Beam Size Monitors for KEKB-ILCDR

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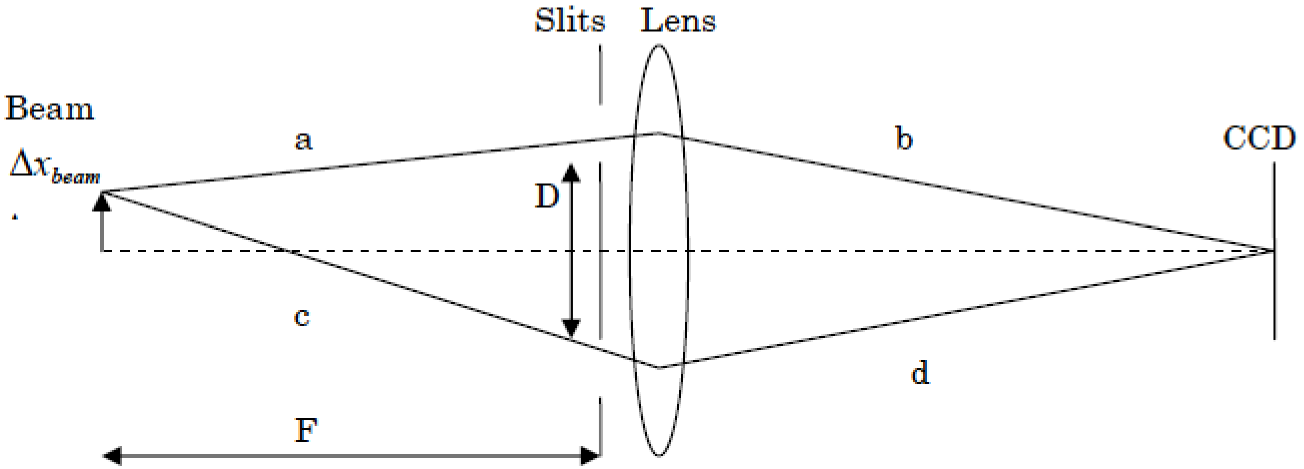
KEKB-ILCDR meeting
19 Sep. 2007

Interferometers

- Beam size currently measured by interferometer.
- Resolution fundamentally limited by opening angle between slits from beam.



Interferometer Source Parameters

LER BWSFRE	KEKB	KEKB-ILCDR	SuperB (LE)
ε x(m)	1.80E-08	1.50E-09	1.00E-09
κ (%)	1%	0.1%	0.1%
ε y(m)	1.80E-10	1.50E-12	1.00E-12
β x(m)	2.42E+01	2.42E+01	2.42E+01
β y(m)	1.77E+01	1.77E+01	1.77E+01
σ x(m)	6.59E-04	1.90E-04	1.55E-04
σ y(m)	5.64E-05	5.15E-06	4.20E-06
σ x(m)/ σ y(m)	11.69	36.97	36.97
I (A)	2	0.5	8
Bending radius ρ (m)	60	60	60
bend angle (mrad)	5	5	5
Beam Energy (GeV)	3.5	2.3	4
Observ. wavelength λ (m)	5.00E-07	5.00E-07	5.00E-07
ω (rad/s)	3.77E+015	3.77E+015	3.77E+015
θ_c (rad)	0.0016	0.0016	0.0016
Max Slit opening-angle D/F	0.0032	0.0032	0.0032
Max Visibility (fringe modulation) γ	90%	90%	90%
Minimum measureable beam size σ_{min} (m)	1.15E-05	1.15E-05	1.15E-05

- Note: $\sigma = \frac{\lambda F}{\pi D}\sqrt{\frac{1}{2}\ln\frac{1}{\gamma}}$ $\frac{D}{F} \leqslant 2\theta_c$ $\theta_c = \left(\frac{3c}{\omega\rho}\right)^{\frac{1}{3}}$ $\omega = 2\pi\frac{c}{\lambda}$
- D = slit separation, F = distance from beam to slits.
- Max slit opening angle also limited physically with current chamber to ~0.003 rad

Interferometers

- Current interferometers cannot quite make it to the resolution needed for KEKB-ILCDR (or SuperB Low-emittance) operation.
- Possible fixes (probably need a combination):
  - Increase vertical beta function at source point
  - Reduce bending radius of source magnet AND increase extraction aperture size
  - Reduce observation wavelength
    - Would gain 20% if 500 um -> 400 um.
  - Accept higher visibility: 90% -> 95% would take us from 12 um to 8 um. But error bars grow rapidly.

X-Ray Monitor

- Used or planned to be used at ATF, CESR, Spring-8, elsewhere.
- To maximize bandwidth and minimize number of components, we are considering the use of **coded aperture imaging.**

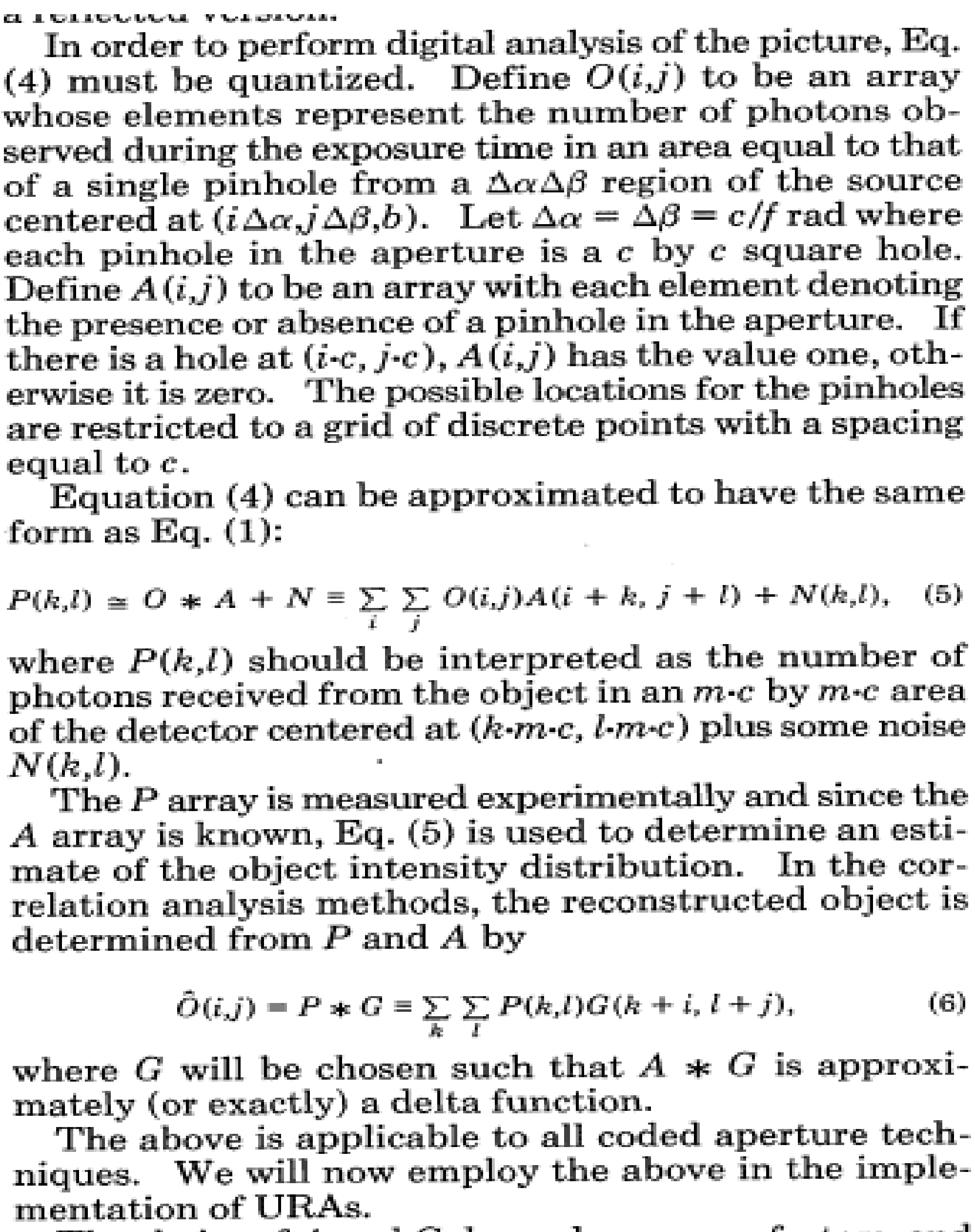
Coded Aperture Imaging

- A coded aperture is a mask used to modulate incoming light.
- A Fresnel zone plates is typically used as an X-ray lens
    - Requires the use of a monochromator
        - Expensive
        - Sensitive to heat load
        - Cuts available light level down drastically (1%), necessitating long exposure times
- A pinhole is the simplest type of coded aperture, requiring no monochromator (good), but having a very small aperture (bad).
- In 1968 R.H. Dicke (APJL, 153, L101, 1968) proposed the use of a random array of pinholes for X-ray and gamma-ray astronomy. The resulting image needs to be deconvolved back through the mask pattern to reconstruct the pattern on the sky.

Coded Aperture Imaging

- Several improved mask designs have since been developed, most notably the Uniformly Redundant Array (URA) mask, which has the nice property that its auto-correlation is a delta function (no sidelobes), and it can achieve open aperture areas of up to 50%.
  - For a good overview and bibliography, see http://astrophysics.gsfc.nasa.gov/cai/
- Several reconstruction methods are in use: inversion, cross-correlation, photon tagging (back-projection), Wiener filtering, and iterative methods such as the Maximum Entropy Method and Iterative Removal of Sources (IROS).
- Coded aperture imaging is now a well-established technique in X-ray astronomy, though it has not found widespread use outside that field.
  - I have found some scattered references to uses in medical imaging, thermal neutron imaging, inertial confinement monitoring, and nuclear blast monitoring, but almost all development work seems to have been done by X-ray and gamma-ray astronomers.
- I have found one reference to use of URA masks for the measurement of phase coherence of undulator radiation (J.J.A. Lin et al., "Measurement of the Spatial Coherence Function of Undulator Radiation using a Phase Mask," PhysRevLett.90.074801), and they reference an earlier application to the same measurement of an x-ray laser (J. E. Trebes, et al., Phys. Rev. Lett. 68, 588–591 (1992).) Note: a 6 pinhole mask was tried at TRISTAN (A. Ogata et al., PAC 1989), but not with coded aperture reconstruction techniques in mind, according to Mitsuhashi.
- I believe coded aperture techniques would be useful for general beam profile and position diagnostics.

Coded Aperture Decoding



a reflected version.

In order to perform digital analysis of the picture, Eq. (4) must be quantized. Define $O(i,j)$ to be an array whose elements represent the number of photons observed during the exposure time in an area equal to that of a single pinhole from a $\Delta\alpha\Delta\beta$ region of the source centered at $(i\Delta\alpha, j\Delta\beta, b)$. Let $\Delta\alpha = \Delta\beta = c/f$ rad where each pinhole in the aperture is a c by c square hole. Define $A(i,j)$ to be an array with each element denoting the presence or absence of a pinhole in the aperture. If there is a hole at $(i{\cdot}c, j{\cdot}c)$, $A(i,j)$ has the value one, otherwise it is zero. The possible locations for the pinholes are restricted to a grid of discrete points with a spacing equal to c.

Equation (4) can be approximated to have the same form as Eq. (1):

$$P(k,l) \cong O * A + N \equiv \sum_i \sum_j O(i,j)A(i+k, j+l) + N(k,l), \qquad (5)$$

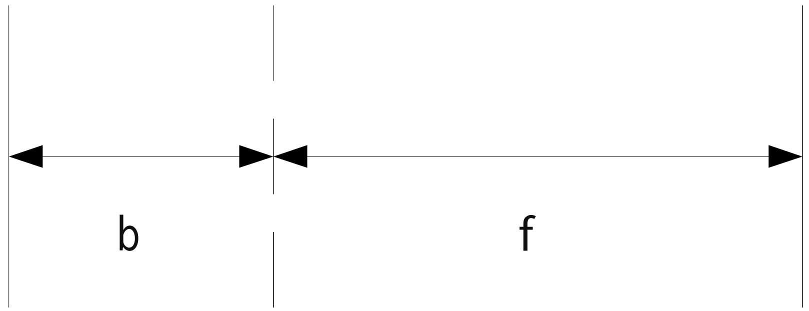
where $P(k,l)$ should be interpreted as the number of photons received from the object in an $m{\cdot}c$ by $m{\cdot}c$ area of the detector centered at $(k{\cdot}m{\cdot}c, l{\cdot}m{\cdot}c)$ plus some noise $N(k,l)$.

The P array is measured experimentally and since the A array is known, Eq. (5) is used to determine an estimate of the object intensity distribution. In the correlation analysis methods, the reconstructed object is determined from P and A by

$$\hat{O}(i,j) = P * G \equiv \sum_k \sum_l P(k,l)G(k+i, l+j), \qquad (6)$$

where G will be chosen such that $A * G$ is approximately (or exactly) a delta function.

The above is applicable to all coded aperture techniques. We will now employ the above in the implementation of URAs.



Source
pix. size
= c(b+f)/f

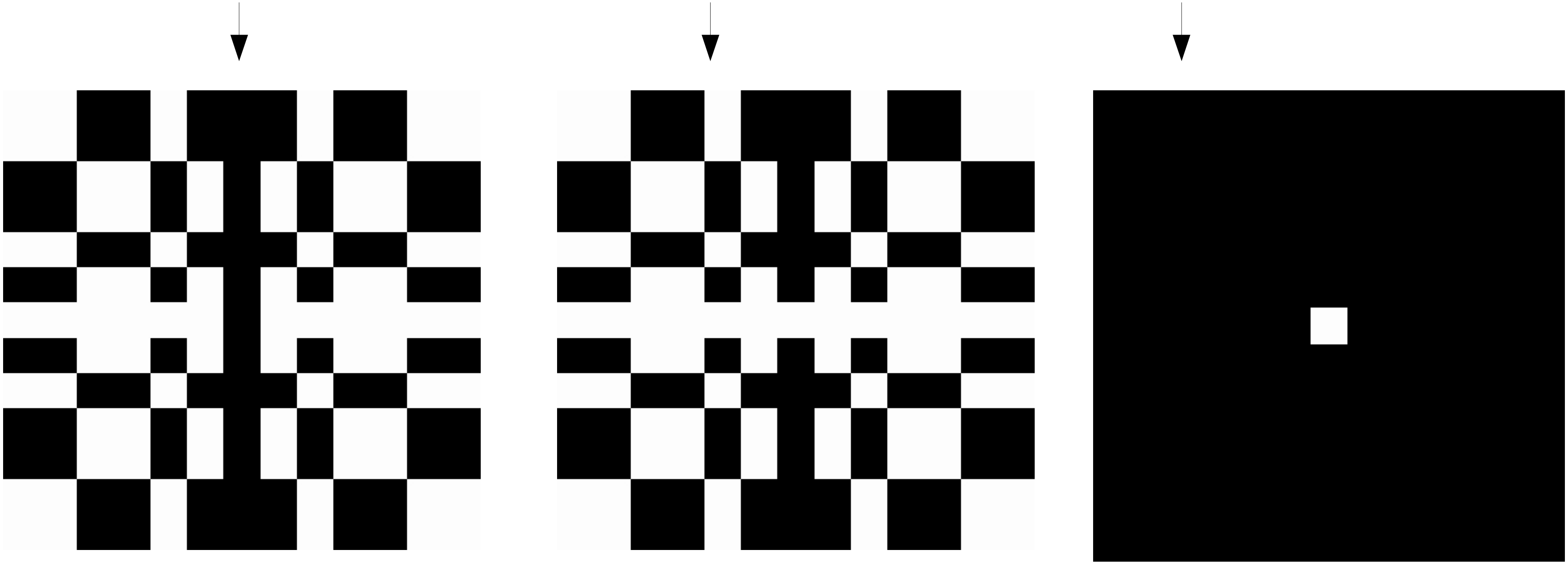
Mask
min. hole size
= c

Detector
pix. size
= c(b+f)/b

- Magnification m=(b+f)/b

- Fenimore and Cannon, Appl. Optics, V17, No. 3, p. 337 (1978)

Modified URA Mask, Anti-mask, and Cross-correlation



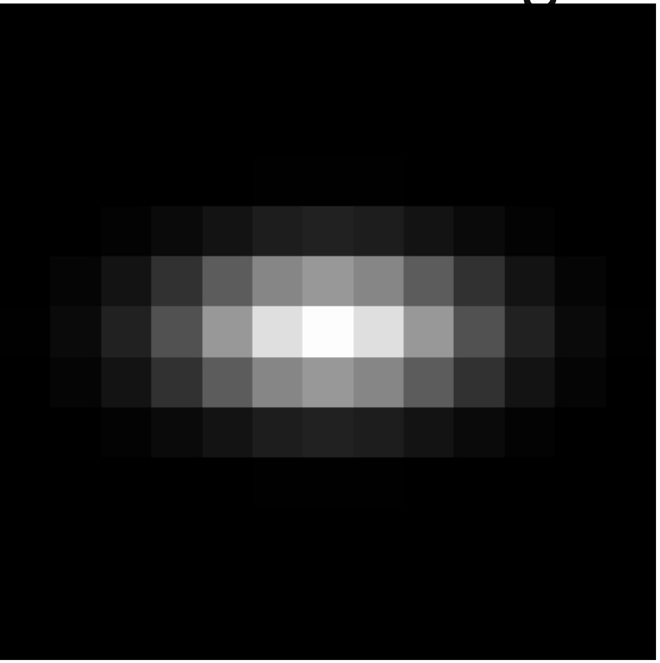
- Image is encoded using mask and decoded using anti-mask, where cross-correlation between mask and anti-mask is delta function.
- Pixel transparency determined by Jacobi function:
  - Is (pixel index)%DIM == (i∗i)%DIM for any 1<i<DIM?
    - Yes/No->Open/Closed.
    - 2-D case based on inverse XOR of both indices.
- Note: Fresnel zone plates can in principle also be used as coded apertures. (Barrett, H.H., Horrigan, F.A.: 1973, Appl. Opt., 12, 2686)

Examples

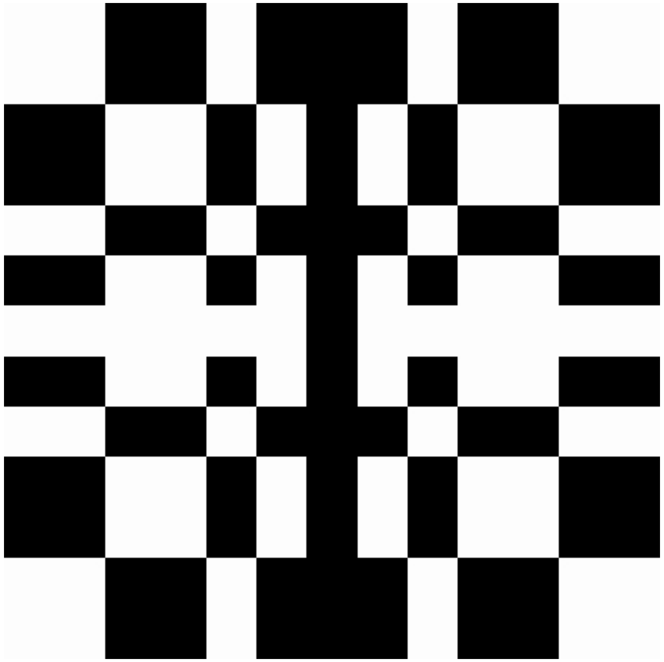
- As an illustrative example, here is a simulation of a 13x13 pixel source image, projected through a 13x13 Modified URA mask onto a 26x26 CCD.
  - The image represents a beam with $\sigma y=5\ \mu m$ (typical of ILC Damping Ring study mode, or SuperB super-low emittance mode) and $\sigma x=10\ \mu m$, with minimum mask pinholes 4 μm on a side.
  - With a 5:1 magnification factor (e.g., mask 6 meters downstream of source, and CCD 24 meters downstream of mask), the CCD pixels would be 25 μm on a side, which is about the size of the x-ray CCD in use at the ATF. The source resolution elements would be 5 μm on a side.
- The reconstruction method used is direct decoding.
- In the second case, a random scattering of 10% noise has been added to the CCD image, which has then been reconstructed via decoding.

URA Mask, decoding via anti-mask

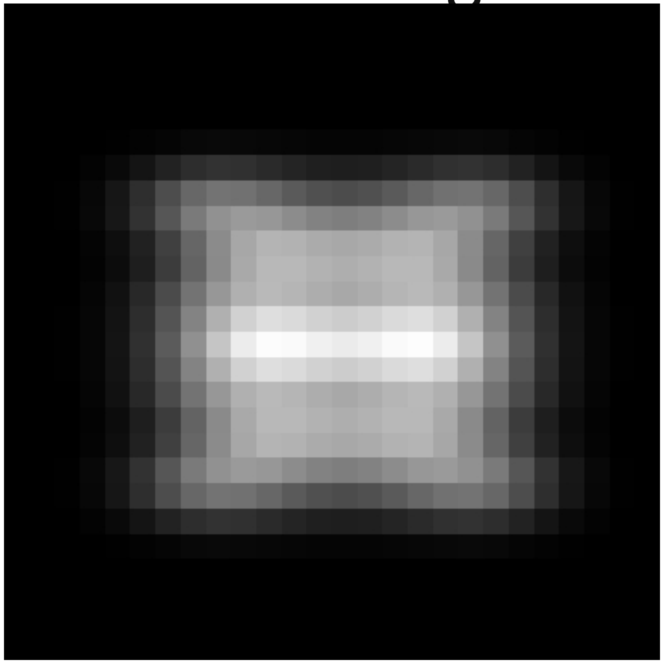
Source Image



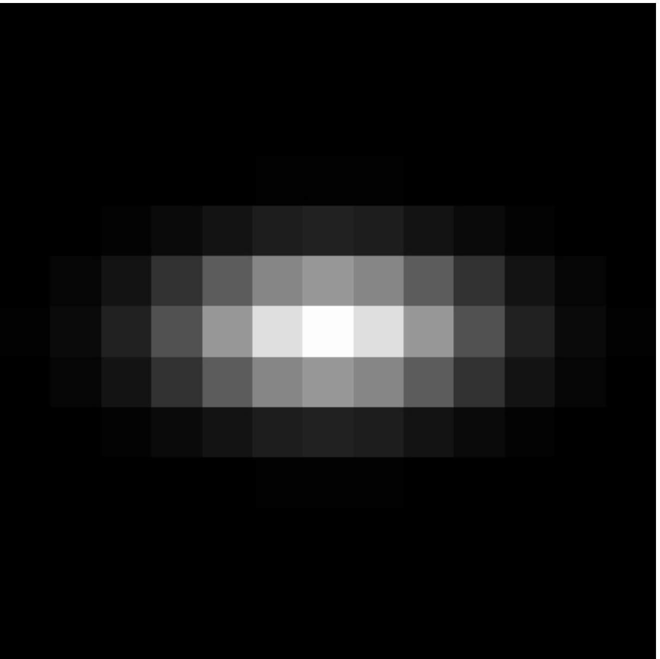
Mask

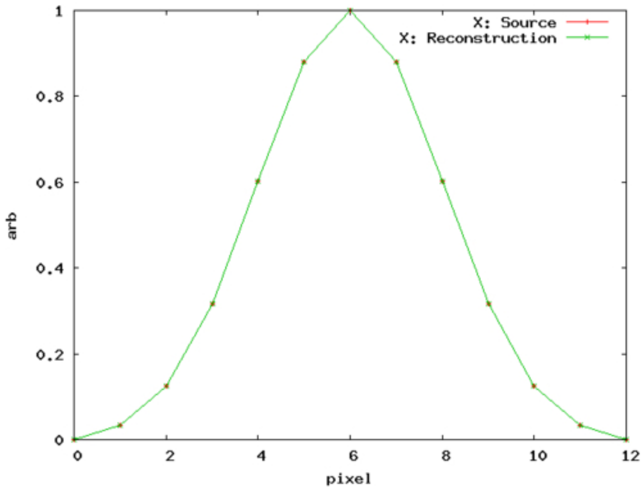


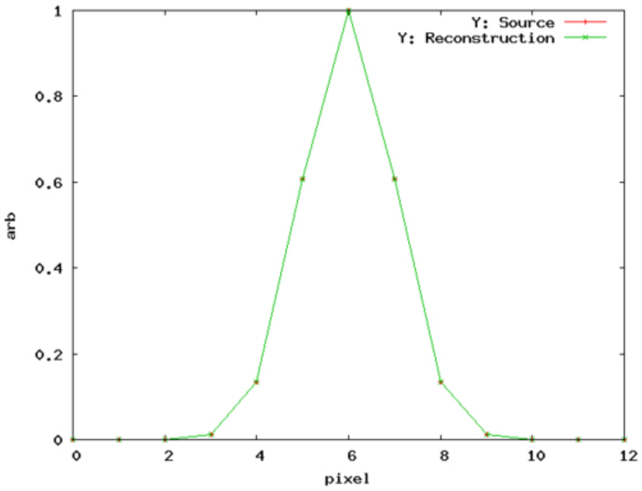
CCD Image



Reconstructed Image and Profiles

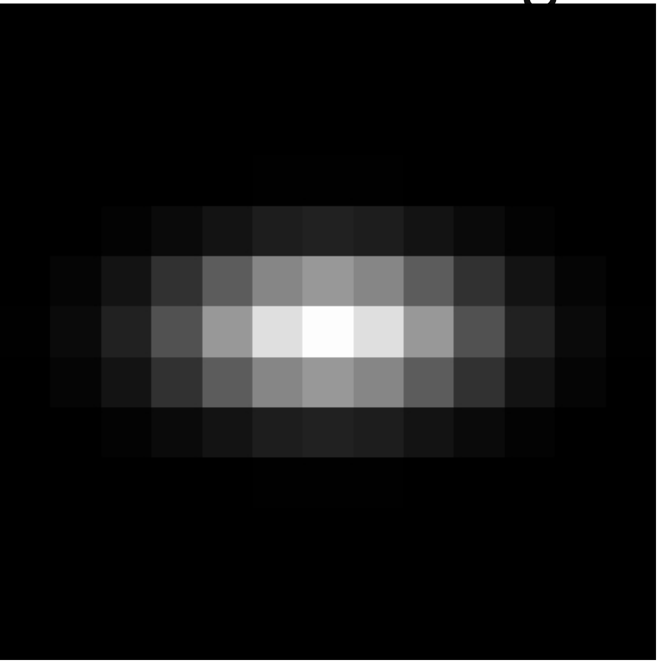




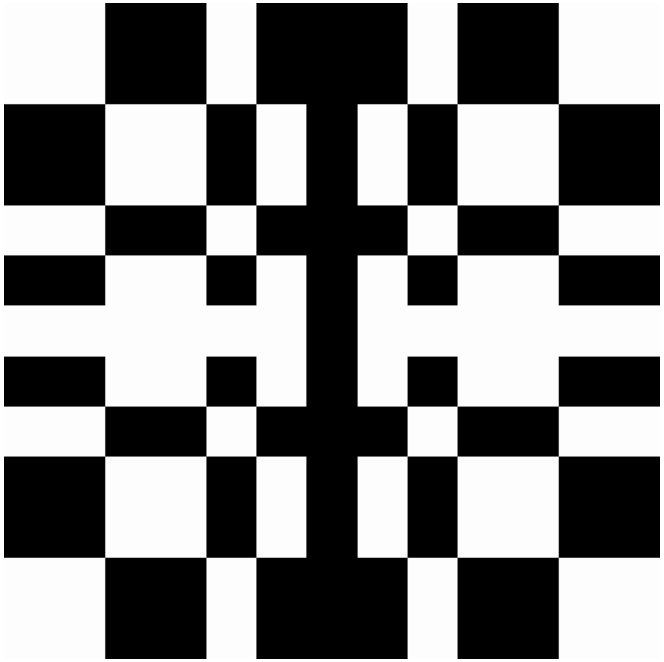


URA Mask, Decoded, with 10% noise on CCD

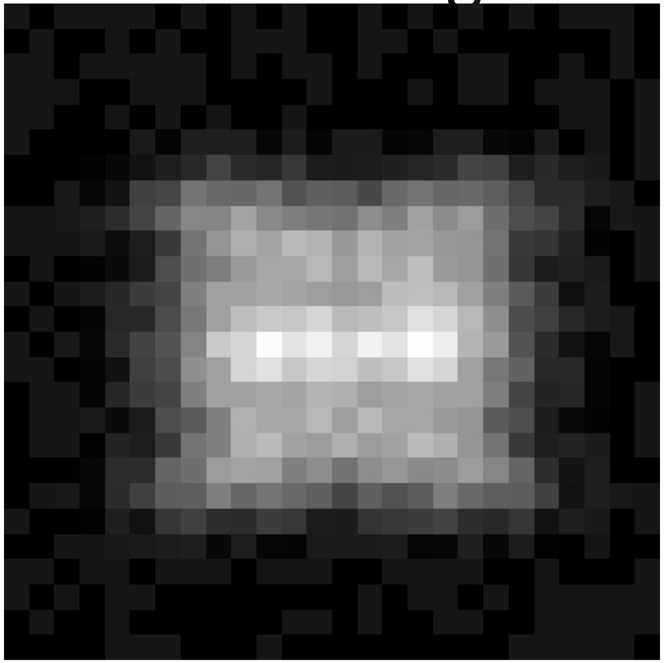
Source Image



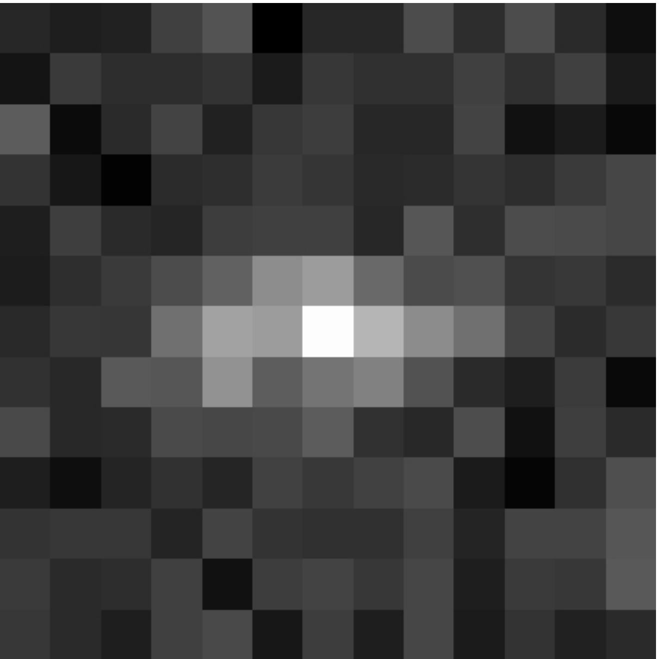
Mask

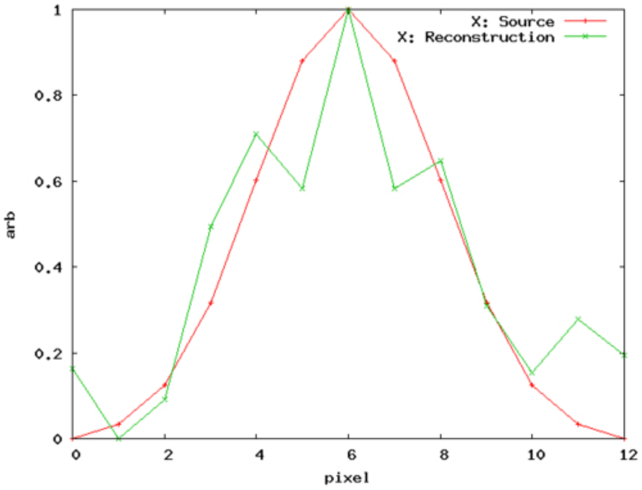


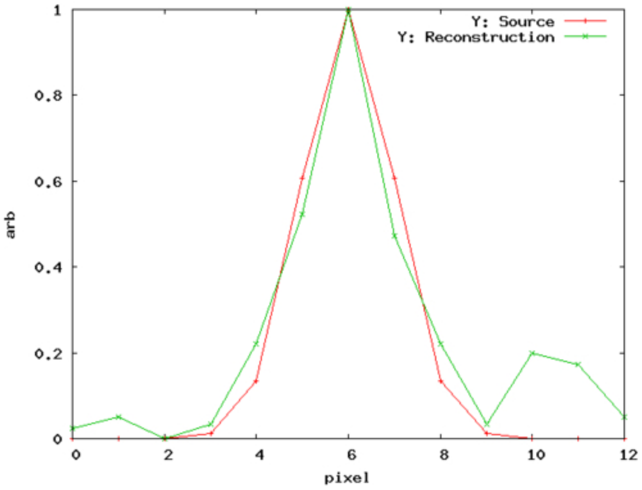
CCD Image



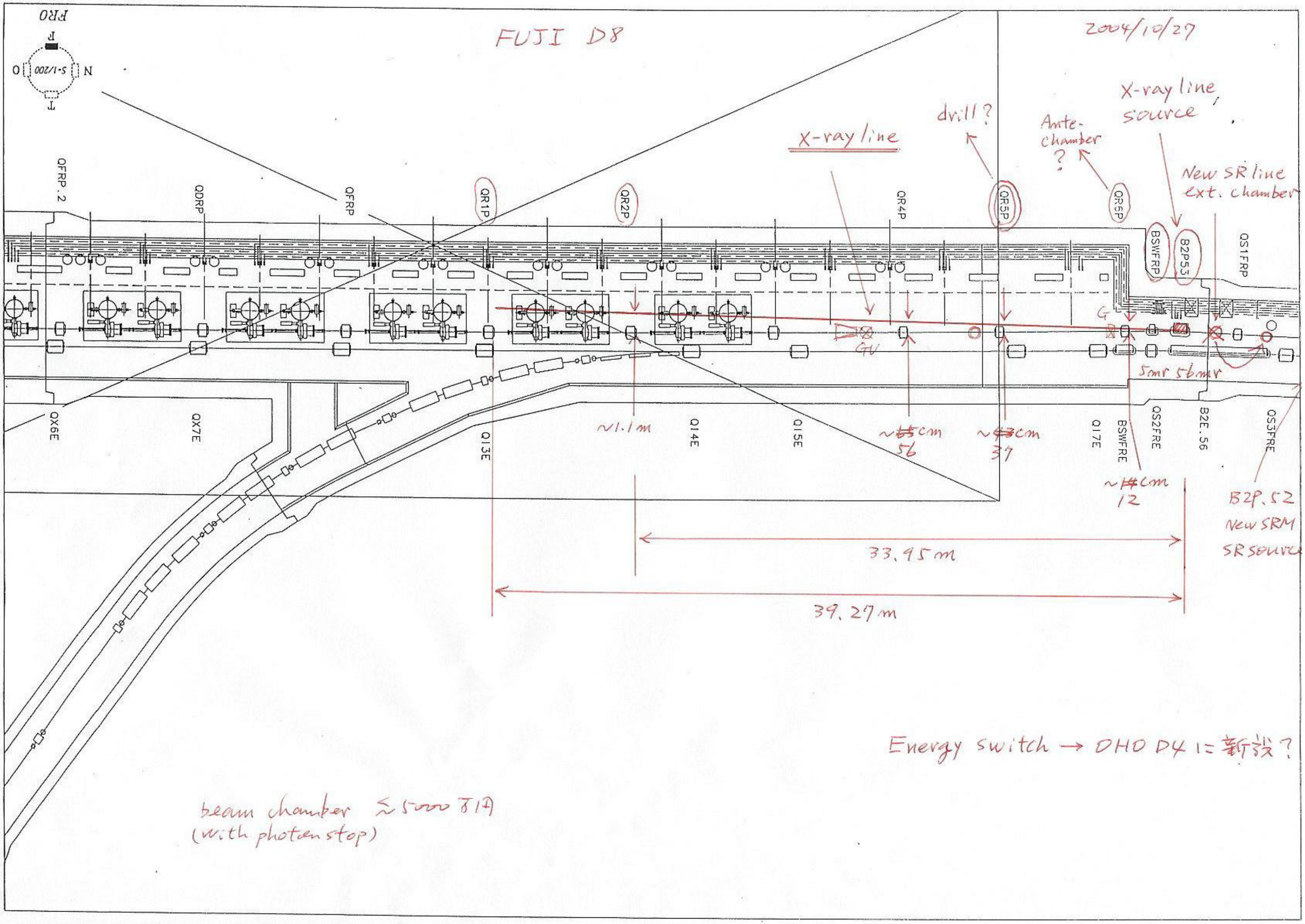
Reconstructed Image and Profiles







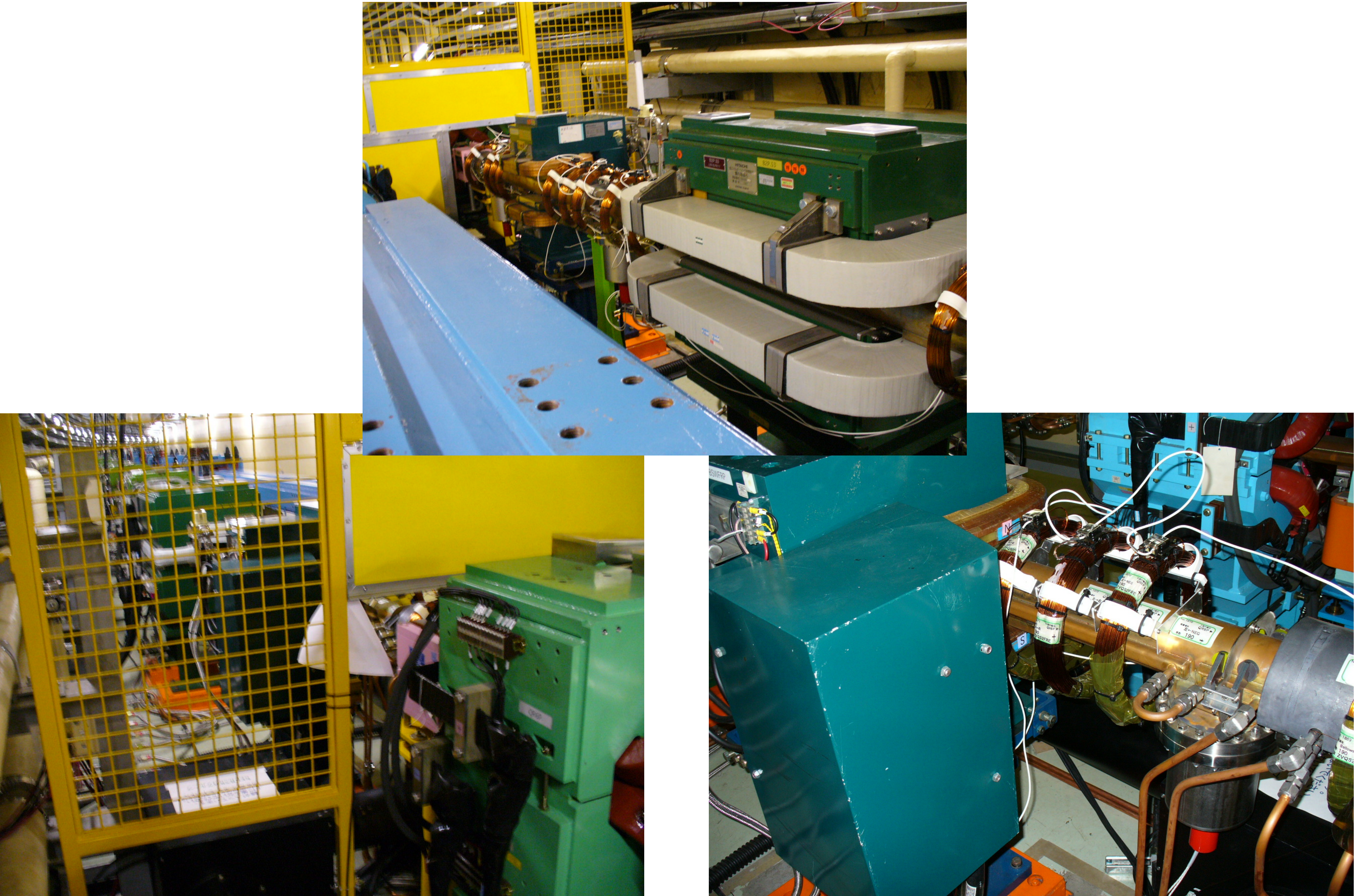
LER X線モニタービームライン（1）



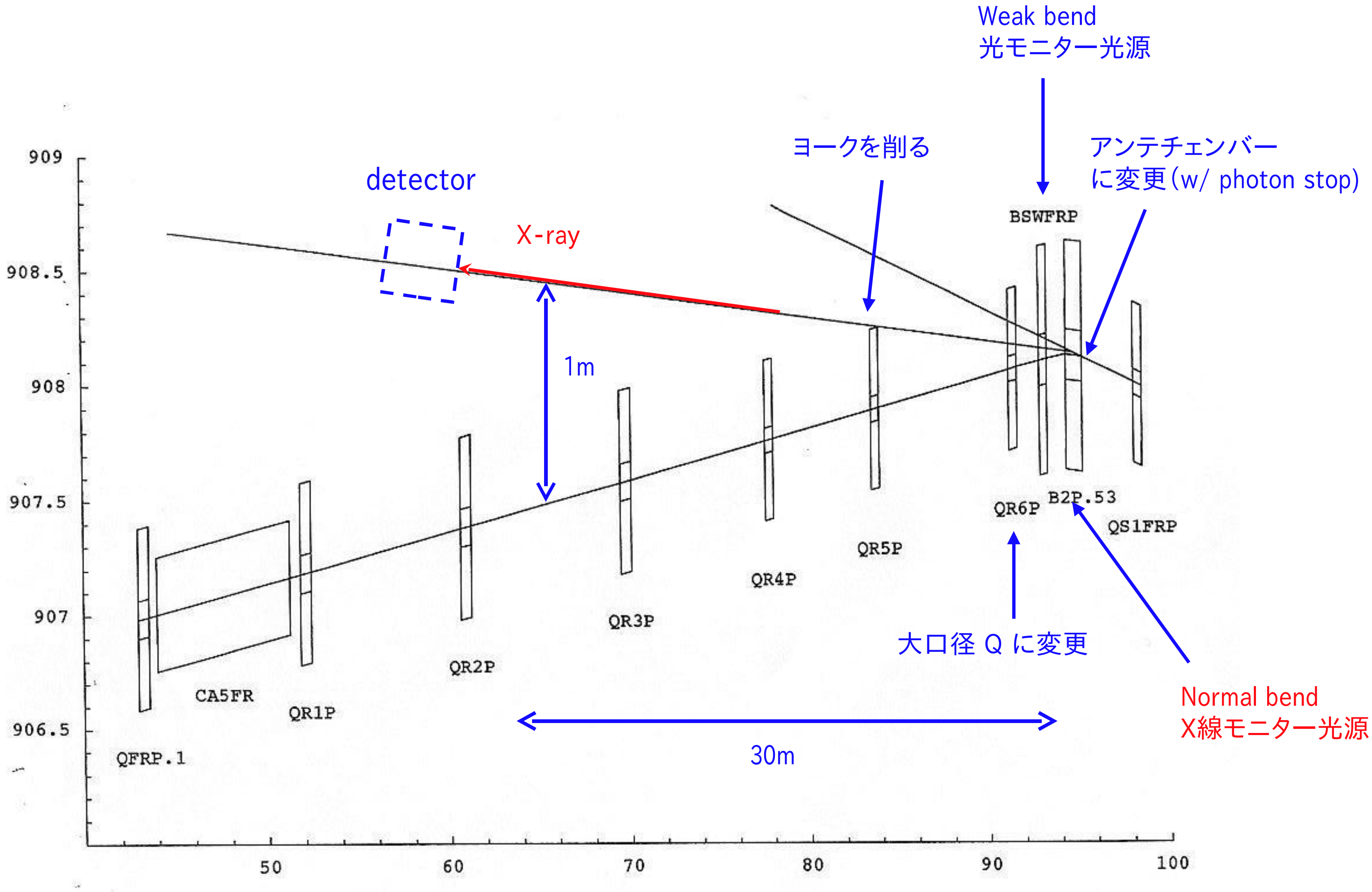
Energy switch → OHO D4 に新設？

beam chamber ≈5000万円
(with photon stop)

X-Ray Source Bend (B2P.53)



LER X線モニタービームライン（2）



Weak bend
光モニター光源

ヨークを削る

アンテチェンバー
に変更（w/ photon stop)

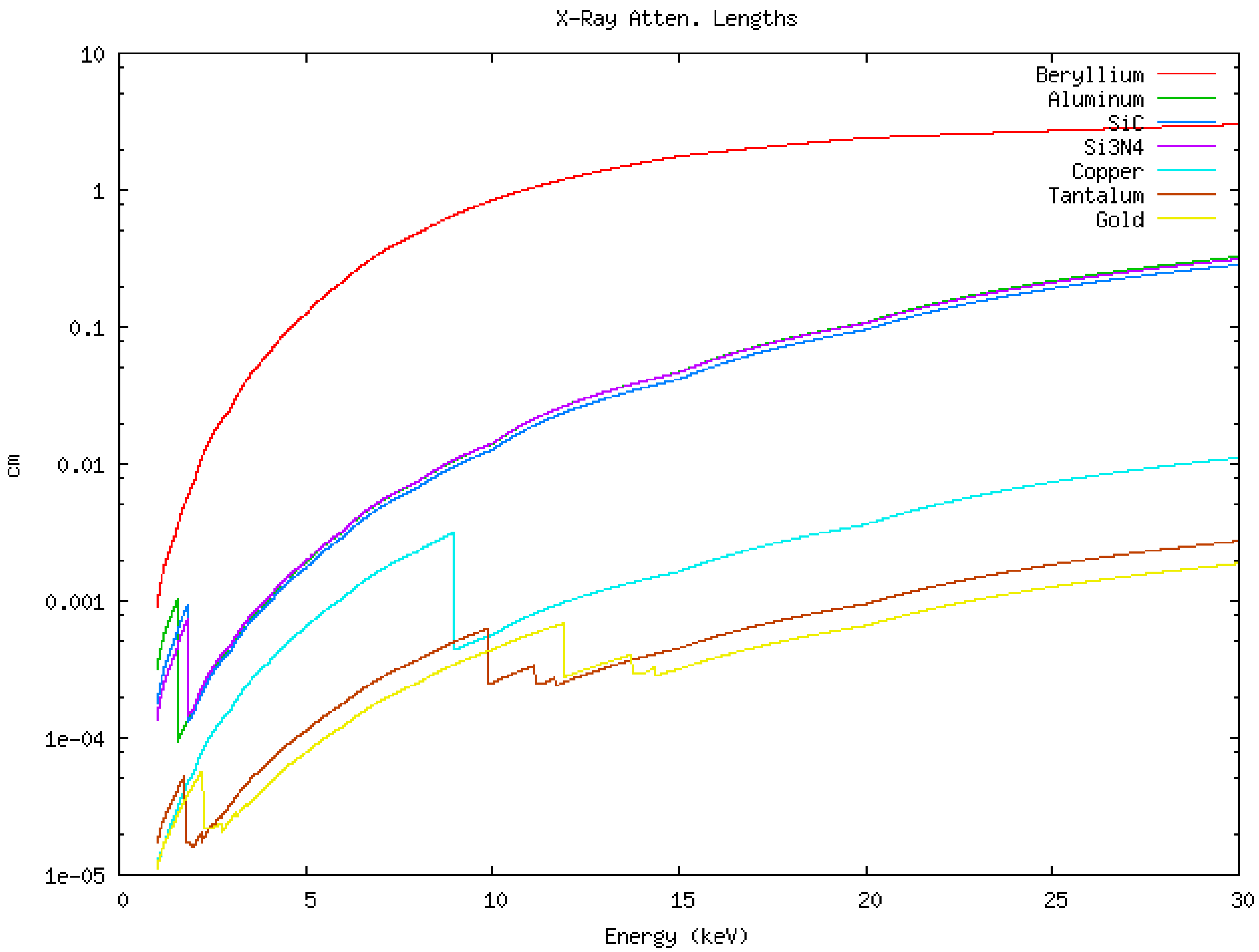
大口径 Q に変更

Normal bend
X線モニター光源

X-Ray Source & Beamline Parameters

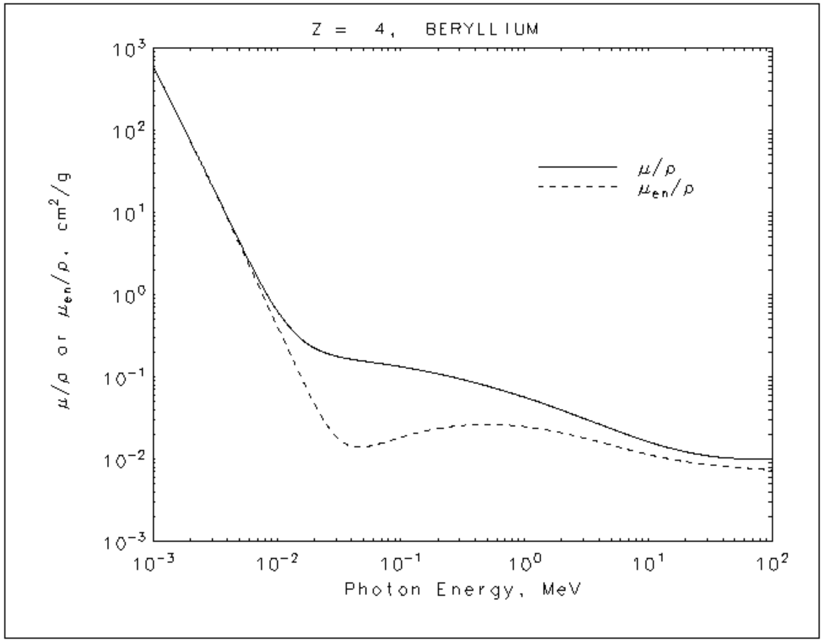
LER B2P.53	KEKB	KEKB-ILCDR	SuperB (LE)
ε x(m)	1.80E-08	1.50E-09	1.00E-09
κ (%)	1%	0.1%	0.1%
ε y(m)	1.80E-10	1.50E-12	1.00E-12
β x(m)	1.80E+01	1.80E+01	1.80E+01
β y(m)	2.20E+01	2.20E+01	2.20E+01
σ x(m)	5.69E-04	1.64E-04	1.34E-04
σ y(m)	6.29E-05	5.74E-06	4.69E-06
σ x(m)/ σ y(m)	9.05	28.6	28.6
I(a)	2	0.5	8
Bending radius (m)	13.76	13.76	13.76
bend angle (mrad)	56	56	56
Beam Energy (GeV)	3.5	2.3	3.8
kW/mrad/Ampere	0.15	0.15	0.15
Window size (mm)	10	10	10
Window to beam (m)	5	5	5
Power on window (kW)	0.600	0.150	2.400
Power after window (kW)	0.300	0.075	1.200
Mask size (mm)	1	1	1
Beam to mask (m)	6	6	6
Power on mask (kW)	0.025	0.006	0.100
Mask to Detector (m)	24	24	24

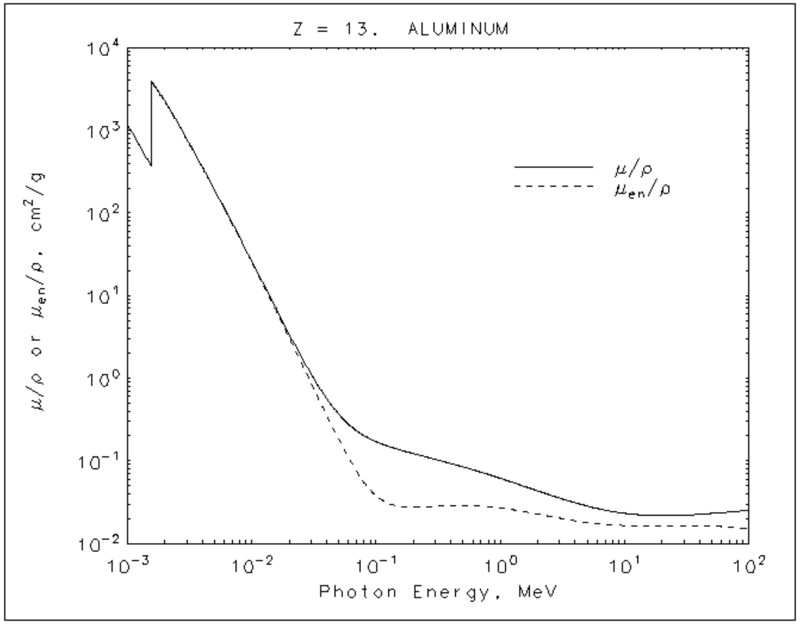
X-ray attenuation lengths

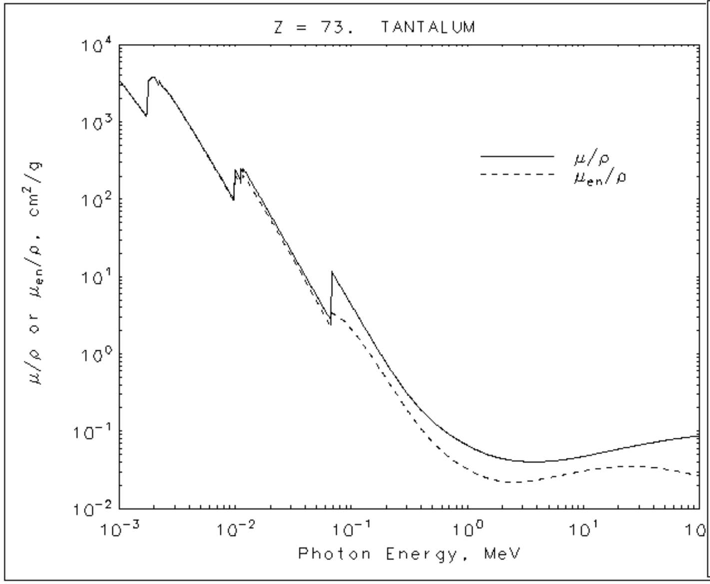


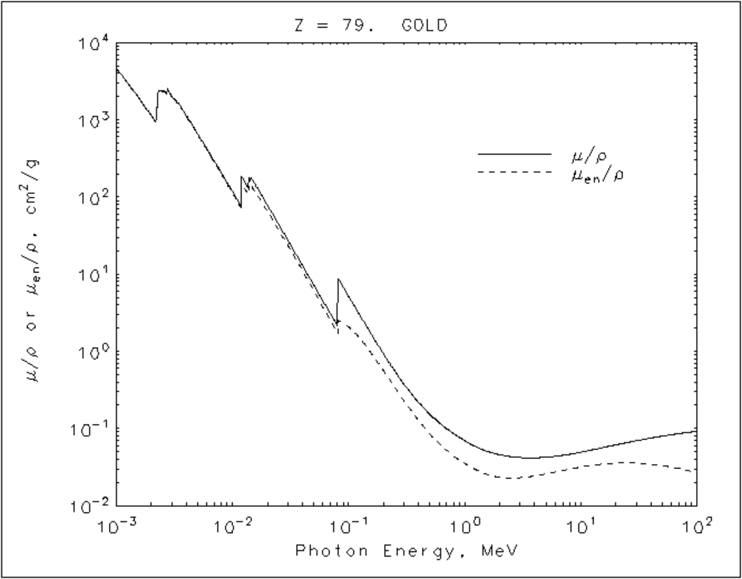
Energy dependence of attenuation and scattering

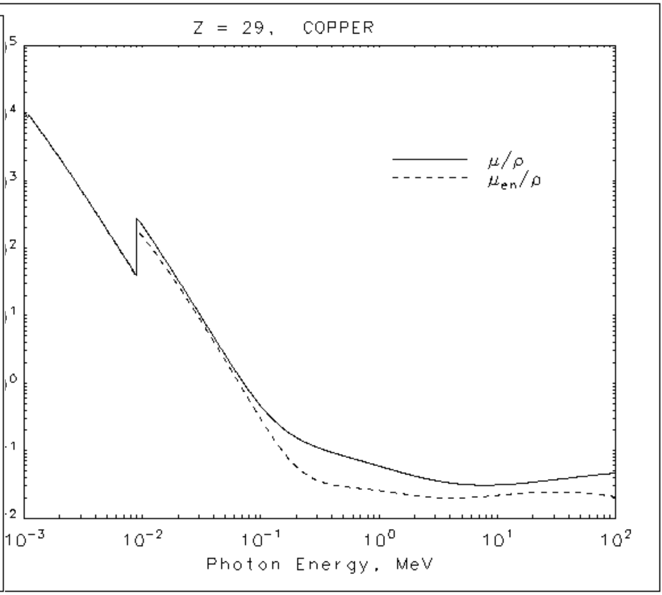
- Compton, Rayleigh scattering start to become significant above ˜ 20 keV





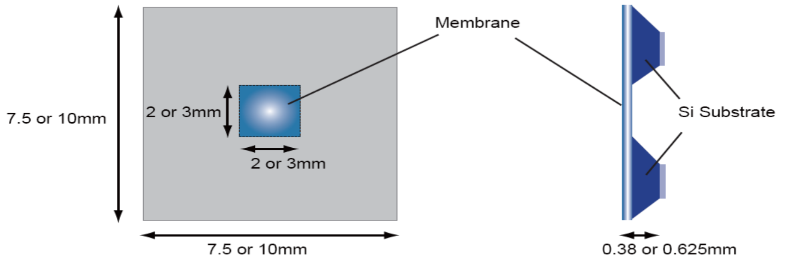






Assumptions

- Beam -> mask: 6 m
- Mask -> CCD: 24 m => 5x magnification
- Be window thickness: 1 mm
- Al filter/window thickness: 0.5 mm
- Mask: 4 um-thick Tantalum on 2 um-thick SiC
  - Outer size: 0.04 mrad (V) x 5*0.04 mrad (H) (0.24 x 1.2 um @ 6 m)
    - Useful vertical size limited by critical angle
- CCD quantum efficiency: 10%
  - ˜true for direct detection CCD
  - higher for fluorescent screen



Schematic of Membrane

Renarks:
The specifications stated in this brochure are representative values
and not guaranteed. Also, please kindly note that the specifications may change without prior notice for product update.

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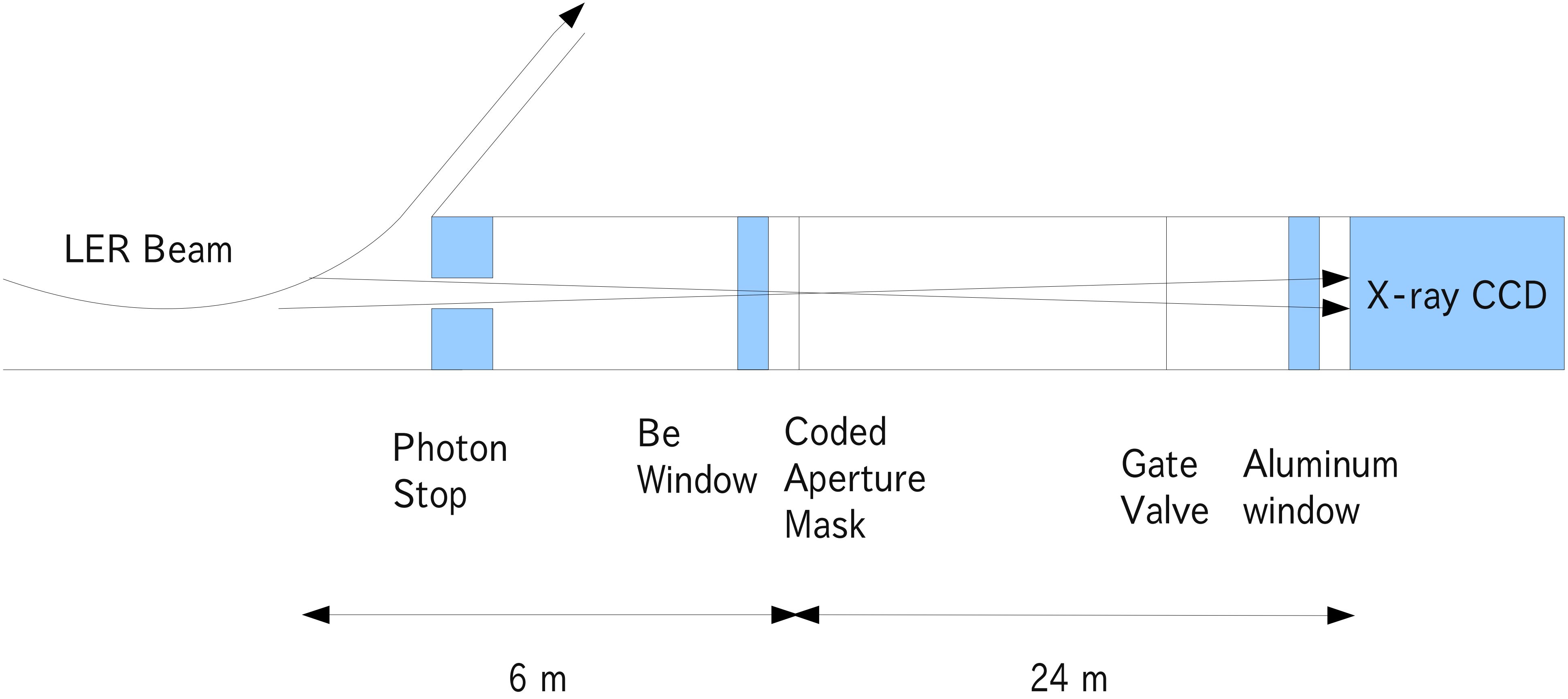
Basic layout



LER Beam

X-ray CCD

Photon Stop

Be Window

Coded Aperture Mask

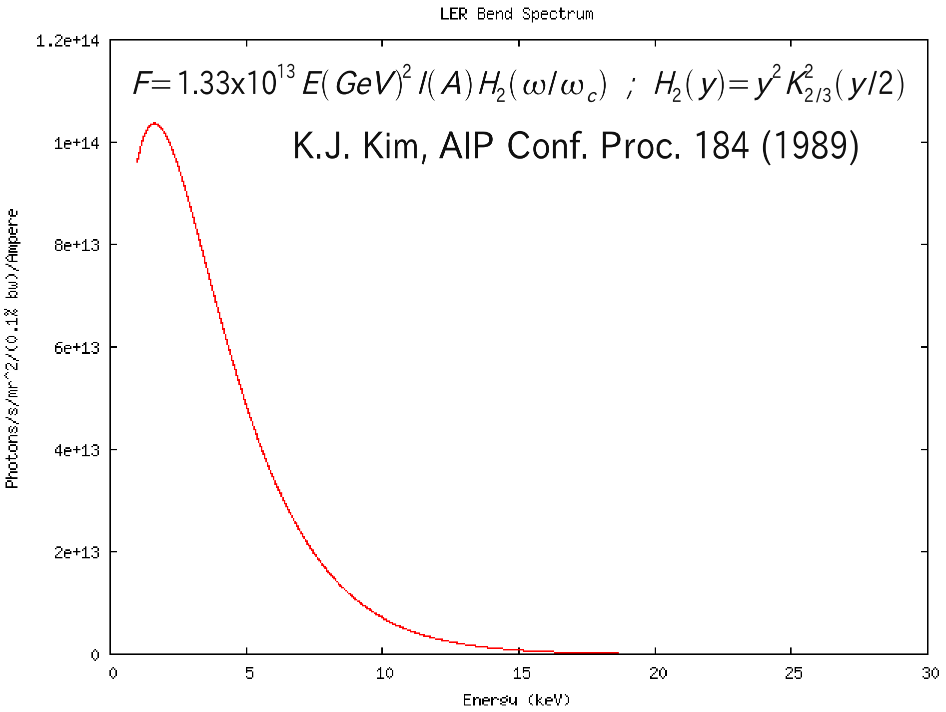
Gate Valve

Aluminum window

6 m

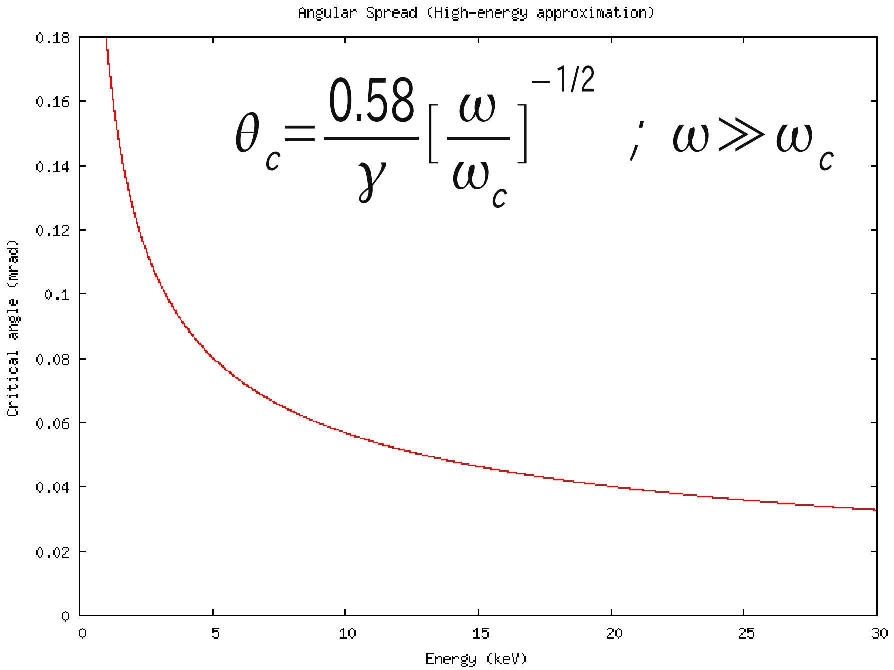
24 m

KEKB-ILCDR mode



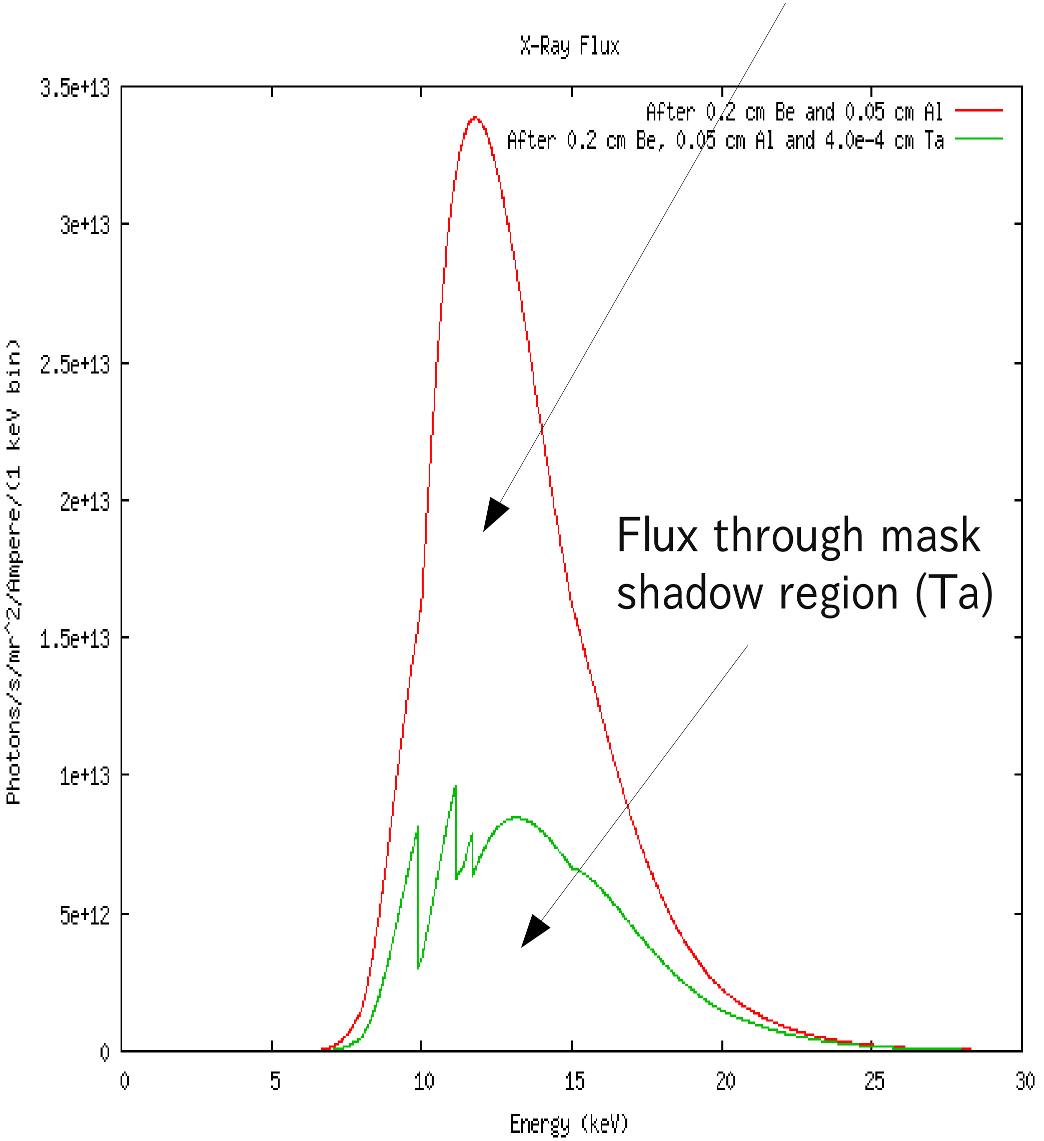
$F = 1.33\times10^{13}\, E(GeV)^2\, I(A)\, H_2(\omega/\omega_c)$; $H_2(y) = y^2 K_{2/3}^2(y/2)$

K.J. Kim, AIP Conf. Proc. 184 (1989)



$$\theta_c = \frac{0.58}{\gamma}\left[\frac{\omega}{\omega_c}\right]^{-1/2} \quad ; \ \omega \gg \omega_c$$

Flux through mask holes

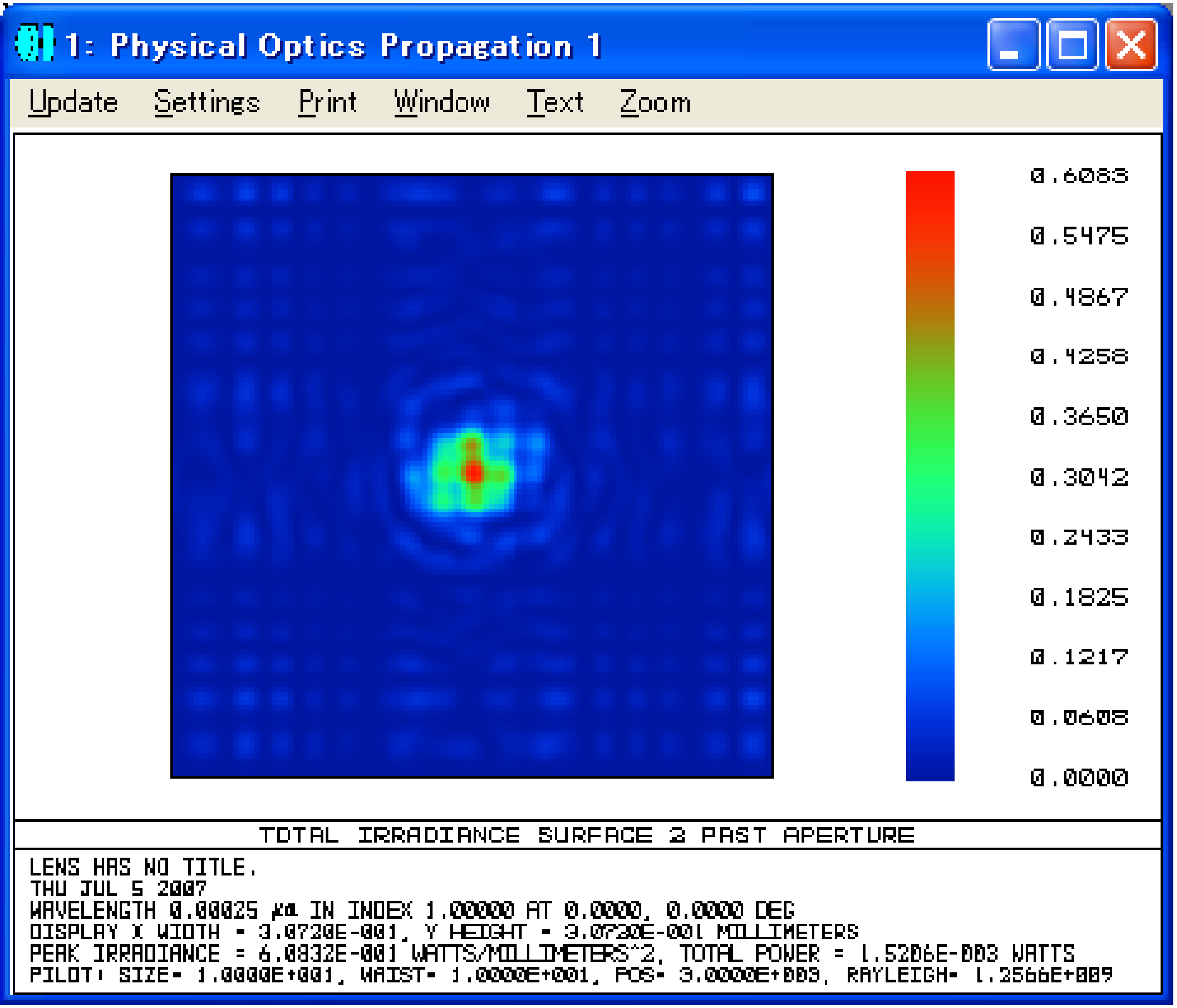


Flux through mask shadow region (Ta)

KEKB-ILCDR mode

```
Gamma =  4.500978e+03
Critical energy =  1.945305e+00  keV
Total source power =  2.812707e-02  kW/mrad
Flux from source:   1.62907e+17  photons/s/mr^2/Ampere
Flux after  0.1  cm Be:   1.91572e+16  photons/s/mr^2/Ampere
Flux after  0.05  cm Al:   2.12417e+14  photons/s/mr^2/Ampere
Flux after  0.0004  cm Ta:   7.37955e+13  photons/s/mr^2/Ampere
Flux after  0.0002  cm SiC:   2.10648e+14  photons/s/mr^2/Ampere
Flux after  10  cm Air:   2.03274e+14  photons/s/mr^2/Ampere
Flux through  0.008  mr^2 mask:  1.6262e+12  photons/s/Ampere
Flux/turn 1.6262e+07  photons/turn/Ampere
Flux/mA/bunch 16262  photons/turn/mA/bunch
Detected signal 1626.2  photons/turn/mA/bunch
Detected background 566.748  photons/turn/mA/bunch
On-axis power from source:   0.0736069  kW/mr^2/Ampere
On-axis power after  0.1  cm Be:   0.0190535  kW/mr^2/Ampere
On-axis power after  0.05  cm Al:   0.000446705  kW/mr^2/Ampere
On-axis power after  0.0004  cm Ta:   0.000164321  kW/mr^2/Ampere
On-axis power after  0.0002  cm SiC:   0.000443388  kW/mr^2/Ampere
On-axis power after  10  cm Air:   0.000429463  kW/mr^2/Ampere
```

But, diffraction effect is not small, as Mitsuhashi points out



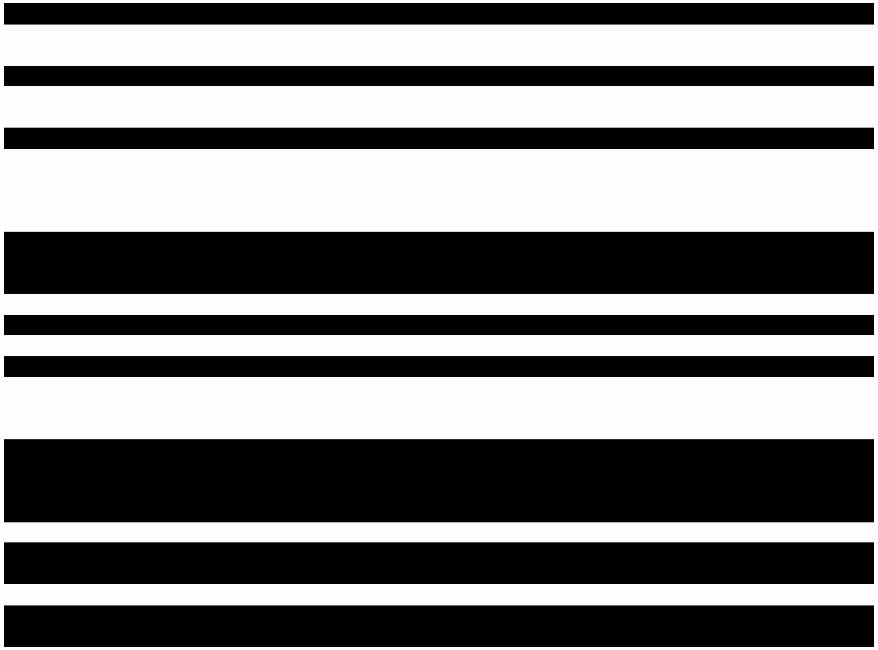
TOTAL IRRADIANCE SURFACE 2 PAST APERTURE

```
LENS HAS NO TITLE.
THU JUL 5 2007
WAVELENGTH 0.00025 µm IN INDEX 1.00000 AT 0.0000, 0.0000 DEG
DISPLAY X WIDTH = 3.0720E-001, Y HEIGHT = 3.0720E-001 MILLIMETERS
PEAK IRRADIANCE = 6.0832E-001 WATTS/MILLIMETERS^2, TOTAL POWER = 1.5206E-003 WATTS
PILOT: SIZE= 1.0000E+001, WAIST= 1.0000E+001, POS= 3.0000E+003, RAYLEIGH= 1.2566E+009
```

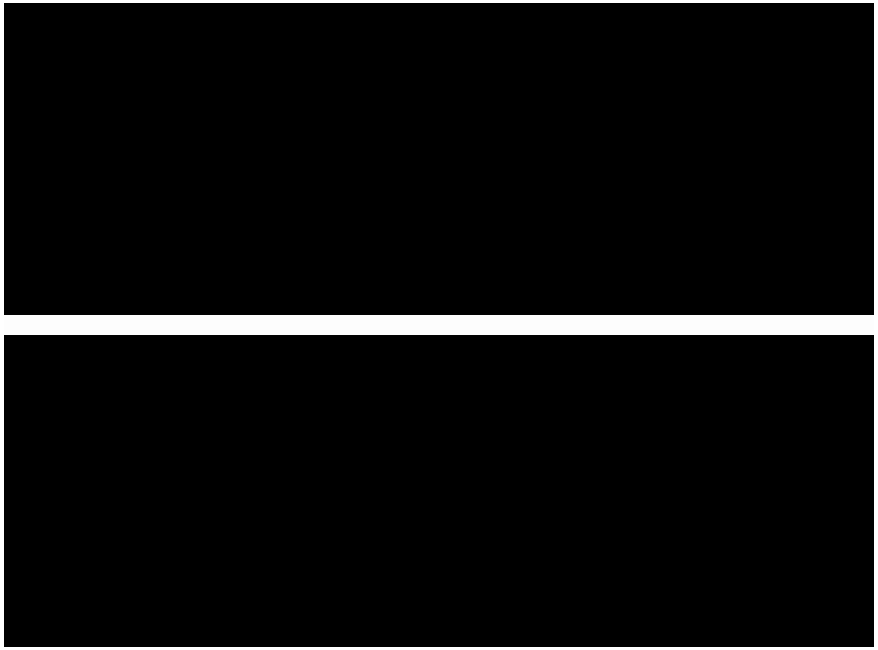
- x-ray: 5 keV
- URA mask: 23x23
- Hole size: 2.4 um
- Distance from mask to camera: 3 m
- Diffraction calculated using Zemax
- This can in principle still be reconstructed if we know the spectrum, using **iterative methods** such as maximum entropy.

Vertical-only mask: 1x31

Much faster reconstruction when using iterative methods
(1-D vs 2-D problem)



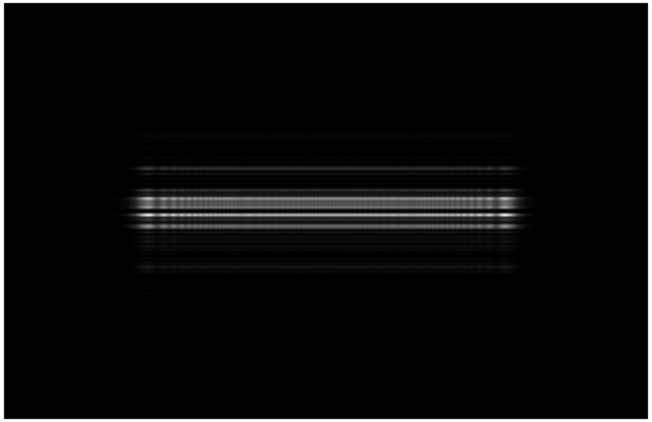
1-D URA Mask



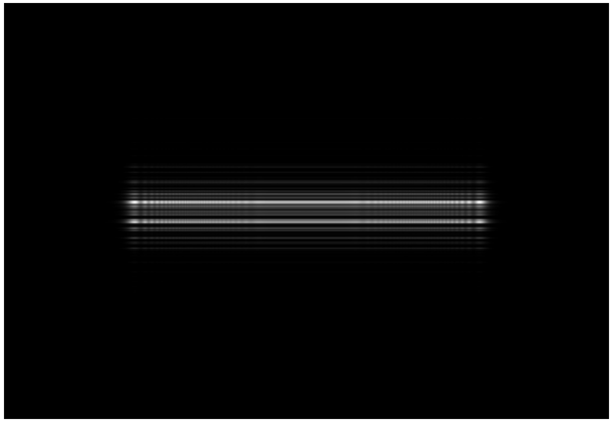
Autocorrelation

Vertical-only mask: 1x31, 4 um min. aperture

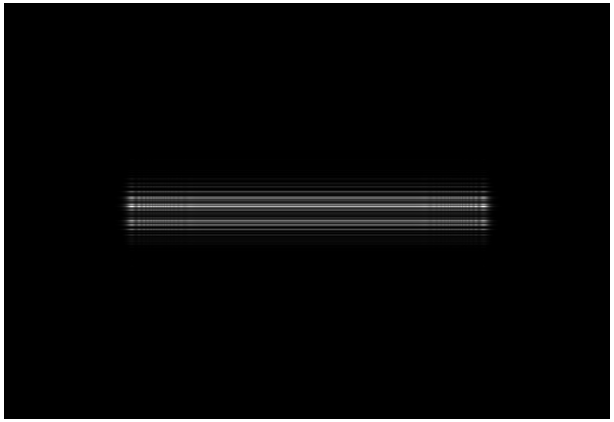
Irradiance as function of photon energy. Mask->detector = 24 m



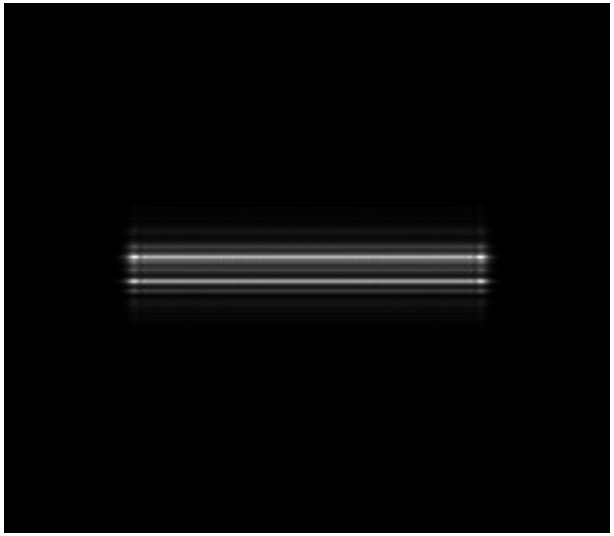
6.2 keV



12.4 keV



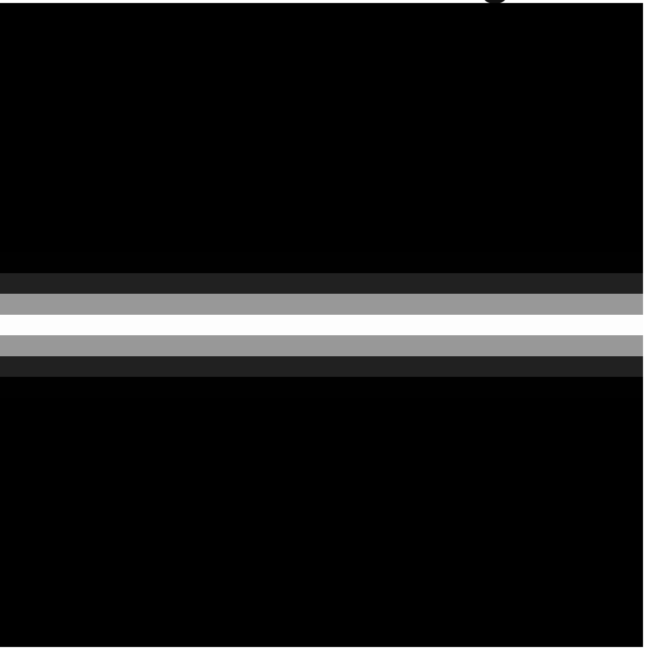
24.8 keV



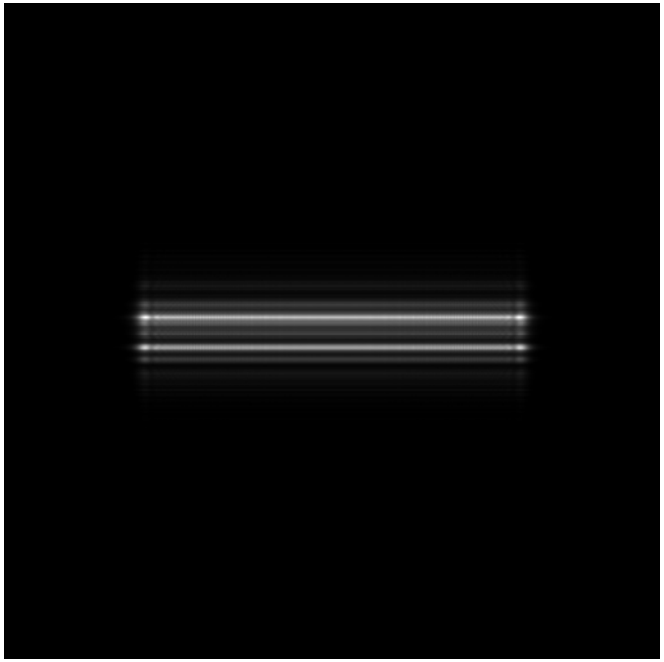
Averaged over spectrum

URA 1x31 x 4 um; **Decoding**; Beam sigy=5 um, spec. 5-30 keV; No Noise

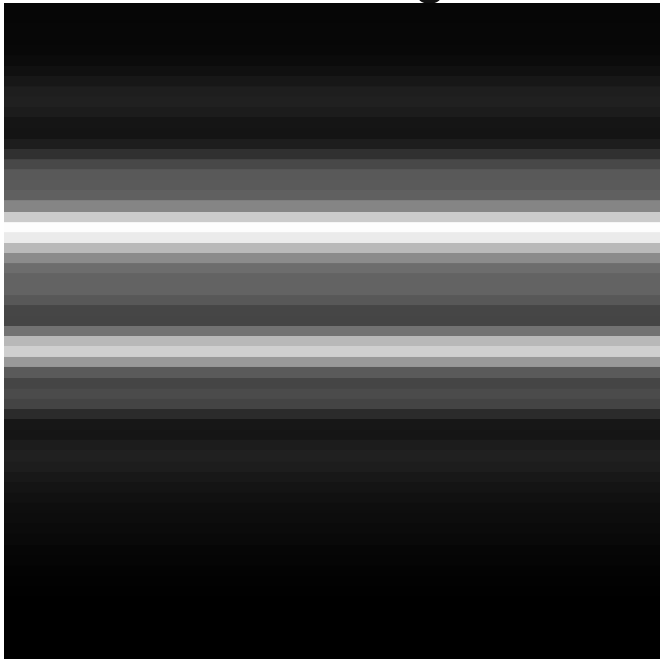
Source Image



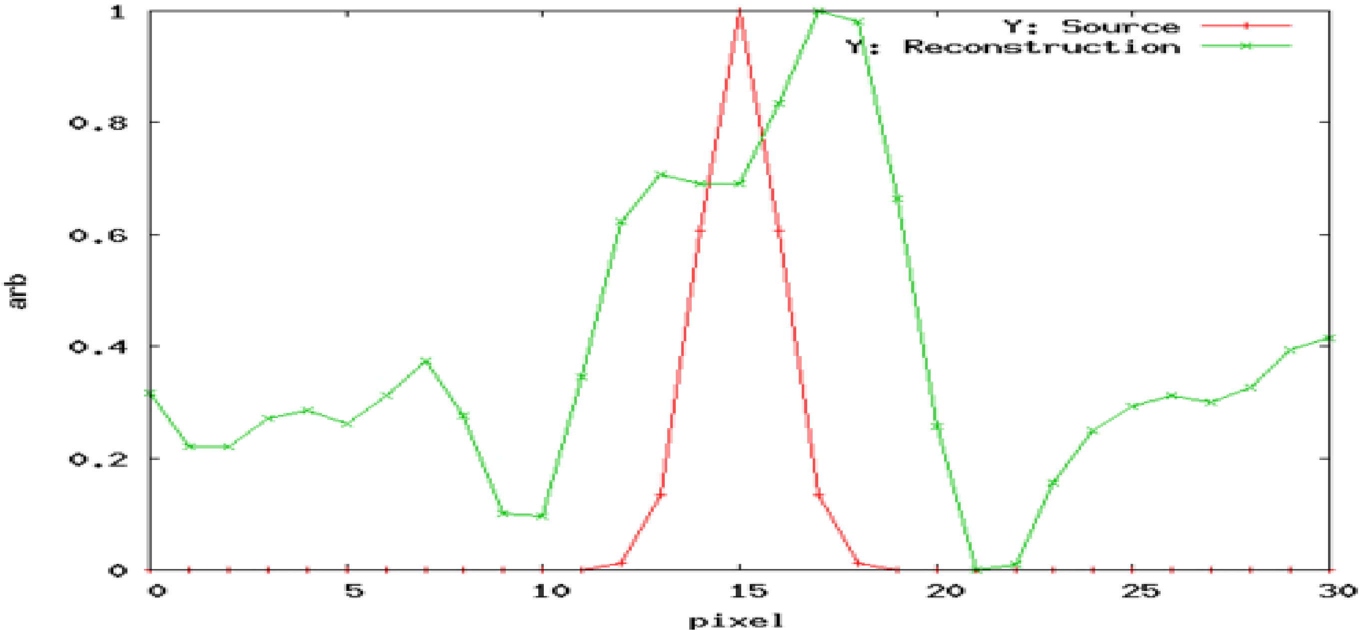
Mask Irradiance w/diffraction



CCD Image

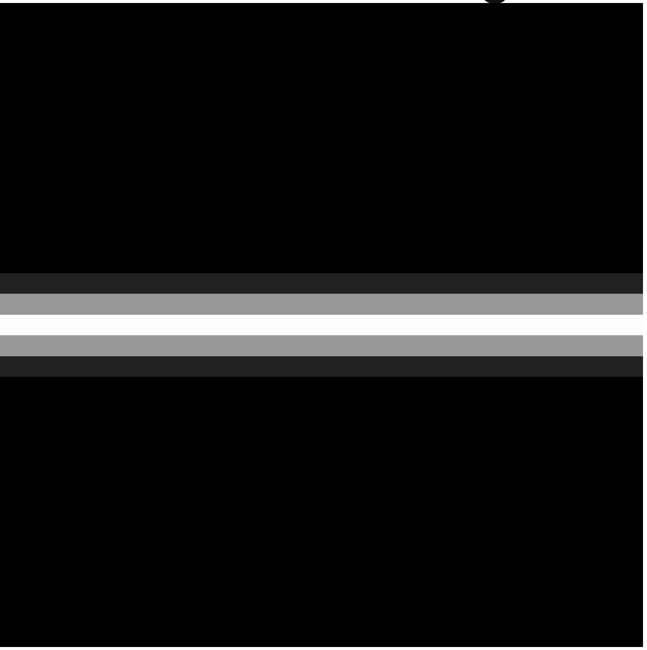


Reconstructed Image and Profile

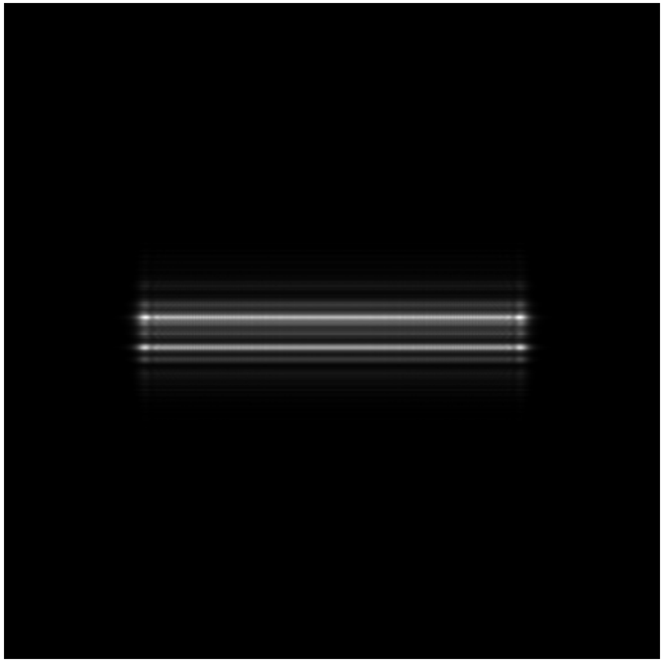


URA 1x31 x 4 um; **Max. Ent. reconstruction**; Beam sigy=5 um, 5-30 keV; No Noise

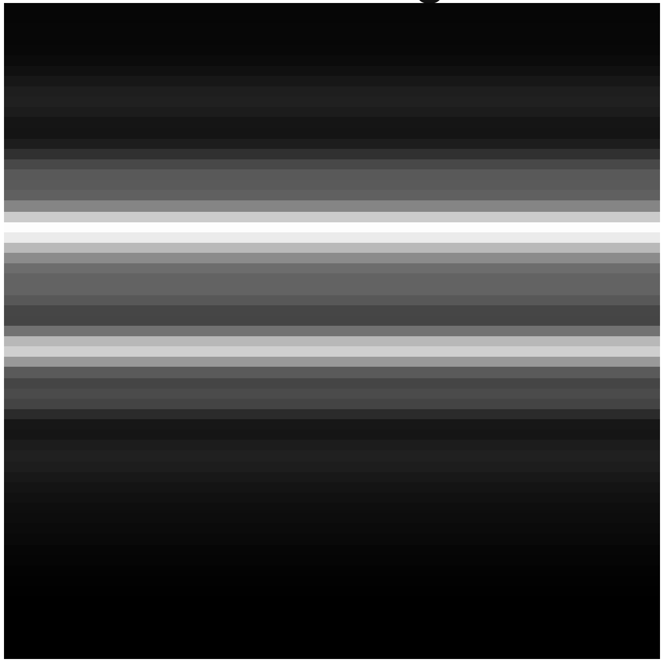
Source Image



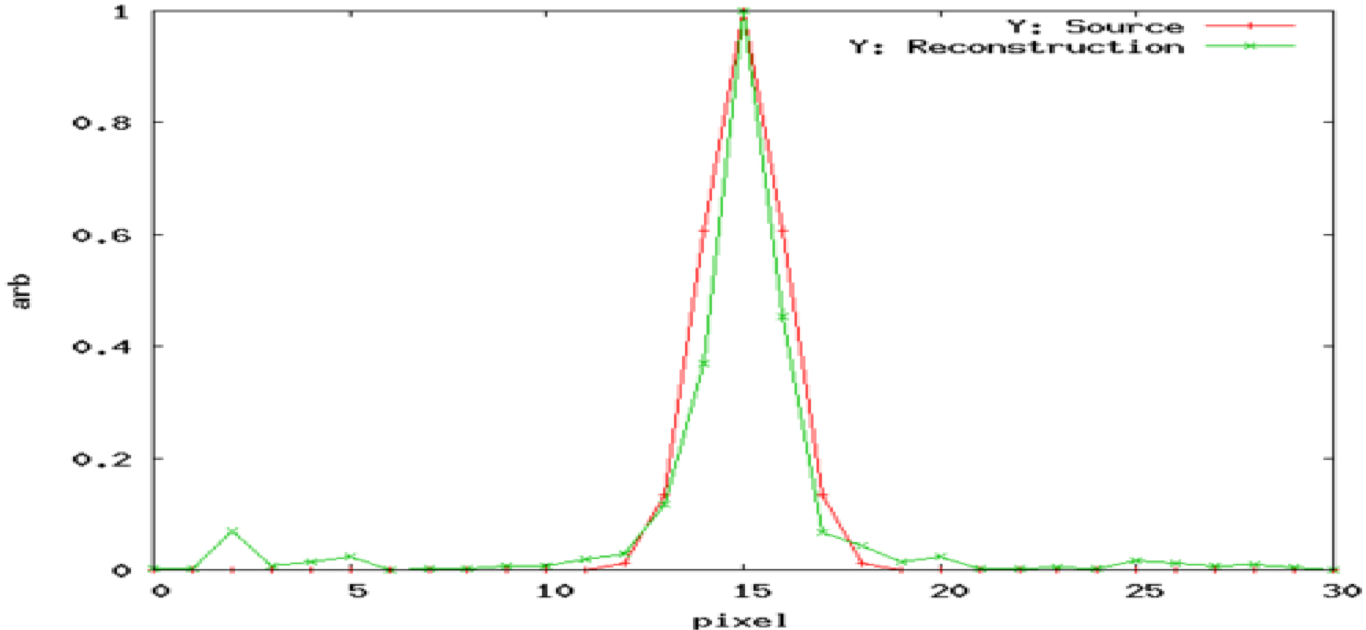
Mask Irradiance w/diffraction



CCD Image

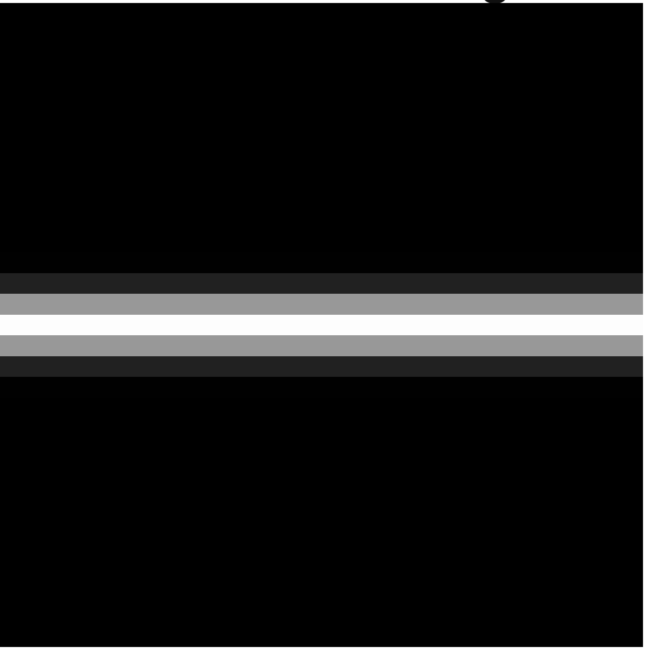


Reconstructed Image and Profile

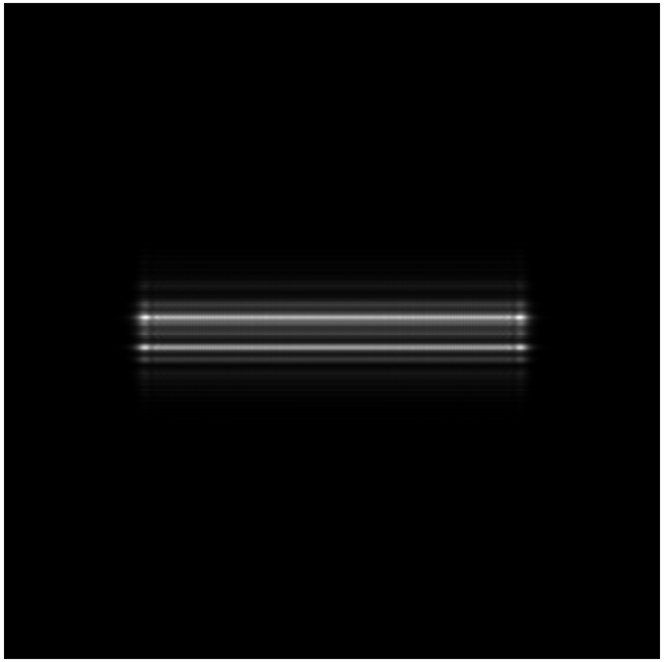


URA 1x31 x 4 um; **Max. Ent. reconstruct.** ; Beam sigy=5 um, 5-30 keV; 10% Noise

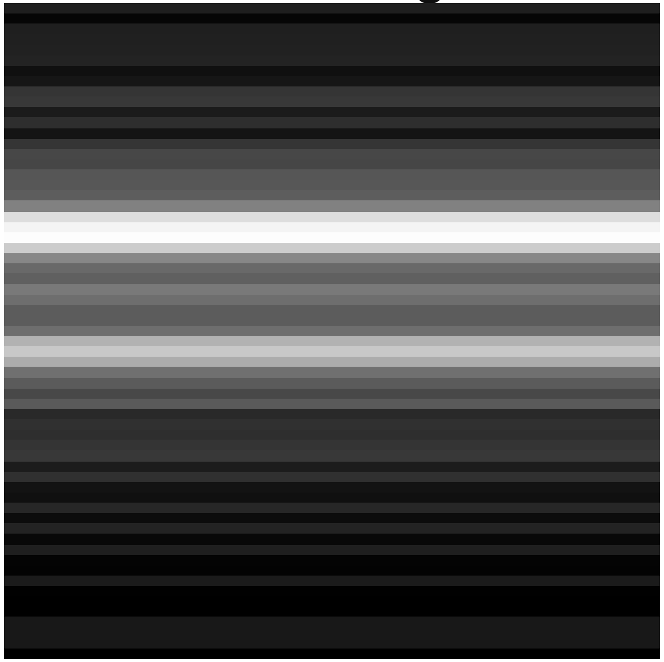
Source Image



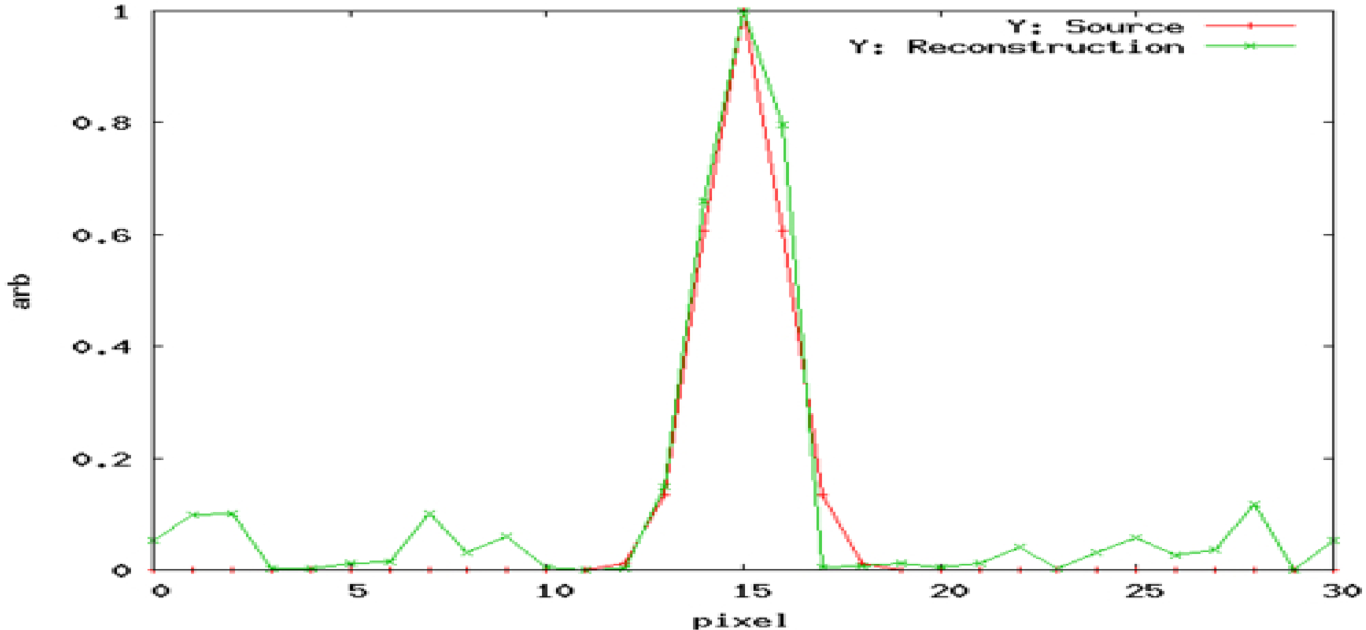
Mask Irradiance w/diffraction



CCD Image



Reconstructed Image and Profile



Other hardware

- In discussion with G. Varner of UH (Belle pixel detector person) on high-speed detector/readout system.
  - 6 GS/s -> slice bunch
- Costs (very rough!):
  - Extraction chamber: 4000 man-yen ($400,000 at 100 yen/$)
  - Mask: 250 man-yen * N (NTT Adv. Tech.)
  - Detector: 750 man-yen?
  - Hole in magnet for extraction line: 250 man-yen
  - Extraction line, Be window, Al window, gate valve, photon stop: 1750 man-yen?
  - Total: ~7500 man-yen?

Conclusion

- Coded Aperture Imaging seems to be a realistic possibility for x-ray beam profile and position monitoring.
- Work needs to be done on selecting an appropriate mask pattern and reconstruction method.
  - URA decoding is very fast, but cannot handle diffraction effects, for which we need iterative methods.
- But in principle, a very simple and relatively low-cost system might be able to be constructed from, say, a beryllium window in the beam pipe at a source bend, a mask, and an x-ray CCD, plus perhaps an aluminum filter if needed to reduce power.
  - Mitsuhashi offers use of x-ray tube at PF to start testing
  - Design with view towards KEKB ILC mode or SuperB low-emittance mode