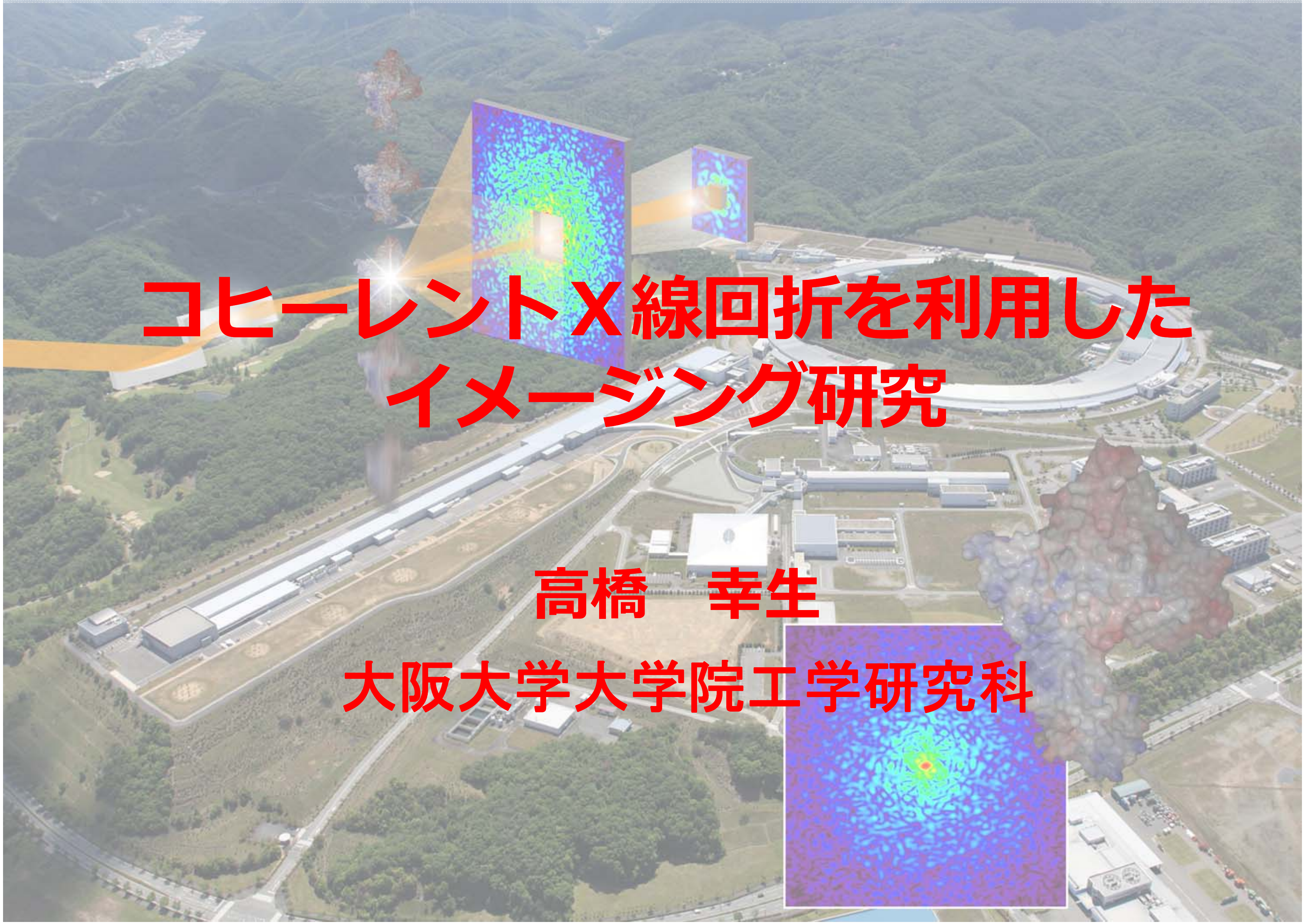


コヒーレントＸ線回折を利用したイメージング研究

高橋　幸生

大阪大学大学院工学研究科

Ｘ線イメージング

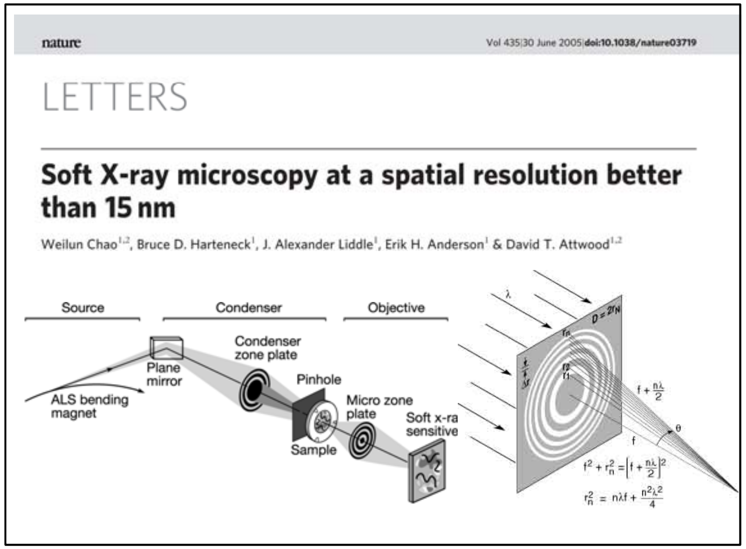
Ｘ線プローブの特長

高い透過力：厚い試料の内部構造情報

短波長性：顕微鏡において高い空間分解能の可能性

物質との多様な相互作用：弾性散乱、非弾性散乱、光電効果

手のＸ線写真

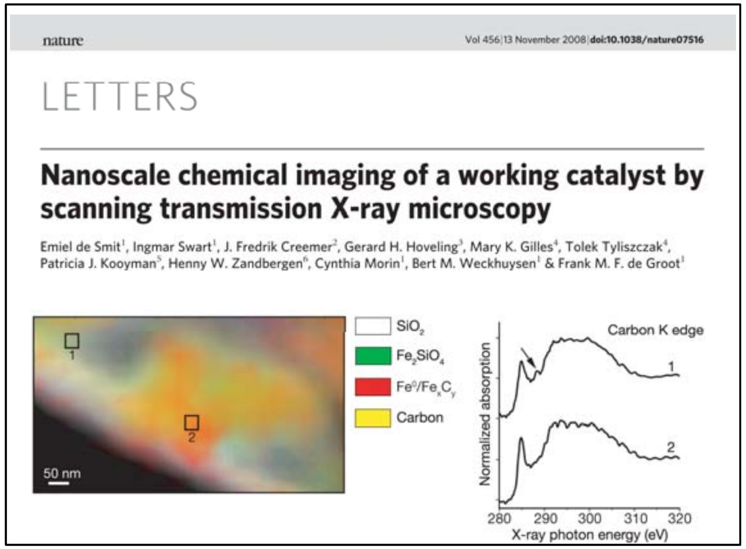


nature Vol 435|30 June 2005|doi:10.1038/nature03719

LETTERS

Soft X-ray microscopy at a spatial resolution better than 15 nm

Weilun Chao[1,2], Bruce D. Harteneck[1], J. Alexander Liddle[1], Erik H. Anderson[1] & David T. Attwood[1,2]



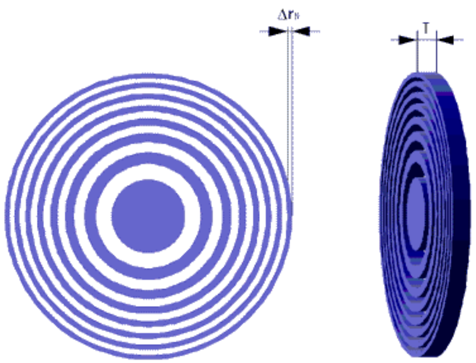
nature Vol 456|13 November 2008|doi:10.1038/nature07516

LETTERS

Nanoscale chemical imaging of a working catalyst by scanning transmission X-ray microscopy

Emiel de Smit[1], Ingmar Swart[1], J. Fredrik Creemer[2], Gerard H. Hoveling[3], Mary K. Gilles[4], Tolek Tyliszczak[4], Patricia J. Kooyman[5], Henny W. Zandbergen[6], Cynthia Morin[1], Bert M. Weckhuysen[1] & Frank M. F. de Groot[1]

ゾーンプレート放射光Ｘ線顕微鏡



ゾーンプレートの模式図

ゾーンプレート

→最外輪帯幅が空間分解能、厚さが集光効率

Ｘ線顕微鏡の高空間分解能化

→最外輪帯幅を小さく、ゾーンプレートを厚く

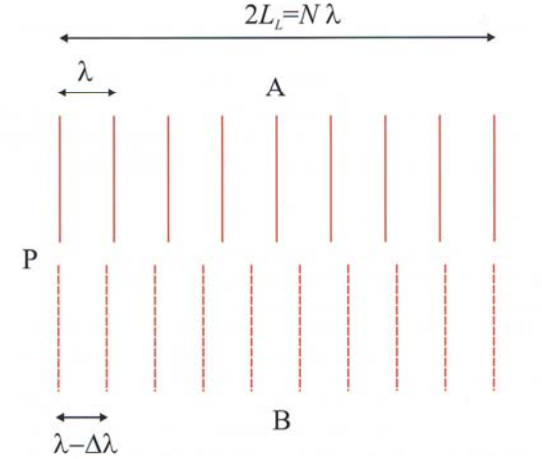
10nmより優れた空間分解能を達成することは光学素子の作製技術上容易でない

コヒーレントX線

コヒーレンス・・・干渉性、可干渉性

時間(縦方向)コヒーレンス：単色性

時間コヒーレンス長 $L_L = \frac{1}{2}\frac{\lambda^2}{\Delta\lambda}$



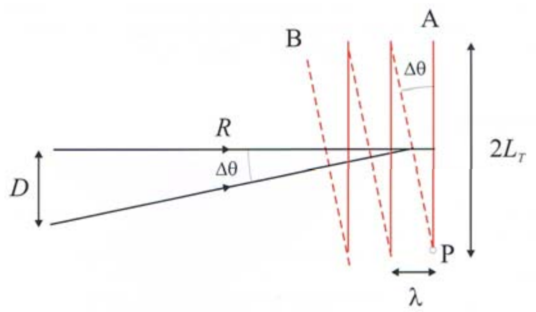
$\lambda = 1\text{Å}$

$\frac{\Delta\lambda}{\lambda} = 10^{-4}$

$L_L = 0.5\mu\text{m}$

空間(横方向)コヒーレンス：平行性

空間コヒーレンス長 $L_T = \frac{\lambda}{2}\left(\frac{R}{D}\right)$



$\lambda = 1\text{Å}$

$D = 100\mu\text{m}$

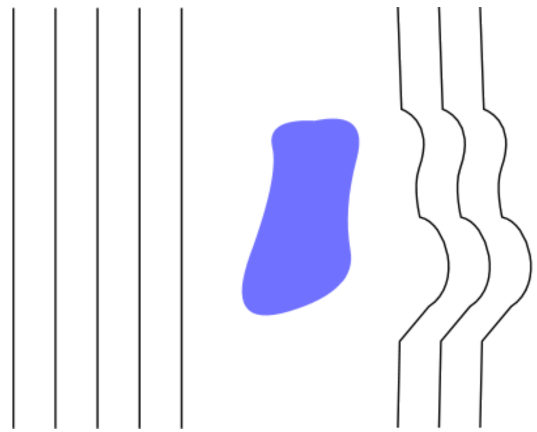
$R = 100\text{m}$

$L_T = 50\mu\text{m}$

コヒーレント照明

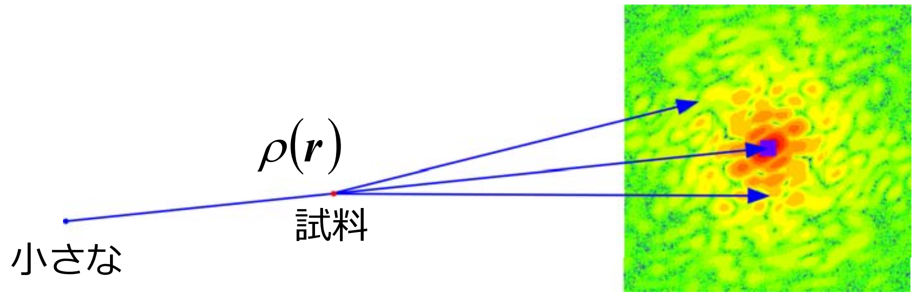
$L_L >$ 最大経路差

$L_T >$ 試料サイズ



コヒーレントX線回折

コヒーレンスが良い場合 $I(Q)$

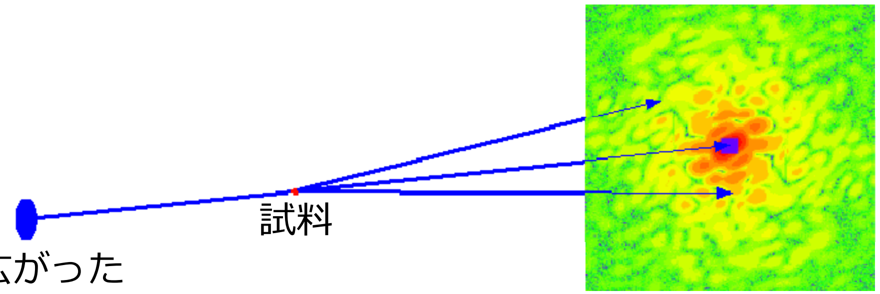


斑点(スペックルパターン)

↓

詳細な試料構造

コヒーレンスが悪い場合



斑点パターンは打ち消される

↓

平均構造

構造因子

$$F(\boldsymbol{Q}) = \int \rho(\boldsymbol{r}) e^{-i\boldsymbol{Q}\cdot\boldsymbol{r}} d\boldsymbol{r}$$

散乱強度

$$I(\boldsymbol{Q}) \propto |F(\boldsymbol{Q})|^2$$

→ **位相問題**

David Sayre (1924-2012)

The Squaring Method: a New Method for Phase Determination

By D. Sayre*

Laboratory of Chemical Crystallography, University Museum, Oxford, England

(*Received* 31 *May* 1951)

A new set of relationships is given which exist among the structure factors of crystals composed only of like atoms and which hold approximately for ordinary organic crystals containing only C, N, O and H. They are the consequence of the similarity between the electron-density function $d(\bar{x})$ and its square, $d^2(\bar{x})$, for such crystals. In spite of considerable differences in form, the relationships found make the same general statement about the structure factors as do the Harker–Kasper–MacGillavry and Karle–Hauptmann–Goedkoop relationships, namely that the phase of $F(a+b)$ is closely related to that of $F(a)\,F(b)$. Because the present relationships apply to a special case (like atoms) and include the condition of a minimum separation of atoms, they should be a more powerful method for phase determination than the other methods, but this fact has not yet been demonstrated directly. The method has been applied to the structure of hydroxyproline, where it was possible in a few days to find the signs of thirty-one structure factors, of which thirty were correct, and to produce a Fourier projection in which the molecule was easily recognizable.

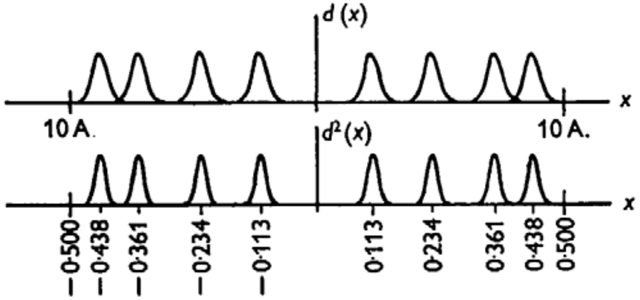


Fig. 1. The unit cell of a one-dimensional crystal composed of identical and non-overlapping atoms, showing the similarity between $d(\bar{x})$ and $d^2(\bar{x})$. This is the crystal used as an example in §2(*a*).

Acta Cryst. **5**, 60 (1951).

Crystallographer who pioneered methods of X-ray imaging and modern computing.

David Sayre, who died on 23 February, was a pioneer in crystallography and diffraction imaging, a visionary in X-ray microscopy and an architect of modern computing. A superb scientist, deep thinker and wonderful mentor, he could have built a scientific empire. But that was not his style. He was driven by the desire to do pure and original science.

Sayre was born on 2 March 1924 in New York. His father was an organic chemist whose ancestors helped to found the town of Southampton, New York, in the sixteenth century. His mother was the daughter of Jewish immigrants. Sayre was educated at Yale University in New Haven, Connecticut, graduating in 1943 at the age of 19 with a bachelor's degree in physics. The Second World War was at its height, so Sayre worked on radar at the Radiation Laboratory at the Massachusetts Institute of Technology in Cambridge.

In 1946, guessing biology would be the next exciting field, Sayre became a graduate student in biology at the University of Pennsylvania in Philadelphia and then at Harvard University in Cambridge. He was not initially interested in what he was learning, but in 1947 Sayre came across an article about X-ray crystallography that changed his life. He joined Raymond Pepinsky's crystallography laboratory at Auburn University in Alabama, where he used a mathematical operation known as the Fourier transform to analyse the structures of crystals probed with X-ray beams.

That year, Sayre married Anne Colquhoun, a fiction writer. She took a teaching position at the Tuskegee Institute, but her involvement in the school, which enrolled black students, was controversial in the Deep South at that time, and the Sayres soon left. They moved to Oxford, UK, where Sayre completed his PhD in the lab of Dorothy Hodgkin in 1951.

Sayre produced his most profound papers during this period, solving the 'phase problem' in crystallography — the loss of phase information in the measurement of diffraction intensity. In 1952, he proposed atomicity — the fact that atoms are small and discrete points relative to the space between them — as a constraint for determining the phases of crystals of small molecules, giving rise to what is now called Sayre's equation. Atomicity is the key concept behind the direct methods used for crystallography today, although Sayre did not share the 1985 chemistry Nobel prize awarded for it. In 1952, Sayre also realized that, even in the absence of regular crystal structure, information could be gleaned from the fine sampling of diffraction patterns.

Sayre saw early on that solving complex crystal structures would require substantial computational resources. In 1956 he joined IBM's Watson Research Center in New York, and eventually became assistant manager of the team that wrote the original FORTRAN compiler. He became corporate director of programming, and later head of the IBM programming research group. In 1969, he and his team proved the efficiency of virtual memory in computing.

In 1972–73, Sayre took a sabbatical, returning to Hodgkin's lab and to crystallography. It was during this time that one of us (J.K.) met the Sayres, forming a lasting friendship and collaboration. Anne Sayre also wrote the influential book *Rosalind Franklin and DNA*, about the outstanding crystallographer and Sayre family friend who had died of cancer at an early age.

After returning to IBM, Sayre became interested in X-ray microscopy. His 1971 idea of focusing X-rays using Fresnel zone plates became a reality through the use of IBM's nanofabrication technology and with the advent of synchrotron radiation sources such as the National Synchrotron Light Source at Brookhaven National Laboratory in Upton, New York. X-ray microscopy based on zone plates is now used in synchrotron-radiation facilities worldwide.

Around 1990, Anne developed scleroderma, a debilitating disease, and David retired from work to care for her. But he continued working to realize his 1952 dream: the reconstruction of molecular structures without the use of crystals. The idea came to fruition almost 50 years later, with the publication in 1999 of the first reconstruction of a non-crystalline model object from its diffraction pattern (which was J.M.'s PhD project). This paper established coherent diffraction imaging (CDI), also called lensless imaging or diffraction microscopy, as the most promising form of high-resolution X-ray imaging. CDI is now one of the fastest-growing fields in X-ray science.

Anne died in 1998, and in the last decade of his life David suffered from Parkinson's disease. But he continued to participate in research and to offer advice. A researcher with exceptional intuition, David lived for science. His passing is a huge loss for all of us. ■

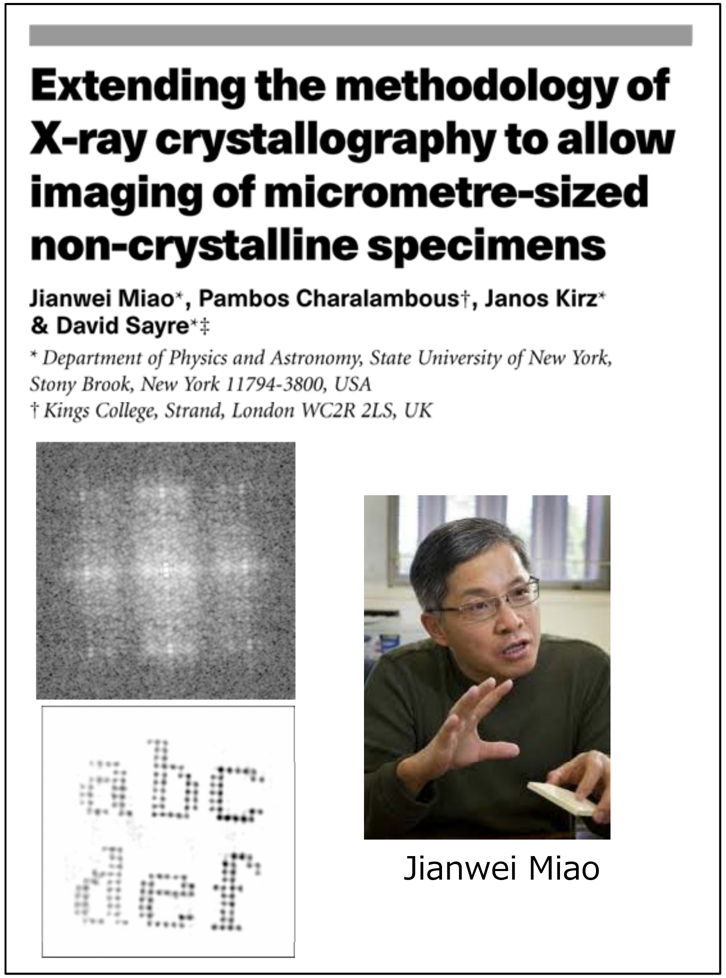
Janos Kirz *is distinguished professor emeritus at Stony Brook University, New York, and scientific adviser for the Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA. He was a collaborator and friend of David for nearly 40 years.* **Jianwei Miao** *is a professor in the Department of Physics and Astronomy and the California NanoSystems Institute, University of California, Los Angeles, California 90095, USA. He worked with David on coherent diffraction imaging beginning in 1996, first as a student, then as a collaborator and friend.*
e-mail: miao@physics.ucla.edu

Nature **484**, 38 (2012).

コヒーレントX線回折イメージングの実証：1999年

レンズレスX線顕微法

- コヒーレントX線回折
- 位相回復計算

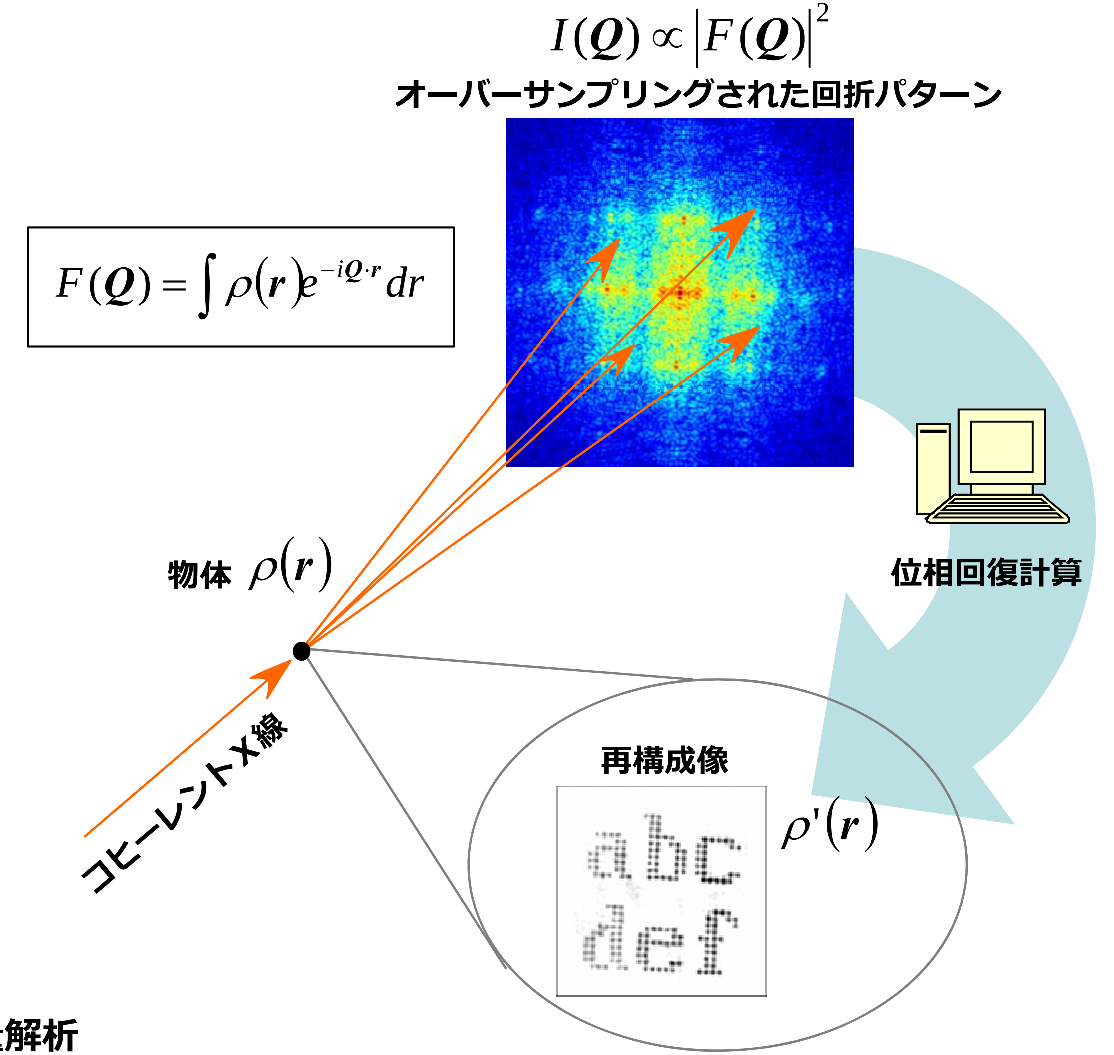


Extending the methodology of X-ray crystallography to allow imaging of micrometre-sized non-crystalline specimens

Jianwei Miao*, Pambos Charalambous†, Janos Kirz* & David Sayre*‡

** Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800, USA*
† Kings College, Strand, London WC2R 2LS, UK

J. Miao *et al.*, *Nature* **400** 342 (1999).



利点

- 厚い試料の観察
- 高い空間分解能
- 電子密度、歪み分布の定量解析

反復的位相回復計算

J. R. Fienup, Optics Letters **3**, (1978) 27.

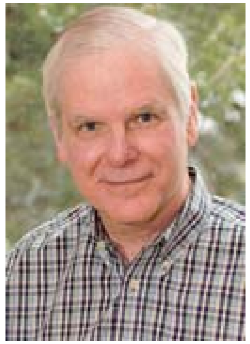
Reconstruction of an object from the modulus of its Fourier transform

J. R. Fienup

Environmental Research Institute of Michigan, P.O. Box 8618, Ann Arbor, Michigan 48107

Received February 23, 1978

We present a digital method for solving the phase-retrieval problem of optical-coherence theory: the reconstruction of a general object from the modulus of its Fourier transform. This technique should be useful for obtaining high-resolution imagery from interferometer data.

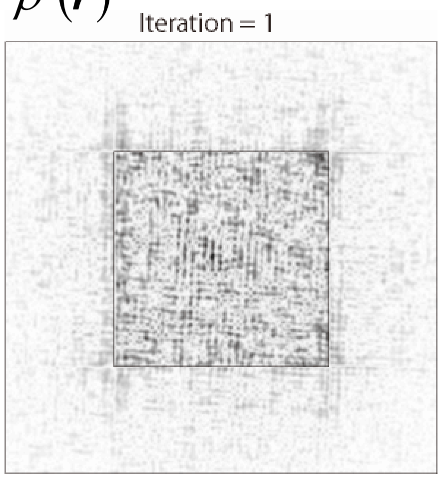


James R. Fienup

Hybrid input-output algorithm

J. R. Fienup, Appl. Opt. **21**, (1982) 2758.

$\rho'(\boldsymbol{r})$



電子密度分布

$\rho(\boldsymbol{r})$ → フーリエ変換 → $|g(\boldsymbol{K})|e^{i\varphi(\boldsymbol{K})}$

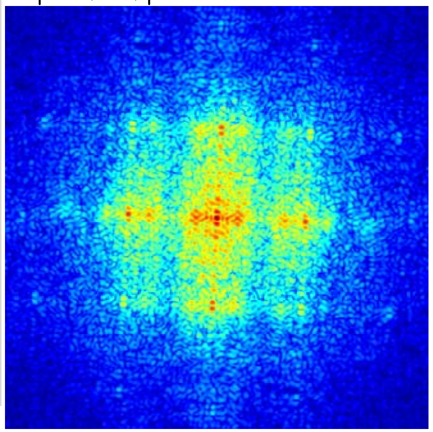
回折波複素振幅

$|g(\boldsymbol{K})|e^{i\varphi(\boldsymbol{K})}$ → 逆空間拘束 → $|f(\boldsymbol{K})|e^{i\varphi(\boldsymbol{K})}$

$|f(\boldsymbol{K})|e^{i\varphi(\boldsymbol{K})}$ → 逆フーリエ変換 → $\rho'(\boldsymbol{r})$

$\rho'(\boldsymbol{r})$ → 実空間拘束 → $\rho(\boldsymbol{r})$

$|f(\boldsymbol{K})|$



$$\rho_{n+1}(\boldsymbol{r}) = \begin{cases} \rho'_n(\boldsymbol{r}), & (r \in S) \wedge (\rho'_n(\boldsymbol{r}) \geq 0) \\ \rho_n(\boldsymbol{r}) - \beta\rho'_n(\boldsymbol{r}), & \text{otherwise} \end{cases}$$

S: Support, β: between 0.5 and 1

平面波照明型コヒーレントX線回折イメージングで得られる再構成像

◆**構造因子** $F(Q)=\int \rho(r) e^{-iQ\cdot r} dr$

$\rho(r)$：電子密度分布

- 弱吸収物体
- 1回散乱近似
- 完全単色平面波

◆**散乱強度** $I(Q)\propto |F(Q)|^2$

$$F(q_x,q_y)=\iint \underbrace{\int \rho(r) dz}_{\text{投影}} e^{-i(q_x x+q_y y)} dxdy$$

$$|F(q_x,q_y)| \xrightarrow{\text{位相回復}} \rho(x,y)$$

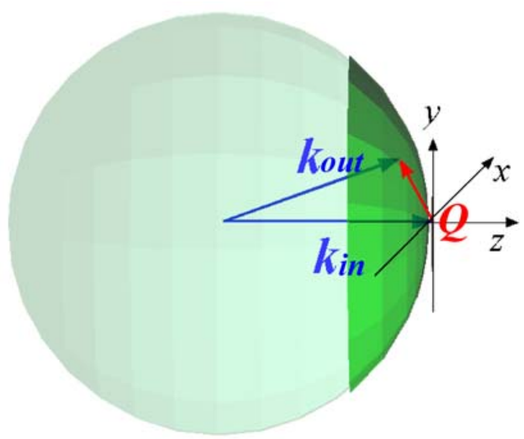
二次元再構成像は試料電子密度分布の投影

$$|F(q_x,q_y,q_z)| \xrightarrow{\text{位相回復}} \rho(x,y,z)$$

三次元再構成像は試料電子密度分布

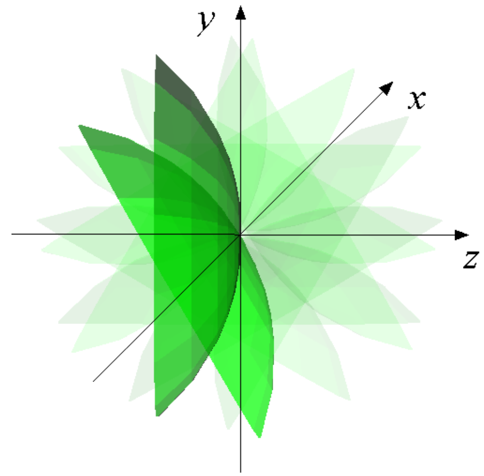
空間分解能はX線の波長によって制限される

エバルト球



三次元

様々なX線入射角度で測定

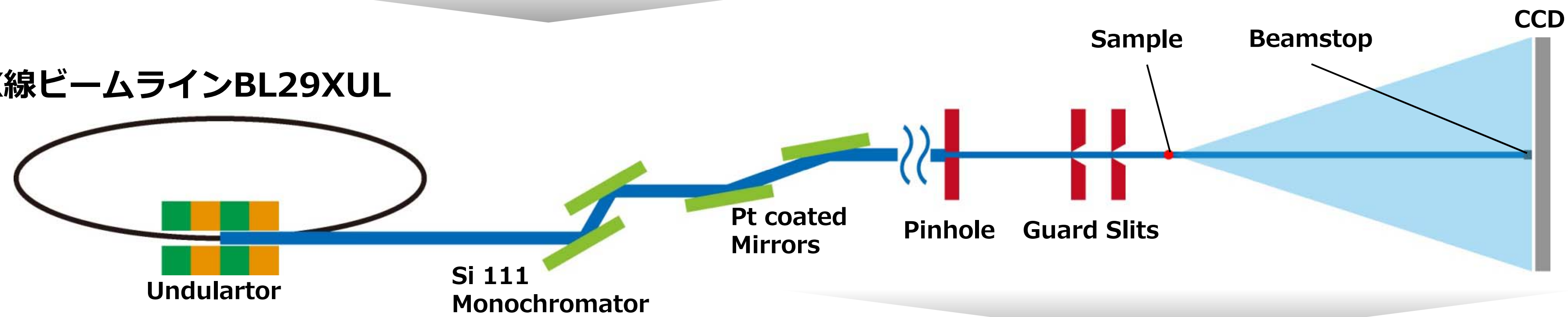


SPring-8における平面波照明型コヒーレントX線回折イメージング装置の開発

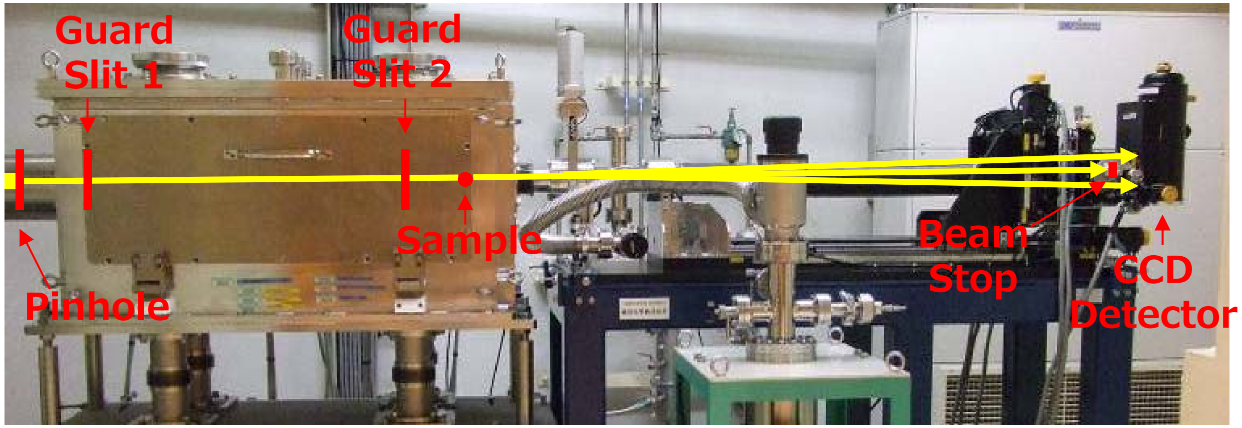
SPring-8

- 第三世代放射光施設
- 高輝度Ｘ線
- 部分コヒーレントＸ線
  (ビーム面積の0.1%程度がコヒーレント)

硬X線ビームラインBL29XUL



SPring-8 BL29XUL 実験ハッチ1



回折イメージング装置

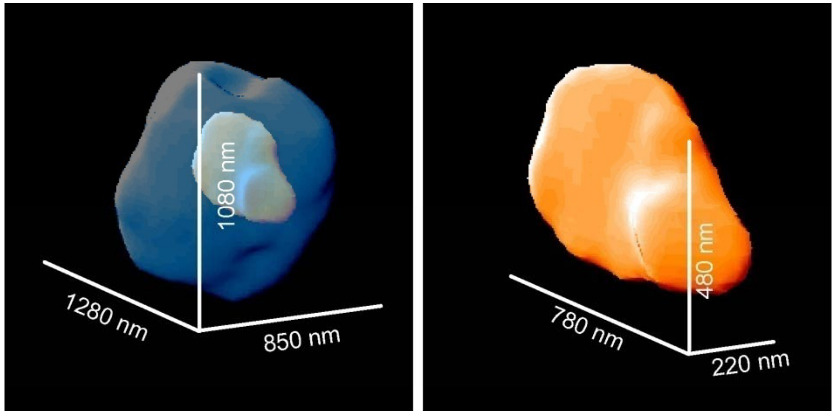
- X線エネルギー: 5-10 keV
- サンプル-検出器間距離: 1-3 m
- 直接撮像型CCD検出器
  Princeton Instruments PI-LCX 1300
  1340 × 1300 Pixels
  Pixel Size: 20 μm × 20 μm
  Direct Illumination Deep Depletion

コヒーレントX線回折イメージングの物質科学・生物学分野への応用

電子顕微鏡では比較的観察が困難な厚い試料の電子密度分布観察

アルミニウム合金

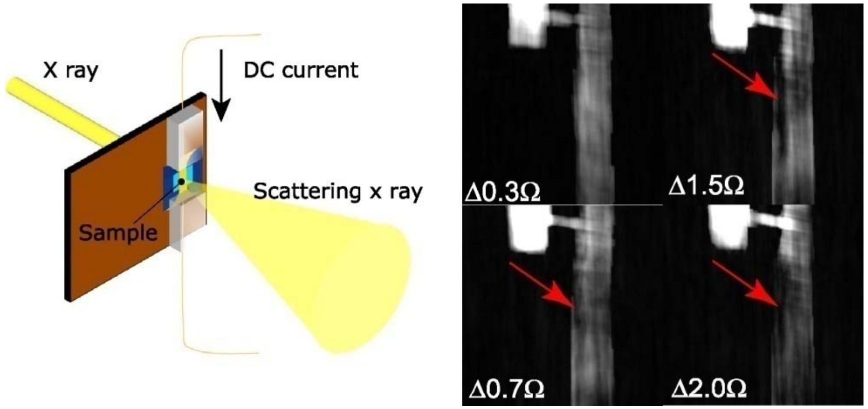
・析出物



Yukio Takahashi *et al.*, *Appl. Phys. Lett.* **90**, 184105 (2007)

銅細線

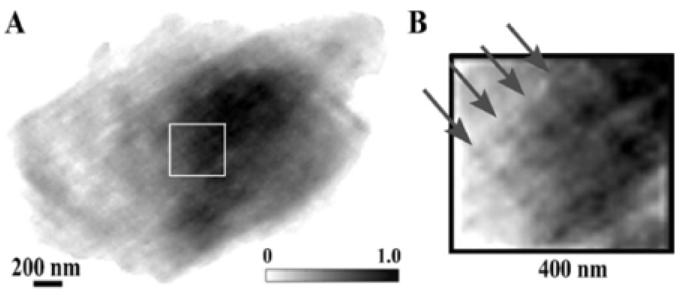
・エレクトロマイグレーションボイド



Yukio Takahashi *et al.*, *J. Appl. Phys.* **105**, 124911 (2009)

魚の骨

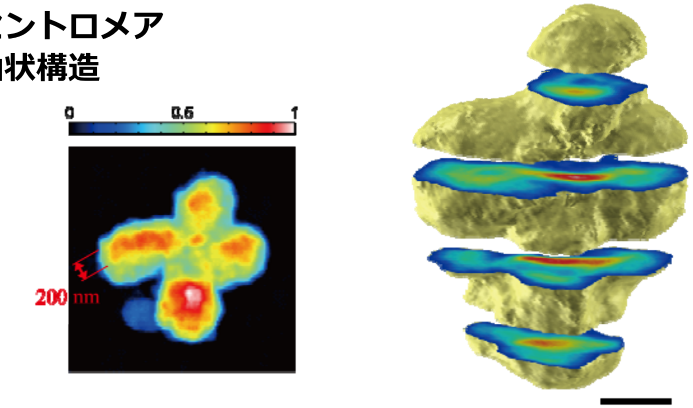
•コラーゲンの微細構造



Huaidong Jiang *et al.*, Phys. Rev. Lett. **100**, 038103 (2008).

ヒト染色体

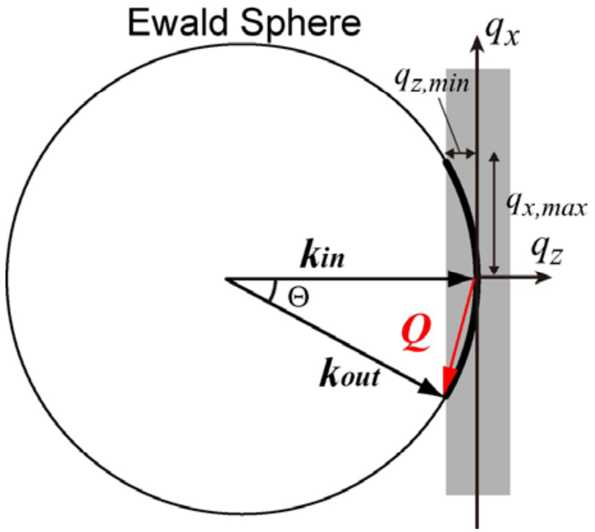
・セントロメア
・軸状構造



Yoshinori Nishino *et al.*, Phys. Rev. Lett. **102**, 018101 (2009)

高分解能コヒーレントX線回折イメージング技術の開発

コヒーレント回折イメージングの空間分解能



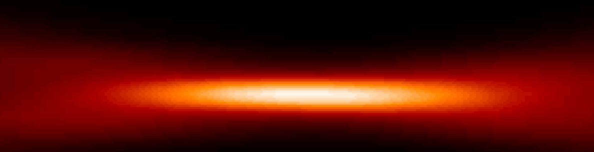
NA=$q_{x,\ max}\lambda$ （λ: X線の波長 ／ $q_{x,\ max}$:エバルト球面上の最大横方向距離）

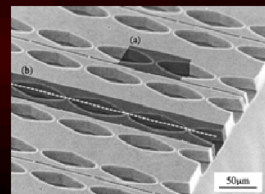
"High-Q 回折パターン"

回折強度はqのベキ乗に比例して減衰(polod則)

"高フラックス密度のコヒーレントX線"

"硬X線集光"

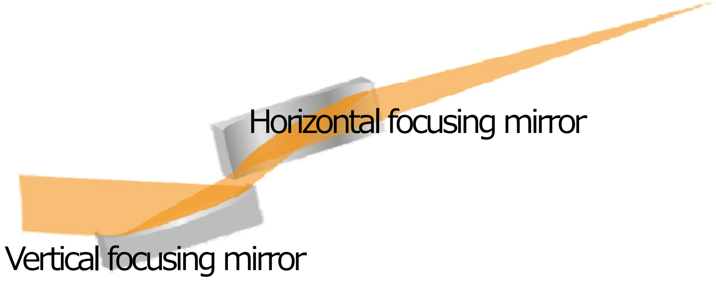




高分解能コヒーレントX線回折イメージング装置の開発

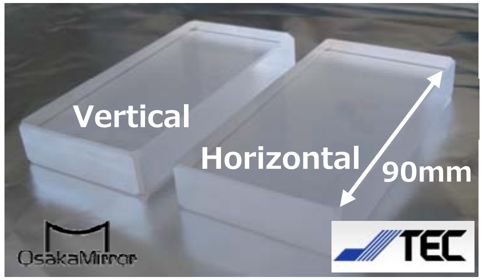
全反射ミラー集光光学系

◆ **Kirkpatrick-Baez (KB) 光学系**



◆ **Elastic Emission Machining**

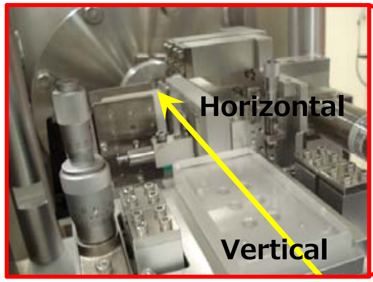
K. Yamauchi *et al.*, Rev. Sci. Instrum. **73**, 4028 (2002).



- 面精度≦1.0nm PV
- 表面粗さ≦0.11nm RMS

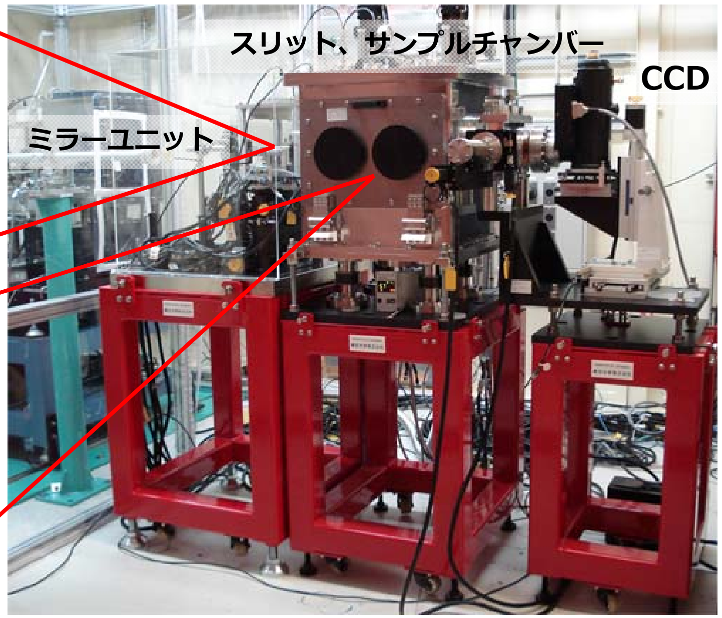
スペックルフリー
高反射率>99%

高分解能コヒーレントX線回折装置



ミラー部分拡大

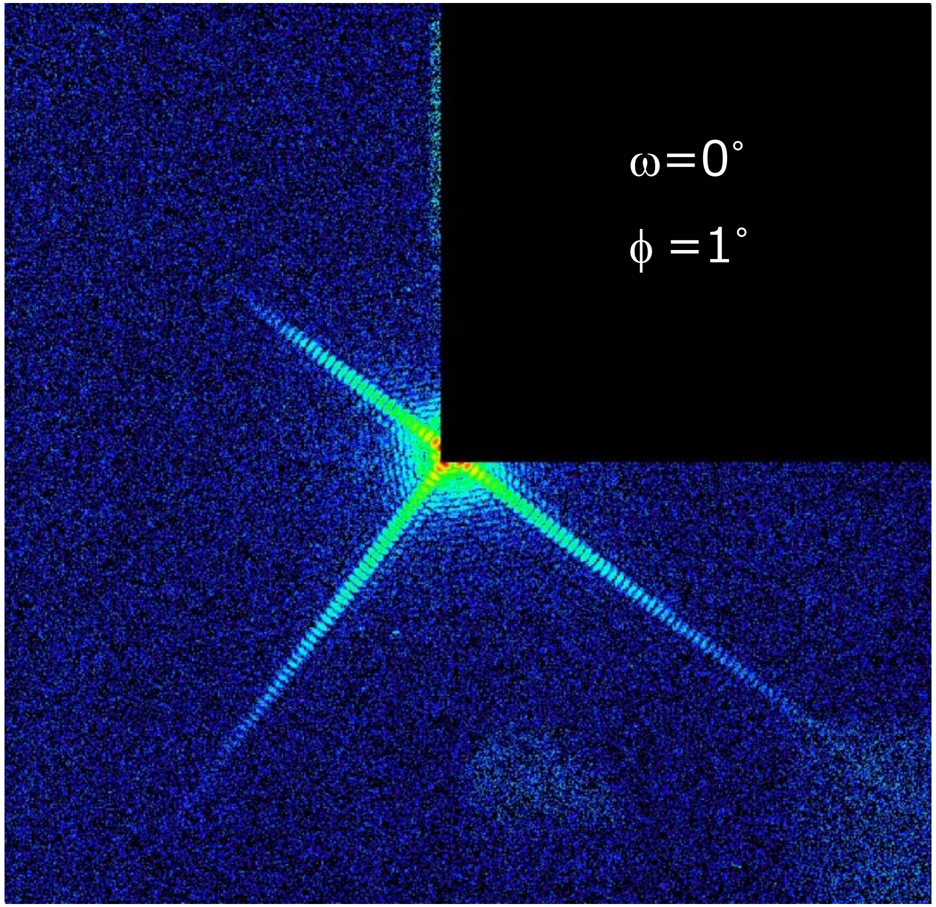
チャンバー内部



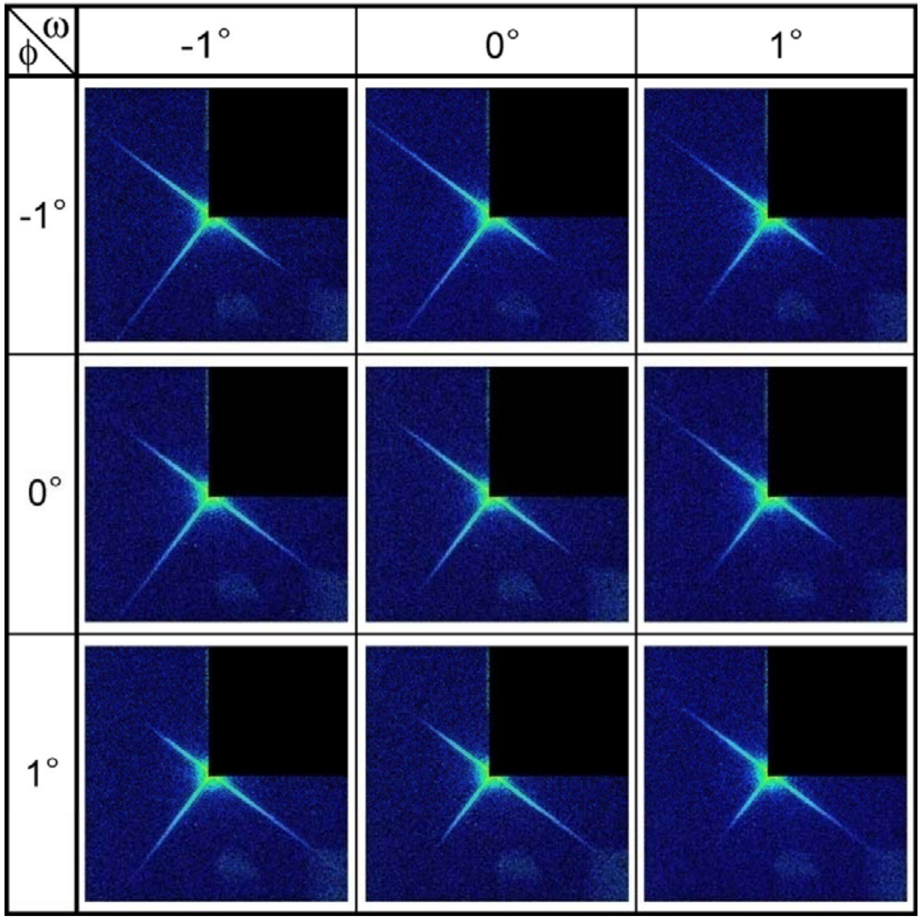
- X線エネルギー：
  8keV～12keV
- 直接撮像型CCD：
  Princeton Instruments PI-LCX:1300
  ピクセルサイズ20μm
  1340×1300 ピクセル

Yukio Takahashi *et al.*, AIP Conference Proceedings **1635**, 231 (2011)

銀ナノキューブのコヒーレント回折パターン



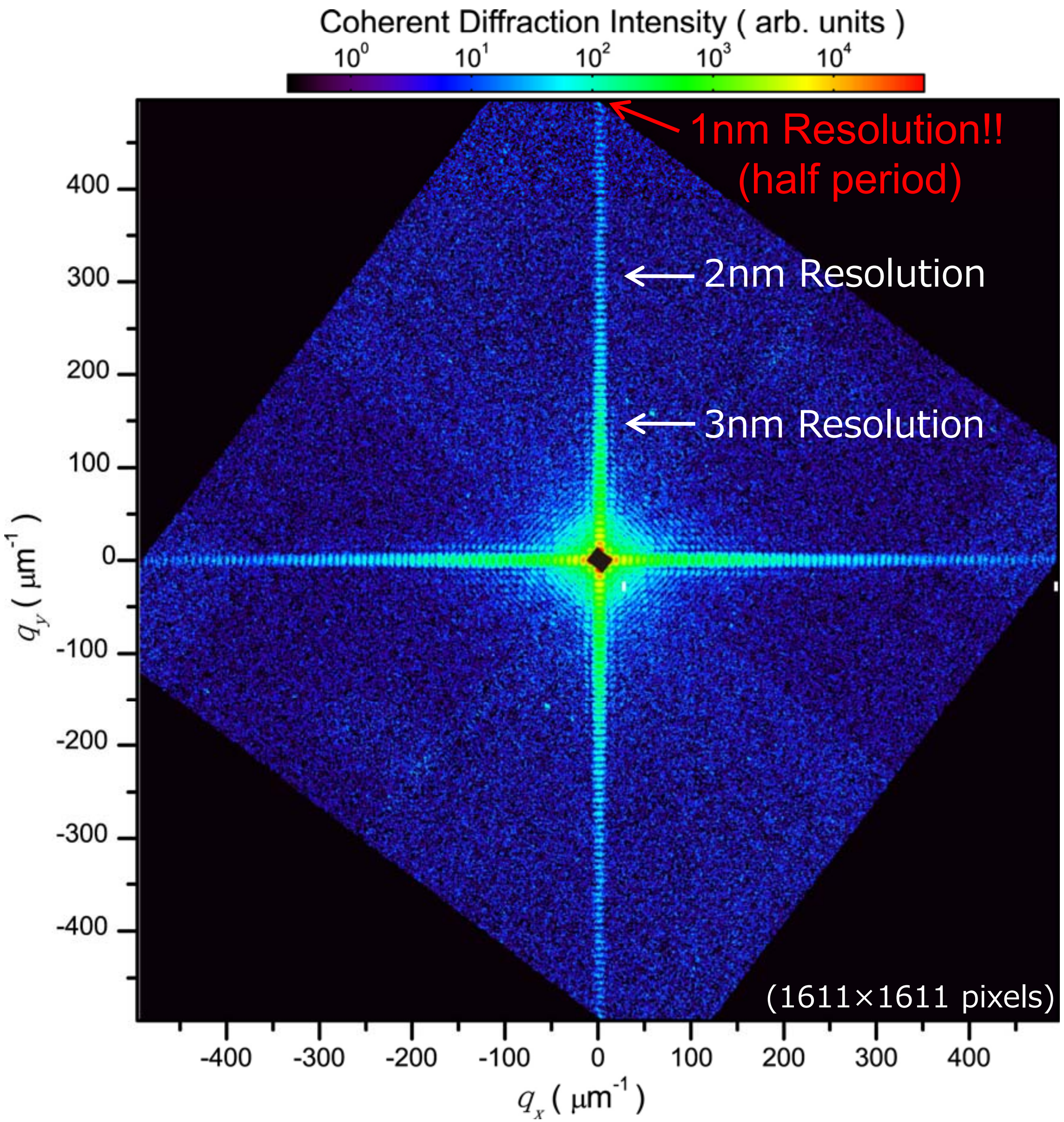
(1340×1300 ピクセル)



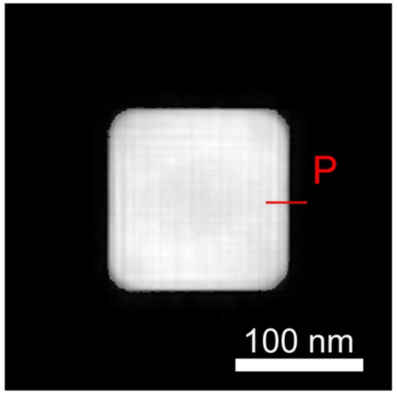
試料厚さの効果(エバルト球の曲率)に由来する高角領域の回折パターンの非対称性

Yukio Takahashi *et al*., Physical Review B **82**, 214102 (2010).

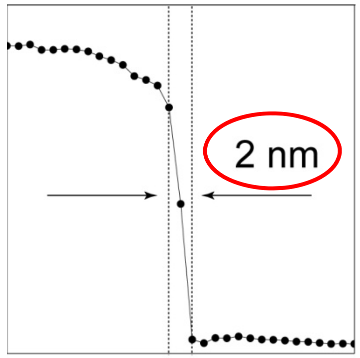
銀ナノキューブのコヒーレントX線回折パターンおよび再構成像



再構成像



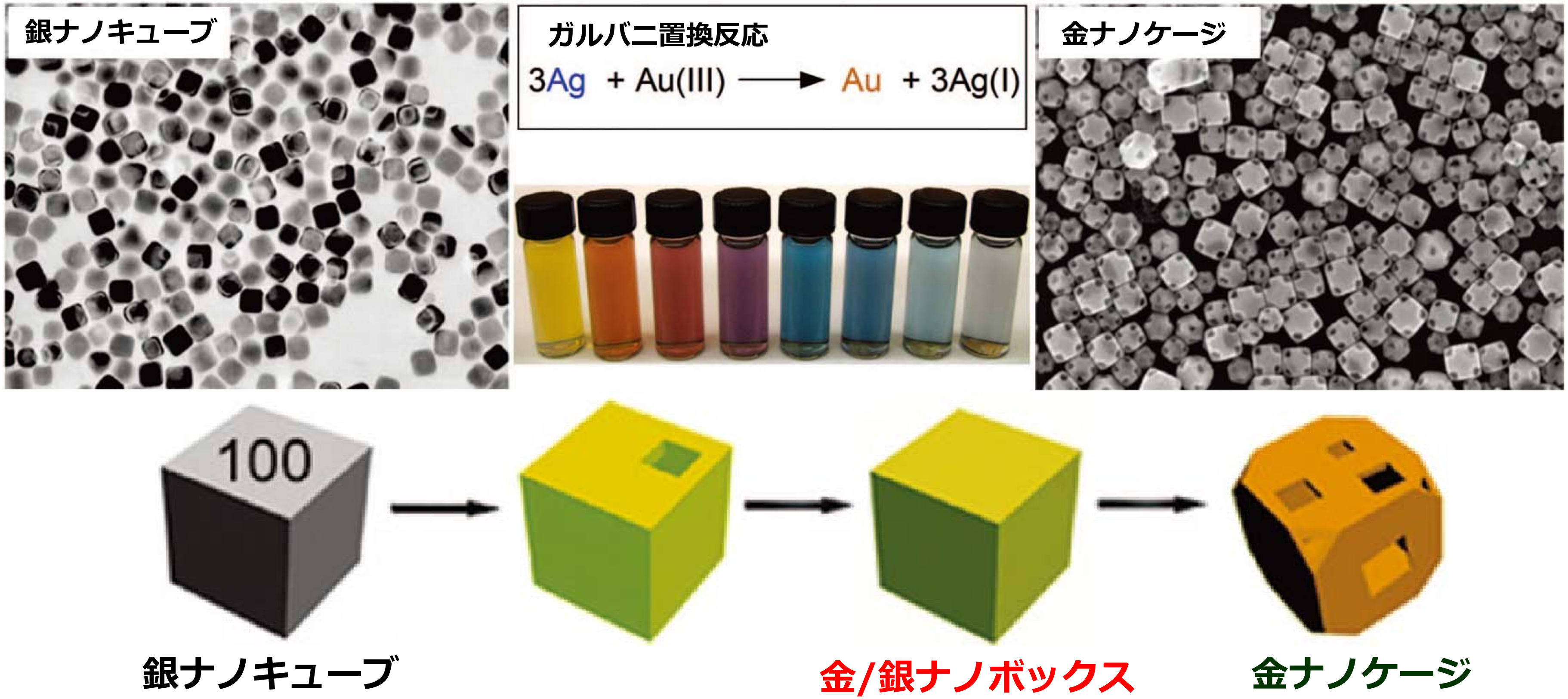
Pixel Size : 1 nm



Line scan through P

Yukio Takahashi *et al*., Physical Review B **82** 214102 (2010).

金ナノケージ



S. E. Skrablak *et al*., *Acc. Chem. Res.* **12** (2008) 1587-1595.

- 表面プラズモンに由来する近赤外領域の吸収バンド：造影剤
- フォトサーマル効果：がん組織破壊

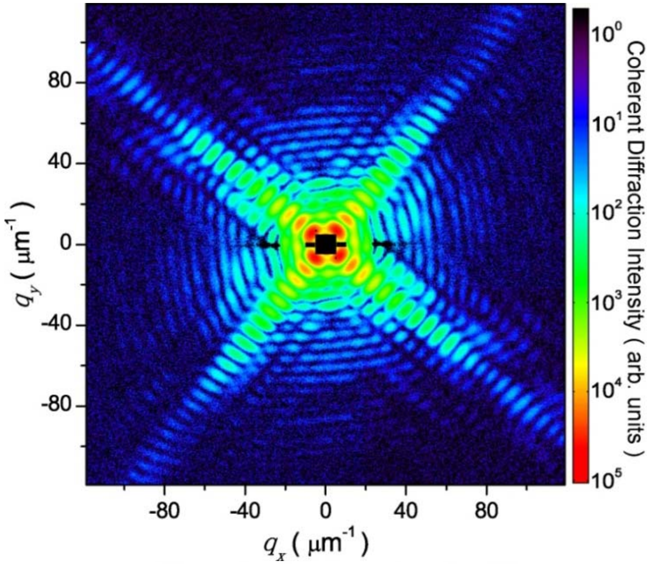
試料作製：名古屋大学 是津信行先生

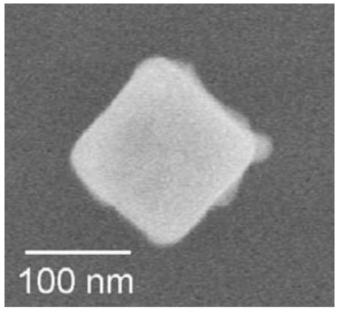
金/銀ナノボックス粒子の観察：電子顕微鏡 vs 高分解能コヒーレントX線回折イメージング

電界放出型走査型電子顕微鏡
日立 S-4800

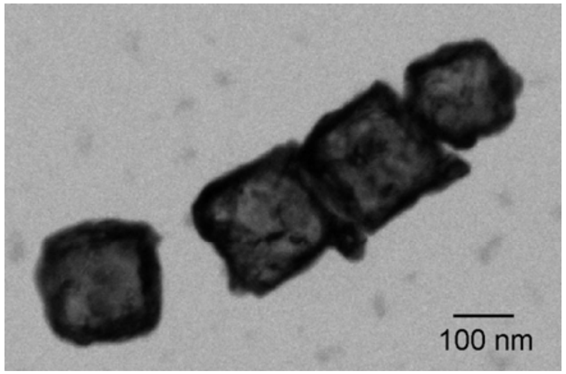
透過型電子顕微鏡
JEOL JEM-2100

高分解能コヒーレントX線回折イメージング

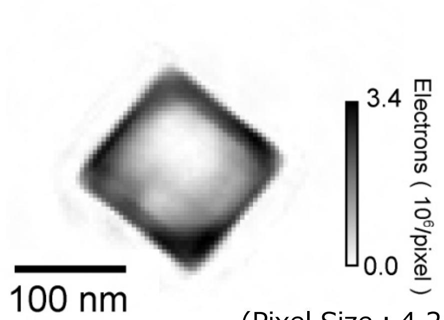




- 表面



- 内部構造
- 多重散乱、非弾性散乱



(Pixel Size : 4.2nm)

- 内部構造
- 電子密度分布

Yukio Takahashi *et al.*, Nano Letters **10** 1922 (2010).

金/銀ナノボックス粒子の三次元再構成

60枚の回折パターン

1251 pixel

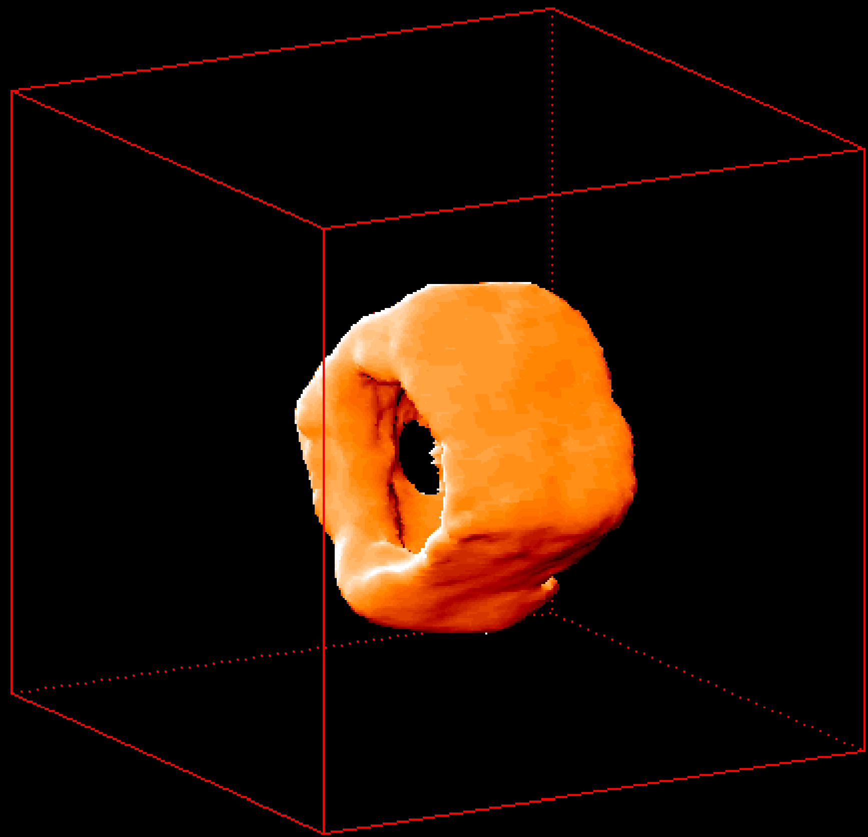
1251 pixel

1251 pixel

位相回復

等電子密度像

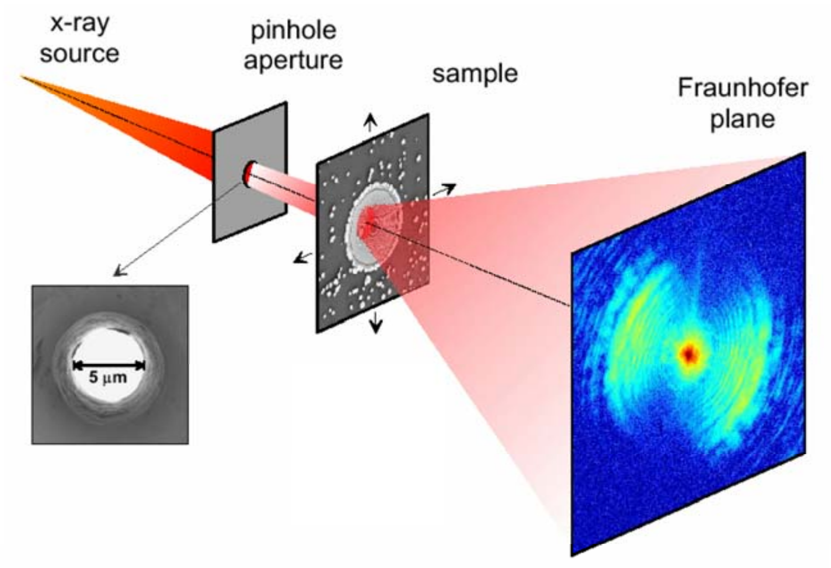
Threshold: 2.1×10^5 electrons/voxel
(銀の電子密度)



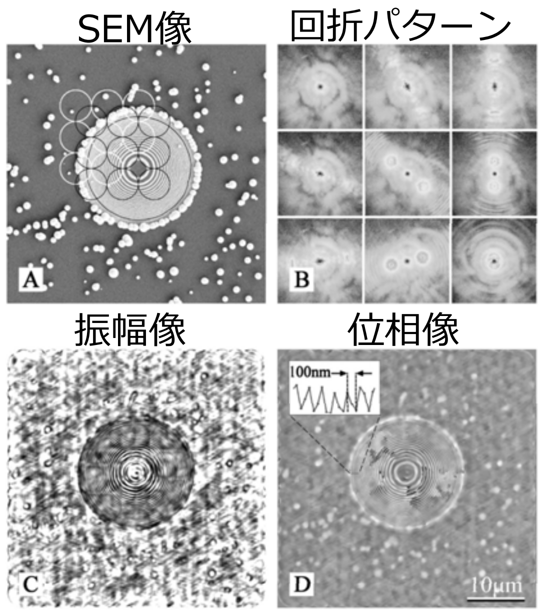
ボクセルサイズ：4.2nm

Yukio Takahashi *et al.*, Nano Letters **10** 1922 (2010).

走査型コヒーレントX線回折イメージング(Ptychography)

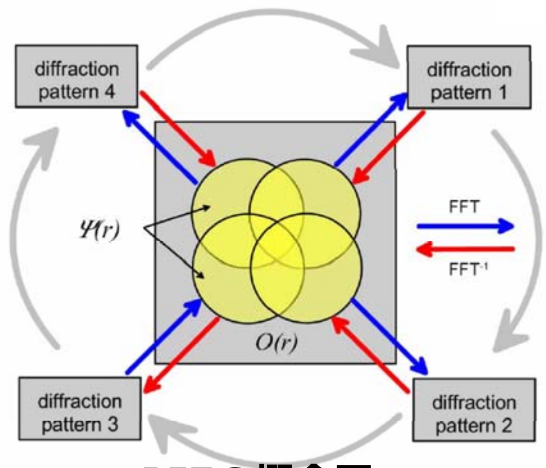


Ptychography(タイコグラフィー)



J.M.Rodenburg *et al.*,Phys.Rev.Lett.**98**,034801(2007)

- ptycho(πτυξ): fold 重なり
- 照射領域が重なるように水平、垂直方向ステップ走査し、各位置で回折パターンを取得
- 重なり領域を実空間拘束、回折強度パターンを逆空間拘束として反復計算を行う (Ptychographical Iterative Engine:PIE)
- 試料が孤立物体に限定されない



PIEの概念図

H. M. L. Faulkner and J. M. Rodenburg, Phys. Rev. Lett. **93**, 023903 (2004)

X線タイコグラフィーで得られる再構成像

- ✓ **平面波照明を仮定しない**
- ✓ **投影近似を適用するしかない**

物体の透過関数：

$$T(x,y) = exp\left(\frac{2\pi i}{\lambda}\int \delta(r) + i\beta(r)\,dz\right)$$

弱位相物体近似を適用すると、

$$T(x,y) \approx 1 + \frac{2\pi i}{\lambda}\int \delta(r)\,dz$$

物質が単一元素で構成される場合：

$$\delta = N\lambda^2 r_e\,(Z + f')/2\pi$$
$$\beta = -N\lambda^2 r_e f''\,/2\pi$$

- N：単位体積中の電子数
- r_e：古典電子半径
- Z：原子番号
- f', f''：異常分散項の実部、虚部
- λ：X線波長

物体背面の波動場：

$$\psi(x,y) \approx P(x,y)\big(1 + i\Phi(x,y)\big)$$

$P(x,y)$: プローブ関数

遠方での回折強度：

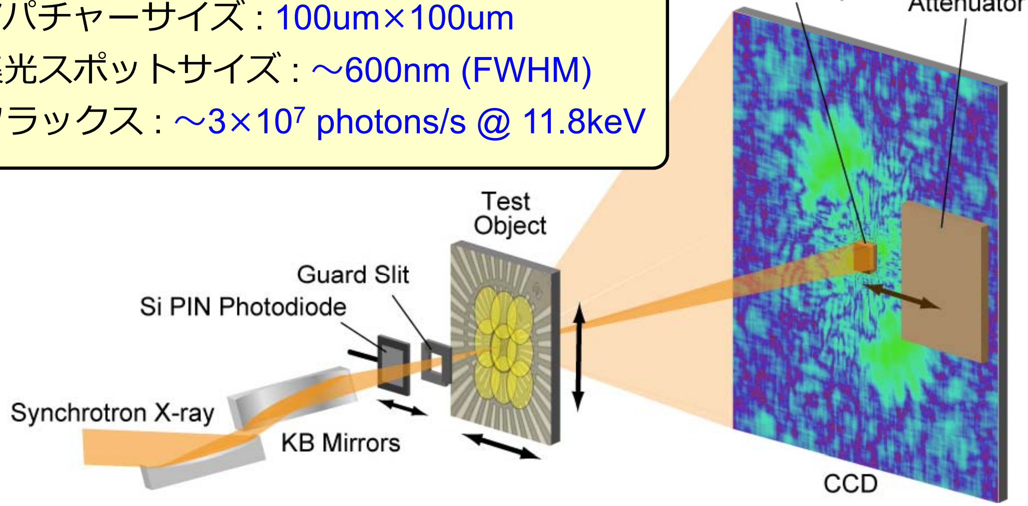
$$I(k_x, ky) = |\mathcal{F}[\psi(x,y)]|^2$$

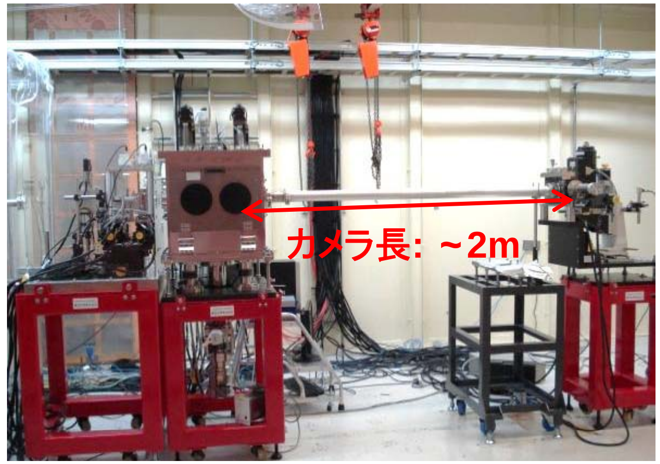
$\mathcal{F}$：フーリエ変換

空間分解能はX線の波長および試料の厚みによって制限される

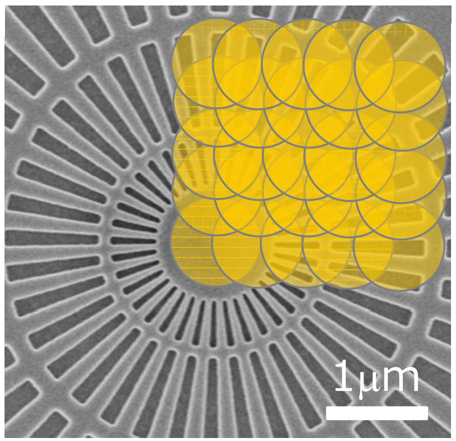
高分解能X線タイコグラフィーの開発

- 仮想光源サイズ：
  10um×10um @50m 上流
- アパチャーサイズ：100um×100um
- 集光スポットサイズ：～600nm (FWHM)
- フラックス：～3×10[7] photons/s @ 11.8keV



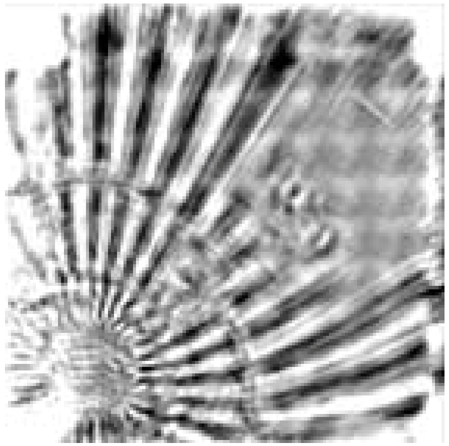


SEM



- シーメンススター
- 200 nm 厚さ タンタル

X線タイコグラフィー像



- 7×7, 500nmステップ
- 測定時間：~1 h

- サンプルと集光ミラー間の位置ドリフトによるX線照射位置エラー
- 温度変化に伴う架台の熱膨張・収縮

恒温化システムの開発

恒温化システム無

恒温化システム有

実験ハッチ : パネルヒーター → 設定温度： 26.0℃

集光システム & サンプルチャンバー : 断熱材 & シートヒーター　→ 設定温度 : 26.4℃

温度を白金測温抵抗体(PT100)でモニターし、PID制御でフィードバックする

12時間での温度変化

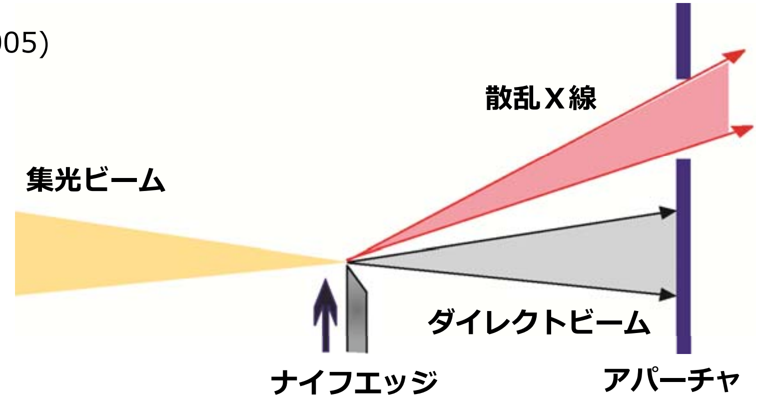
	恒温化システム無	恒温化システム有
実験ハッチ	0.5℃ →	**0.05℃**
集光システム	0.5℃ →	**0.02℃**

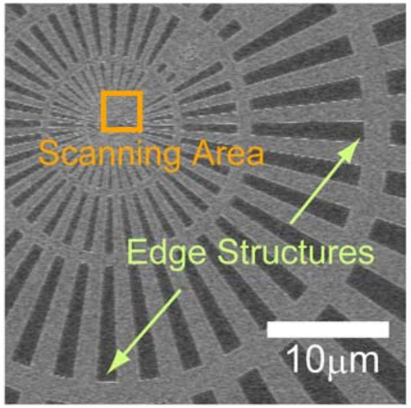
X線照射位置修正法の開発

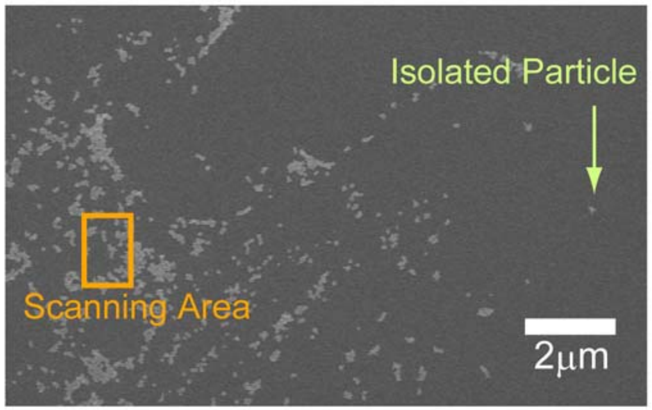
暗視野ナイフエッジ走査法

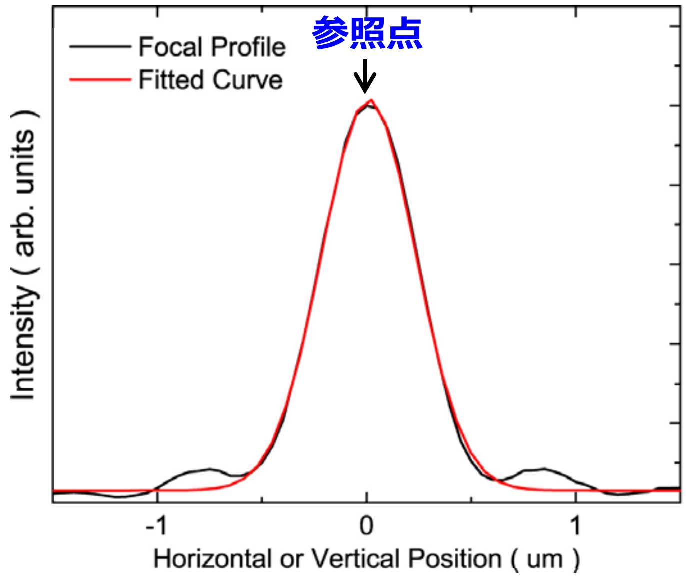
Yoshio Suzuki *et al.*, Jpn. J. Appl. Phys. **44**, 1994 (2005)

- ナイフエッジでX線ビームを走査し、散乱X線強度をモニターする。
- 良いS/N比で集光プロファイルが得られる。



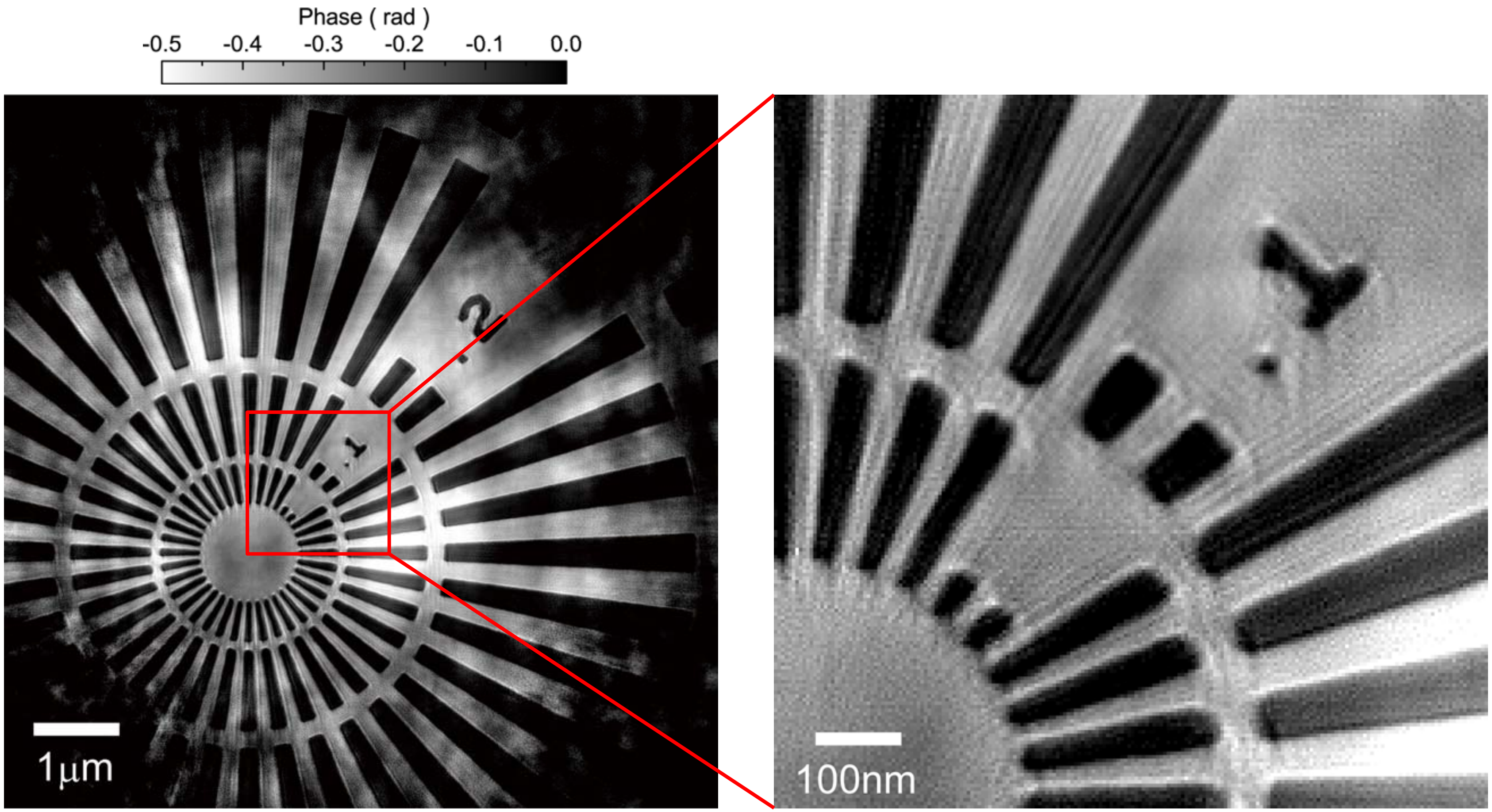






走査各点でのコヒーレント回折強度測定前に、サンプル内のエッジ構造あるいは孤立粒子を用いた暗視野ナイフエッジ測定を行い、X線照射位置の修正を行う。

高分解能X線タイコグラフィーの実証



- 7×7, 500nmステップ
- 測定時間 : ～10 h
- 観察領域 : ～5×5 μm^2
- ピクセルサイズ : 8.3 nm

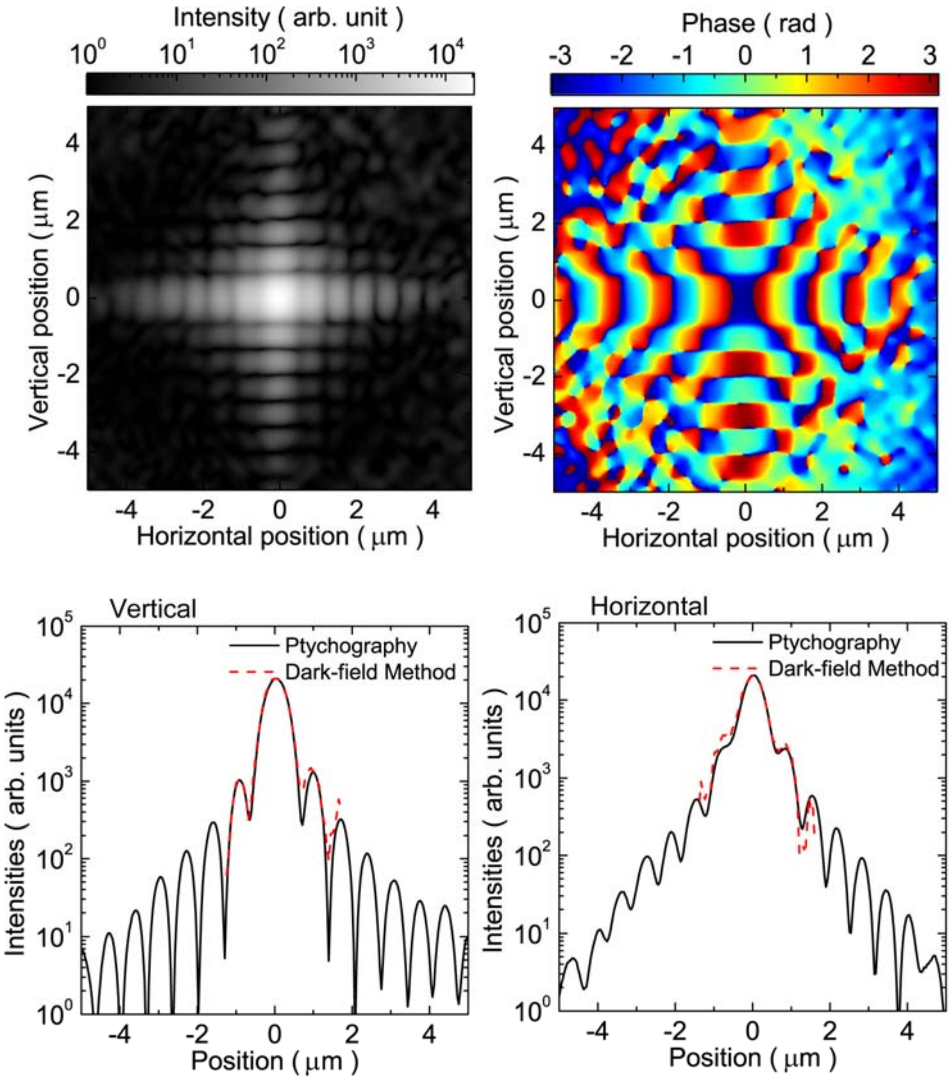
- X線照射位置エラーによるアーティファクト激減
- 50nmの最小構造が分解

正確な位置へのX線照射
再構成像の高い信頼性

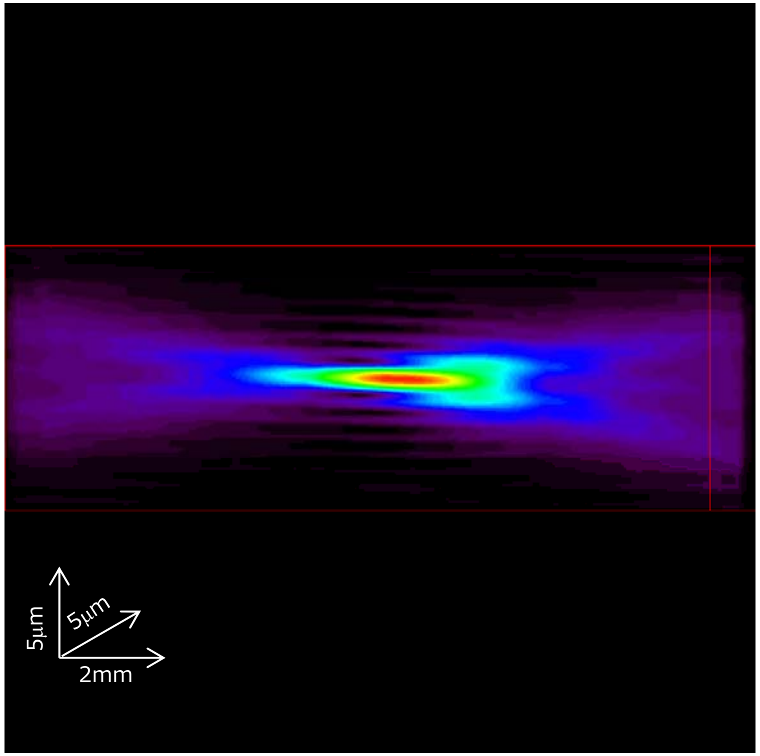
Yukio Takahashi *et al*., *Physical Review B* **83**, 214109 (2011).

X線集光ビームのキャラクタリゼーション

サンプルに照射されたX線の波動場



集光点周辺の波動場: 振幅



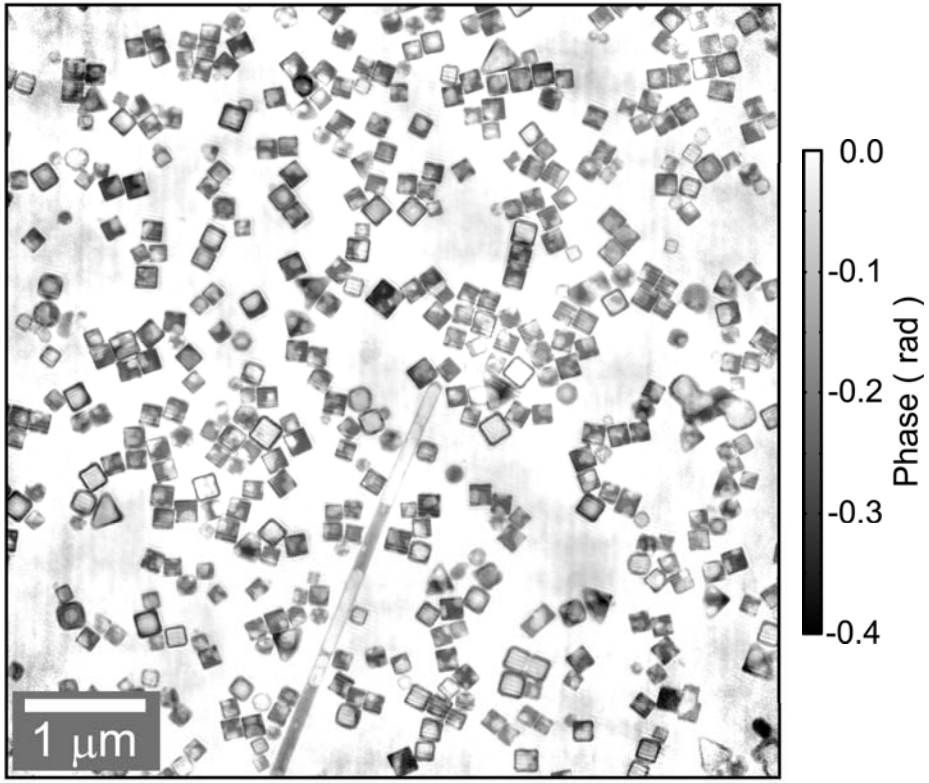
- X線プローブのキャラクタリゼーション
- 試料の再構成の際の初期照射関数

迅速かつ信頼性の高い像再生

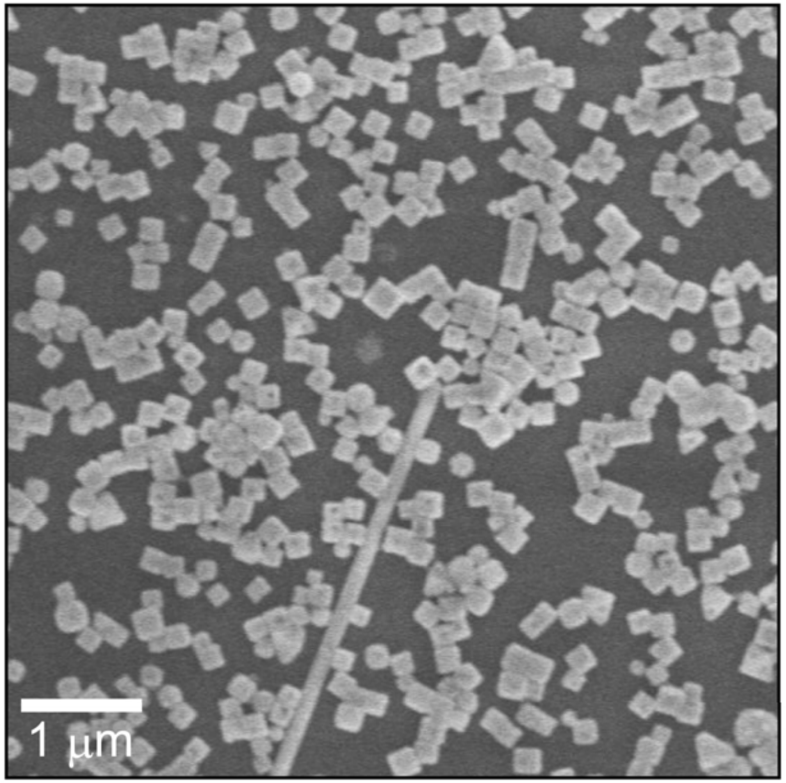
Yukio Takahashi *et al*., *Physical Review B* **83**, 214109 (2011).

Au/Agナノ粒子の観察: SEM vs. X線タイコグラフィー

X線タイコグラフィー像



FE-SEM



- X線エネルギー: 11.7 keV
- 7×7, 500nmステップ
- 測定時間 : ~12 h
- 各点でのX線照射時間 : 280 s
- 視野 : ～5×5 μm^2
- ピクセルサイズ : 8.3 nm

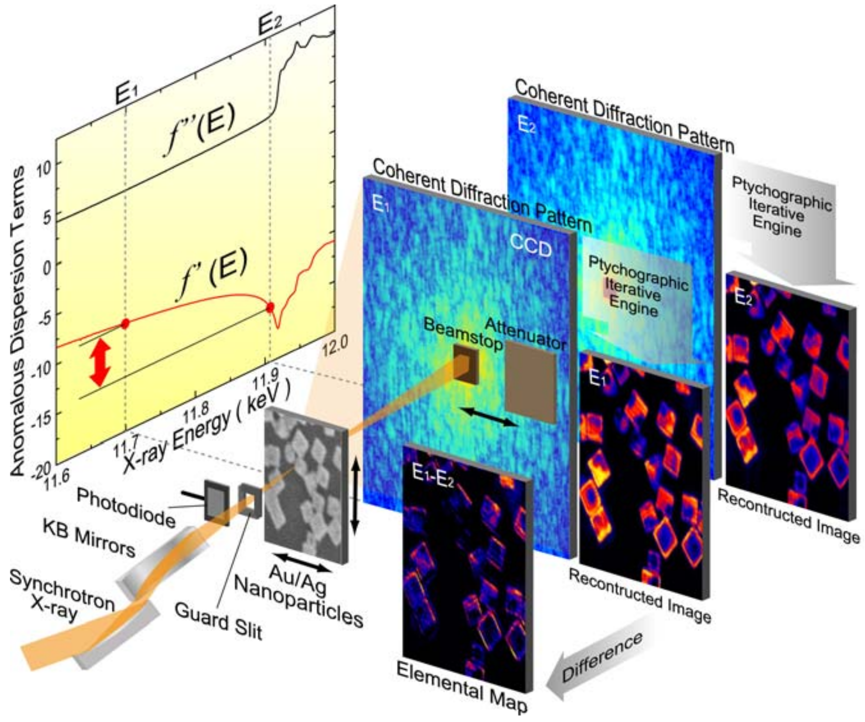
- **約450個のナノ粒子、一本のナノロッド**
- **ホーロー構造、チューブ構造**
- **0.1 radの位相シフトが3.4×10^5electrons/nm^2に対応**

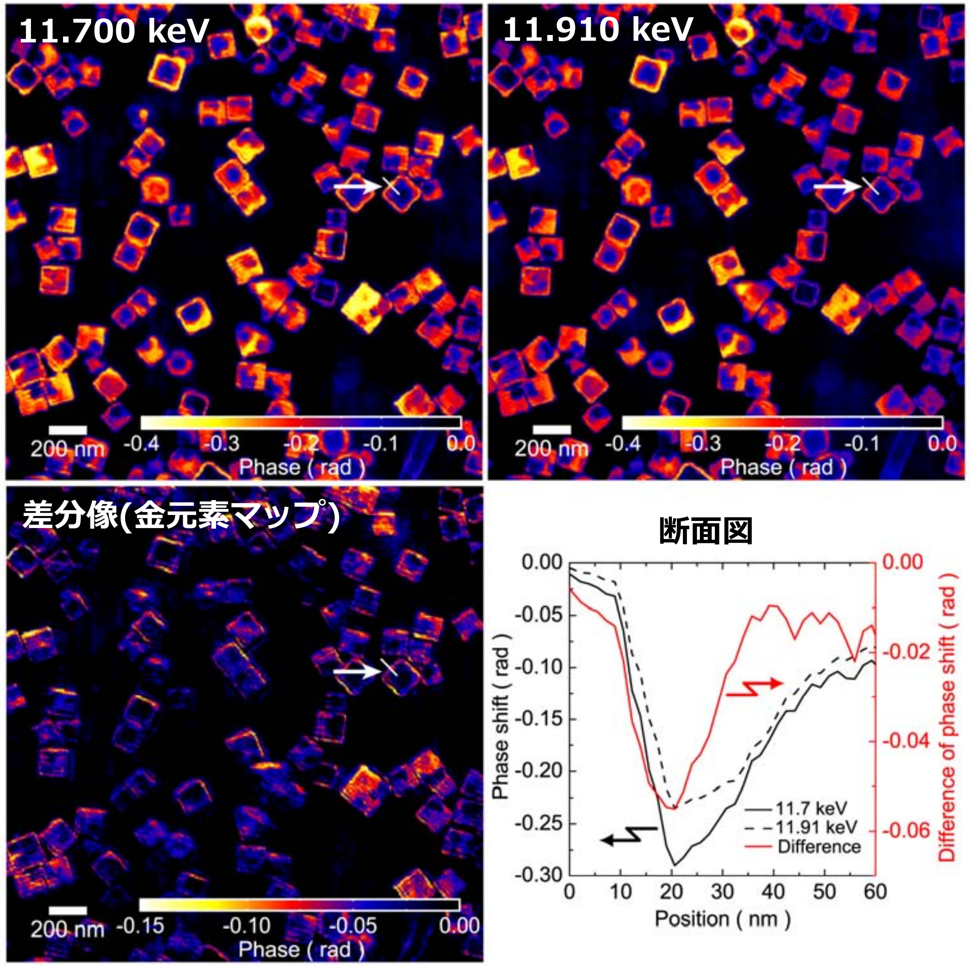
定量的な電子密度イメージング

Yukio Takahashi *et al*., *Applied Physics Letters* **99**, 131905 (2011).

異常散乱現象を利用した元素識別Ｘ線タイコグラフィー

- ターゲット元素の吸収端下の二つのＸ線エネルギーで測定を行う。
- 二つのエネルギーの*f'*の差からターゲット元素が識別される。





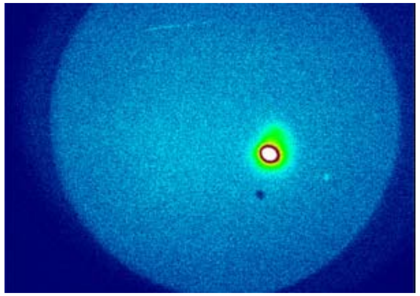
- **金リッチ領域が各粒子の表面に分布**

硬Ｘ線領域での元素識別Ｘ線タイコグラフィーの実証

Yukio Takahashi *et al*., *Applied Physics Letters* **99**, 131905 (2011).

SPring-8キャンパスのX線自由電子レーザー施設SACLA

SACLA: **S**Pring-8 **A**ngstrom **C**ompact Free Electron **La**ser



2011年6月7日：世界最短波長(1.2Å)となるＸ線レーザーの発振に成功.

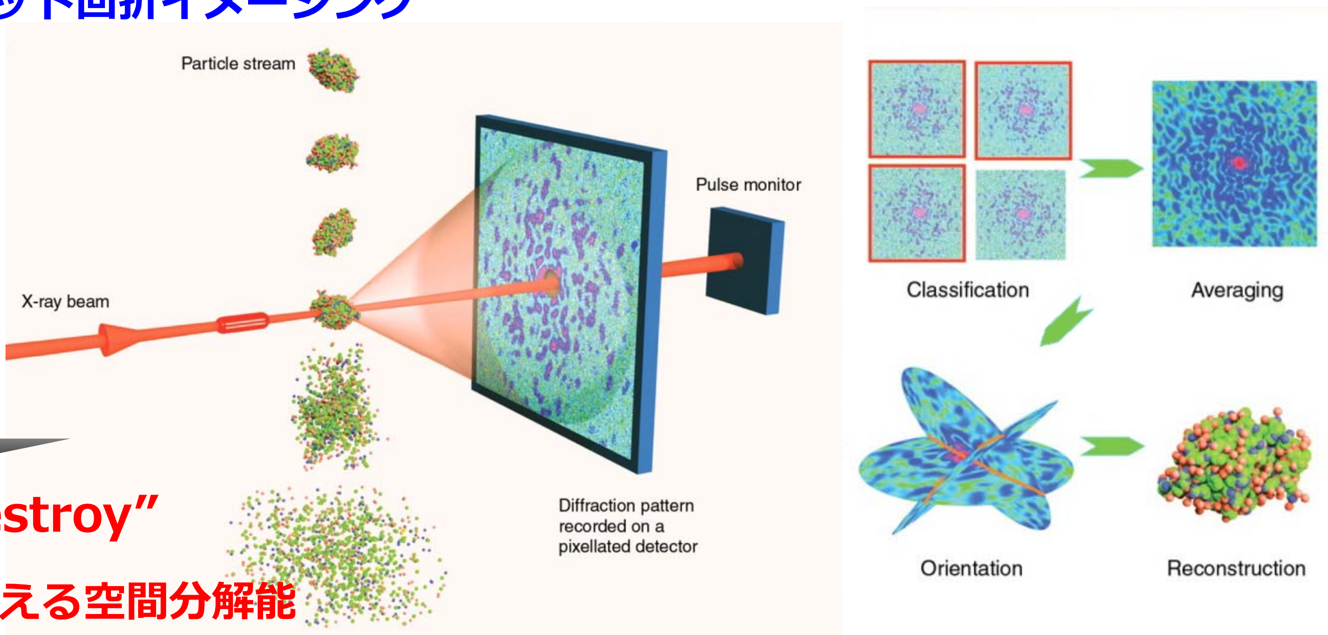
2012年3月～ ：供用運転開始.

XFELによるシングルショット回折イメージング

- **空間的に完全コヒーレント**
- **超短パルス**
  10～30 fs
- **高いピーク輝度**
  10^{10}～10^{11} photons/pulse

"Diffract and Destroy"

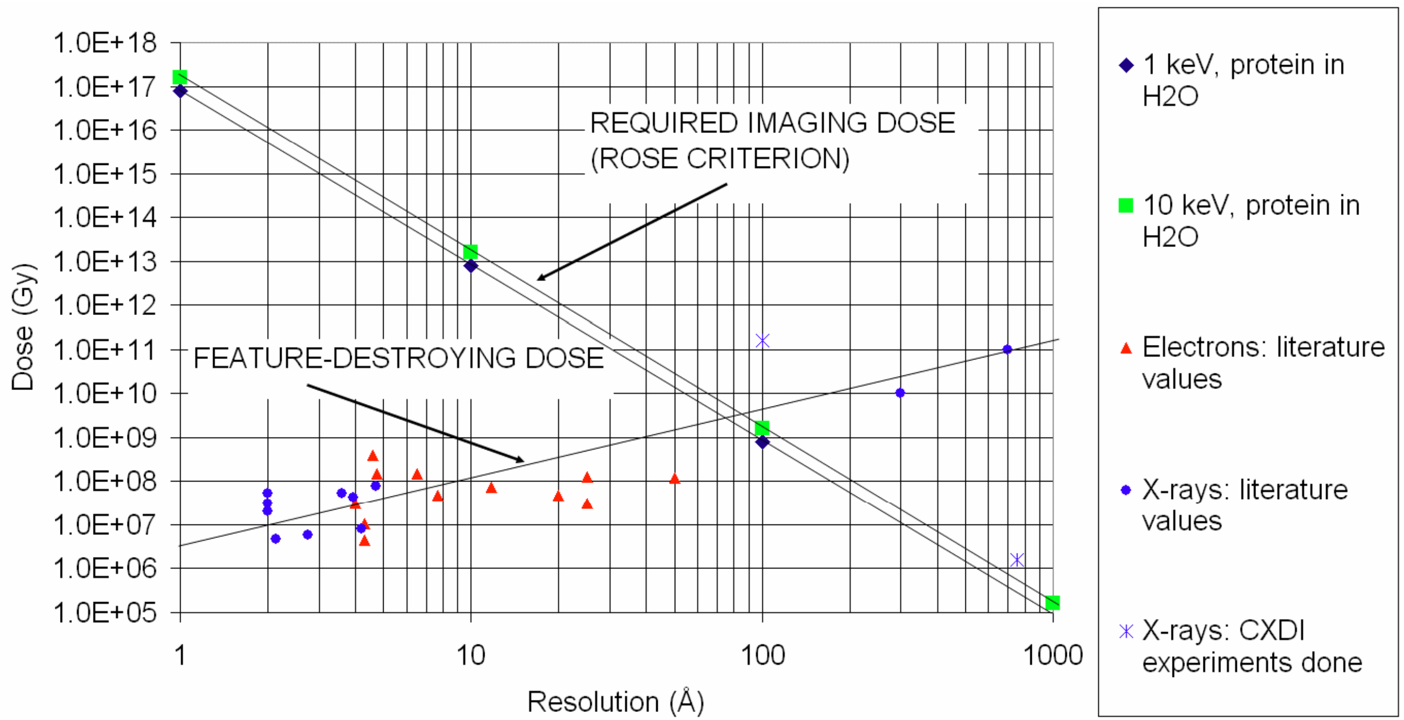
X線照射損傷による限界を超える空間分解能
3D：コピー作製可能な試料



K. J. Gaffney, H. N. Chapman., *Science* **316**, 1444 (2007).

X線照射損傷による空間分解能の制限

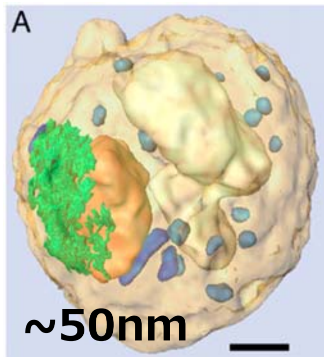
S. Marchesini *et al.*, *Opt. Express* **11**, 2344 (2003).



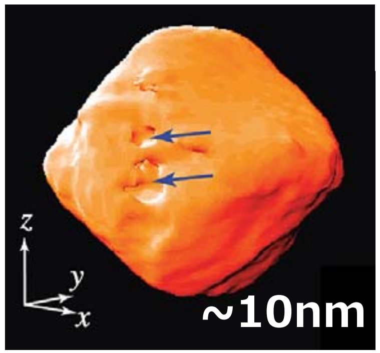
試料非破壊で達成可能な3D分解能

- **凍結水和生物試料 ~10nm**
- **材料科学試料 1~2nm**

現状



H. Jiang *et al.* *PNAS* 2012



Y. Takahashi *et al.* *Nano Lett.* 2010

次世代リング型光源によるコヒーレントX線回折イメージング

次世代リング型光源

- Energy Recovery Linac
- SPring-8 Ⅱ

コヒーレントフラックス3-4桁増加

- 効率的な集光

分解能～1桁改善

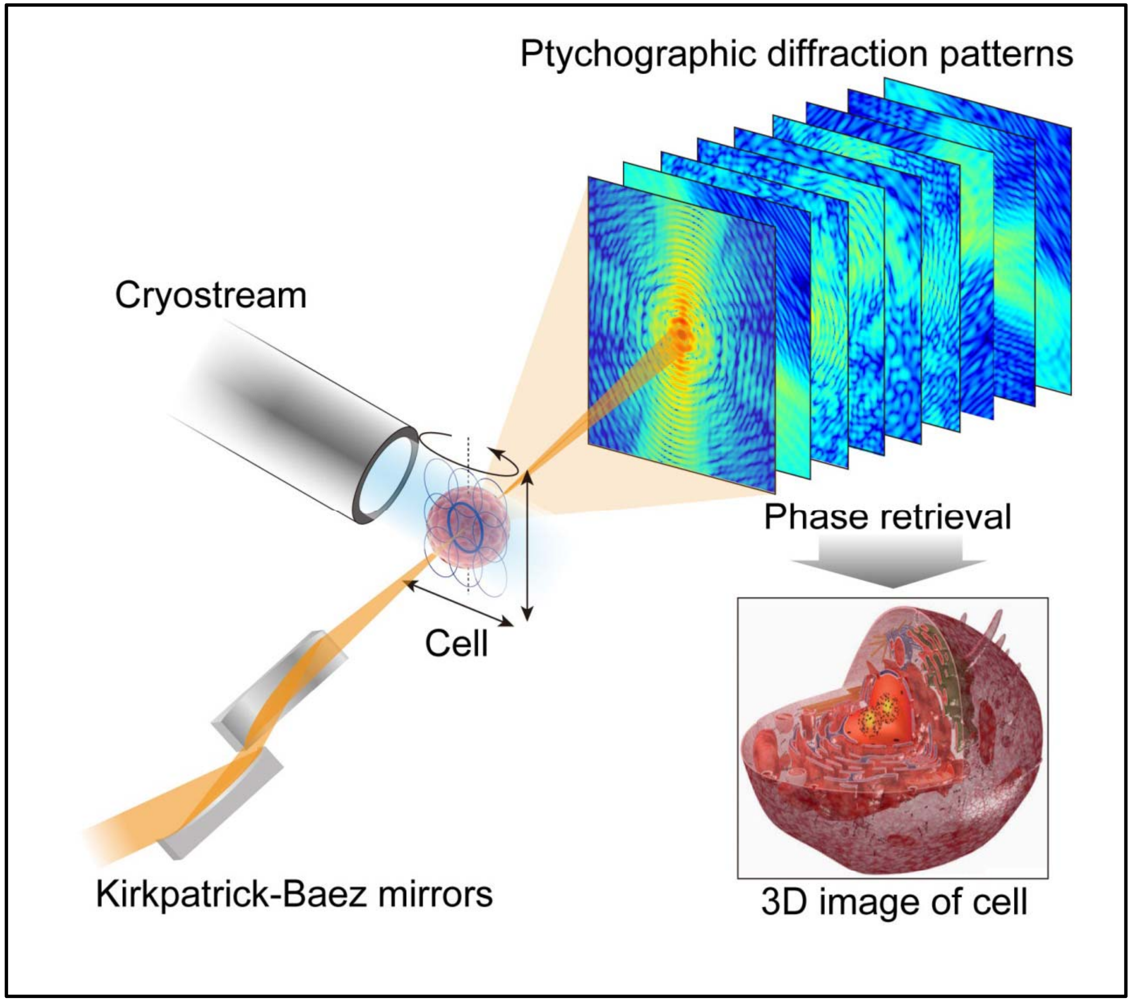
➢ **究極の非破壊イメージング**

- 生物試料 ～10nm
- 材料科学試料 1～2nm

高分解能三次元X線タイコグラフィー

Energy Recovery Linac Preliminary Design Report

3.1 Diffraction imaging using coherent beams

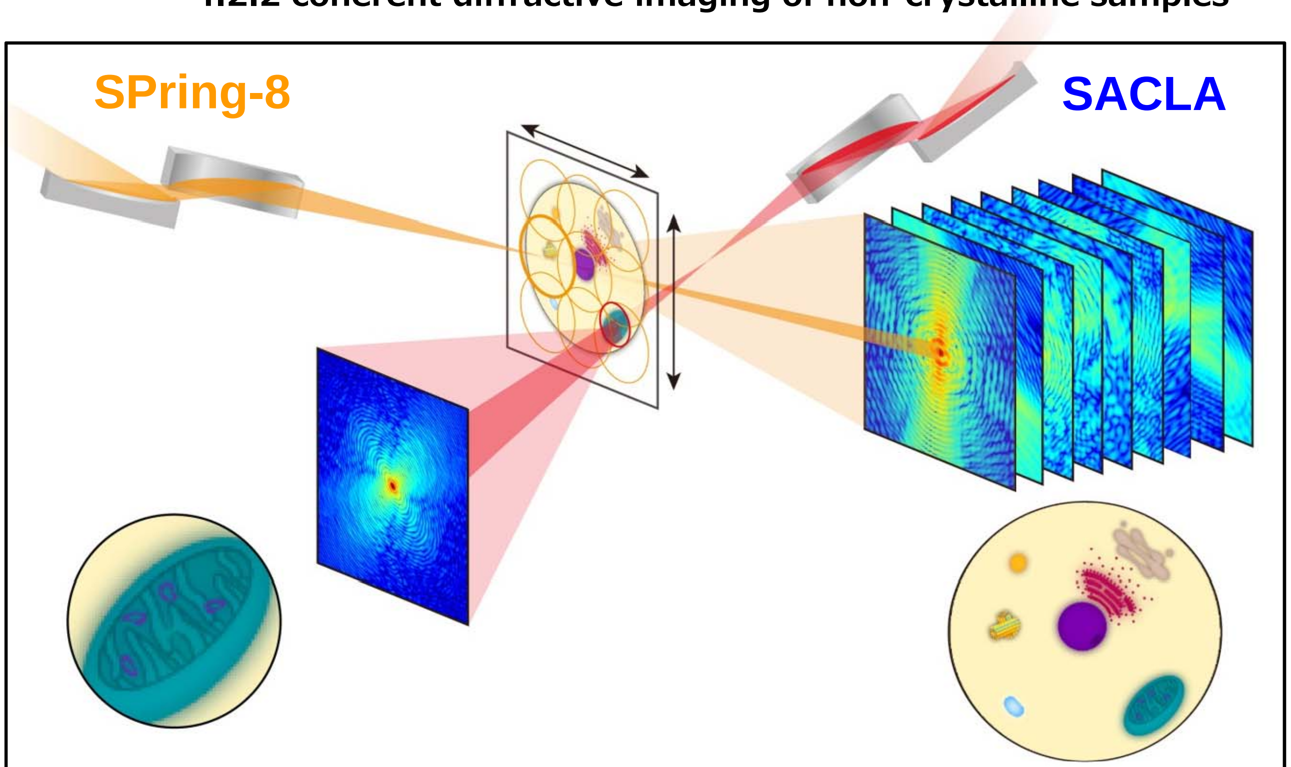


放射光と自由電子レーザーの相互利用によるコヒーレントX線回折イメージング

マルチスケール時空間イメージング

SPring-8 Upgrade Plan Preliminary Report
4.2.2 coherent diffractive imaging of non-crystalline samples

- **空間階層構造**
  0.1nm～100um
- **局所領域のダイナミクス**
  10fs-30fs



シングルショットCXDI
- 選択された小器官
- 物質移動のダイナミクス

X線タイコグラフィー
- 細胞全体
- 小器官の空間分布