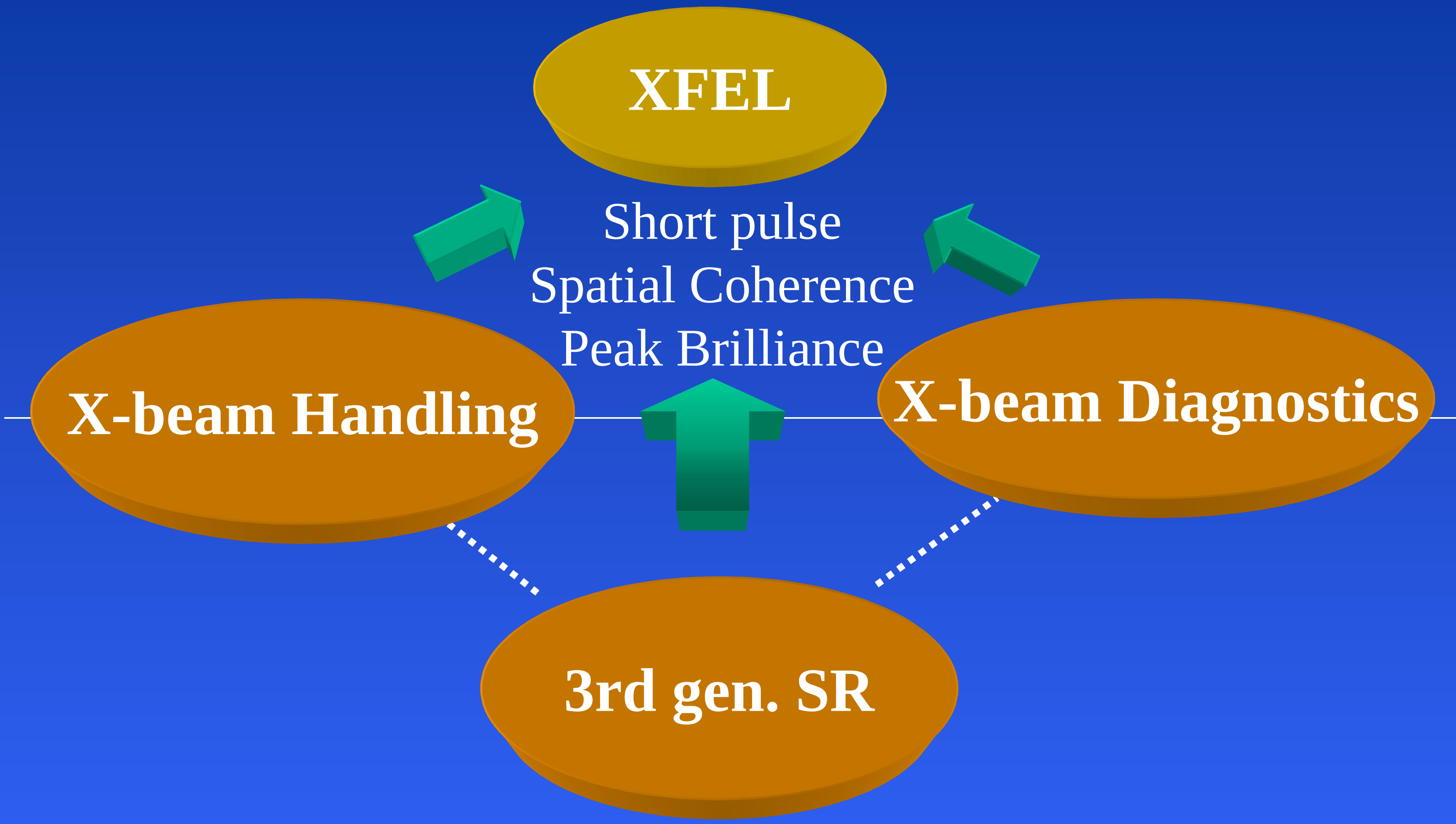
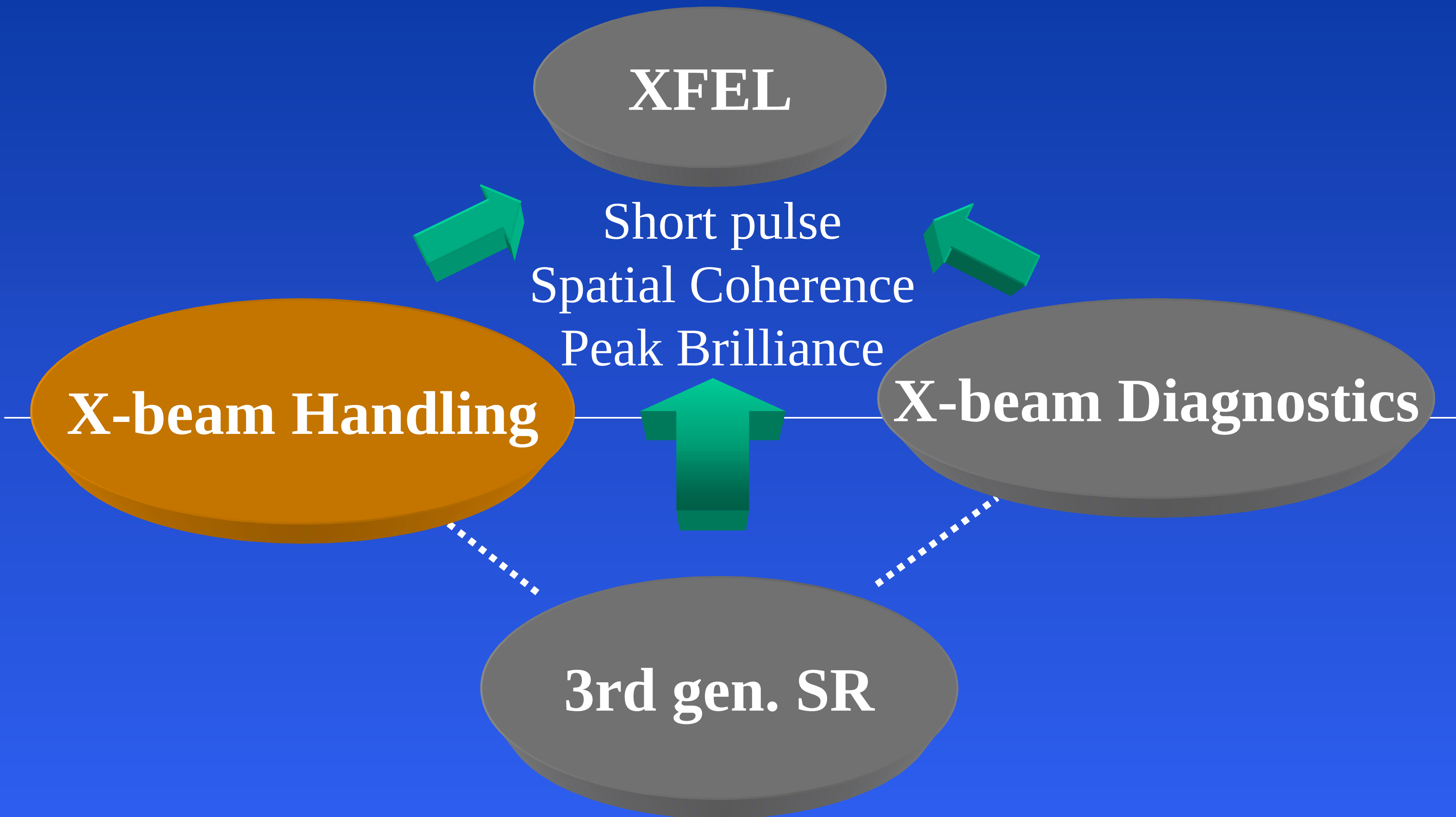
Overview of x-ray techniques

Makina YABASHI

SPring-8/JASRI

ICFA Future Light Sources Subpanel
Miniworkshop on XFEL Short Bunch Measurement and Timing
Stanford Linear Accelerator Center
July, 26 2004


XFEL
Short pulse
Spatial Coherence
Peak Brilliance
X-beam Handling
X-beam Diagnostics
3rd gen. SR


XFEL
Short pulse
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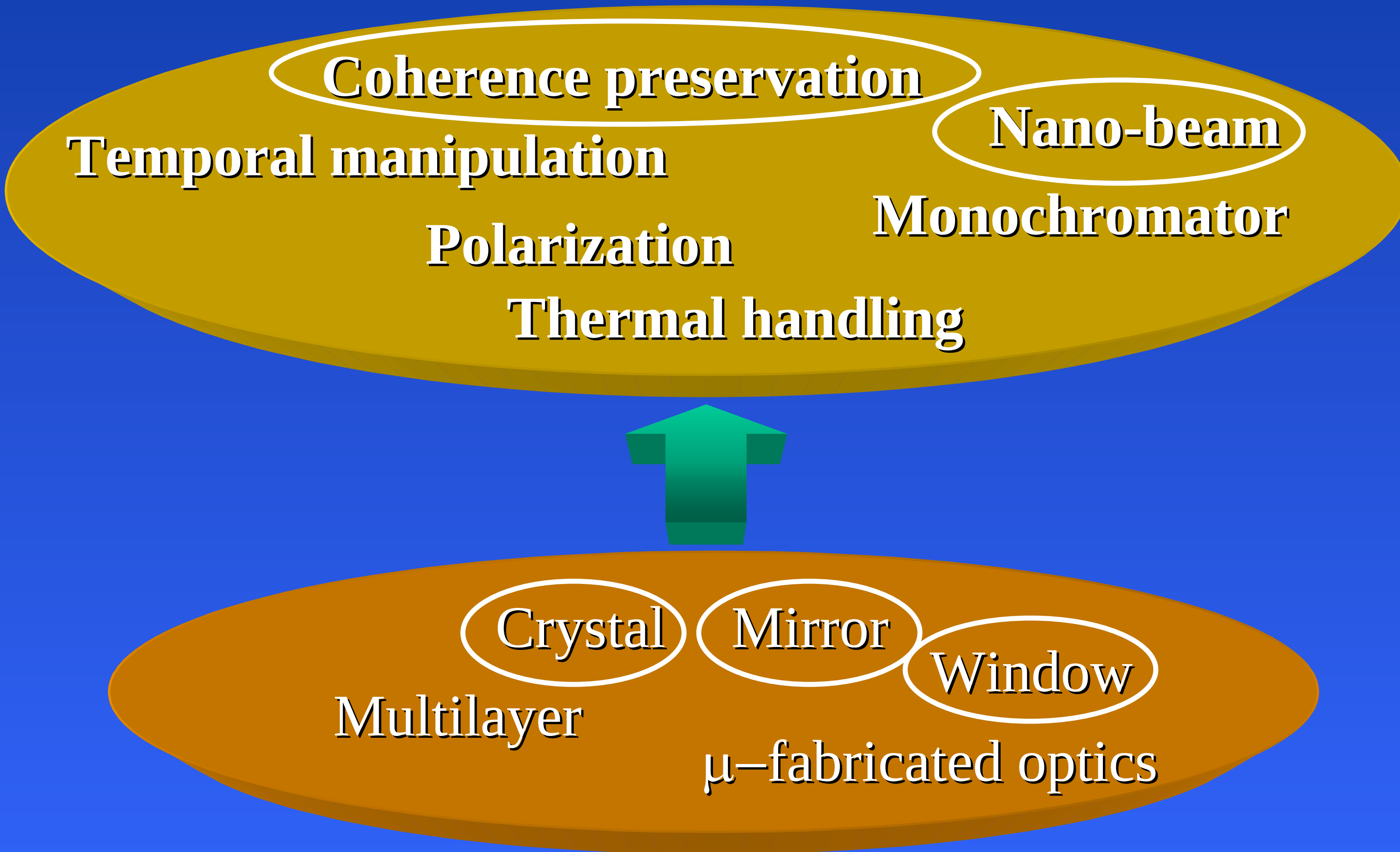
3rd gen. SR

X-ray handling

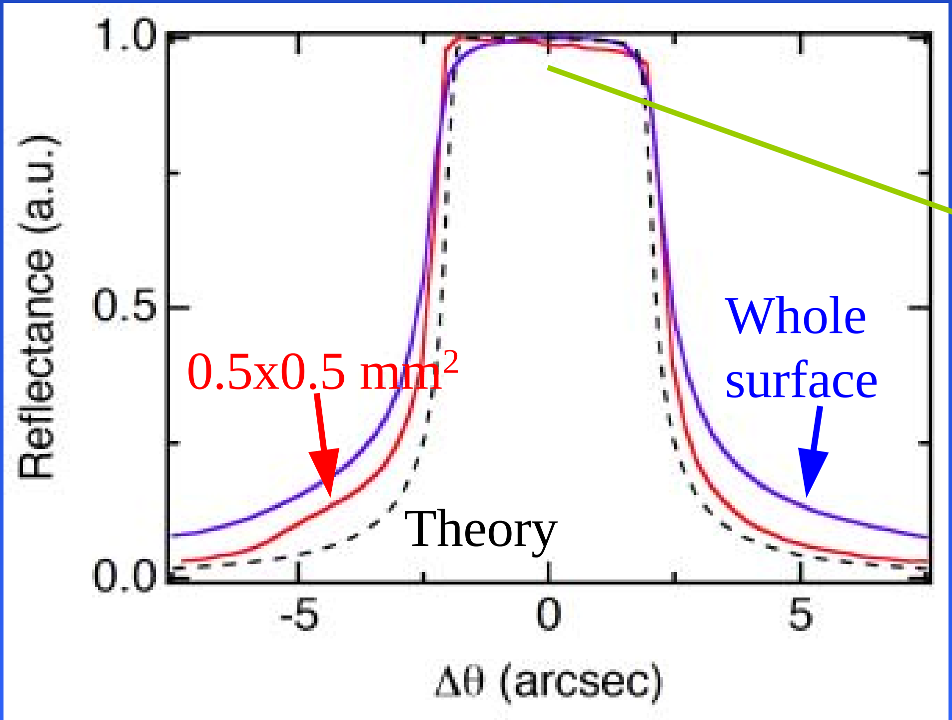


Crystal: Diamond

Diamond workshop @ ESRF, May 24-25, 2004

Tamasaku et al: "Characterization of synthetic IIa diamonds at SPring-8"

Bragg Geometry Si 220(b=20.9)-C 111 @9.44 keV



5 mm

g_{111}

1 mm

(Sumitomo IIa)

Mirror

Can we use under coherent illumination ?

Mirror: SP8 - Osaka Univ. collaboration

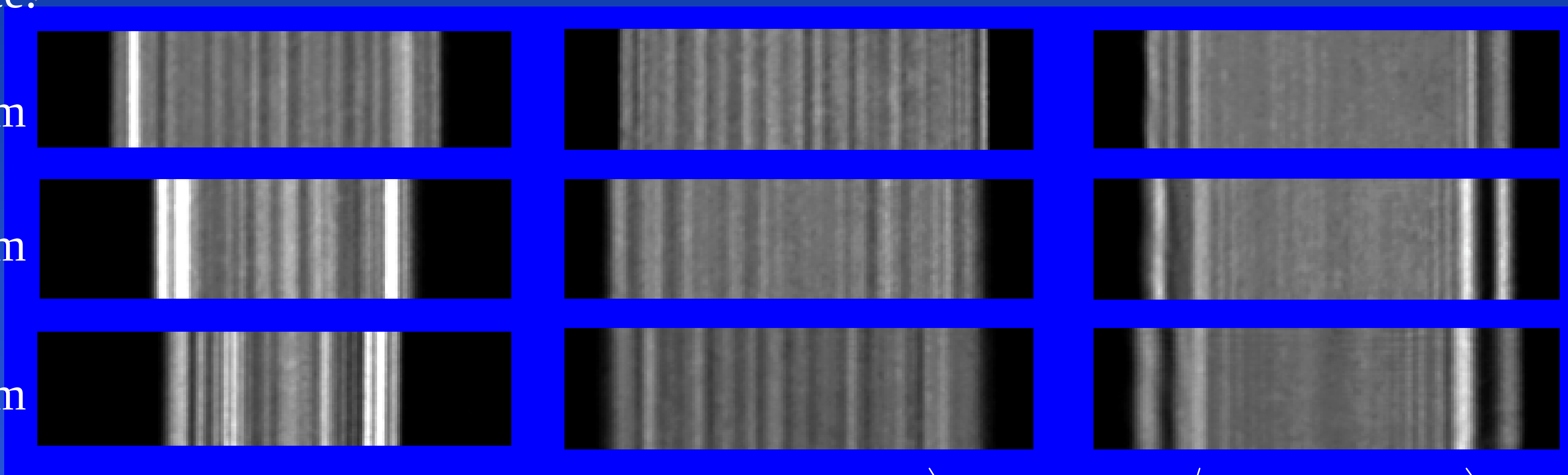
Mirror: Silicon (001) / Incident angle 1.2 mrad / Mirror length 100 mm

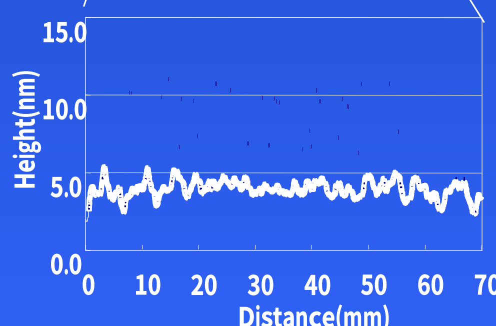
Camera distance: | Premachined surface | CVM surface | CVM+EEM surface

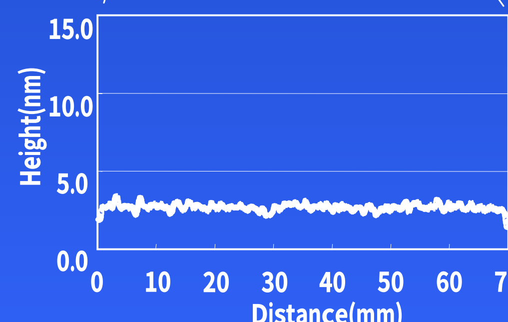
166 mm

566 mm

066 mm





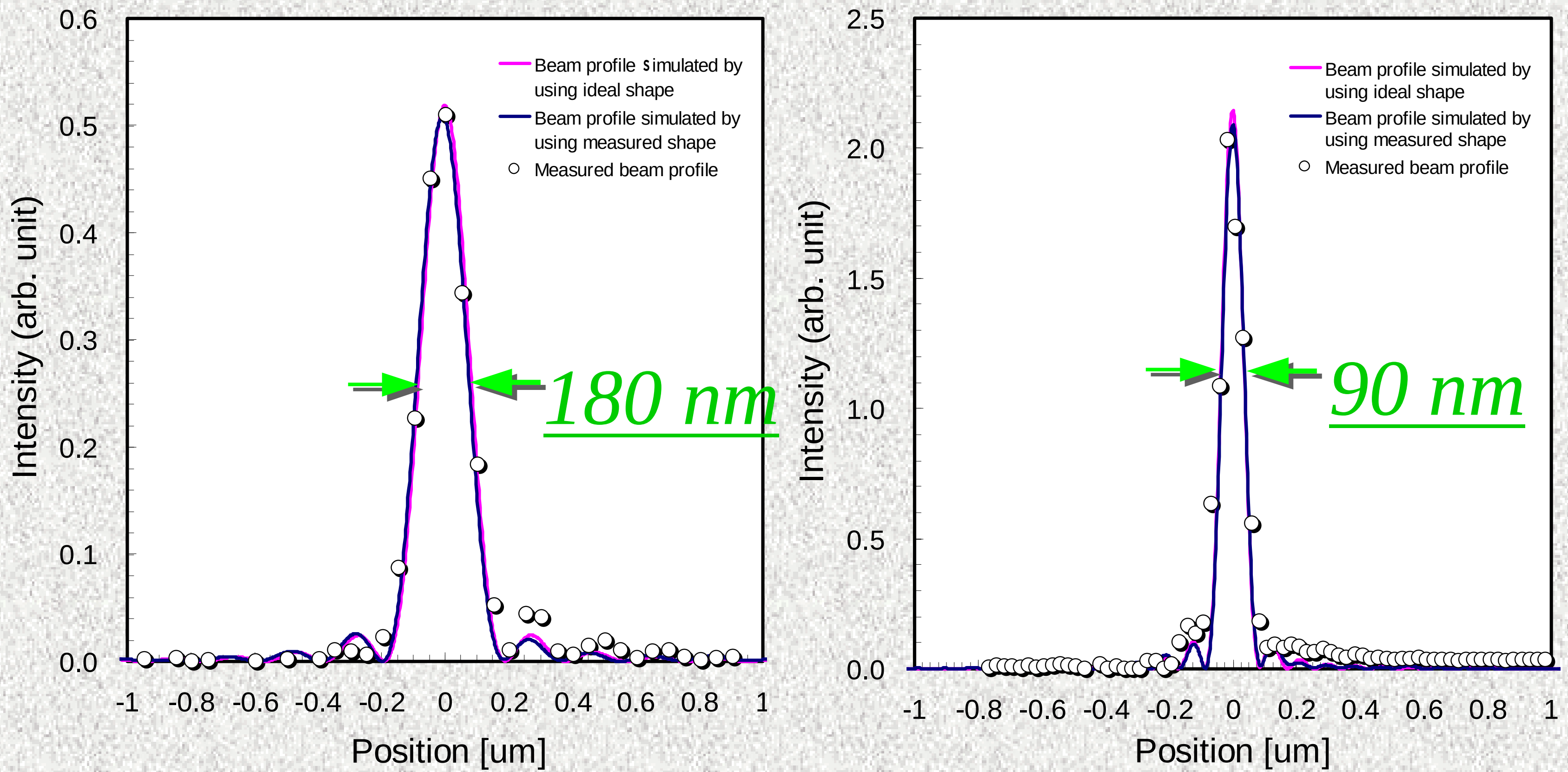


Mori *et al*, *Proc. SPIE* (2001)

Mirror: Nanobeam

Summer in 2003

E=15 keV(**λ** =0.8 Å)

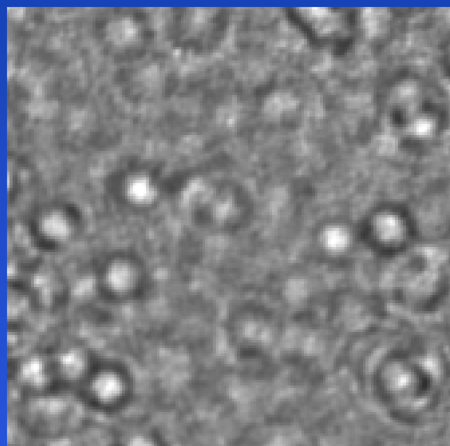


July 2004: **40 nm** focus was achieved !

Mimura et al.

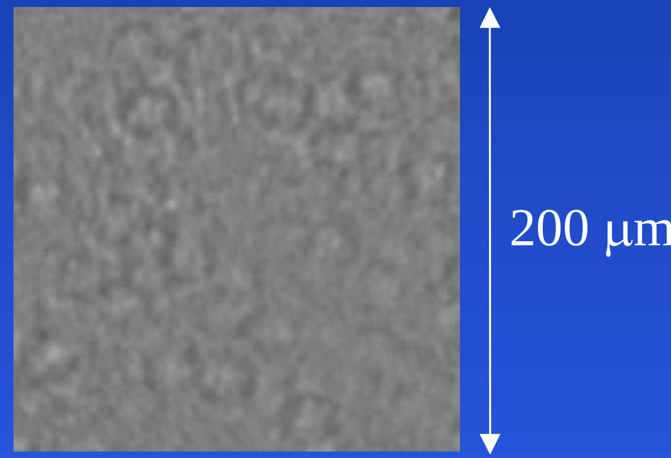
Window: Be

NGK, BR-3



Purity: 98.5 %
Roughness: > 1 μm Ra
Thickness: 200 μm

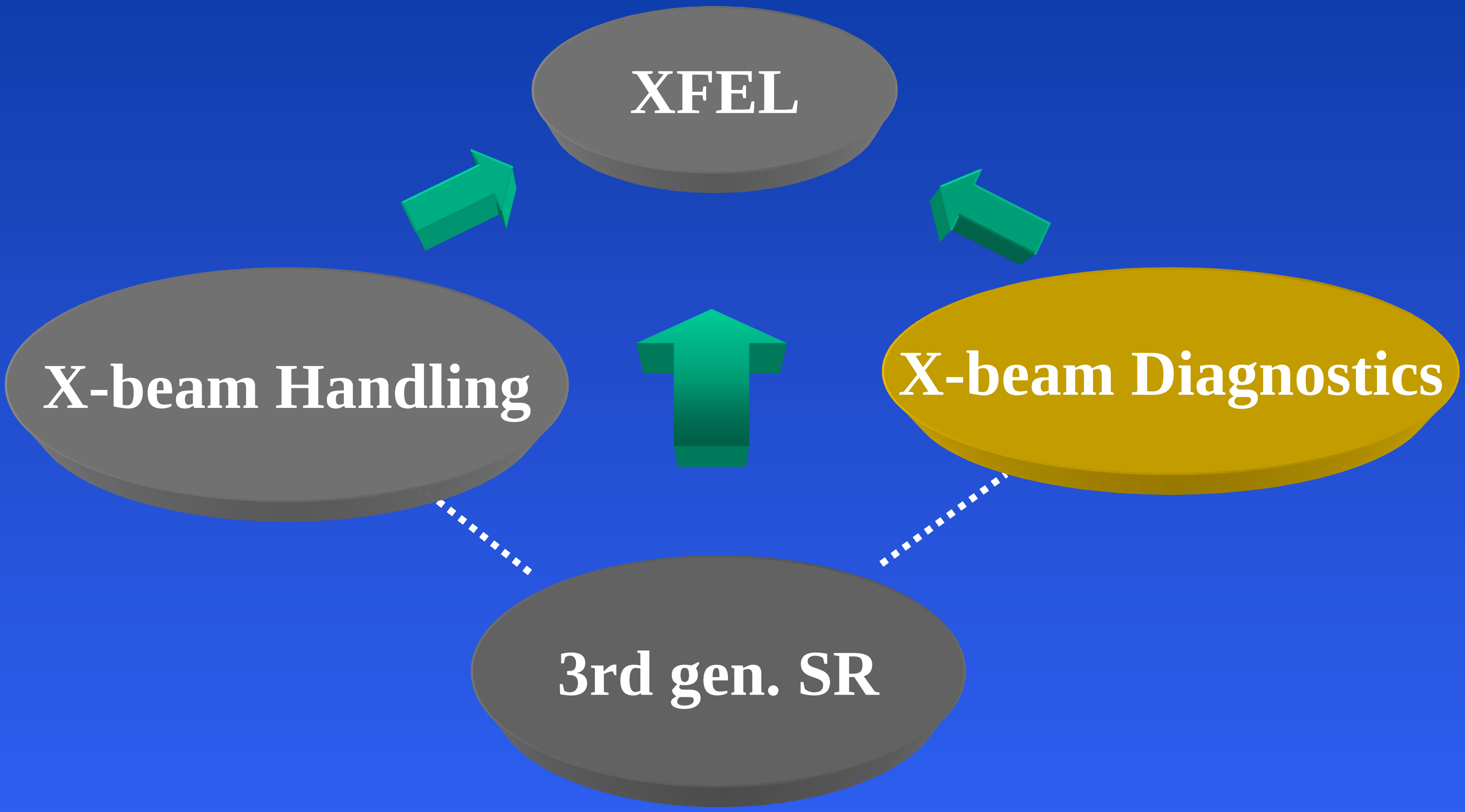
Brush-Wellman, IF-1



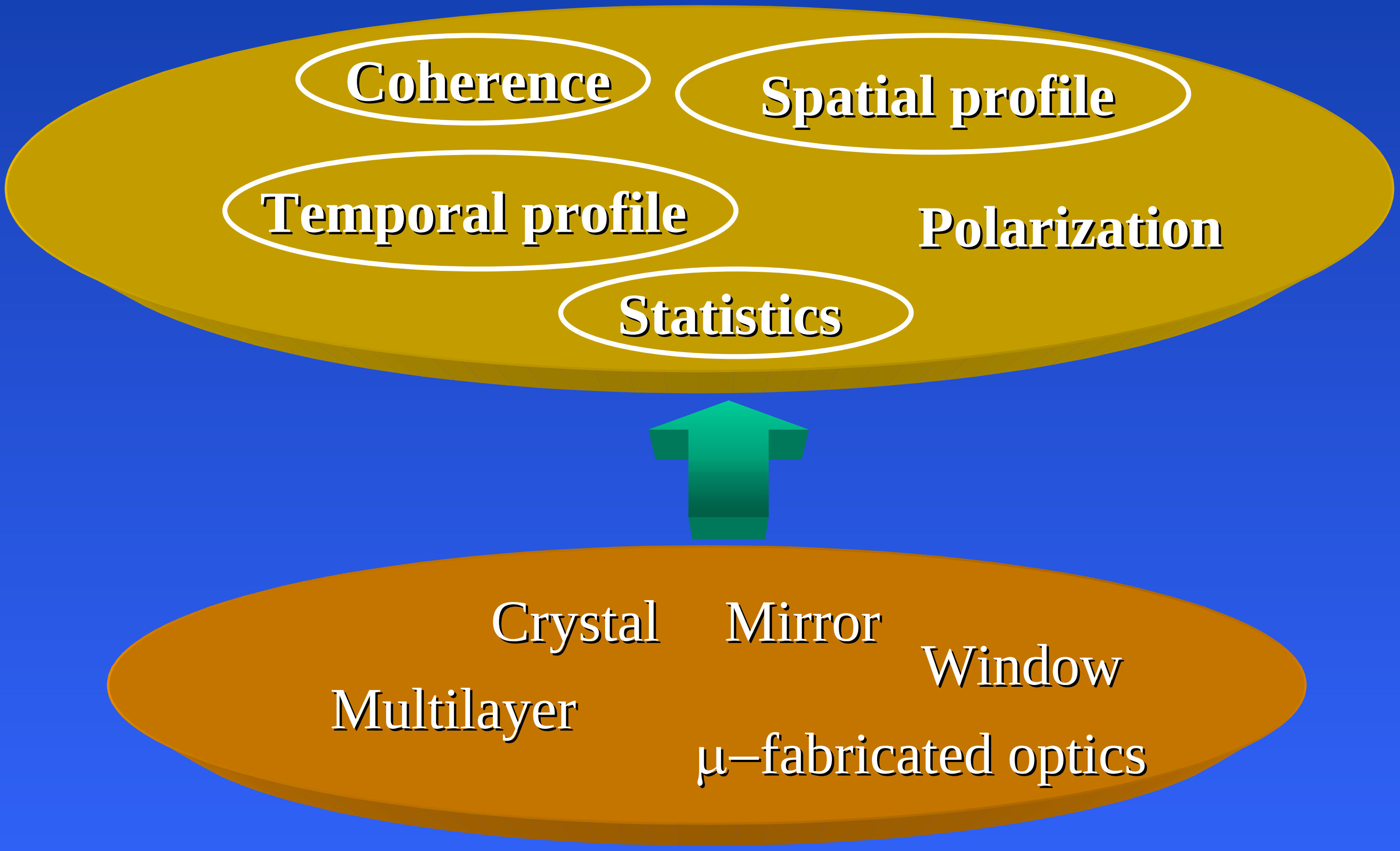
Purity: 99.8 %
Roughness: 0.1 μm Ra
Thickness: 250 μm t

Phase contrast imaging @ 1-km BL
(0.5 μm res., *L* ~1.8 m, λ ~1 Å)

S. Goto et al: Proc. SRI2003


XFEL
X-beam Handling
X-beam Diagnostics
3rd gen. SR

X-ray diagnostics



Temporal profile

	Resolution	Envelop	Repeat
Present	~ ps	Simple (Gaussian)	Multi-shot (average)
Target	~ fs, as	Complex (arbitrary)	Single-shot

How to measure

Temporal domain

Laser & X-ray coincidence

Fourier transform

Frequency domain

X-ray Spectral

Interferometry

Spatial profile: Coherence

Real-space domain

e-beam size measurement

Fourier transform

Reciprocal-space domain

X-ray Interferometry

Diagnostics

Temporal domain

Laser & X-ray coincidence

Real-space domain

e-beam size measurement

Fourier transform

Frequency domain

X-ray Interferometry

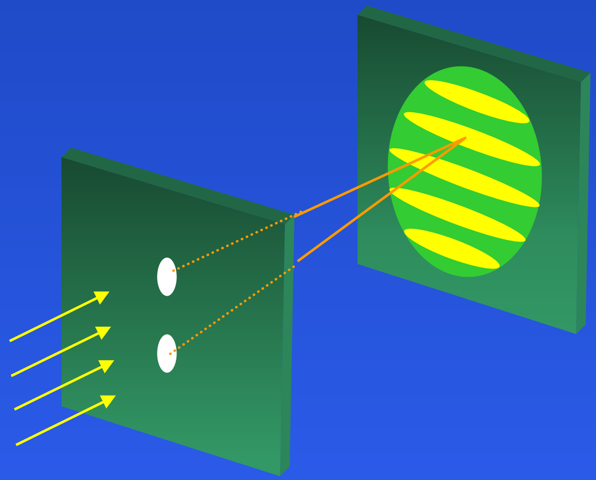
Reciprocal-space domain

X-ray Interferometry

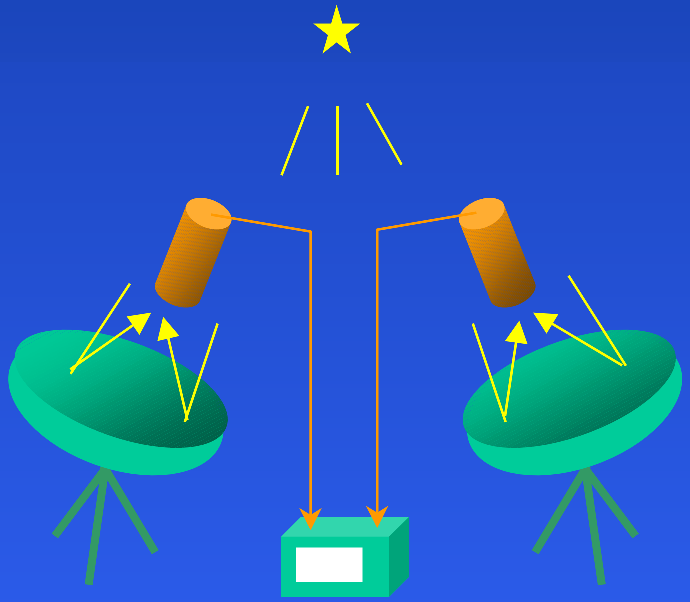
Interferometry

Amplitude interferometry

Intensity interferometry



Thomas Young, 1807



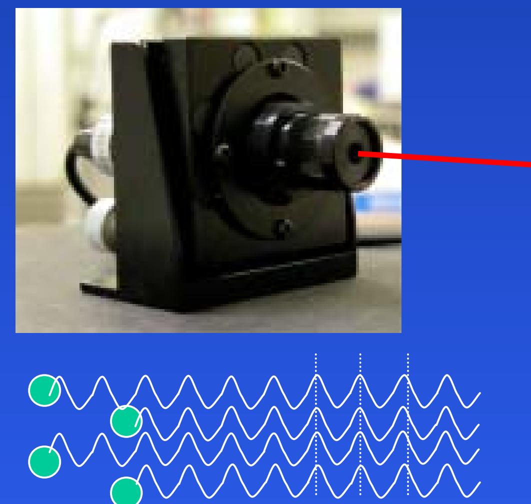
Hanbury-Brown and Twiss, 1956

Photon Statistics

Photon statistics

July 2004

Chaotic light



Coherent light

Intensity interferometry (2nd-order interferometry)

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Instantaneous wave field

Point / Coherent source

$$E(r,t) \propto N_e \exp\left[\frac{2\pi i r}{\lambda}\right] e^{i\omega t}$$

Point / Chaotic source

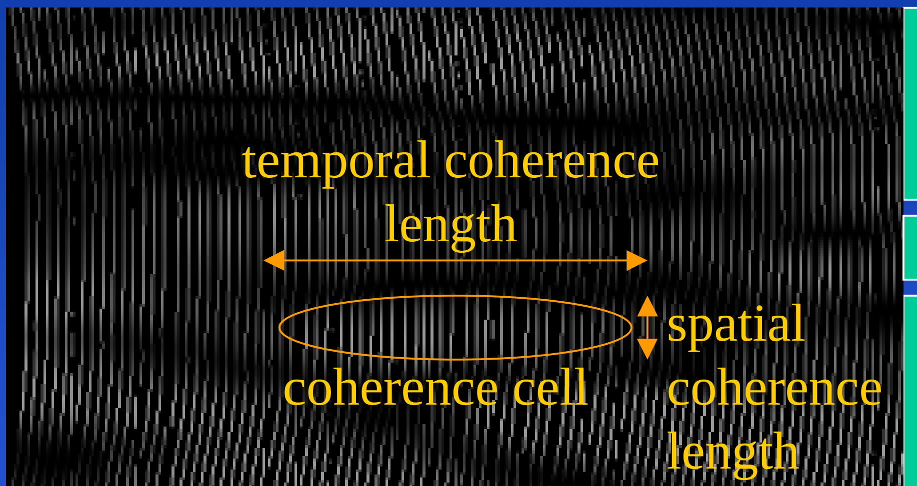
$$E(r,t) \propto \sum_i^{N_e} \exp\left[\frac{2\pi i r}{\lambda} + \boxed{i\phi_i(t)}\right] e^{i\omega t}$$

Planer /Chaotic source

$$E(r,t) \propto \sum_i^{N_e} \exp\left[\frac{2\pi i \left| r - \boxed{s_i} \right|}{\lambda} + i\phi_i(t)\right] e^{i\omega t}$$

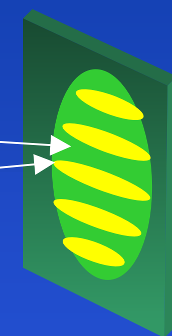
Loudon, 1983
Goodman, 1985

Wave packet



$$\langle I \rangle = \langle I_A \rangle + \langle I_B \rangle + \Gamma_{AB} + \Gamma^*_{A}$$

$$\Gamma_{AB} = \langle E^*_A E_B \rangle$$

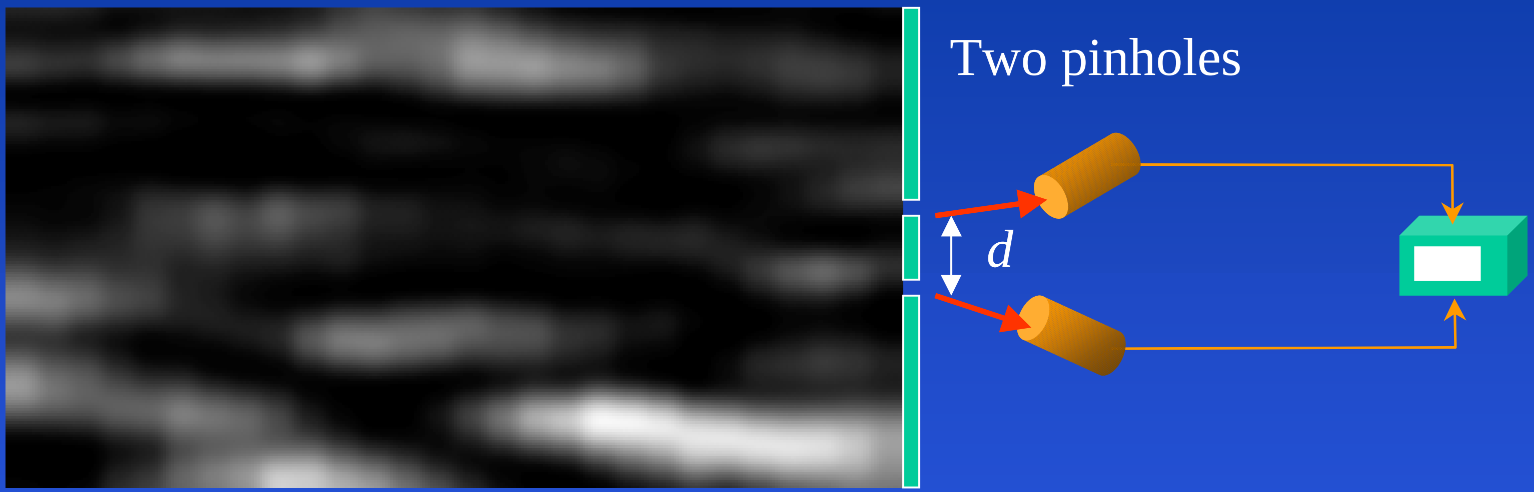


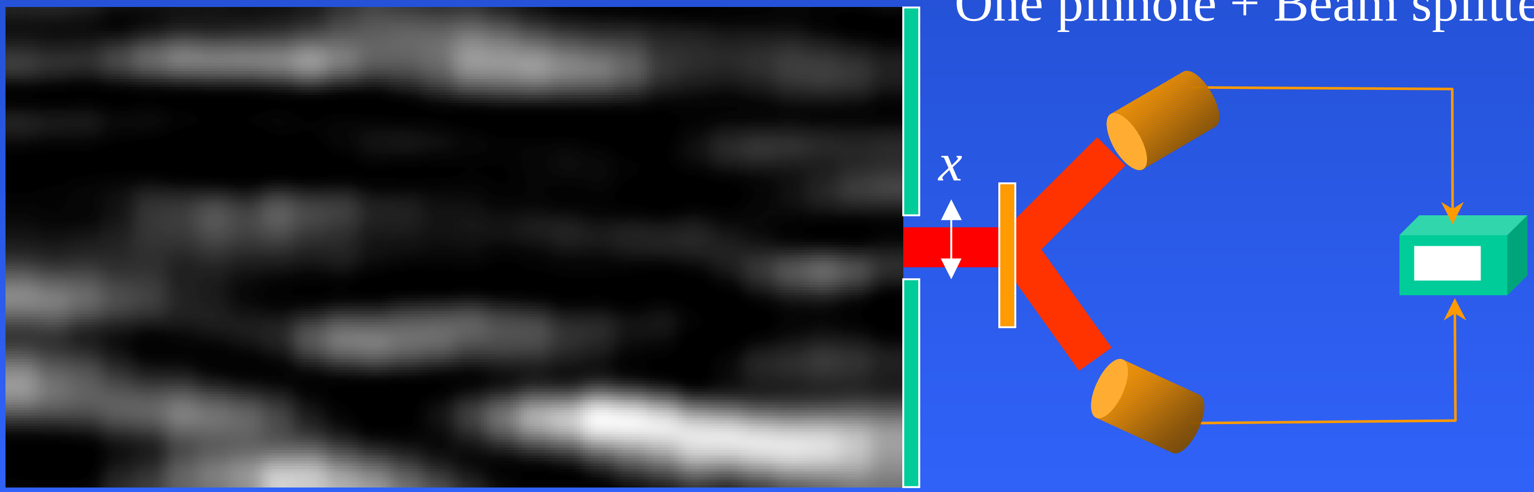
$$(x,t) =$$

$$E(x,t)|^2$$

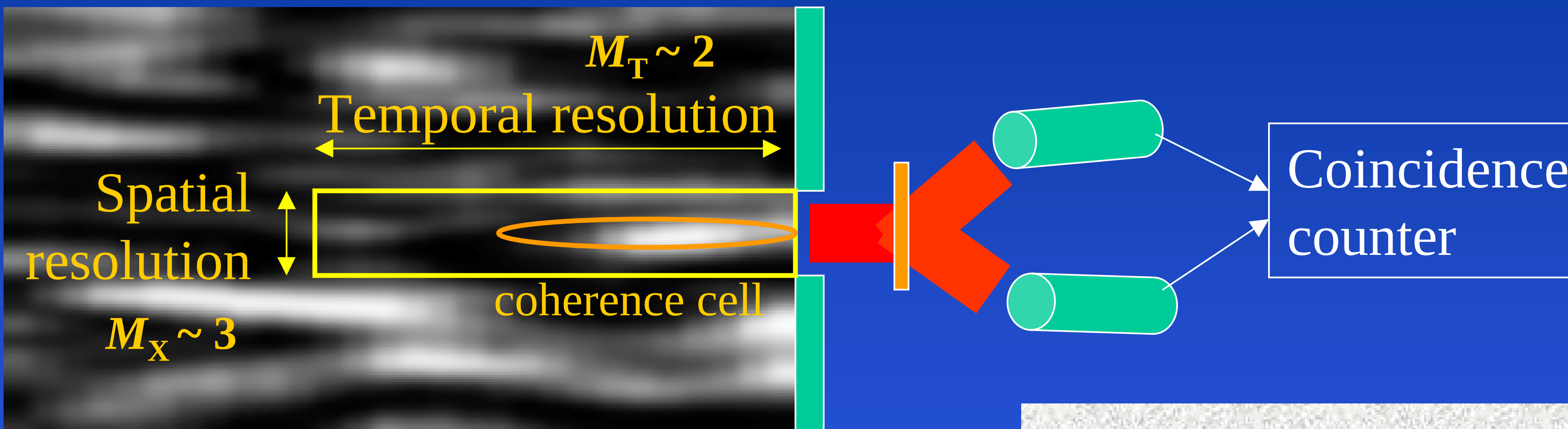
$$\langle I_A I_B \rangle = \langle I_A \rangle \langle I_B \rangle + |\Gamma_{AB}|^2$$

Variation





Mode number



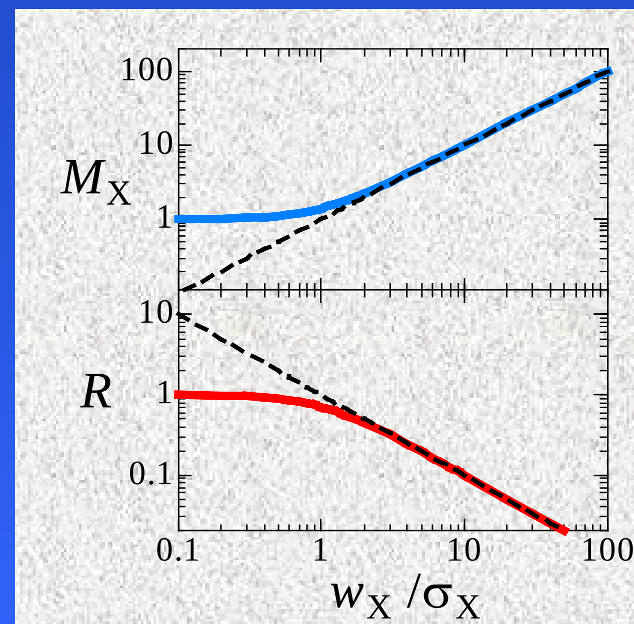
Mode number ***M*** : Number of coherence cells in the resolution function ($\boldsymbol{M = M_X M_Y M_T}$)

$$\langle I_A I_B \rangle = \langle I_A \rangle \langle I_B \rangle (1 + 1/M)$$

$$R \equiv \frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} - 1 = \frac{1}{M}$$

Small ***M***

Large ***R***



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- Experiment at 3rd. gen SR
  - Spatial domain
  - Temporal domain
- Proposal for SPPS
- Proposal for XFEL

Difficulty in 3rd gen. SR

$$M_T = \sqrt{1 + \left(\frac{s_T}{\sigma_T}\right)^2}$$

s_T ~ **10 - 100 ps** (pulse width of SR)

σ_T ~ **sub-fs** ($N_U\lambda/c$) for raw undulator radiation

$M_T \sim 10^5 - 10^6$

$R = 1/M_T \sim 10^{-5} - 10^{-6}$

$\sigma_T = \lambda^2/\Delta\lambda = \lambda E/\Delta E \propto$ **$1/\Delta E$**

Use of high-resolution monochromator (HRM)

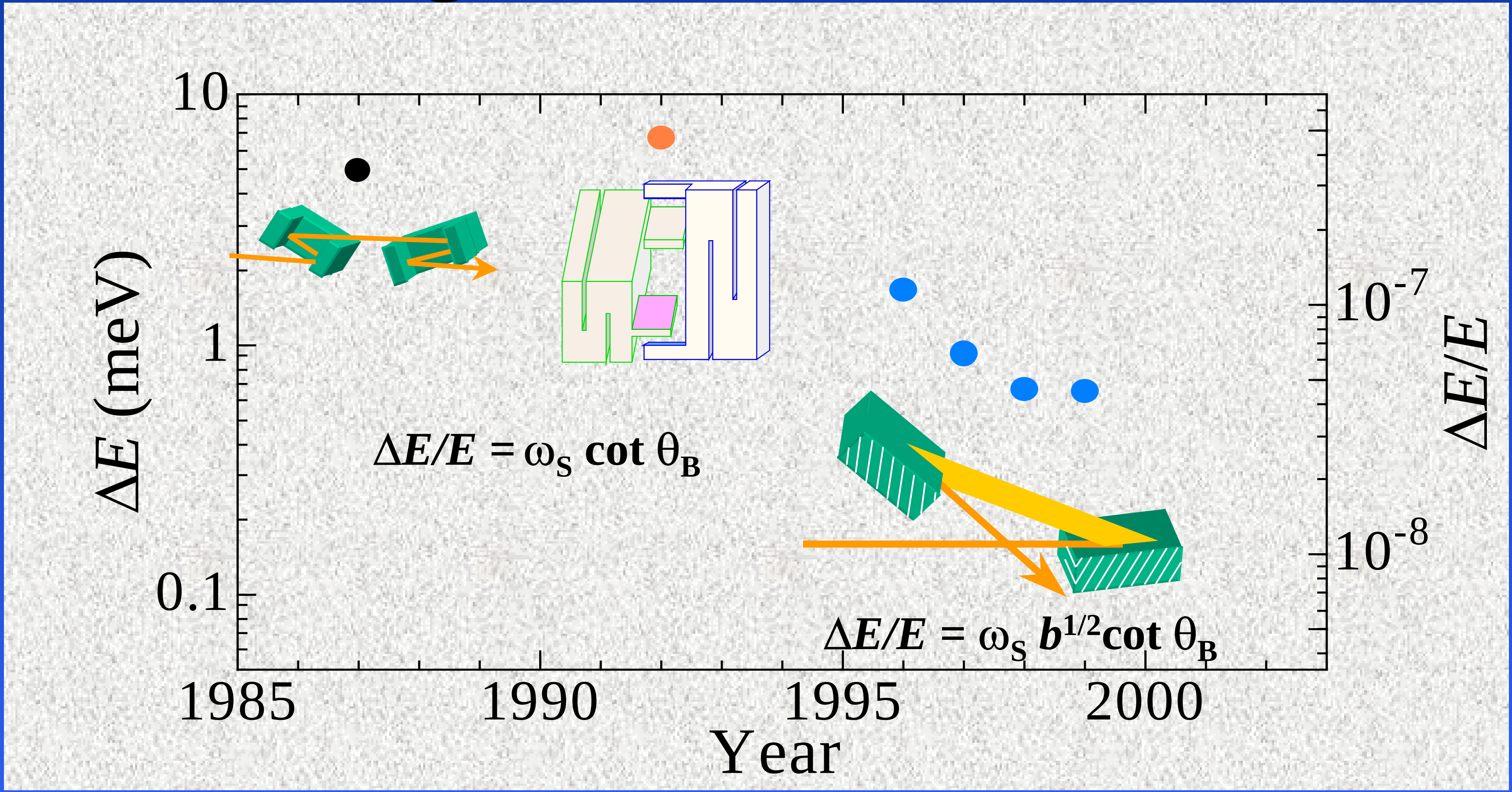
Optimized condition: $\sigma_T \sim s_T$ (~ 10 ps)

ΔE ~ *sub* meV

Y. Kunimune et al. JSR (1998)

E. Gluskin et al. JSR (2000)

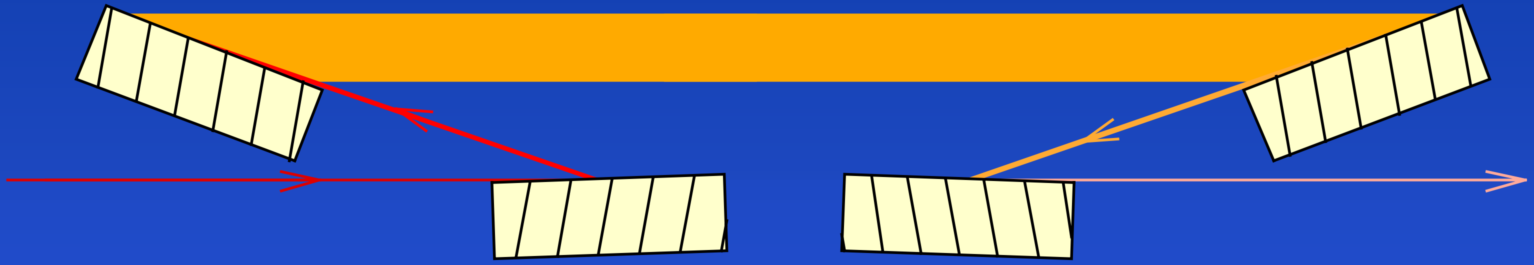
High-Resolution Mono



Energy Resolutions at E=14.4 keV

G. Faigel et al. 1987; T. Ishikawa et al. 1992;
T. Toellner et al. 1992, 1997; A.I. Chumakov et al. 1996, 2000

Design



E = 14.4 keV

Si 11 5 3

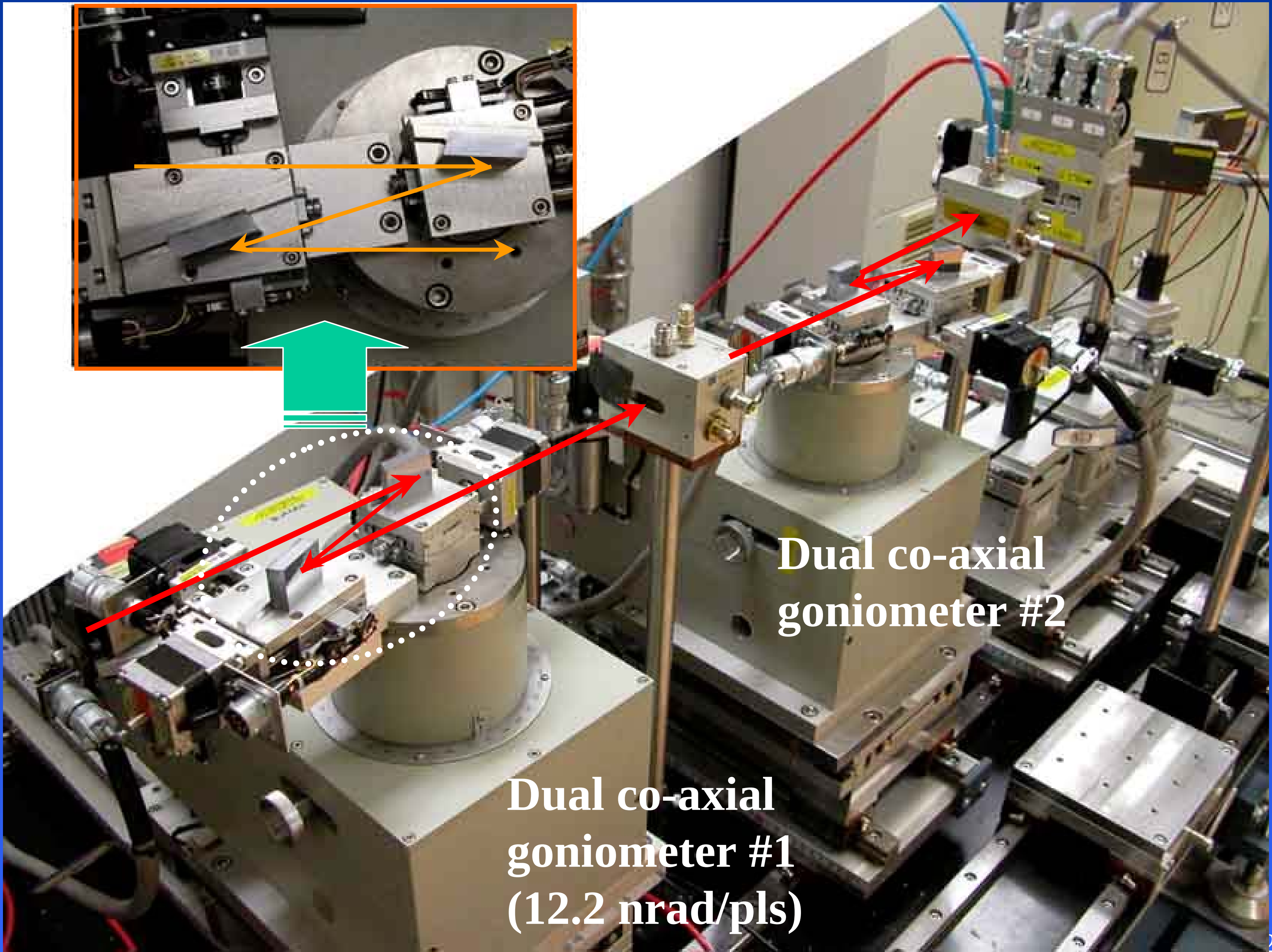
Glancing angle = 2°

$b = b_1 = b_2 = 1/b_3 = 1/b_4 = 1/10.4$

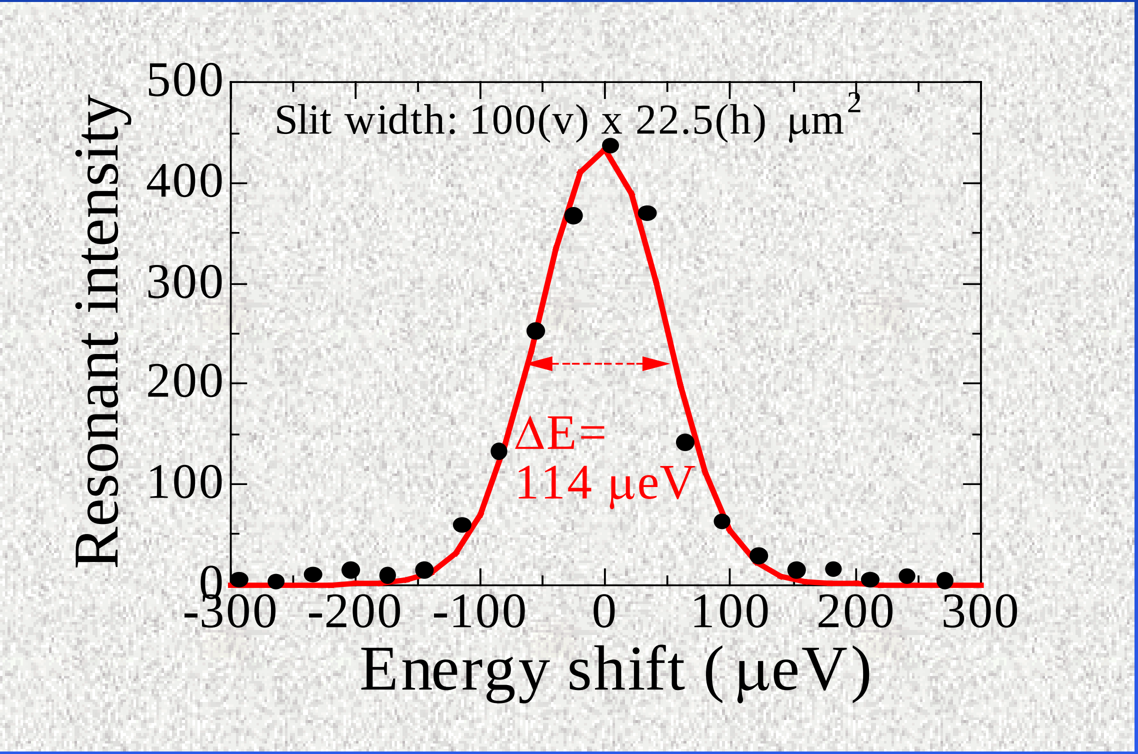
Crystal size: 30 ×15 ×12 mm^3

Spatial acceptance = 100 µm

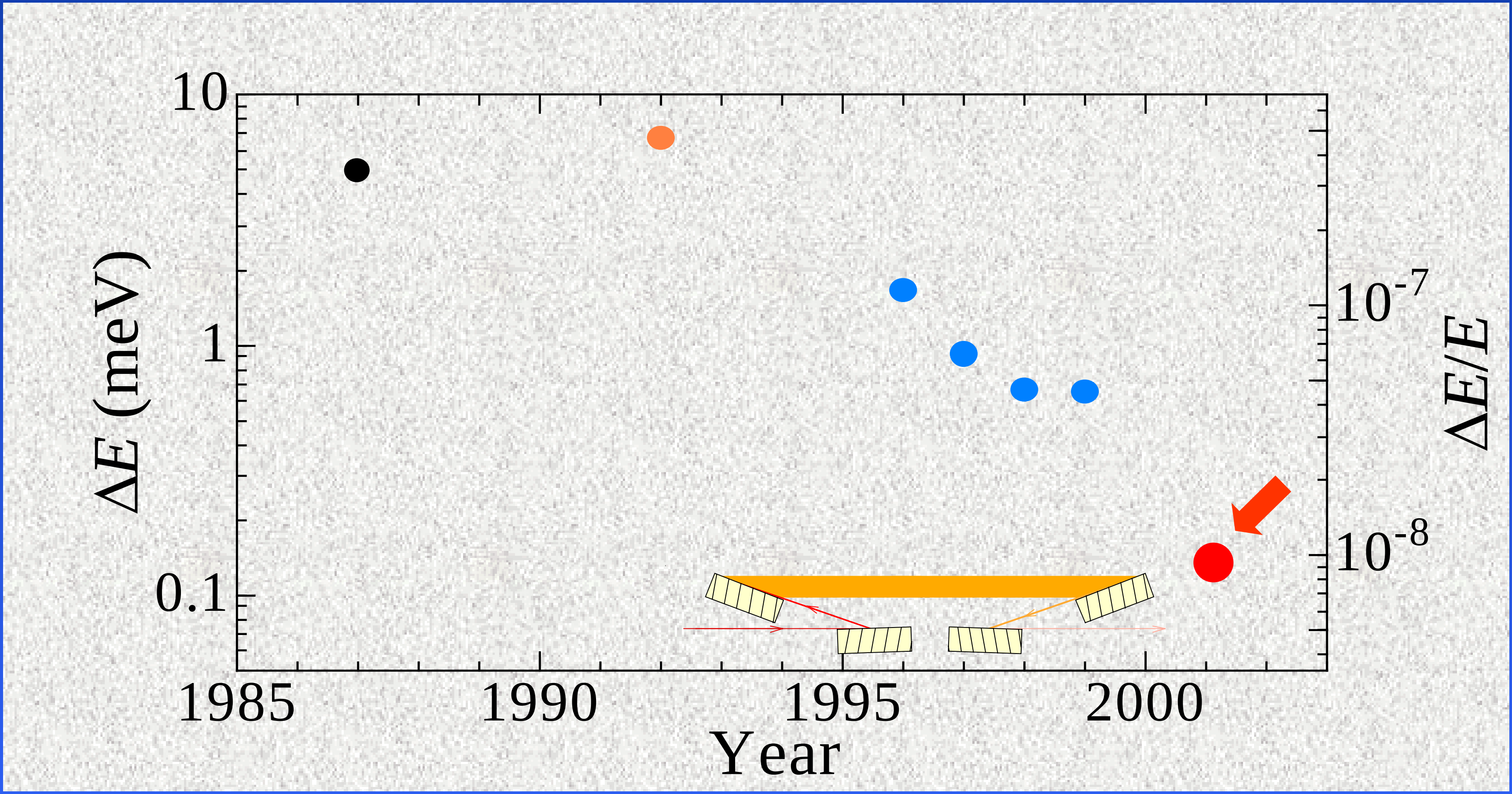
ΔE = 100 µeV


Dual co-axial
goniometer #2
Dual co-axial
goniometer #1
(12.2 nrad/pls)

Result

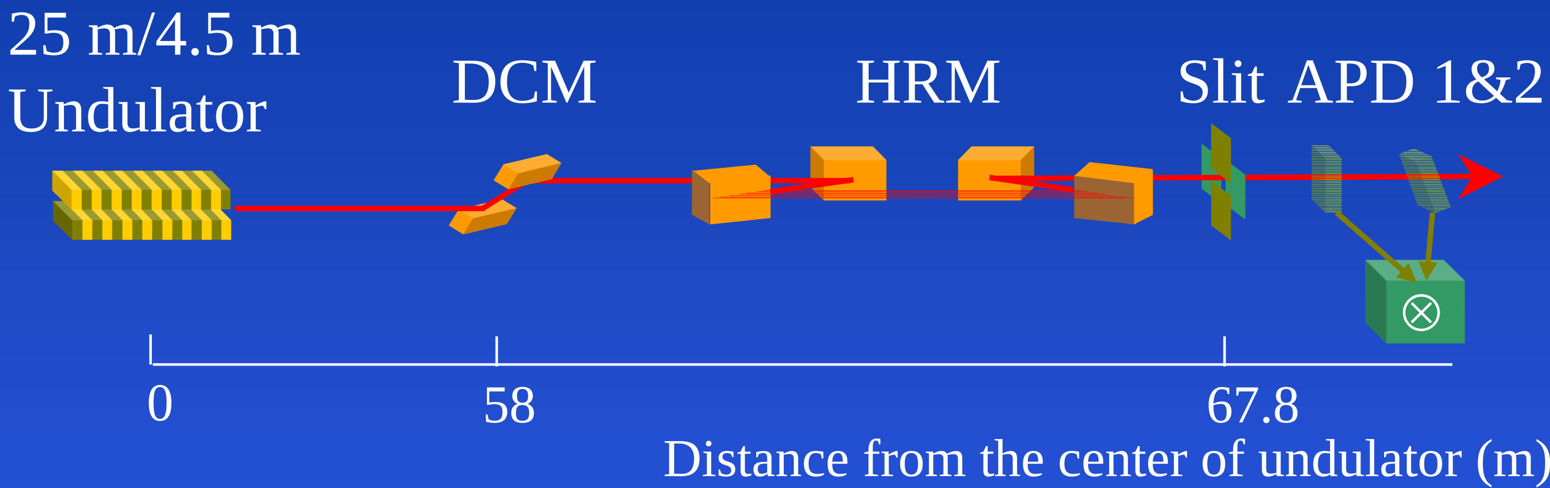

Slit width: 100(v) x 22.5(h) μm²
ΔE=
114 μeV
Resonant intensity
0
100
200
300
400
500
-300
-200
-100
0
100
200
300
Energy shift (μeV)

Achieved Resolution

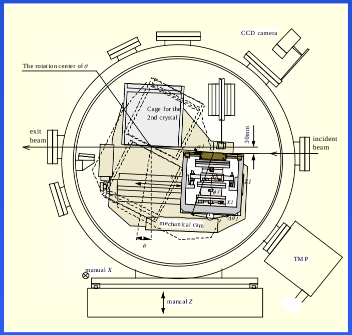


M. Yabashi, K. Tamasaku, S. Kikuta, and T. Ishikawa, *Rev. Sci. Instrum.* **72**, 4080 (2001).

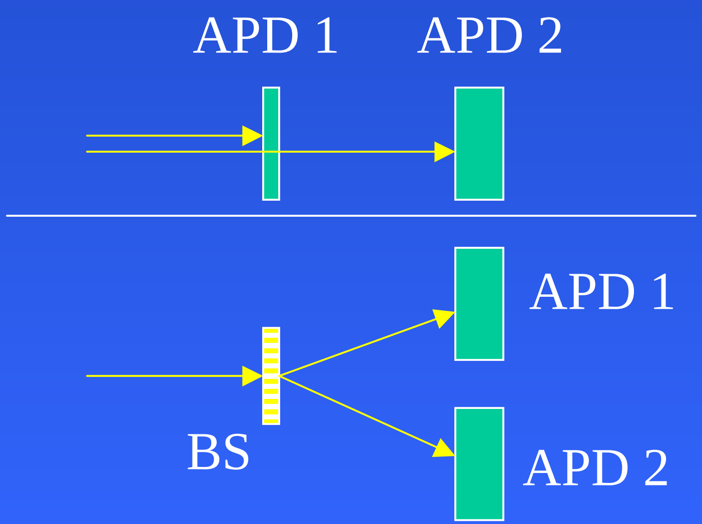
Setup



Kitamura et al., NIM A, 2001



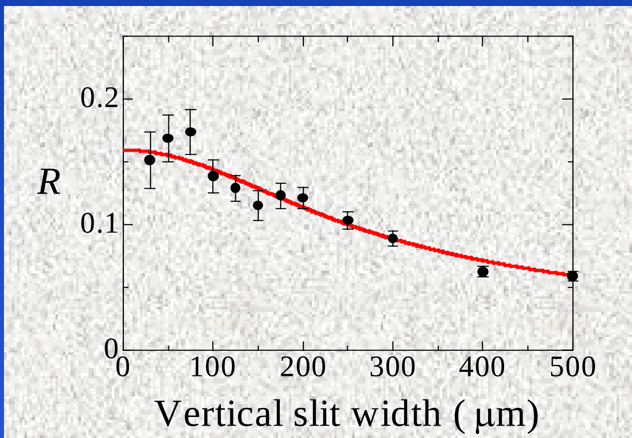
Yabashi et al., SPIE 1999;
Tamasaku et al., SPIE 2002,



Spatial domain

$$\sigma_y = \frac{\lambda z}{2\pi s_y}$$

ε = 6 nm.rad



$\sigma_y = 124.3 \pm 6.9$ μm

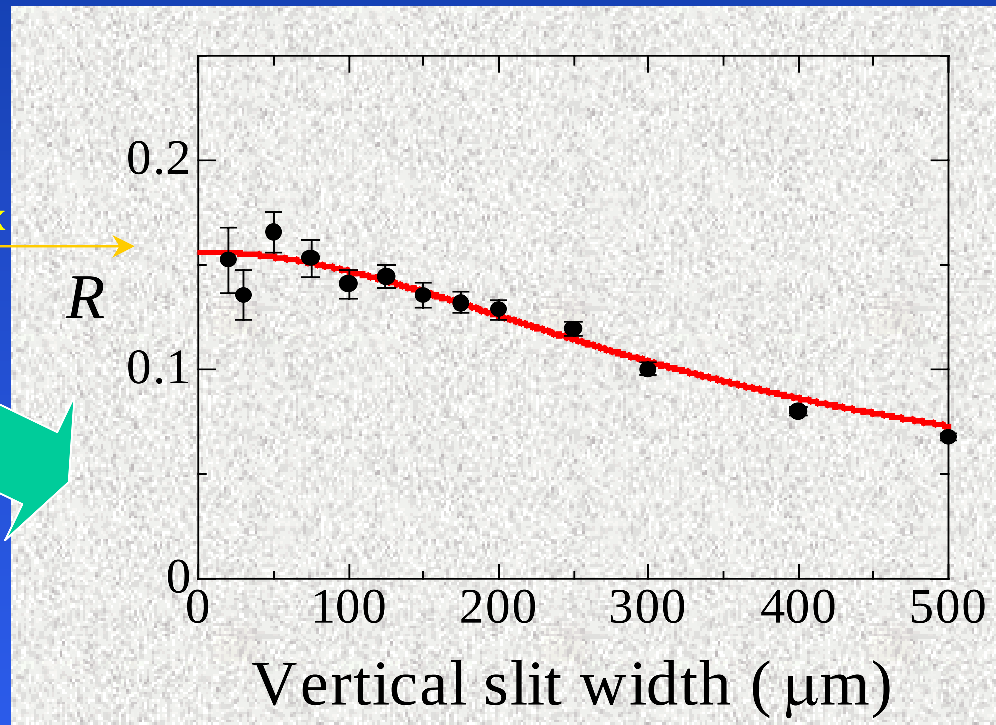
$s_y = 5.9 \pm 0.3$ μm

$\varepsilon_y = 6.0 \pm 0.7$ pm.rad

$\kappa = 0.10$ %

ε = 3 nm.rad

***R*max**



$\sigma_y = 161.3 \pm 5.0$ μm

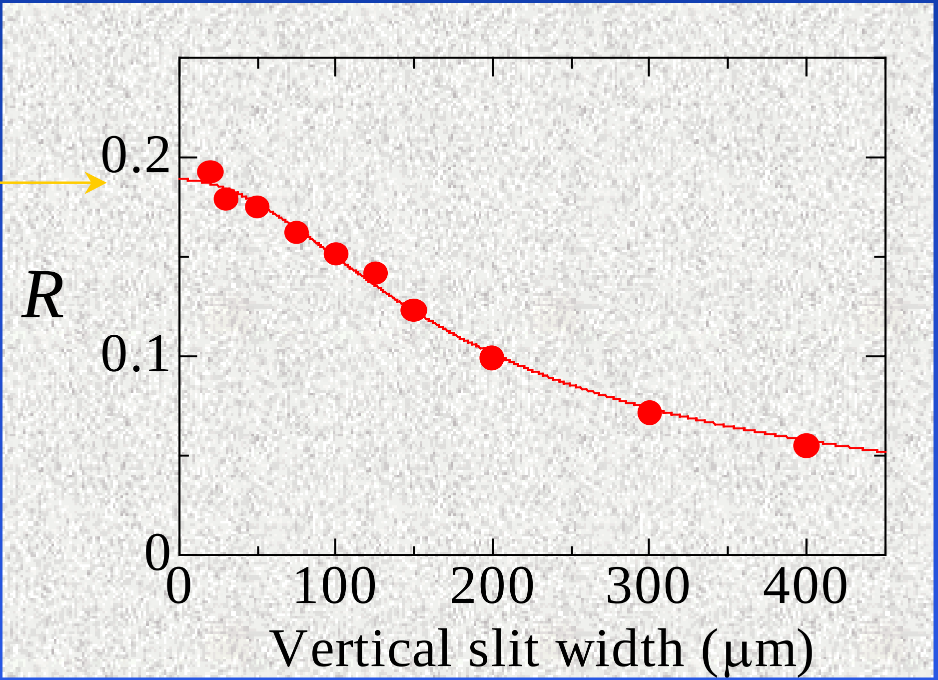
$s_y = 4.6 \pm 0.14$ μm

$\varepsilon_y = 3.6 \pm 0.2$ pm.rad, $\kappa = 0.12$ %

I. Yabashi, K. Tamasaku & T. Ishikawa,
hys. Rev. Lett. **87**, 140801 (2001);
hys. Rev. A **69**, 023813 (2004).

Pulse width

R_{max}



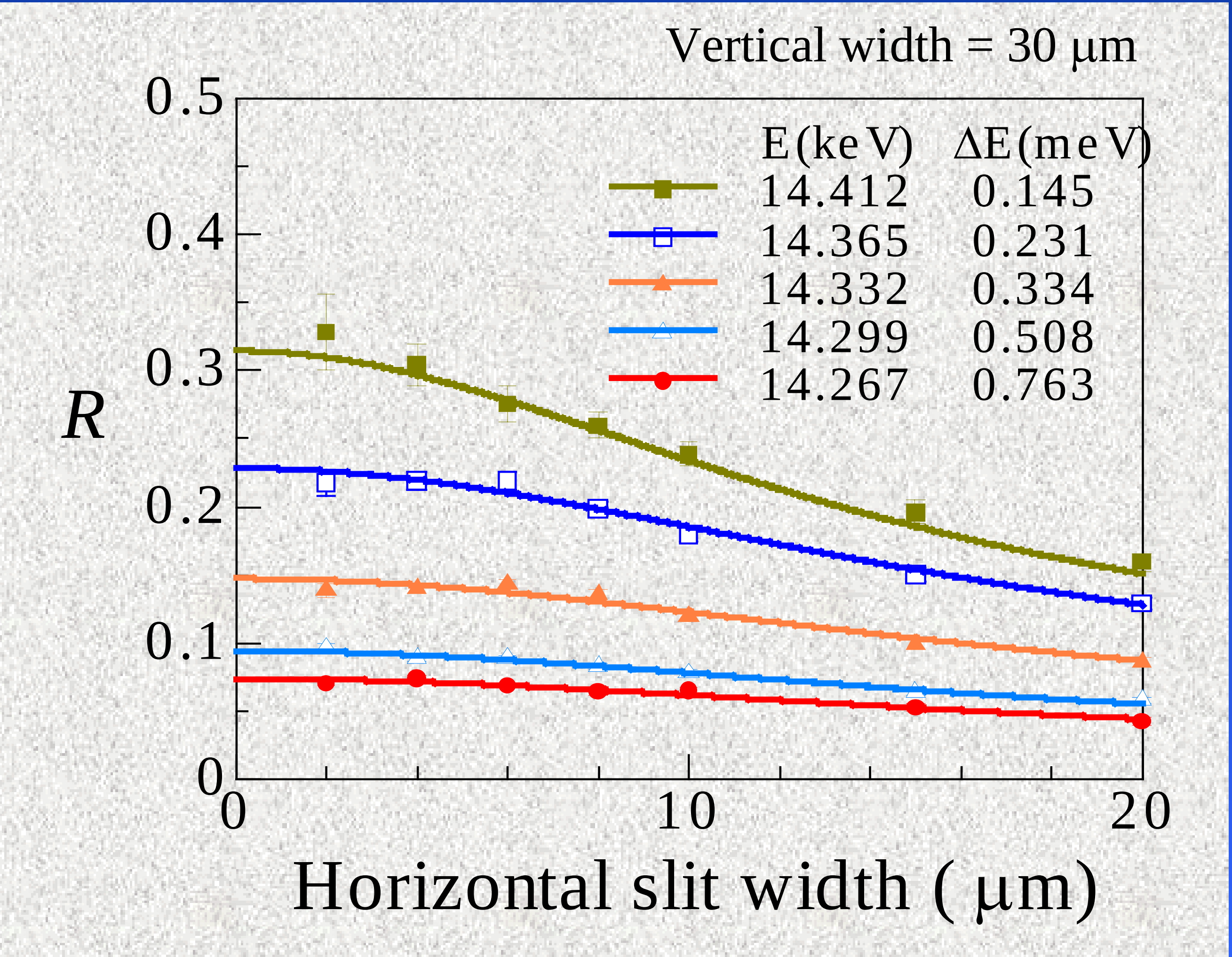
$R_{max} = 1/ M_T = (1+ \sigma_T^2 / s_T^2)^{-1/2}$

$(M_X = M_Y = 1)$

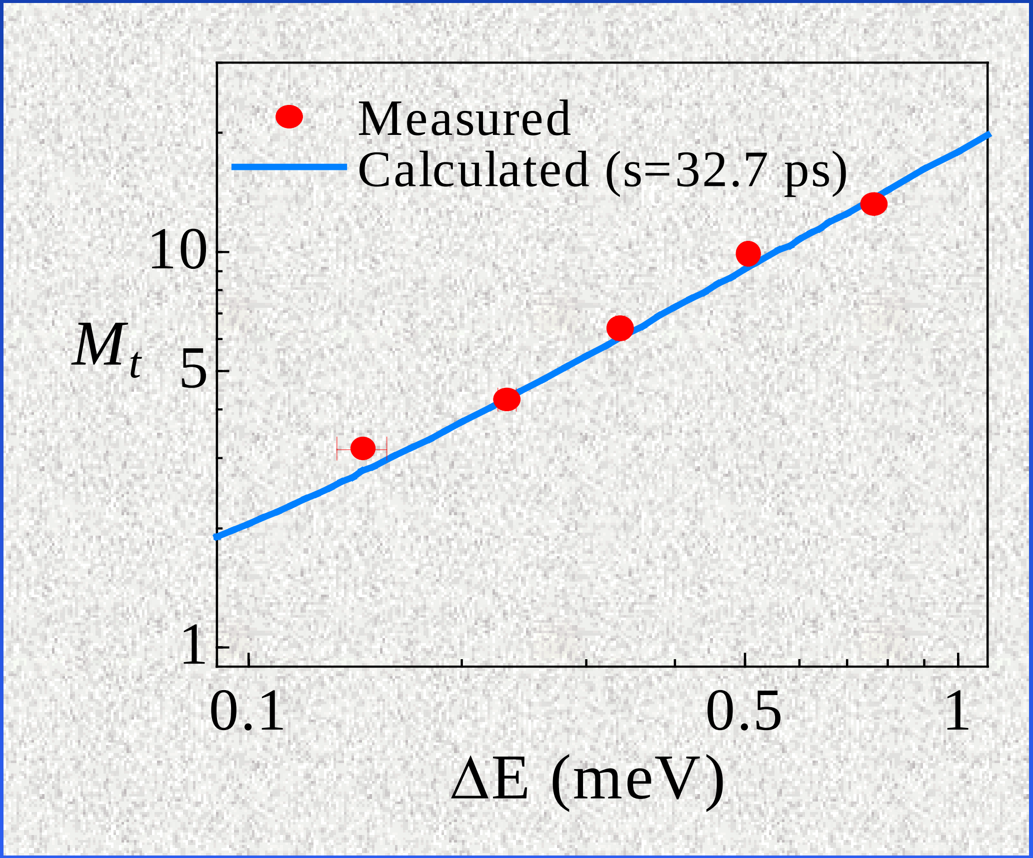
$\sigma_T = 4h \ln 2/\Delta E$

Measure pulse width s_t

Result


Vertical width = 30 μm
0.5
0.4
0.3
0.2
0.1
0
R
E(keV) ΔE(meV)
14.412 0.145
14.365 0.231
14.332 0.334
14.299 0.508
14.267 0.763
0
10
20
Horizontal slit width (μm)

Mode number vs. bandwidth



$$M_t = 1/R_{\max} = \sqrt{1 + \left(\frac{4\hbar \ln 2}{\Delta E \cdot s_t}\right)^2}$$

s_T = 32.7 ±1.6 ps

Streak camera: 32 ps

M. Yabashi, K. Tamasaku, and T. Ishikawa, *Phys. Rev. Lett.* **88**, 244801 (2002).

Contents

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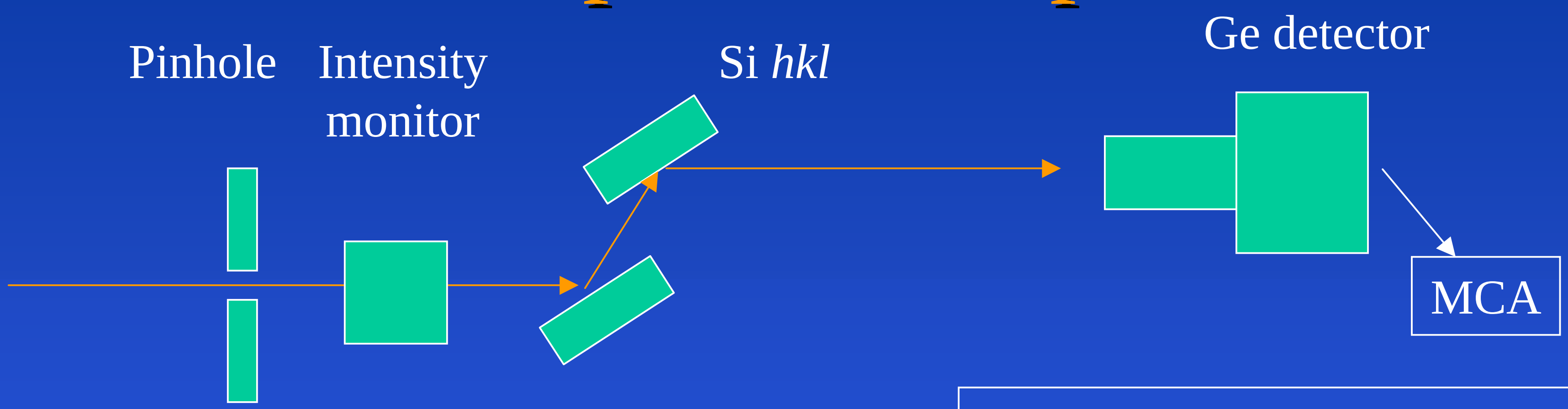
Proposal for SPPS

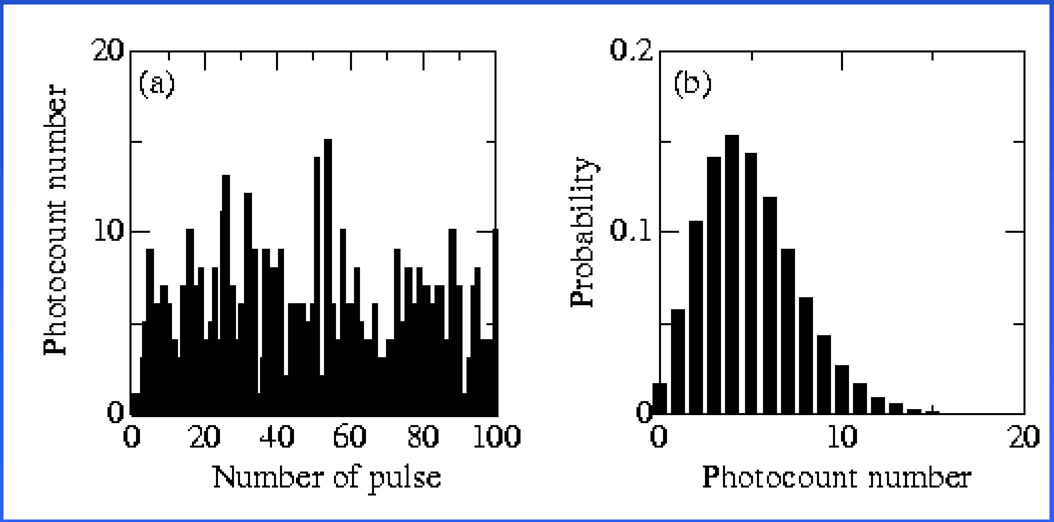
Proposal for XFEL

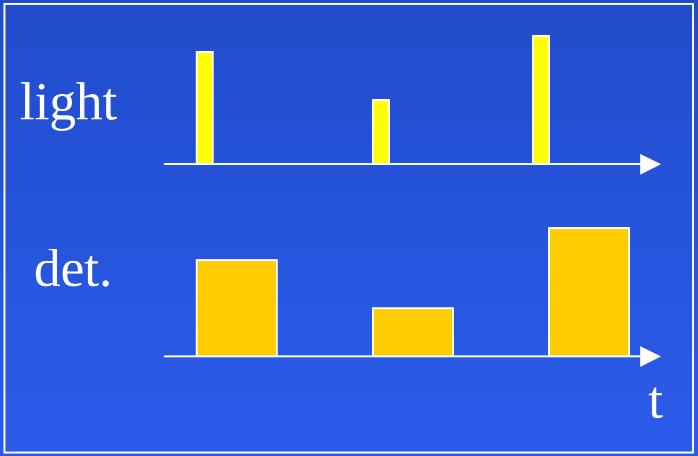
SPPS

	Pulse width	Optimized bandwidth	
3rd gen.	30 ps	0.2 meV	complicated
SPPS	80 fs	70 meV	simple

Proposed Setup







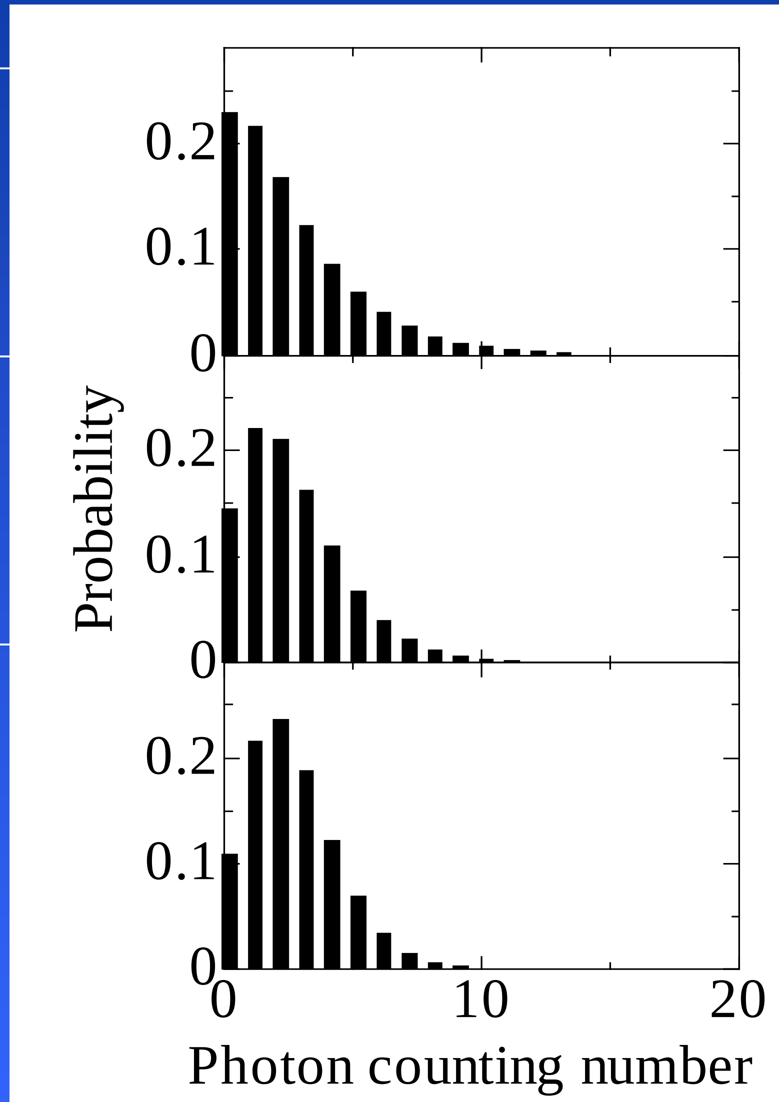
$$M = \frac{\overline{K}^2}{\sigma_K^{\ 2} - \overline{K}}$$

Simulation

	ΔE (meV)	M
Si 800	25	1.5
Si 440	80	3.9
Si 400	220	9.3

E = 9.3 keV, s_t = 80 fs
average counting number = 2.5

Mandel's formula



B-E

Poisso

Key for success

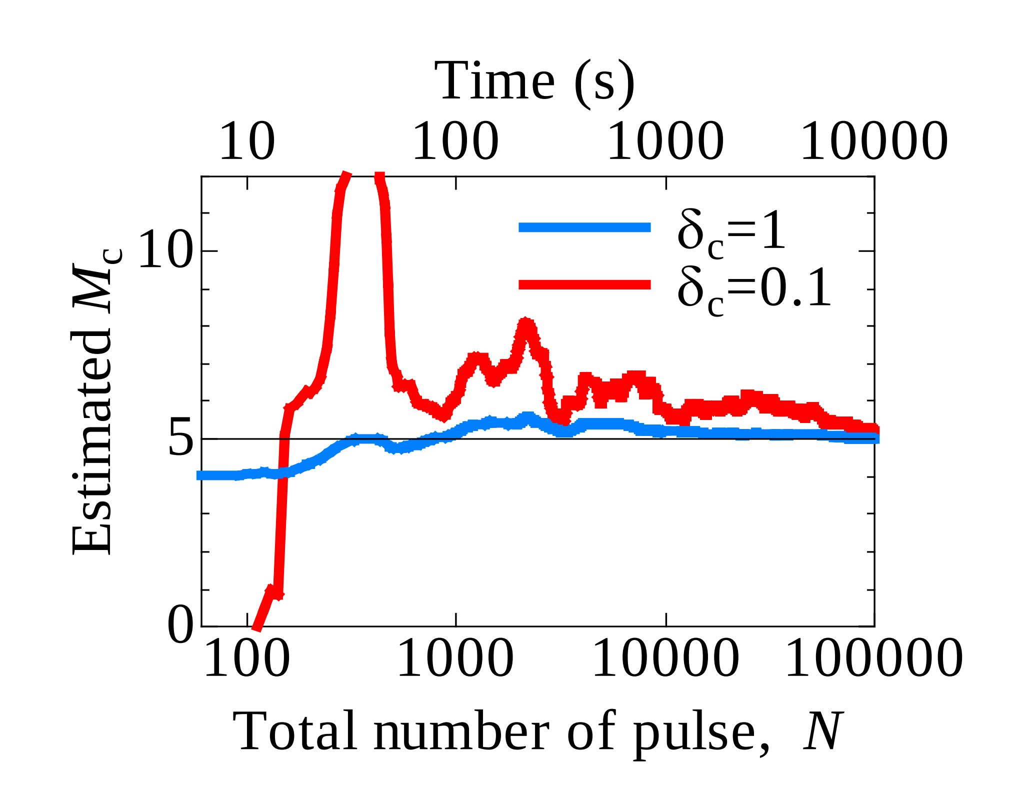
1. Bose degeneracy

$$S/N \propto \delta\, \eta\, (f\, T)^{1/2}$$

	SP8 25-m U	SPPS
Degeneracy δ :	~ 0.3	~ 90
	(B_P ~ 6×10^{23}	(B_P ~ 5×10^{25}
	λ ~0.086 nm)	λ ~0.13 nm)
Efficiency η:	10^{-2}	10^{-1}
Repetition rate f :	36 MHz	10 Hz
$\delta\, \eta\, f^{1/2}$:	18	30
Time:	~ 10 min	< 10 min ??

2. Normalization of intensity fluctuation unrelated to interference

Required time



$$T \propto \delta_c^{\ 2}$$

δc	# of pulses	Time
1	200	20 sec
0.1	20000	2000 sec ~ 1 hour
0.01	2000000	200000 sec ~ 2 days

Key for success

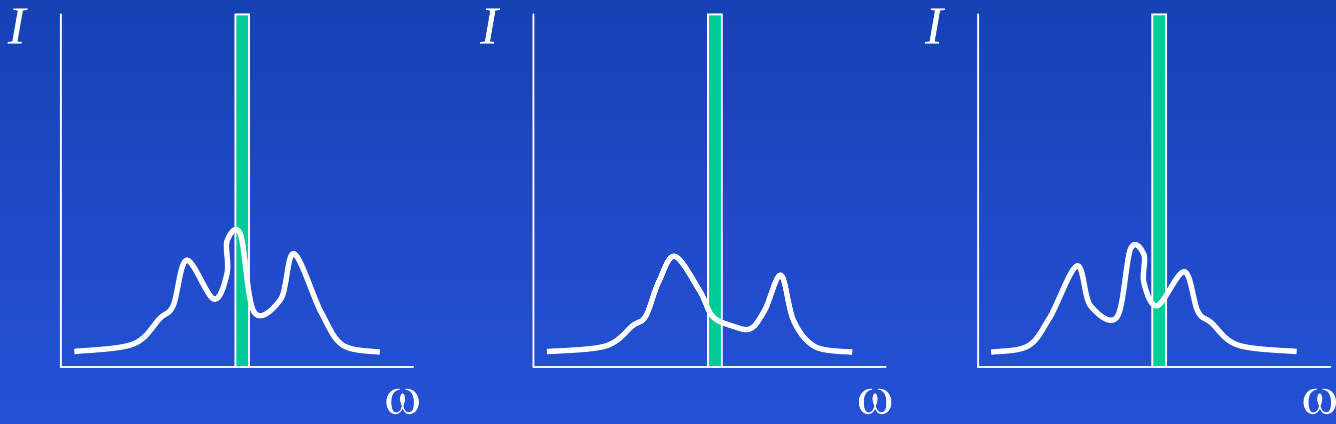
1. Bose degeneracy

$S/N \propto \delta\, \eta\, (f\, T)^{1/2}$

Degeneracy δ :	~ 0.3	~ 90
	(B_P ~ 6×10^{23}	**(B_P ~ 5×10^{25}**
	λ ~0.086 nm)	λ ~0.13 nm)
Efficiency η:	10^{-2}	10^{-1}
Repetition rate f :	36 MHz	10 Hz
$\delta\, \eta\, f^{1/2}$:	18	30
Time:	~ 10 min	< 10 min ??

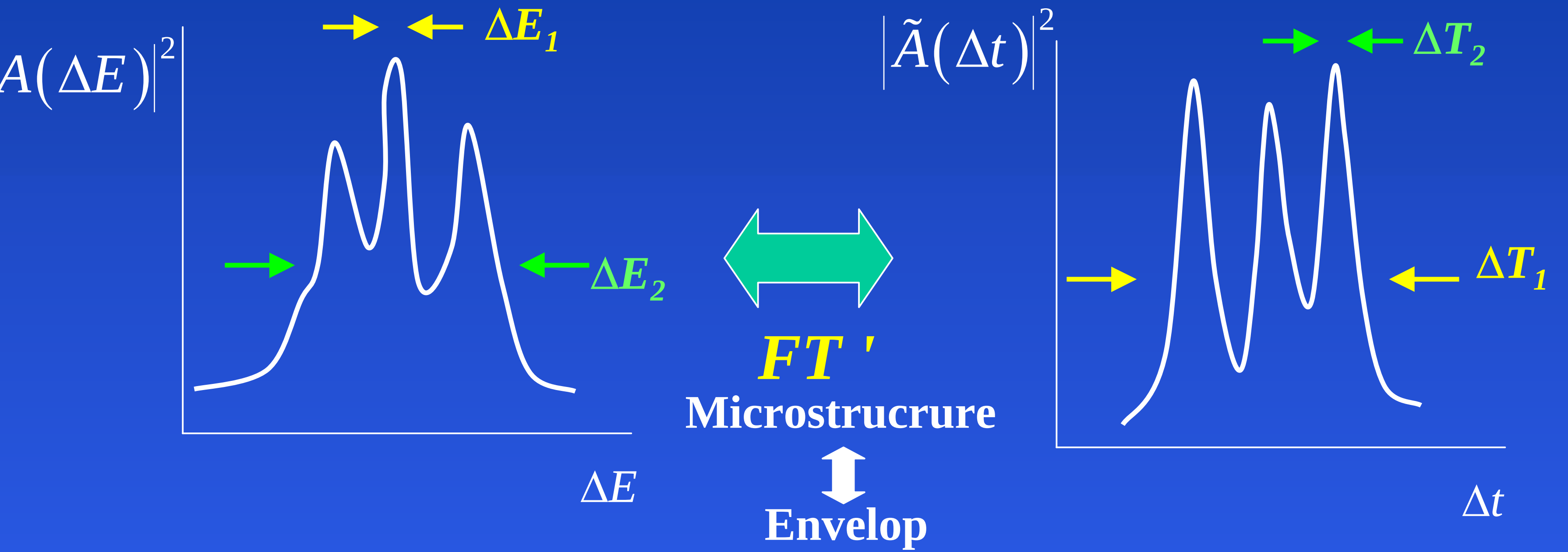
2. Normalization of intensity fluctuation unrelated to interference

Average for repeated pulses



More intense beam

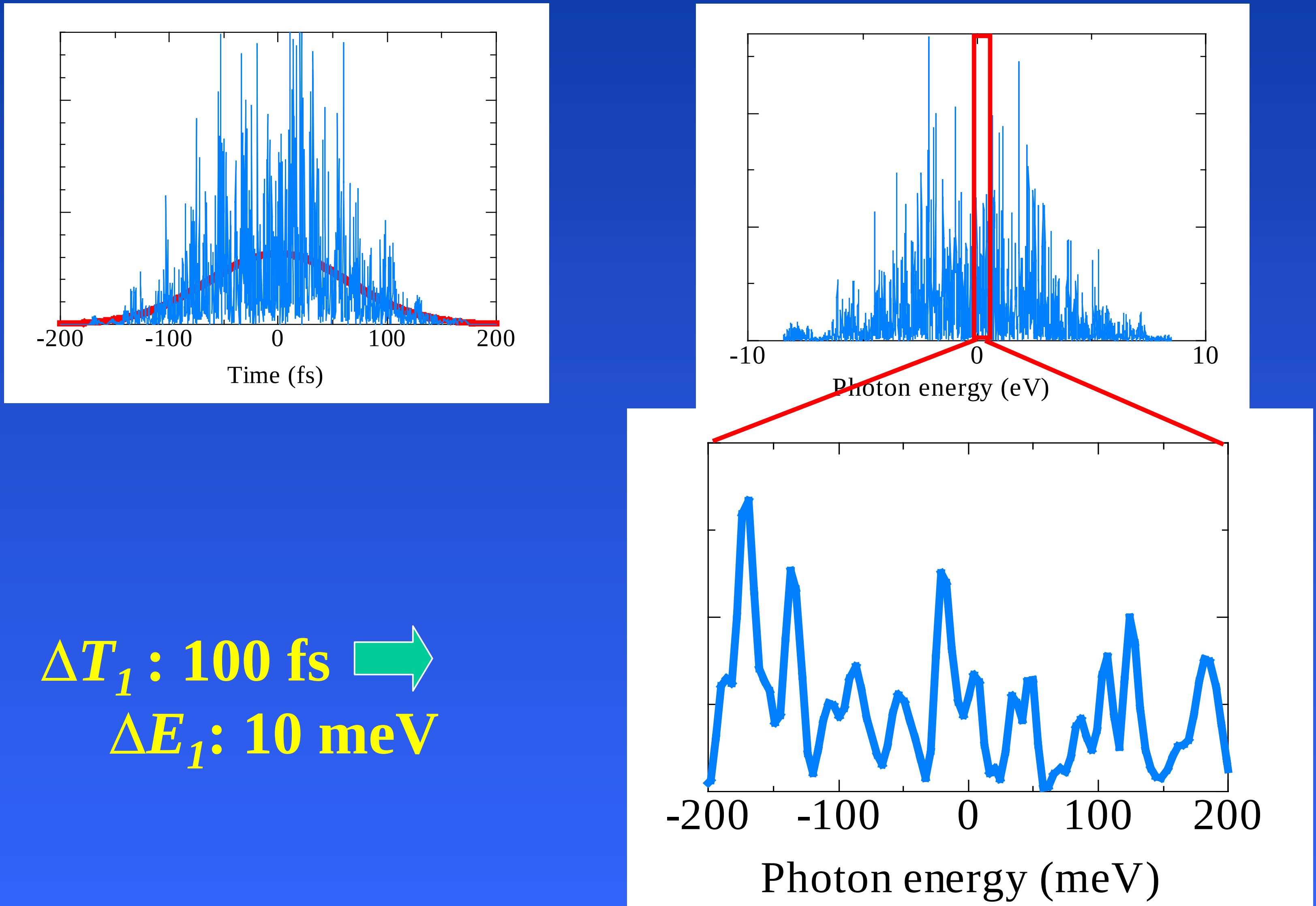
Single-shot Measurement



$$\Delta T_1 \simeq h / \Delta E_1$$

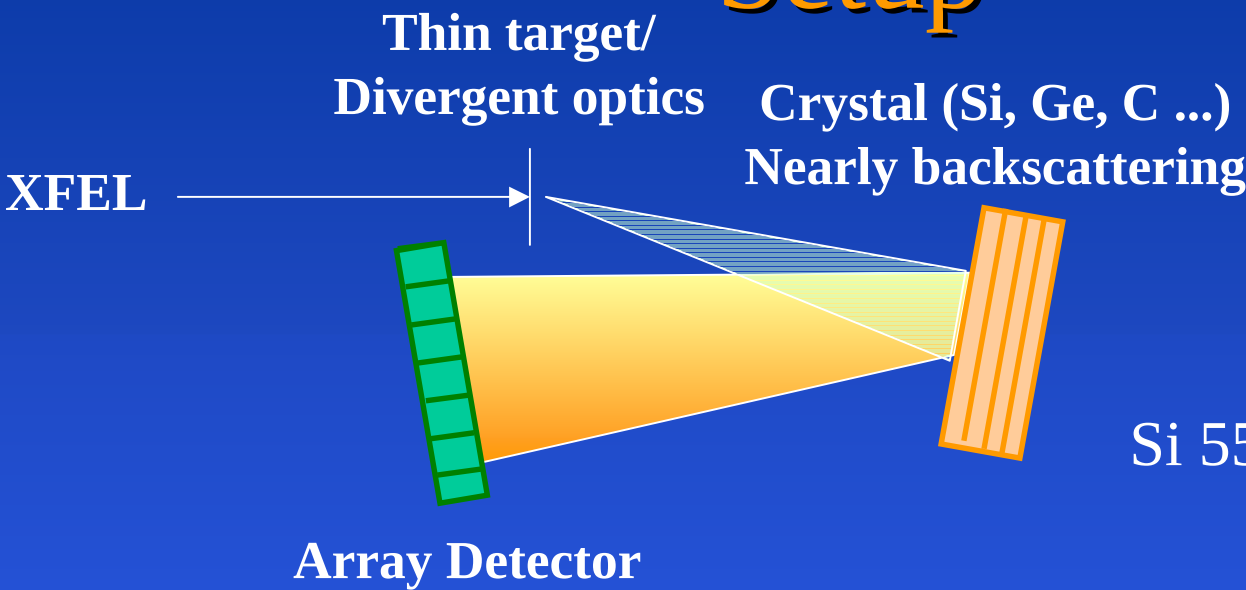
J. Krzywinski, E. Saldin et al. NIM A (1997)

Simulation



ΔT_1 : 100 fs ➡
ΔE_1: 10 meV

Setup



$$I(\Delta E) = |A(\Delta E)|^2$$

$$\frac{\Delta E}{E} \simeq \chi_g$$

Si 555: $\Delta E = 16$ meV

@ $E \simeq 9.9$ keV

Pulse width estimation (a priori knowledge of pulse shape)

⇨ OK

Detailed information

$$\left|A(\Delta E)\right|^2 \;\overset{FT}{\not\Longleftrightarrow}\; \left|\tilde{A}(\Delta t)\right|^2$$

$$A(\Delta E) \;\overset{FT}{\Longleftrightarrow}\; \tilde{A}(\Delta t)$$

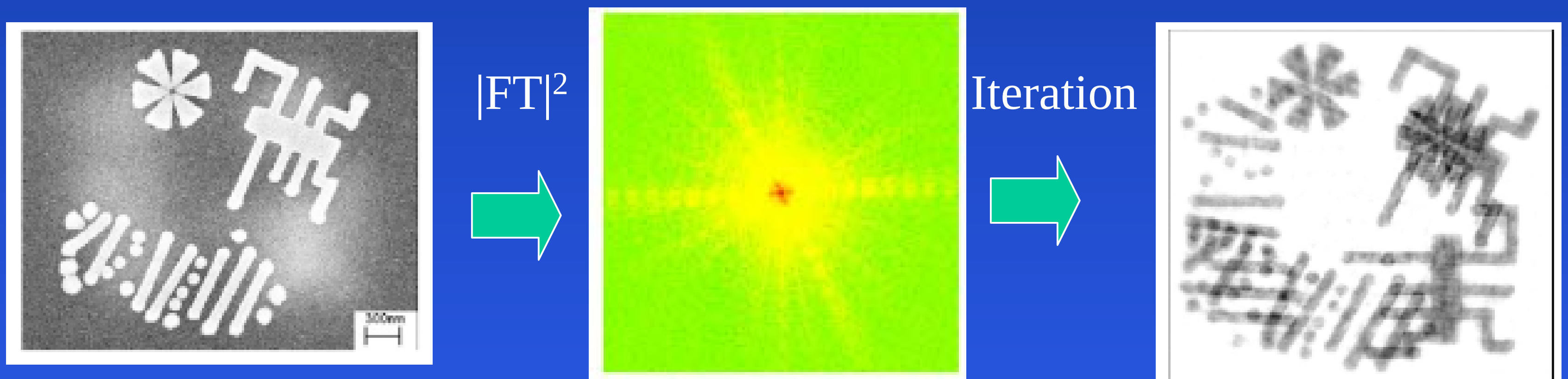
Require phase information

Phase retrieval

Oversampling method

2D: OK

Miao et al. PRL **89** (2002) 088303.



SEM image of Ni pattern on SiN

Coherent Scattering Pattern

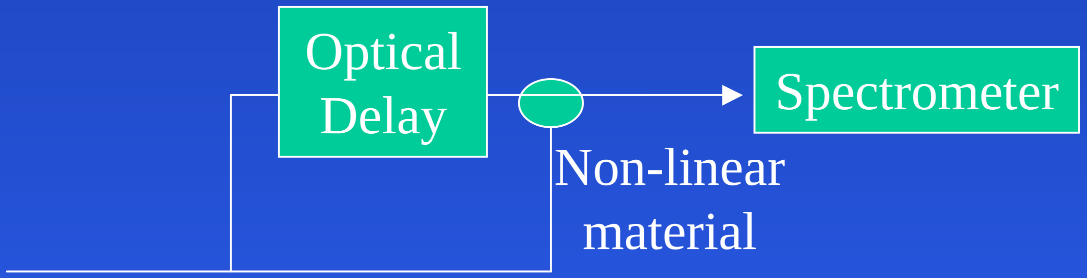
2D Reconstructed Image (<10 nm resolution)

1D: generally impossible for complex object

Example: FROG

Frequency Resolved Optical Gating

Measure energy spectrum with changing delay time



R. Trebino and D. J. Kane, JOSA A (1993).

2D Phase Retrieval

XFROG ?

Summary

- We can apply intensity interferometry to measure spatial and temporal profile of 3rd gen. SR source.
- For shorter pulse, much easier.
- For single-shot detection, extension of conventional spectroscopy technique will be useful.
- For determination of pulse shape, we have to retrieve phase information. Further considerations & discussions are required.

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