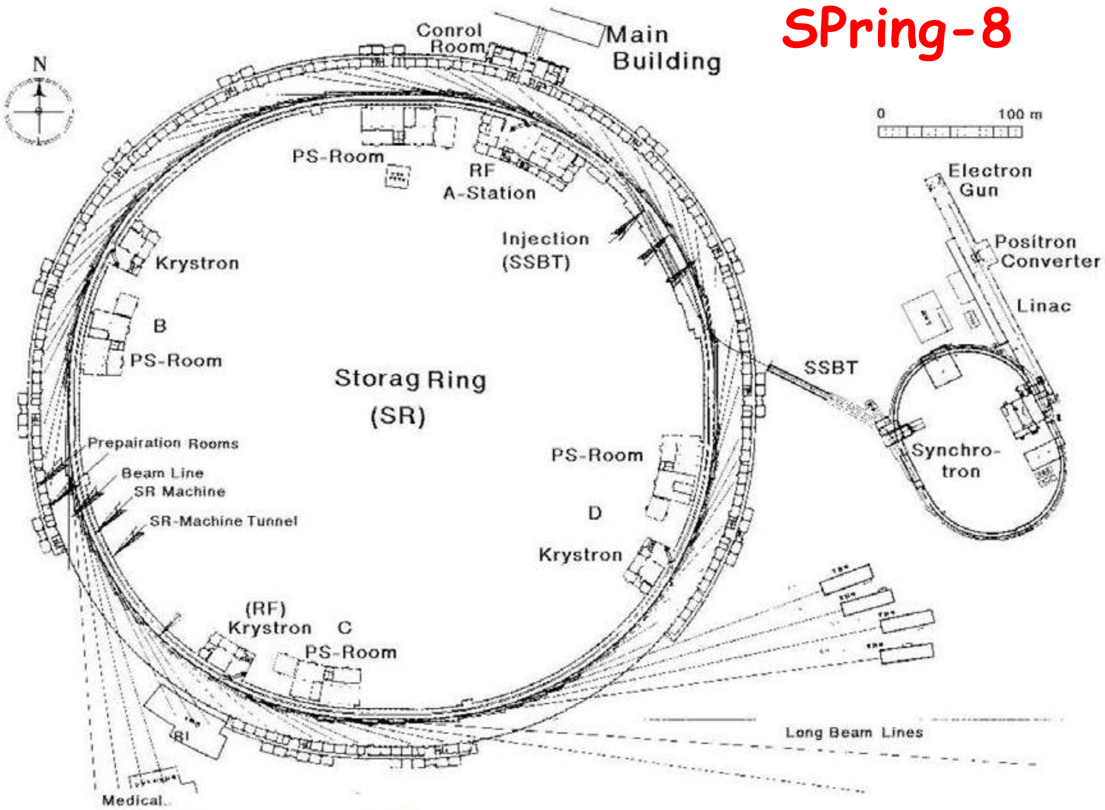
小型高性能放射光源の応用の展望とその実現へ向けてのレーザー加速への期待

加藤 政博

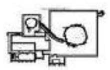
広島大学/分子科学研究所

SPring-8 vs. UVSOR

SPring-8

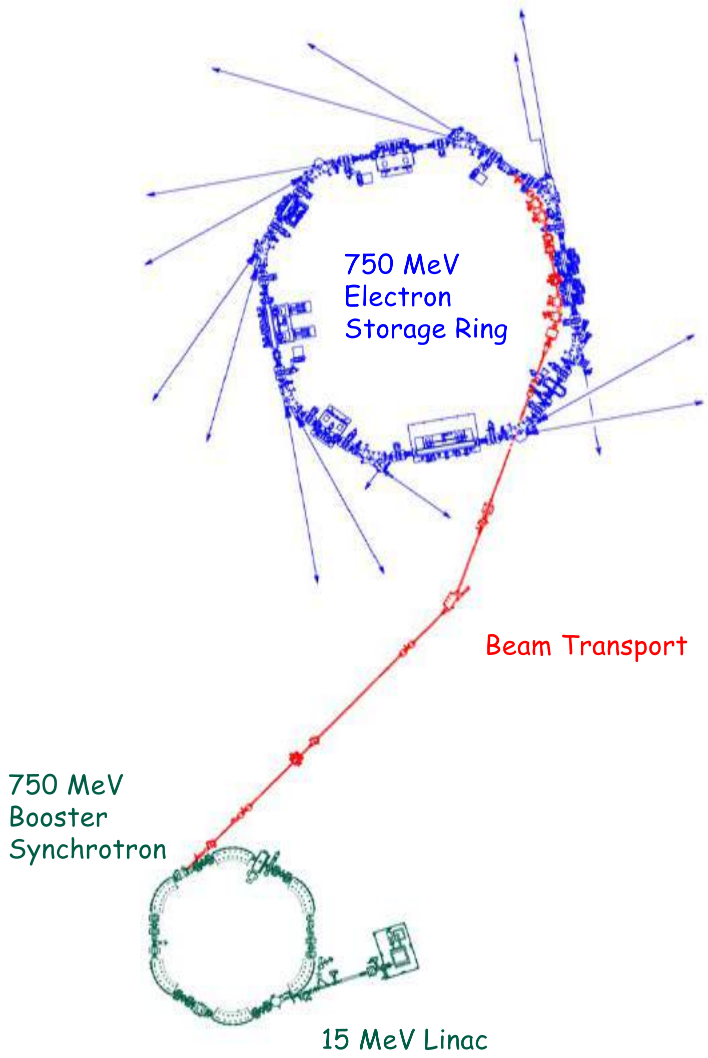


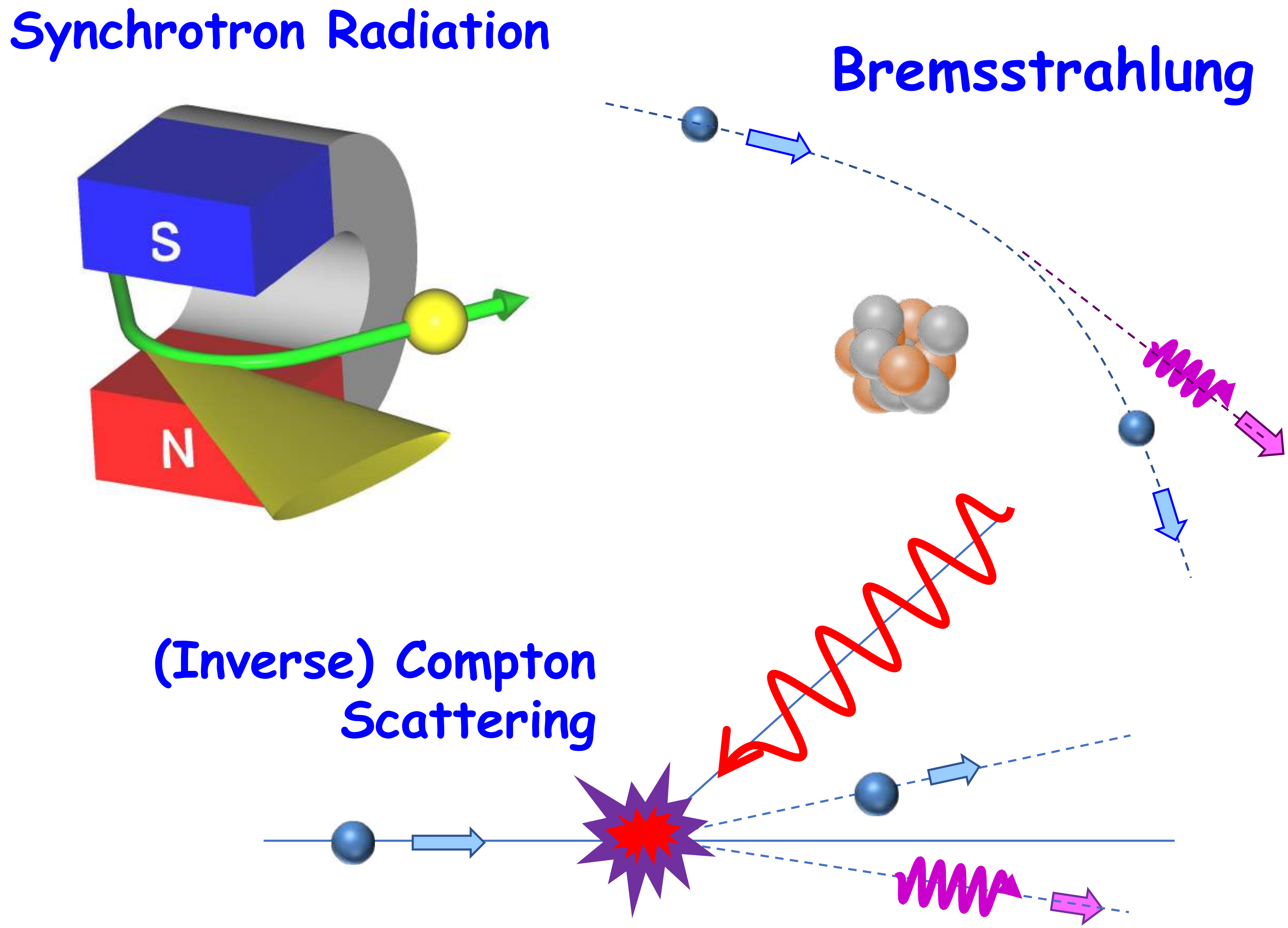
UVSOR



SPring-8 (http://www.spring8.or.jp) (C=1400m, E=8GeV, ε_{x0}=5.9nm-rad)

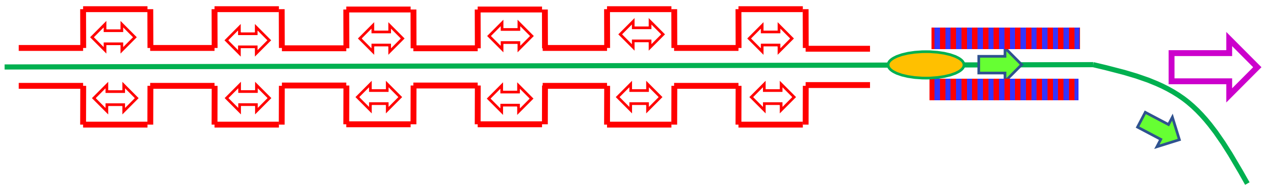
UVSOR Synchrotron, Institute for Molecular Science

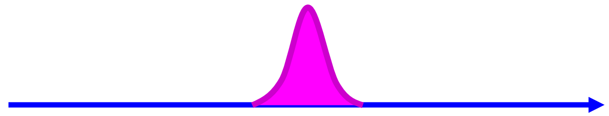



Synchrotron Radiation
S
N
Bremsstrahlung
(Inverse) Compton
Scattering

Synchrotron vs. Linac

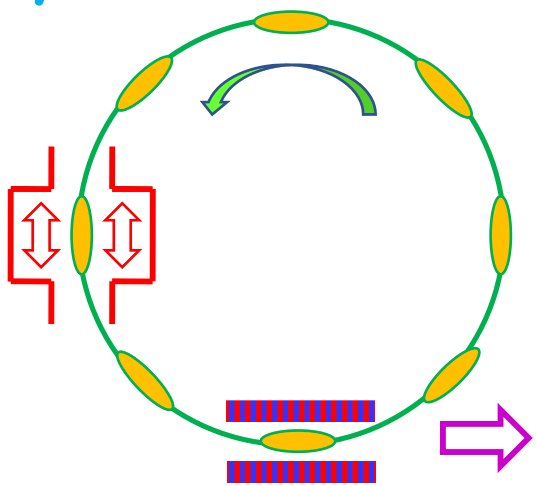
Linear Accelerator

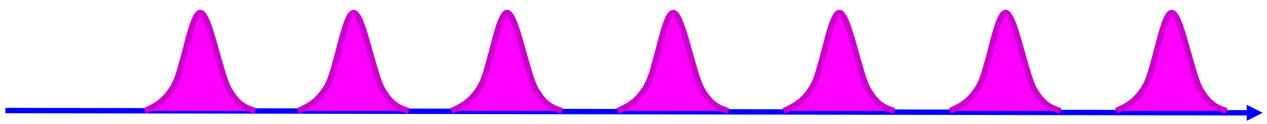




- **Average Beam Current: $I_b = N_e \times e \times f_{rep}$**
  - Synchrotron
    - I_b=~100mA = 10^{12} [e^-/ring] x 1.6×10^{-19} [C] x ~10^6 [Hz]
  - Linear Accelerator
    - I_b=~0.1 μA = 10^{10} [e^-/pulse] x 1.6×10^{-19} [C] x ~100 [Hz]
- **Radiation: $\propto dN_e/dt$**
  - Synchrotron
    - $dN_e/dt = N_e/\tau$ =~ 10^{12}[e^-/ring]/~10[hr] ~ 10^8 [e^- /sec]
  - Linear Accelerator
    - $dN_e/dt = N_e f_{rep}$ = ~ 10^{10}[e^-/pulse] x ~100 [Hz] ~10^{12} [e^-/sec]

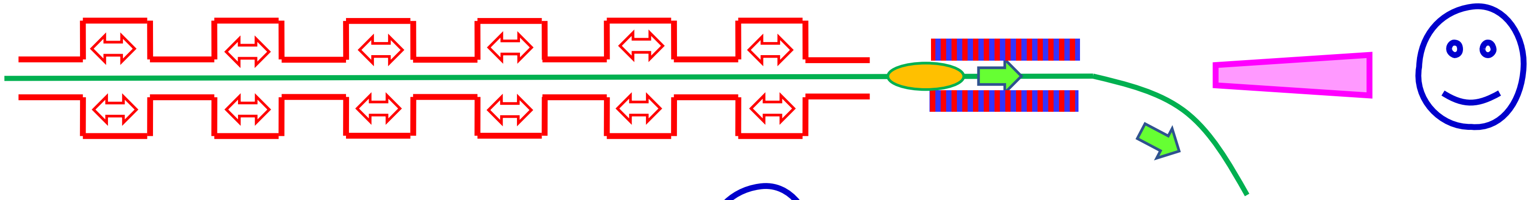
Synchrotron



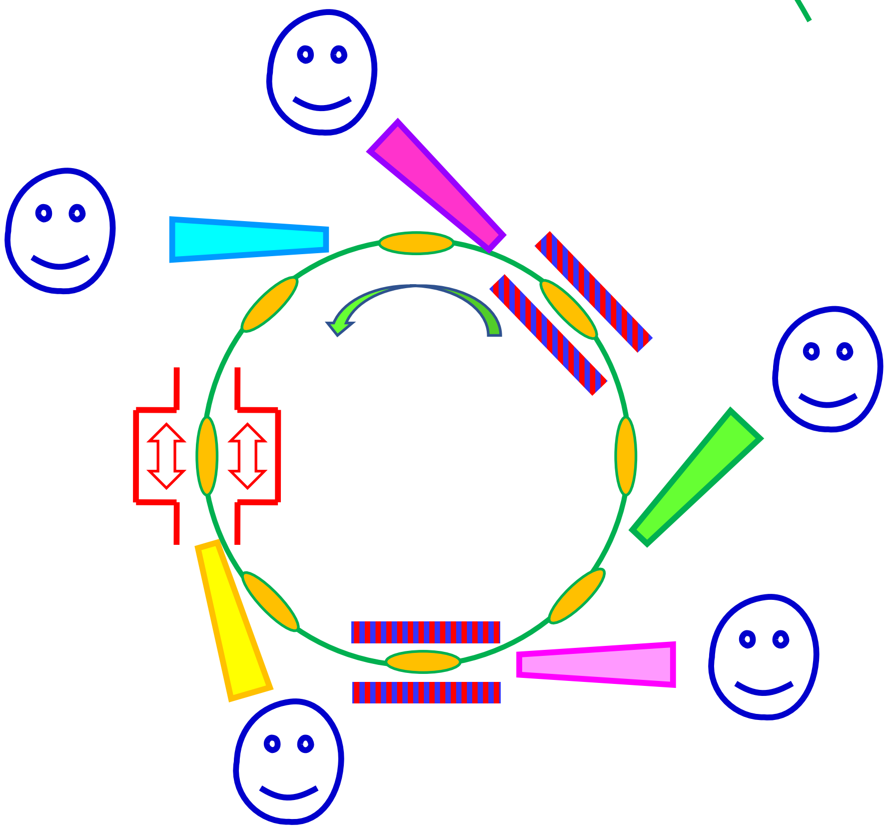


Synchrotron vs. Linac (2)

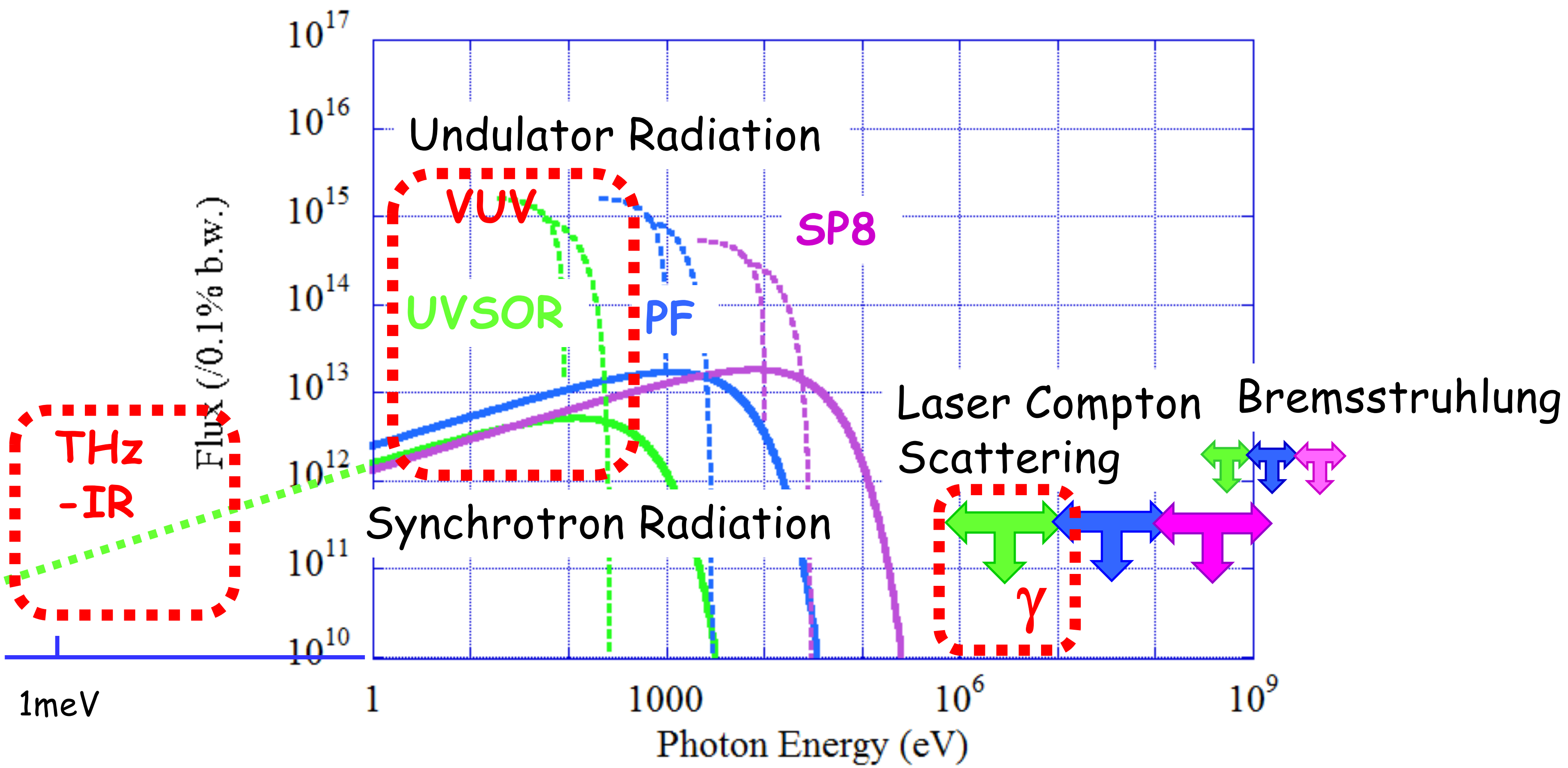
Linear Accelerator



Synchrotron

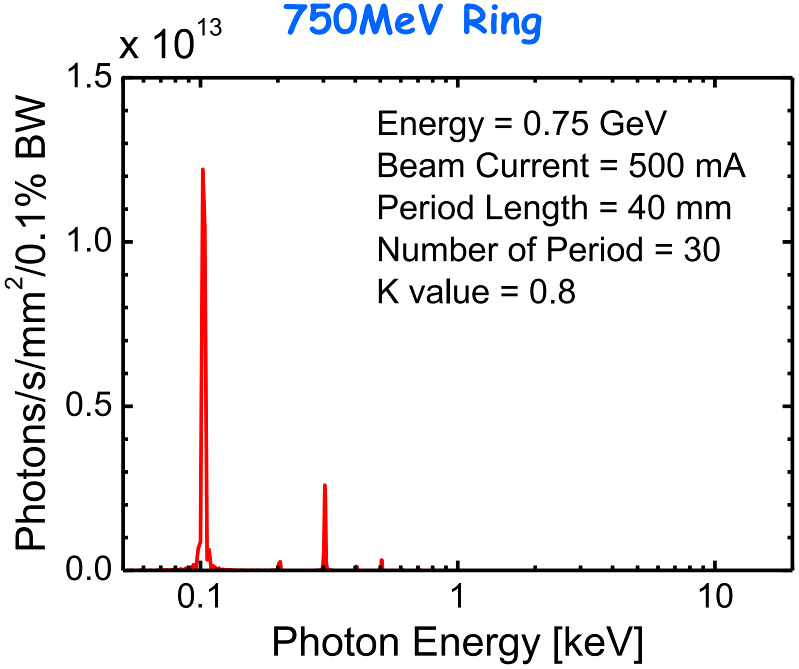


Typical Energy Ranges of Photon Beams from Synchrotrons

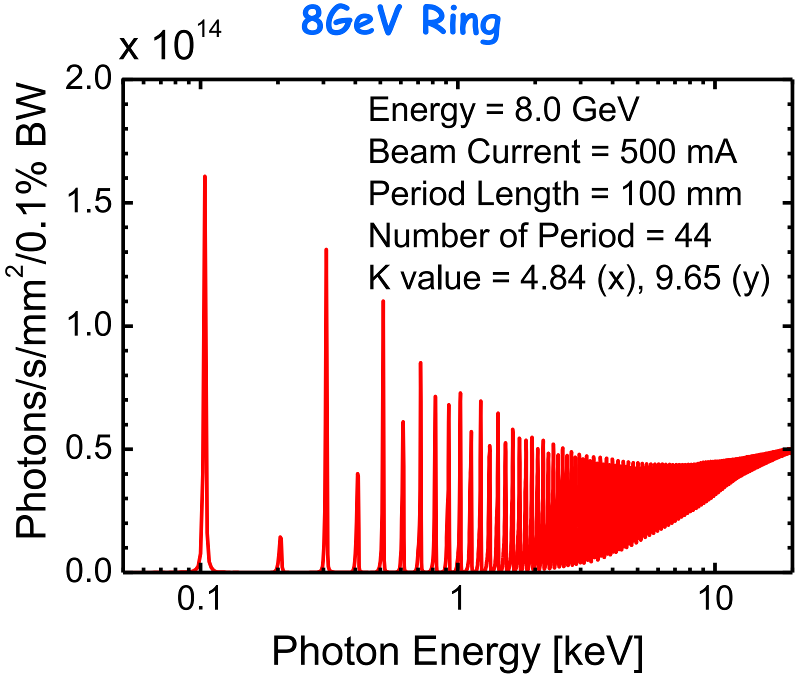


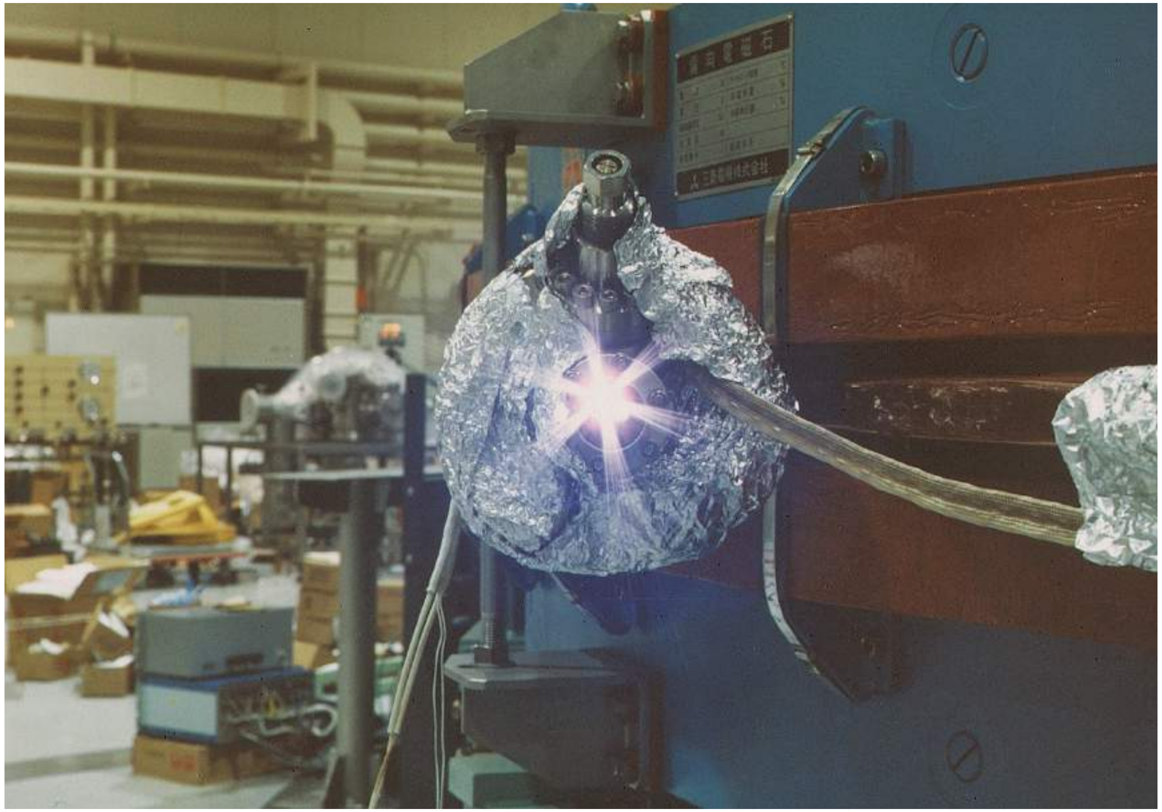
大は小を兼ねるが・・・

100eV light from
750MeV Ring



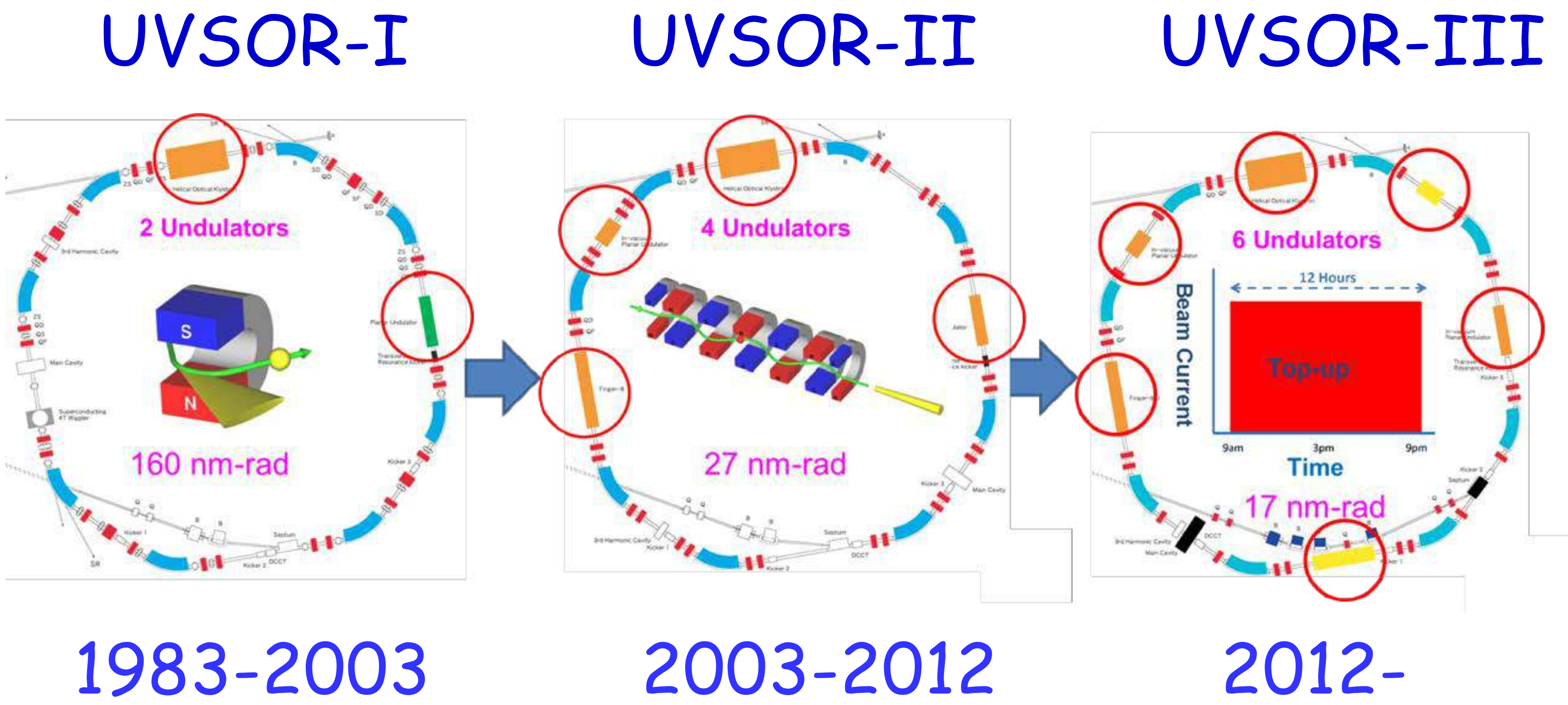
100eV light from
8GeV Ring





The First Light of UVSOR in 1983

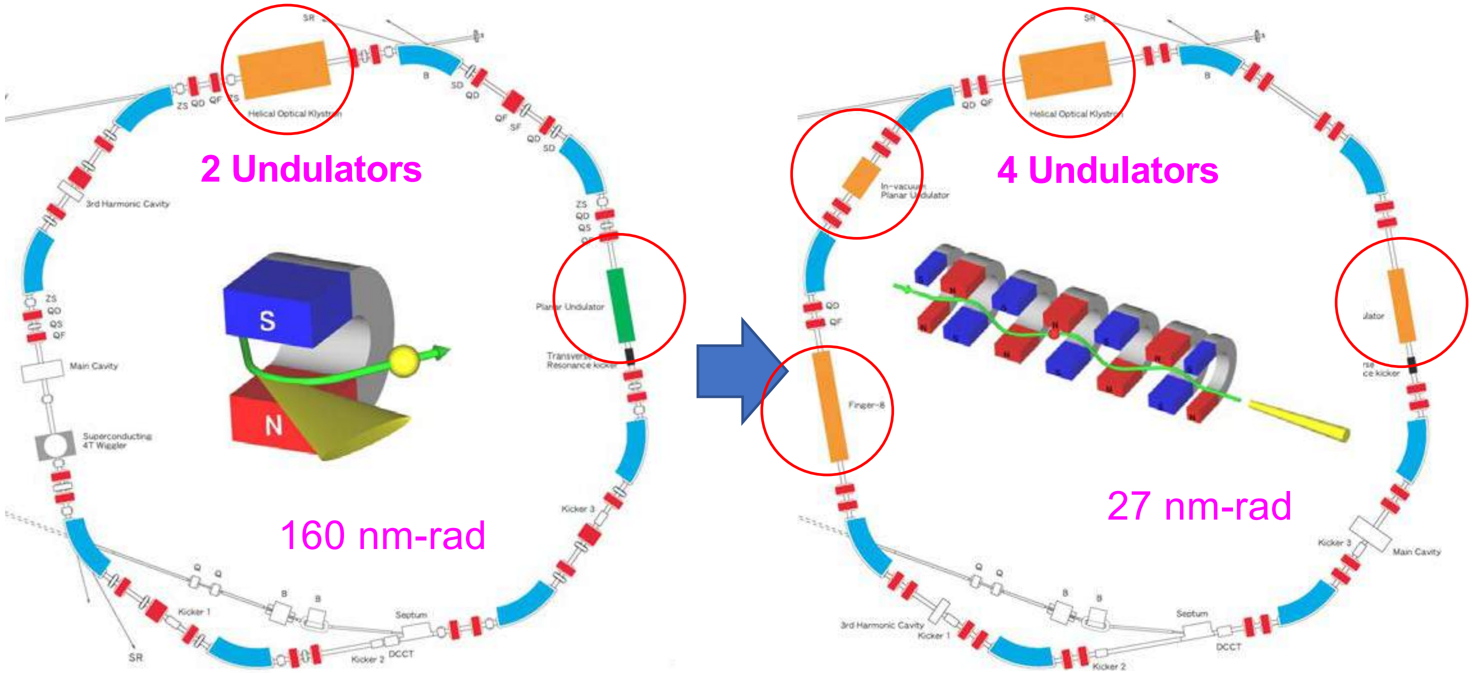
Upgrade History of UVSOR



UVSOR-I ⇒ UVSOR-II

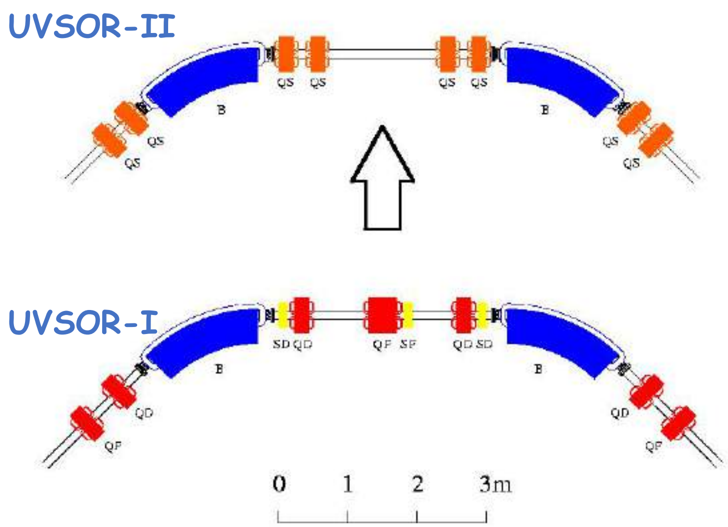
2nd Gen. ⇒ 3rd Gen.

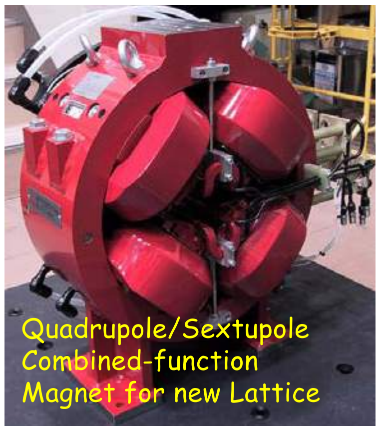
- Brilliance Upgrade by improving Magnetic Lattice (from 160nm-rad to 27nm-rad)
- Increase of Straight Sections and Undulators (from 2 to 4)
- Construction of Undulator Beam-lines (BL3U, BL6U, BL7U)

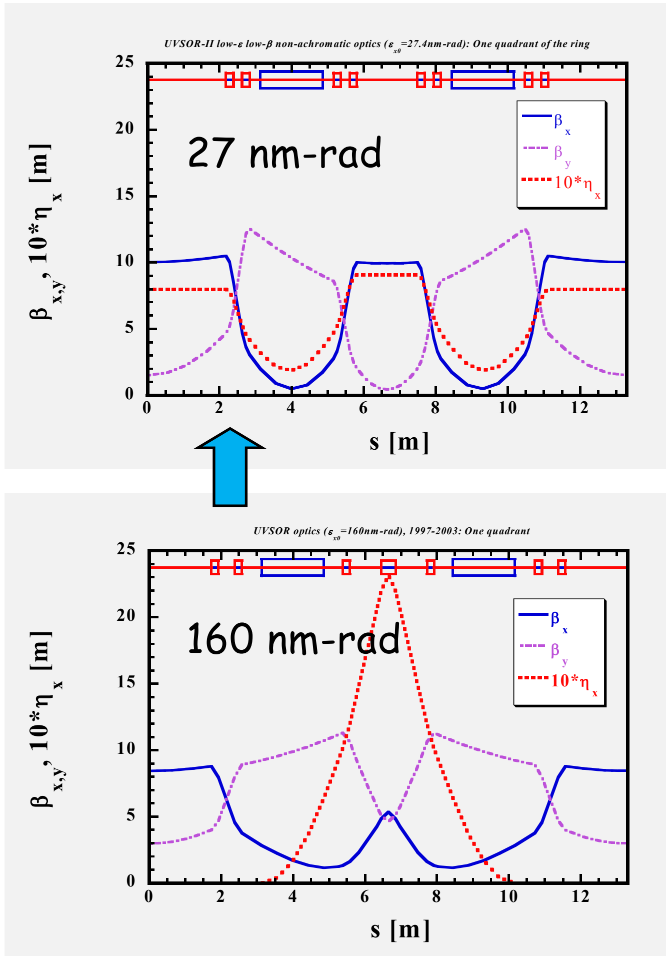


Upgrade of Magnetic Lattice

low-ε, more straight sections, low-β_y at s.s.

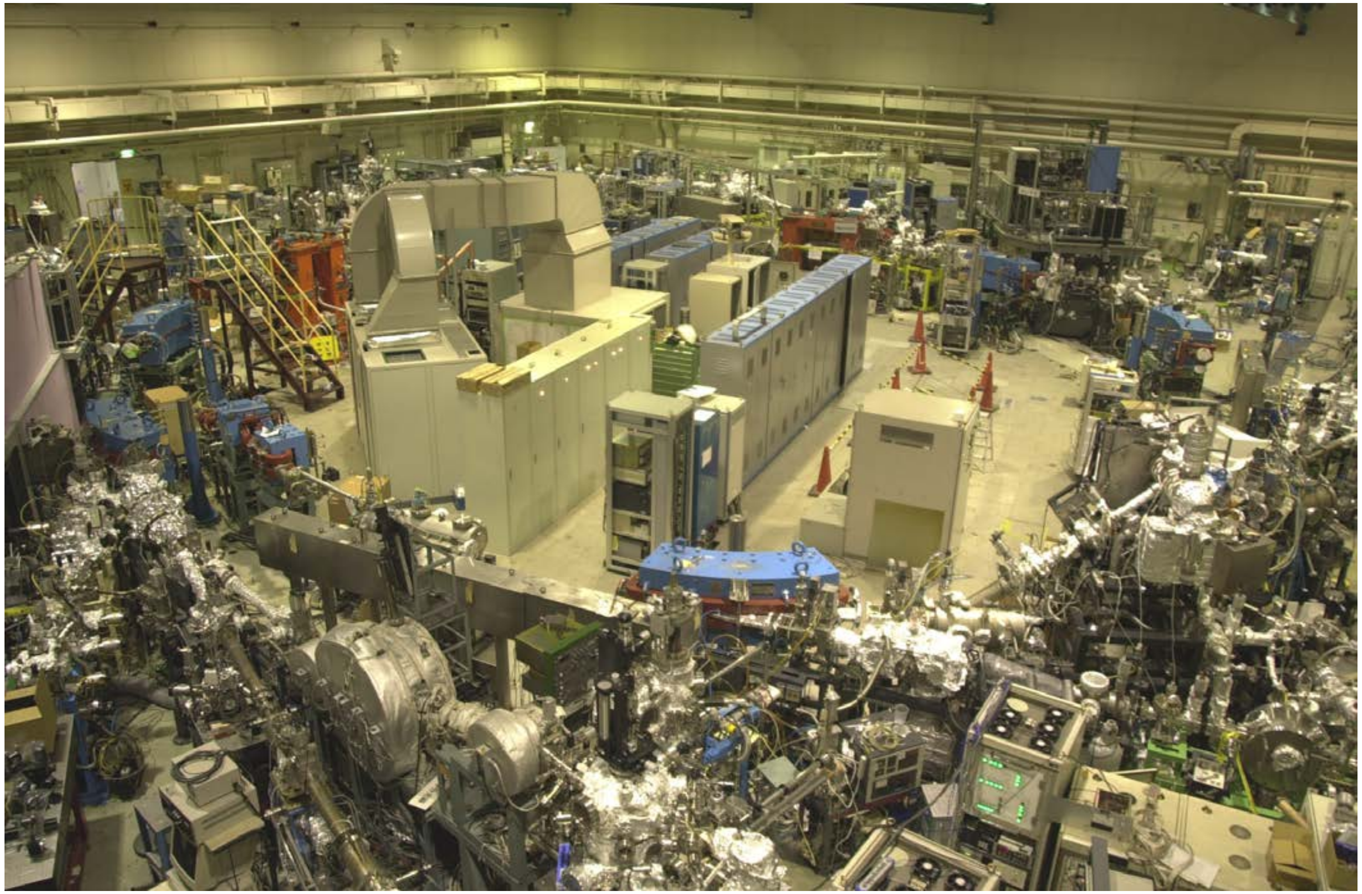






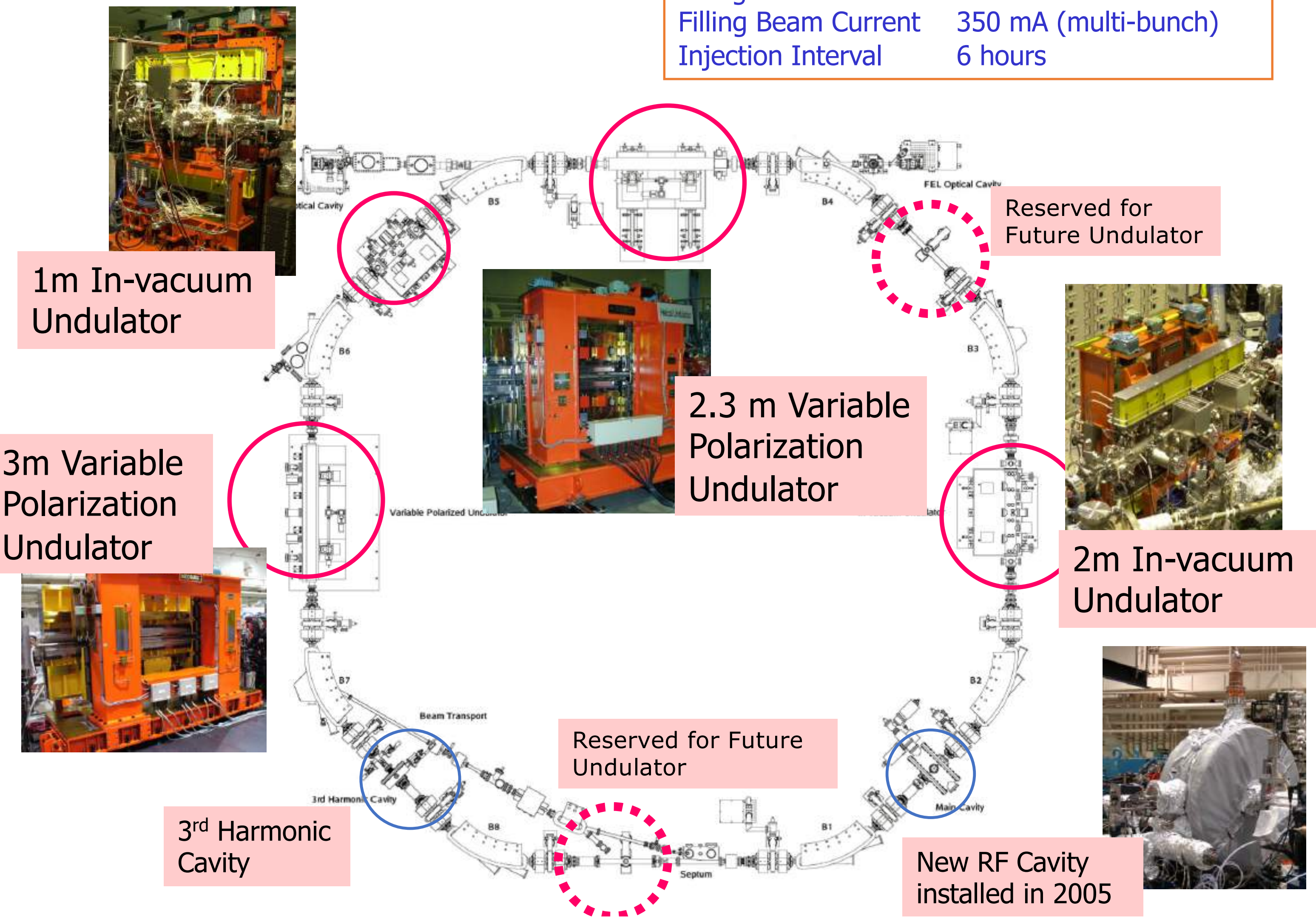
UVSOR-I → UVSOR-II

（April, 2003）



UVSOR-II

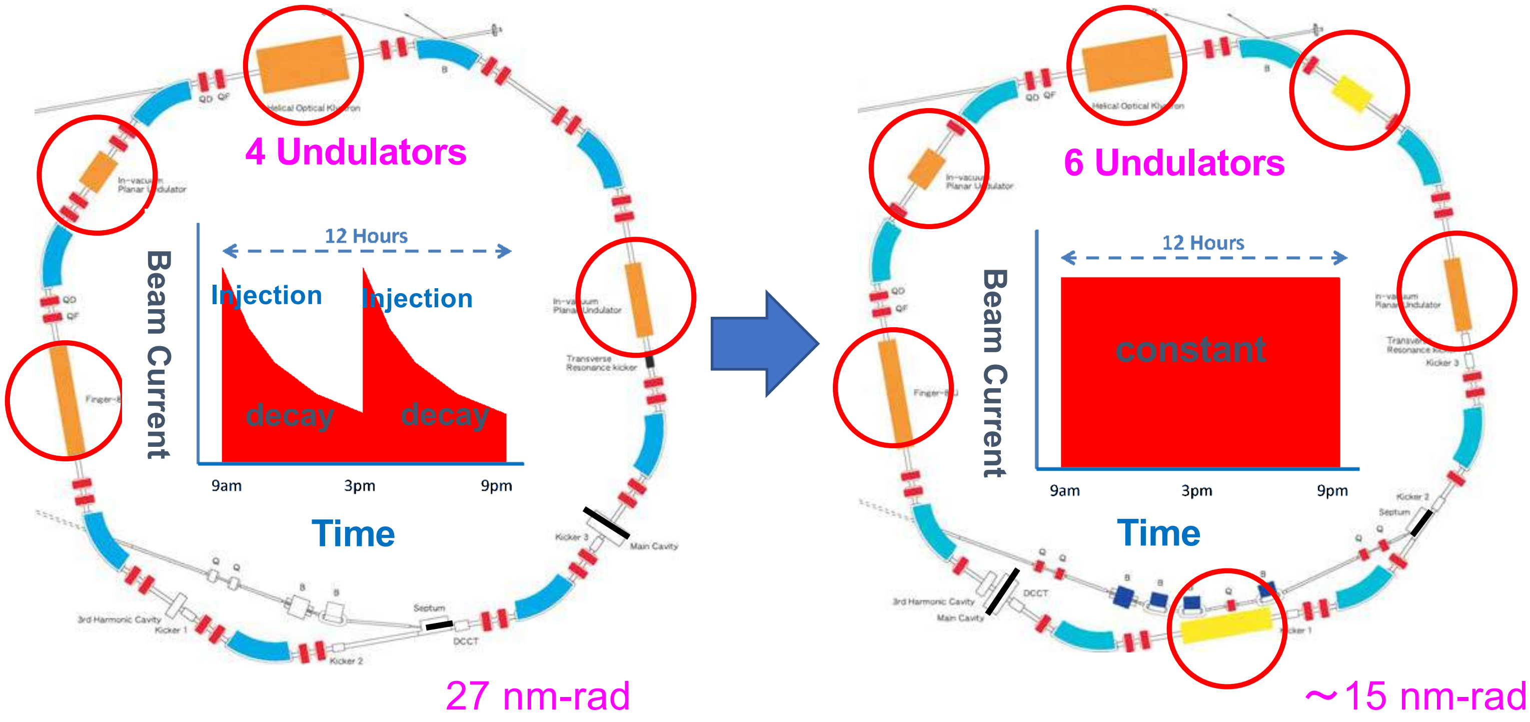
Electron Energy	750 MeV
Emittance	27nm-rad
Straight Sections	4mx4+1.5mx4
Filling Beam Current	350 mA (multi-bunch)
Injection Interval	6 hours



UVSOR-II⇒UVSOR-III

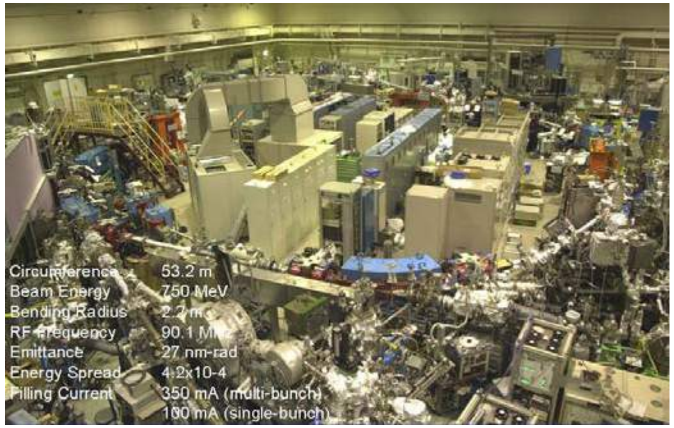
3rd Gen. ⇒ 3.5th Gen.

- Make all four long straight sections available for undulators (by moving the injection point) <2010>
- Further Brilliance Upgrade (by intoroducing combined function bending magnets) ; from 27nm-rad to ~15nm-rad <2012>
- Top-up operation (constant intensity operation) <2010>



Towards Top-Up Injection

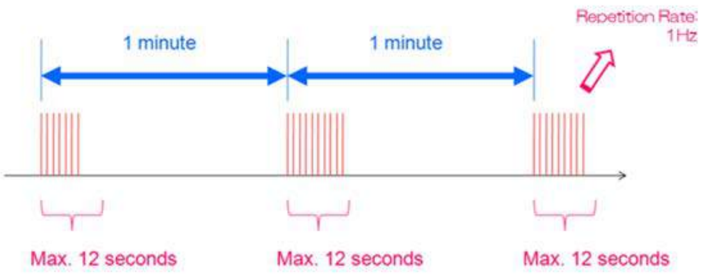
Energy Upgrade of Booster Synchrotron
and BT completed in 2006, 2007

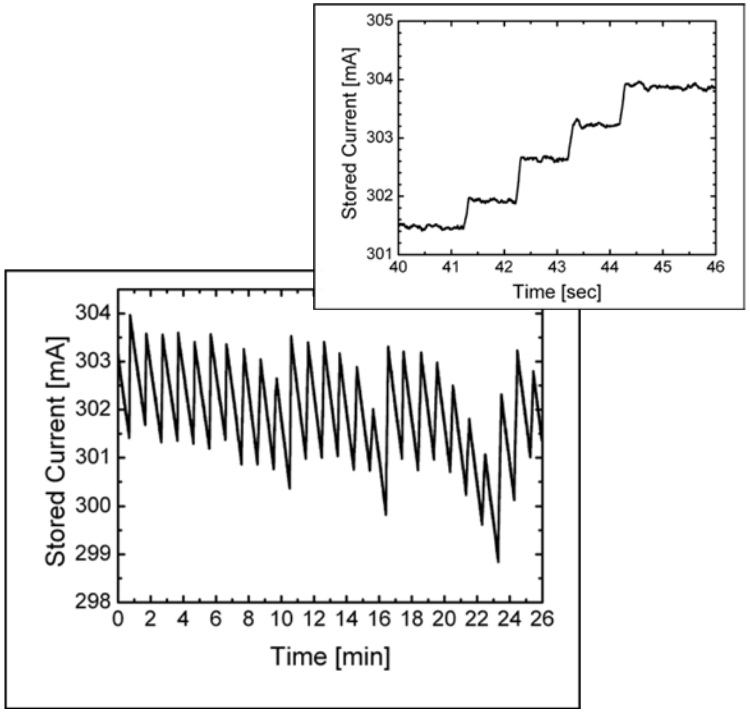


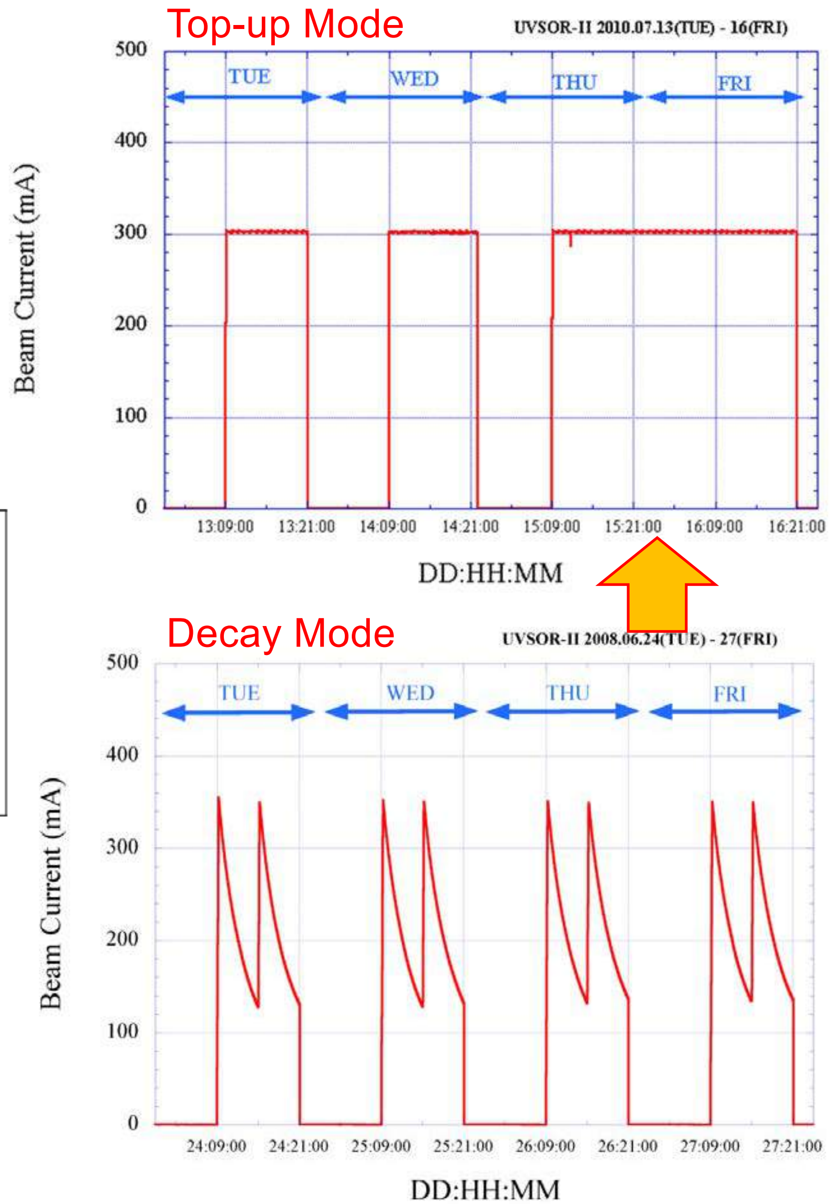
Reinforcement of Radiation
Shielding in 2006

Improvements in Beam Monitor
System & Control System in 2008

Top-up Injection at UVSOR

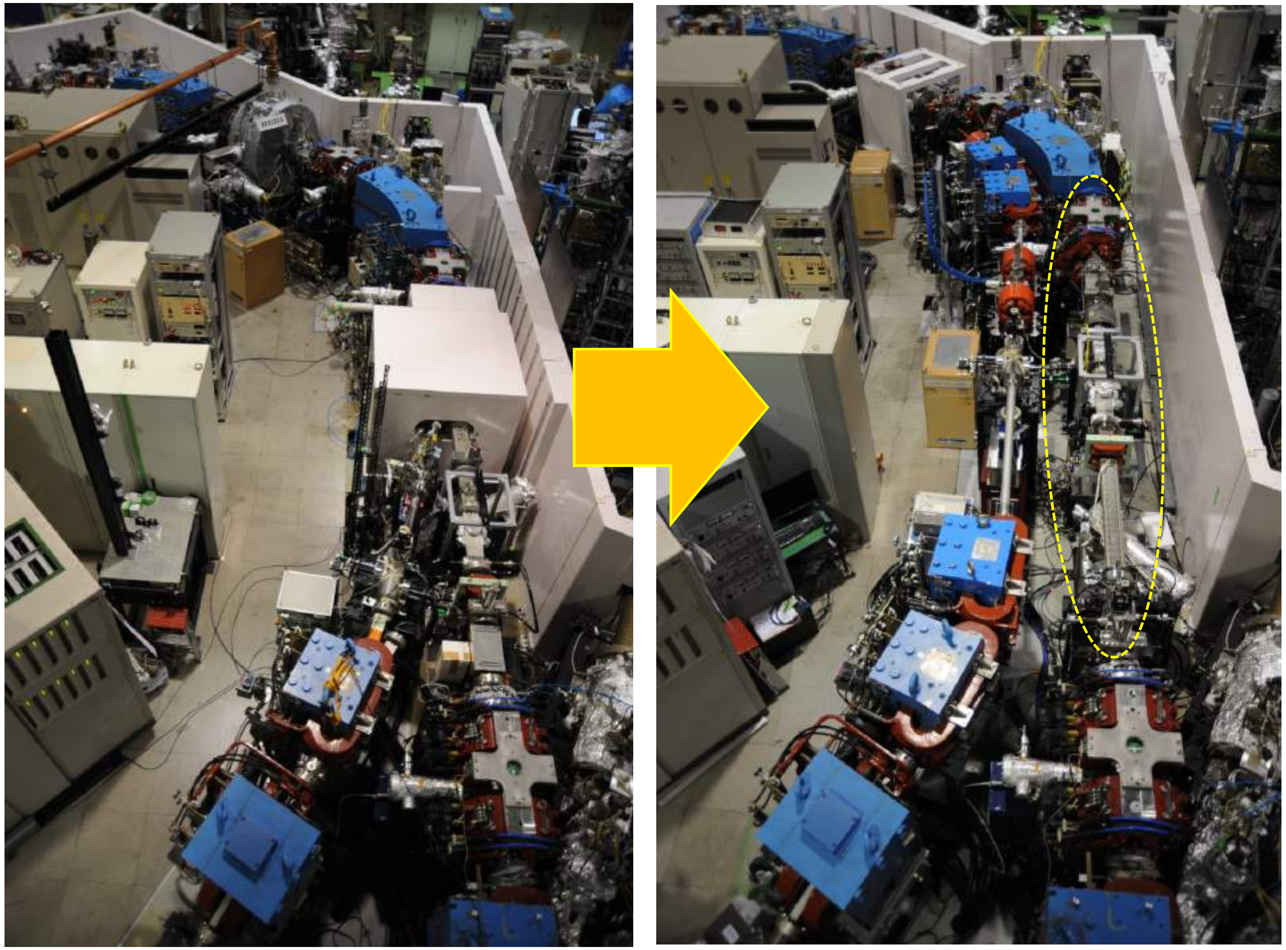






New 4m Straight Section by moving Injection Point

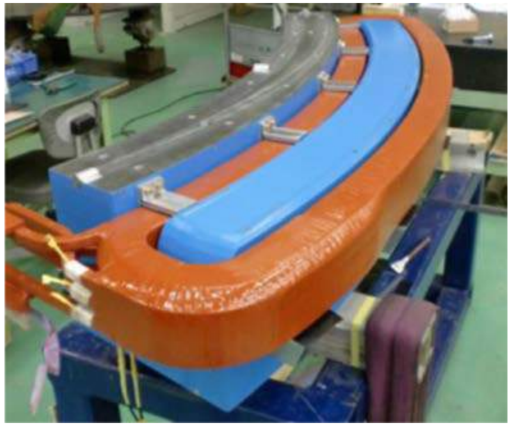
Apr, 2010

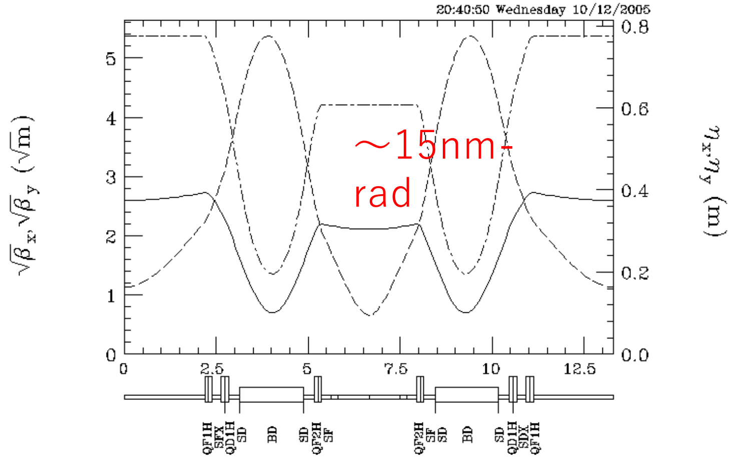


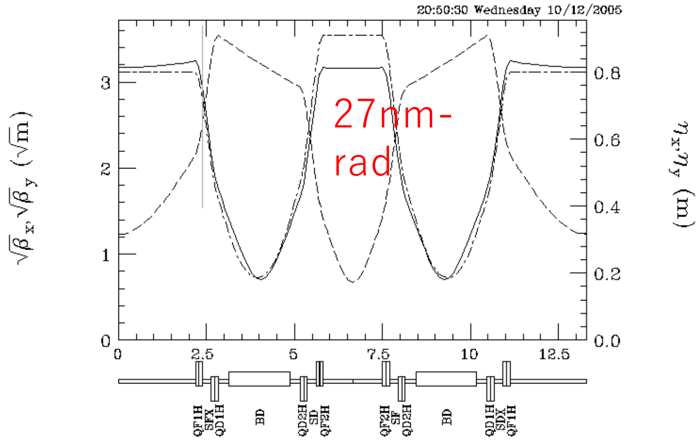
Further Emittance Upgrade by Combined-func. Bends.

In 2012

Bending radius	2.2 m
Magnetic Length	1.728 m
Bending Angle	45 deg
Field Index (n)	3.36
K1(pole shape)	-1.2 m^{-1}
K2(edge shape)	-2.43x2 m^{-2}
Pole Gap (Min.)	48 mm

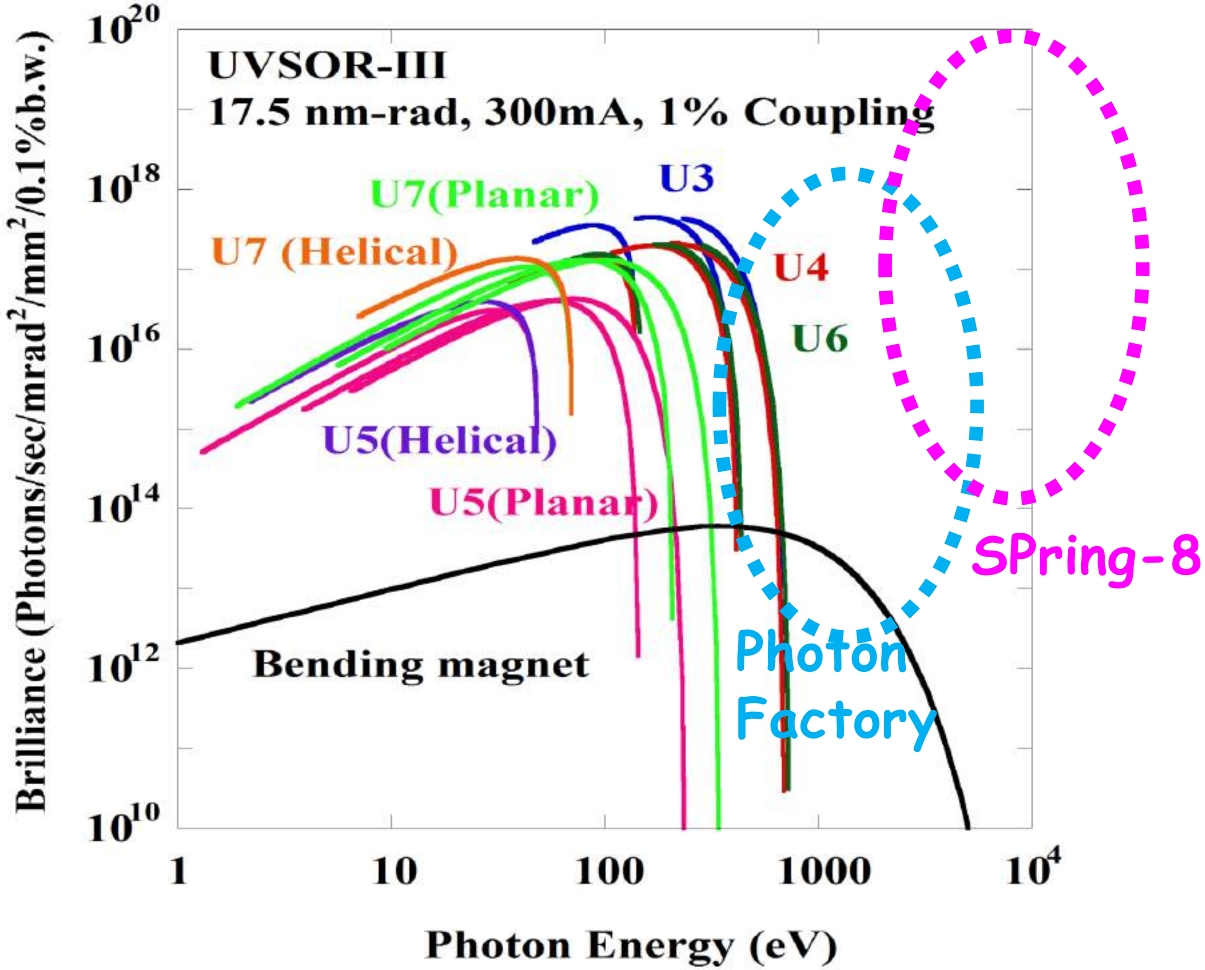




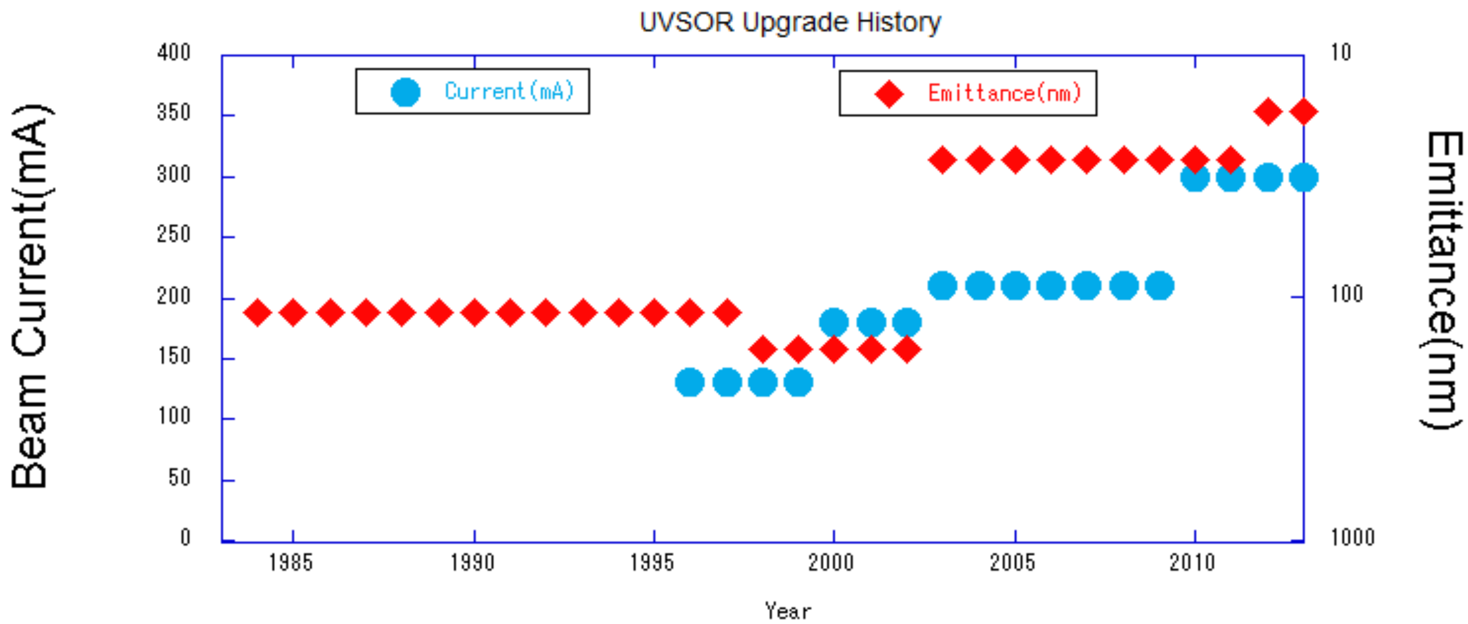


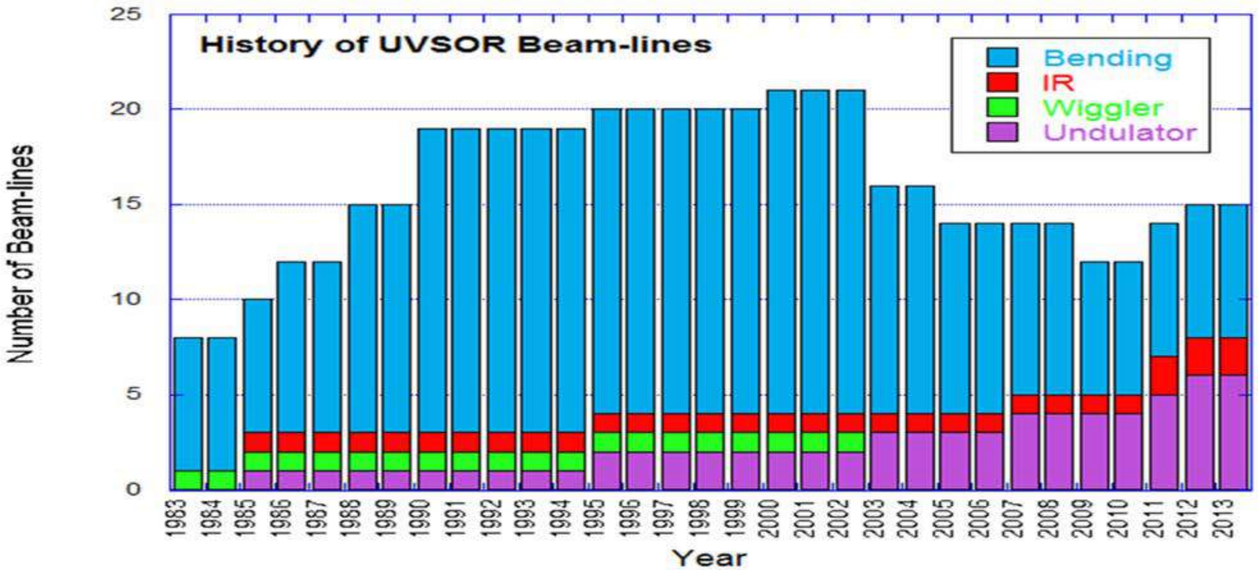
Undulators in UVSOR-III

SR Spectra of UVSOR-III



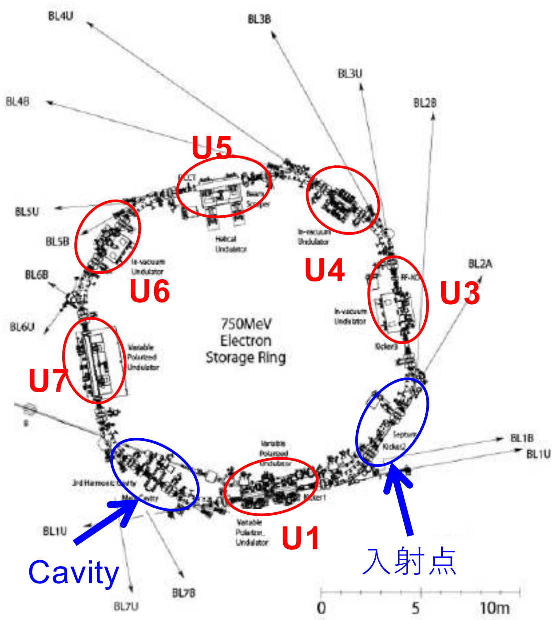
Histor


UVSOR Upgrade History
Current(mA)
Emittance(nm)
Beam Current(mA)
Emittance(nm)
400
350
300
250
200
150
100
50
0
10
100
1000
1985
1990
1995
2000
2005
2010
Year


History of UVSOR Beam-lines
Bending
IR
Wiggler
Undulator
Number of Beam-lines
25
20
15
10
5
0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Year

（経済教室）老朽化するインフラ(下)
長期の社会コスト減 重視を　ー　予防保全、長寿命化を左右
中村光・名古屋大学教授
（2019/2/26付日本経済新聞記事より抜粋）

「最後に新設構造物の問題にも触れたい。無駄を省き最適化したものを作ることがよいとされていたが、その考えを今後見直すべきではないか。使用期間が短ければ、ある機能に特化しその最適化を求めることが合理的だろう。しかしインフラは100年以上使うものだ。その間に社会状況が変わり、社会が求める機能も変化もしくは新たな事項が付け加わる可能性が高い。従来は成長過程で求められる機能に最適化するようにインフラを廃棄し新設することが社会の成長を促した。しかし長寿命化社会では、時には無駄な物を許容する「冗長性」のある構造物を建設し、社会の変化に合わせてインフラに少し手を加えるだけで十分な機能を発揮し続けて長く使える構造物が望ましい場合もある。既設・新設インフラともに発想の転換が求められる。」

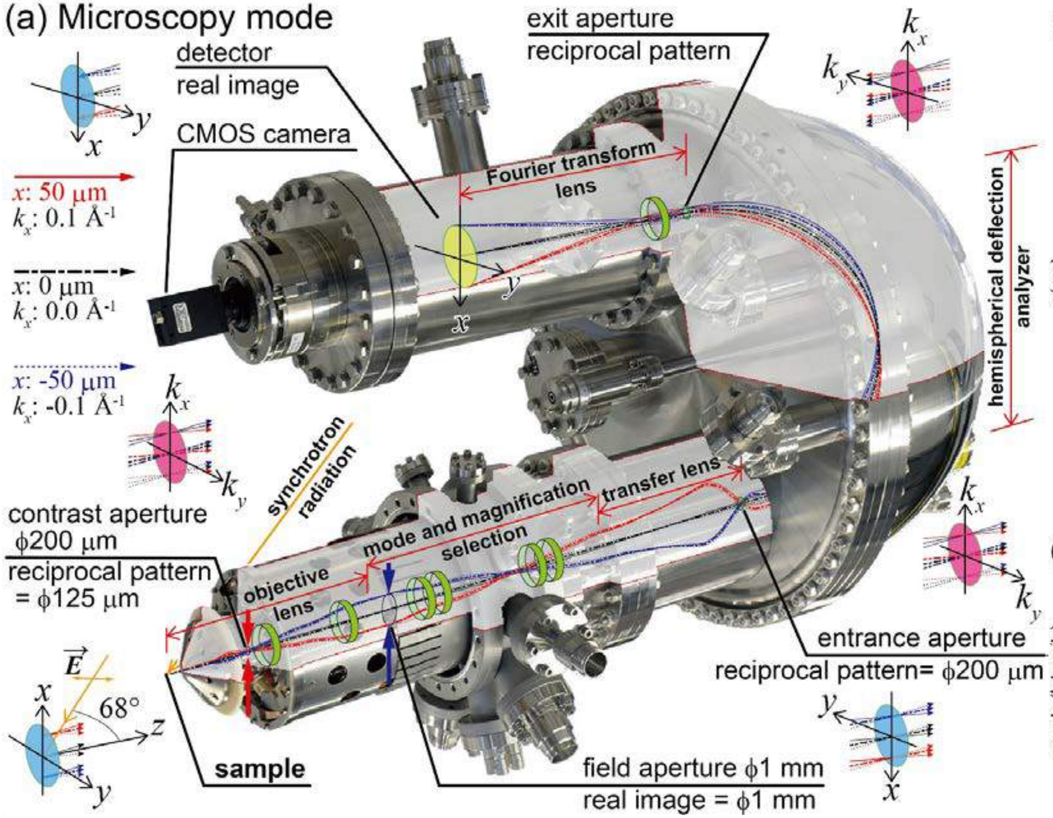


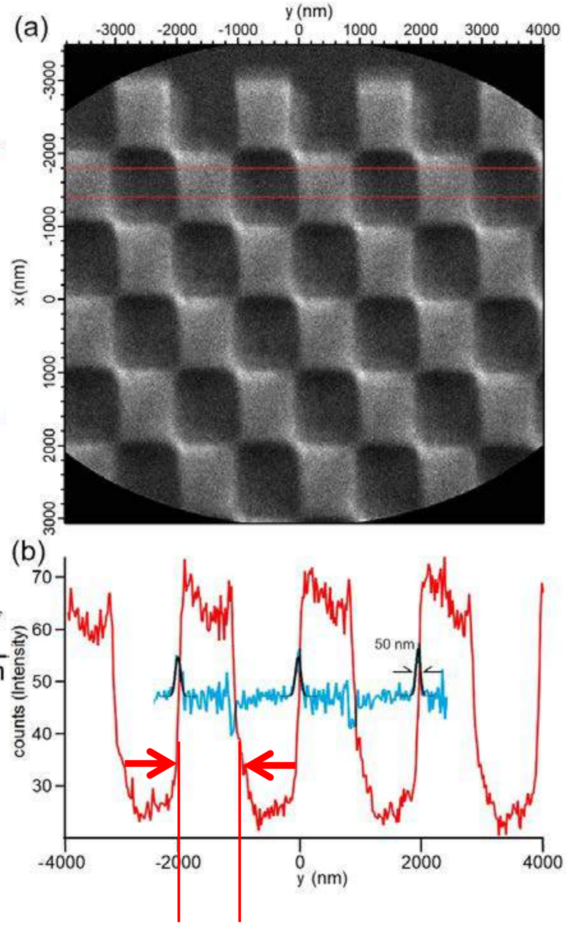
ビームライン14本
うちアンジュレータ
6本

Beamline	Optics	Energy Range	Targets	Techniques
BL1B	Martin-Puplett FT-FIR	0.5-30 meV	Solid	Reflection/Adsorption
BL6B	Michelson FT-IR	4 meV-2.5 eV	Solid	Reflection/Adsorption
BL7B	3-m normal incidence	1.2-25 eV	Solid	Reflection/Adsorption
BL3B	2.5-m off-plane Eagle	1.7-31 eV	Solid	Reflection/Absorption
BL5B	Plane grating	6-600 eV	Solid	Calibration/Absorption
BL2B	18-m spherical grating (Dragon)	23-205 eV	Solid	Photoionization Photodissociation
BL4B	Varied-line-spacing plane grating (Monk-Gillieson)	25 eV-1 keV	Gas, Liq. Solid	Photoionization, XAFS Photodissociation, XMCD
BL2A	Double crystal	585 eV-4 keV	Solid	Reflection/XAFS
BL1U	Tandem undulators/ Free electron laser	1.6-13.9 eV	Gas Solid	Laser Compton Scattering Orbital Momentum Light
BL7U	10-m normal incidence (modified Wadsworth)	6-40 eV	Solid	Photoemission
BL5U	Varied-line-spacing plane grating (Monk-Gillieson)	20-200 eV	Solid	ARPES Spin-resolved ARPES
BL6U	Variable-inc.-angle-varied-line-spacing plane grating	40-700 eV	Solid	ARPES XAFS / XPD
BL4U	Varied-line-spacing plane grating (Monk-Gillieson)	50-700 eV	Gas, Liq. Solid	XAFS Microscopy (STXM)
BL3U	Varied-line-spacing plane grating (Monk-Gillieson)	60-800 eV	Gas, Liq. Solid	XAFS / Photoemission Photon-emission

1B	テラヘルツ時分割測定、R&D
6B	THz-IR顕微分光、ユーザー開拓
7B	Single bunch:前置鏡冷却なしで供用
3B	材料評価でニーズがある システム高度化へ
5B	
2B	有機固体： 競争力低下
4B	楕円偏光： XMCD
2A	-4 keV迄のXAS測定, 素子・分析器R&D
1U	先進光源開発：新たなユーザー開拓
7U	超高分解能ARPES
5U	微小領域ARPES, スピン分解開発中
6U	広角取込軟X線ARPES → PMM稼働開始
4U	液体試料in situ, Liも対象, フル稼働
3U	液体試料in situ/operando XAS

Photoelectron Momentum Microscope



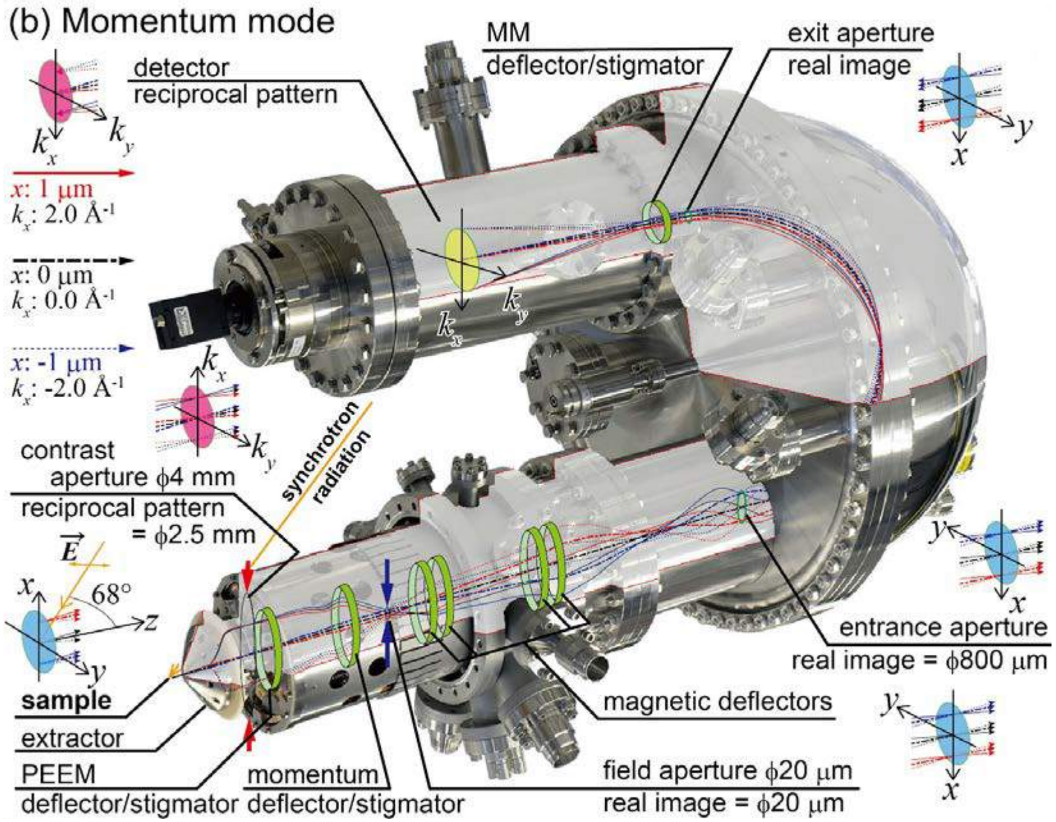


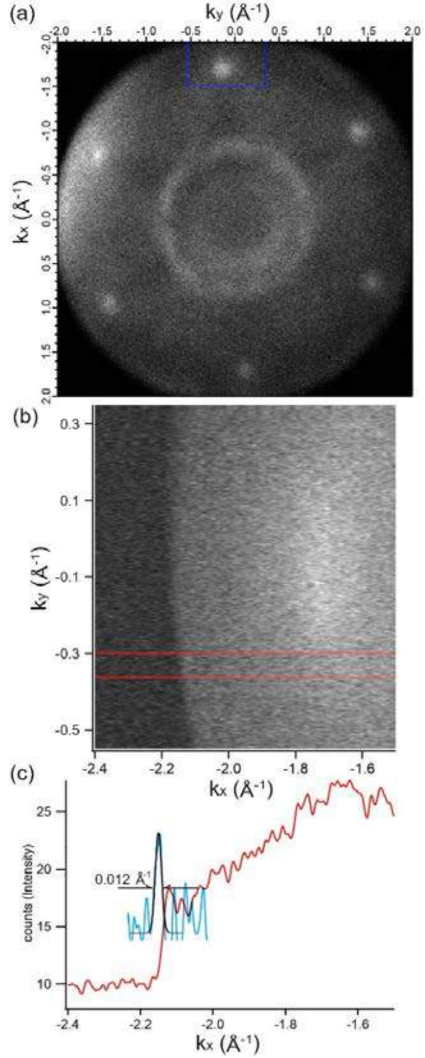
Au checkerboard pattern

Microscopic imaging by photoelectron
➔ element selective
➔ work function sensitive

F. Matsui, et al., JJAP **59** (2020) 067001

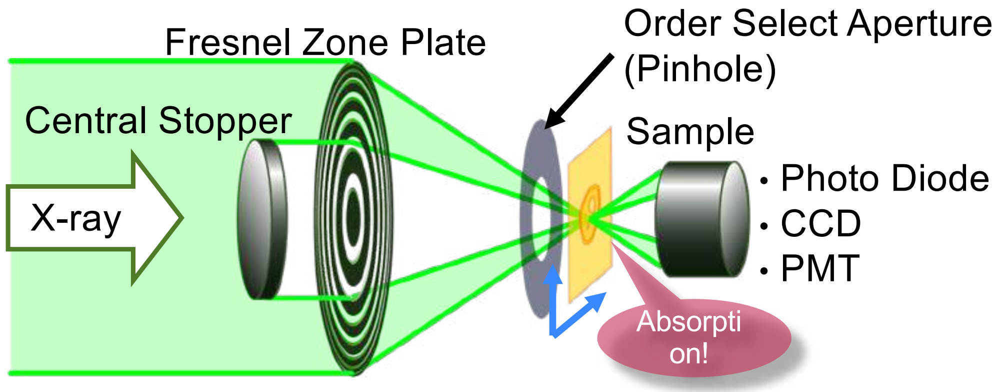
Photoelectron Momentum Microscope



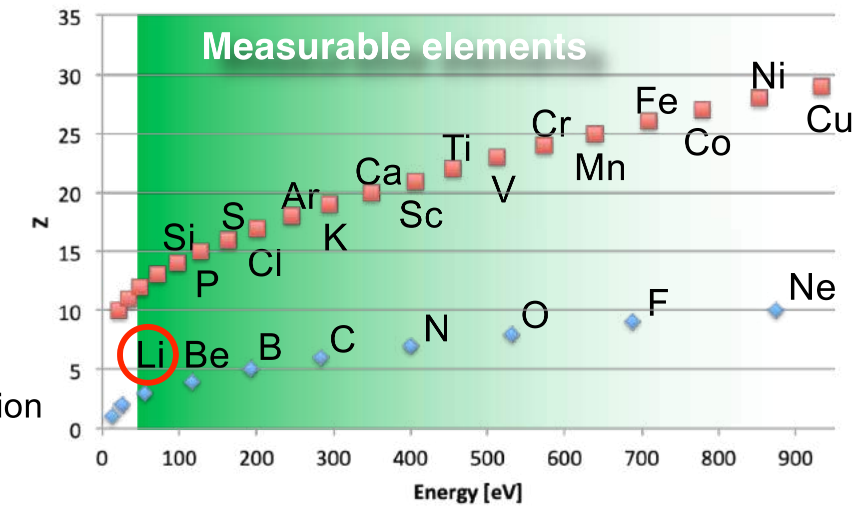


Valence band 3D dispersion mapping
➔ Wide **k** acceptance (±3 Å^{-1})
➔ high **k** resolution (Δ 0.01 Å^{-1})

Scanning Transmission X-ray Microscopy: STXM

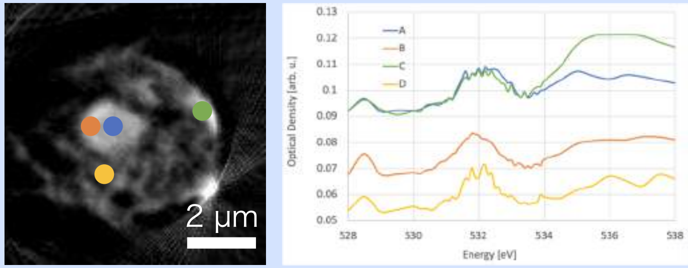


- High spatial resolution (20 nm~)
  - Local X-ray absorption spectroscopy
- High transmittance
  - Non-destructive observation by CT (3D)
  - Lower radiation dose than electron beam
  - In-situ Observation
    - Samples in air, in solution or in vacuum
- Used in soft X-ray region
  - Absorption edges: light elements and transition metals



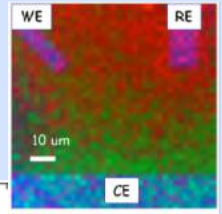
応用研究例

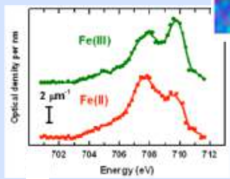
3D spectroscopy of nucleus



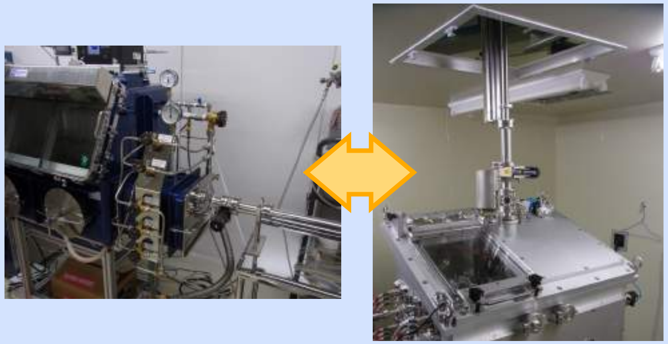
In-situ electrochemistry

Electrochemistry of
FeSO4 solution





Analysis of Hayabusa2 return sample

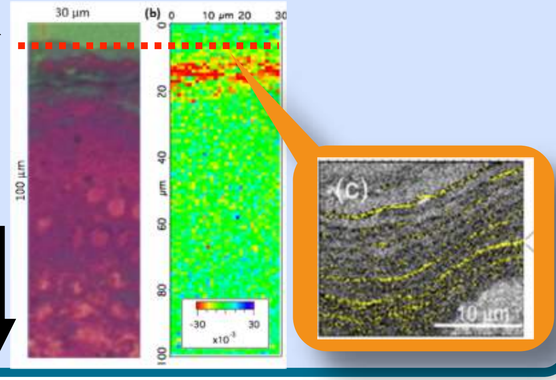


Uptake of drug into human skin

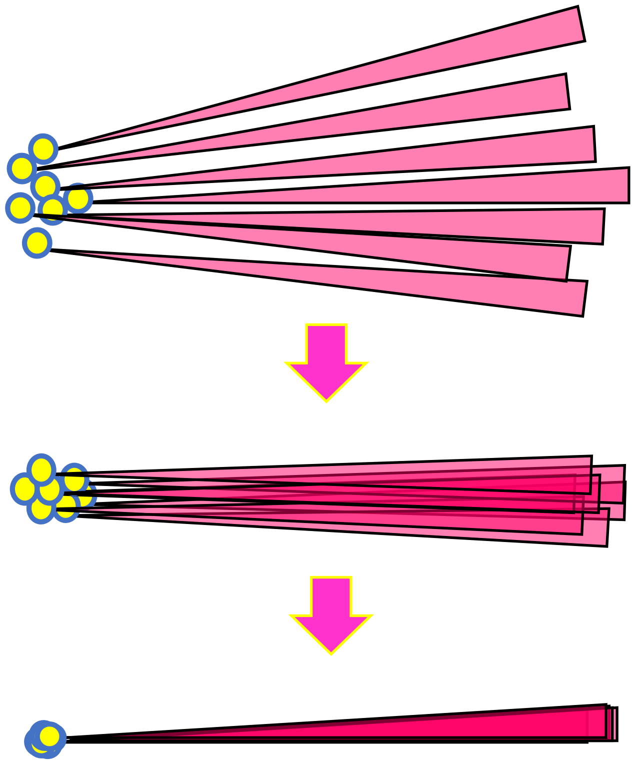
光学顕微鏡 X線顕微鏡

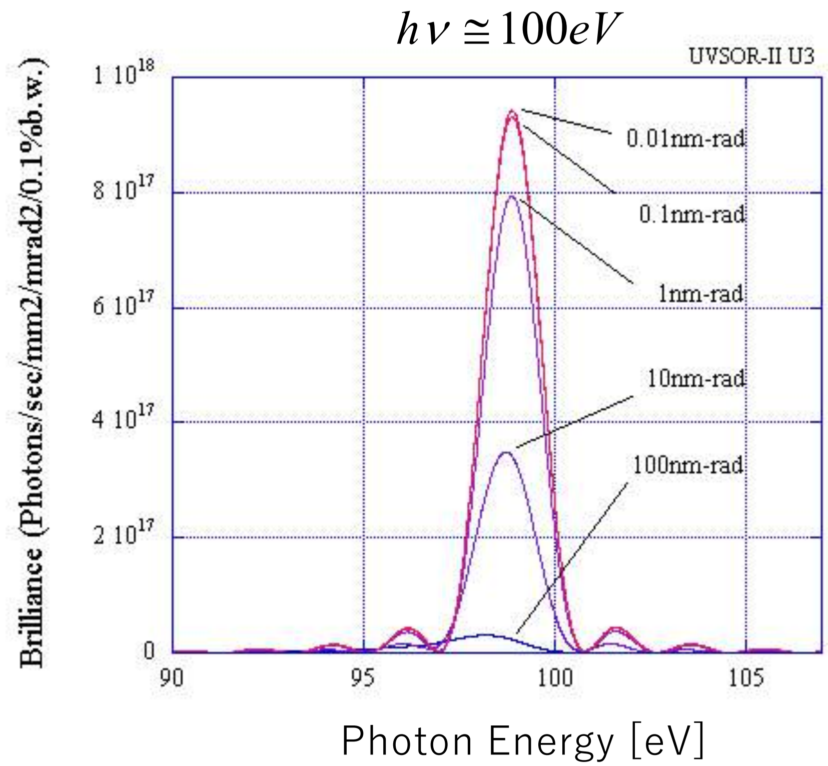
皮膚表面

深さ方向



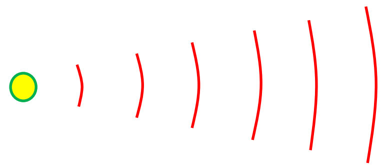
Diffraction Limit ?





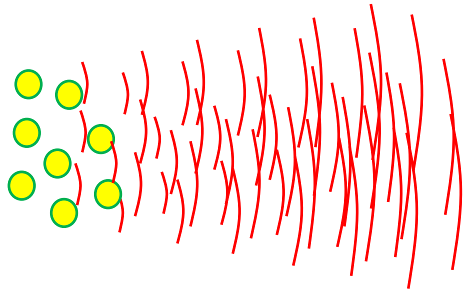
Coherence of Synchrotron Radiation

Undulator radiation
from a single electron



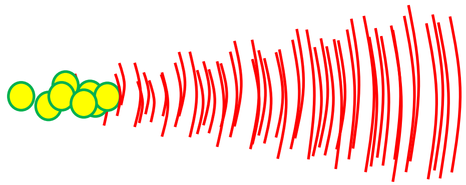
Spatially coherent
Temporally coherent

Undulator radiation
from an electron bunch



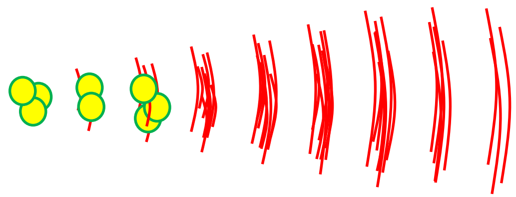
Spatially incoherent
Temporally incoherent

Diffraction-limited
Undulator radiation



Spatially coherent
Temporally incoherent

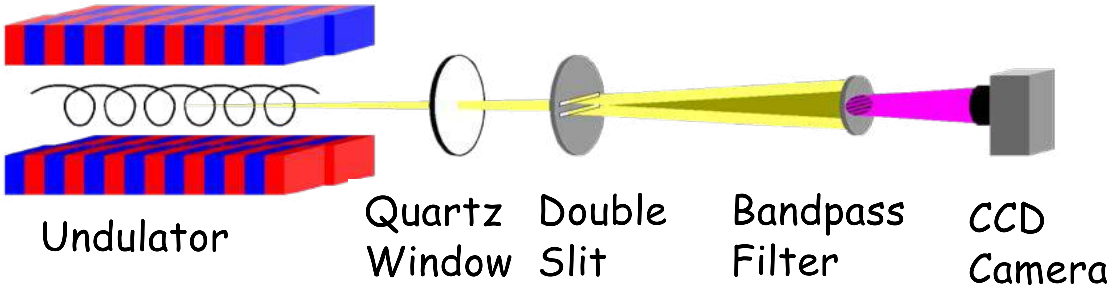
Free Electron Laser

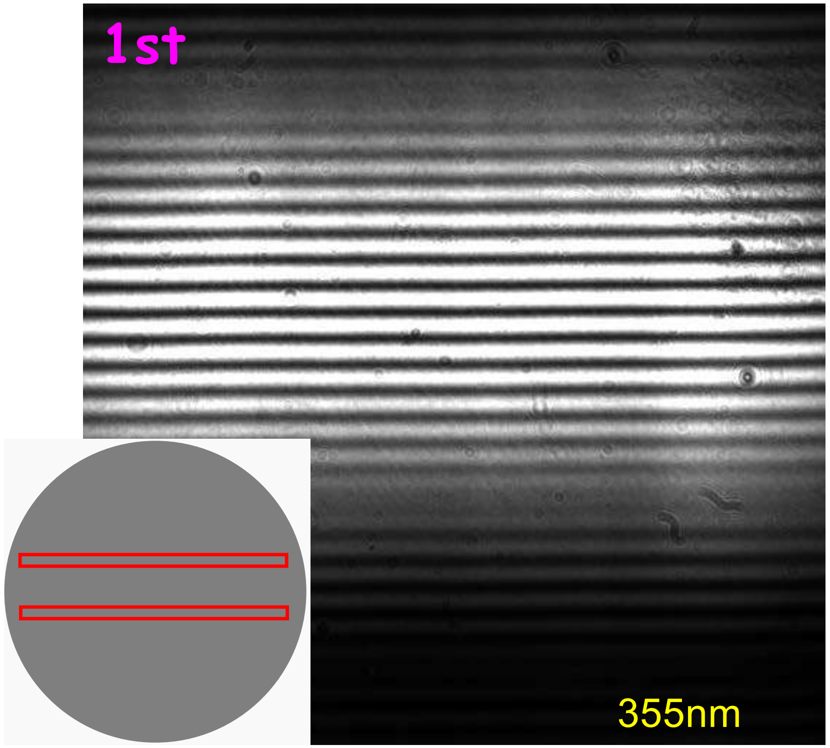


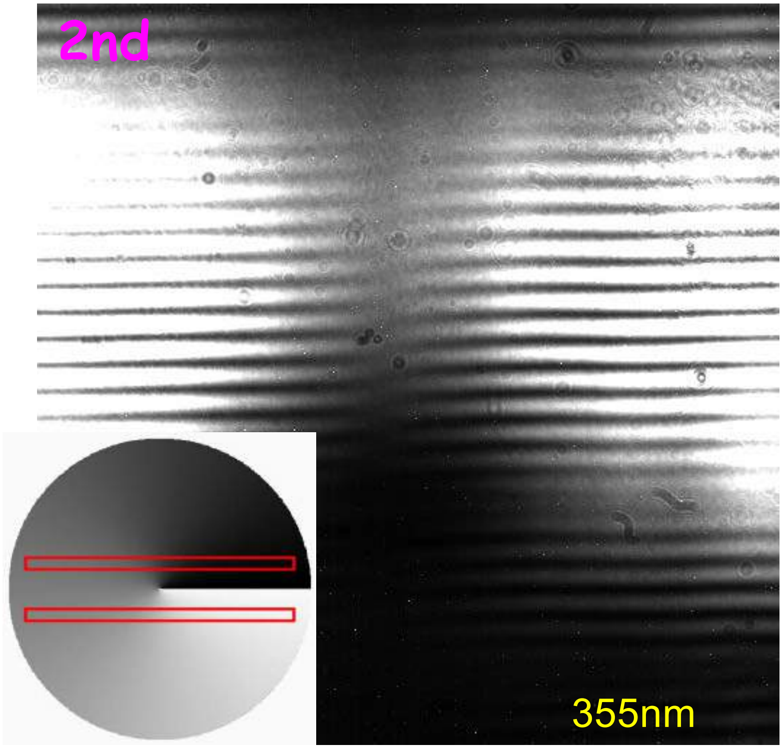
Spatially coherent
Temporally coherent

M.K. et al. Sci. Rep. 7, 6130 (2017)

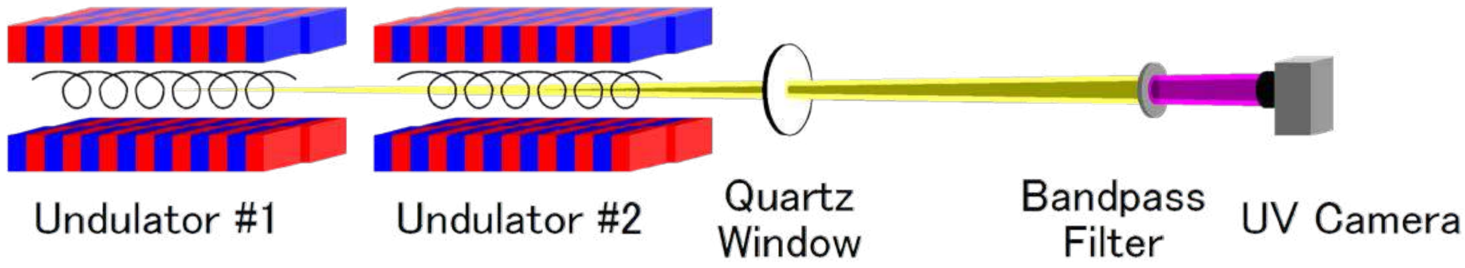
Double-slit Diffraction of Helical Undulator Radiation





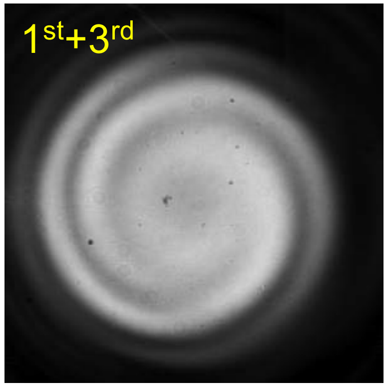


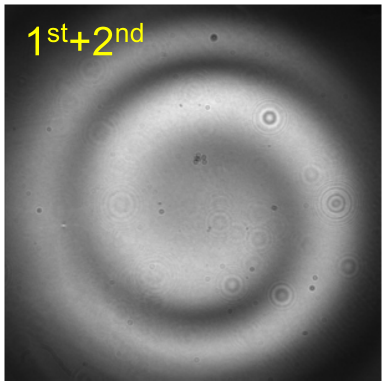
Interference between harmonic radiations from helical undulators in tandem

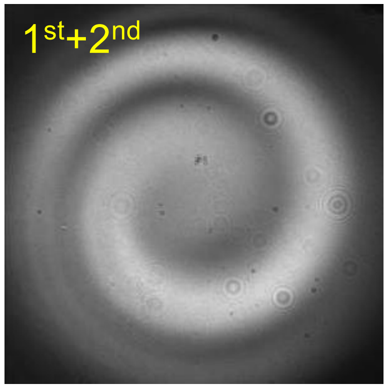


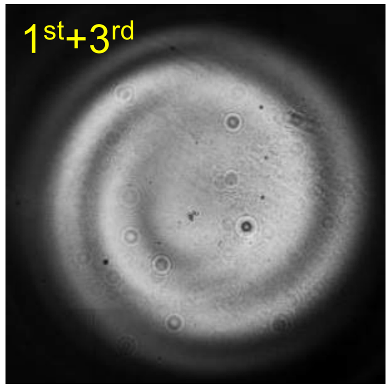
$355nm(1.3nm)$

$\#1; S=-1, L=0$	$\#1; S=-1, L=0$	$\#1; S=+1, L=0$	$\#1; S=+1, L=0$
$\#2; S=-1, L=-2$	$\#2; S=-1, L=-1$	$\#2; S=+1, L=+1$	$\#2; S=+1, L=+2$



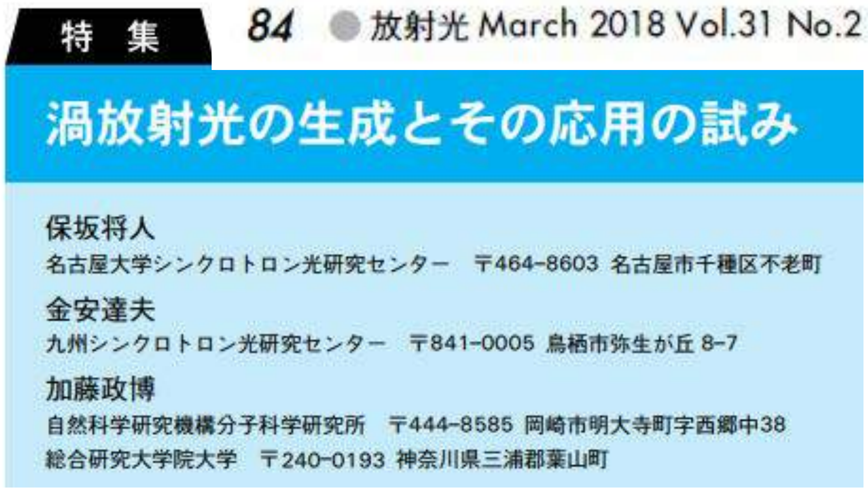






M.K. et al. Sci. Rep. 7, 6130 (2017)

Harmonics of Helical Undulator Radiation
= Optical Vortex carrying Orbital Angular Momentum


特 集　84 ● 放射光 March 2018 Vol.31 No.2

渦放射光の生成とその応用の試み

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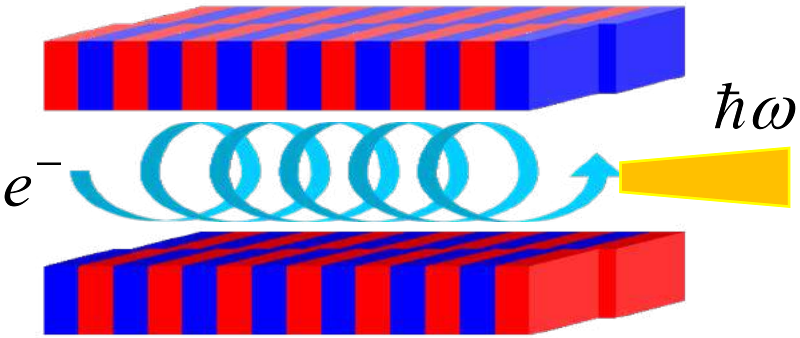
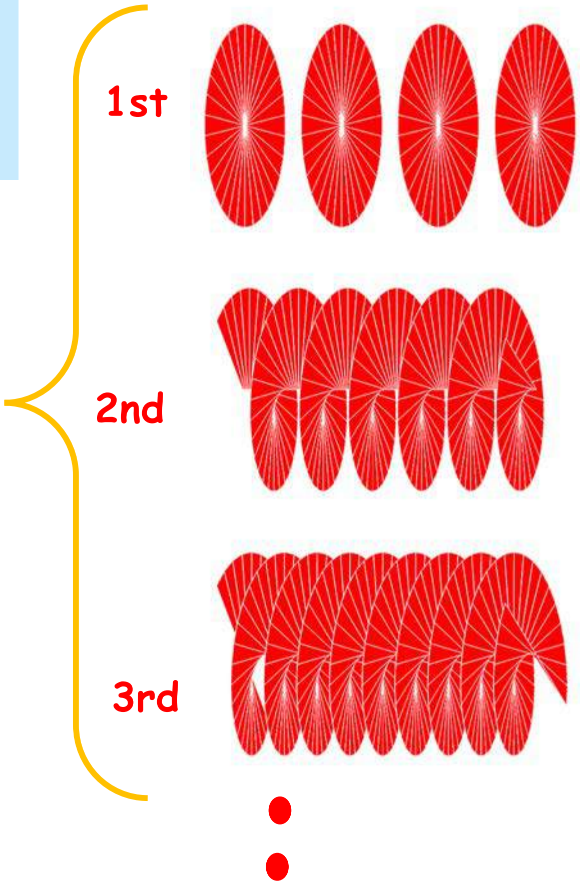
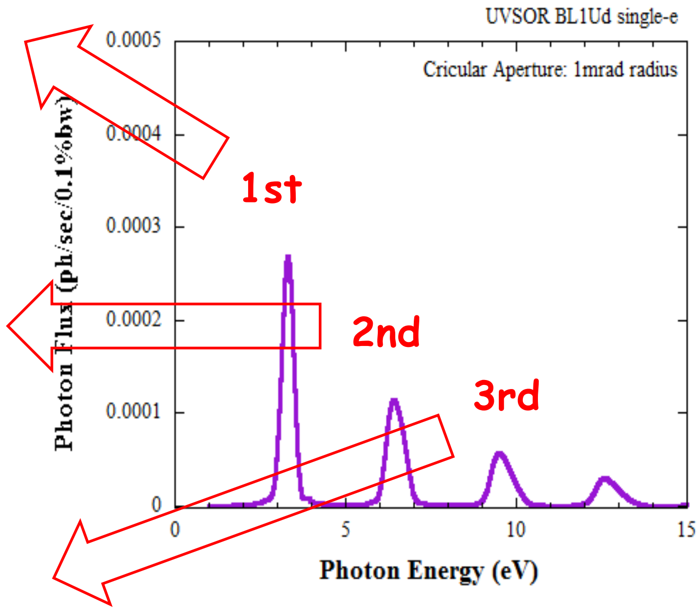
総合研究大学院大学　〒240-0193 神奈川県三浦郡葉山町







O. Chubar et al., NIM A 435 (1999) 495
S. Sasaki & I. McNulty, PRL 100, 124801 (2008)
J. Bahrdt et al., PRL. 111, 034801 (2013)
M. K. et al., PRL 118, 094801 (2017)
M. K. et al., SREP 7, 6130 (2017)

Vector Beam from Undulator

S. Matsuba et al., Appl. Phys. Lett. 113, 021106 (2018)

トピックス

タンデムアンジュレータによる放射光ベクトルビームの生成

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加藤政博
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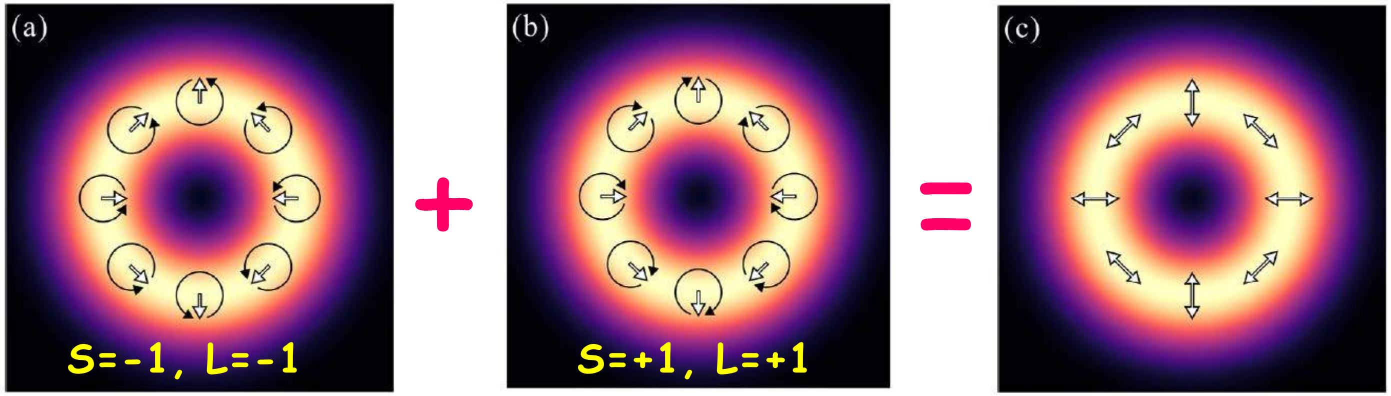
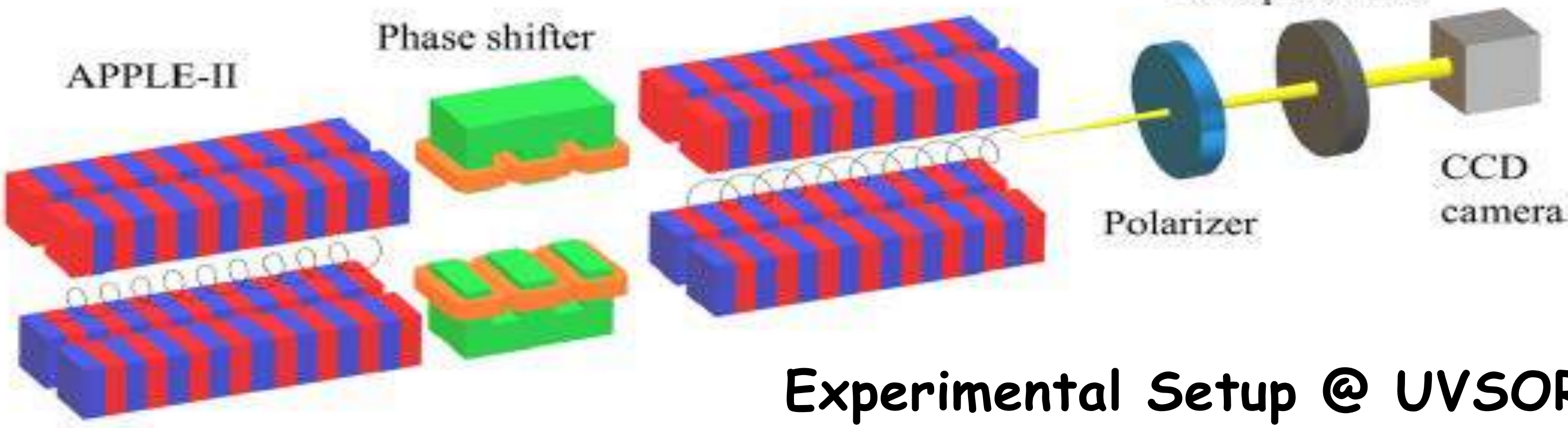
放射光 May 2020 Vol.33 No.3 231

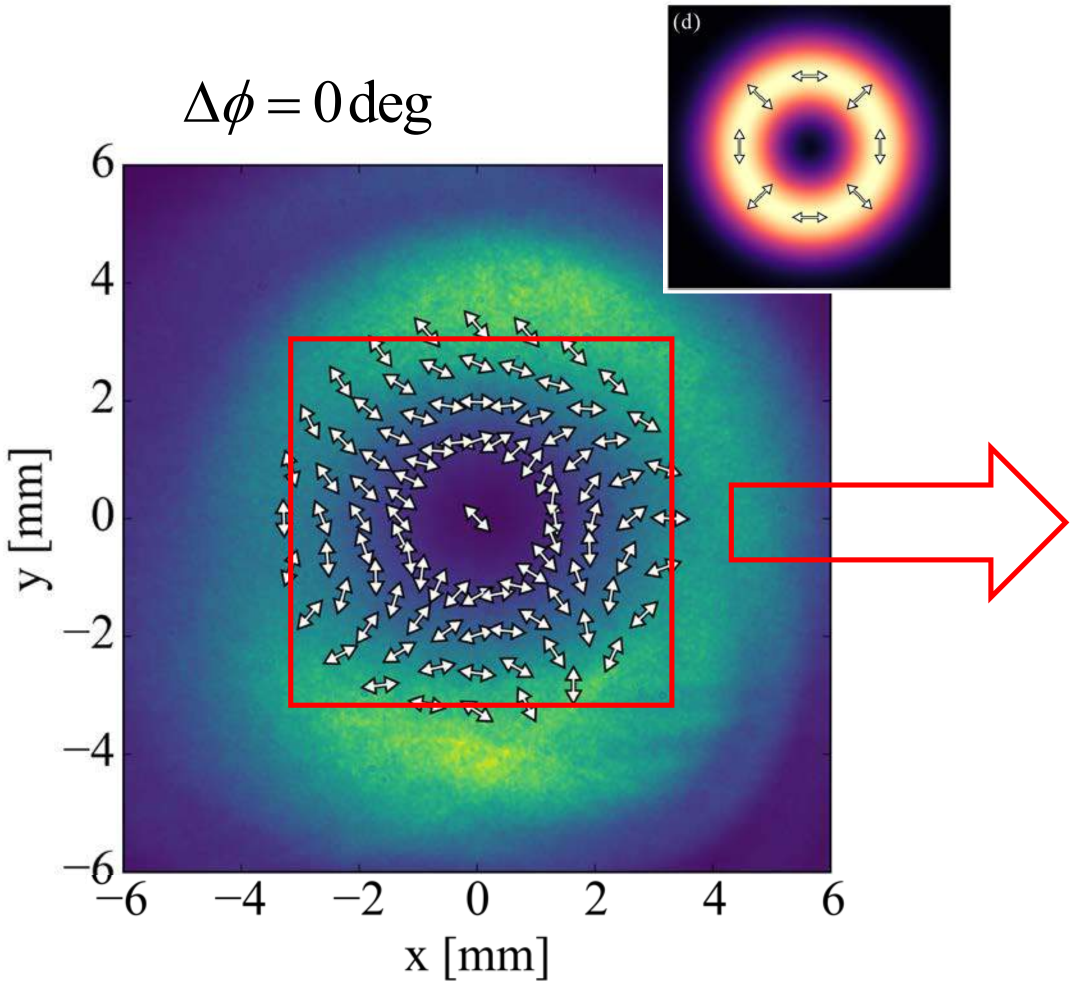


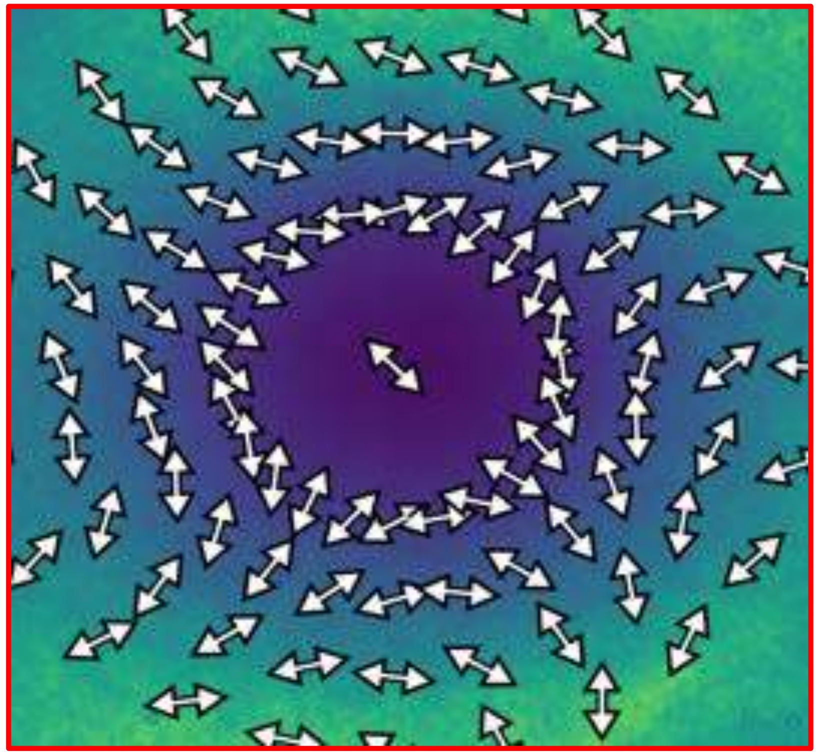


Experimental Setup @ UVSOR-BL1U

Vector Beam from Tandem Undulator at UVSOR BL1U

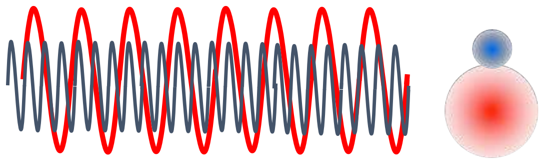
S. Matsuba et al., Appl. Phys. Lett. 113, 021106 (2018)

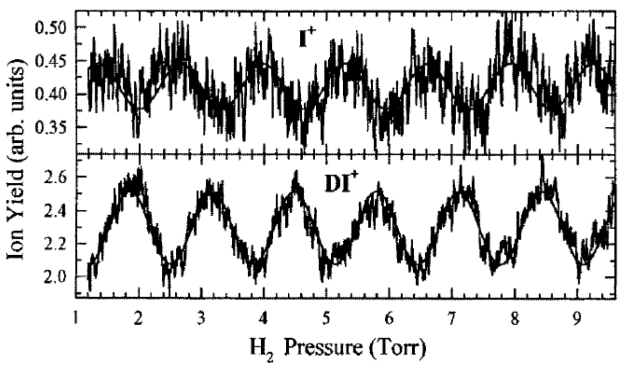




Coherent Control

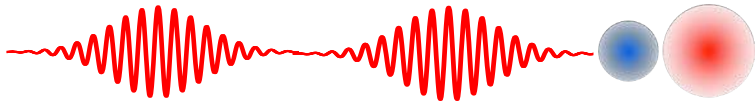
Brumer-Shapiro ($3\omega_1/\omega_3$) Scheme

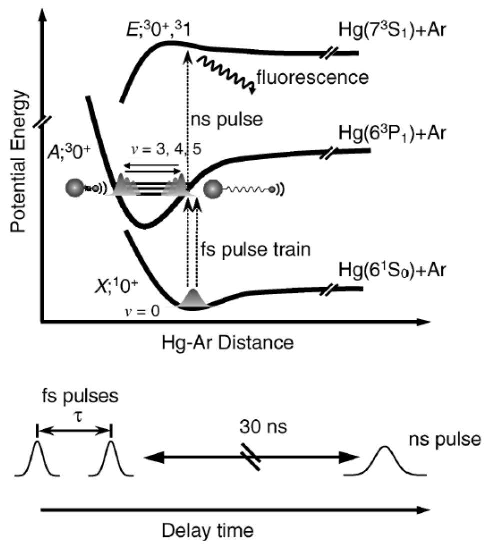


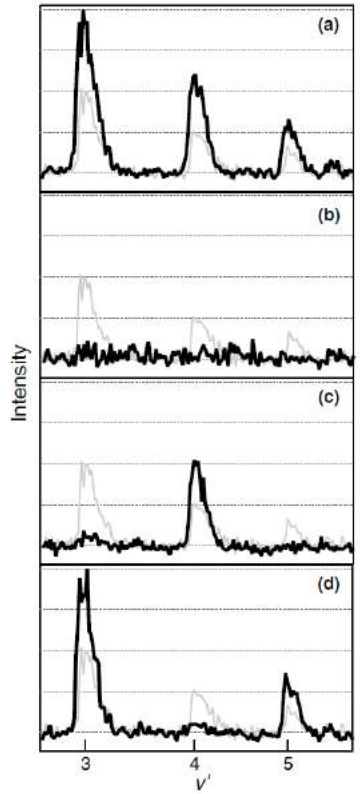


L. Zhu et al., PRL **79** 4108 (1997)

Wave Packet Interferometry Scheme



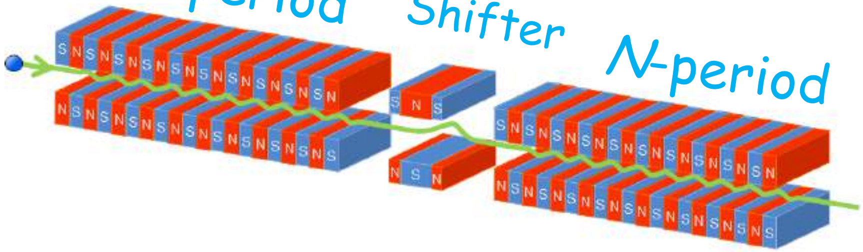




K. Ohmori et al.,
PRL **91** 243003 (2003)

“Double-pulse” structured light from Tandem Undulator

Tandem Undulator




トピックス

放射光による原子のコヒーレント制御

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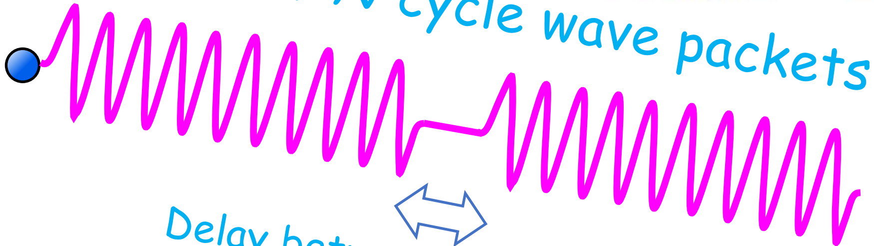
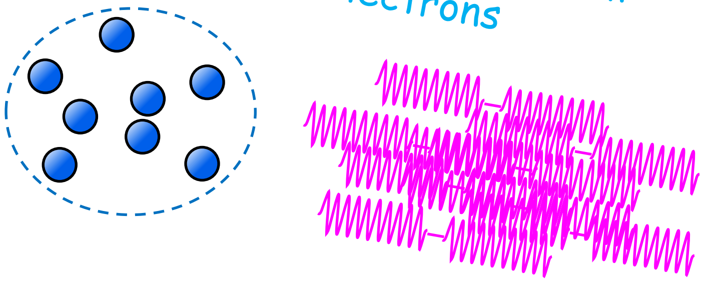
放射光 Sept. 2020 Vol.33 No.5 ● 1

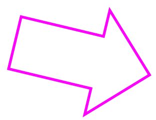
A pair of N-cycle wave packets



Delay between two wave packets can be controlled by the phase shifter magnet

Incoherent Radiation from a bunch of electrons

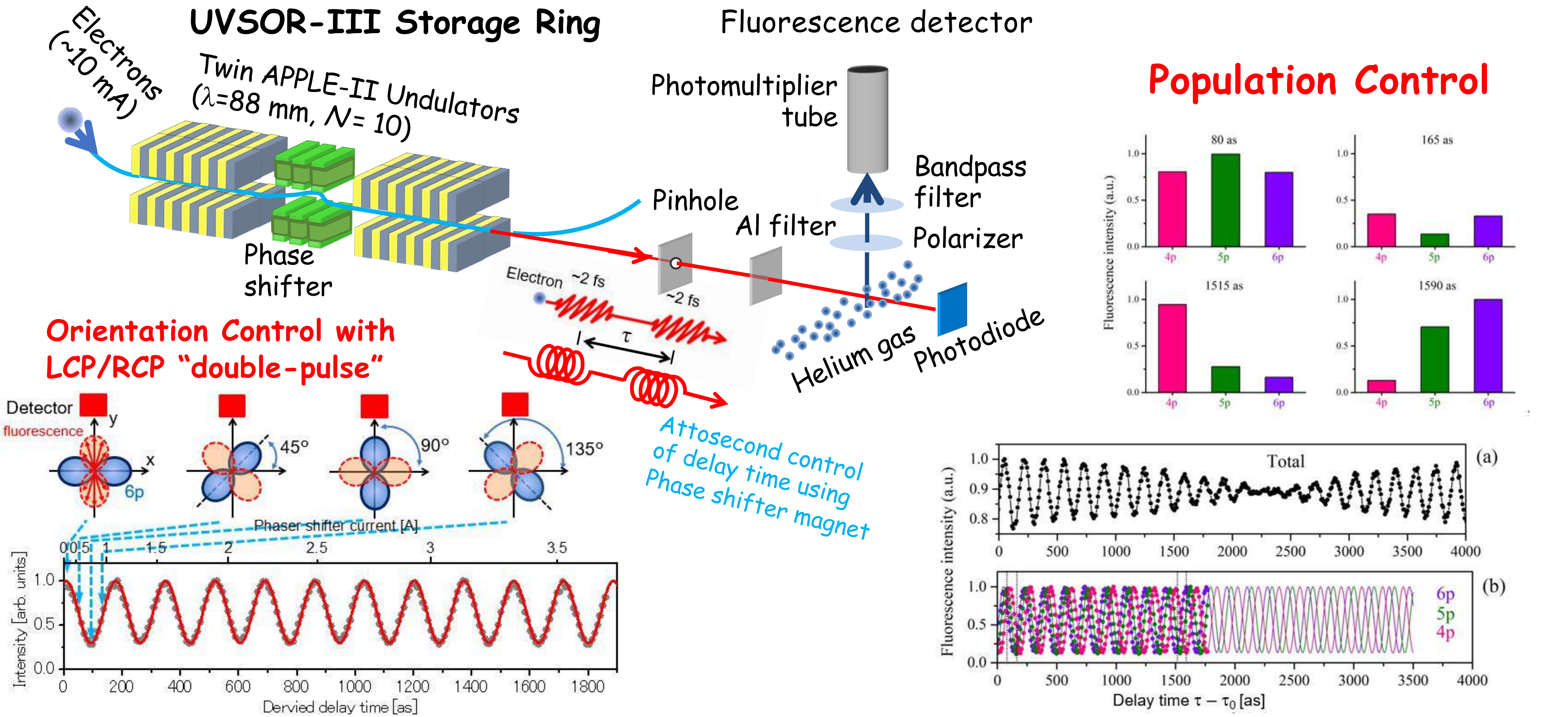




?

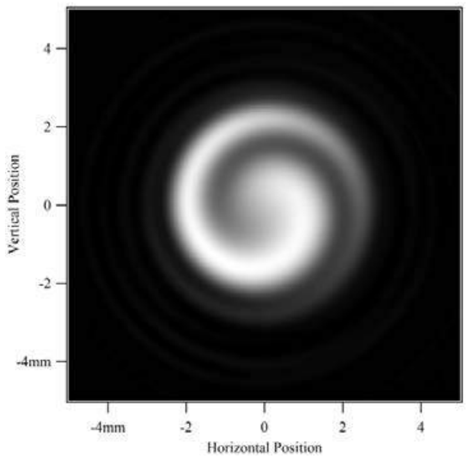
Y. Hikosaka et al., Nat. Commun. 10, 4988 (2019)
T. Kaneyasu et al., Phys. Rev. Lett. 123 233401 (2019)

Coherent Control of Atoms using "double-pulse" structured light from Tandem Undulator

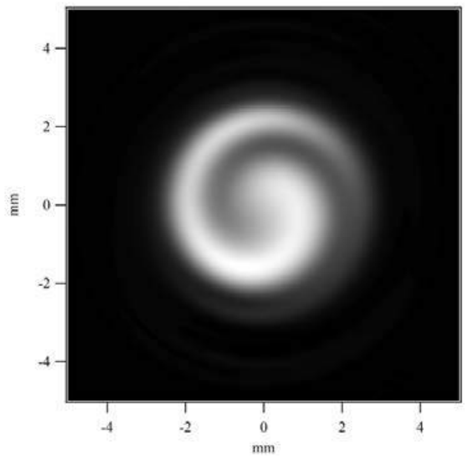


Effect of e-Beam Emittance

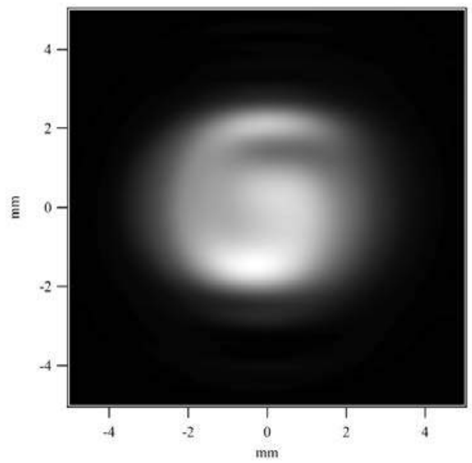
Simulation



Zero Emittance



Design Emittance



Design Emit x 10

J. Synchrotron Rad. (2017). 24, 934-938

Diffraction-limited VUV LS ?

$$h\nu \leq 100[\mathrm{eV}]$$

Undulator Radiation

$$h\nu[\mathrm{keV}] = \frac{0.95E_e^2[\mathrm{GeV}]}{(1+K^2/2)\lambda_u[\mathrm{cm}]} \qquad \left(K = \frac{eB_0\lambda_u}{2\pi mc} \approx (1 \sim 5) \right)$$

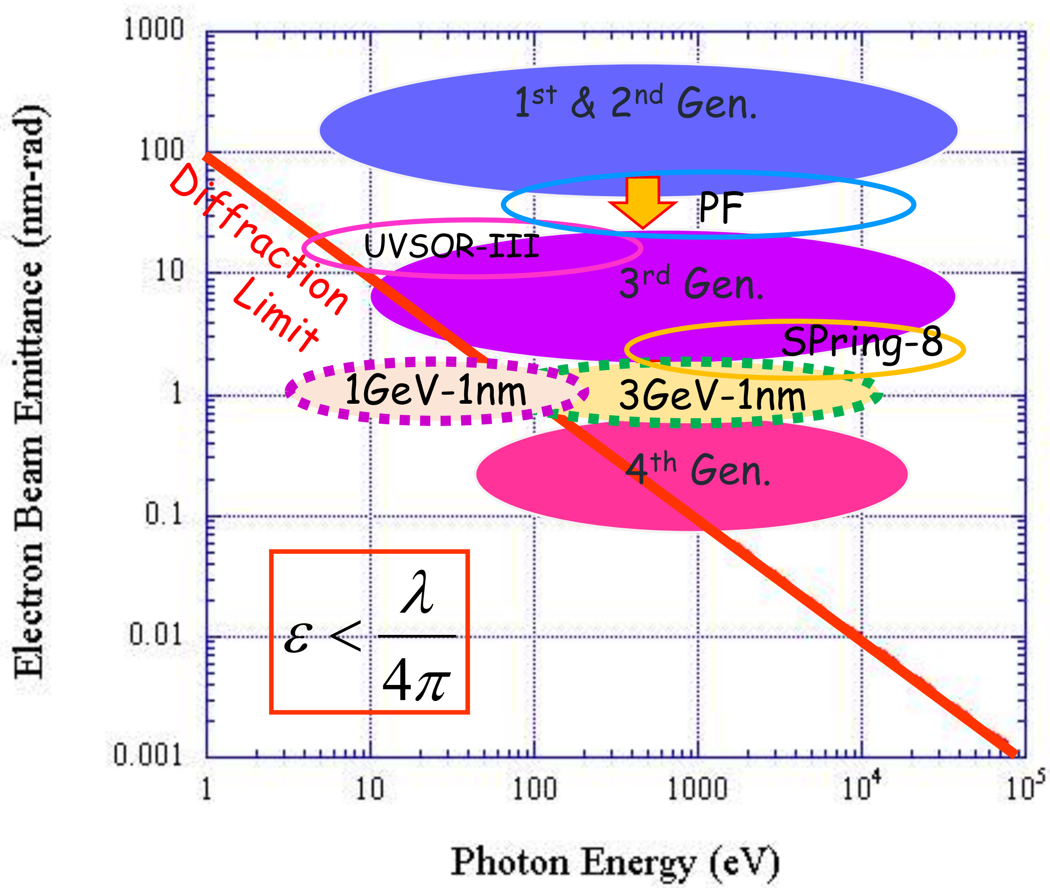
$$h\nu = 0.1[\mathrm{keV}]$$

$$K \approx 1.5 \qquad \Rightarrow \qquad E_e[GeV] \approx 1[GeV]$$

$$\lambda_u \approx 5[cm]$$

$$\varepsilon \leq \frac{\lambda}{4\pi} = \frac{12.4[nm]}{4\pi} \qquad \Rightarrow \qquad \varepsilon \approx 1[nm]$$

Diffraction-Limited Light Sources ?

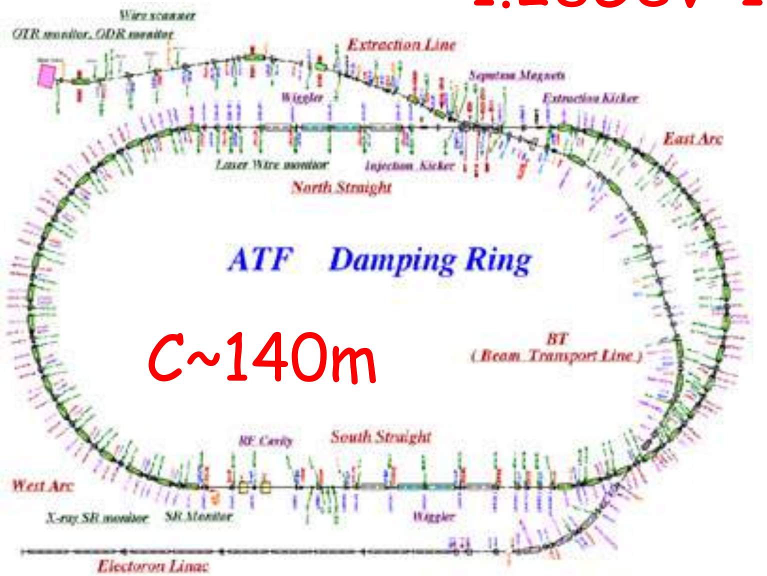


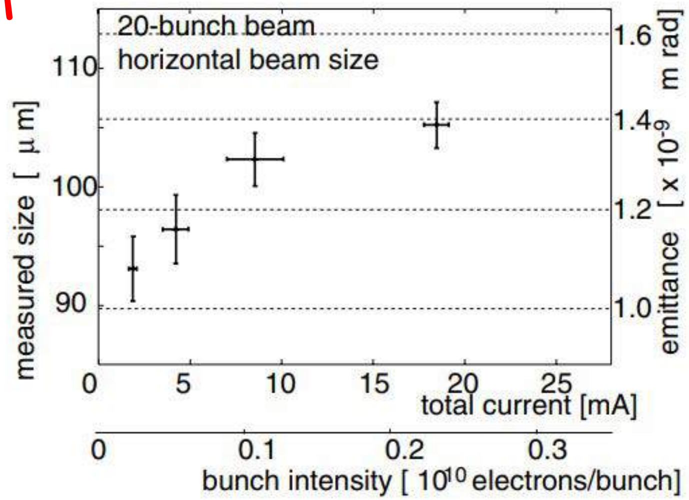
KEK ATF Damping Ring

http://www-atf.kek.jp/atf/introduction.html

Major Performance ;	
Beam energy :	1.28 GeV
Beam intensity single bunch operation :	$1.0x10^{10}$ electrons/bunch
multi bunch operation :	$0.7x10^{10}$ electrons/bunch x 20 bunch
Beam reputation :	0.7 ~ 6.4 Hz
X emittance (extrapolated to 0 intensity) :	$1.0x10^{-9}$rad.m (at 1.28GeV)
Y emittance (extrapolated to 0 intensity) :	$1.0x10^{-11}$ rad.m (at 1.28GeV)
Typical beam size :	70μm x 7μm (rms horizontal x rms vertical)

1.28GeV-1nm

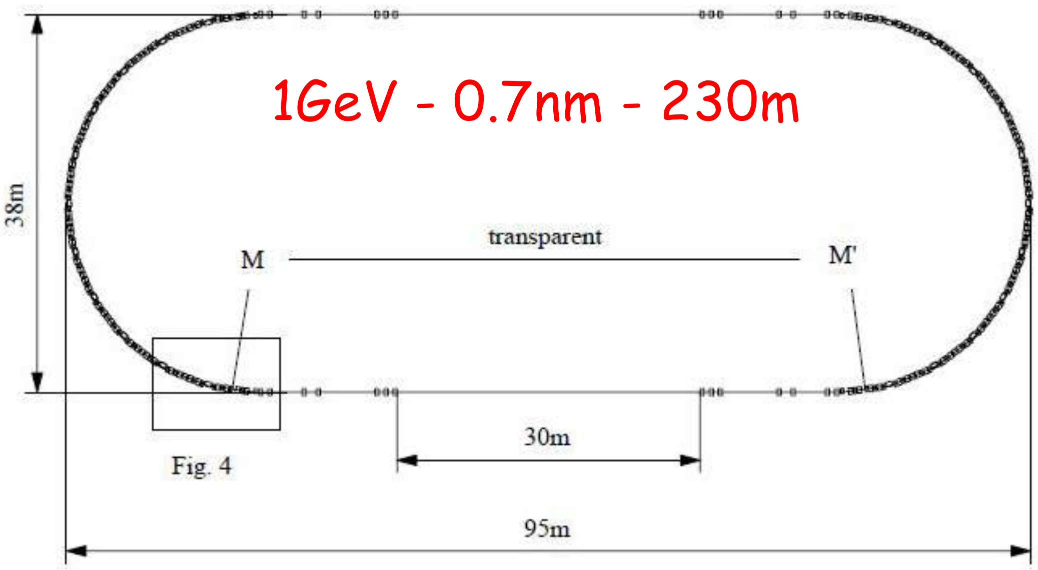


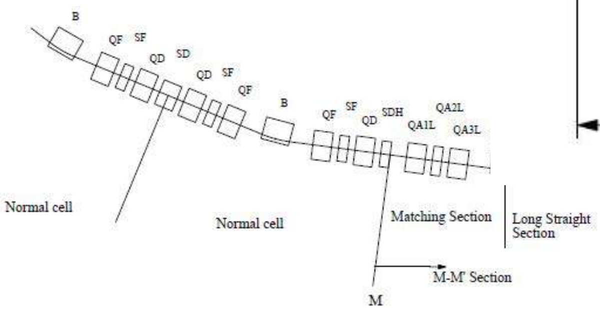


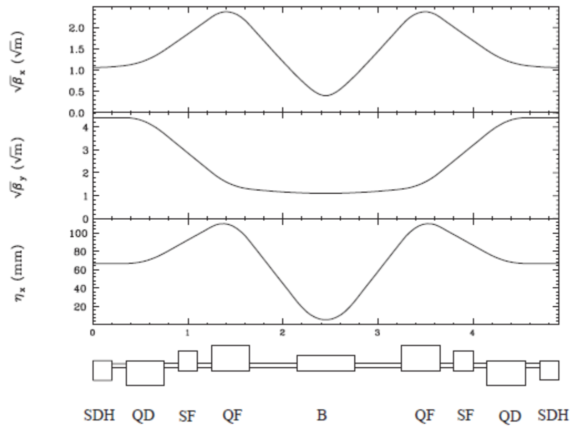
Y. Honda et al., PRSTAB 6 092802 (2003)

ISSP VSX
(Plan)

Y. Kamiya et al., EPAC'98







Energy	E [GeV]	1.0
Lattice type		Theoretical Minimum Emittance
Superperiod	Ns	~22
Circumference	C [m]	233.2
Long straight section		30 m x 2
Natural emittance	ε_{x0} [nm•rad]	0.715
Energy spread	σ_E /E	5.67×10^{-4}

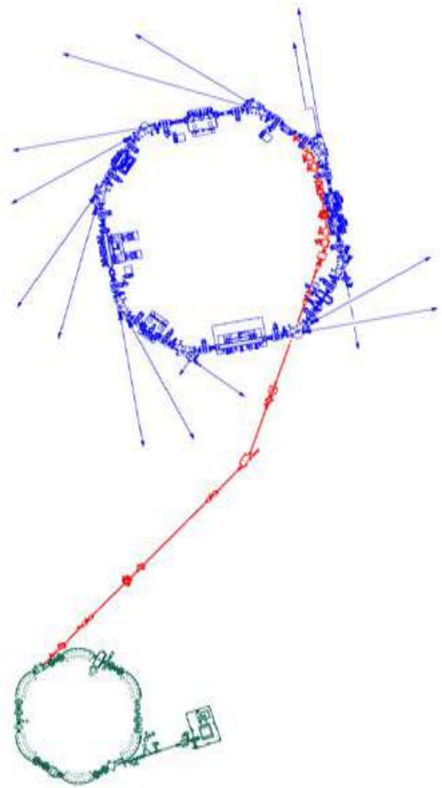
Construction Cost of Synchrotron Facility

- Total Cost = Building + Injector + Synchrotron + Beam-lines

- Building ≒ Injector ≒ Synchrotron ～ [Beam-lines]

  - E_b~500MeV
    - Building ≑ Injector ≑ Synchrotron ~ 1B¥
  - E_b~1GeV
    - Building ≑ Injector ≑ Synchrotron ~ 2B¥
  - ・・・

    - Cost ∝ Electron Energy



Full-energy Injector for VUV Ring

Number of electrons in the storage ring

$$I_b = N_e e f_{rev}$$

$$I_b = 300[mA]$$

$$e = 1.6 \times 10^{-19}[C]$$

$$f_{rev} = c / L = 3 \times 10^8 [m / \sec] / 53[m] = 5.6 \times 10^6 [Hz]$$

Beam Filling Time ~ 1000 sec (0mA to 300 mA)

Number of electrons in the storage ring

$$\Rightarrow \quad N_e = 3 \times 10^{11}$$

Requirements for the injector

$$\frac{\Delta N_e}{\Delta T} = 3 \times 10^{11} / 1000 = 3 \times 10^8 \Rightarrow 1 \times 10^9 [\text{electrons/sec}]$$

(Considering efficiency)

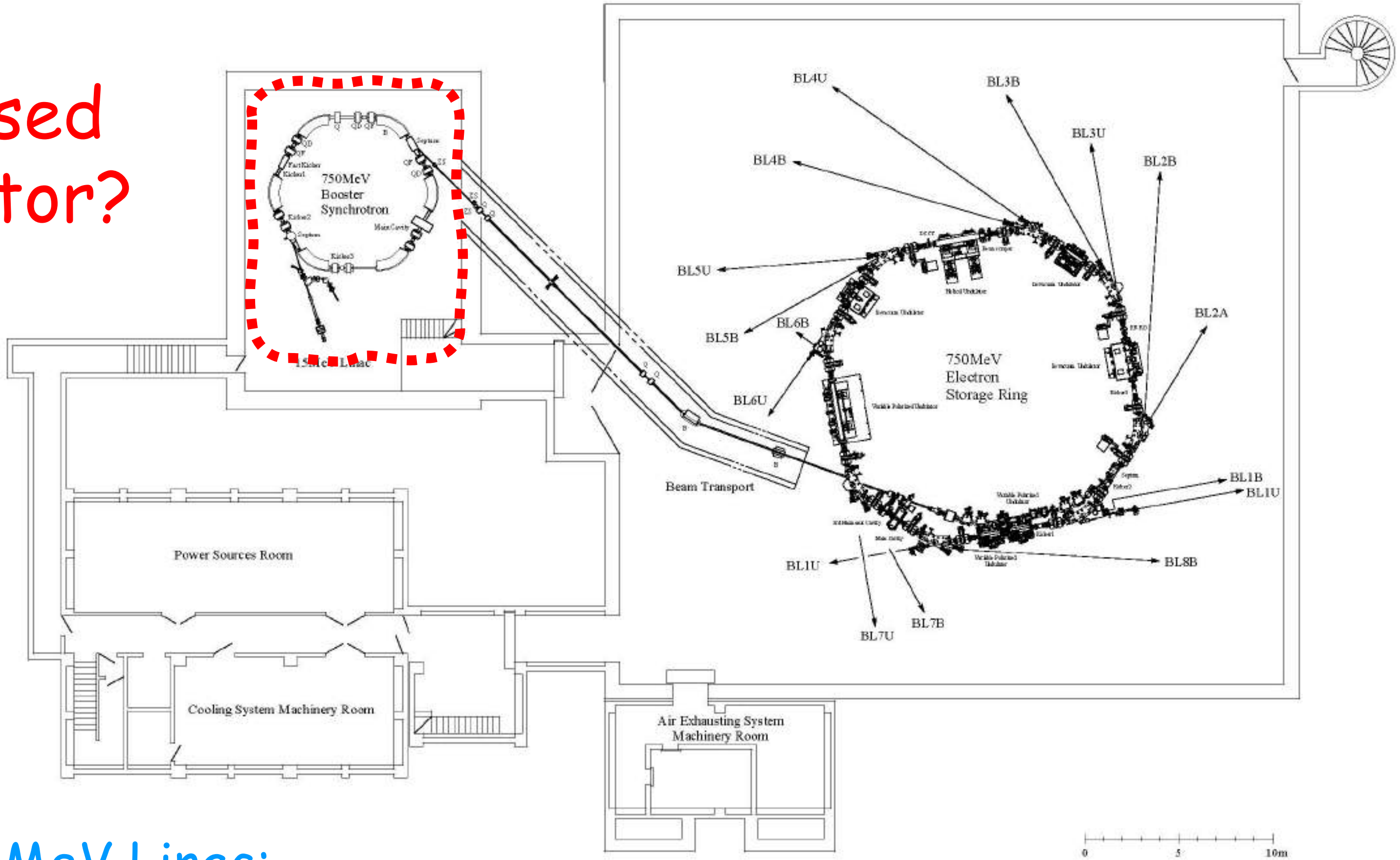
$$E = 750[MeV]$$

$$\varepsilon <\sim 100 \times 10^{-9}[m]$$

$$\Delta\gamma / \gamma <\sim 10^{-3}$$

UVSOR Facility

Laser-based
Accelerator?



Length of 750MeV Linac;
750MeV / (10~100)MeV/m = 7.5~75 m