X線回折顕微法における二次元X線検出器

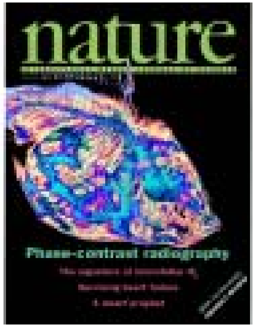
西野 吉則 (SPring-8 / RIKEN)

RCNP研究会 'マイクロパターン検出器の開発と展望'
Jan. 26 - 27, 2006

Yoshinori Nishino

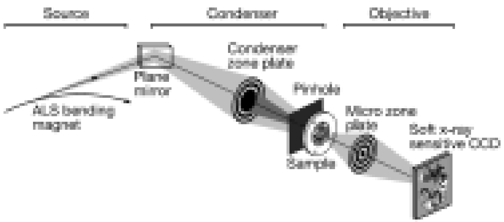
X線を用いた可視化手法 (特に、二次元検出器を用いる手法)

吸収コントラストイメージング
W.C. Röntgen,
Nature **53,** 274-277 (1896)



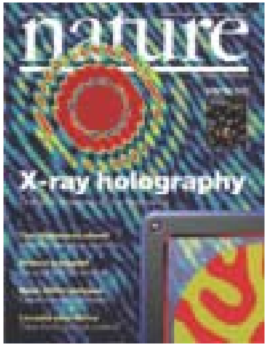
位相コントラストイメージング
S.W. Wilkins *et al*.,
Nature **384**, 335 (1996)

プローブ深さ (非破壊透視)

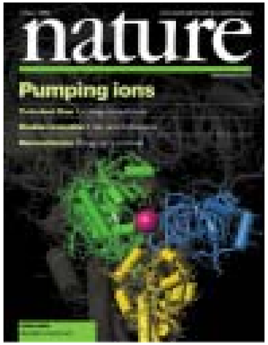


結像型顕微鏡
W. Chao *et al*., Nature **435**, 1210 (2005)

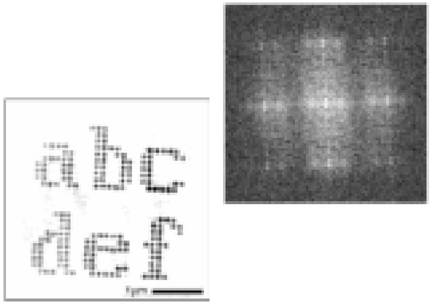
光学 (可視光) 顕微鏡よりも高い空間分解能



ホログラフィー
S. Eisebitt *et al*.,
Nature **432**, 885 (2004)



X線結晶構造解析
C. Toyoshima *et al*.,
Nature **405**, 647 (2000)



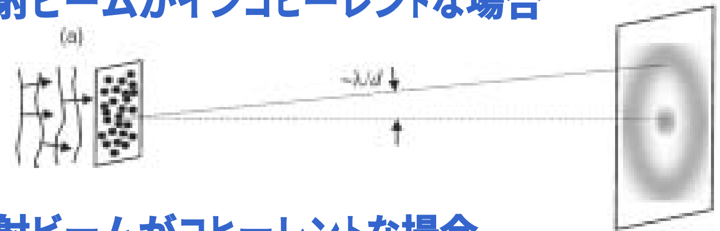
X線回折顕微法
J. Miao *et al*.,Nature **400**, 342 (1999).

位相回復 (散乱の逆問題) ← コヒーレントX線の利用

コヒーレントX線による構造解析

散乱過程は、コヒーレント（弾性）散乱が主要
電子の静止質量エネルギーはX線のエネルギーはよりも大 → 電子の反跳は無視できる

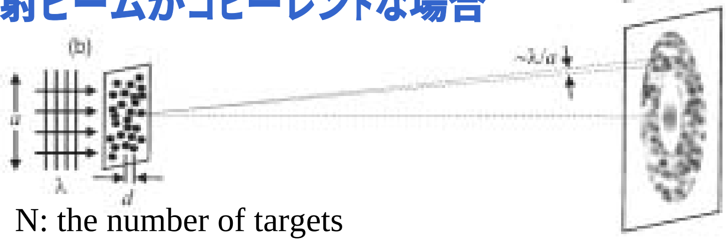
- **入射ビームがインコヒーレントな場合**



$$I(\boldsymbol{K}) \propto N$$

散乱強度分布は
試料の平均構造にのみ依存

- **入射ビームがコヒーレントな場合**



N: the number of targets

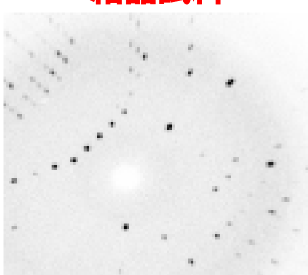
$$I(\boldsymbol{K}) \propto \left|\mathrm{FT}\left[\rho(\boldsymbol{r})\right]\right|^2$$

散乱強度分布は
試料の構造の違いに敏感

F. van der Veen, F. Pfeiffer, J. Phys: Condens. Matter **16**, 5003 (2004).

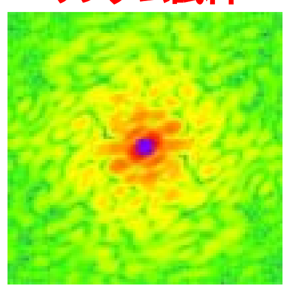
angular size of a speckle $\sim \frac{\lambda}{a}$ e.g. $\frac{0.1\,\mathrm{nm}}{1\,\mu\mathrm{m}} = 100\,\mu\mathrm{rad}$

結晶試料



規則的な回折点

ランダム試料

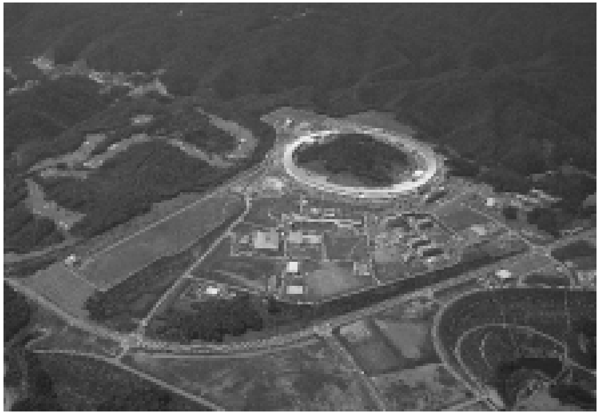


スペックル（斑点）

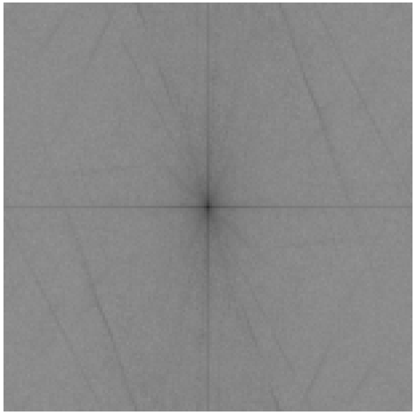
X線回折顕微法における
二次元検出器への要請

連続的に分布 → 高い空間分解能
コントラストが高い → 広いダイナミックレンジ
→ 高い量子効率
顕微法の高分解能化 → 大ピクセル数

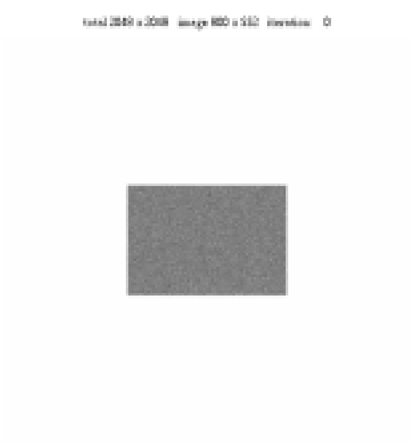
Simulation



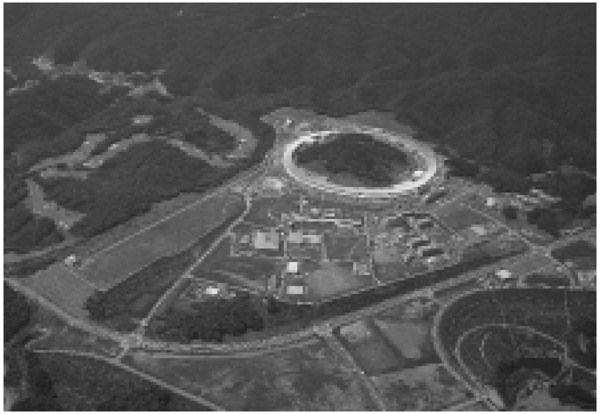
Original Image



Calculated Diffraction Pattern



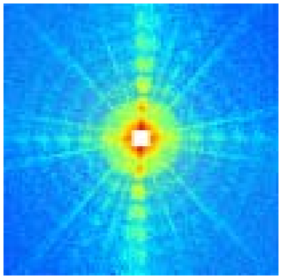
Iterative Image Reconstruction

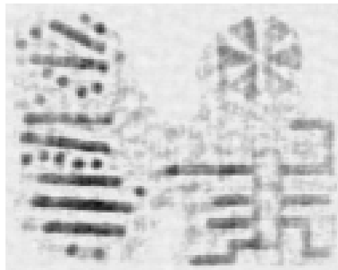


reconstructed image after 5000 iteration

X-ray Diffraction Microscopy Experiment at SPring-8

硬X線回折強度パターンのみからの世界初の試料像再生

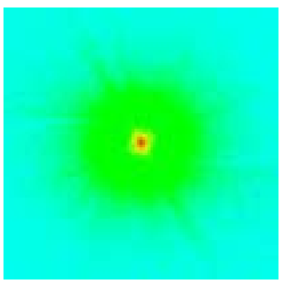




ナノ構造を持つ金製のパターン試料
(2.5 μm × 2.0 μm)

Y. Nishino, J. Miao, and T. Ishikawa, PRB **68**, 220101(R) (2003).

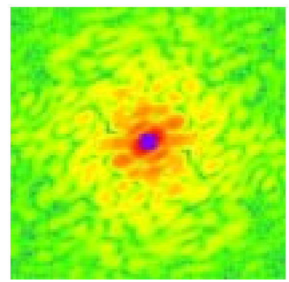
生物試料への世界初の応用

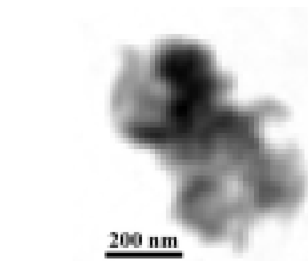


大腸菌

J. Miao, K.O. Hodgson, T. Ishikawa, C.A. Larabell, M.A. LeGros & Y. Nishino, PNAS **100**, 110 (2003).

材料科学への応用



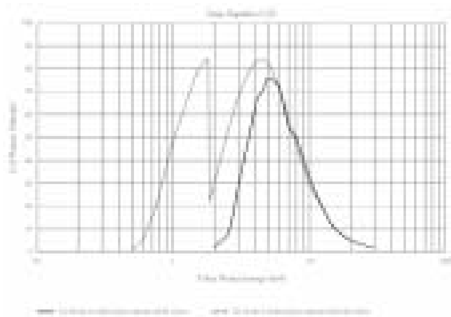


青色発光ダイオードの材料
窒化ガリウム

J. Miao, Y. Nishino, Y. Kohmura, B. Johnson, C. Song, S.H. Risbud & T. Ishikawa, PRL **95**, 085503 (2005).

Deep-Depletion Direct-Illumination CCD

量子効率が高い Deep-Depletion



空間分解能が高い Direct Illumination

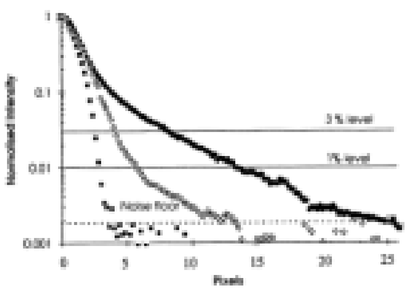
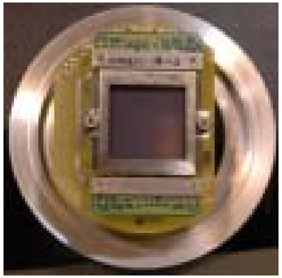


Fig. 2. Point spread functions for etched and unetched scintillator face-plates. For comparison, the PSF of a direct detection CCD is also shown. Scintillator thickness is 40 μm.

C.M. Castelli, N.M. Allinson, K.J. Moon, D.L. Watson
NIM A348, 649 (1994)

Princeton Instruments
PI-LCX:1300
EEV CCD 36-40 1300×1340F



光子数容量が小さい

full potential well ~ 400 ke$^-$
5 keV photon creates 1370 e$^-$/hole pairs.

読み出し速度が遅い

~ 1.8 s / full ROI @ 1 MHz ADC

大面積化が比較的困難

顕微鏡の高空間分解能化に必須

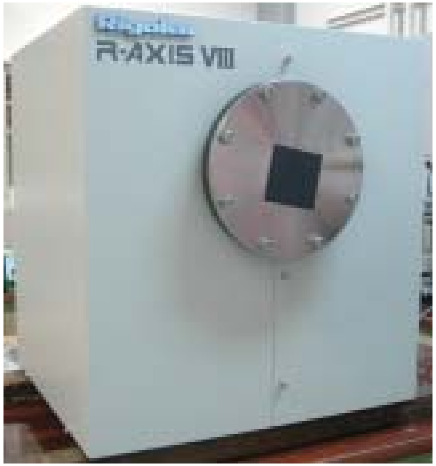
In-Vacuum Imaging Plate Detector

larger area detector
for higher spatial resolution microscopy

extremely slow in reading (~5 min/full ROI)
and erasing (>2 min)

Imaging Plate (in Vacuum) } two sets
Reader and Eraser (in Air) }

taking data with an imaging plate
while reading & erasing the other



R-AXIS VIII (Rigaku Inc.)

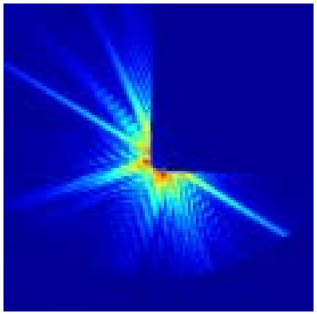
A CCD detector can be mounted downstream of
the IP detector for quick aligment of the sample and optical components.

	R-AXIS VIII	PI-LCX CCD
Total Area	125 mm square	26 mm × 26.8 mm
Pixel Size	25 μm square	20 μm square
Total Pixel	5000 × 5000	1300 × 1340
Photon Capacity	~10^5	~10^2 (direct illumination w/o phosphor)

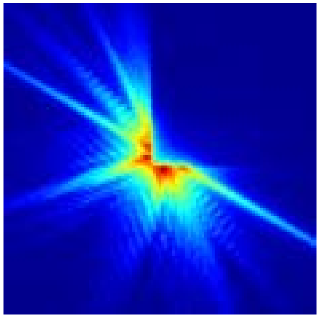
Evaluation of the Imaging Plate Detector

試料: Pt **単一粒子、粒径〜**4 μm
X線エネルギー = 5 keV

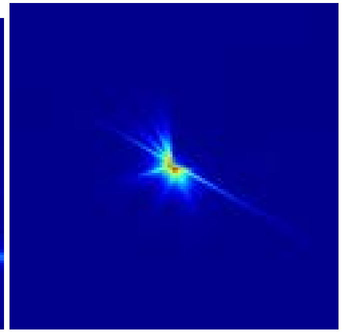
試料: $Ge_{18}Te_{82}$ **一粒子、粒径〜**1.5 μm
X線エネルギー = 5 keV



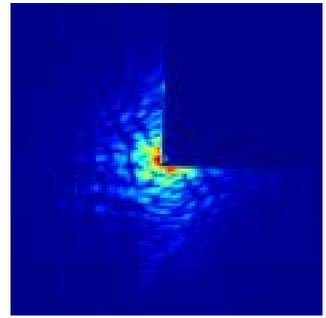
CCD検出器
1001✕1001 pixels
0.01 s ✕ 500 = 5 s



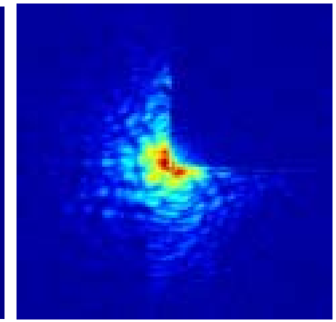
IP検出器
555✕555 pixels
10 s ✕1 = 10 s



IP検出器
2001✕2001 pixels
10 s ✕ 1 = 10 s
(左と同じデータ)

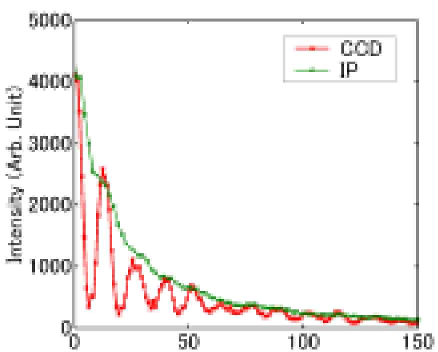


CCD検出器
1001✕1001 pixels
0.15 s ✕ 500 = 75 s



IP検出器
555✕555 pixels
75 s ✕ 1 = 75 s

長く伸びるストリーク上の強度プロファイル



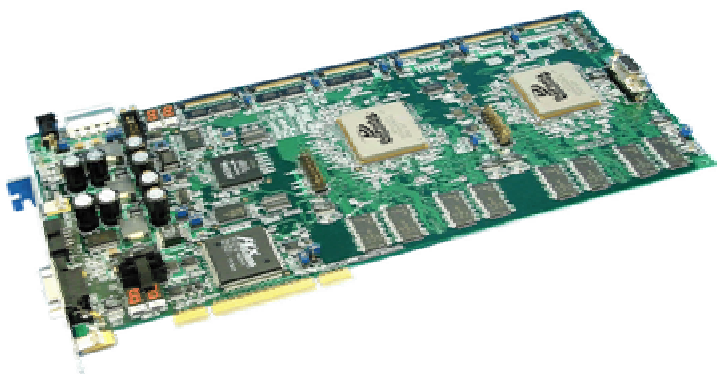
空間分解能が低い

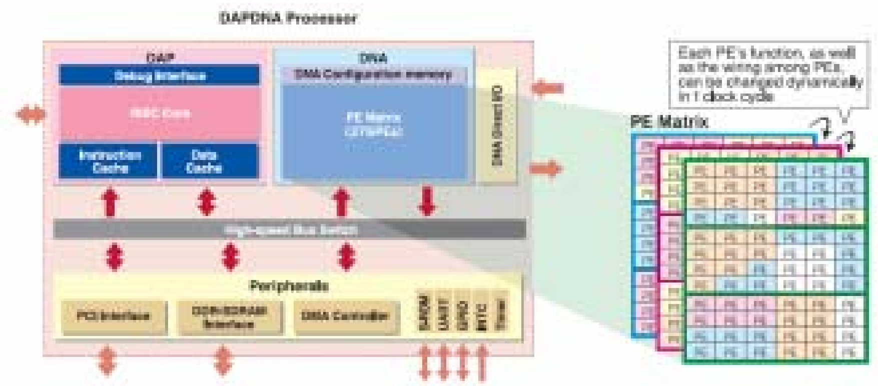
左図: IP**位置での強度変動の空間周期**
~178 μm (~ 7 pixel)**が分解出来ない**

量子効率が低い
ノイズが大きい

Dynamic Reconfigurable Processor

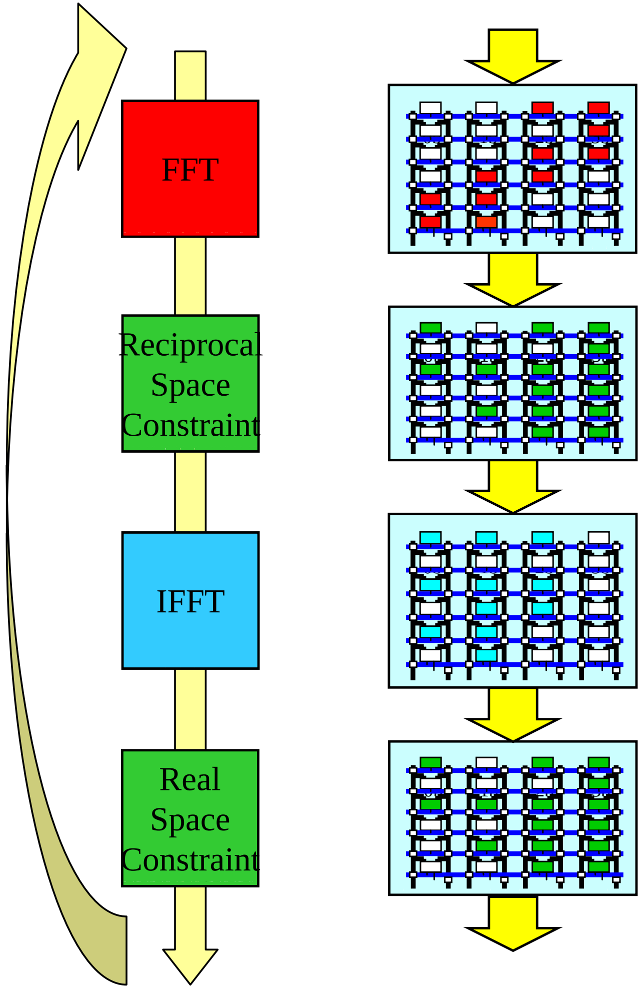
- von Neumann architecture ← most computers
  - general purpose hardware
  - application specific software
- ASIC (Application Specific Integrated Circuit)
- FPGA (Field Programmable Gate Array)
  - static reconfigurable
- Dynamic Reconfigurable Processor





DAPDNA-EB4 (PCI card)
IP FLEX inc.

Image Reconstruction with Dynamic Reconfigurable Processor



reconfiguration in one clock cycle
~ 6 ns with 166 MHz clock frequency

FFT / IFFT
~ 13 times faster
than 3.60 GHz Pentium 4 Processor

It takes 87 sec for 1000 iterations of
1024 × 1024 pixel image reconstruction

X線FELでの利用を目指した二次元X線検出器

- Coherent
- Intense
  ~ 10^{12} photons/pulse
- Short-Pulse
  sub-pico second pulse duration

⇩

試料構造のフェムト秒スナップショット/スナップショットムービー

電荷積分型ピクセル検出器を候補に検討を始める

Collaborators

Experiment at SPring-8 BL29XUL

Yukio Takahashi, Yoshiki Kohmura, Tetsuya Ishikawa (SPring-8/RIKEN)
Jianwei Miao, Changyoung Song (UCLA)
Bart Johnson (SSRL/SLAC)

In-Vacuum Imaging Plate Detector

Yukio Takahashi, Masaki Yamamoto, Tetsuya Ishikawa (SPring-8/RIKEN)
RIGAKU (http://www.rigaku.co.jp/)

Dynamic Reconfigurable Processor

Kuniaki Koike, Toshikazu Ebisuzaki (RIKEN)
Tetsuya Ishikawa (SPring-8/RIKEN)
IP FLEX Inc. (http://www.ipflex.com/)

X-ray Detector for X-Ray FEL (plan)

Atsushi Taketani, Hideto En'yo, Toshikazu Ebisuzaki, *et al*. (RIKEN)
Hidenori Toyokawa *et al*. (SPring-8/JASRI)
Tetsuya Ishikawa *et al*. (SPring-8/RIKEN)