiation from
Micro-bunched Electron Beam

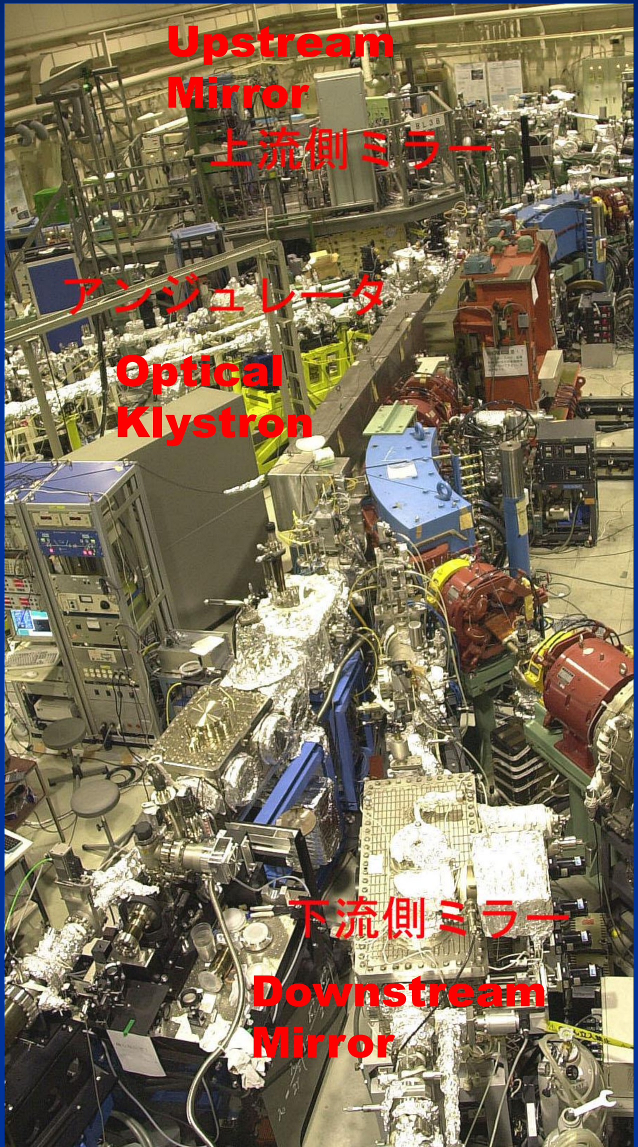


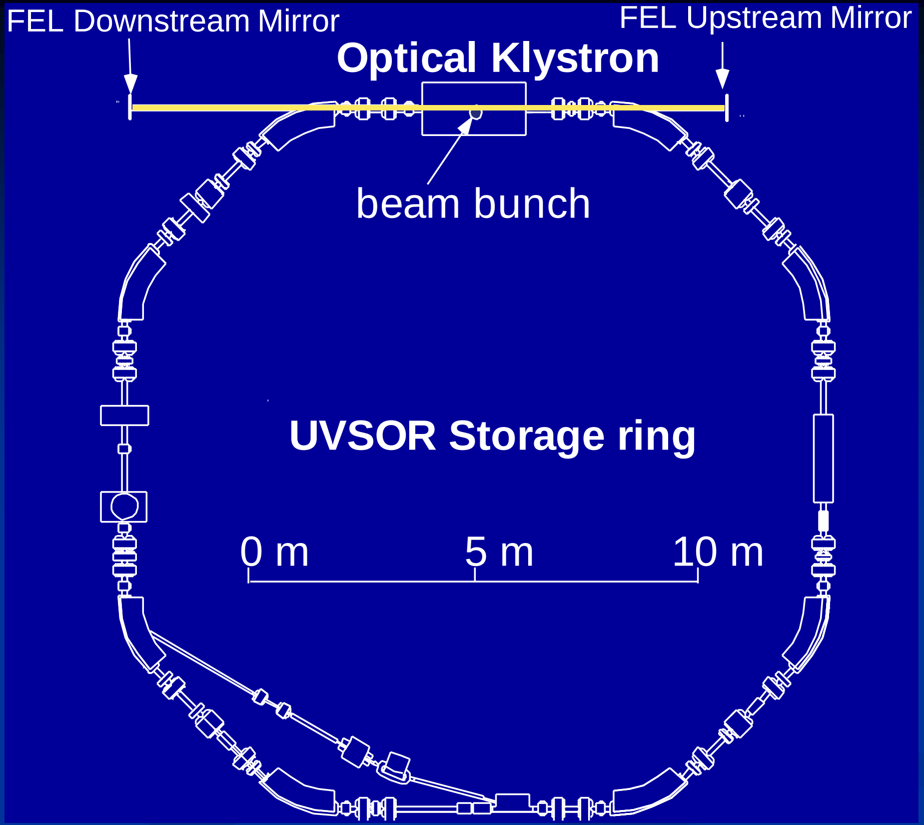
Free Electron Laser

Resonator-type Free Electron Laser



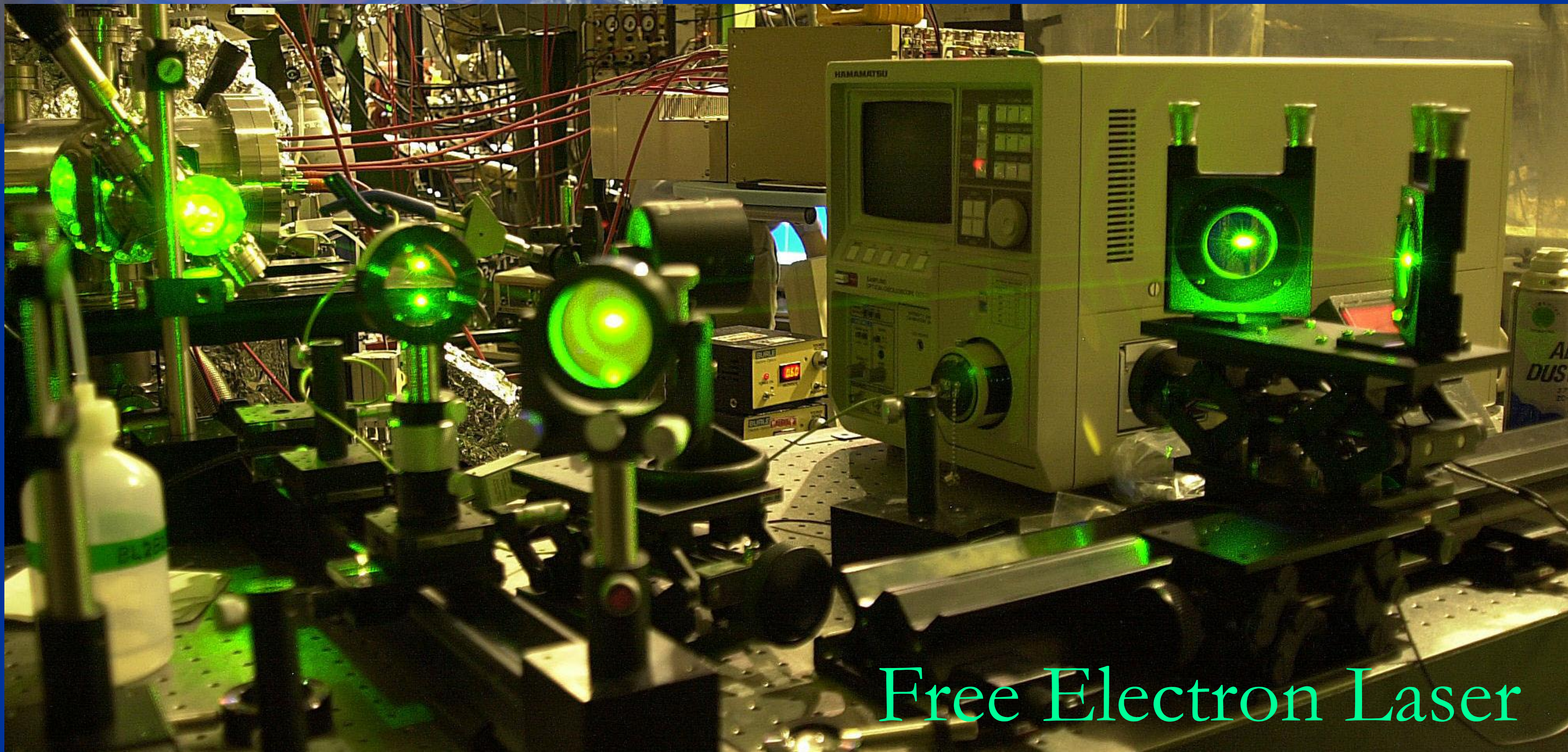
UVSOR-II
Free Electron Laser





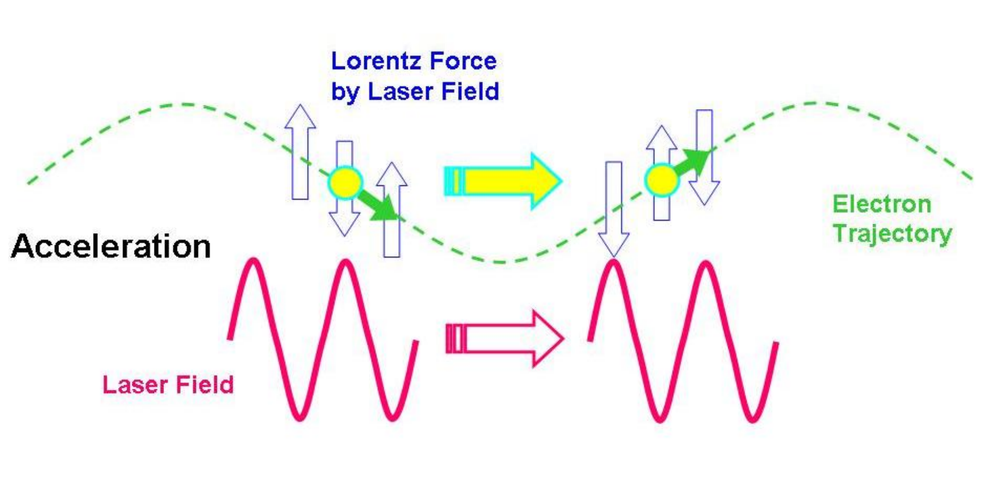
Laser	
Wave Length	**199～800 nm**
Spectral Band Width	**～10^{-4}**
Polarization	**Circular/Linear**
Pulse Rate	**11.26 MHz**
Max. Average Power	**～1 W**
Optical Cavity	
Type	**Fabry-Perot**
Cavity Length	**13.3 m**
Mirror	**HfO_2, Ta_2O_5 ,Al_2O_3multi-layer**
Optical Klystron	
Polarization	**Circular/Linear**
Length	**2.35 m**
Period Length	**11 cm**
Number of Periods	**9 + 9**

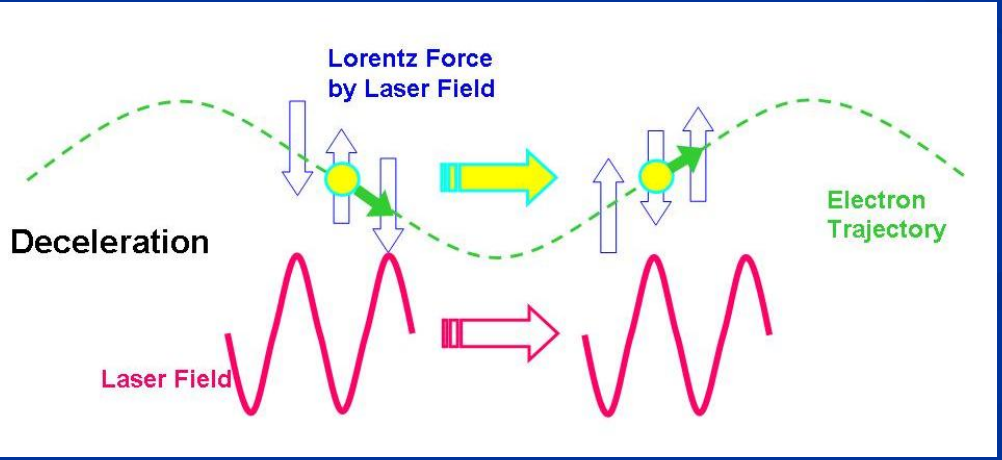
UVSOR II
since 2003



FEL Process (1)

Energy Exchange between Electrons and Radiation Field in Undulator



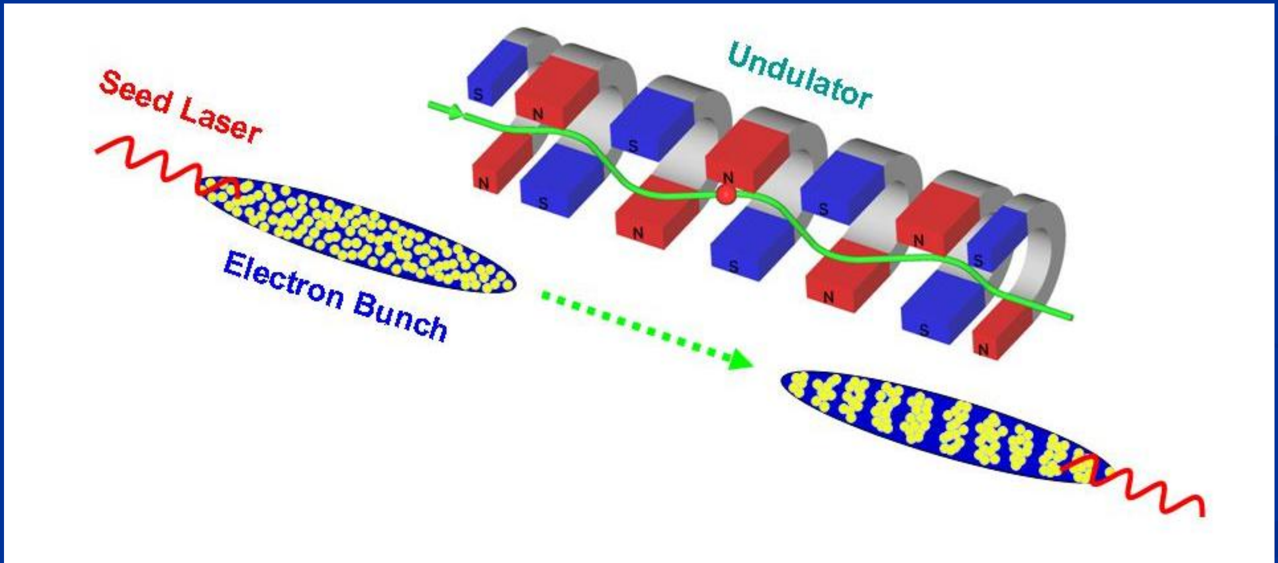


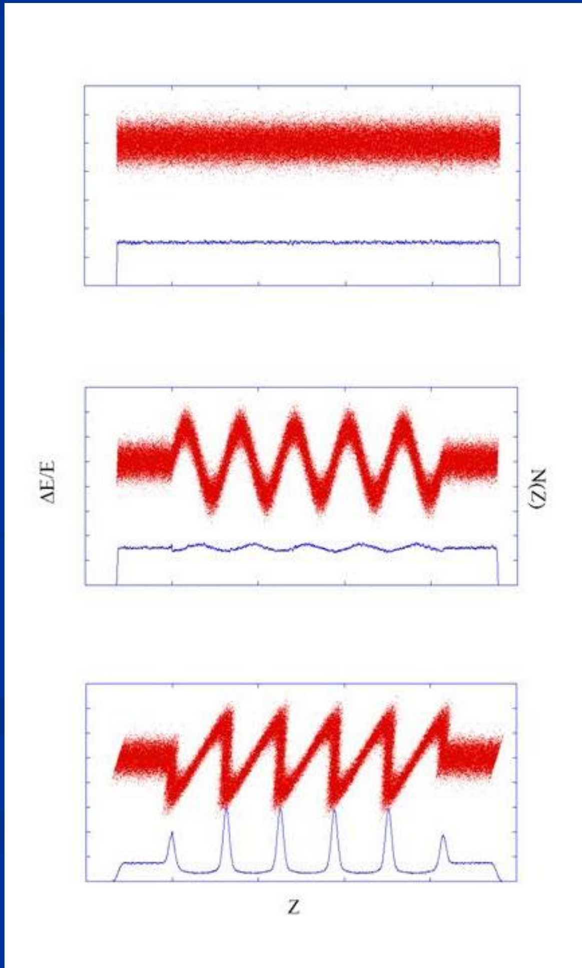
Electrons can be accelerated or decelerated depending on their relative position to the laser field under a resonance condition;

$$\lambda_{laser} = \frac{1 + K^2/2}{2\gamma^2}\lambda_{undulator}$$

FEL Process (2)

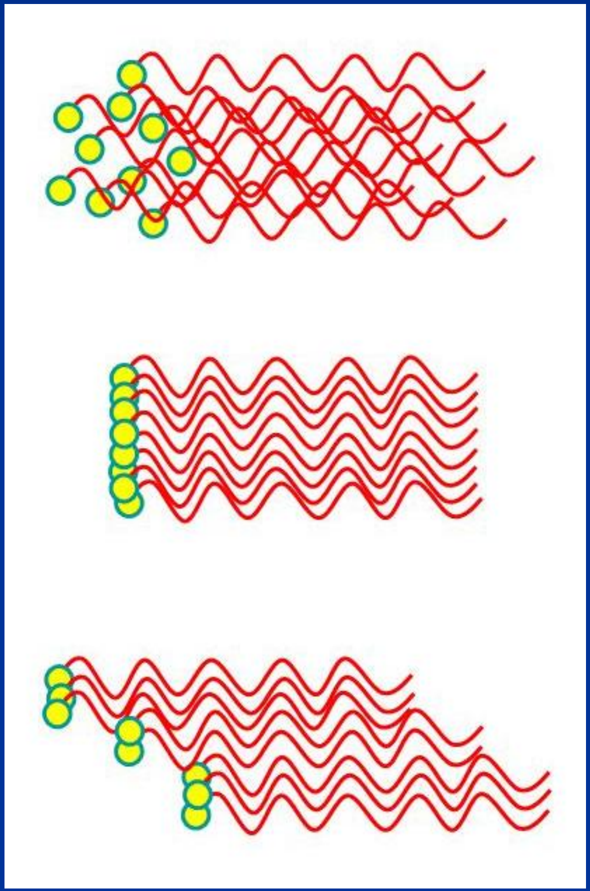
Micro-bunching by Laser-Electron Interaction

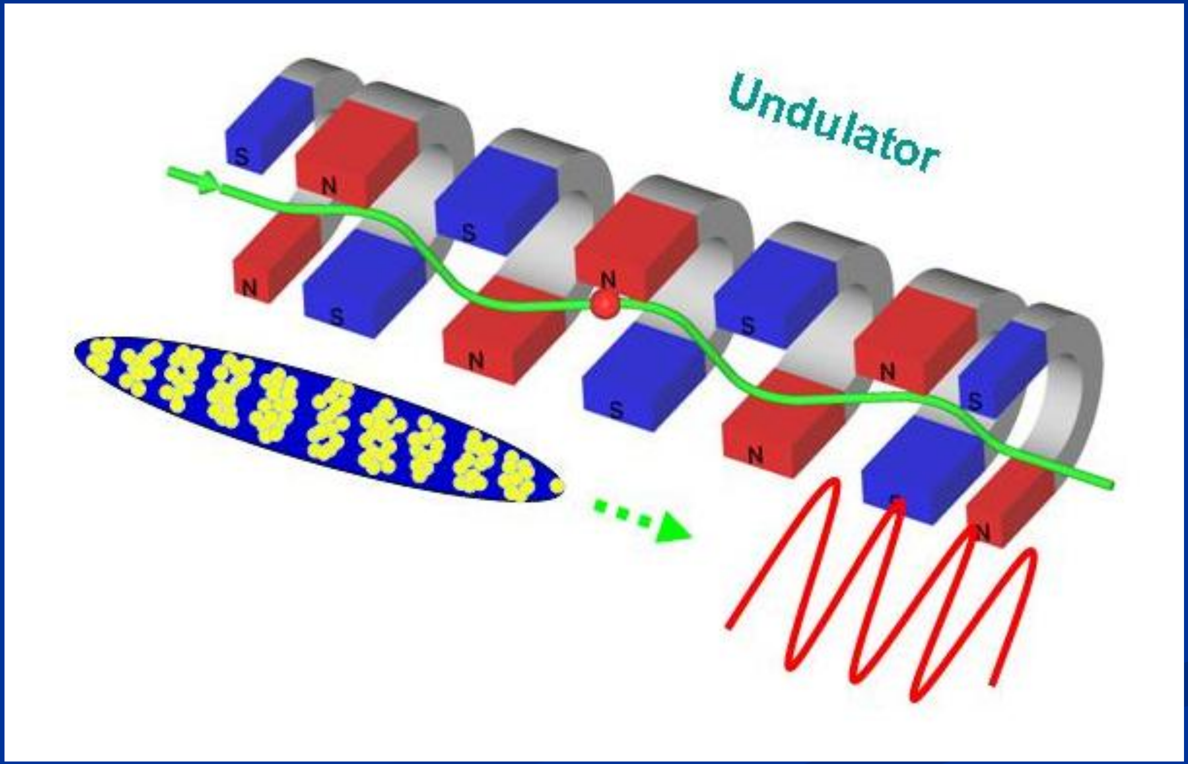




FEL Process (3)

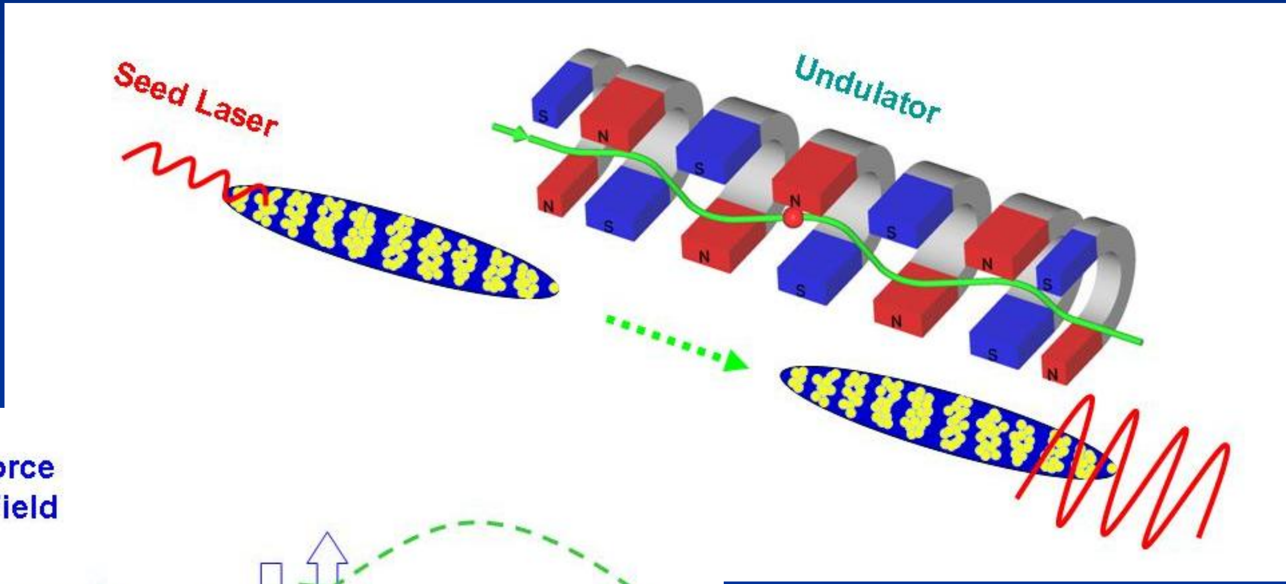
Coherent Radiation from Micro-bunched Beam

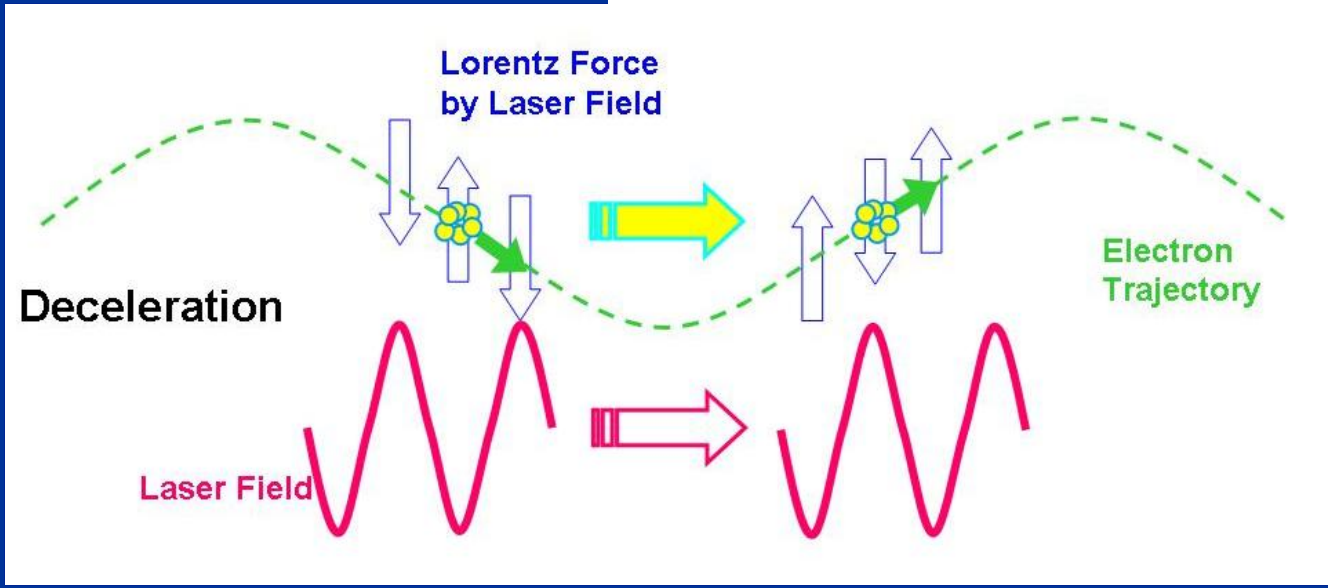




FEL Process (4)

Amplification of EM field by micro-bunched e-beam

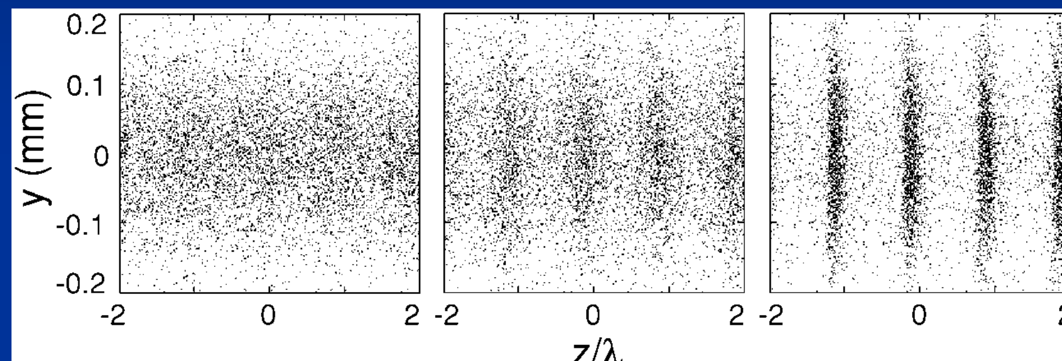




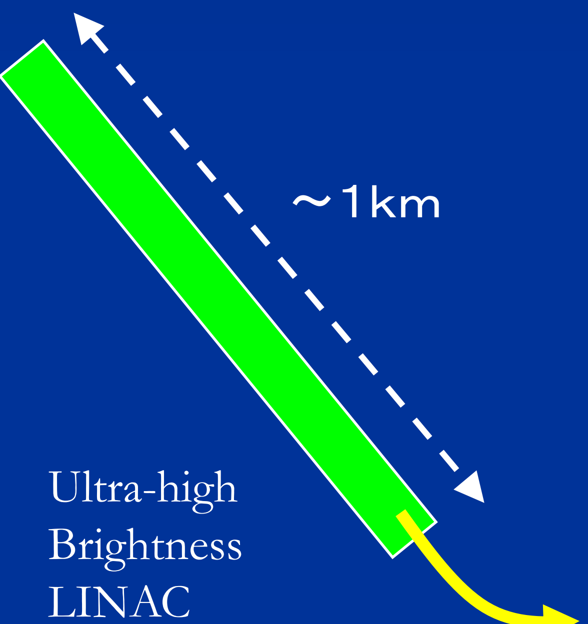
Free Electron Laser without Optical Cavity

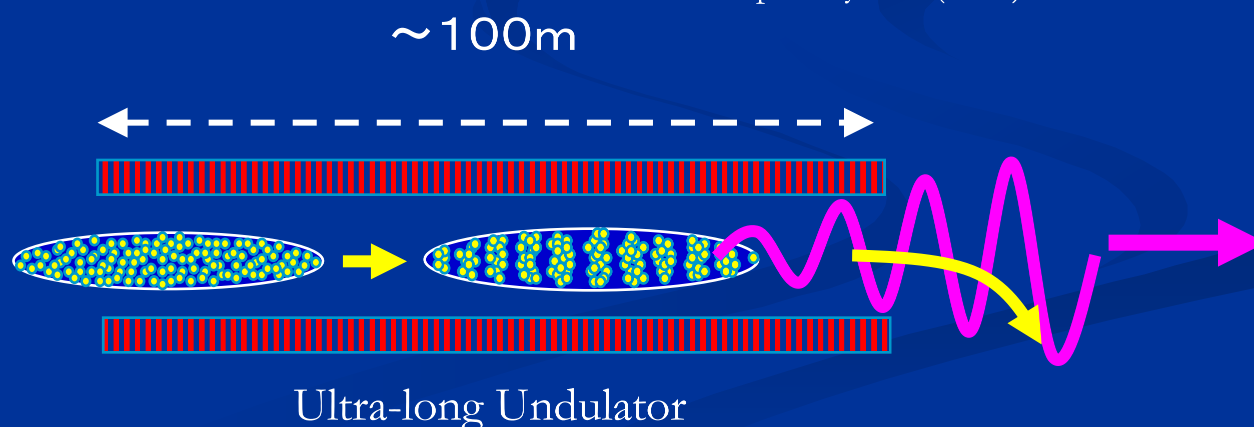
Single Pass X-ray Free Electron Laser

based on Self-Amplified Spontaneous Emission (SASE) Principle



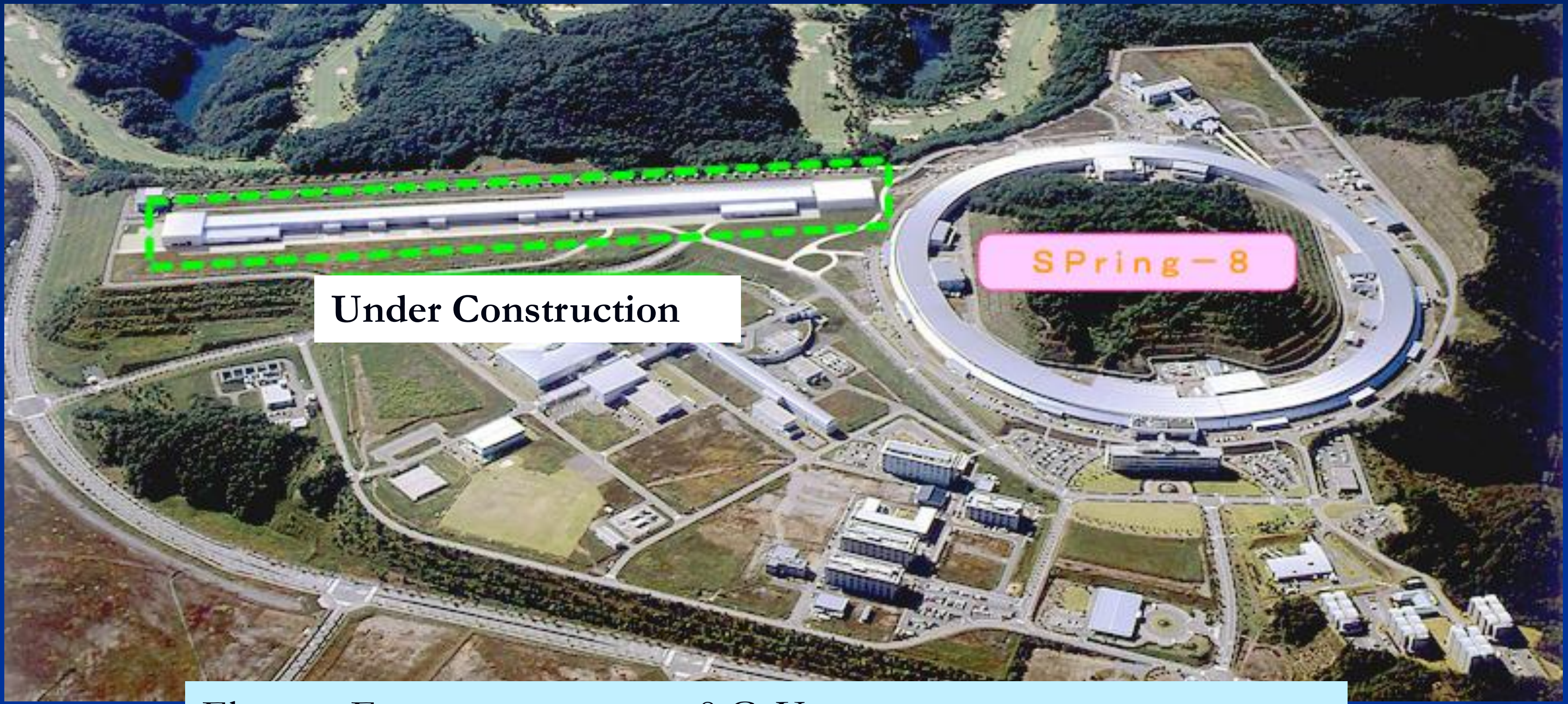
J Feldhaus, J Arthur, J B Hastings, J. Phys. B: At. Mol. Opt. Phys. 38 (2005) S799–S819





X-ray Free Electron Laser Project in Japan

http://www.riken.jp/XFEL/eng/whatis/index.html



Electron Energy	8 GeV
Electron Beam Size	40 micron
X-ray Wavelength	>0.06 nm
X-ray Peak Power	5 GW
X-ray Pulse Length	<100 fsec
X-ray peak Brilliance	10^{33} photons/s/mm^2/mrad^2/0.1%b.w.

シンクロトロン光源

- 電子蓄積リング
  - 安定性、経済性、汎用性
- エネルギー回収型ライナック
  - 回折限界、超短パルス
- シングルパス自由電子レーザー
  - コヒーレント、超短パルス、超高ピークパワー