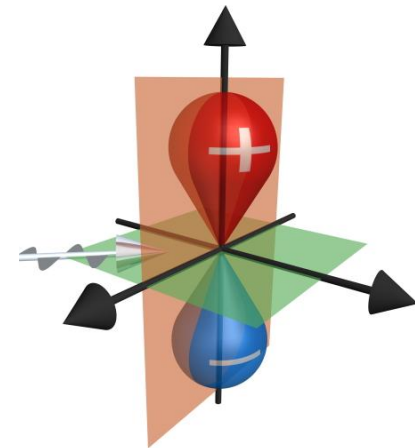




高分解能ARPESによる物性研究： HiSORの現状と将来展望

広島大学放射光科学研究センター

島田賢也



文部科学省により認定された
全国共同利用・共同研究拠点（H22.4～）
「放射光物質物理学研究拠点」

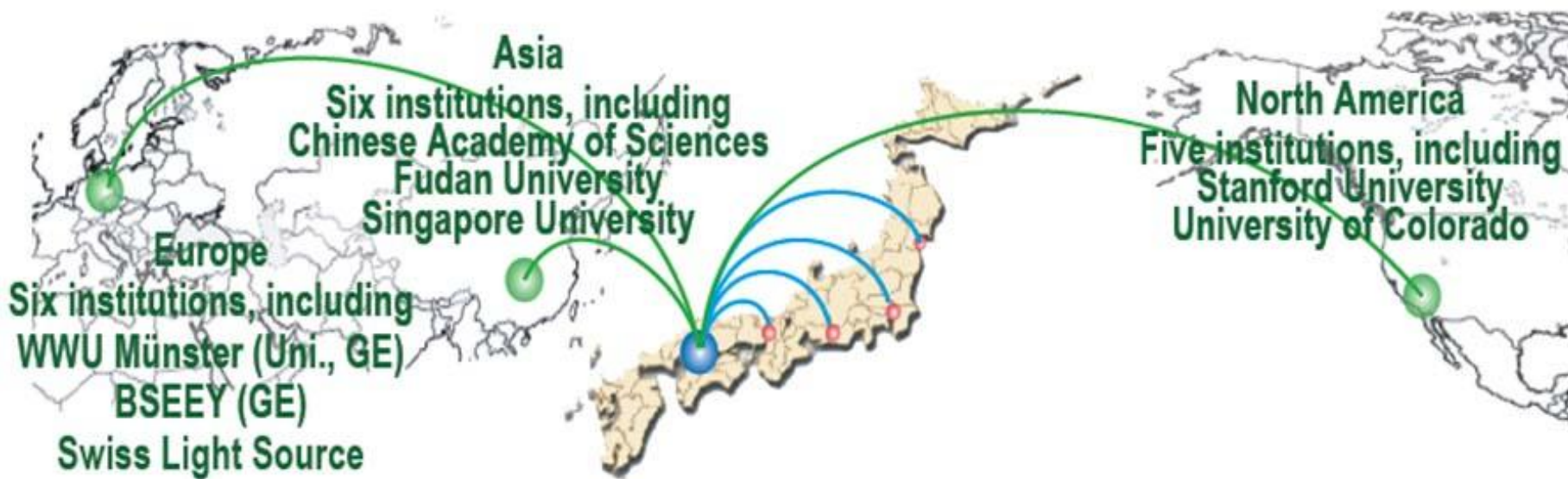
広島大学放射光科学研究センター



真空紫外線から軟X線域の放射光を用いた
物質科学研究

- ・独創的・先端的学術研究の推進
- ・共同研究拠点としての特色を活かした人材育成

文部科学省により認定された
全国共同利用・共同研究拠点 (H22.4~)
「放射光物質物理学研究拠点」



国内 34機関
海外 13機関
研究者実人数 163人
研究課題実施数 70件



2010年の主な研究成果

HiSOR BL-1, 9A, spin ARPES

IF > 7

Nature Commun. (1編)、Phys. Rev. Lett. (10編)

Highlights

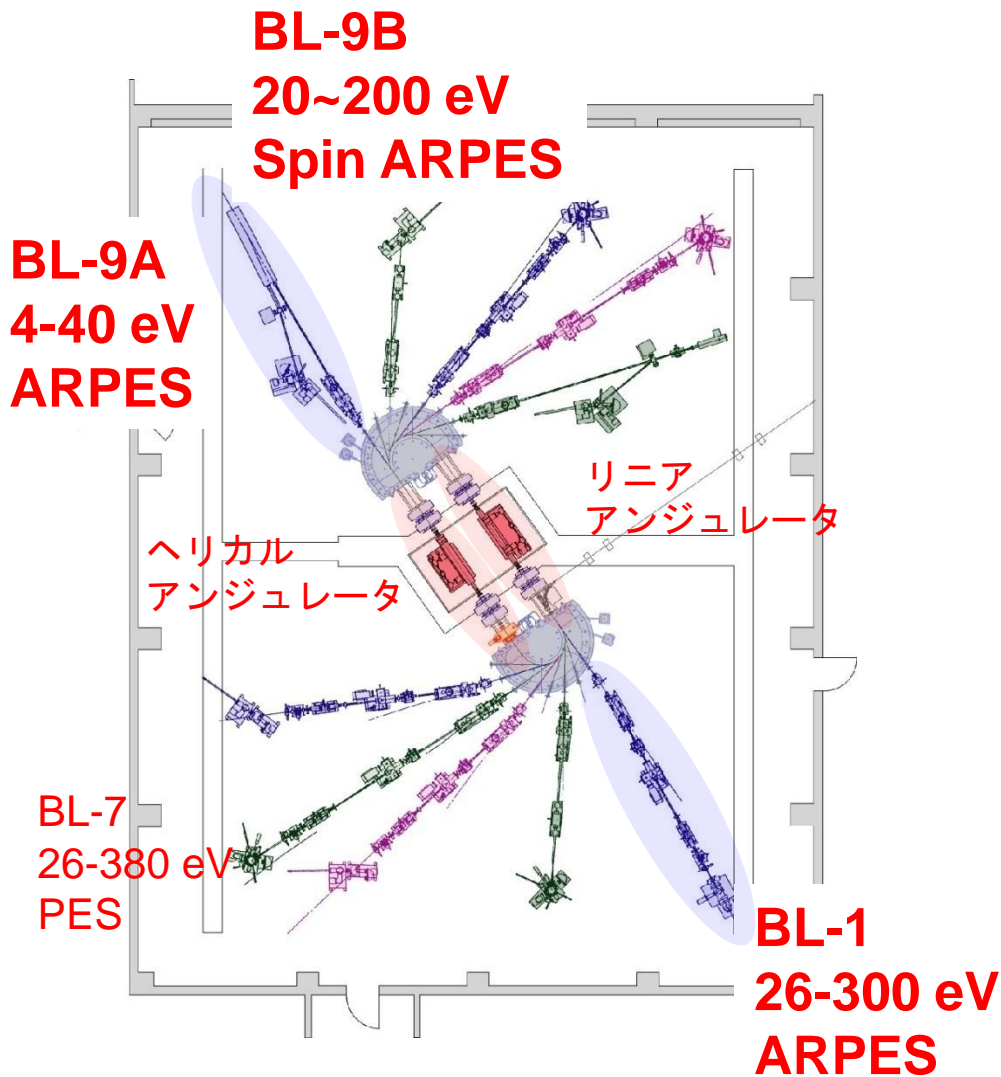
APS Synopses	2件
APS Editors Suggestions	2件
NPG Asia Materials highlights	1件
Nature Japann Nature Communications highlights	1件

※論文リストの詳細、海外からの申請課題の詳細、新聞報道等についてはウェブページ (<http://www.hsrb.hiroshima-u.ac.jp/>) を参照。

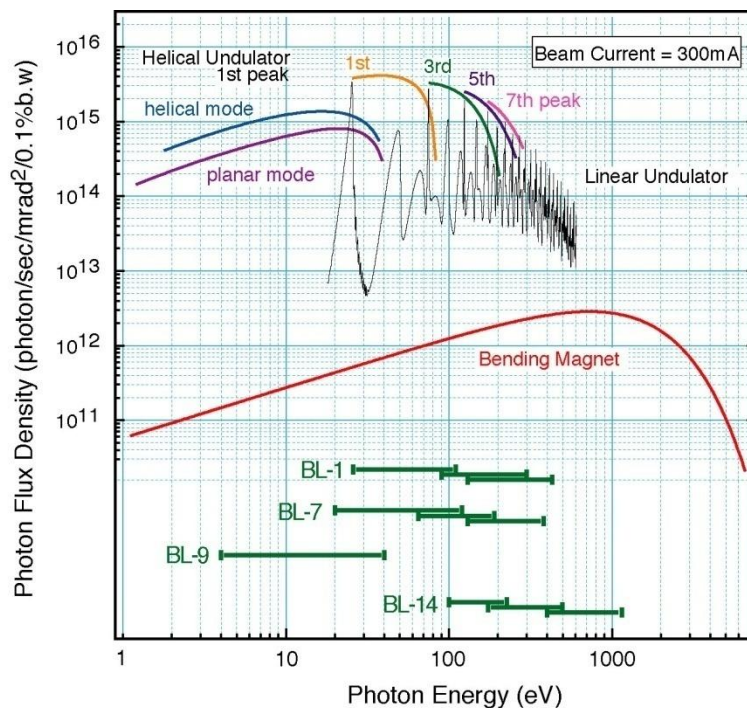


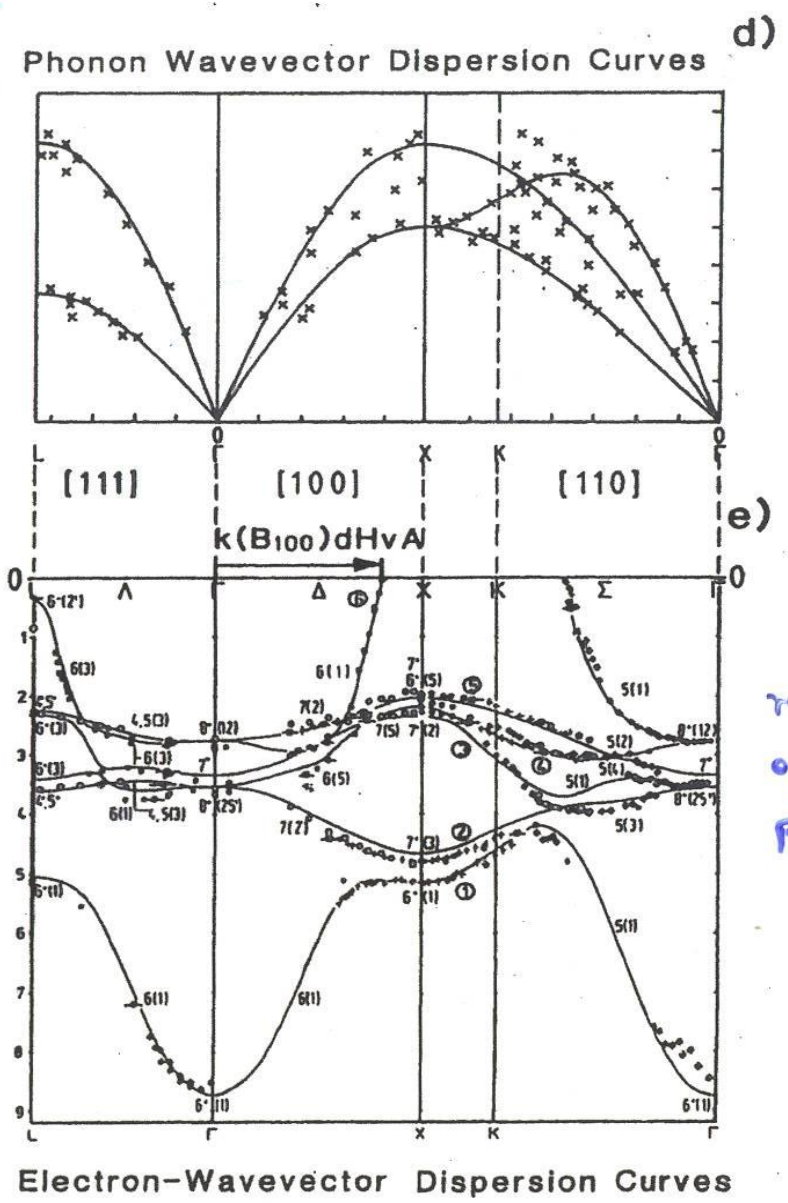
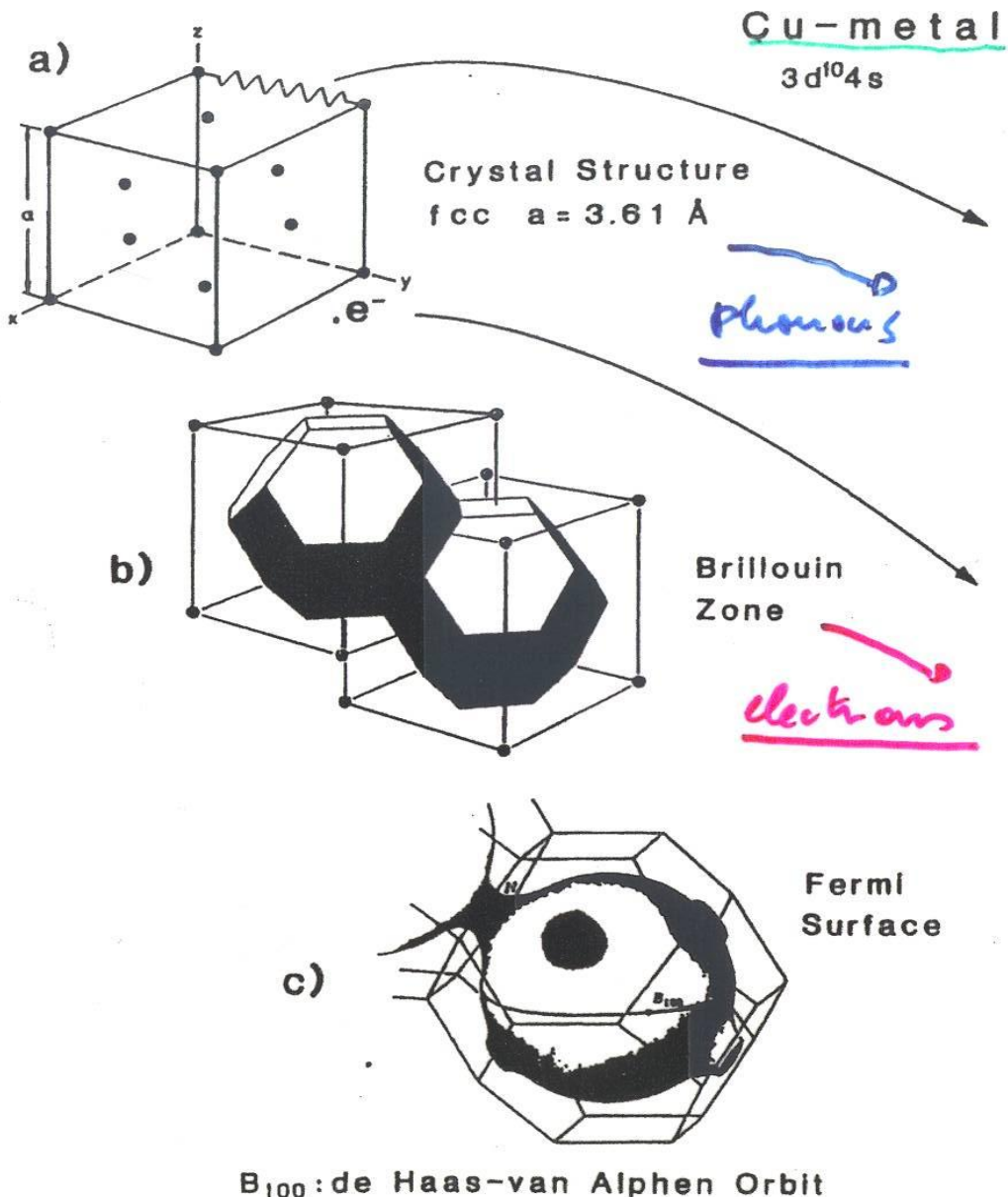
放射光を利用した物質科学研究

光電子分光 (PES)



700 MeV
最大蓄積電流: $I_b = 350$ mA





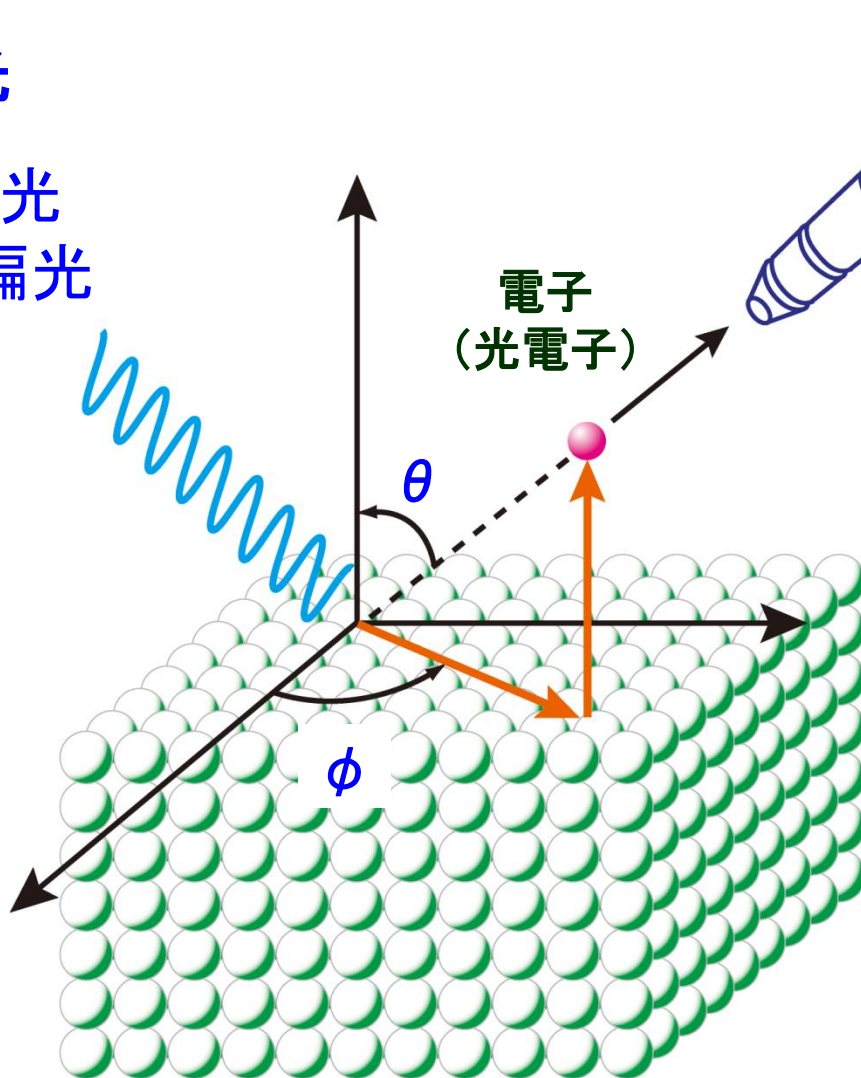
S. Huefner, Photoelectron Spectroscopy



角度分解光電子分光

放射光

直線偏光
左右円偏光



電子
(光電子)

電子のエネルギー
 E_k

電子エネルギー分析器

電子の放出角度
 θ, ϕ

5軸・6軸マニピュレータ
(iGONIO)



“Single-band” system Cu(110)

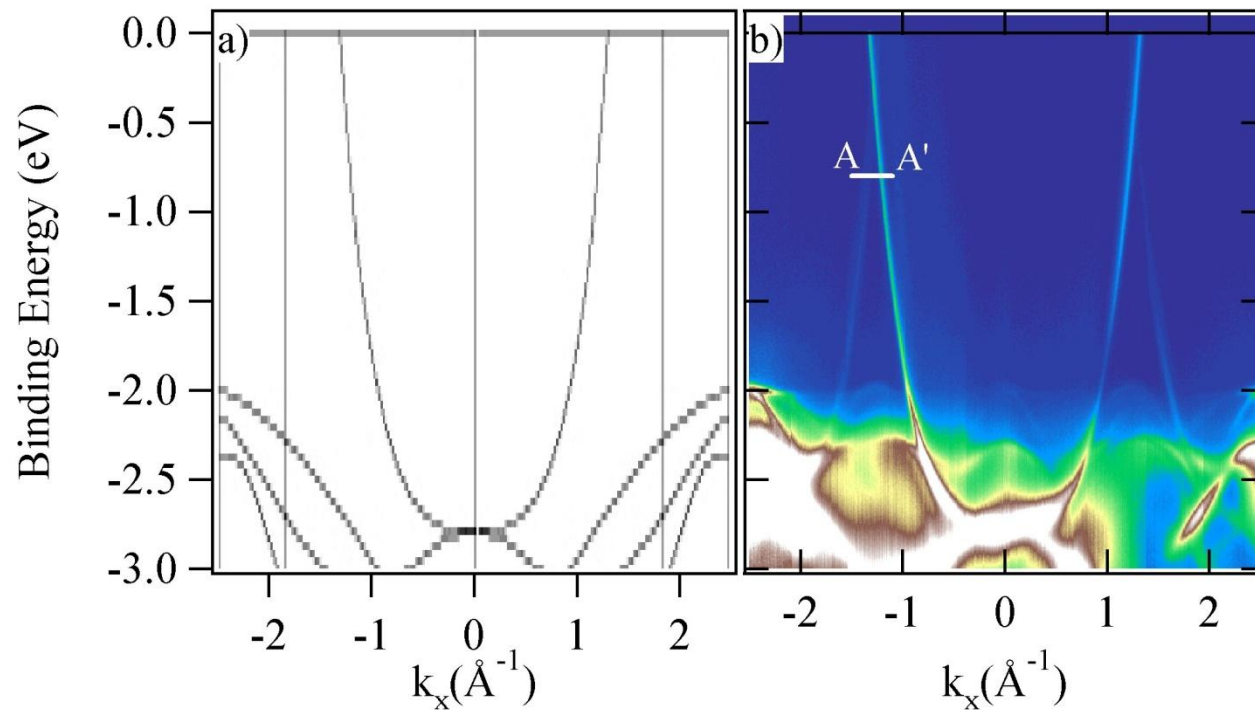
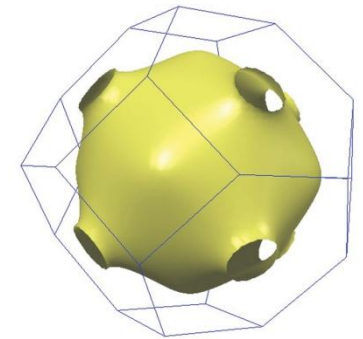
Γ -X direction

LDA calculation

ARPES

HiSOR BL-1

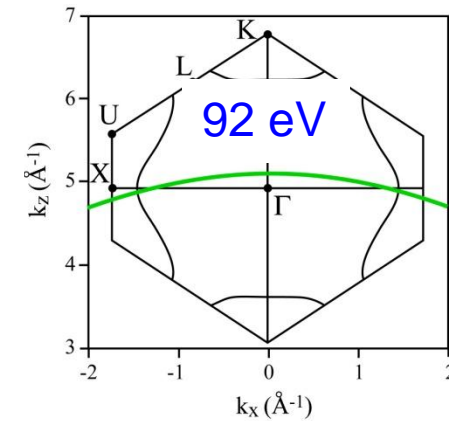
$h\nu=92$ eV



High



Low





Cu(110)

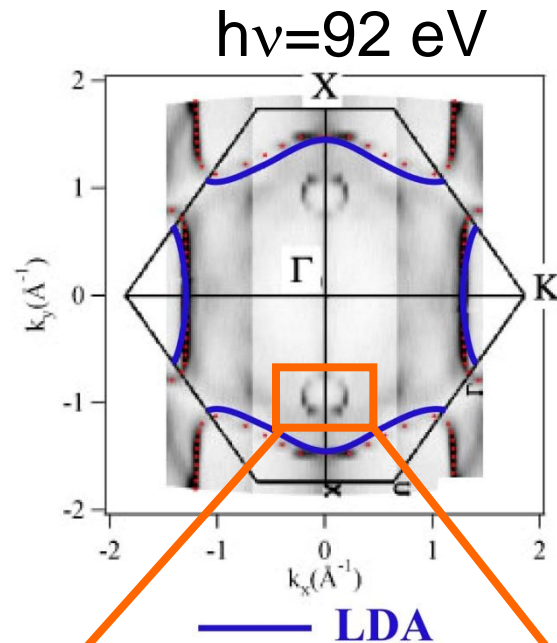
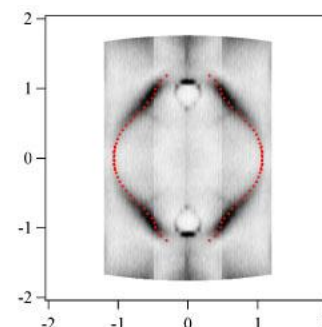
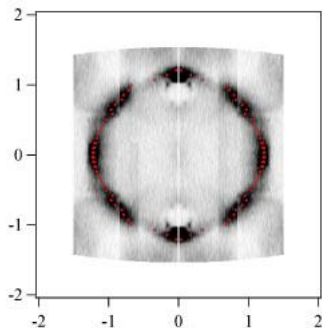
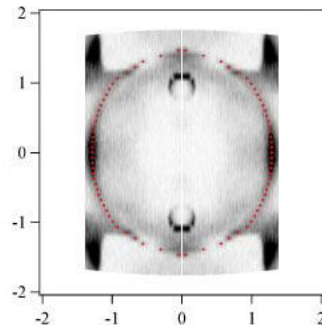
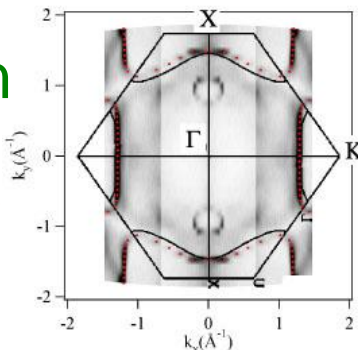
h ν scan

92 eV

82 eV

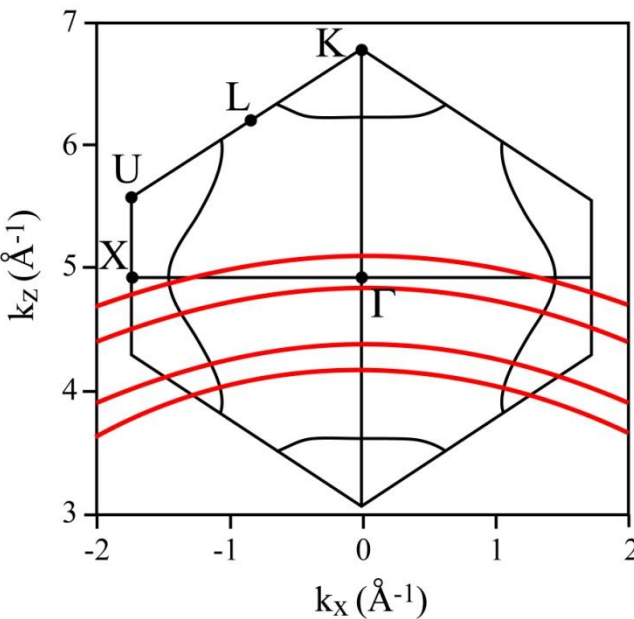
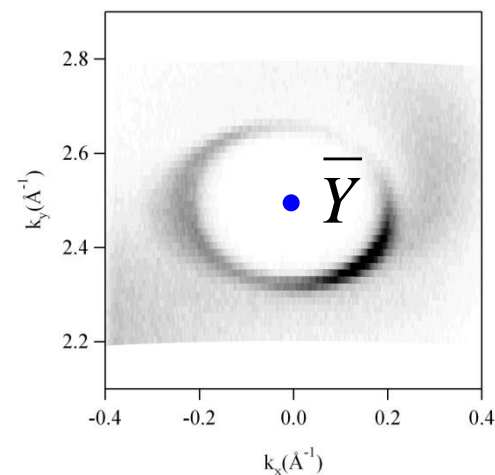
66 eV

59 eV



Shockley State
(surface state)

h ν =71 eV



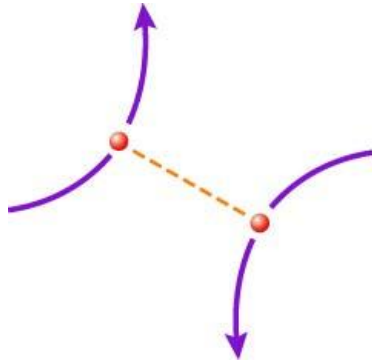
Bulk state

3D Fermi surface
mapping



Many-body interactions in Solids

characteristic energy scales

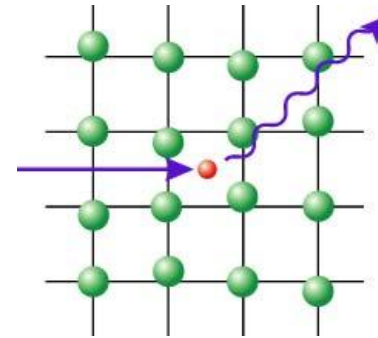


electron-electron
interaction

$$\Gamma_{el-el}$$

Beyond LDA
Electron correlation

Band width
~1 eV



electron-phonon
interaction

$$\Gamma_{el-ph}$$

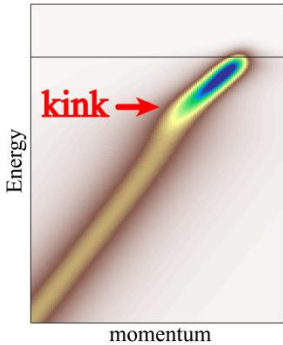
Debye energy
~0.01 eV

$$\Delta E = \frac{\hbar}{\tau} = \Gamma_{el-el} + \Gamma_{el-ph}$$



Lineshape analyses of ARPES spectra

Spectral function and self-energy

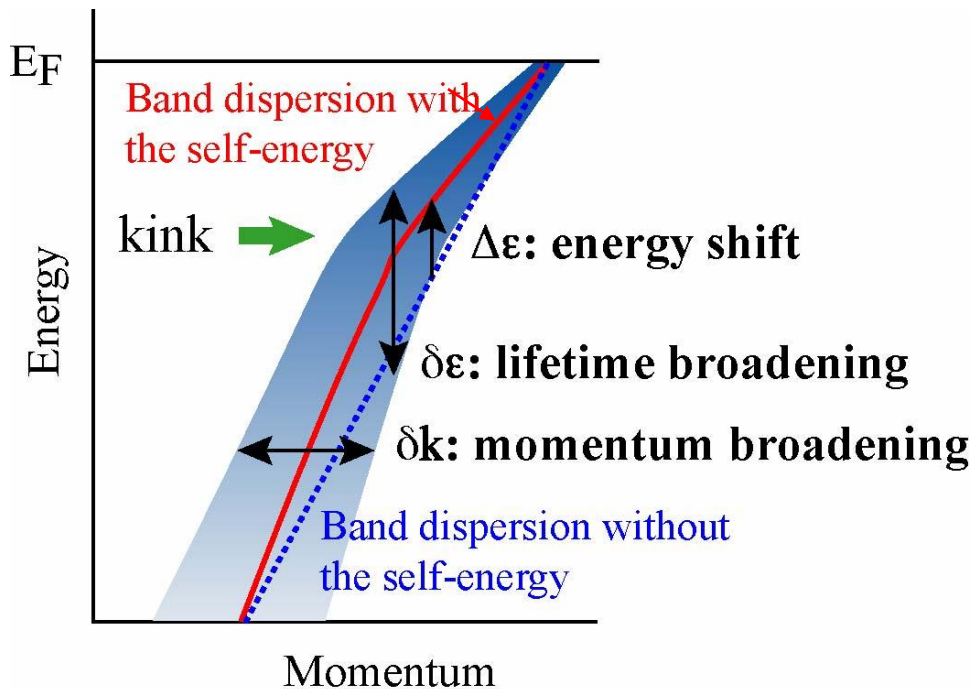


ARPES spectra



Spectral function

$$A_{\sigma}(k, \omega) = -\frac{1}{\pi} \frac{\text{Im} \Sigma_{\sigma}(k, \omega)}{[\omega - \varepsilon_k^{\sigma} - \text{Re} \Sigma_{\sigma}(k, \omega)]^2 + [\text{Im} \Sigma_{\sigma}(k, \omega)]^2}$$



Quasiparticle spectrum

Self-energy correction

Real part: $\text{Re}\Sigma$
Energy shift

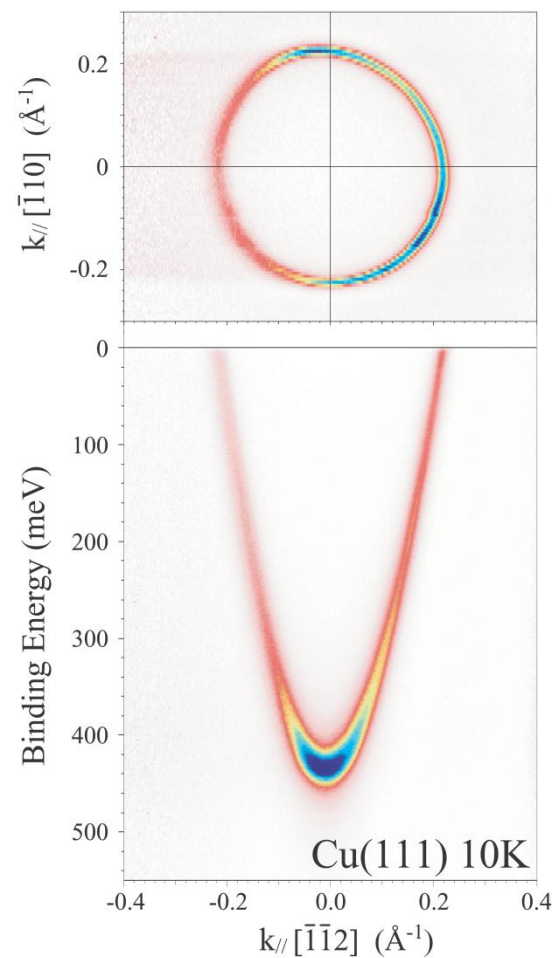
Imaginary part: $\text{Im}\Sigma$
Lifetime broadening



Shockley states in Cu(111)

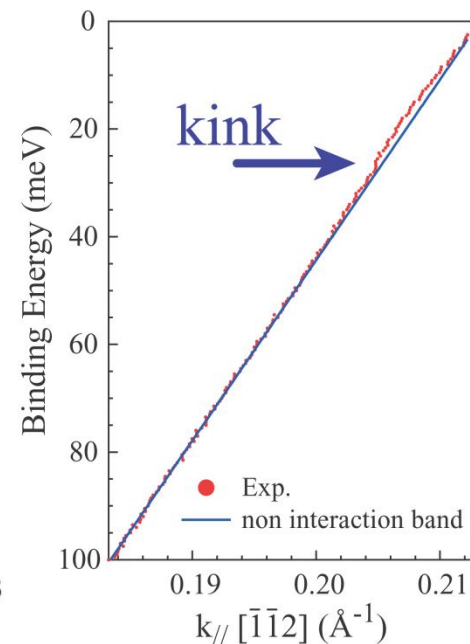
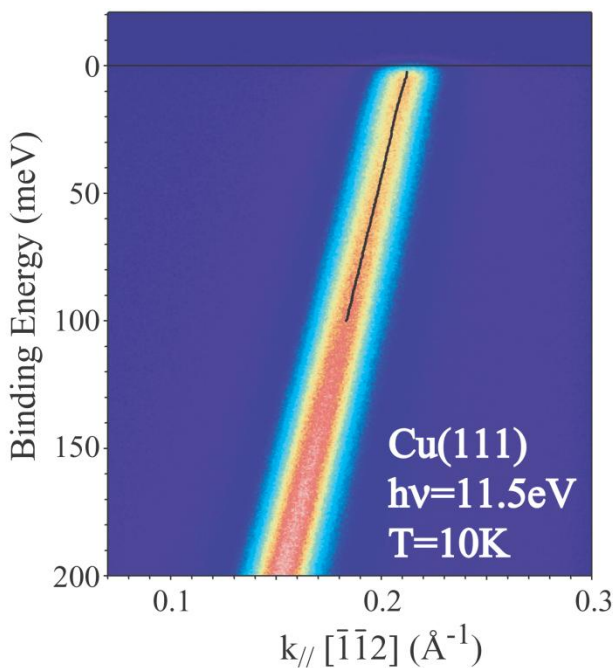
High-resolution ARPES with low-energy SR

Fermi surface



$h\nu=11.5$ eV, 10 K
 $\Delta E=4$ meV, $\Delta k=0.007$ Å⁻¹

Band dispersion near E_F



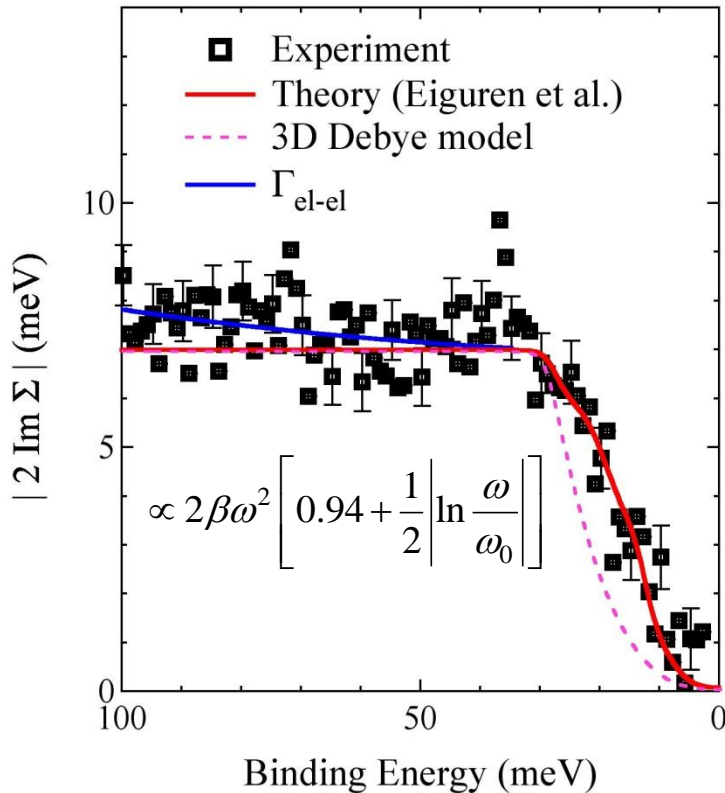
- kink structure at ~ 25 meV
- Debye temperature $\Theta_D=343$ K, $k_B\Theta_D=29.5$ meV (bulk)

$$\omega_0 = 433 \pm 5 \text{ meV}$$



Shockley states in Cu(111)

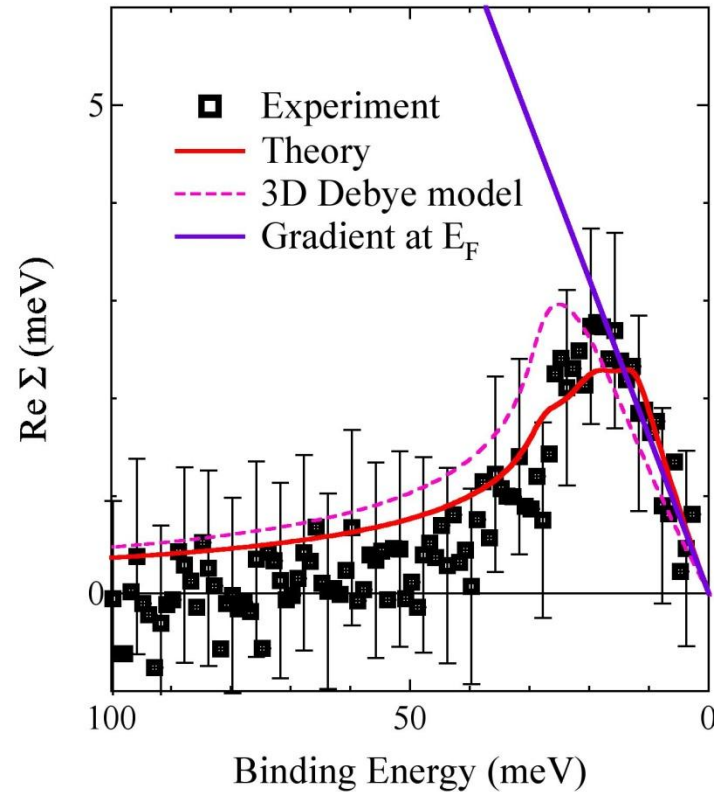
Self-energy



Electron-electron interaction:

$$2\beta = 0.09 \pm 0.01 \text{ (eV}^{-1}\text{)}$$

→ $\lambda_{\text{el-el}} \sim \beta \omega_0 = 0.02$
 K-K



Electron-phonon interaction:

$$\lambda_{\text{el-ph}} = 0.16 \pm 0.01$$

Theoretical value (Eiguren et al.) $\lambda = 0.16$

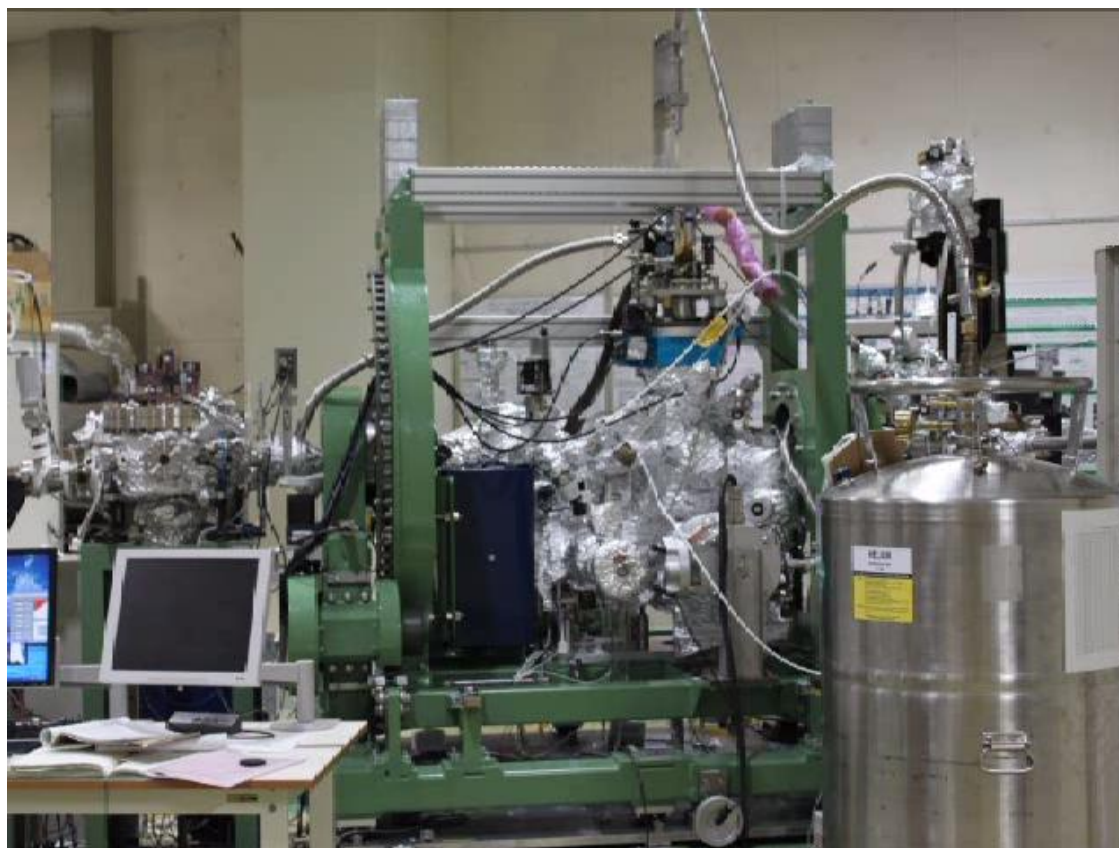
直線偏光
放射光

高分解能


試料の多軸
方位制御

放射光の
偏光制御

直線偏光放射光を活用した 高分解能角度分解光電子分光装置



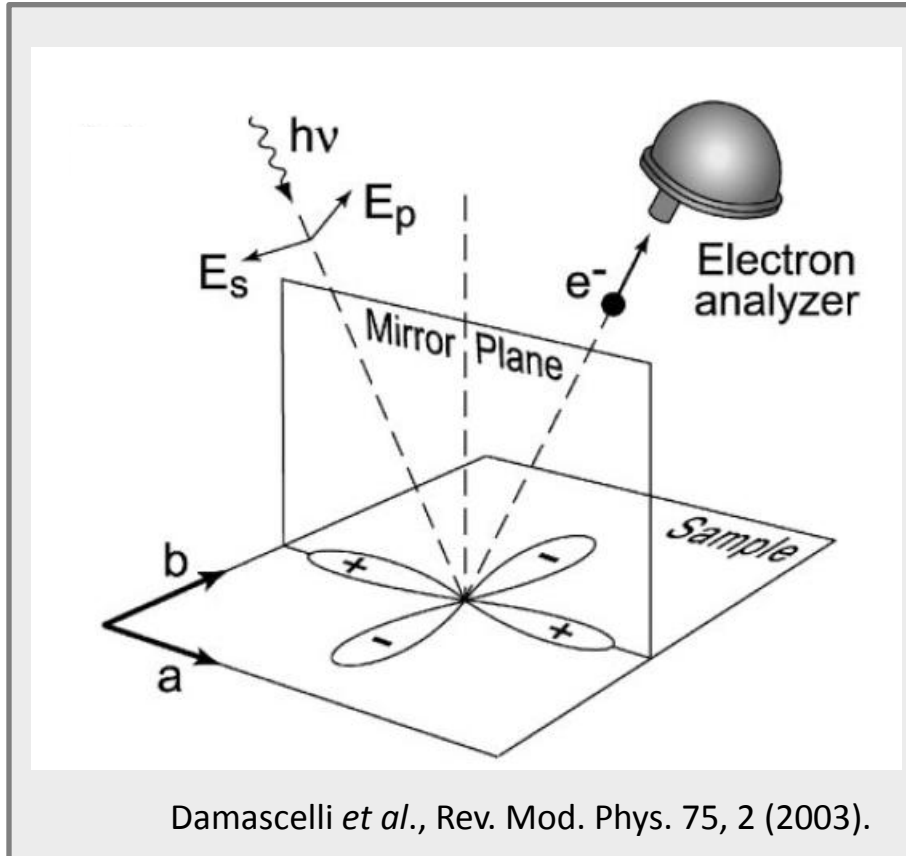
HiSOR BL-1

 広島大学


National Institute of
Advanced Industrial Science
and Technology
AIST



Dipole selection rule for transition



Matrix Element

$$M_{fi} \equiv \langle f | \mathbf{A} \cdot \mathbf{p} | i \rangle \quad |i\rangle : \text{initial state}$$

Symmetry with respect to the mirror plane

$|f\rangle$: final state \rightarrow Even

(1) p-polarization $\mathbf{A} \cdot \mathbf{p}$: Even

$$M_{fi} \begin{cases} \neq 0 & |i\rangle : \text{Even} \\ = 0 & |i\rangle : \text{Odd} \end{cases}$$

(2) s-polarization $\mathbf{A} \cdot \mathbf{p}$: Odd

$$M_{fi} \begin{cases} \neq 0 & |i\rangle : \text{Odd} \\ = 0 & |i\rangle : \text{Even} \end{cases}$$

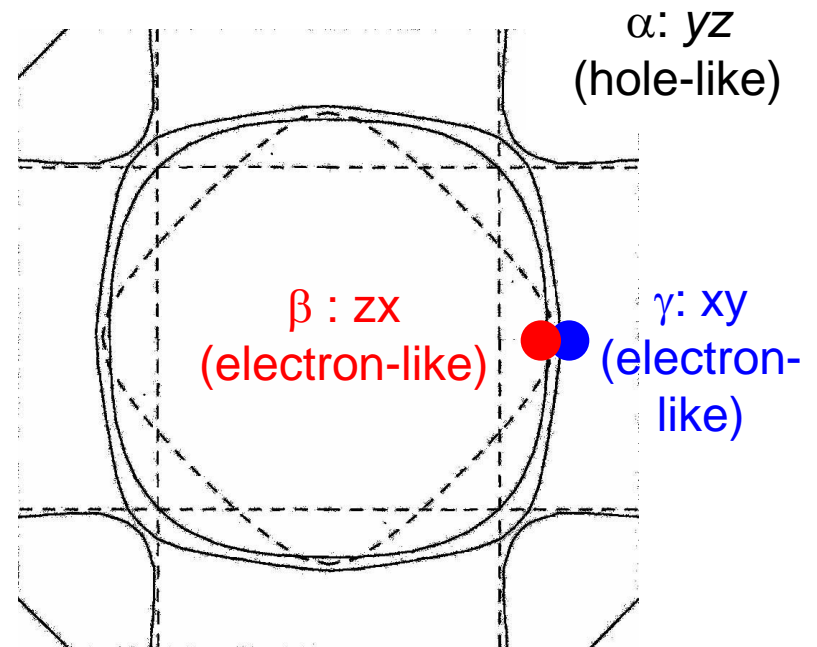
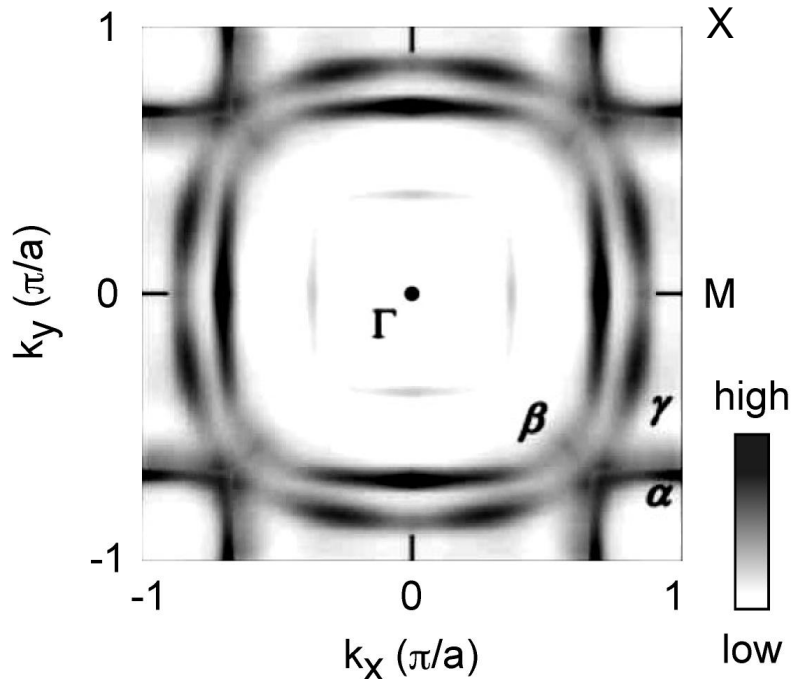
By switching linear polarization, we can select observable initial states.



Layered superconductor Sr_2RuO_4

Circular polarization
(KEK-PF BL-28)

$h\nu=65$ eV



H. Iwasawa et al. Phys. Rev. B 72 (2005)
104514.

LDA calculation
T. Oguchi, Phys. Rev. B 51 (1995)
1385.

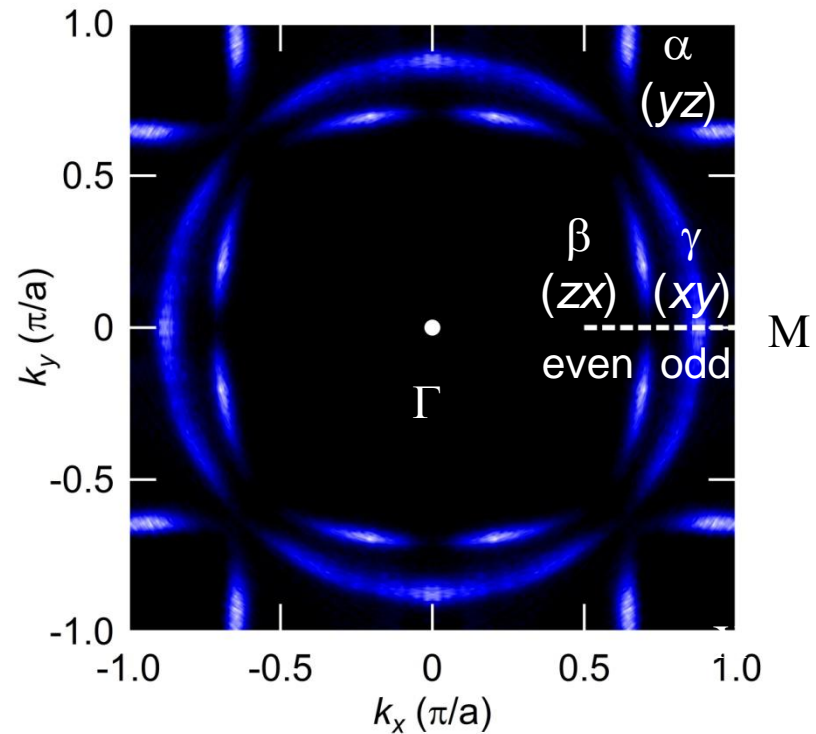
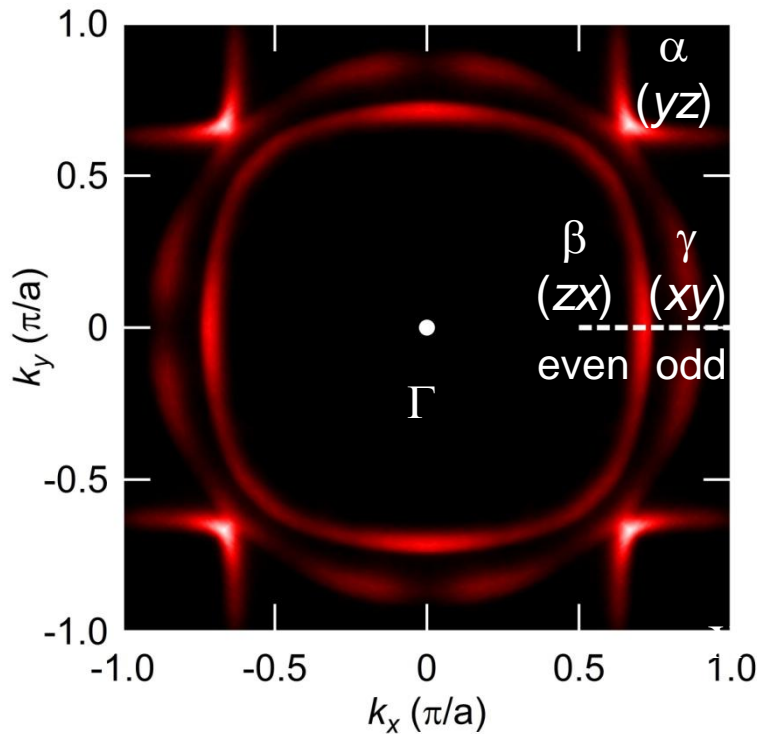


Polarization dependent Fermi surface mapping Sr_2RuO_4 (HiSOR BL-1)

p-polarization
(even)

$h\nu=65$ eV

s-polarization
(odd)

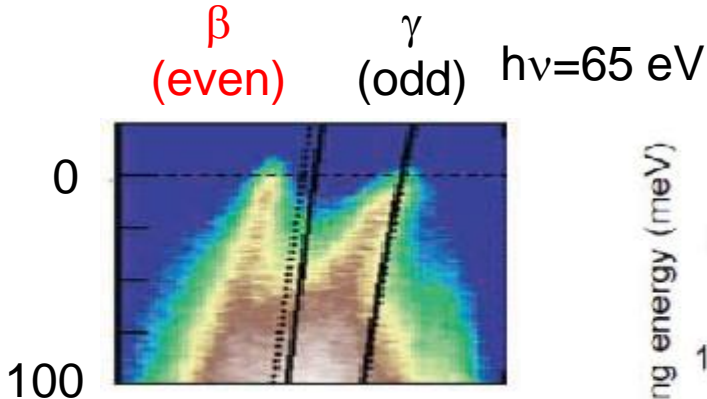


Spectral weight strongly depends on the polarization



Band dispersion along ΓM direction

circular polarization
(PF BL28)

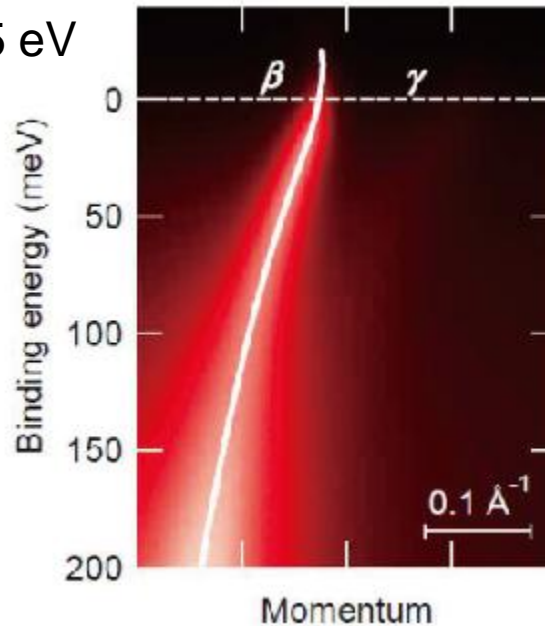


H. Iwasawa et al.
 Phys. Rev. B 72 (2005)
 104514.
 Black lines indicate
 calculated
 energy-band dispersions.

Selective observation of the electronic states.
 An effective method to study multi-band systems

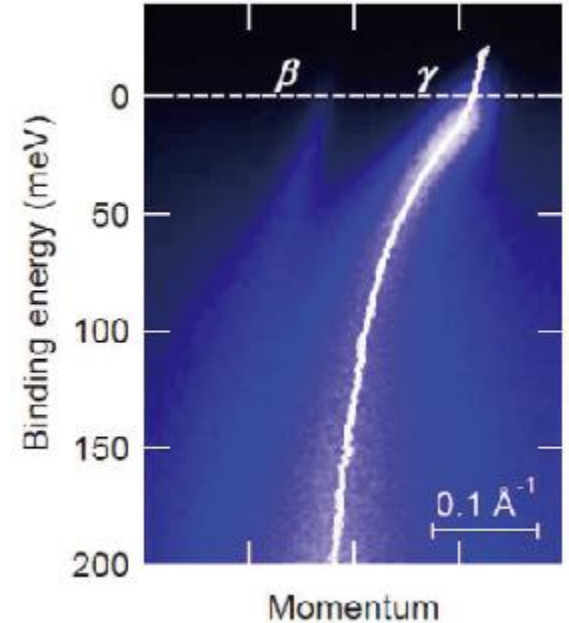
p-polarization

β : zx (even)



s-polarization

γ : xy(odd)

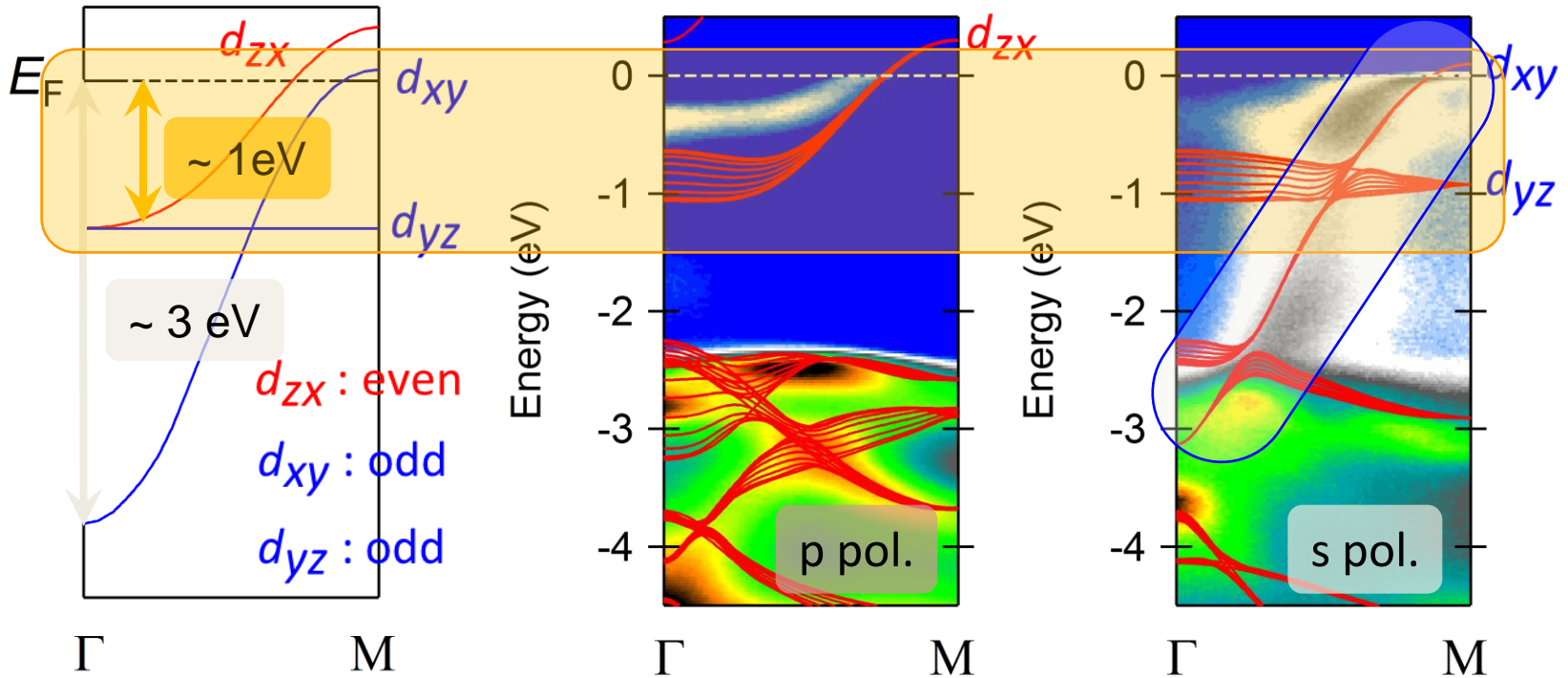


Self-energy analysis is now possible!

Iwasawa and Aiura et al. PRL (2010).



Wide electronic structure : Γ M line



- Narrow 1D bands (α, β)

$$W_{zx, yz} \text{ (LDA)} \sim 1 \text{ eV}$$



$$W_{zx, yz} \text{ (ARPES)} \sim 0.3\text{-}0.4 \text{ eV}$$

- Wide 2D band (γ)

$$W_{xy} \text{ (LDA)} \sim 3 \text{ eV}$$

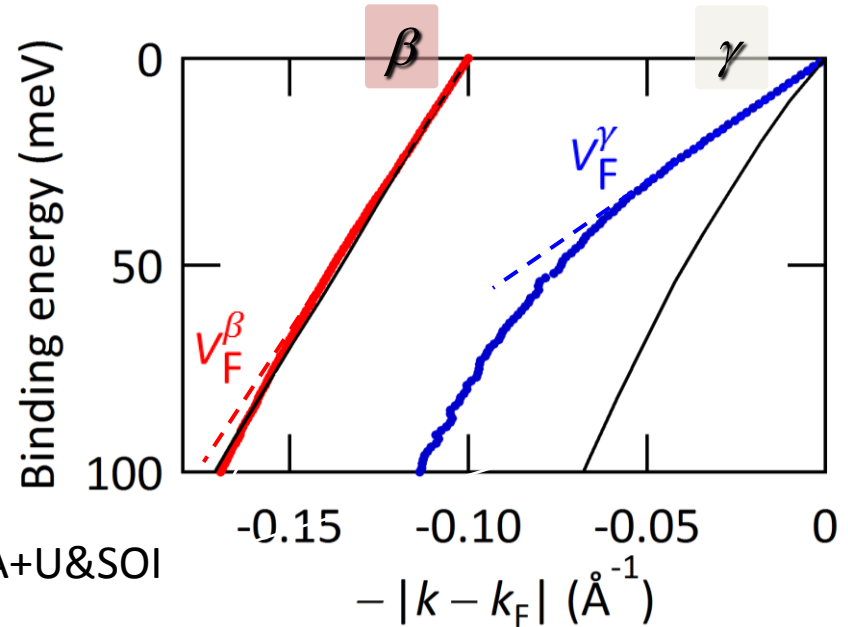
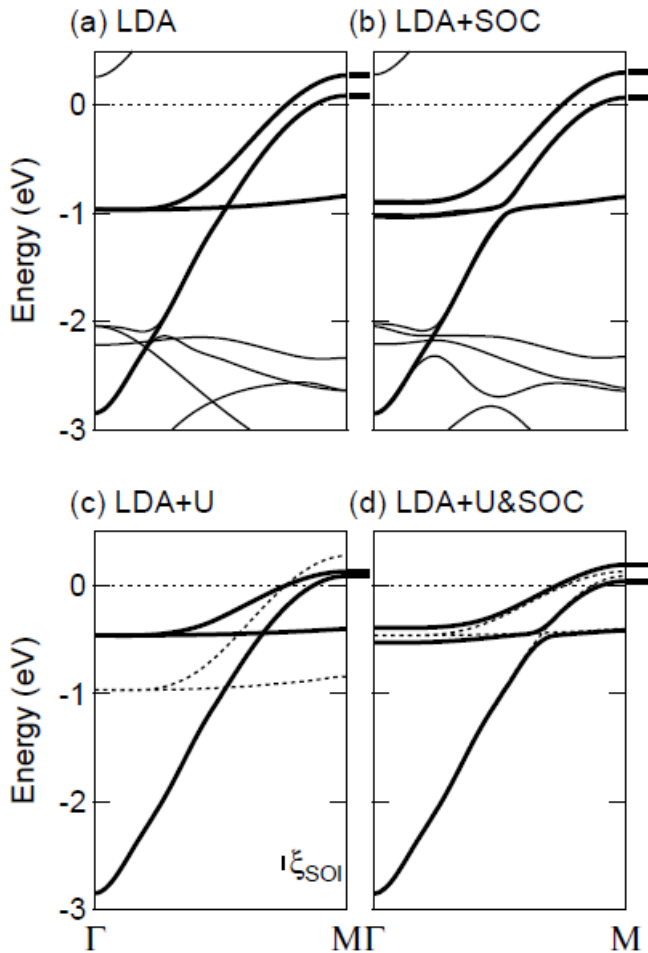


$$W_{xy} \text{ (ARPES)} \sim 3 \text{ eV}$$



FS dependent electron-boson interaction

Comparison between ARPES and model calculations



LDA+U&SOI

- FS dependent electron boson interaction (EBI)

β : very tiny

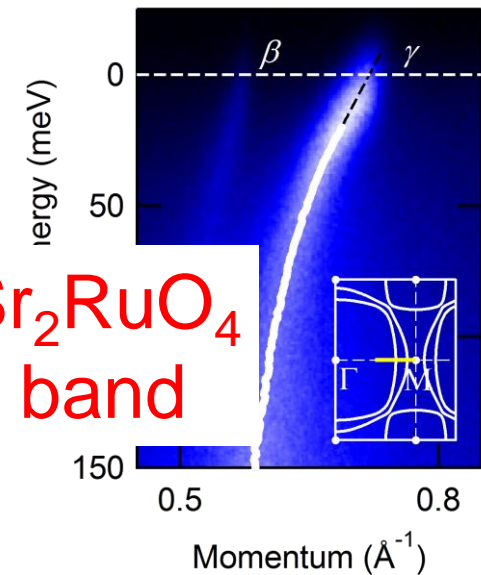
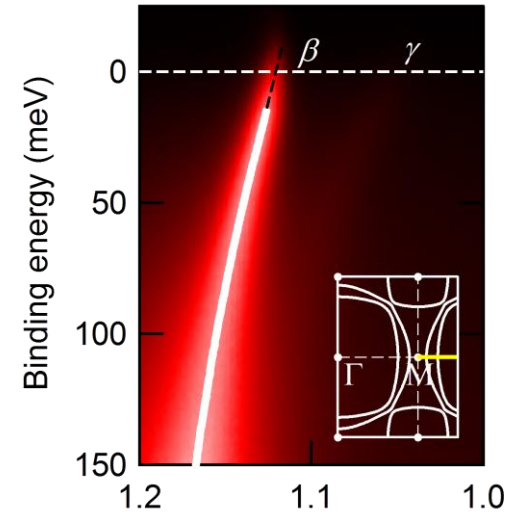
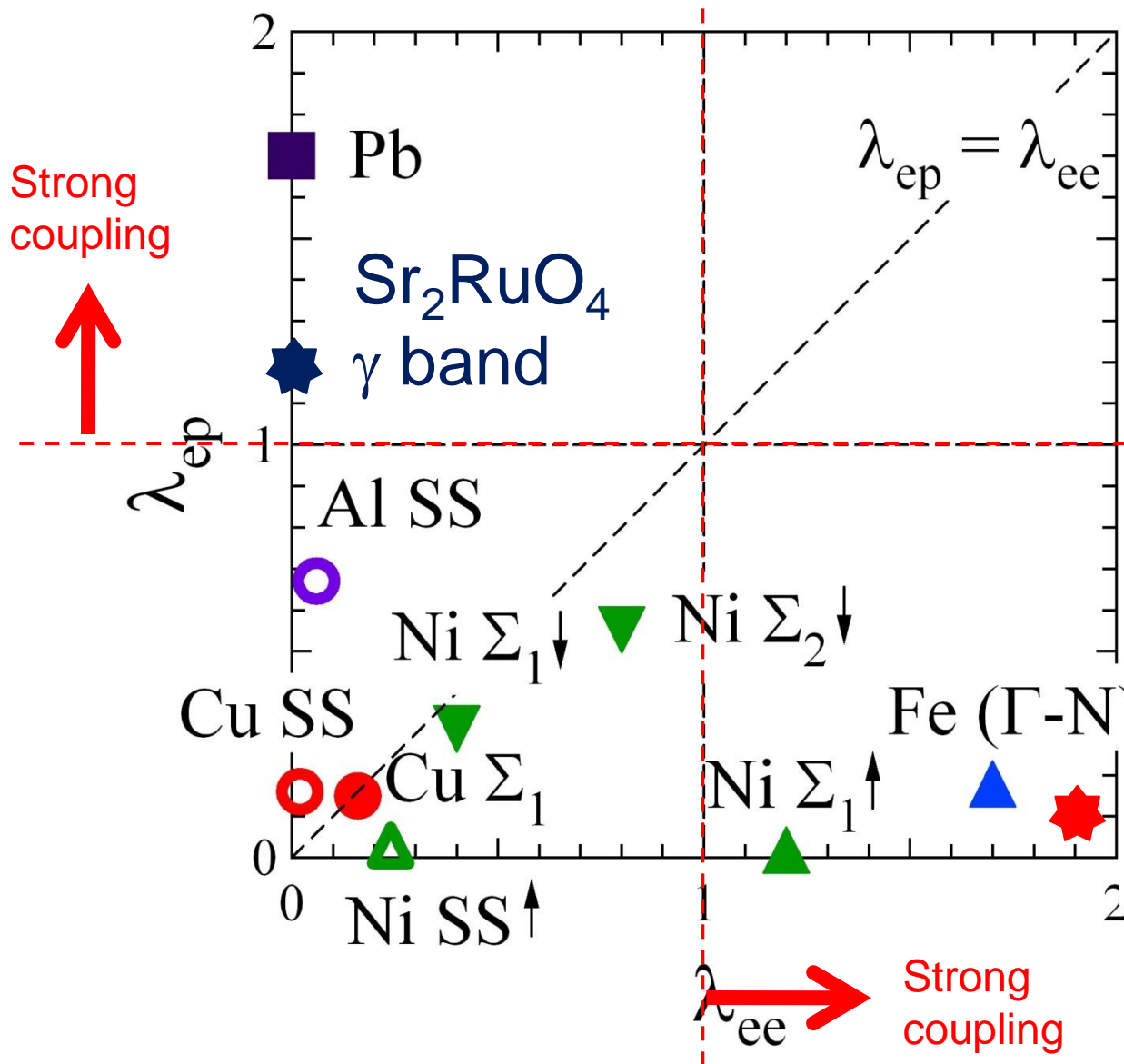
γ : significant

- Coupling parameter of EBI

$$\lambda^\beta \sim 0.1 \pm 0.01 \quad \lambda^\gamma \sim 1.3 \pm 0.1$$



Electron-phonon and electron-electron coupling parameters



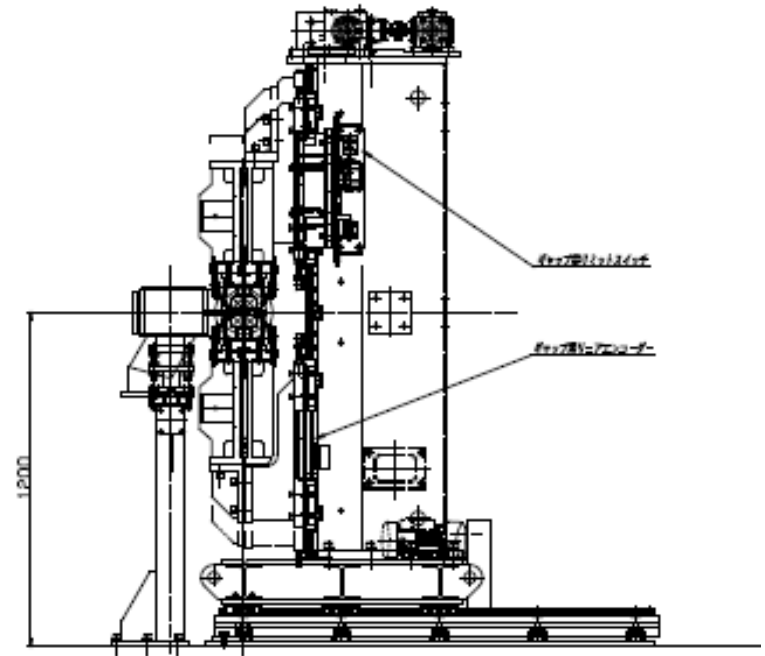
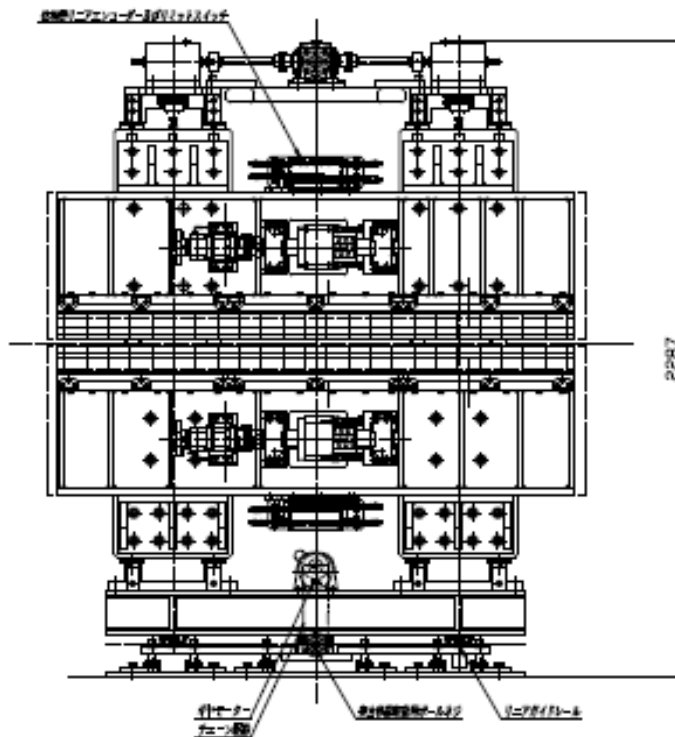
Sr_2RuO_4
 β band



ヘリカルアンジュレータの更新 (BL-9A, B) (準周期APPLE型可変偏光アンジュレーター)

平成23年8月～

HiSOR APPLE-Undulator Drawings





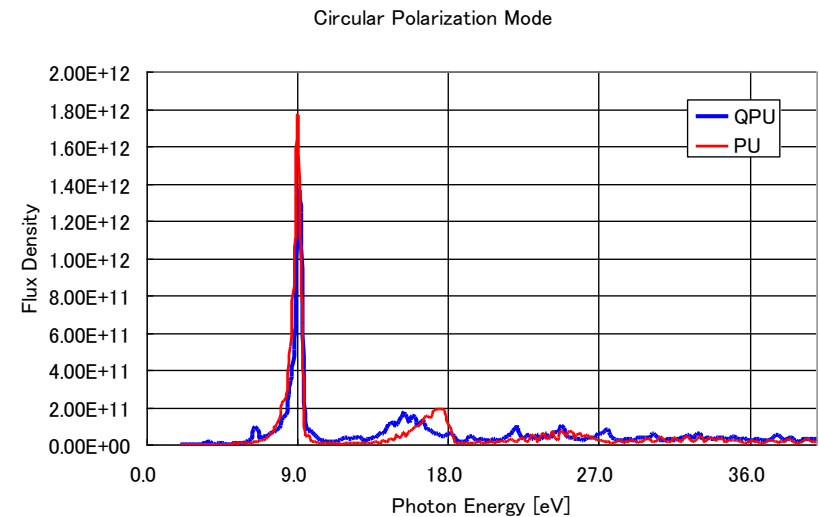
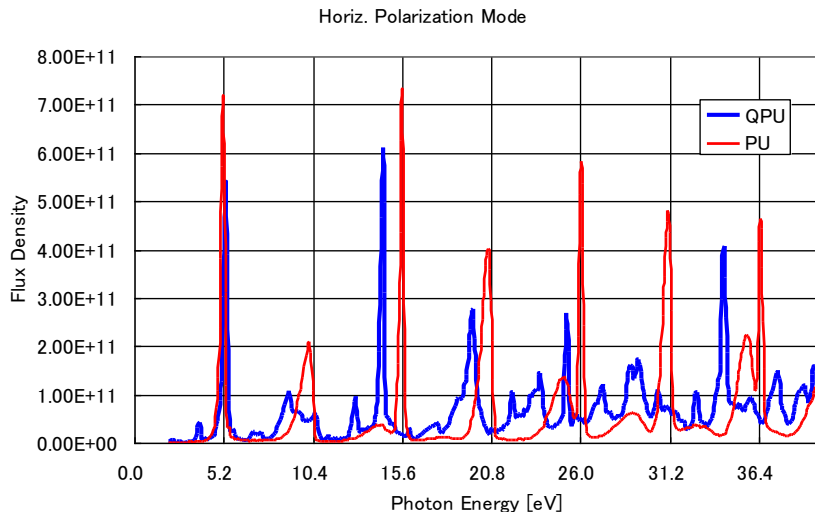
準周期APPLE型可変偏光アンジュレータ

性能

磁場周期長: 78 mm 磁場周期数: 23 全長: 約1.8 m
最小ギャップ: 22 mm 最小光子エネルギー: 全てのモードで6 eV

左右円偏光、垂直・水平直線偏光

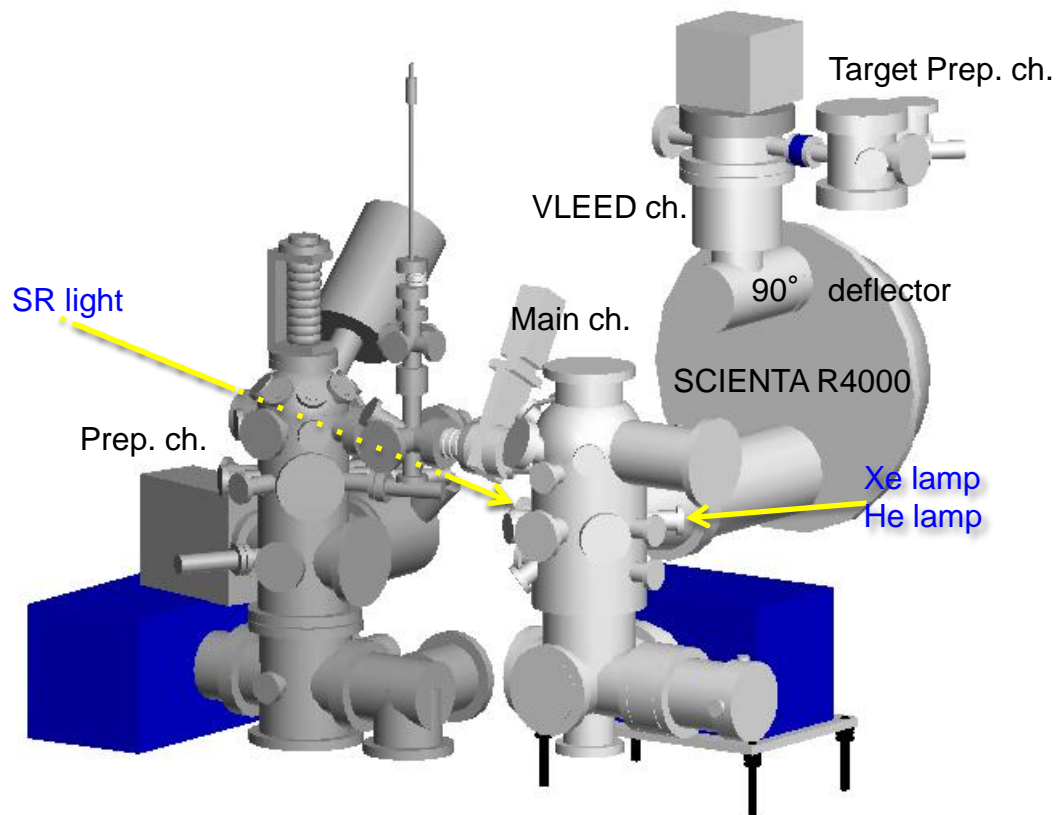
必要に応じて準周期と周期アンジュレータモードに変更可能





Spin ARPES @HiSOR BL-9B

Efficient SPin REsolved Spectroscopy
Observation (ESPRESSO) machine



Analyzer (SCIENTIA R4000)
 $\Delta E = 1 \text{ meV}$ ($E_p = 2 \text{ eV}$), $\Delta\theta = \pm 0.1^\circ$

Manipulator (i-gonio)
 $T_{min} \sim 10 \text{ K}$
polar & tilt rotatable (motor drive)

Spin (VLEED)
Transverse and Perpendicular

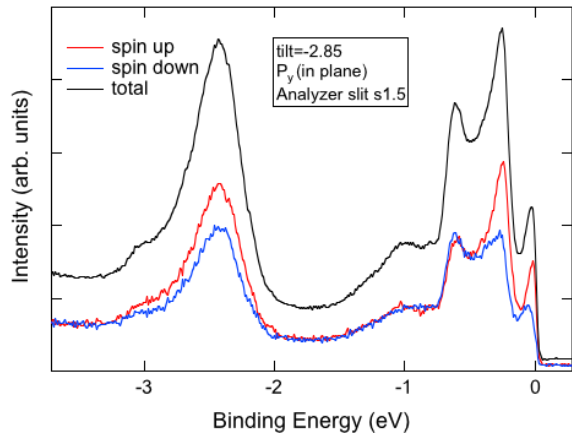
Light sources
Xe lamp (8.9 eV),
He lamp (21.2 eV)
SR from BL-9B (16-300 eV)

2D high resolution ARPES can be performed simultaneously.
SR-FS mapping can be done with i-gonio manipulator
Goal: SARPES with $\Delta E < 10 \text{ meV}$ and $\Delta\theta < \pm 0.5^\circ$



First data by ESPRESSO-H

Spin resolution

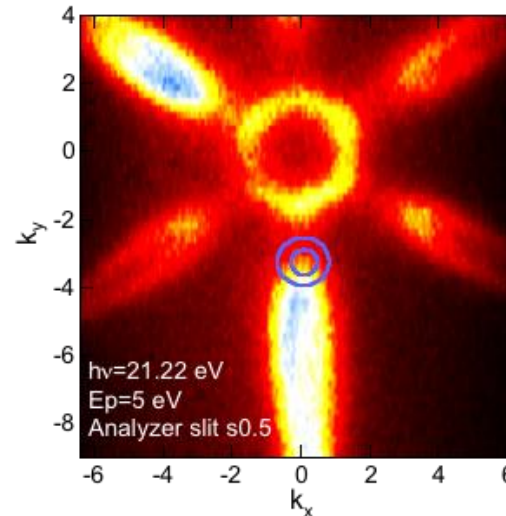
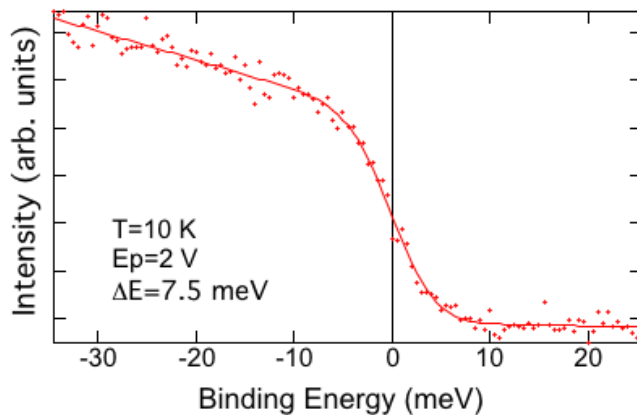


Both high energy and angular resolutions

$$\Delta E < 8 \text{ meV}$$
$$\Delta \theta \sim \pm 0.375^\circ$$

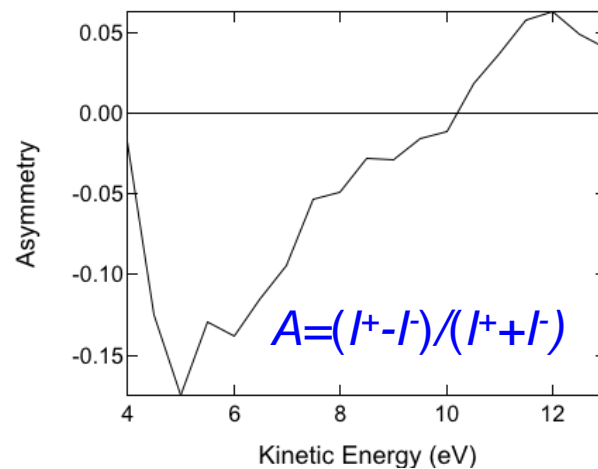
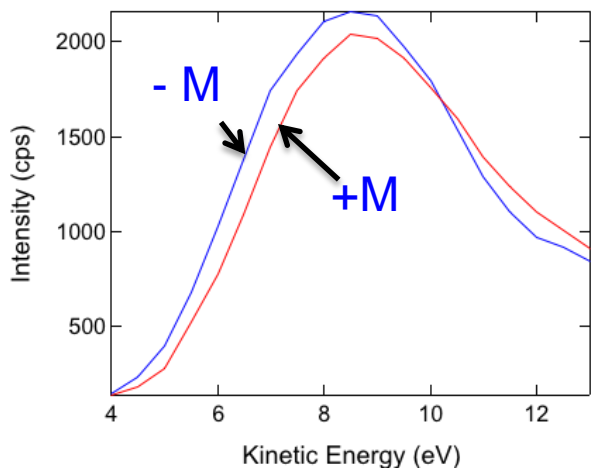
have been achieved.

Energy and Angular resolutions

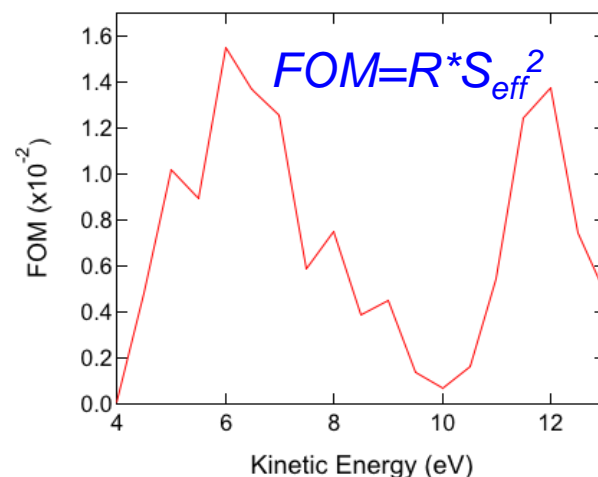
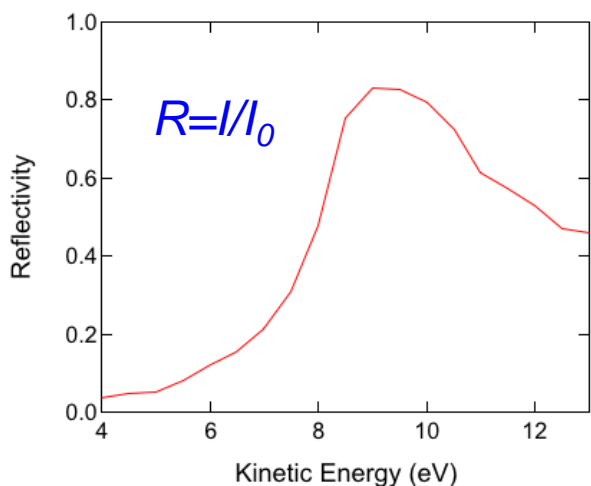




Estimation of Figure of Merit

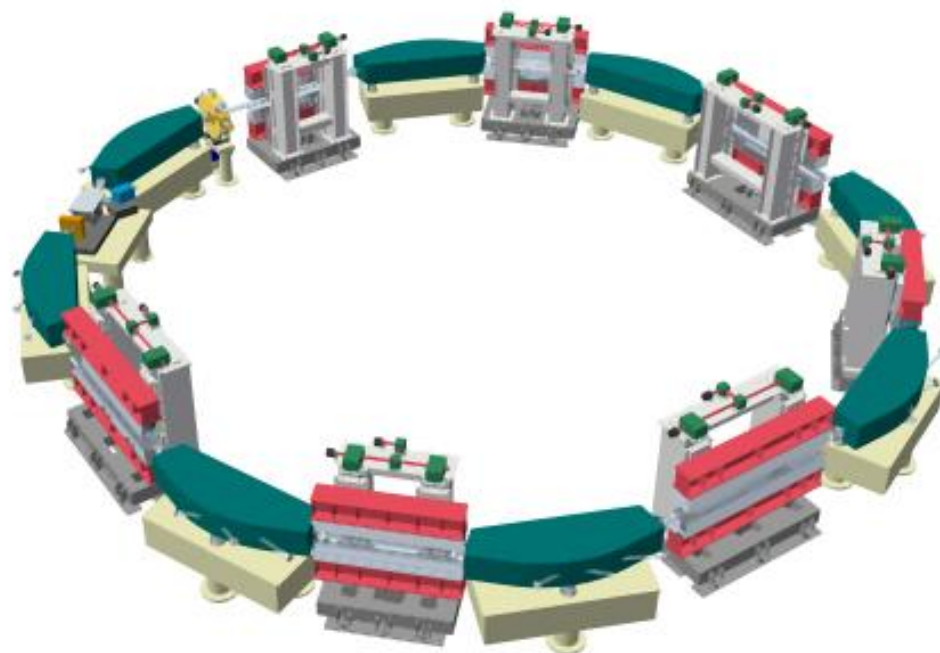


$S_{eff} \sim 0.4$



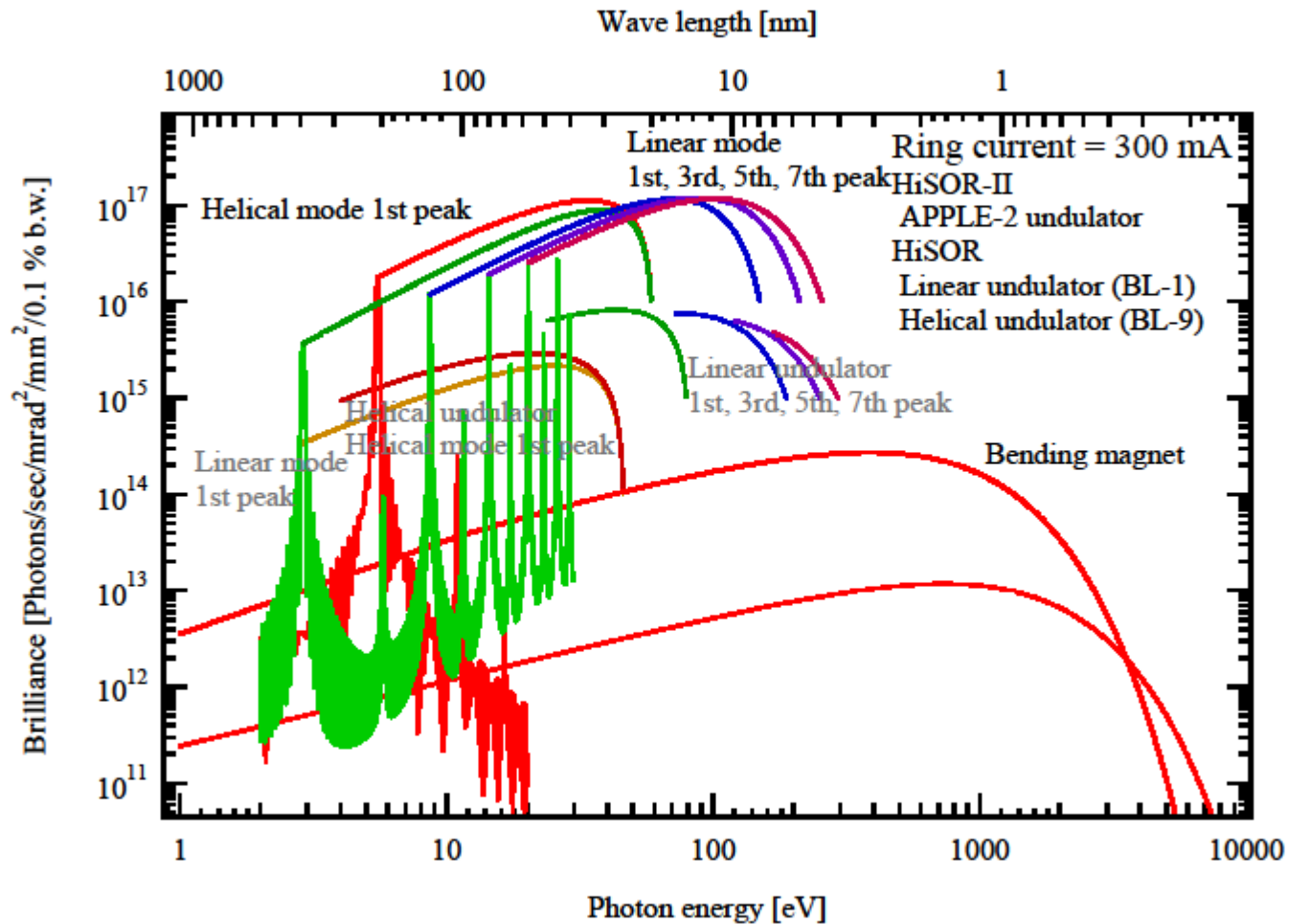
$FOM \sim 1.6 \times 10^{-2}$

Beam energy [MeV]	700
Circumference [m]	40.079
Betatron tune	3.761, 2.846
Natural emittance [nmrad]	13.57
Momentum spread	5.79e-04
Momentum compaction	0.0319
Bunch length [mm]	37.0
Harmonic number	7
RF frequency [MHz]	52.4
Radiation dumping time [msec]	L:11.44 H: 8.57 V:14.70
Touschek lifetime [hour]	2.7
Straight sections	3.4 m × 4 2.0 m × 4





HiSOR II





小型光源リングの限界？

1. 到達可能なエミッタンスに限界がある (MAX III が世界最高レベル？)
2. アンジュレーターを挿入出来る直線部の数が限られている
3. 周長が短いため、シングルバンチ運転をしても、放射光パルス到達時間間隔が短すぎる (例: 40 m のリングで 133 nsec, 7.5 MHz)

たとえば、ARTOF Photoelectron Spectroscopy の実験が出来ない



新たな可能性の追求

新しいアイデア

佐々木茂美、宮本篤

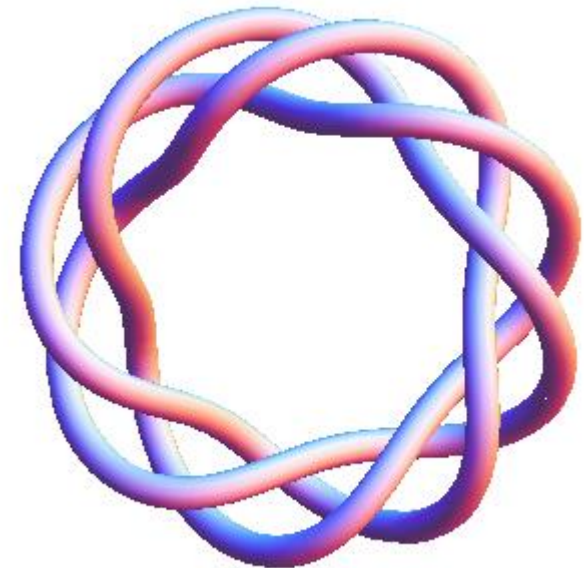
- ビーム軌道がリング一周で閉じず、数回廻って閉じるような構造はないか？

答はある！

たとえば、メビウスの輪



あるいはトーラスの結び目

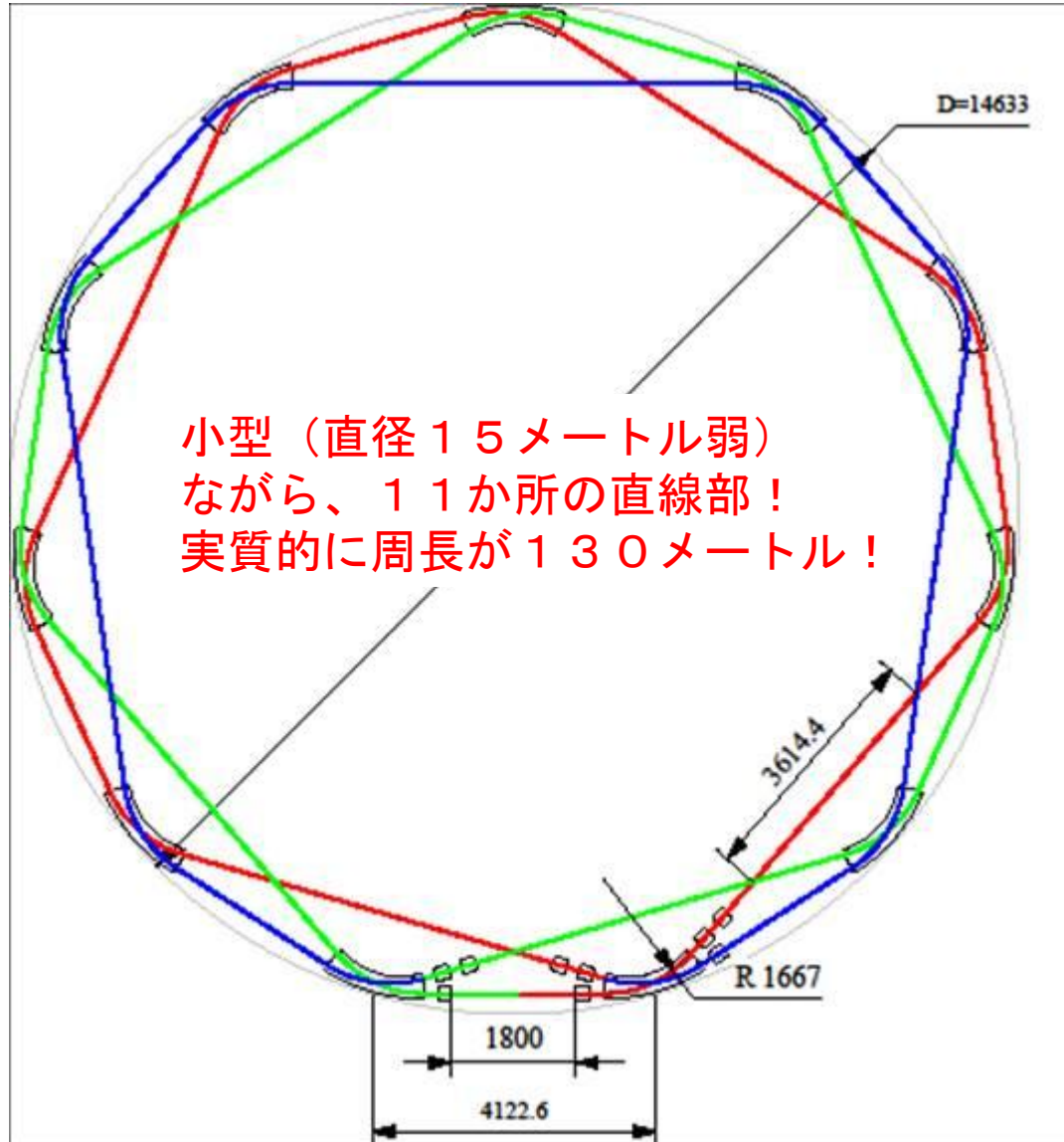


実際のリングは水平の二次元平面に乗っているので、トーラスの結び目を平面に投影する。

HiSOR II+ラティスの例

11角形の
ラティス

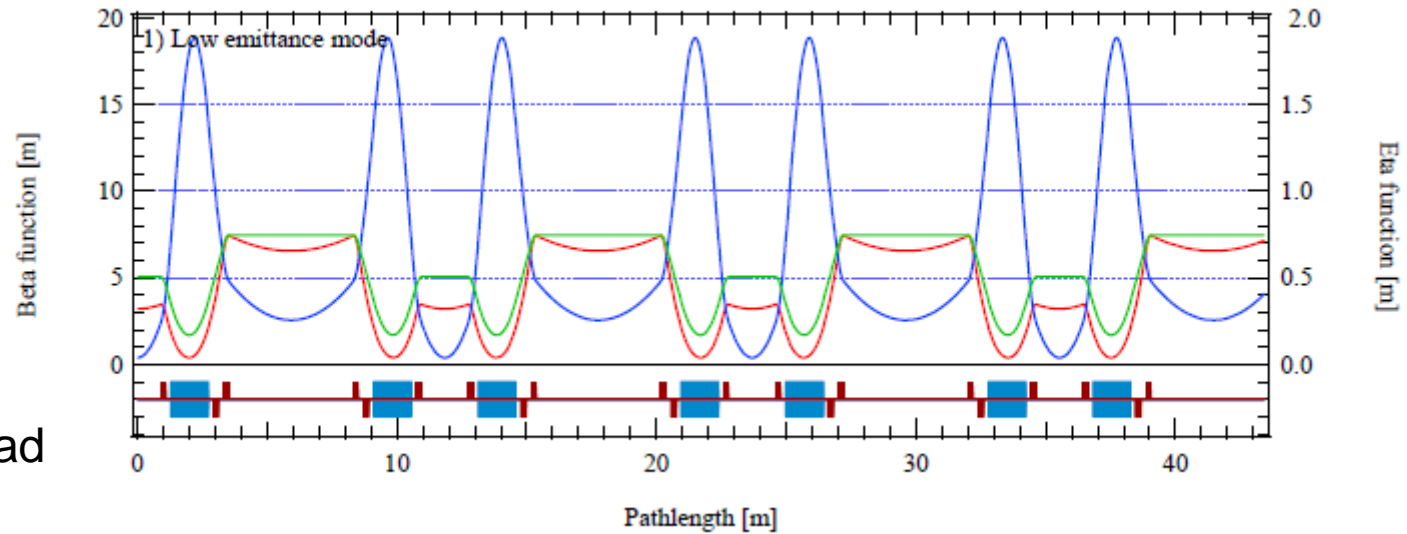
3回廻って
元に戻る



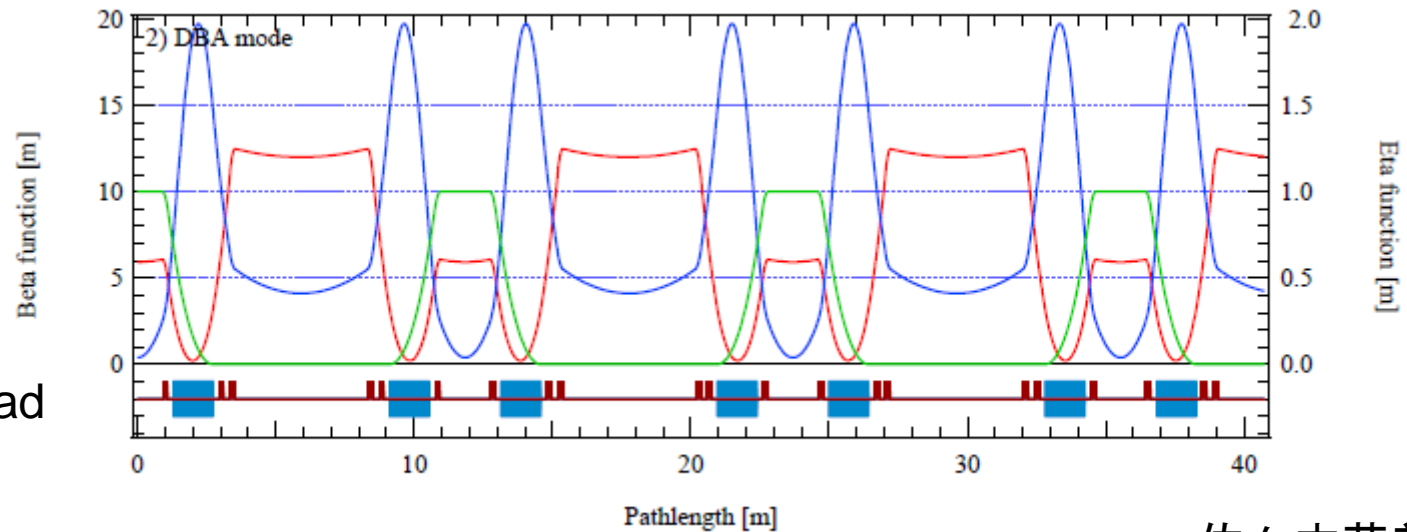
電子軌道の全長
130.3 m
一周の距離
43.4 m



電子ビーム光学



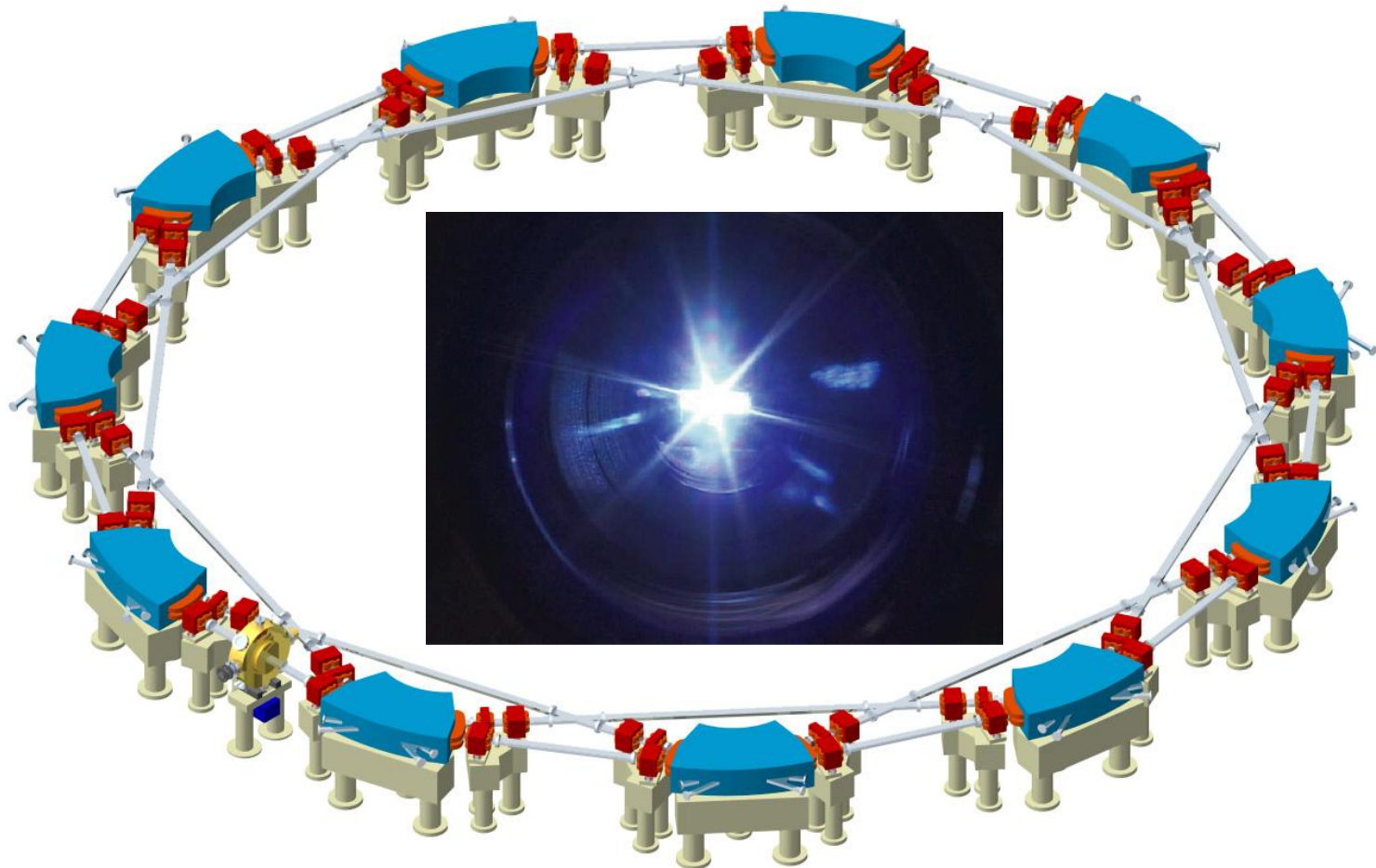
$\varepsilon_0 = 17.7$ nmrاد



$\varepsilon_0 = 34.6$ nmrاد



新しい小型高輝度VUV光源による 固体電子状態の超精密解析





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