Fabry-Perot Resonator for Hard X-Rays

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Research Team

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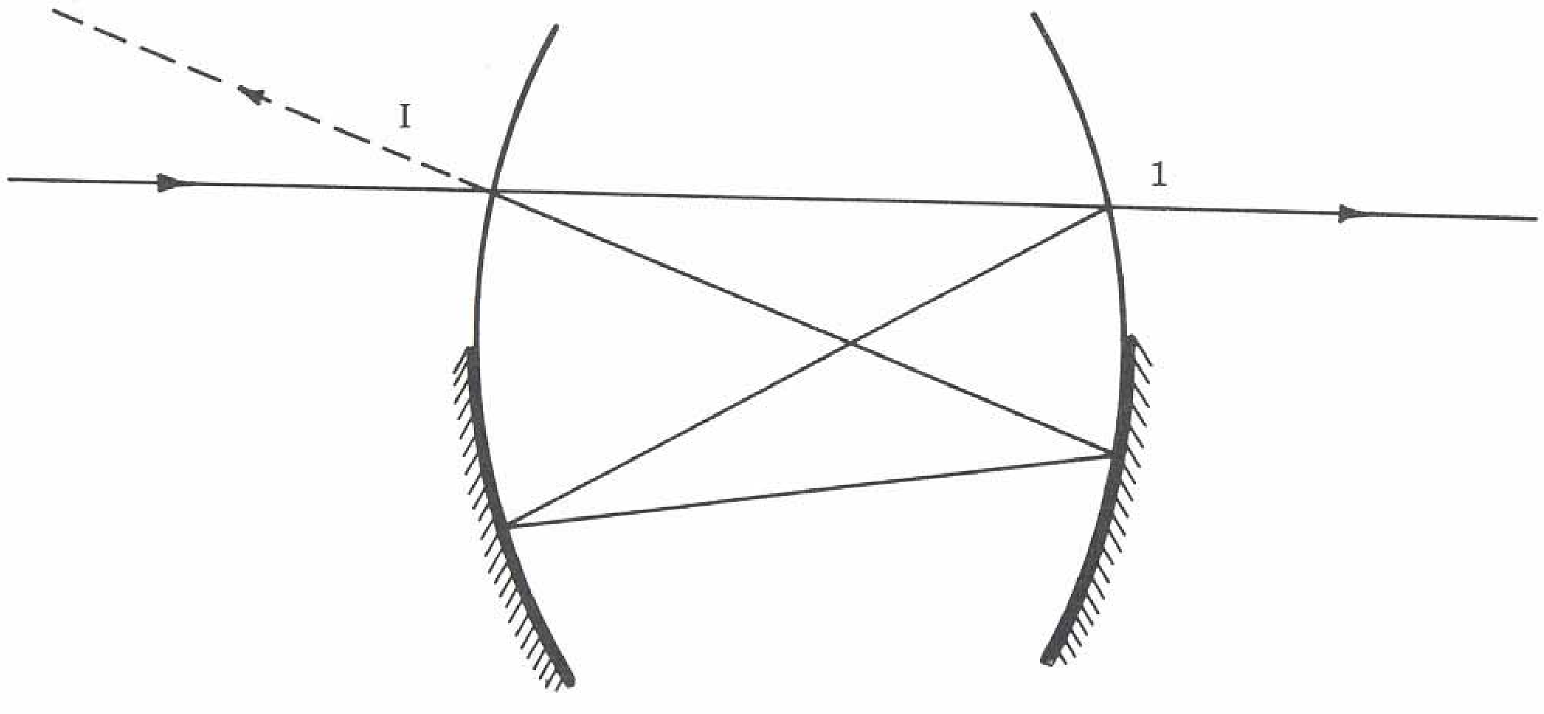
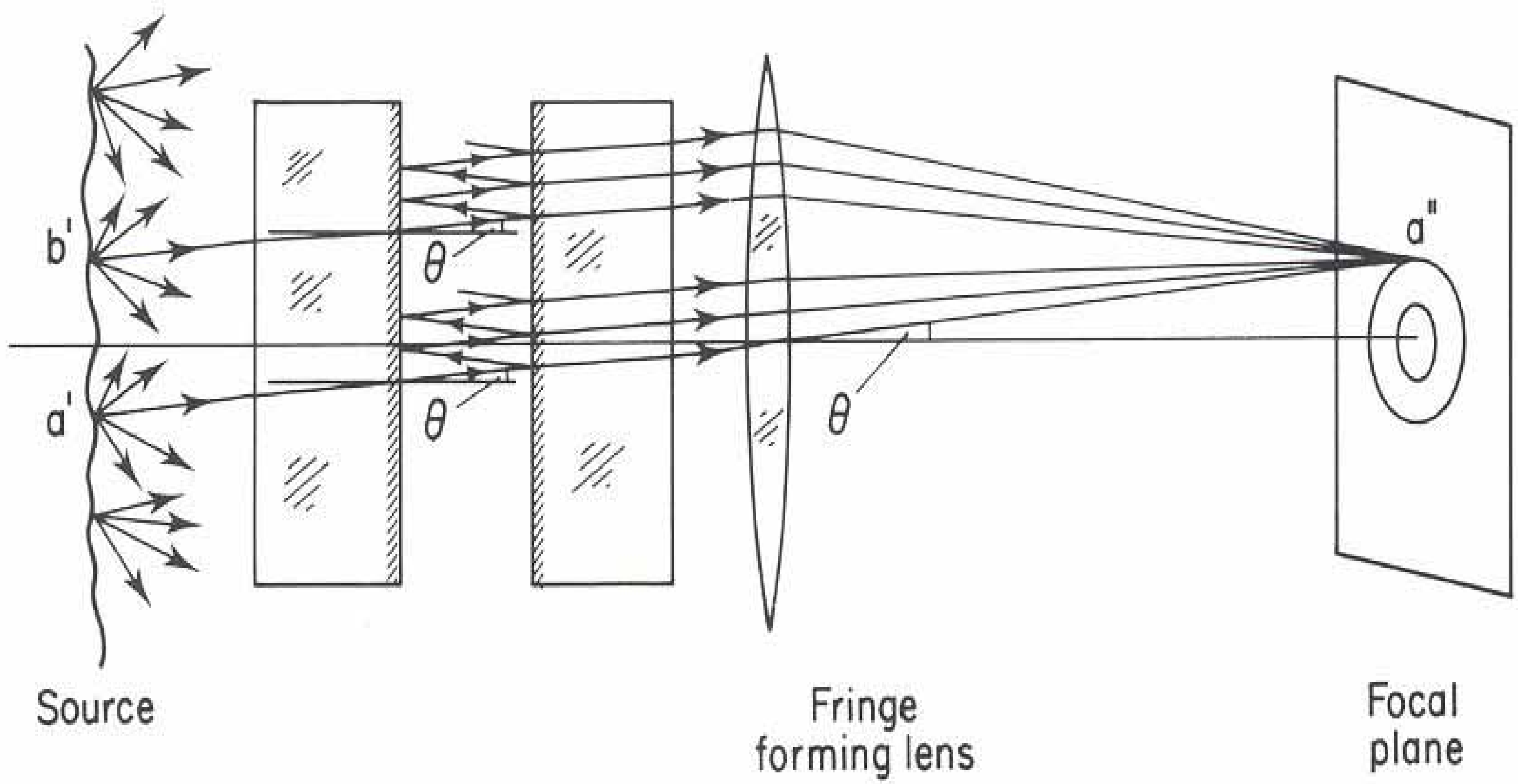
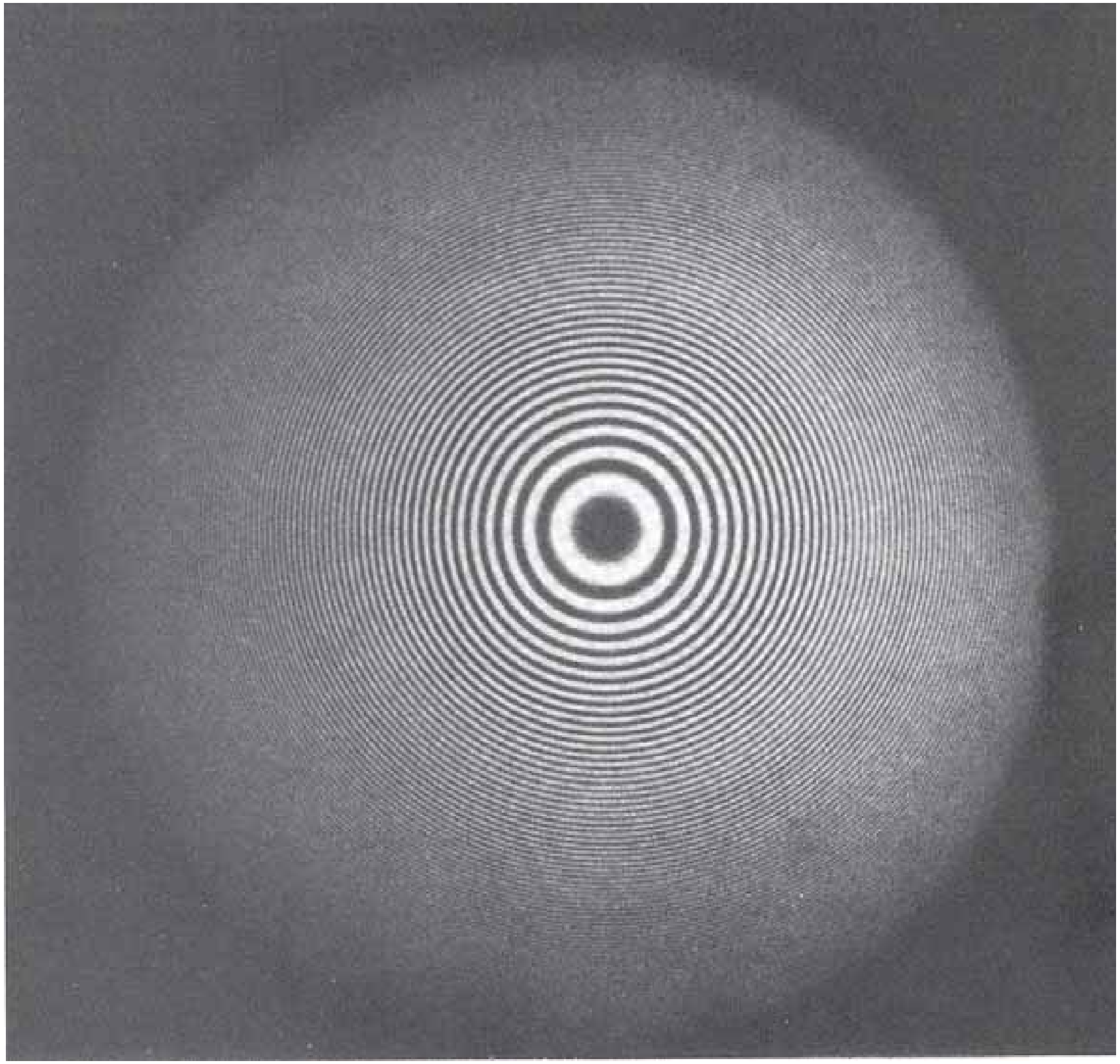
Optical Fabry-Parot Interferometer



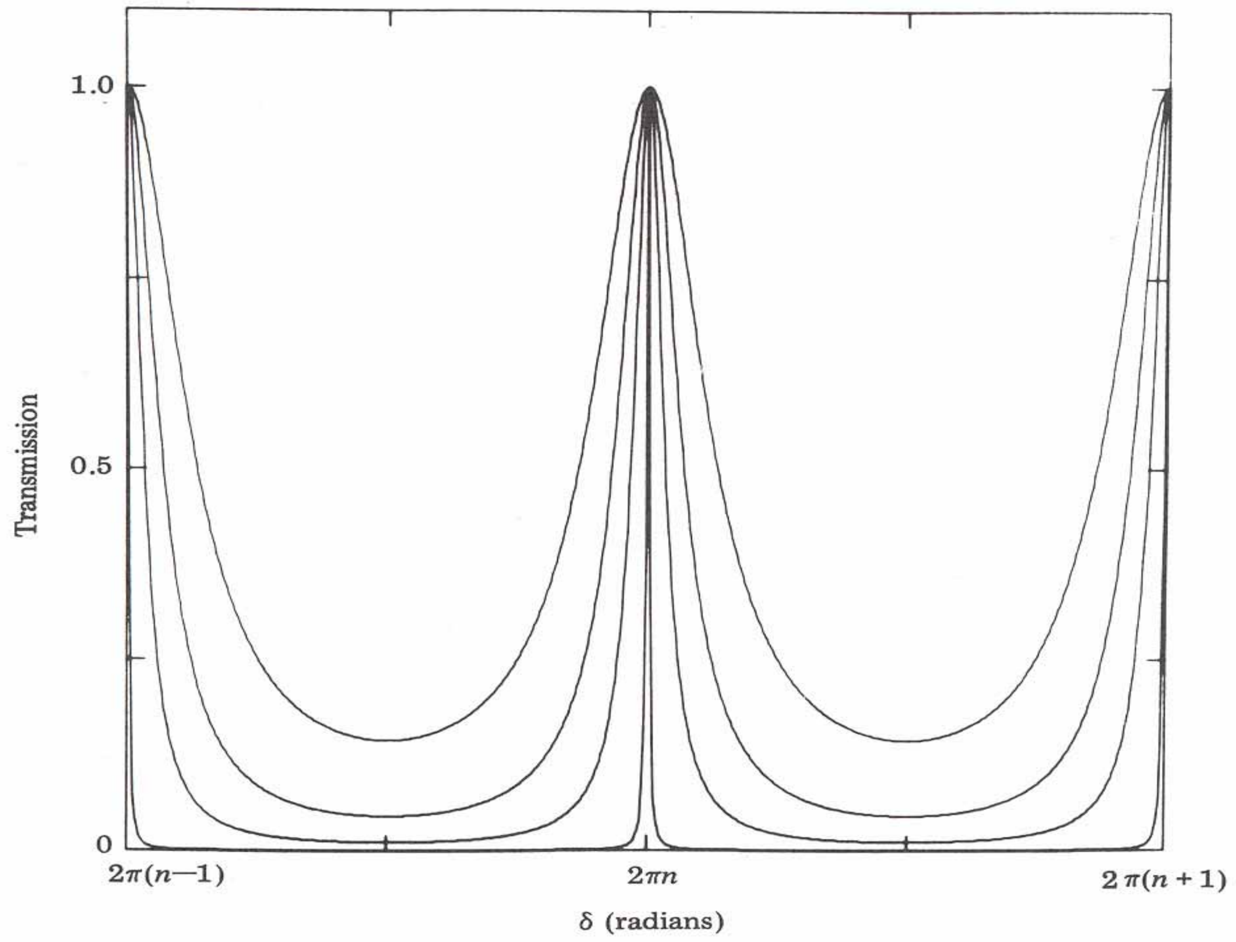
Optical Fabry-Parot Interferometer



Transmitted radiation of a Fabry-Perot etalon

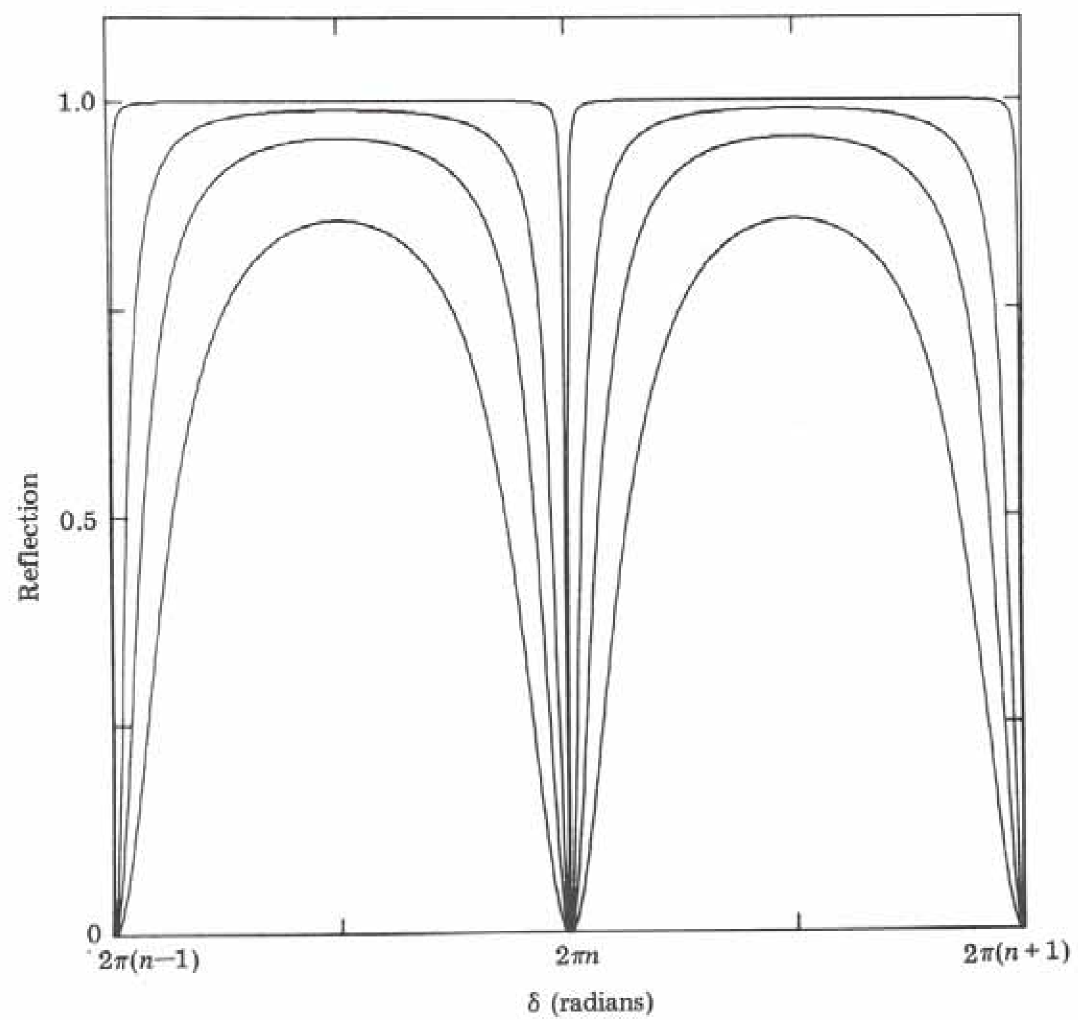


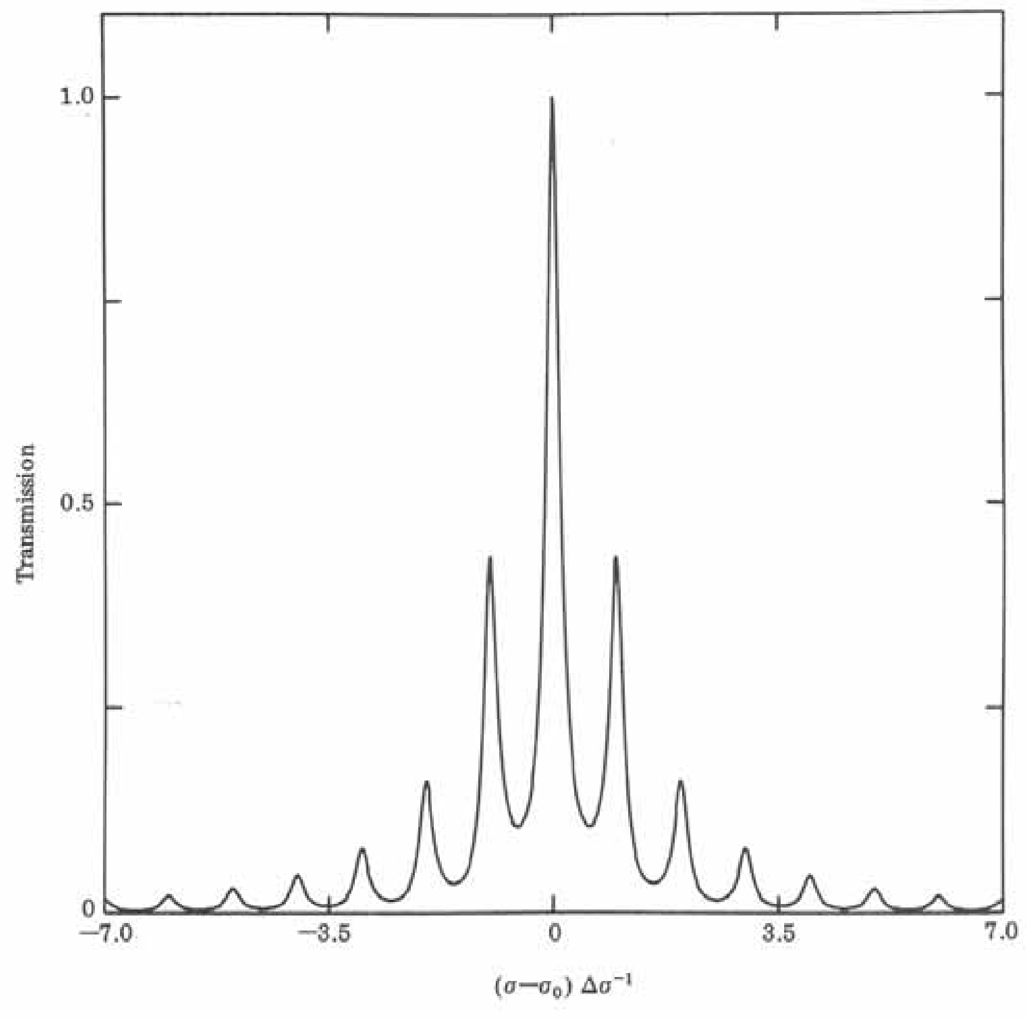
Transmitted radiation of a Fabry-Perot etalon as a function of the phase retardation of the beams for various reflectivities.



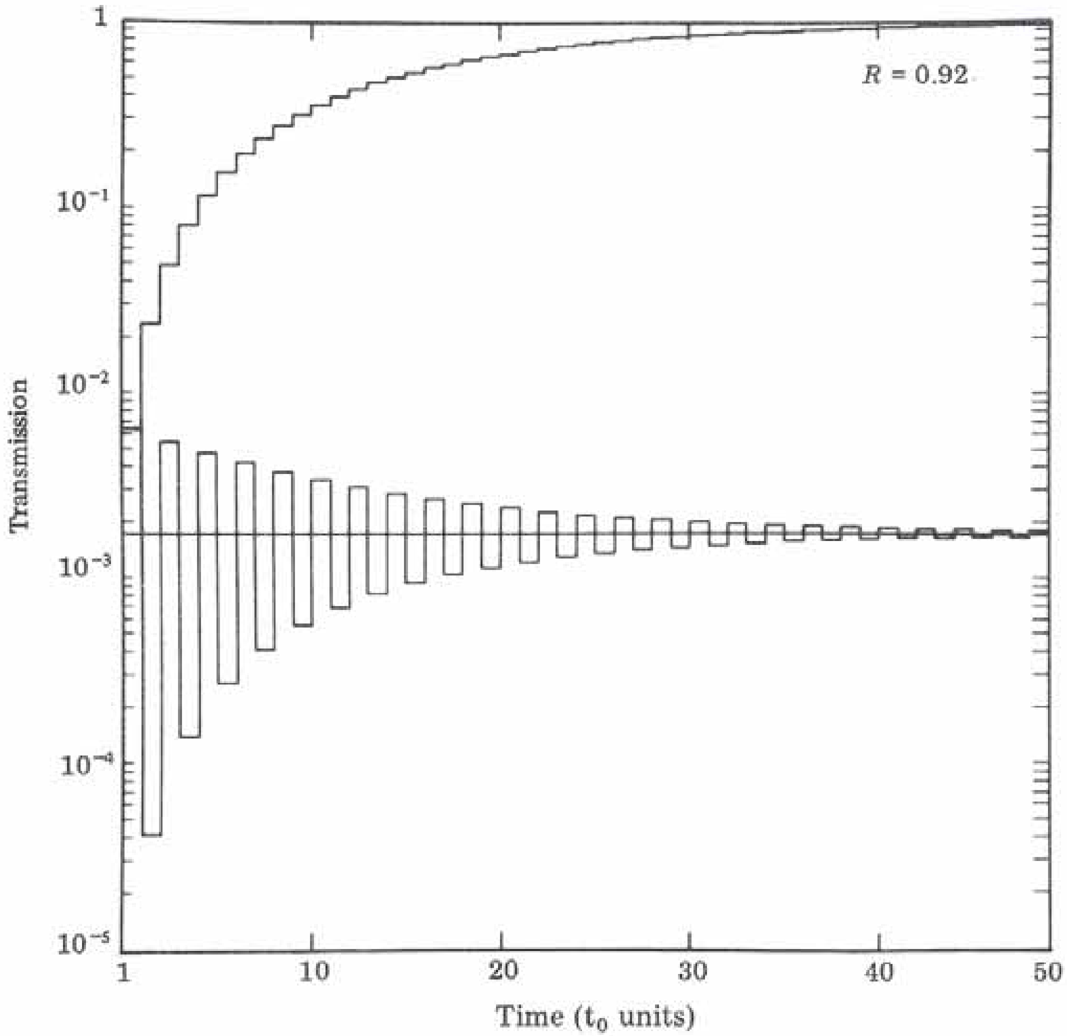
$$\delta = 2\pi\,(2\,R\,d\cos\theta)\,/\,\lambda$$

Reflected radiation of a Fabry-Parot etalon as a function of the phase retardation of the beams.





Transmission of an etalon combined with a Lorentzian filter.



δ **t is a pulse of lenght ; and** t_r **is response time.**

Response of an etalon to a pulse of length δ **t greater than** t_r **.**

Literature (for X-rays)

1. Bond, W. L., Duguay, M. A. & Rentzepis, P. M.
   "Proposed resonator for an X-ray laser".
   Appl. Phys. Lett. **10**, 216-218 (1967).

2. Deslattes, R. D.
   "X-ray monochromators and resonators from single crystals".
   Appl. Phys. Lett. **12**, 133-135 (1968).

3. Liss, K. D., Hock, R., Gomm, M., Waibel, B., Magert, A., Krisch, M. & Tucoulou, R.
   "Storage of X-ray Photons in a crystal resonator".
   Nature **404**, 371-373 (2000).

4. Shvyd'ko, Yu. V., Lerche, M., Wille, H.-C., Gerdau, E., Lucht, M. & Rutter, H.D.
   "X-ray interferometer with microelectronvolt resolution".
   Phys. Rev. Lett. **90**, 013904(1)-013904(4) (2003).

Gamma-Ray Lasers (proposals)

- Baldwin, G.C. & Solem, J.C.

  "Approaches to the Development of Gamma-Ray Lasers"

  Rev. Mod. Phys. **53**, 687 (1981)

  Photon channeling in crystals

  Standing-wave fields in crystals

2. Baldwin, G.C. & Solem, J.C.

   "Recoilless Gamma-Ray Lasers"

   Rev. Mod. Phys. **69**, 1085 (1997)

   Crystals as resonators

Literature (for X-rays)

1. Bond, W. L., Duguay, M. A. & Rentzepis, P. M.
   "Proposed resonator for an X-ray laser".
   Appl. Phys. Lett. **10**, 216-218 (1967).

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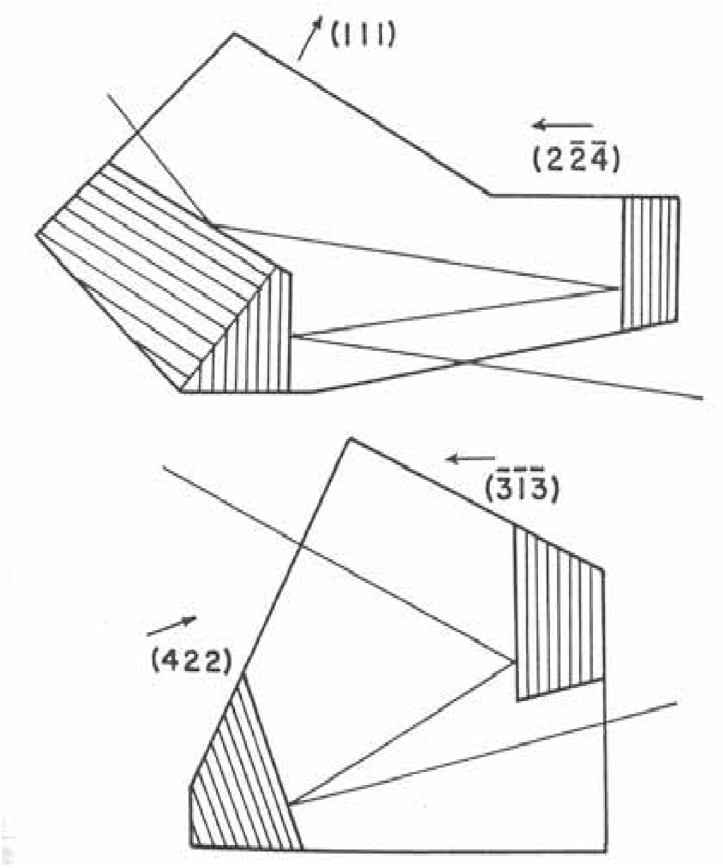
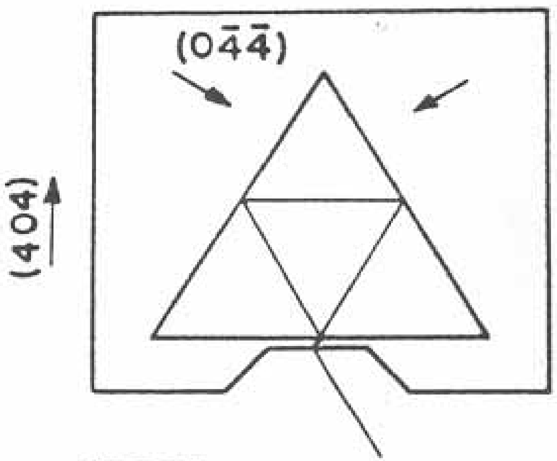
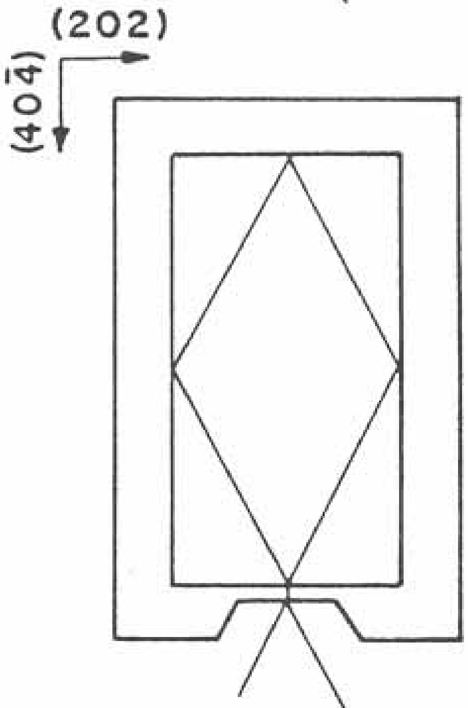
   Phys. Rev. Lett. **90**, 013904(1)-013904(4) (2003).

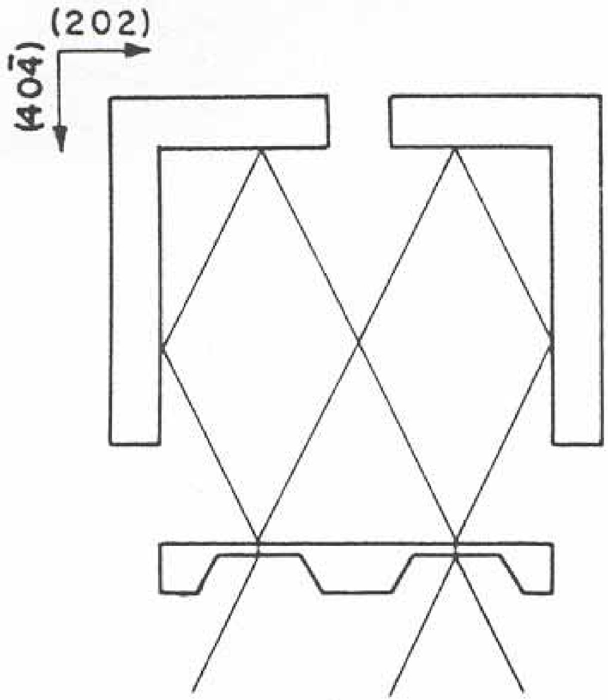
Proposed X-ray Cavity Geometry

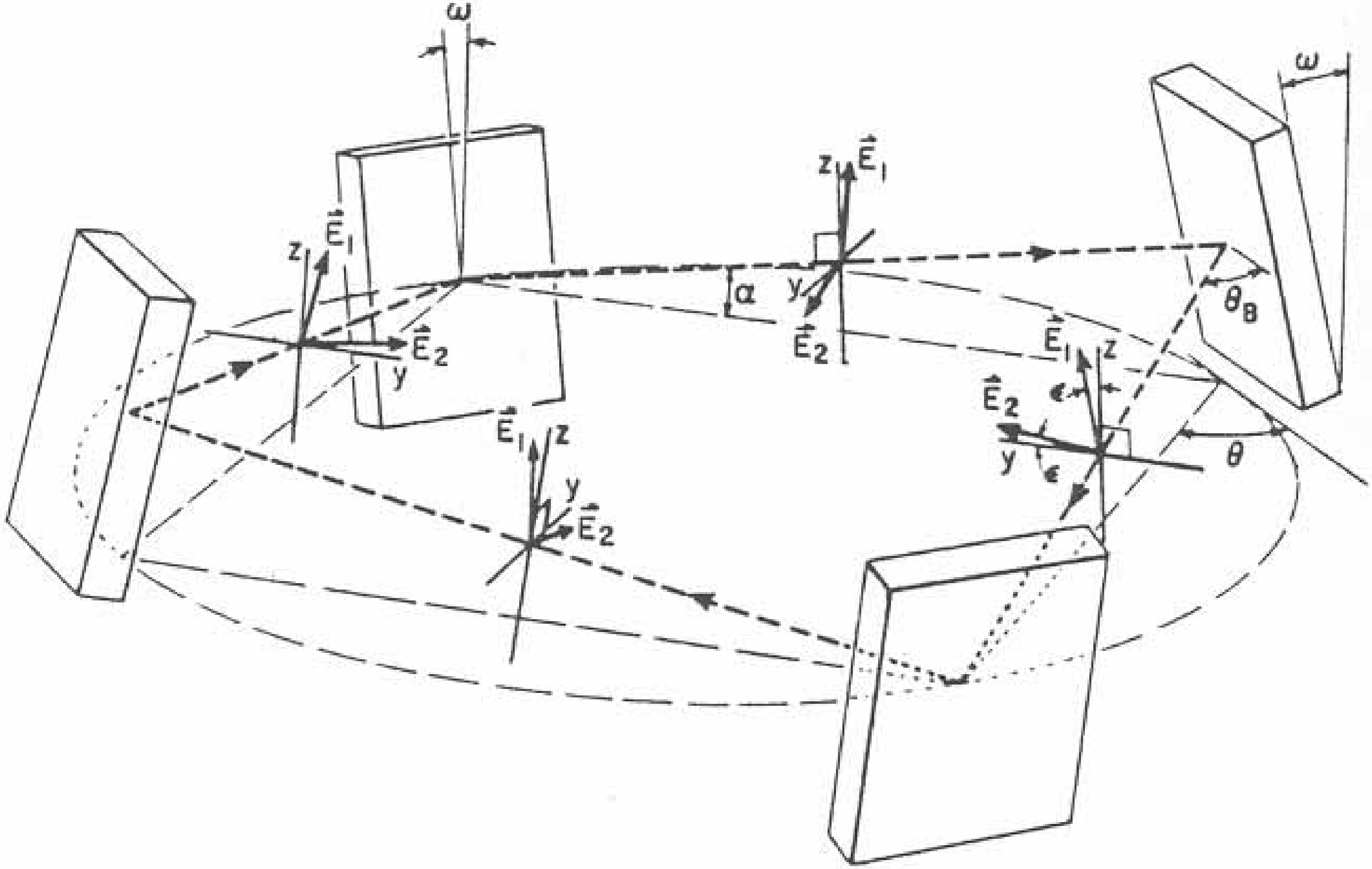


Deslattes, *Appl. Phys. Lett.* **12**, 133 (1968)


(0$\bar{4}\bar{4}$)
(404)

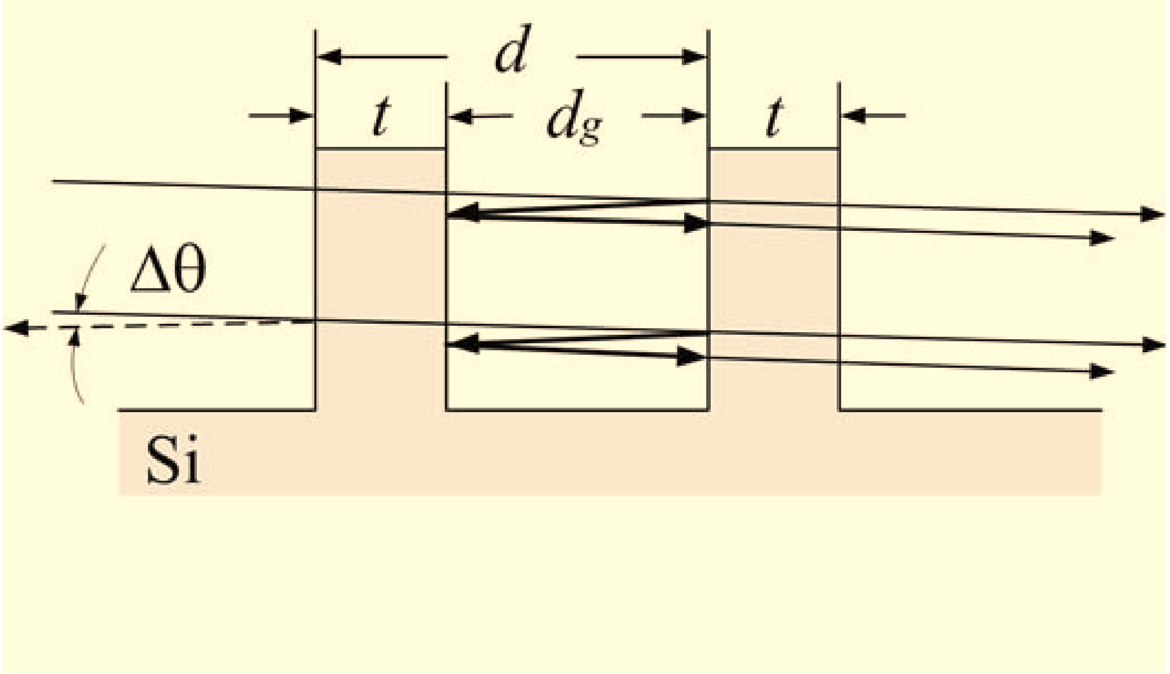

(202)
(40$\bar{4}$)


(202)
(40$\bar{4}$)



ω
ω
z
$\vec{E}_1$
$\vec{E}_2$
y
α
θ_B
θ
ε

X-ray Fabry-Perot resonator

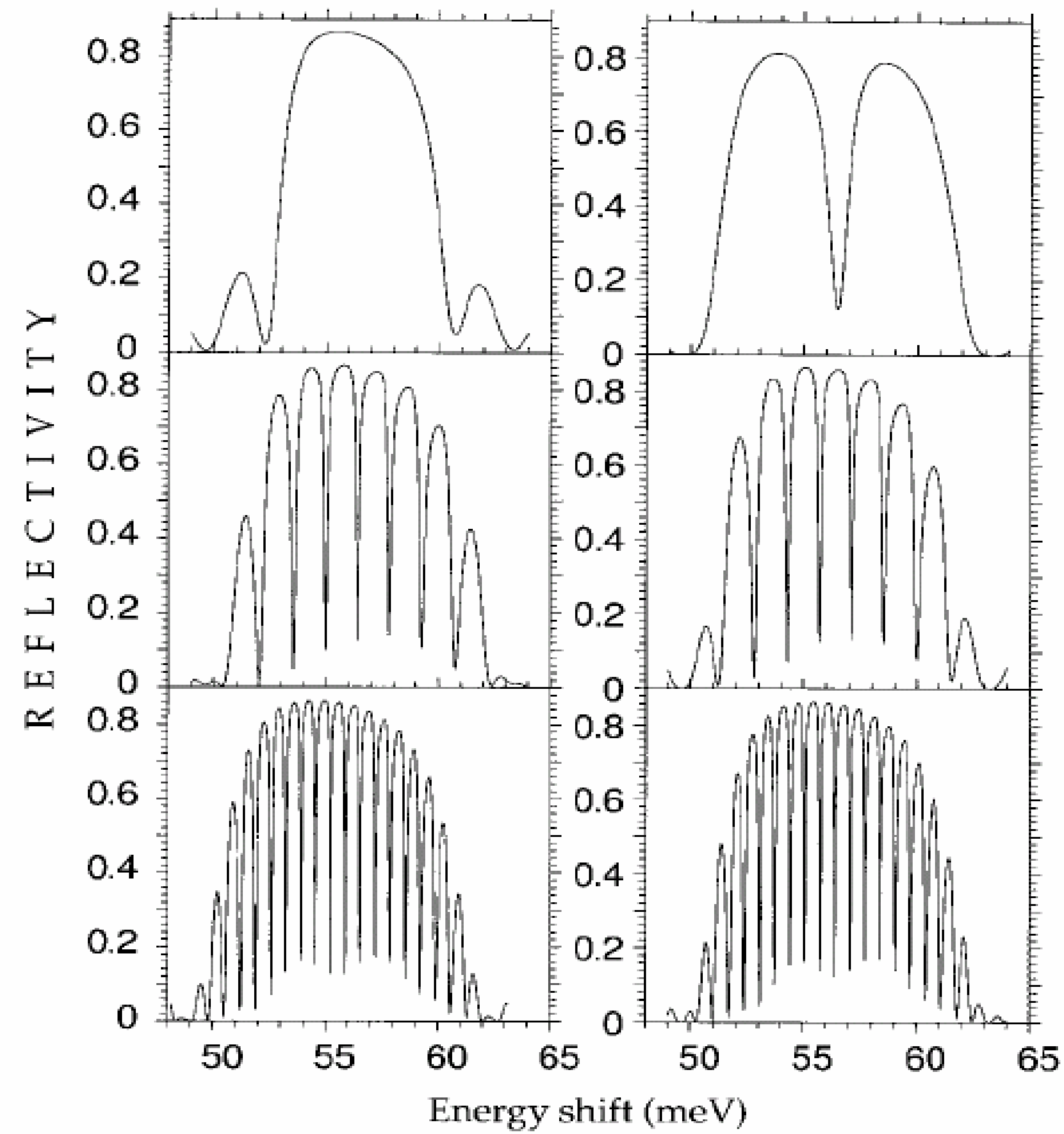


X-ray Fabry-Perot resonator

Cavity resonance occurs when an incident X-ray is reflected back and forth coherently， both spatially and temporally， between the two plates， thus generating interference frings .

X-ray back diffraction (Bragg angle=90 deg.)

Theoretical calculation



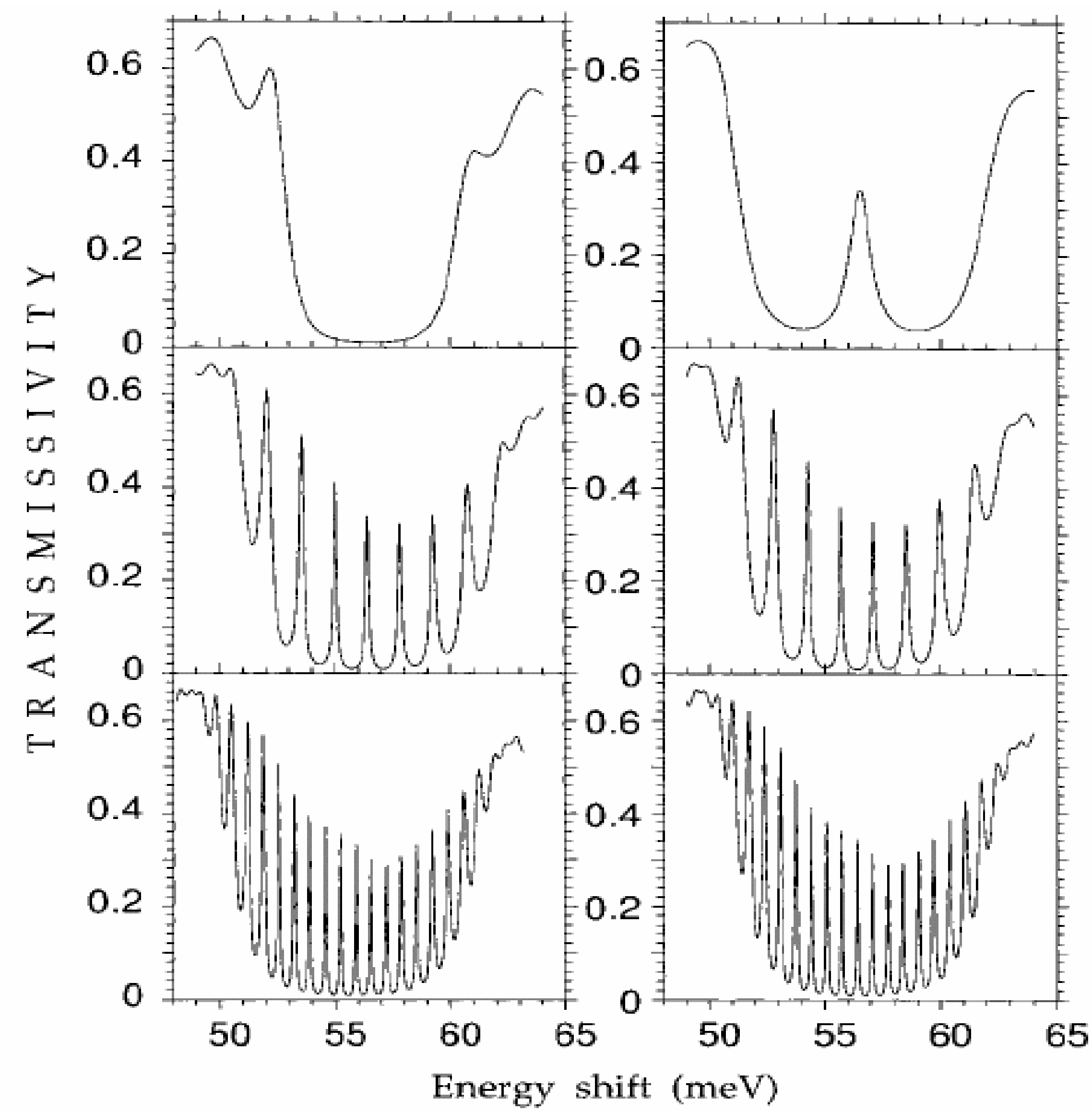
Reflectivity of an X-ray Fabry-Perot interferometer with the same parameters as the transmissivity

Resonance fringes appearing inside the energy gap in energy scan (the total reflection range in angle scan)

Pendellosung for thin crystal plates

Defect states (photonic crystals)

Theoretical calculation



Transmissivity of an X-ray Fabry-Perot interferometer as function of the X-ray energy E with respect to the Bragg energy E_B =14.4125keV.

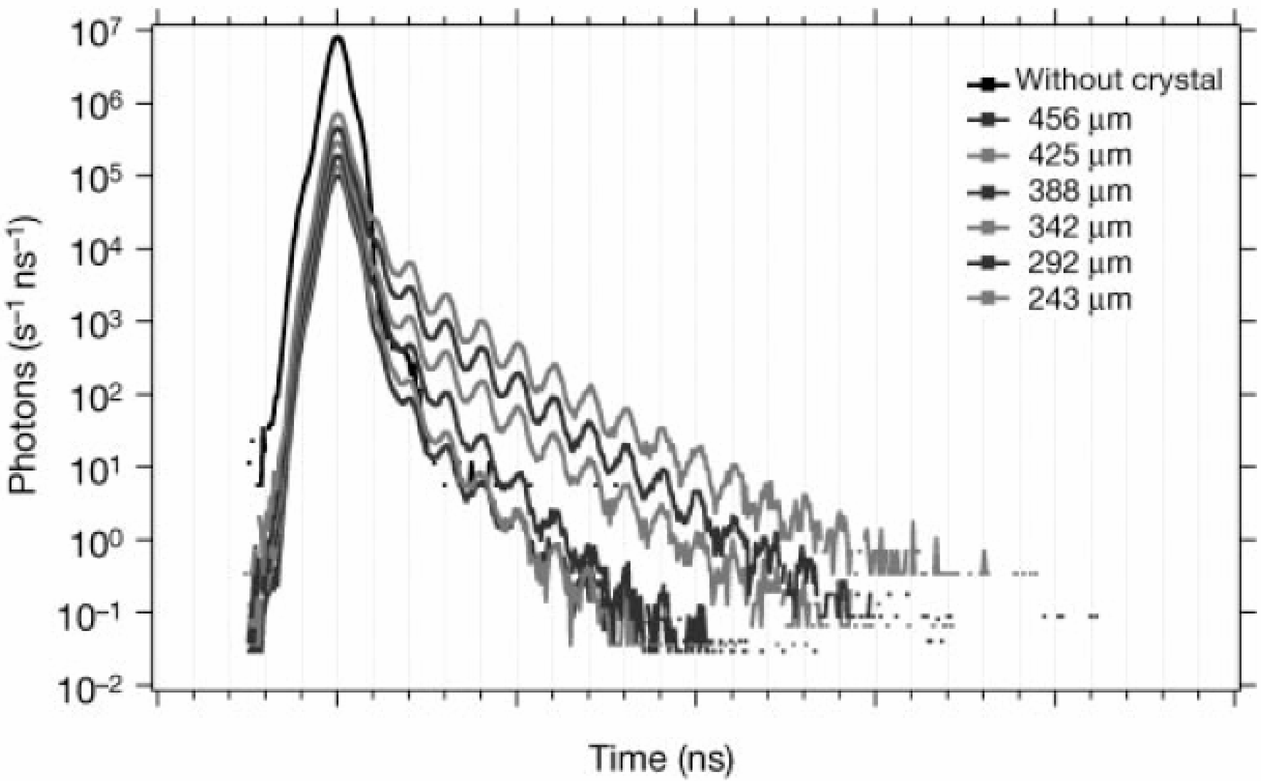
Normal incidence is assumed to the reflecting planes (1,3,-4,28) of sapphire(Al_2O_3)

crystal plates of thickness d_1=d_2=100 μ m separated by a gap of thickness d_g=0(top),0.5mm(middle) and 1mm(bottom).

The relative shift of crystal lattices in the mirrors is s = 0(left) and s = 0.5(right)

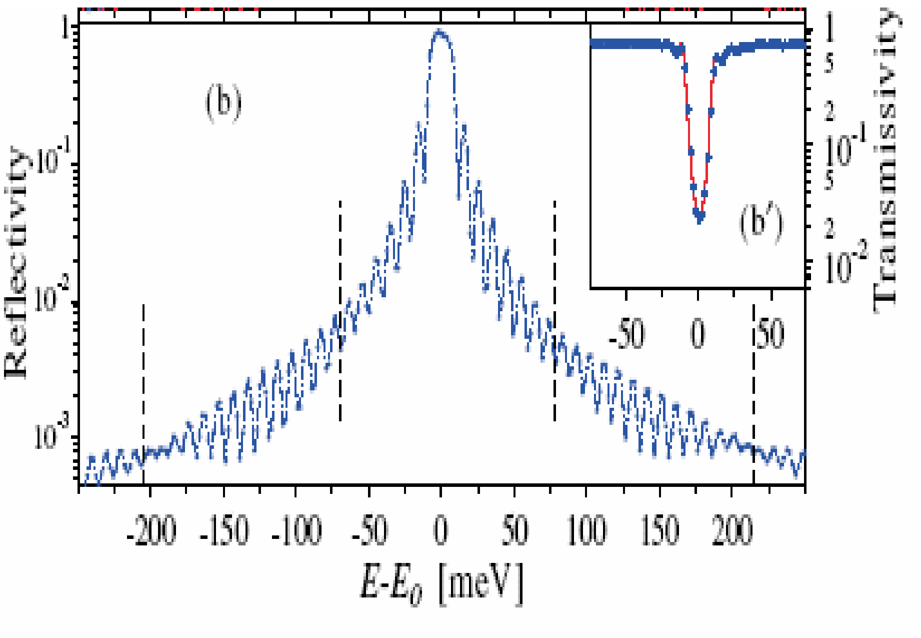
K.-D. Liss et al. (Nature 2001)

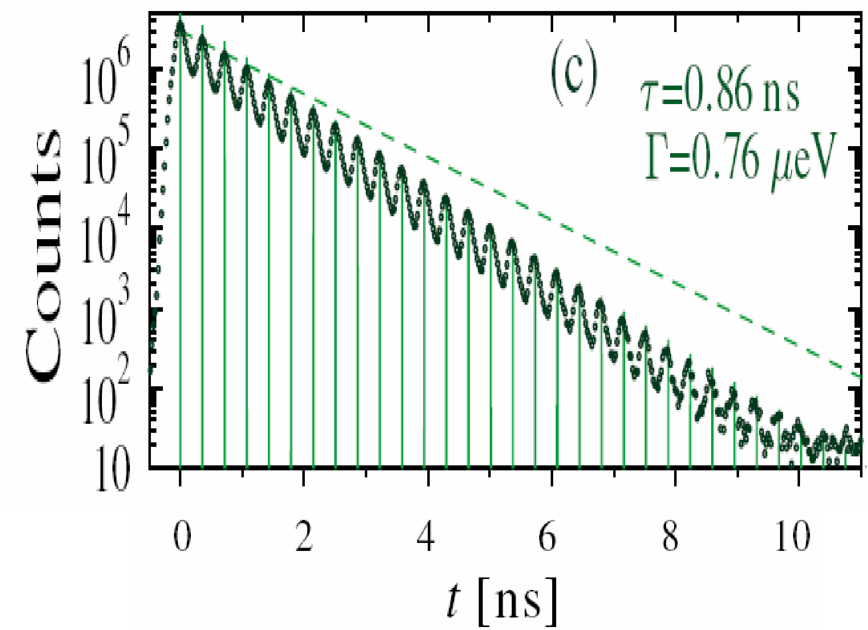
d_G= 15 cm t=243 um~456 um $\Delta E/E \sim 10^{-7}$



Shvyd'ko et al (PRL 2003):

d_G= 0.5 cm t_1=63um t_2=59um $\Delta E/E \sim 10^{-7}$





X-ray Cavity Research in Phys. Dept. NTHU

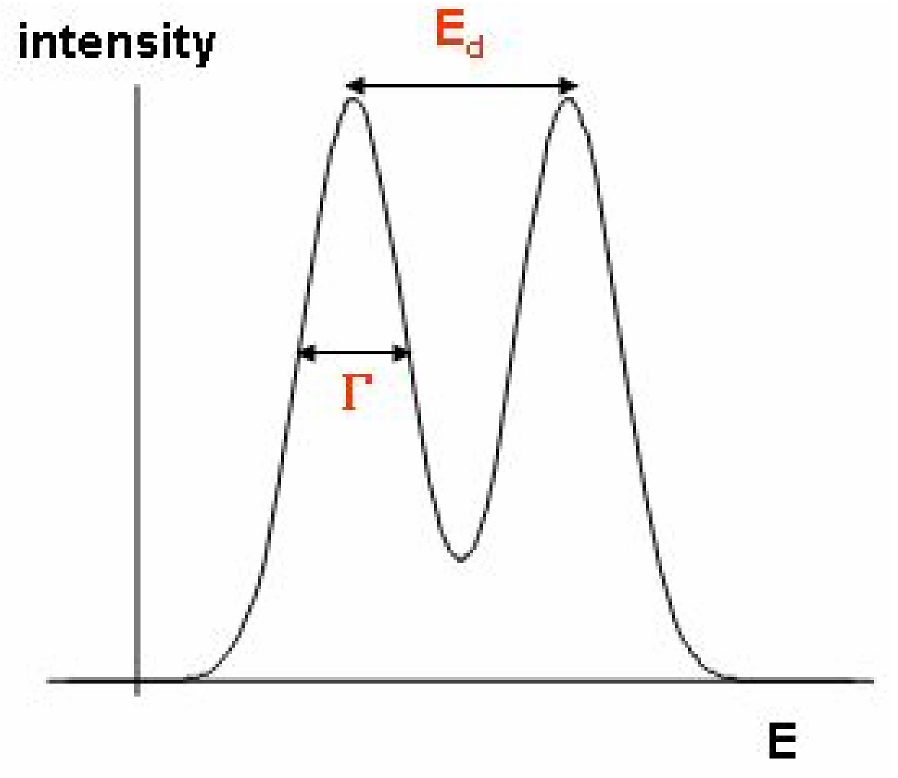
1984 Seminar on "Feasibility of X-ray lasers"

1997 First two crystals prepared

1999~2003 Experiments at beamline 19XU,
Spring-8 (3 more crystals prepared)

2004 Experiments at beamline 12XU, NSRRC
beamline at Spring-8 (4 more crystals prepared)

Resolution of two spectral components



Criteria for observing cavity resonance fringes

a. $\Delta E < E_d$ (ΔE = the energy resolution of the incident X-ray beam ; $E_d = hc/2d$)

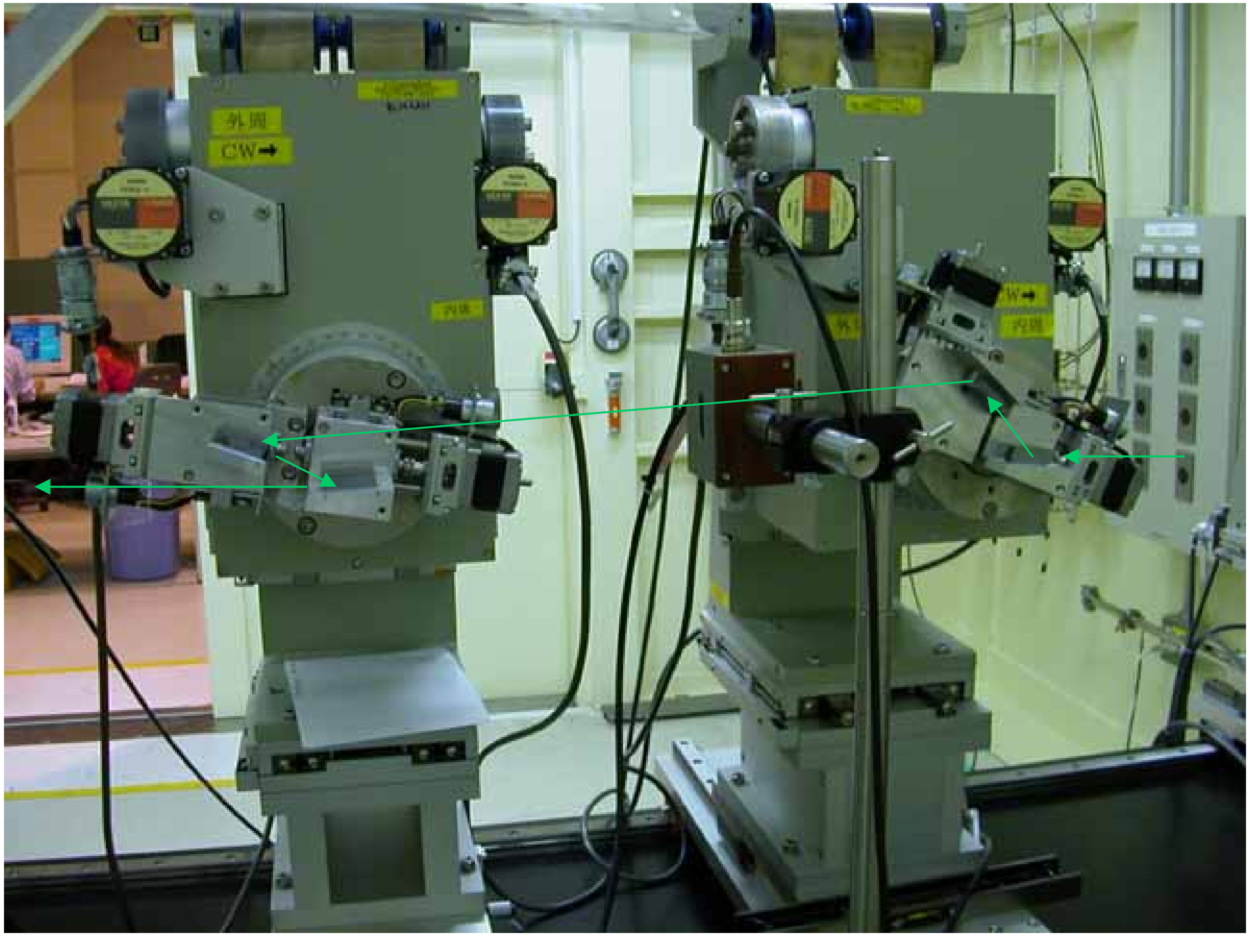
b. $\Delta E < \Gamma$

c. $\Gamma < E_d$

d. $\Delta t > t_f / 2\pi$ ($\Delta t = \hbar / \Delta E$, the coherent time of the incident beam ; $t_f = h / E_d = 2d / c$)

e. $\ell_L = <\lambda^2 / \Delta\lambda> = <\lambda / (\Delta E / E)> > 2d$

4-crystal Monochromator



Eenergy resolution :

$\Delta E = 0.36 meV$

$\Delta E/E = 2.5 * 10^{-8}$

at 14.4388 keV

(0.8588 A)

1 step=0.005 arcsec.

=58.548 ueV

◎ Cavity size：

t=25 um~100 um, d_g=40~150 um, d=t+dg=65 um~250 um

ΔE(=0.36 meV) < E_d (=3.6 meV) Criterion (a) is satisfied.

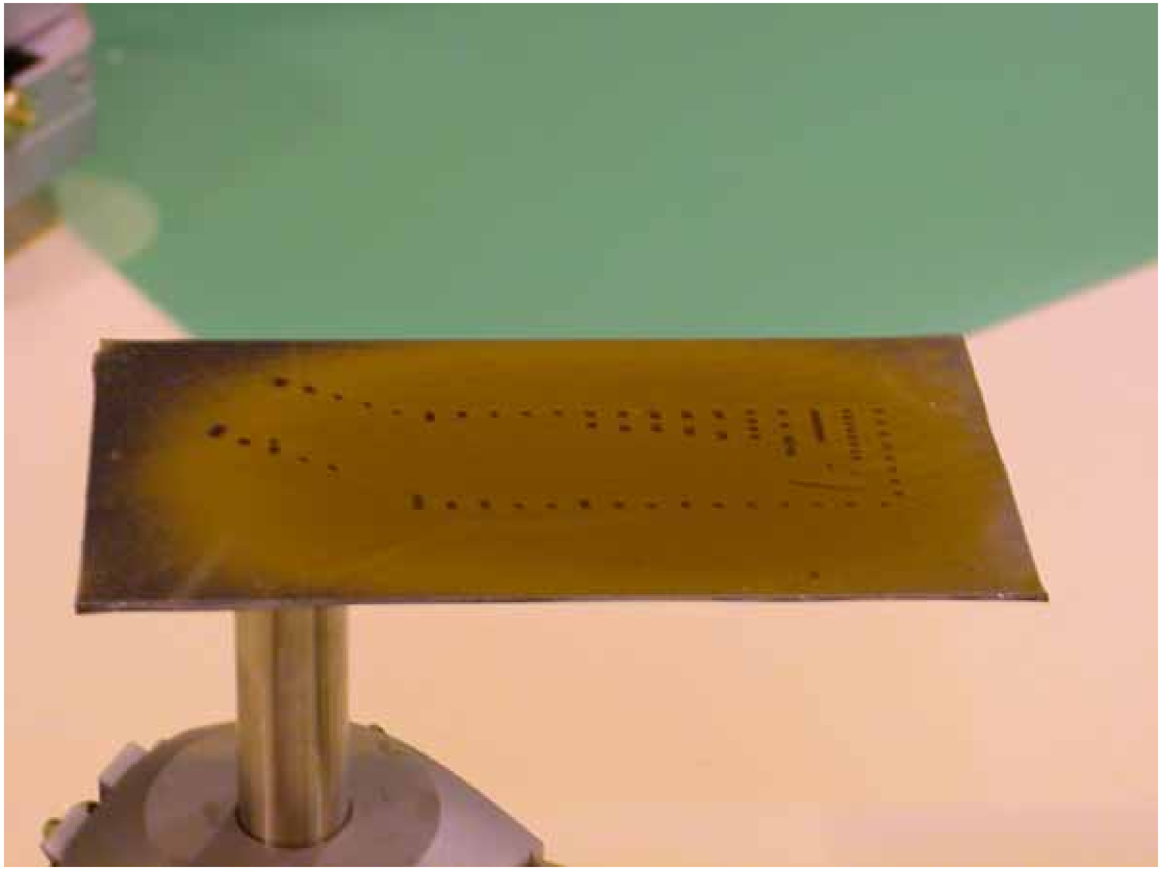
ΔE(=0.36 meV) < Γ (= 1.60 meV) Criterion (b) is satisfied.

Γ (=1.60 meV) < E_d (=3.6 meV) Criterion (c) is satisfied.

Δt (=1.8 ps) > $t_f/2\pi$ (=0.1 ps) Criterion (d) is satisfied.

l_L (=1717 um) > 2d (=340 um) Criterion (e) is satisfied.

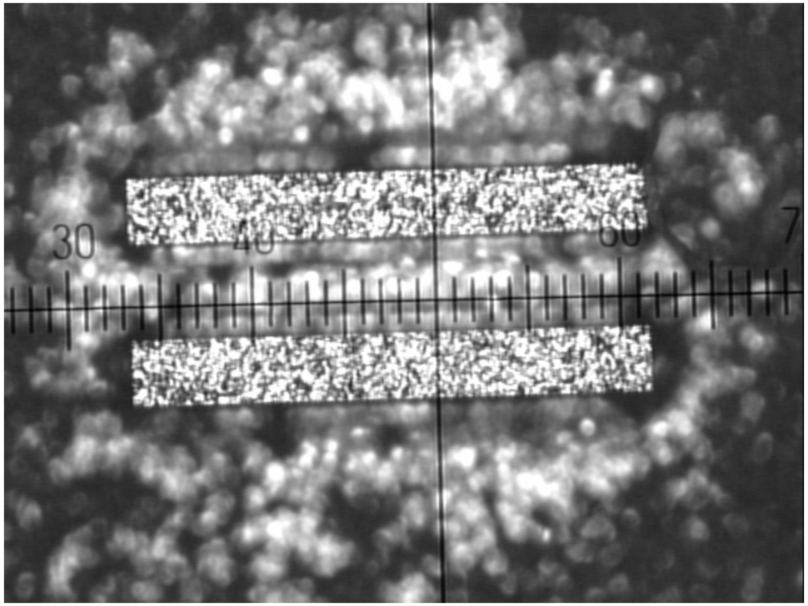
Crystal Cavities (Si)

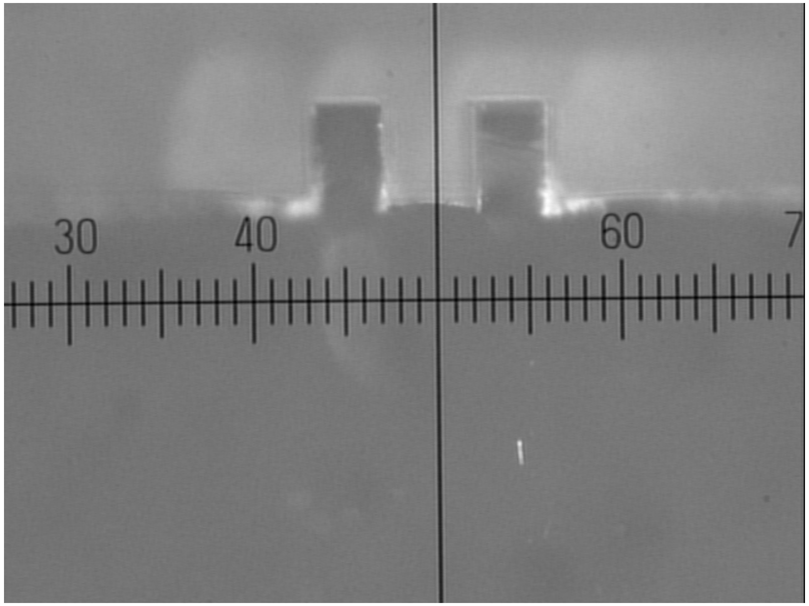


Lithography

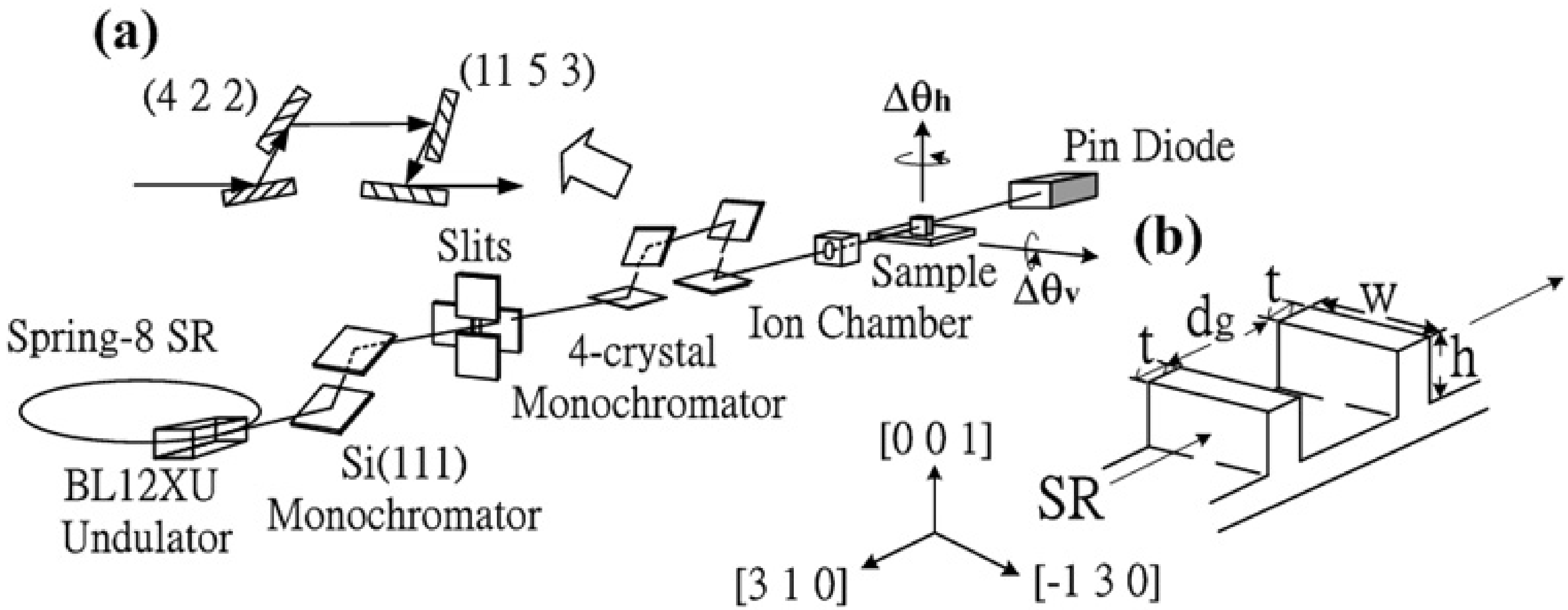
Ion-beam dry etching

Top-view & side-view



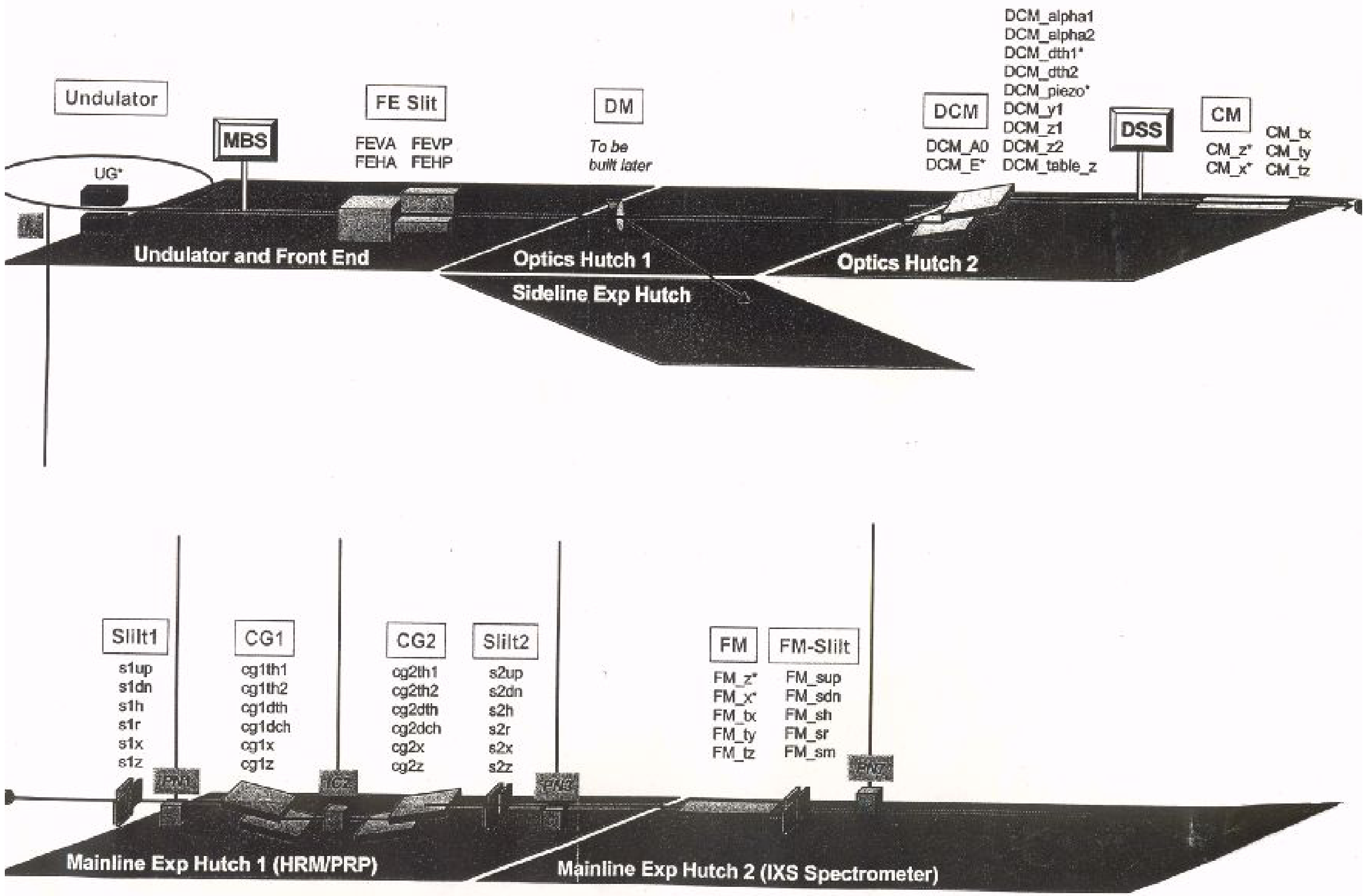


Experimental set-up



Spring-8 (Super Photon ring-8 GeV) Japan

8 GeV; $\gamma = 15{,}700$; 1.44 km circumference



Undulator
MBS
FE Slit
FEVA FEVP
FEHA FEHP
DM
To be built later
DCM
DCM_A0
DCM_E*
DCM_alpha1
DCM_alpha2
DCM_dth1*
DCM_dth2
DCM_piezo*
DCM_y1
DCM_z1
DCM_z2
DCM_table_z
DSS
CM
CM_z*
CM_x*
CM_tx
CM_ty
CM_tz
UG*
Undulator and Front End
Optics Hutch 1
Optics Hutch 2
Sideline Exp Hutch
Sliit1
s1up
s1dn
s1h
s1r
s1x
s1z
CG1
cg1th1
cg1th2
cg1dth
cg1dch
cg1x
cg1z
CG2
cg2th1
cg2th2
cg2dth
cg2dch
cg2x
cg2z
Sliit2
s2up
s2dn
s2h
s2r
s2x
s2z
FM
FM_z*
FM_x*
FM_tx
FM_ty
FM_tz
FM-Sliit
FM_sup
FM_sdn
FM_sh
FM_sr
FM_sm
Mainline Exp Hutch 1 (HRM/PRP)
Mainline Exp Hutch 2 (IXS Spectrometer)

A Huber 8-circle diffractometer

1 step=0.0005 deg.

$\Delta T = 0.1^{o}$ C

At 14.4388 keV, a 24-beam diffraction takes place

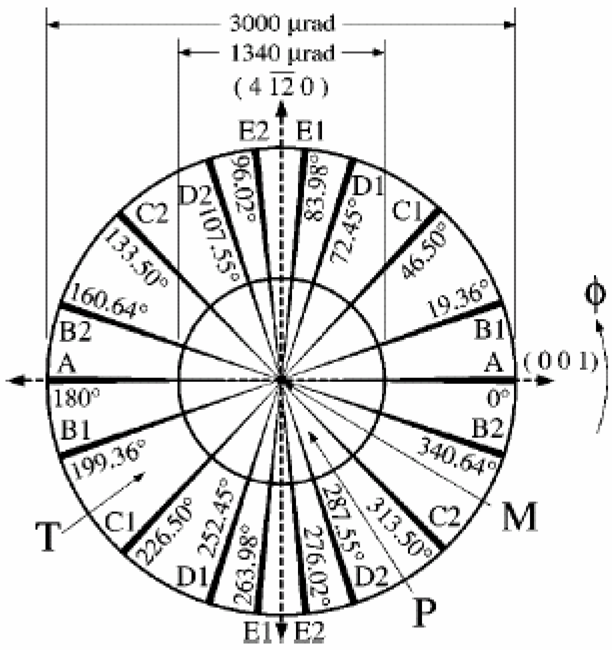
9 coplanar diffractions C1 – C9

C1: (040), (4-40), (480), (8-40), (880), (12 0 0)
C2: (6-4-2), (682)
C3: (022), (12 2 -2)
C4: (60-6), (646)
C5: (426), (82-6)
C6: (42-6), (826)
C7: (606), (646)
C8: (02-2), (12 2 2)
C9: (6-42), (68-2)

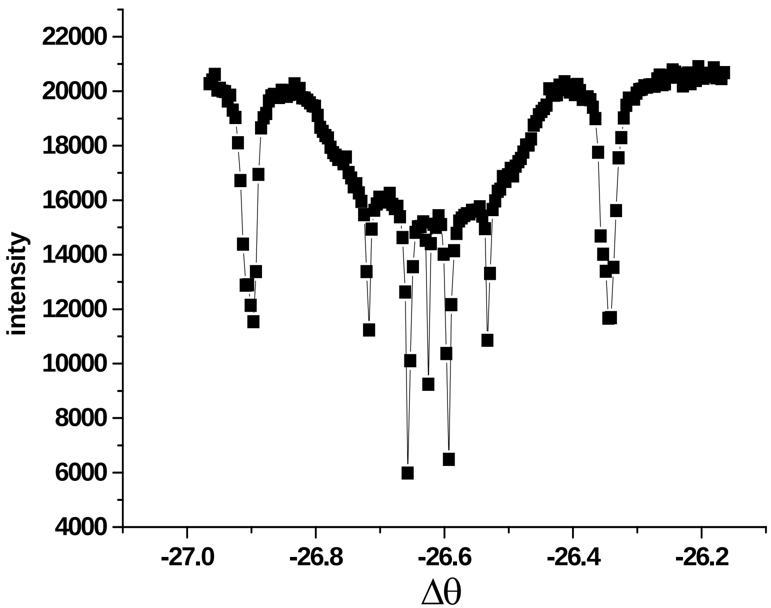
(000) and (12 4 0) reflections (back diffraction)

At 14.4388 keV, a 24-beam diffraction takes place

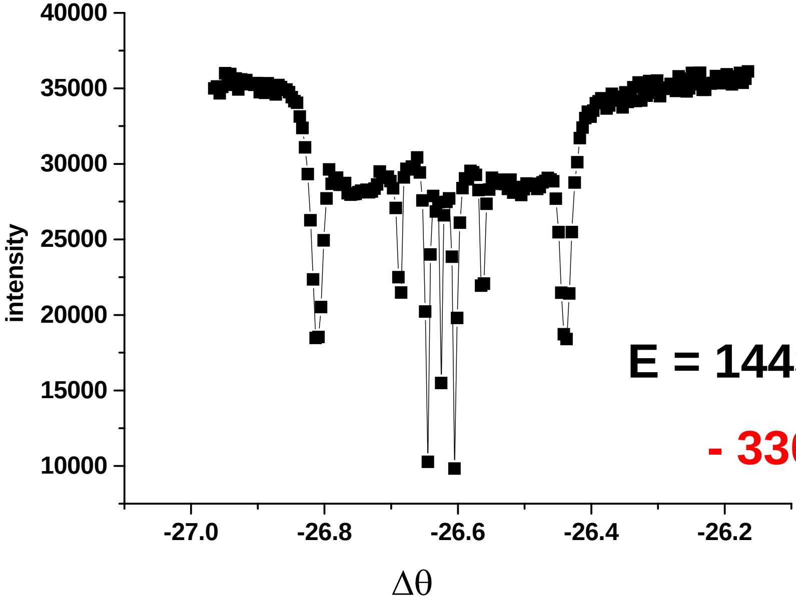
No.	(hkl)	$\tilde{\theta}_B$ (°)	ϕ_{ref} (°)	No.	(hkl)	$\tilde{\theta}_B$ (°)	ϕ_{ref} (°)
1	(8 2 6)	53.729	6.017	12	(4 2 $\bar{6}$)	36.271	186.017
2	(6 0 6)	42.130	17.548	13	(6 4 $\bar{6}$)	47.870	197.548
3	(12 2 2)	77.079	43.492	14	(0 2 $\bar{2}$)	12.921	223.492
4	(6 $\bar{4}$ 2)	36.271	68.432	15	(6 8 $\bar{2}$)	53.729	248.432
5	(12 0 0)	71.565	90.000	16	(0 4 0)	18.435	270.000
6	(4 $\bar{4}$ 0)	26.565	90.000	17	(8 8 0)	63.435	270.000
7	(8 $\bar{4}$ 0)	45.000	90.000	18	(4 8 0)	45.000	270.000
8	(6 $\bar{4}$ $\bar{2}$)	36.271	111.568	19	(6 8 2)	53.729	291.568
9	(12 2 $\bar{2}$)	77.079	136.508	20	(0 2 2)	12.921	316.508
10	(6 0 $\bar{6}$)	42.130	162.452	21	(6 4 6)	47.870	342.452
11	(8 2 $\bar{6}$)	53.729	173.983	22	(4 2 6)	36.271	353.983



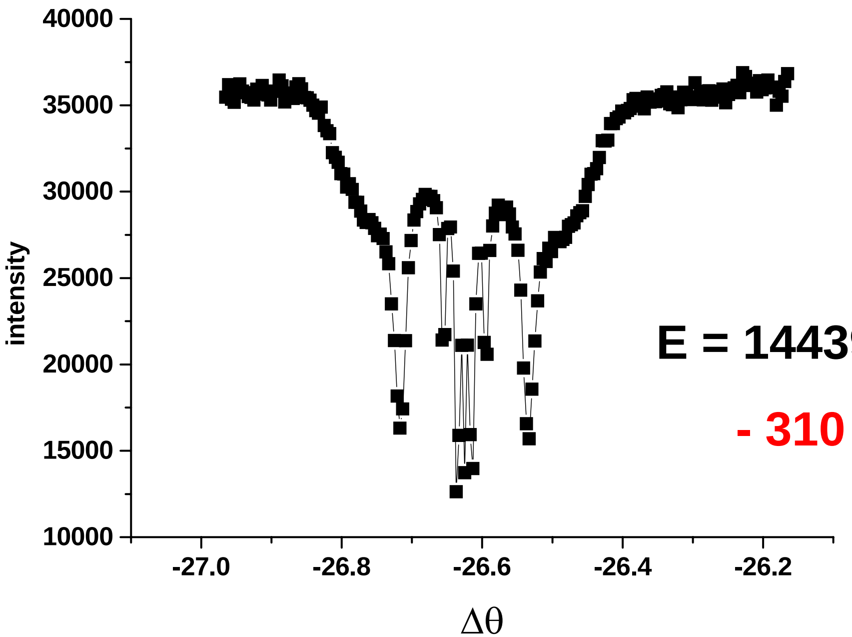
The comparison of Δθ-scans



E = 14439.5eV - 350 meV

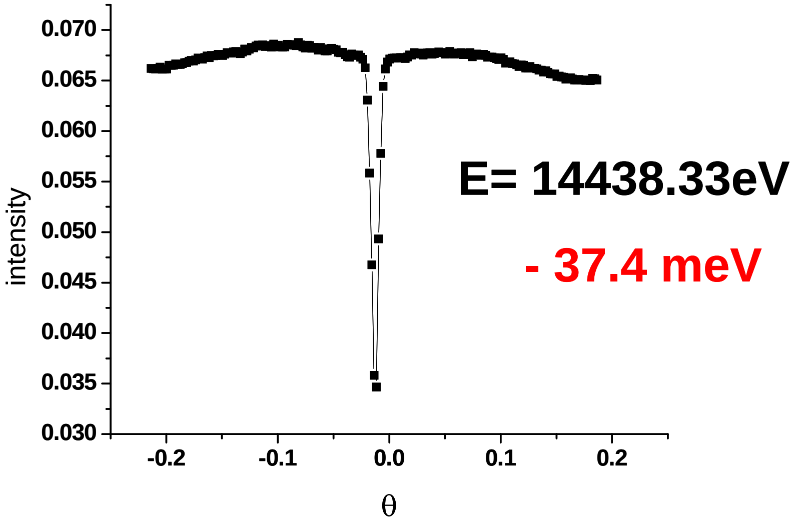


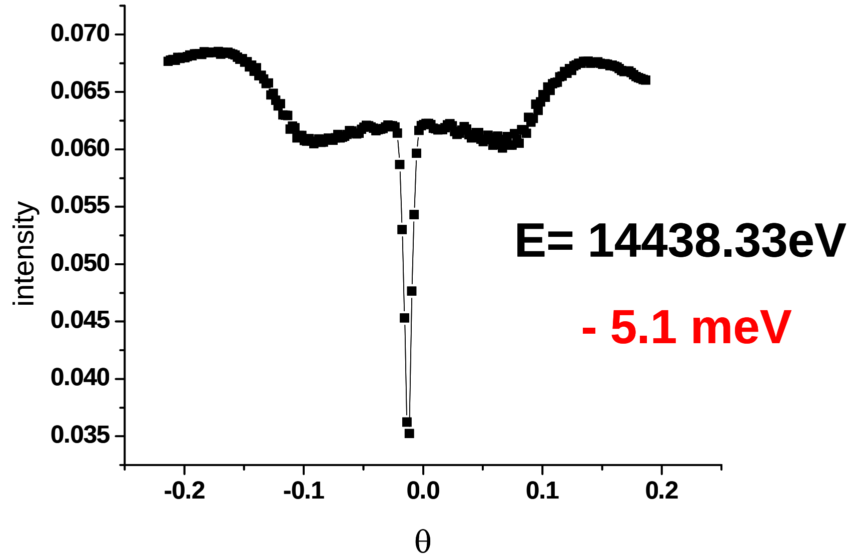
E = 14439.5eV - 330 meV

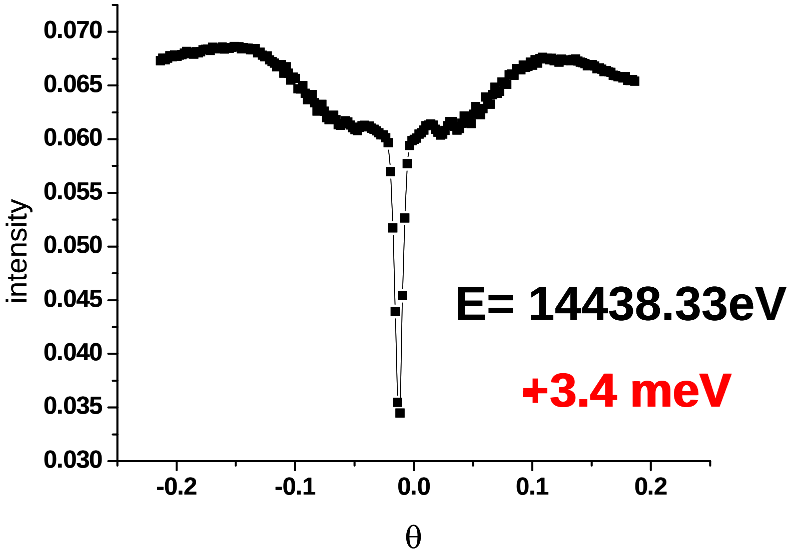


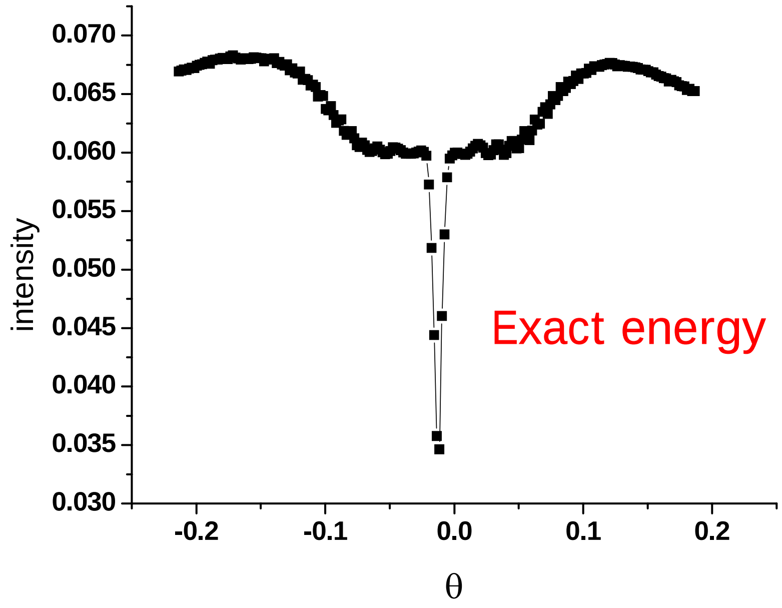
E = 14439.5eV - 310 meV

The comparison of Δθ-scans

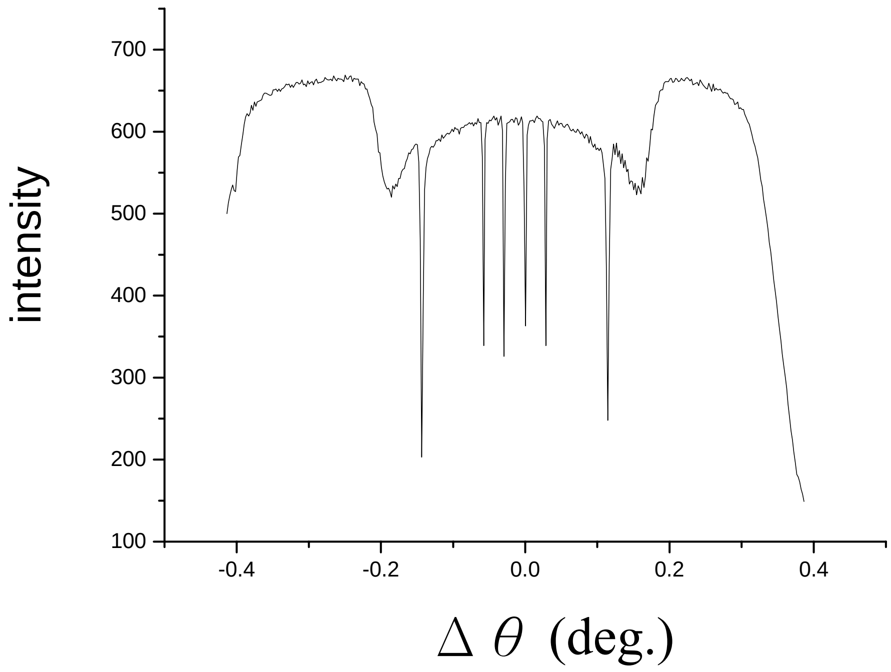




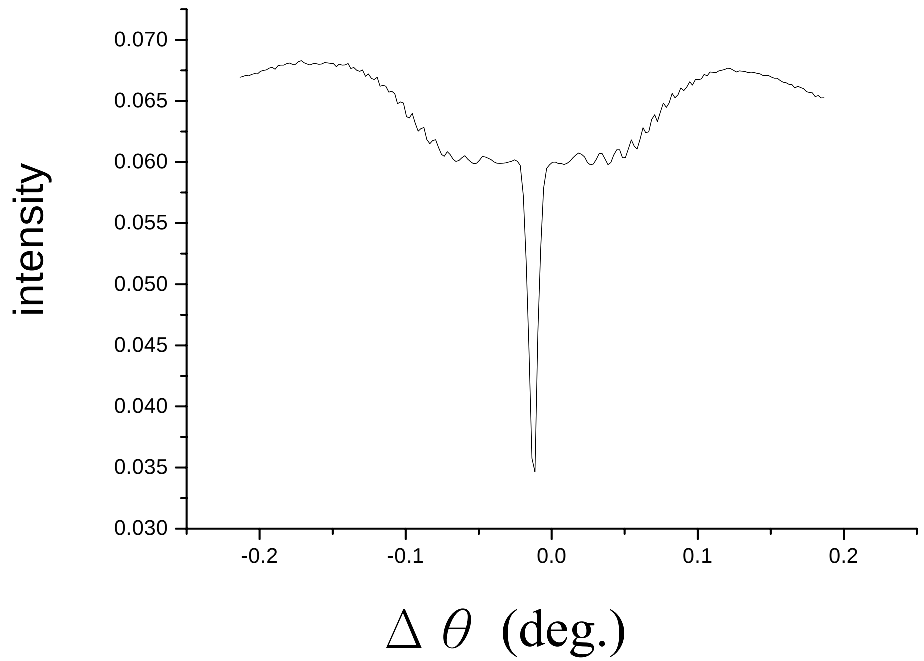




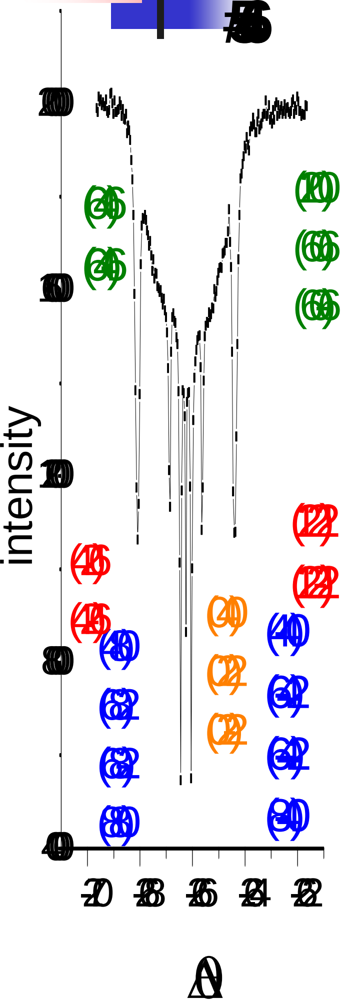
Δ θ -scans

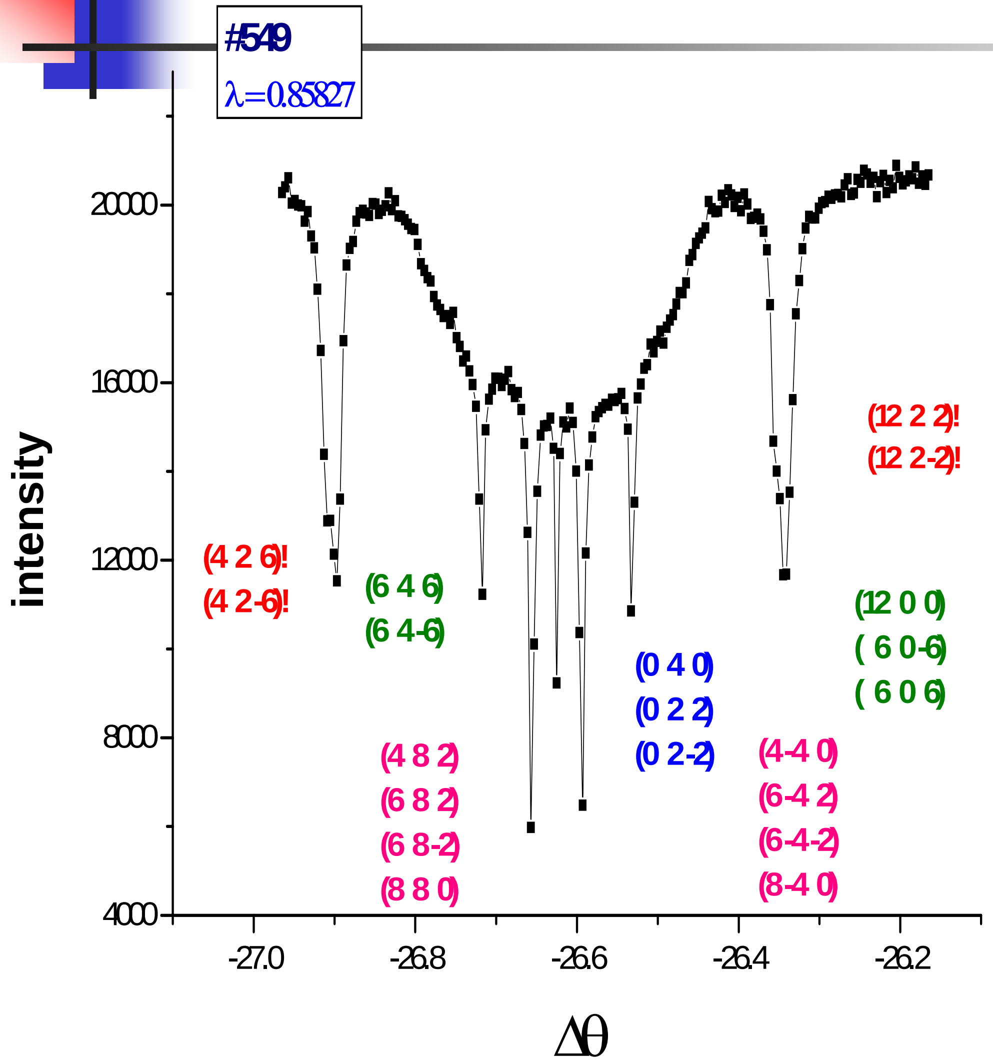


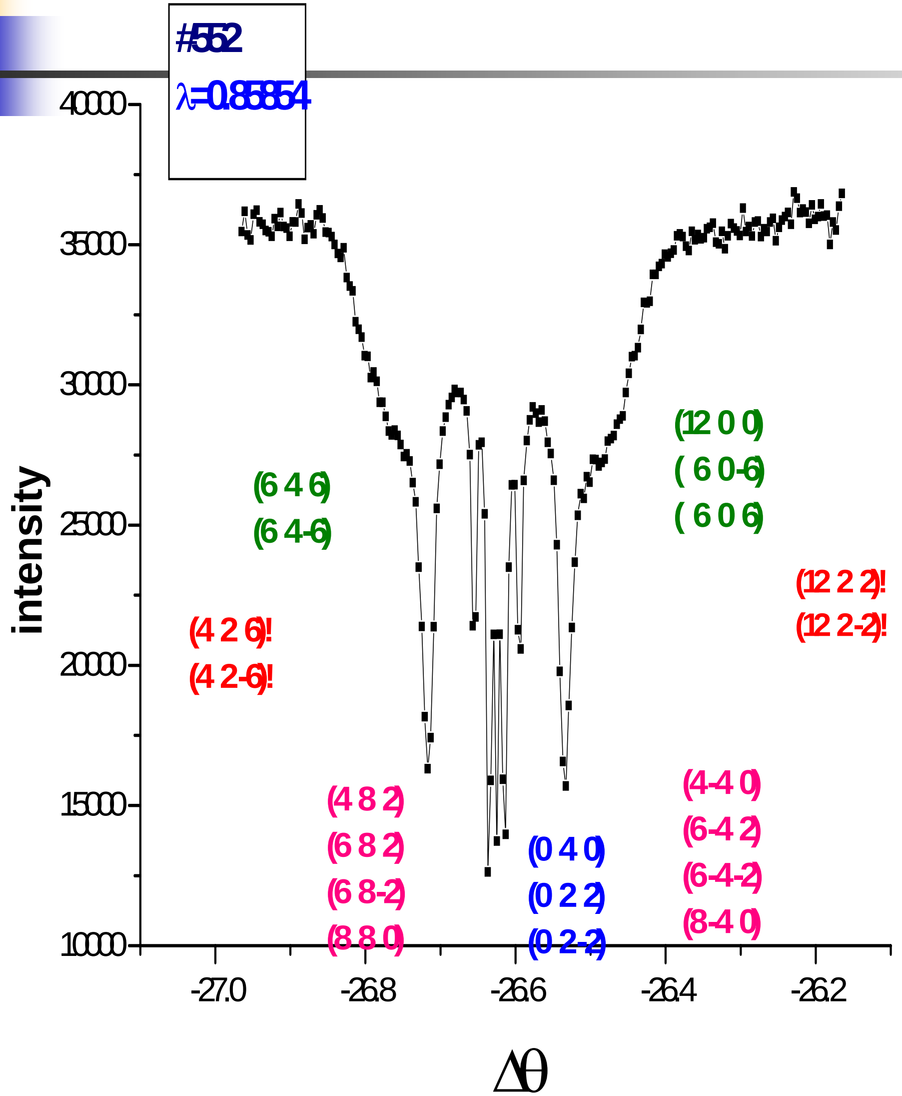
$E \neq E_o = 14.4388$ keV



$E = E_o = 14.4388$ keV


intensity

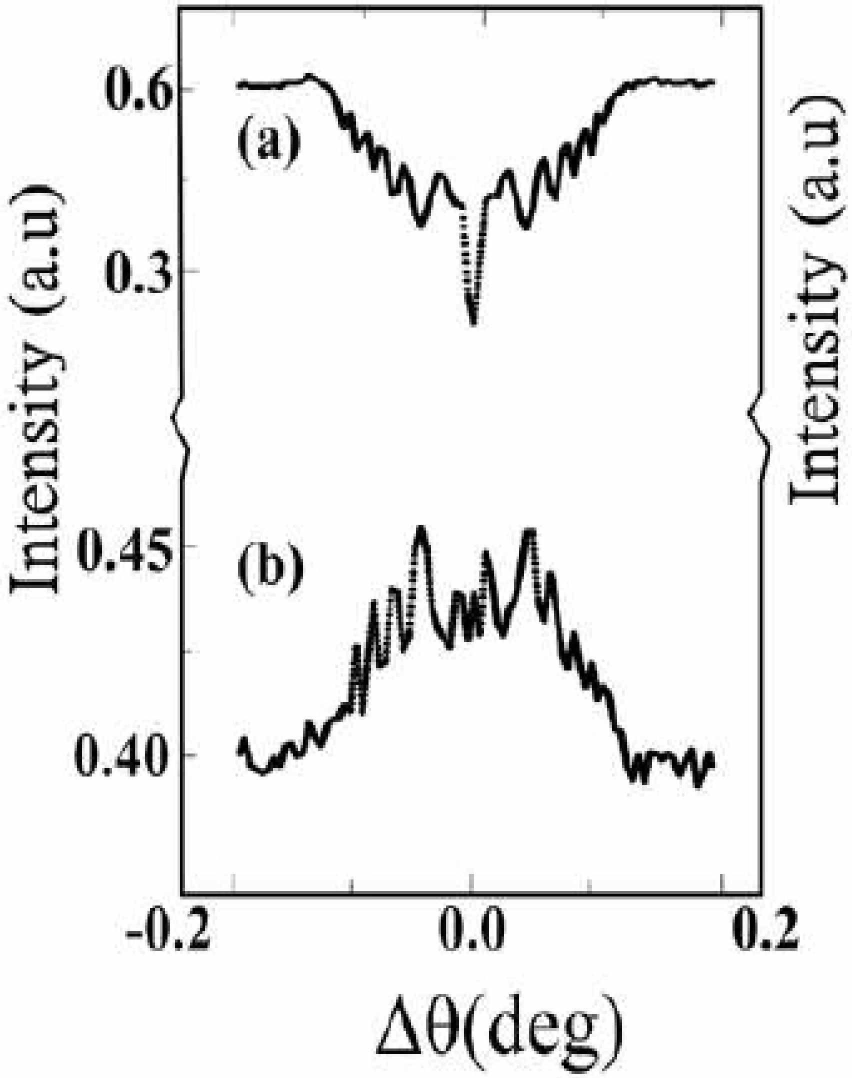

#549
λ=0.85827
intensity
20000
16000
12000
8000
4000
-27.0
-26.8
-26.6
-26.4
-26.2
Δθ
(4 2 6)!
(4 2-6)!
(6 4 6)
(6 4-6)
(4 8 2)
(6 8 2)
(6 8-2)
(8 8 0)
(0 4 0)
(0 2 2)
(0 2-2)
(4-4 0)
(6-4 2)
(6-4-2)
(8-4 0)
(12 2 2)!
(12 2-2)!
(12 0 0)
(6 0-6)
(6 0 6)



#552
λ=0.8854
intensity
40000
35000
30000
25000
20000
15000
10000
-27.0
-26.8
-26.6
-26.4
-26.2
Δθ
(6 4 6)
(6 4 -6)
(4 2 6)!
(4 2 -6)!
(4 8 2)
(6 8 2)
(6 8 -2)
(8 8 0)
(0 4 0)
(0 2 2)
(0 2 -2)
(12 0 0)
(6 0 -6)
(6 0 6)
(12 2 2)!
(12 2 -2)!
(4 -4 0)
(6 -4 2)
(6 -4 -2)
(8 -4 0)

$\Delta\ \theta$ - scans at $\Delta E = 9$ meV

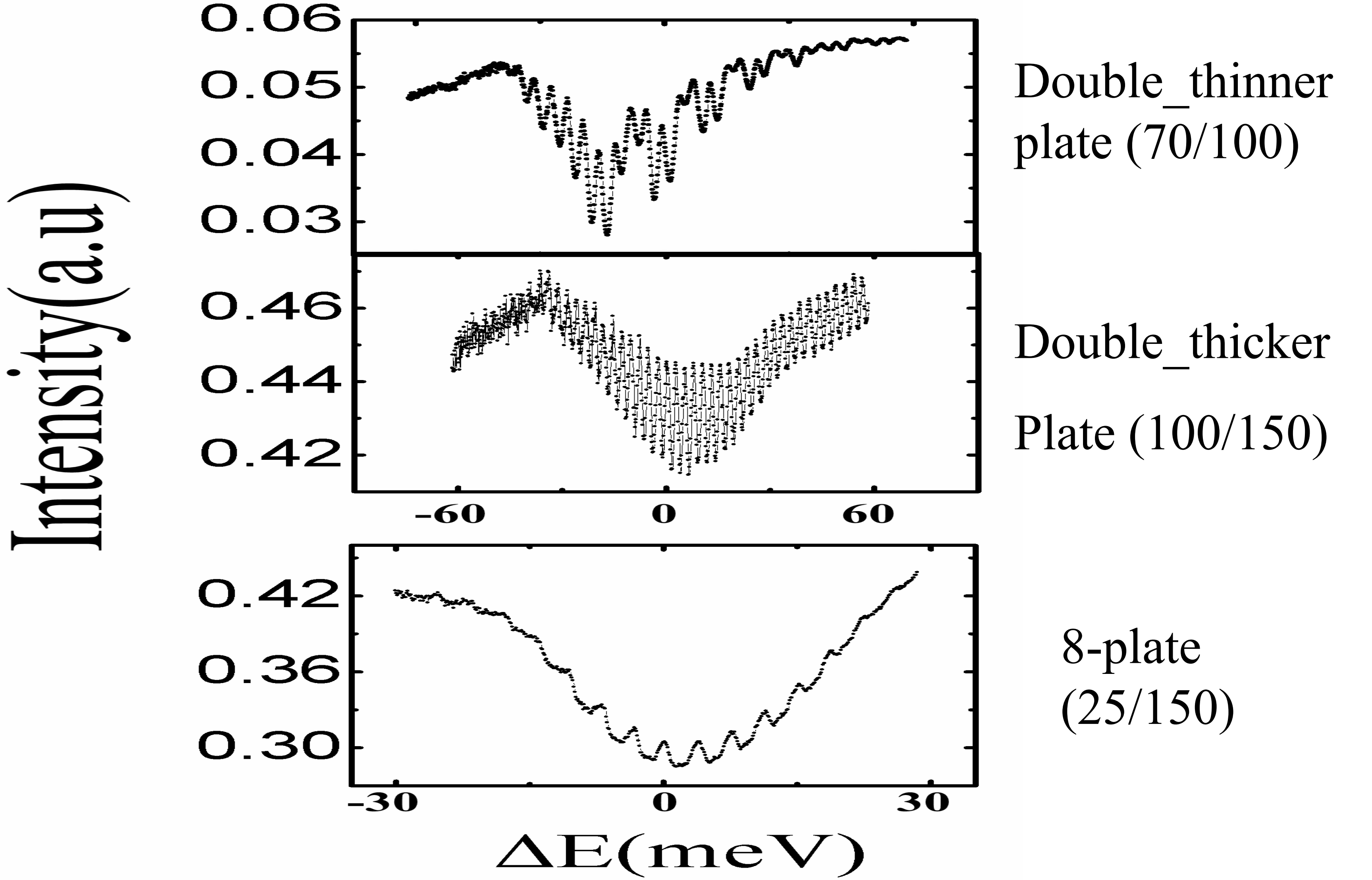
The $\Delta\ \theta$ -scan at 0.002 deg./step



(a) Forward-transmitted (0 0 0) beam

(b) Back-reflected (12 4 0) beam

Energy scans



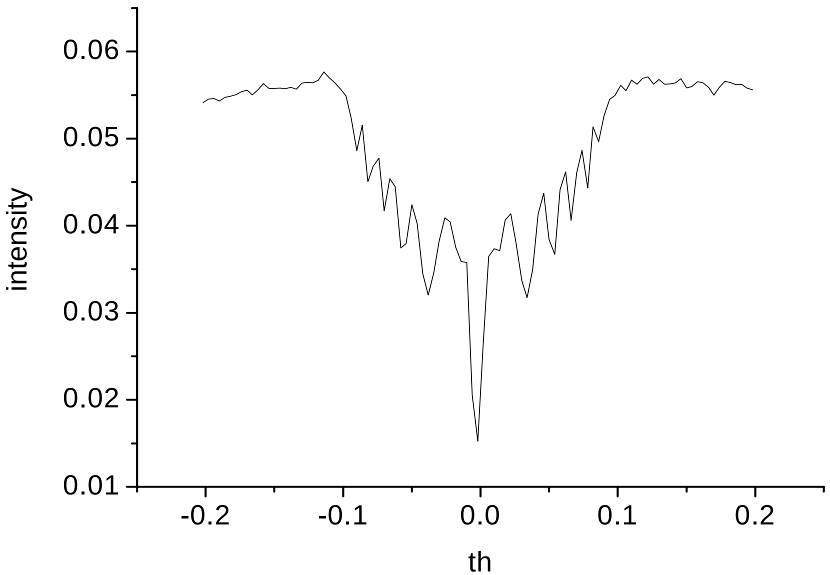
The energy ΔE scan (1 step=58.548 μeV)

The spectral width Γ =1.60 meV of fringes.

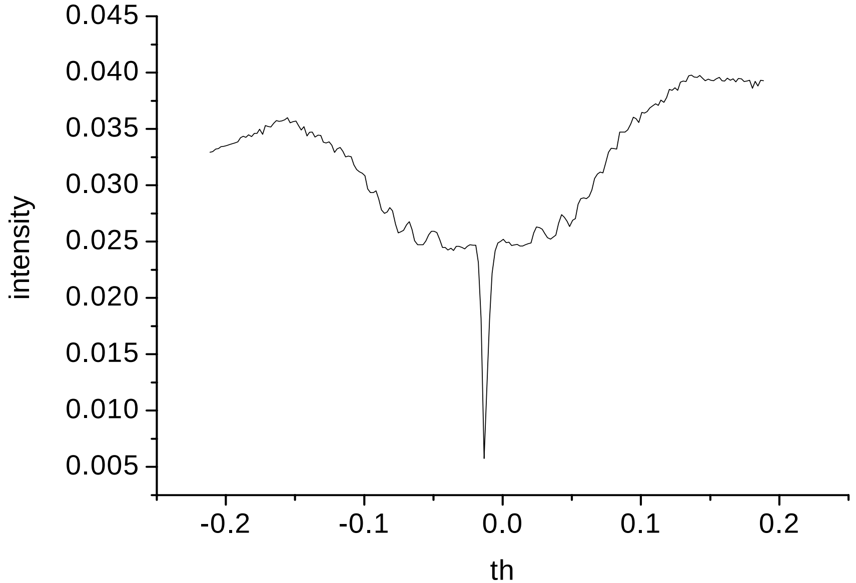
Finesse, $F=E_d/\Gamma$ = 2.3
(designed value F= 4.0 with
R= 50% T=50%)

Absorption

The $\Delta\,\theta$ -scans show obvious oscillations, even not at the exact energy.

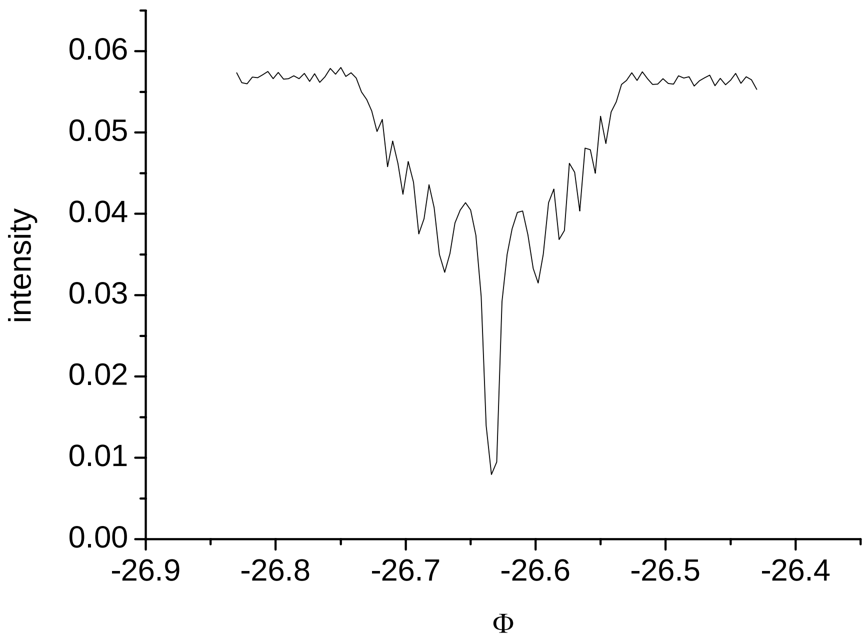


Double_thinner plate

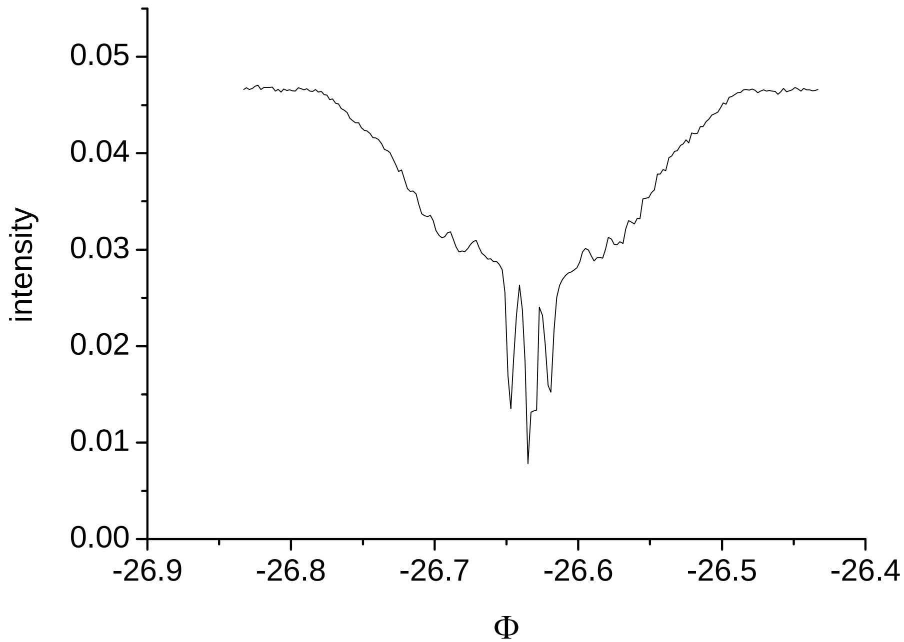


8-plate

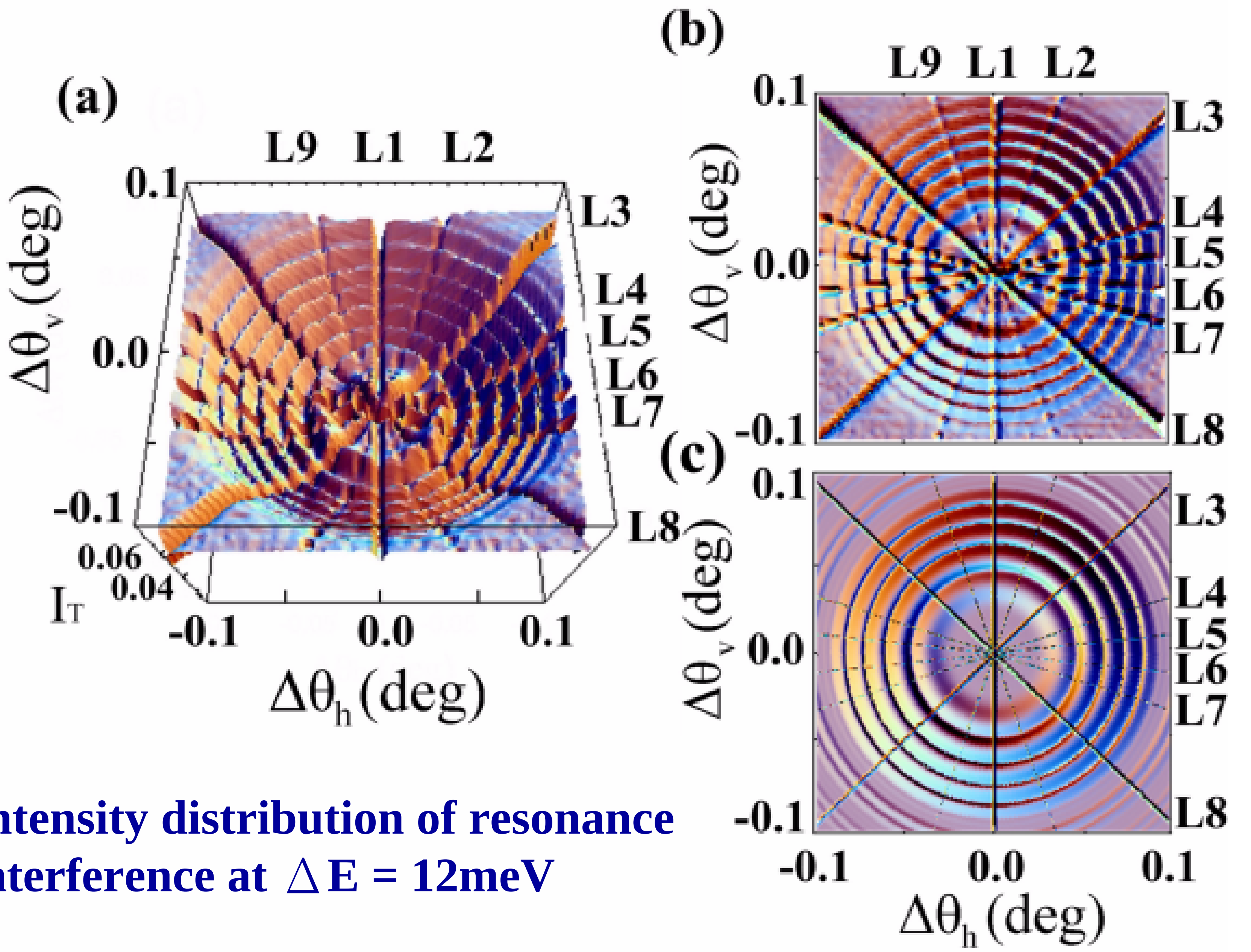
The $\Delta\phi$ -scans show obvious oscillations, even not at the exact energy.



Double_thinner plate



8-plate



Intensity distribution of resonance interference at ΔE = 12meV

Shvyd'ko et al (PRL 2003):

ΔE(=2 meV) > E_d (=12.4 ueV) Criterion (a) is not satisfied.

ΔE(=2 meV) > Γ (= 0.64 ueV) Criterion (b) is not satisfied.

Γ (=0.64 ueV) < E_d (=12.4 ueV) Criterion (c) is satisfied.

Δt (=0.33 ps) < $t_f/2\pi$ (=53 ps) Criterion (d) is not satisfied.

l_L (=310 um) < 2d (=100000 um) Criterion (e) is not satisfied.

Pendellosung fringes due to diffraction from thin crystals (60 um).

K.-D. Liss et al. (Nature 2001)

ΔE(=3.7 meV) > E_d (=4.12 ueV) Criterion (a) is not satisfied.

ΔE(=3.7 meV) ? Γ (no information about Γ, but should be smaller than E_d =4.12 ueV for observable fringes). Criterion (b) is not likely to be satisfied.

Γ ? E_d (No information about Γ).

t (=0.18 ps) < t_f /2 (=159 ps) Criterion (d) is not satisfied.

l_L (=170 um)< 2d (=300000 um) Criterion (e) is not satisfied.

Conclusion

(1) Resonance of X-rays always takes place in a normal incident X-ray diffraction from two parallel crystal plates in a monolithic crystal. Although the resonance fringes are always there, it is, however, very difficult to be observed.

For a normal incidence X-ray cavity, the required conditions for observing fringes:

Spatial coherence: photon emittances (1 deg.)

Temporal coherence: $\Delta t > t_f / 2\pi$

$$\ell_L \geq 2d$$

Conclusion

(2) The current experiments extend the spectral range of Fabry-Perot resonators (interferometers) from the visible spectra to hard X-ray and near-gamma ray regime

Conclusion (Applications):

1. Since the fixed phase relation between the forward transmitted and the back-reflected beams and the narrow energy and angular widths of X-rays from the cavity, this crystal cavity can be used for phase-contrast and high-resolution X-ray optics, such as high-resolution monochromator using the back reflection and narrow-band filter with the transmission.

2. Application for high-resolution X-ray scattering, spectroscopy, and phase-contrast microscopy in many physical, chemical, and biological studies, such as investigation of dynamics of solids, liquids, and bio-molecules, precise measurements of wavelength and lattice constant, etc.

3. Crystal cavities of the present type with better finesse might be useful for the development toward hard X-ray (or gamma-ray) lasers, if suitable lasing materials could be developed.

4. Seeding for Free electron lasers

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Thank you for your attention !!