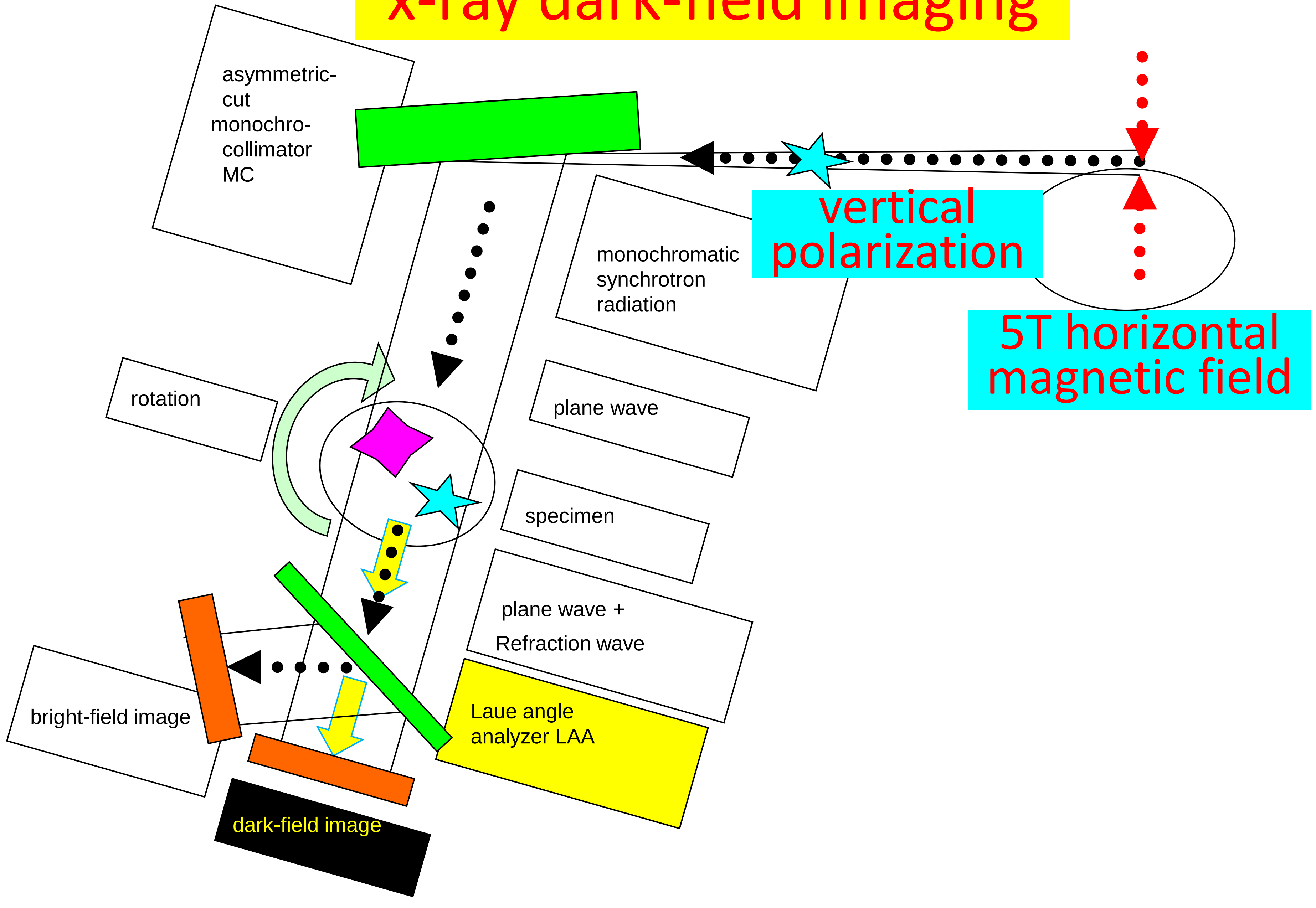
X-ray Dark-Field Imaging : Recent Developments towards Clinical and Pathological Applications

M. Ando

x-ray dark-field imaging



Collaborators

KOREA: KIM Jong-Ki: CUD, Kim Hongtae: CUD, Lim Jae-Hong: PLS,

CHINA: JIANG Xiaoming : BSRF, LI Gang: BSRF,

USA: GUPTA Rajiv: MGH,

AUSTRALIA: MAKSIMENKO Anton : AS

JAPAN: ICHIHARA Shu: NMC, JIN Ge: KIT, MORI Kensaku: NAGOYA U., SUNAGUCHI Naoki: GUNMA U., SUZUKI Yosifumi: KIT, YUASA Tetsuya: YAMAGATA U. , OHURA Norihiko: KYORIN U.

SOMETHING SPECIAL

- crystal based refraction contrast using a Laue angle analyzer LAA
- vertical polarization that makes setting up x-ray optics so easy and comfortable

Flow of talk

- (1) what we have been developing ~

  X-ray dark-field imaging (XDFI) optics
- (2) what applications are ongoing
- (3) to which direction we want to go
- (3-1) clinical
- (3-2) pathological

XDFI condition

- $I_{FD}(w,H) = (w^2 + \cos^2\pi H(1 + w^2)^2/\Lambda))/(1 + w^2)$ (1)

- $I_D(w,H) = (w^2 + \sin^2\pi H(1 + w^2)^2/\Lambda))/(1 + w^2))$ (2)
- available from X-ray dynamical diffraction theory

- w: angular parameter H: thickness of LAA
- $\Lambda = \lambda\cos\Theta_B/|P||\chi_G|$: Pendellosung fringe period
- Θ_B=Bragg angle P : polarization $\chi_G = (\lambda^2 r_e \pi V)F_G$: susceptibility r_e : classical electron diameter V : unit cell volume F_G : crystal structure factor

- $I_{FD} = \cos^2(\pi H/\Lambda)|_{w=0} = 0$
- $H = (p+1/2)\Lambda$: thickness of LAA

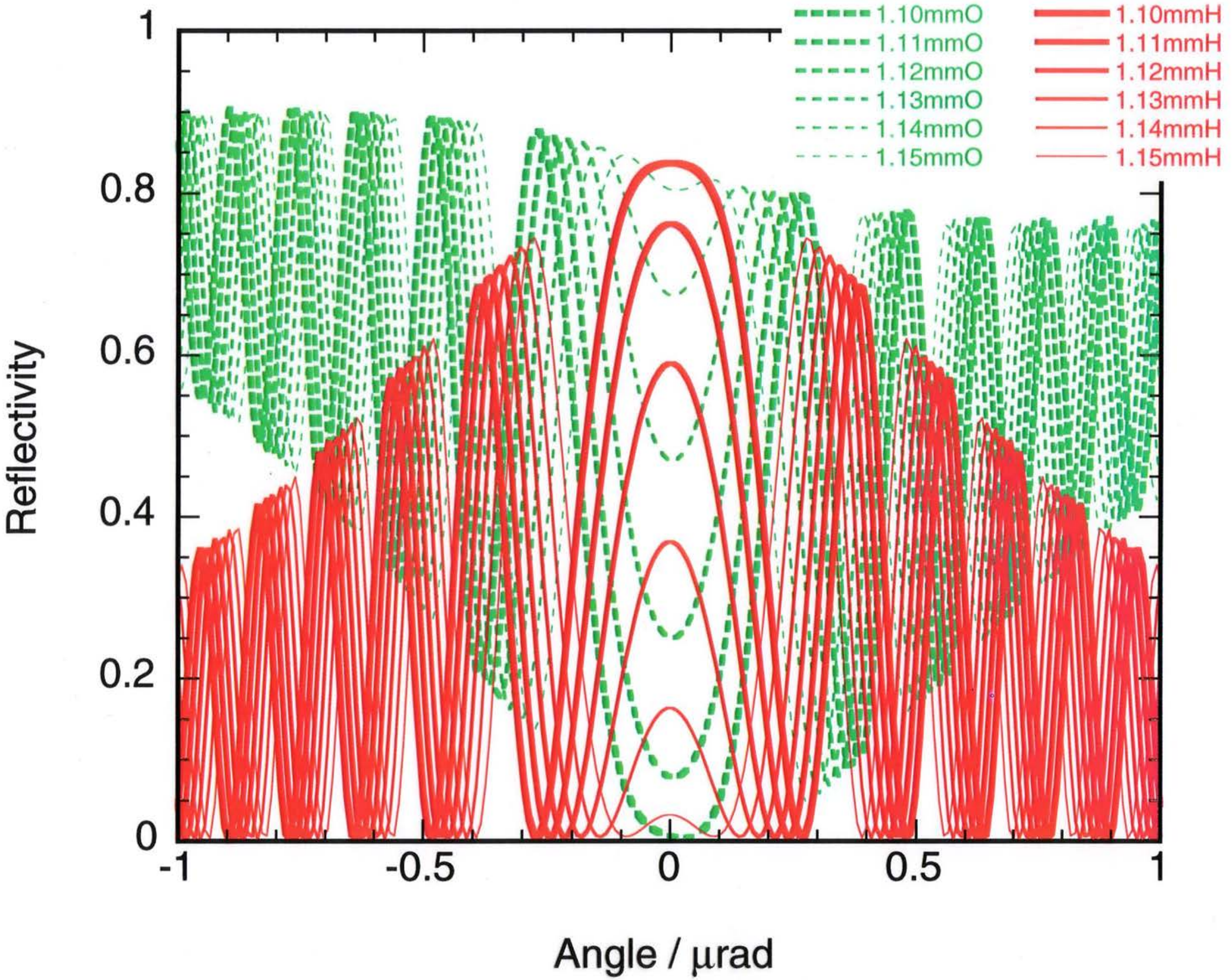
  p: integer
- Λ : Pendellosung period ~100μm

- $I_{FD}(0,H)|_{w=0} = \cos^2\pi H/\Lambda$ (4)
- $I_{D}(0,H)|_{w=0} = \sin^2\pi H/\Lambda$ (5)
- $I_{FD}(0,H)|_{w=0} + I_{D}(0,H)|_{w=0} = 1$ (6)

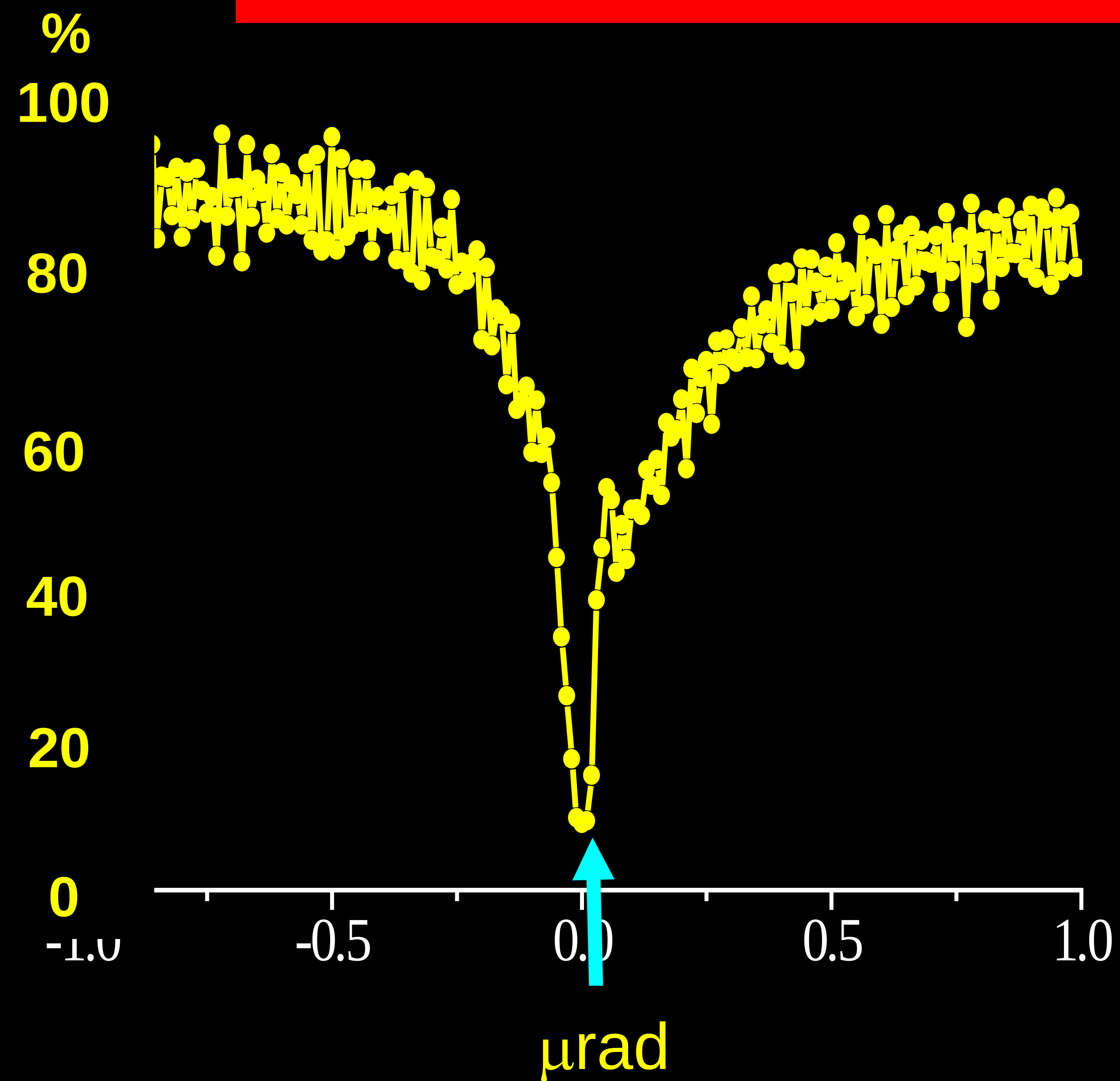
FD and D profile on Si 440 Laue case at

FD:
convex
downward

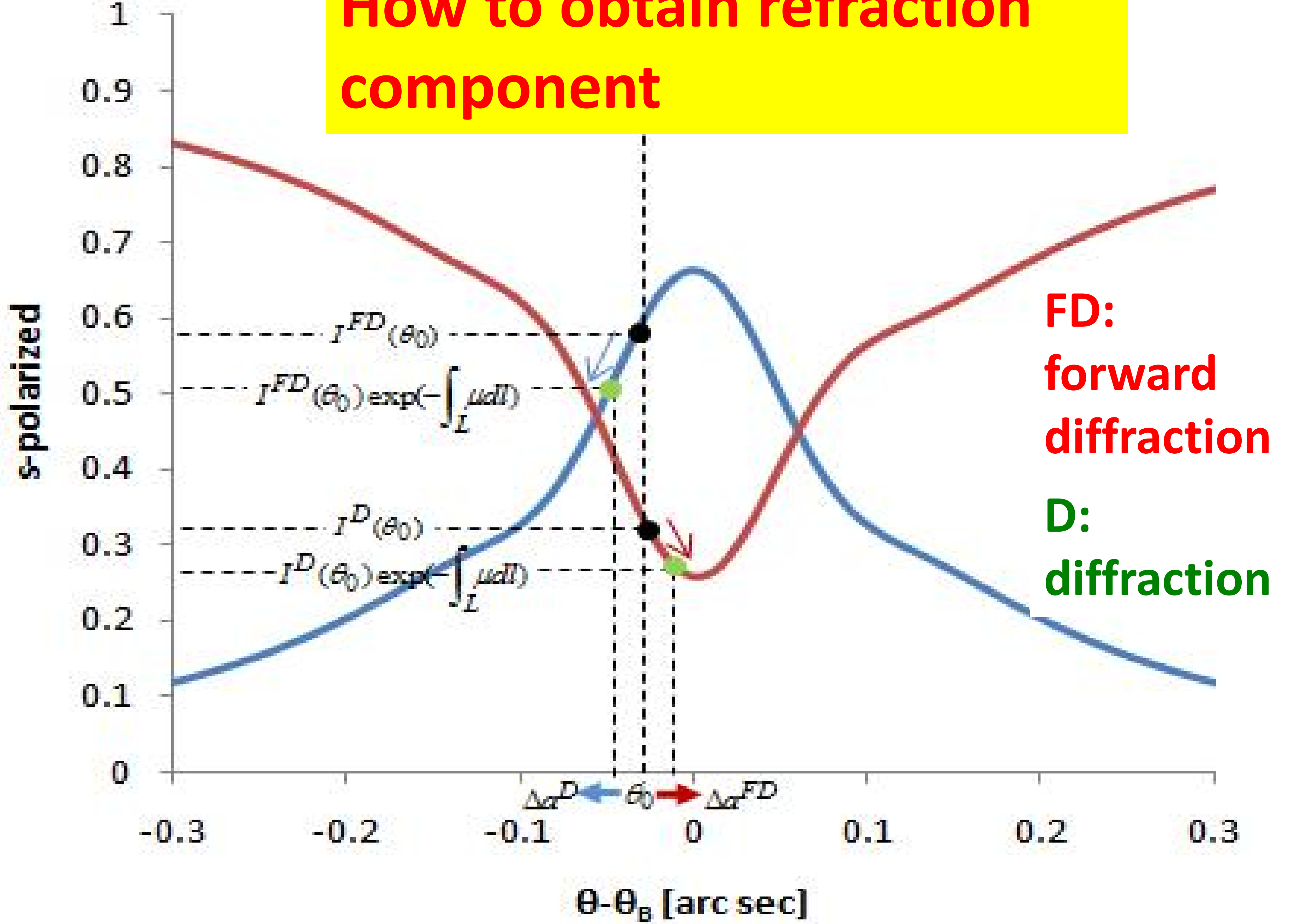
D:
convex
upward

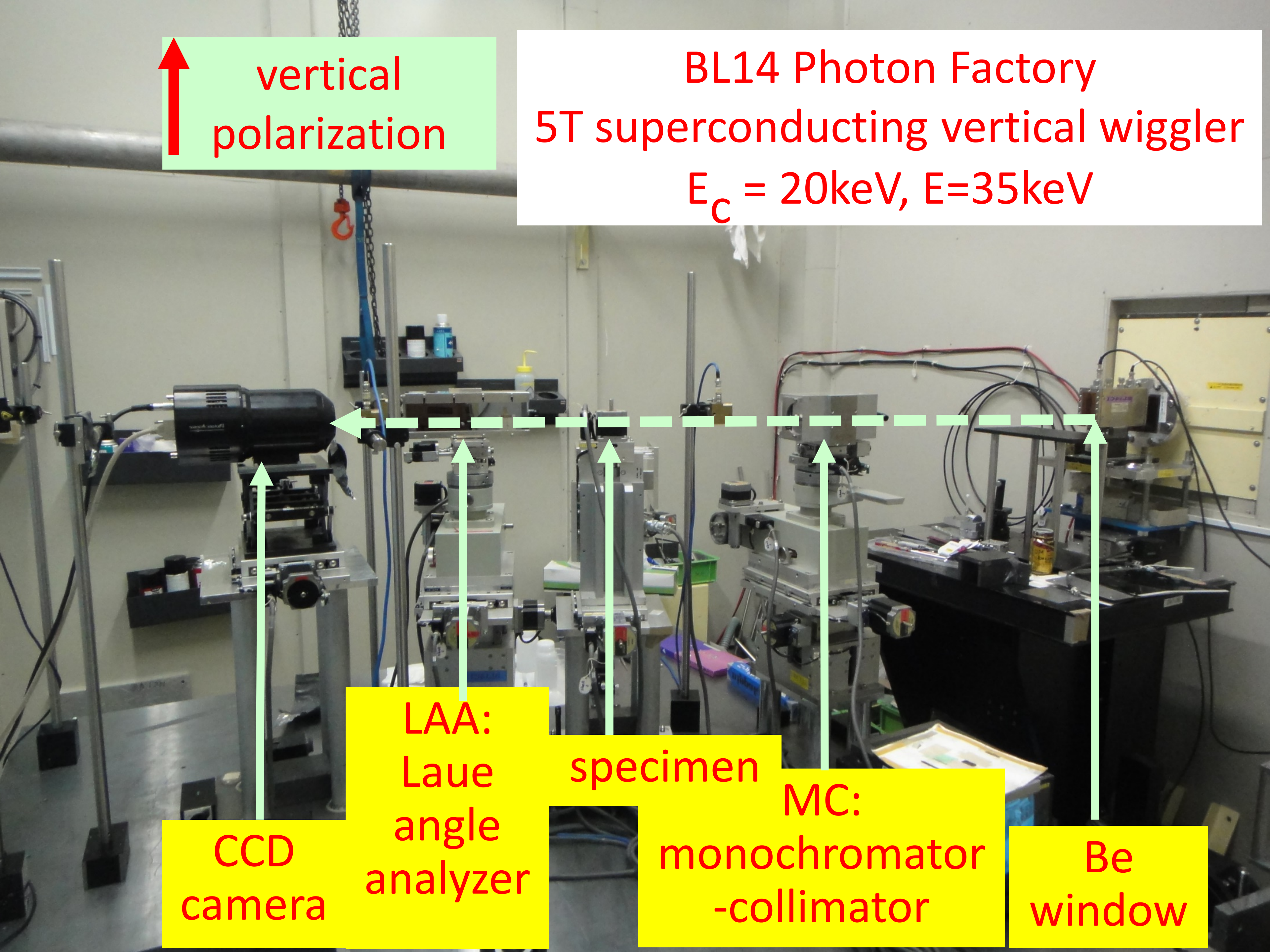


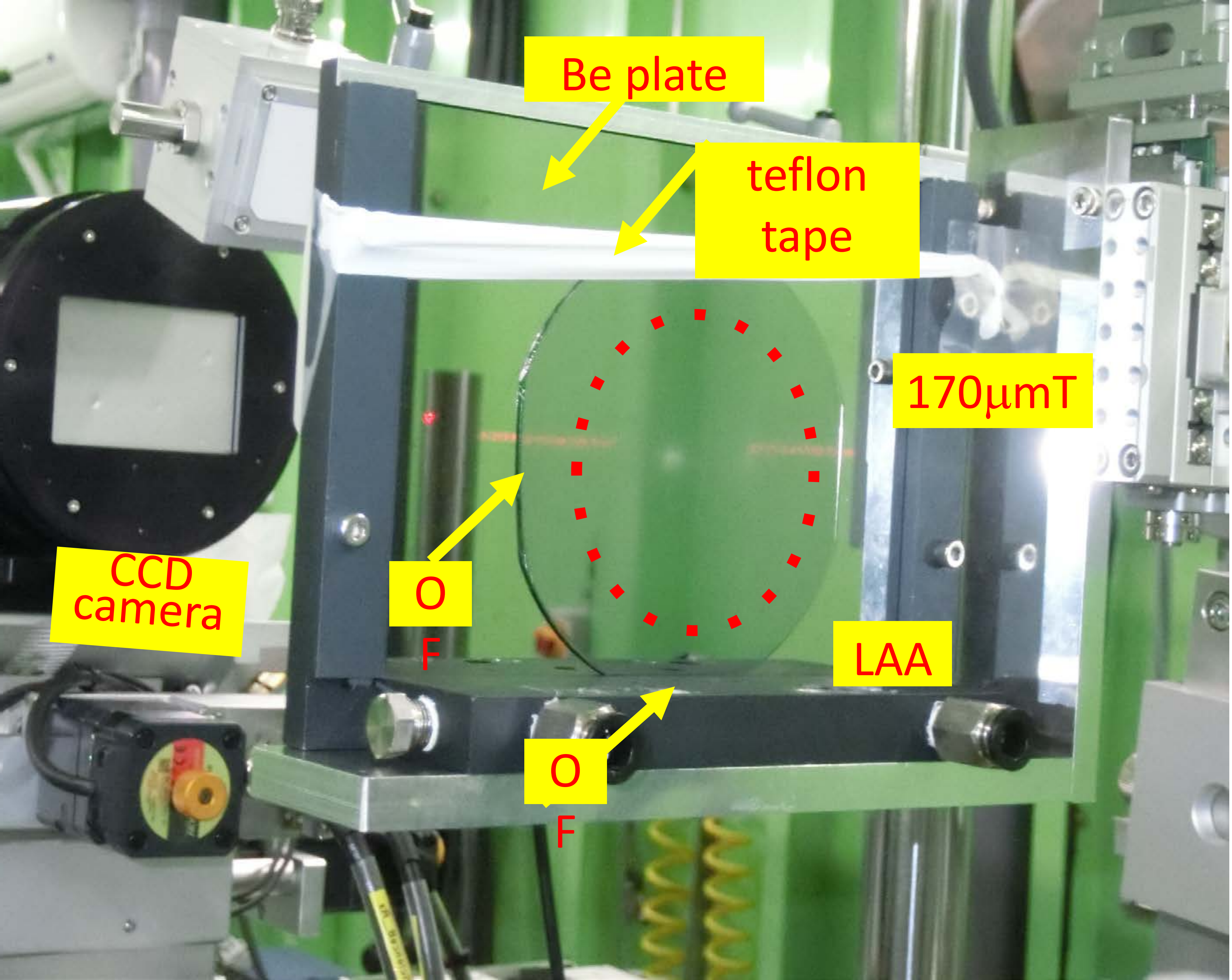
FD at LAA

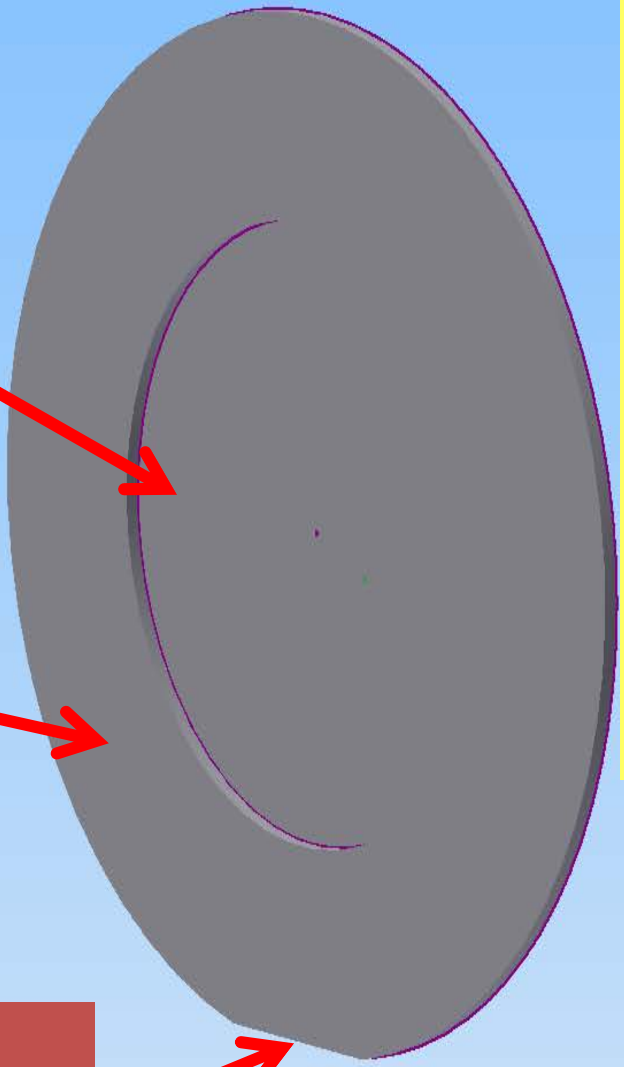


How to obtain refraction component




vertical polarization
BL14 Photon Factory
5T superconducting vertical wiggler
E_C = 20keV, E=35keV
CCD camera
LAA: Laue angle analyzer
specimen
MC: monochromator -collimator
Be window


Be plate
teflon tape
170μmT
CCD camera
O F
O F
LAA



170μm thick

3mm thick

<110>
OF :orientation flat

FZ crystal : **SUMCO**

grinding : **DISCO**

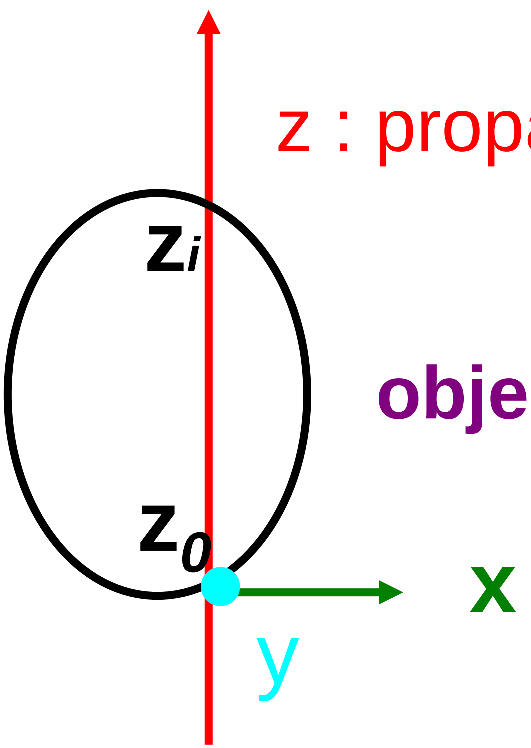
acid $(HF+HNO_3)$ etching : **Mimasu**

13

refraction angle: α

$$\alpha = r_e h^2 c^2 / E^2 2\pi \int_{z0}^{zi} \partial n(r)/\partial x \, dz$$

$n = 1 - \delta$

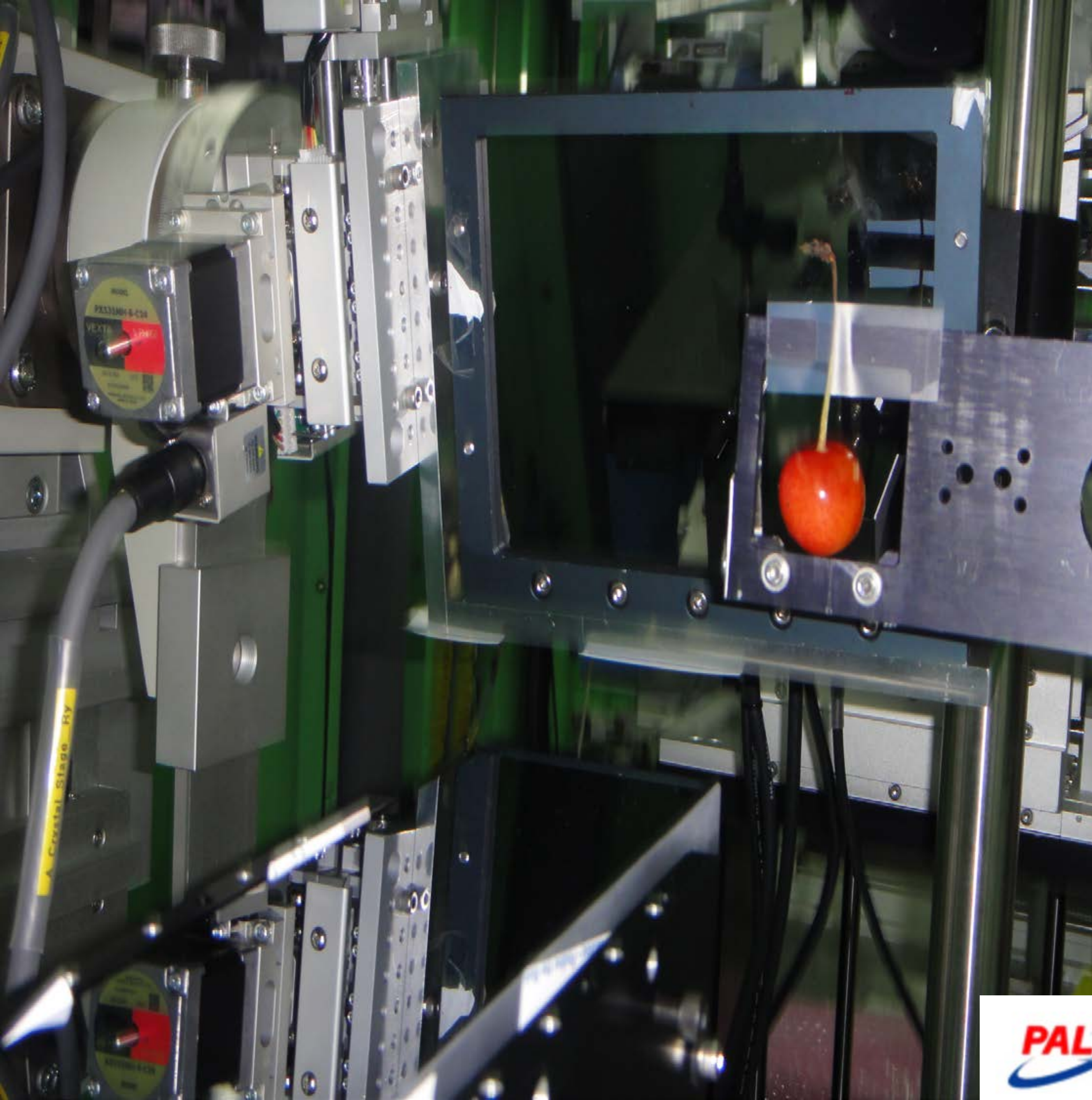


15 keV, 35 keV x-ray

$n=1-\delta$

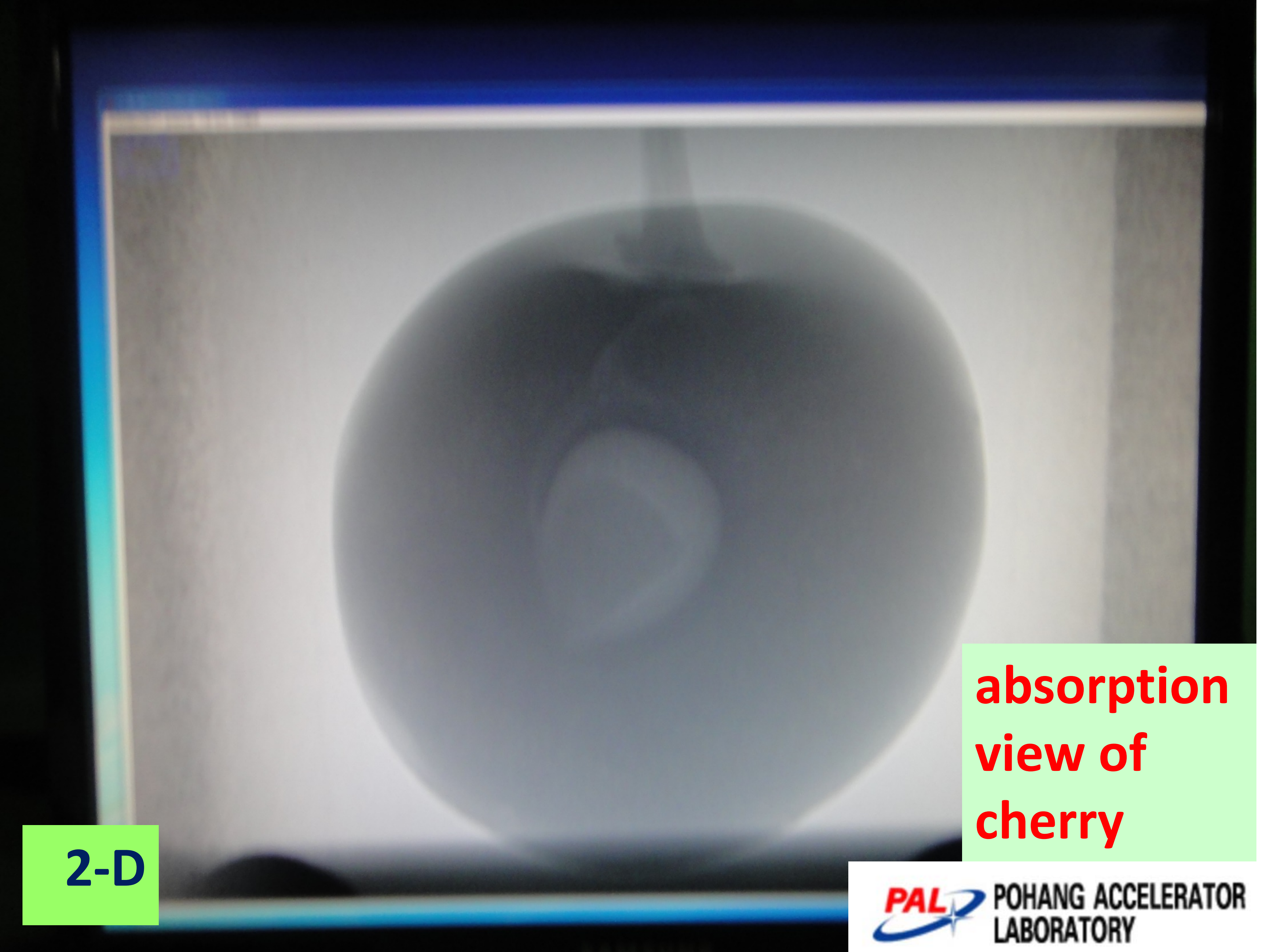
energy(keV)	Ca
15	1.4×10^{-06}
35	2.6×10^{-07}

2-DIMENSIONAL MED IMAGES



cherry in XDFI

PAL POHANG ACCELERATOR LABORATORY

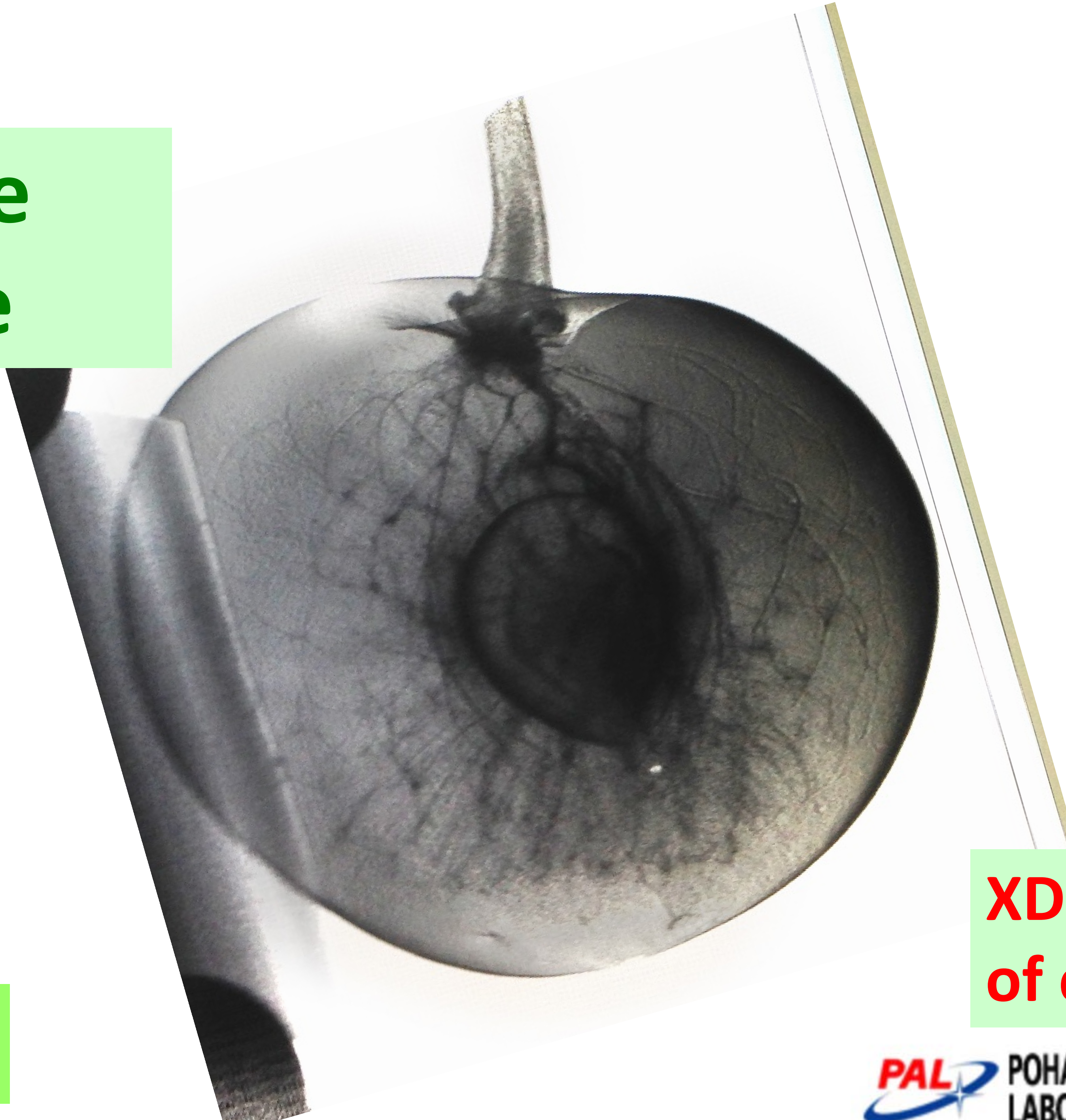


absorption view of cherry

2-D

POHANG ACCELERATOR LABORATORY

sieve tube

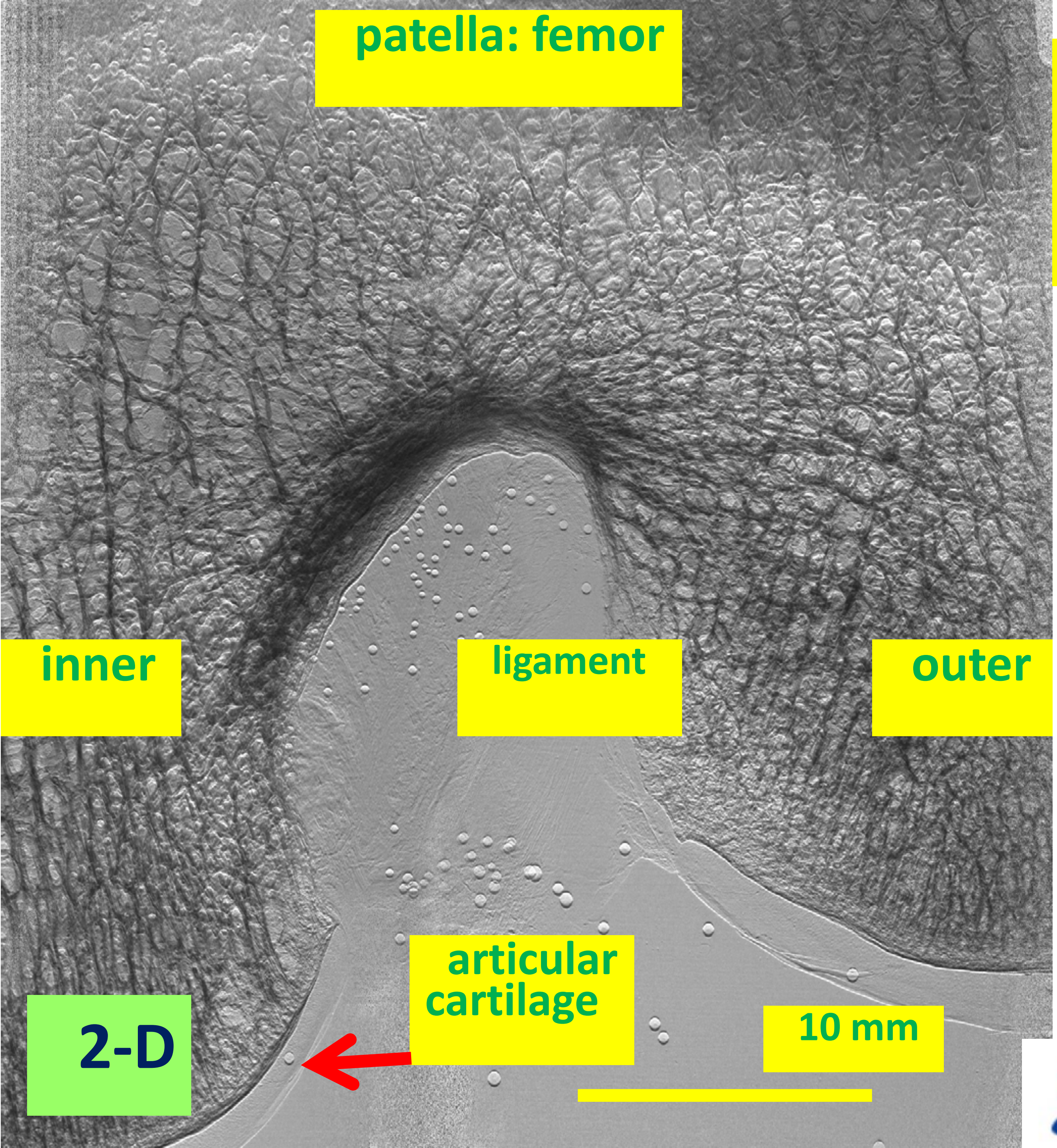


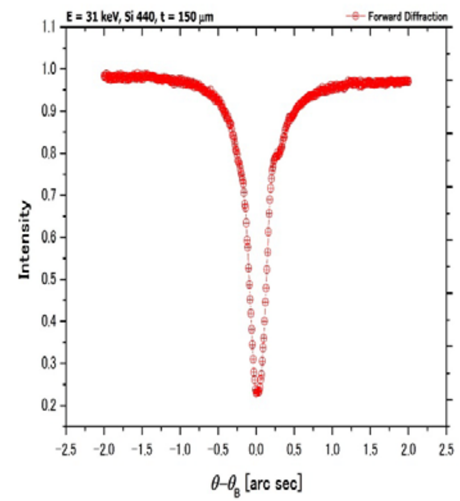
2-D

XDFI view of cherry

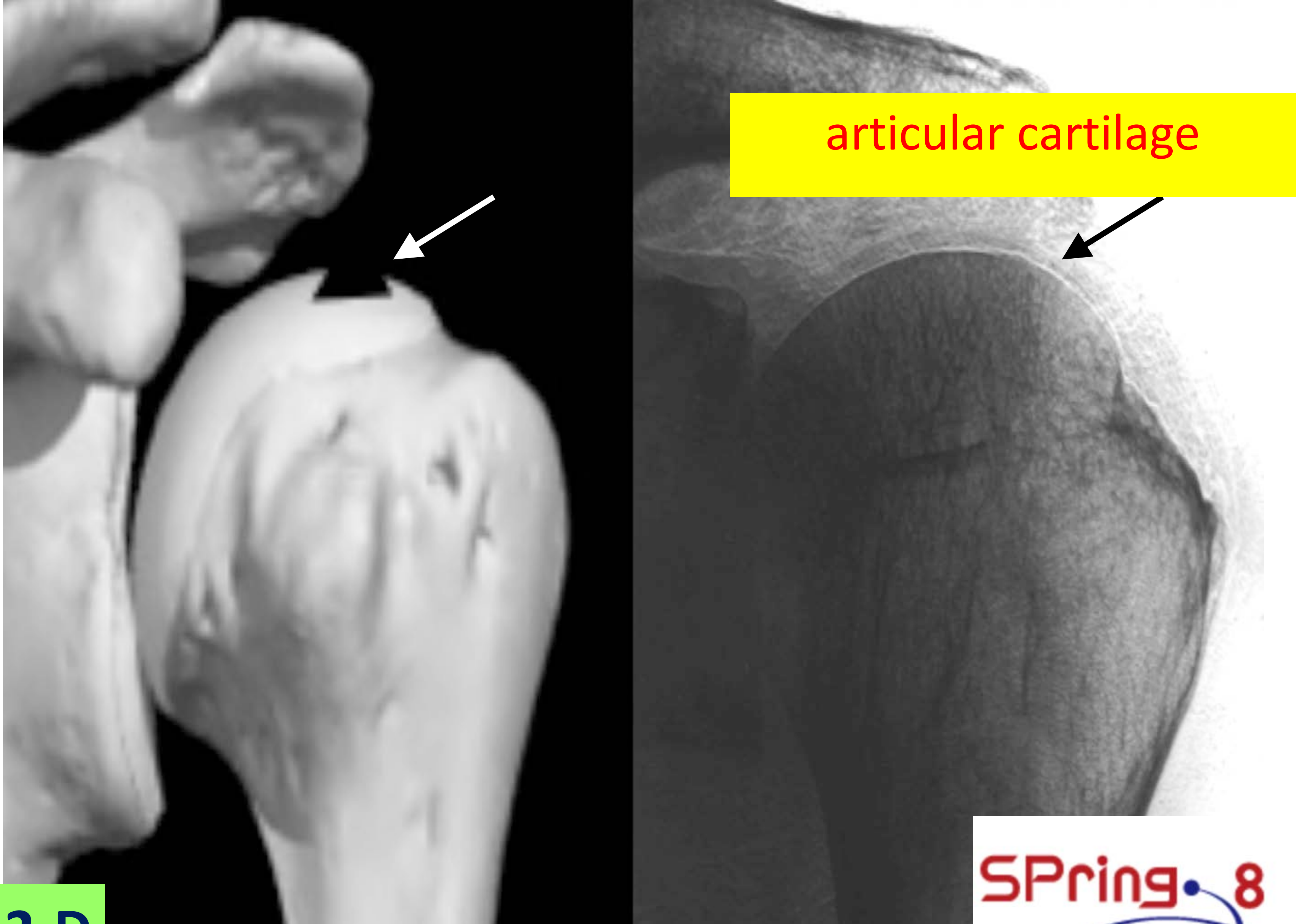
PAL POHANG ACCELERATOR LABORATORY

human articular cartilage at knee taken with XDFI





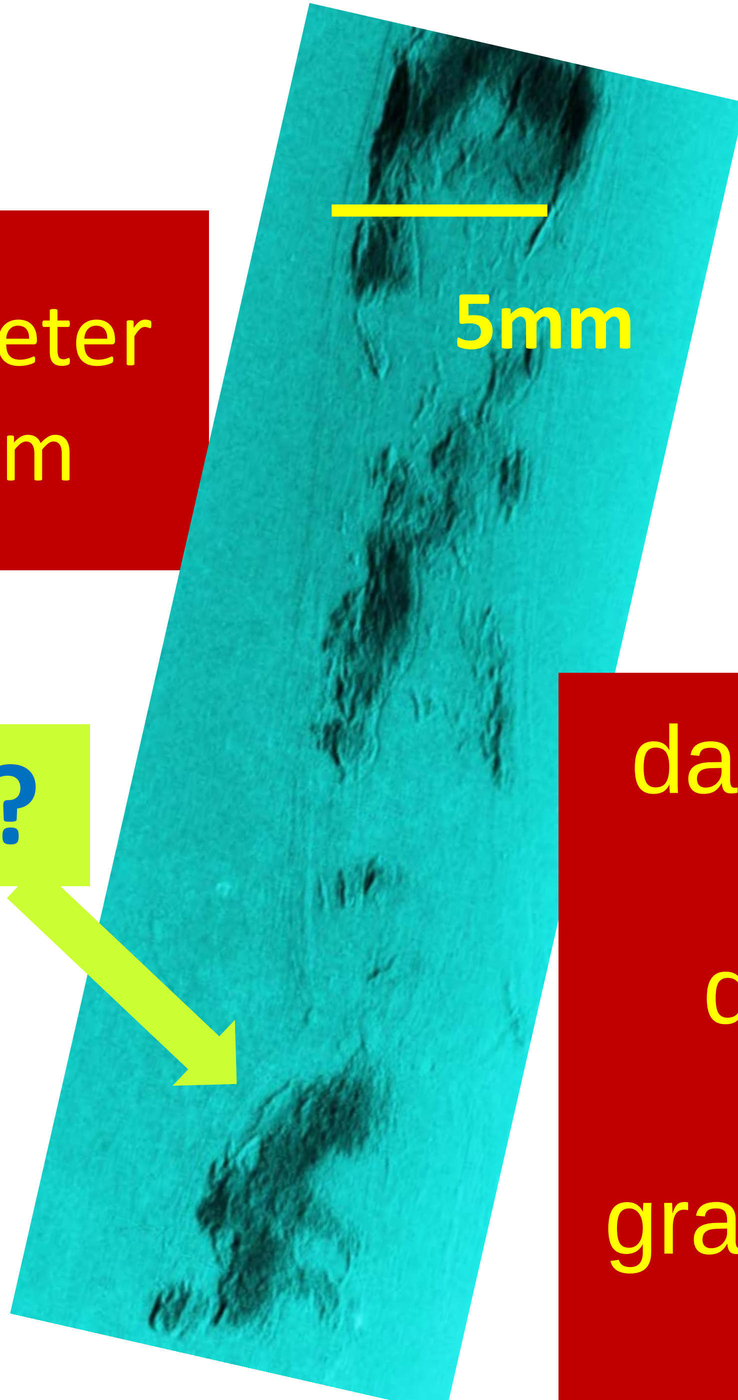
POHANG ACCELERATOR LABORATORY



2-D

human shoulder, cadavar

diameter
5mm

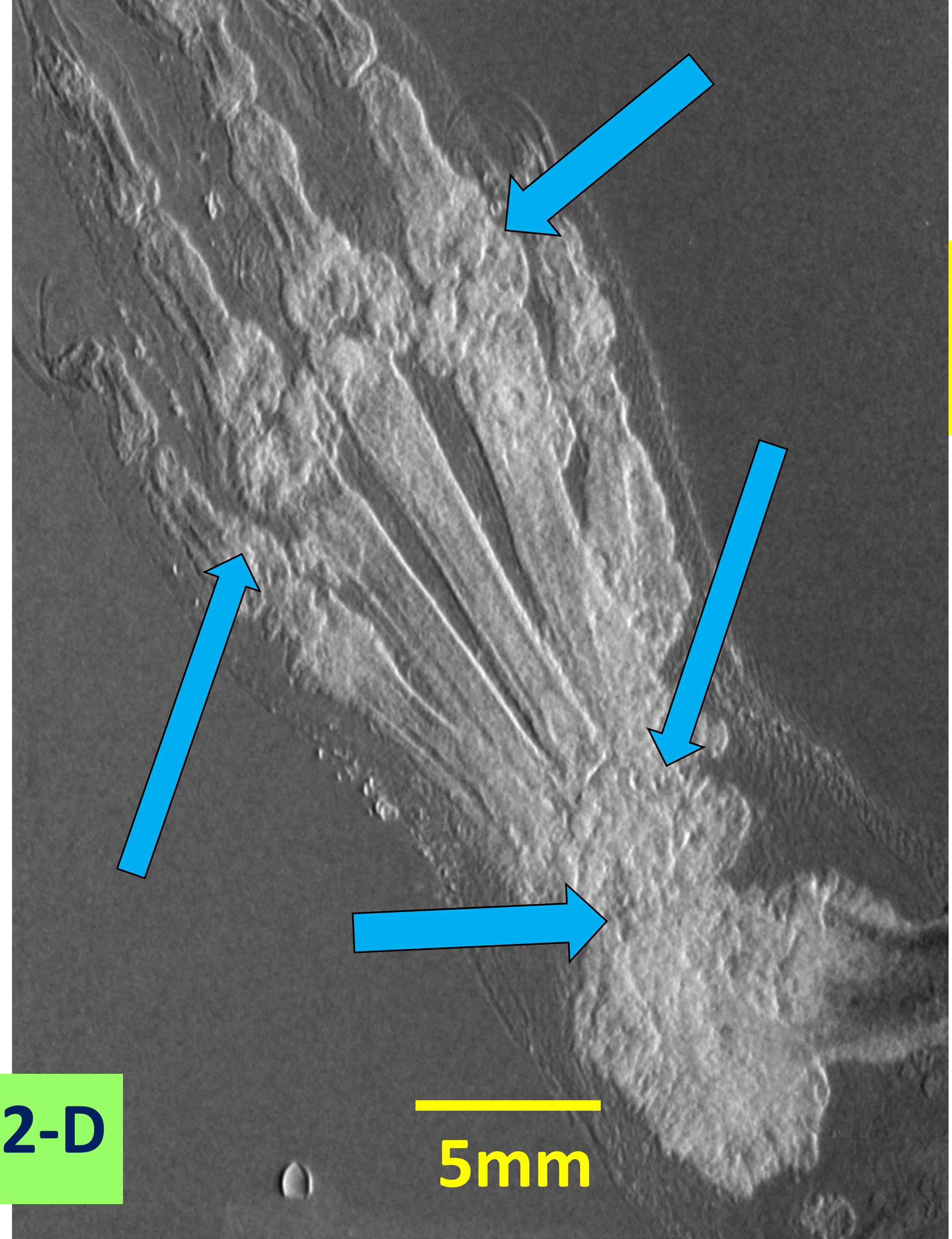


Ca?

damage to femoral
artery
due to diabetes

grafting with healthy
artery/vein

2-D



2-D

rheumatoid arthritis in rat

2 wks later after adjuvant injection at rat right foot

articular cartilage

3-DIMENSIONAL MED IMAGES

rat foot 2 wks after adjuvant injected

3-D

abs

XDFI

mod XDFI

Sunaguchi et al. PLOS ONE (2015) 0135654

eye

ball

axial

3-D

Ando et al.
3029

eye ball
sagittal

3-D

Gupta
al 201

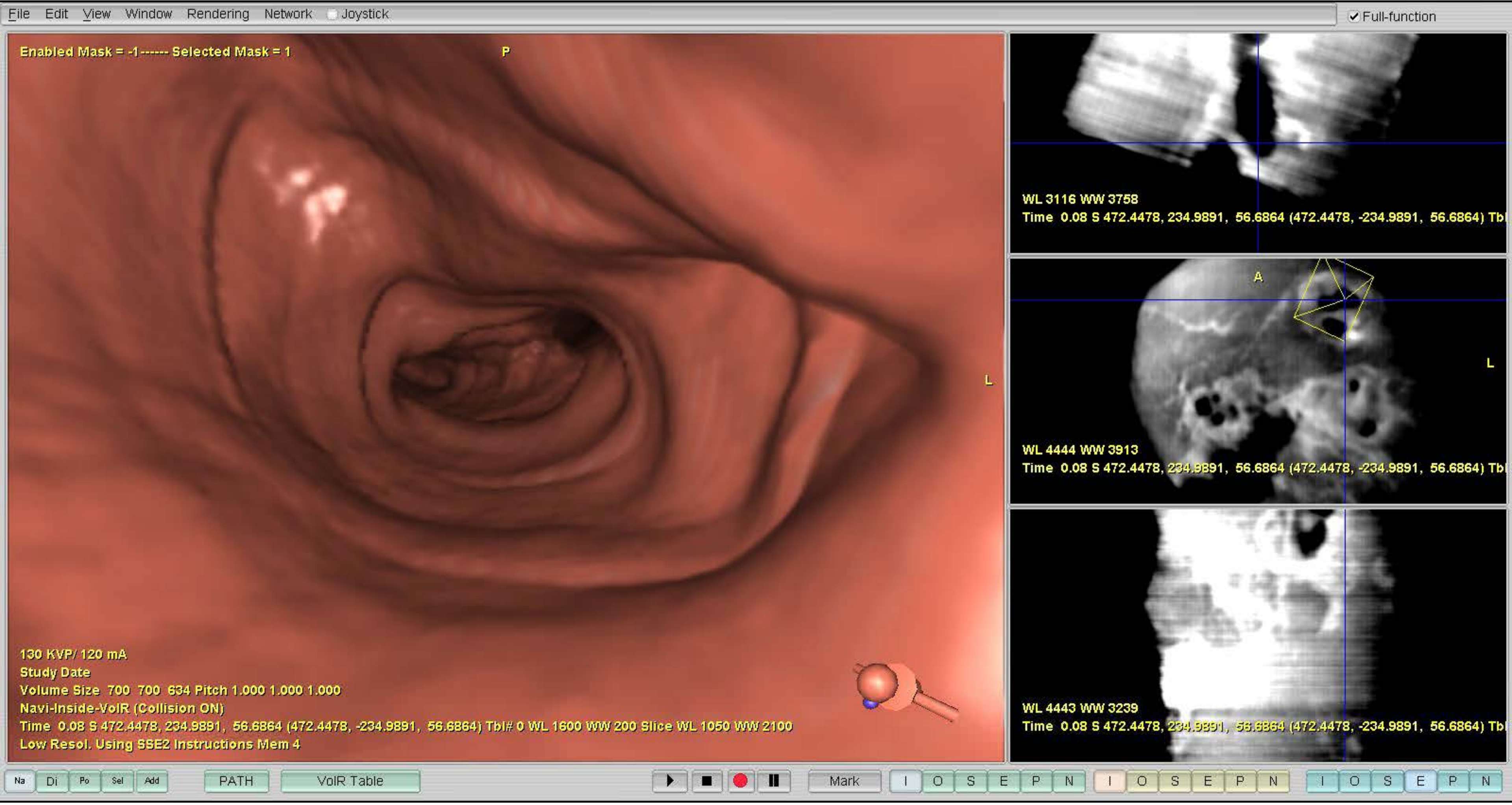
globe and optic nerve
insertion of the same
specimen. lens; i
muscle; ciliary bo
pupil; cornea; op
nerve sheath; scle
central retinal art
nerve fascicles
retinachoroid; su
choroidal spac

Gupt
et al
2012

3-D

3-D

DCIS absorption



DCIS endoscopy

3-D

Ichihara et al Virchows Archiv 451 (2008) 41-47

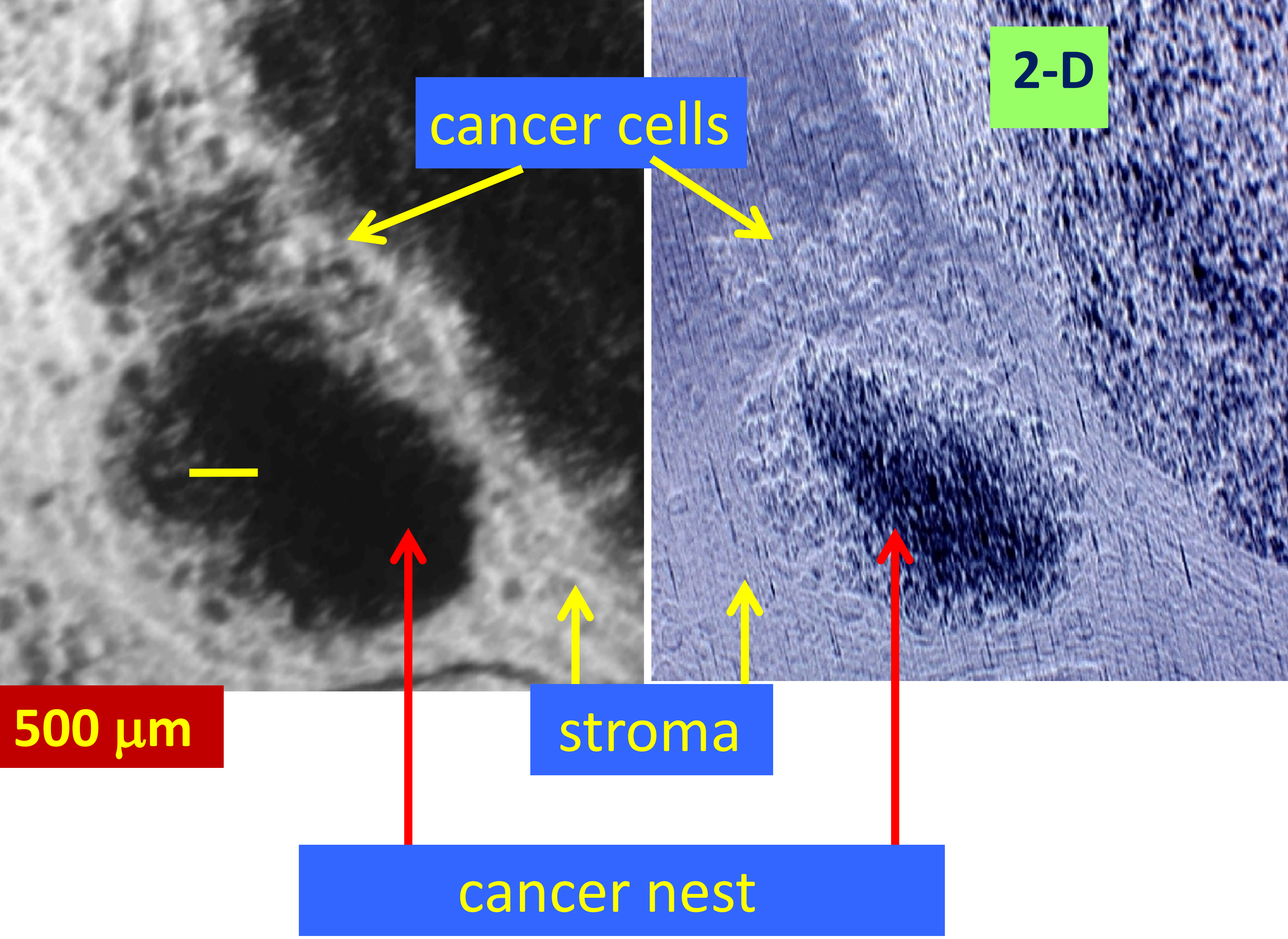
STILL CHALLENGING TOWARDS

1) **FOV SUITABLE FOR CLINICAL TRIAL ~ 26 CM X 26CM**

2) **DIFFICULT TISSUE SUCH AS BRAIN TUMOUR WITH SKULL**

3) **HIGHER SPATIAL RESOLUTION IN 2D AND CT IMAGE ~ 2-3 MICRON**

4) **CLINICAL DIRECTION AND PATHOLOGICAL DIRECTION**

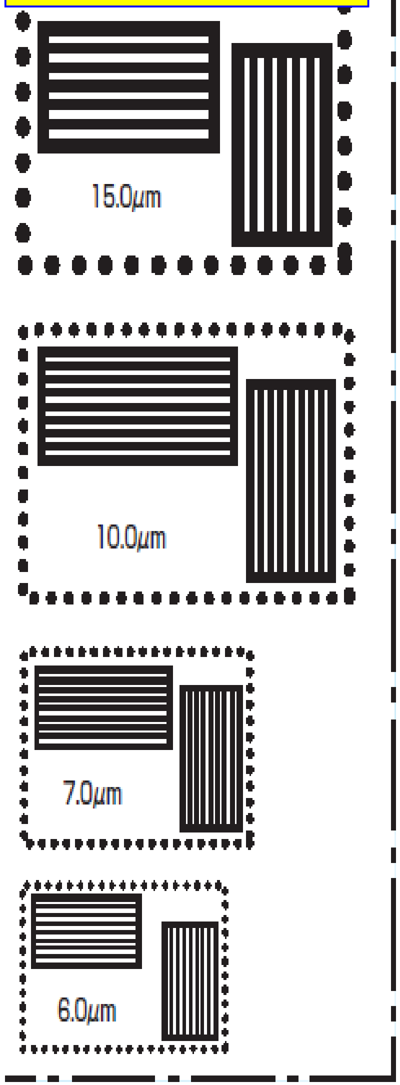

2-D
cancer cells
500 μm
stroma
cancer nest

spatial resolution measured by using MTF chart

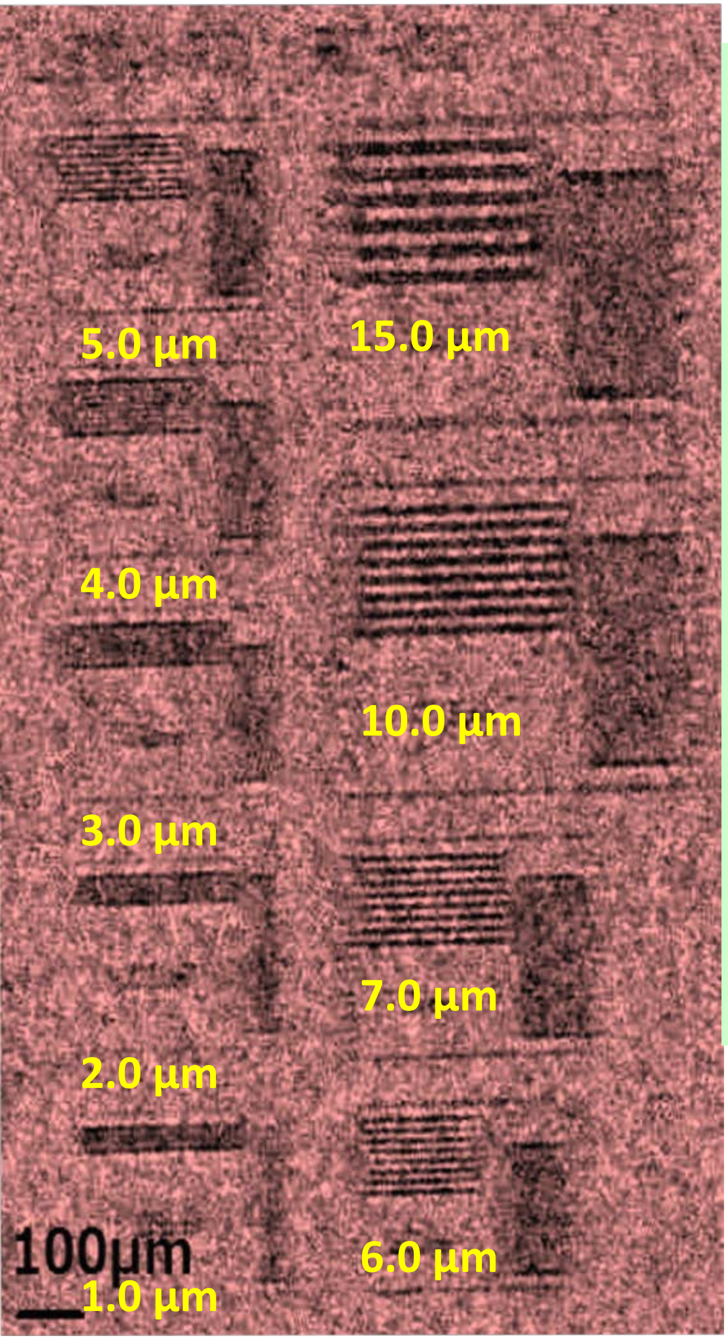
material :
W 1.0μm^{T}
X-ray energy:
31keV

CCD camera :
3μm/pixel
LAA thickness :
150μm

MTF chart

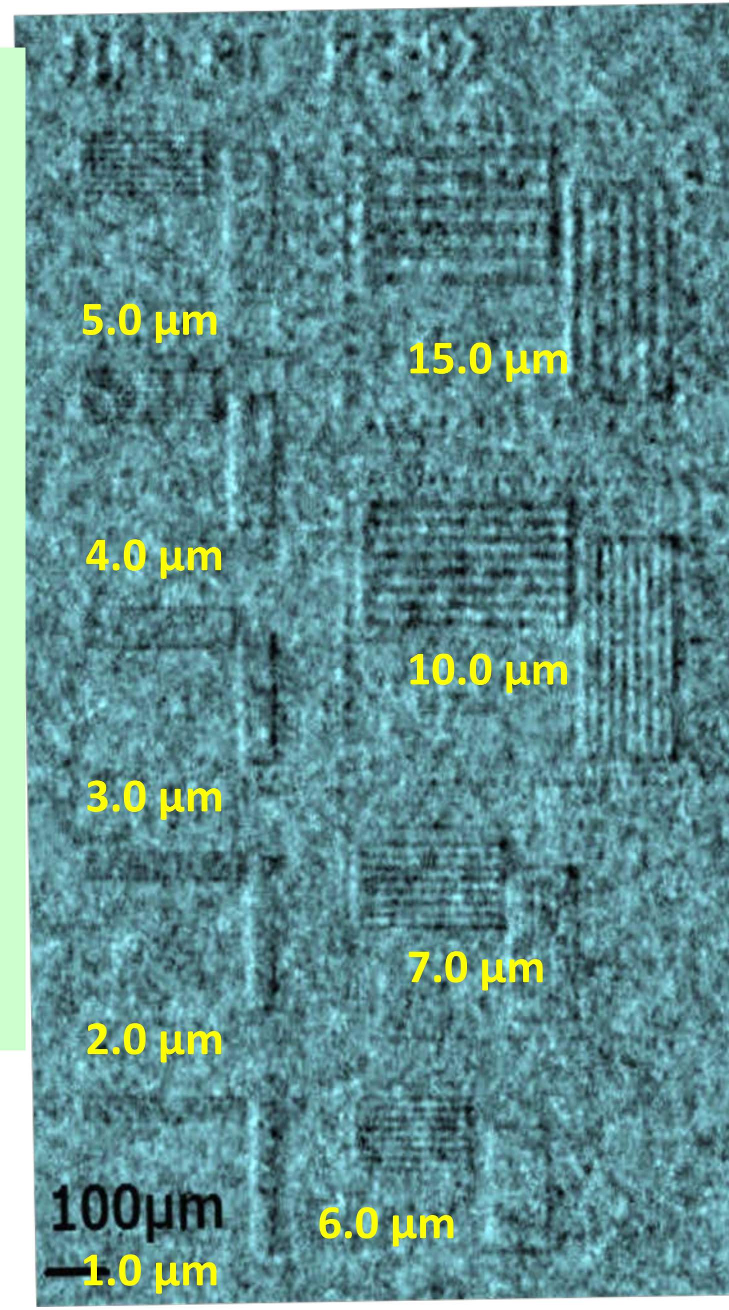


JIMA RC-02B
1μm^{T} W



left:
without MC
right:
with MC

31keV
150µm

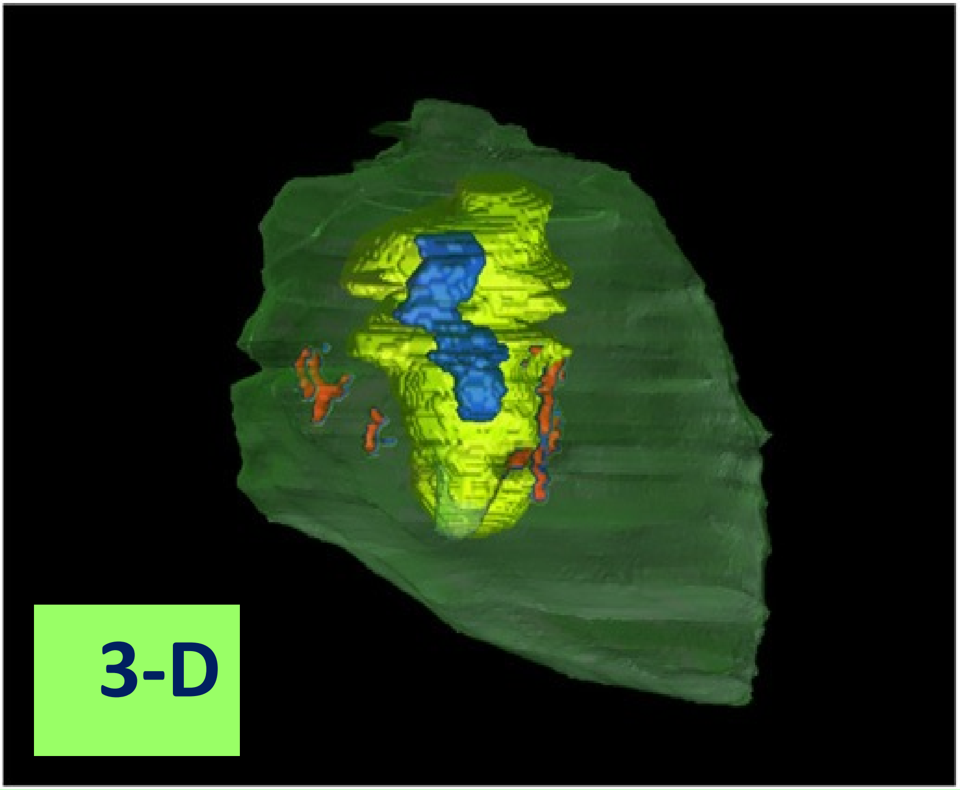


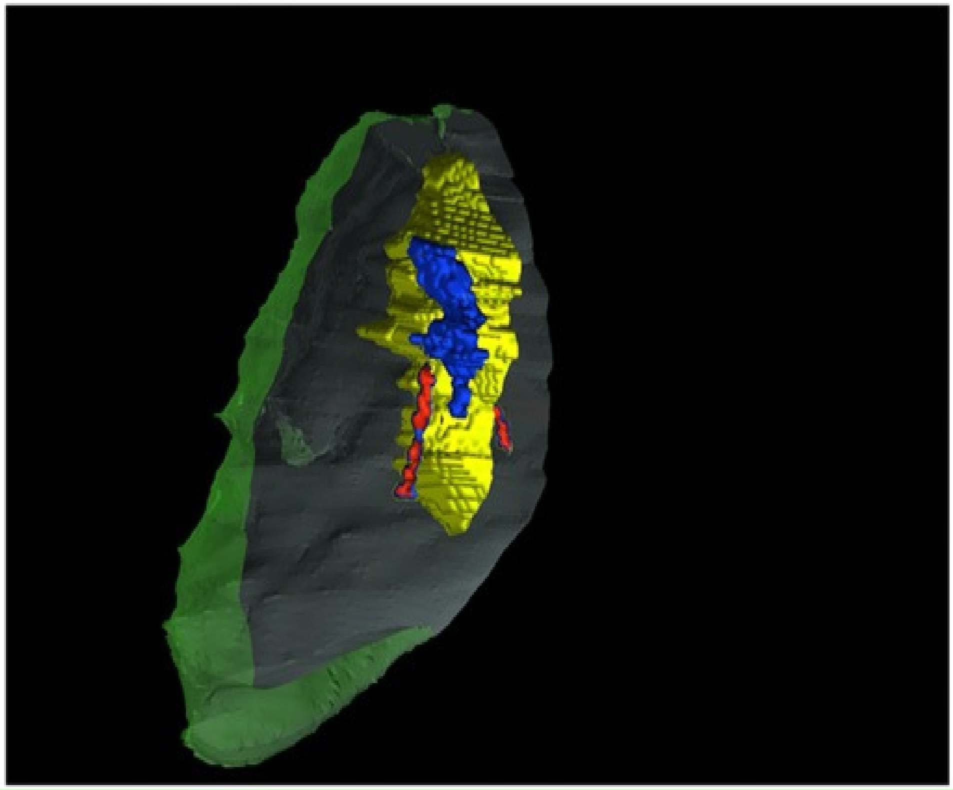
Requirement for x-ray optics in medical imaging

	FOV	Spatial resolution in 2D	Detector pixel number
Clinical	25cm x 25cm > 10cm x 10cm	25μm < 100μm	100,000,000 > 10,000,000
Pathological	2.5cm(H) x 2.5cm(V)	1μm < 2~3μm < 7.4μm (Photonics Science)	625,000,000 100,000,000 34,000,000

Thank you very much for the kind attention !

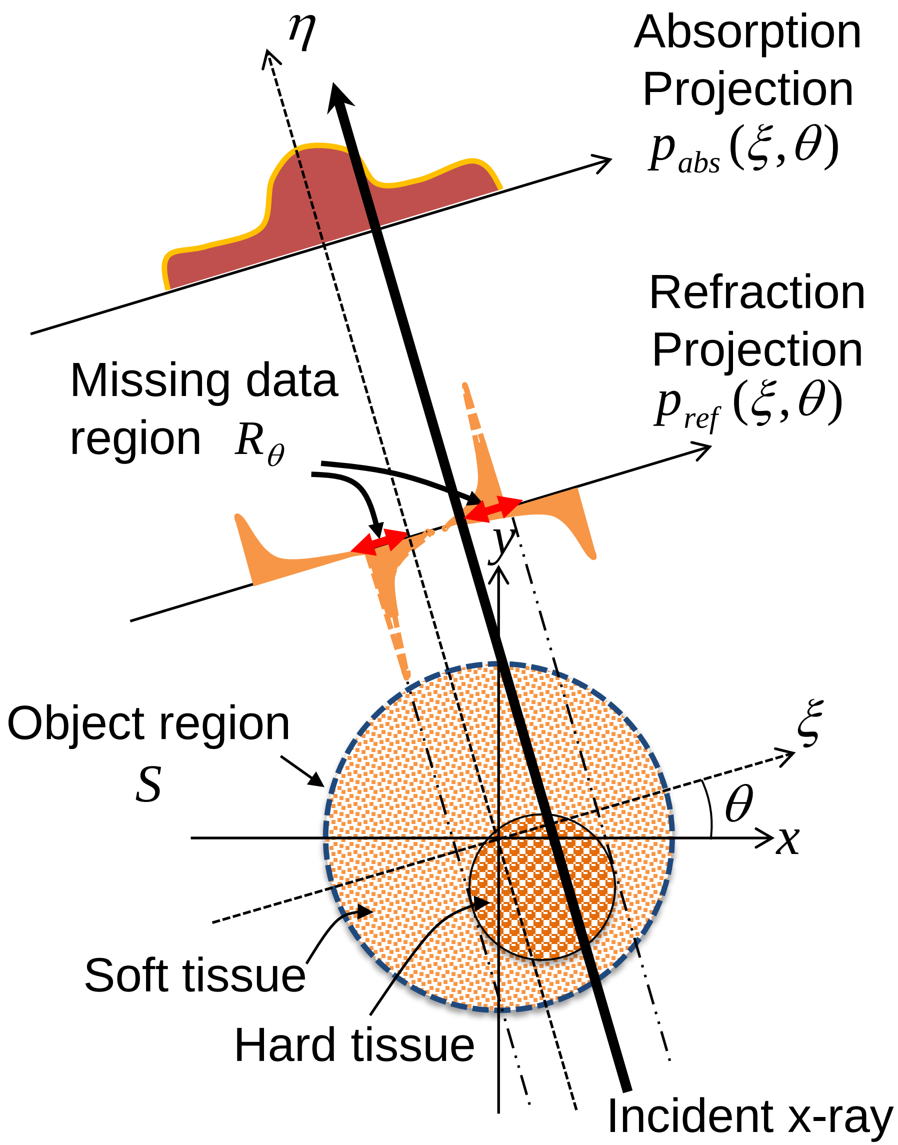
Looking very much forward to more collaboration





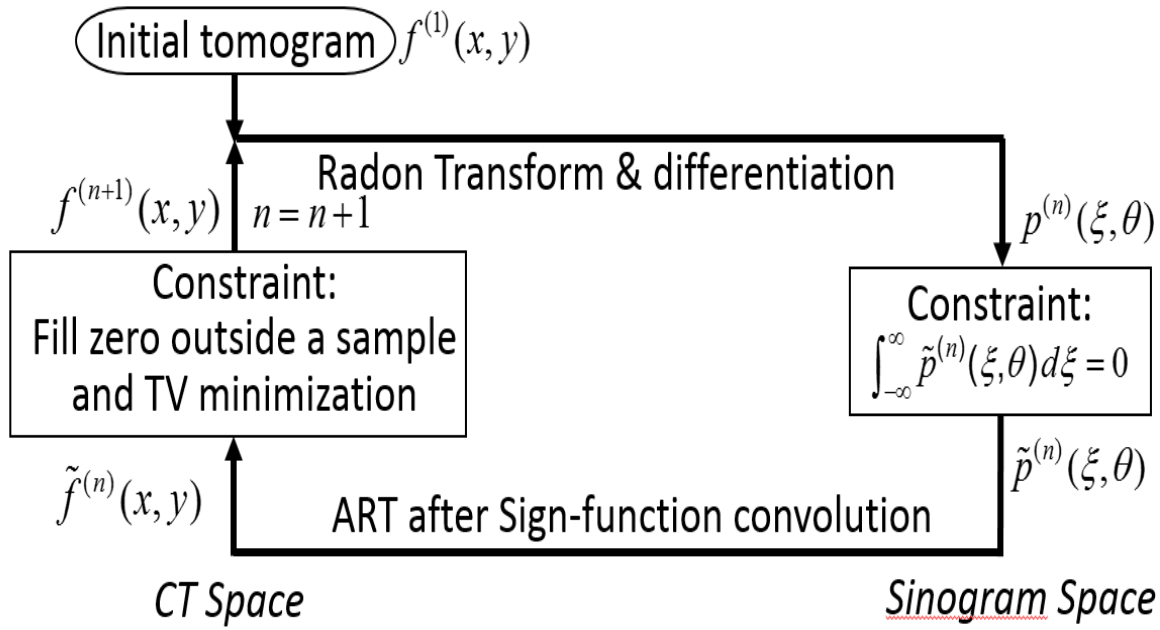
rat brain model with skull removed: DEI-CT view delineates, edema (green), viable tumor (yellow), necrosis (blue) and MVP (red) were visualized.

S.-J. Seo, N. Sunaguchi, M. Ando, K.-H. Choi, H. Kim, W.-S. Chang, K.-H. Kim, J.-K. Kim, PMB **57** (2012) 1251-1262.

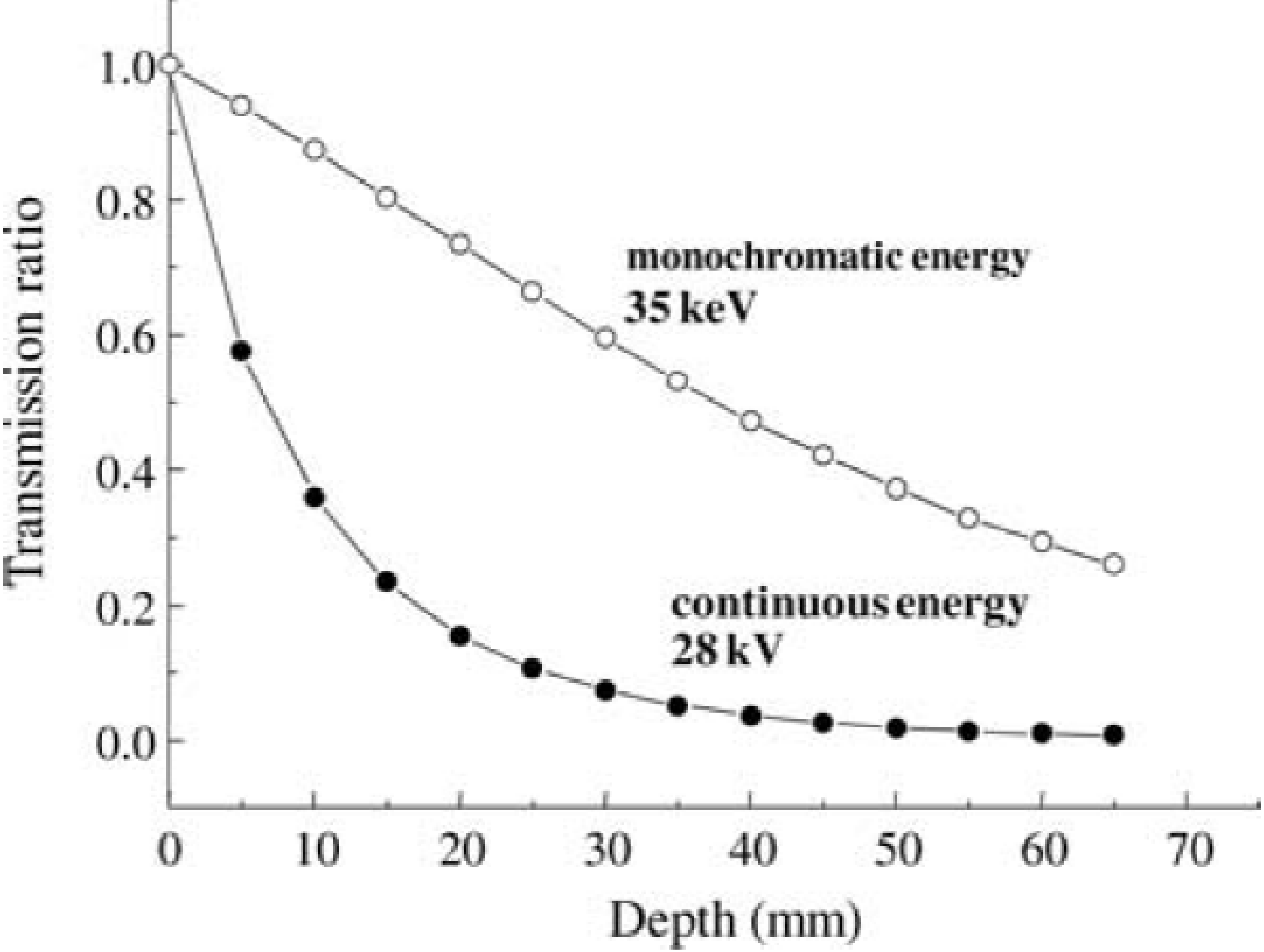


η
Absorption
Projection
$p_{abs}(\xi,\theta)$
Refraction
Projection
$p_{ref}(\xi,\theta)$
Missing data
region R_θ
y
Object region
S
ξ
θ
x
Soft tissue
Hard tissue
Incident x-ray

Fig. 4

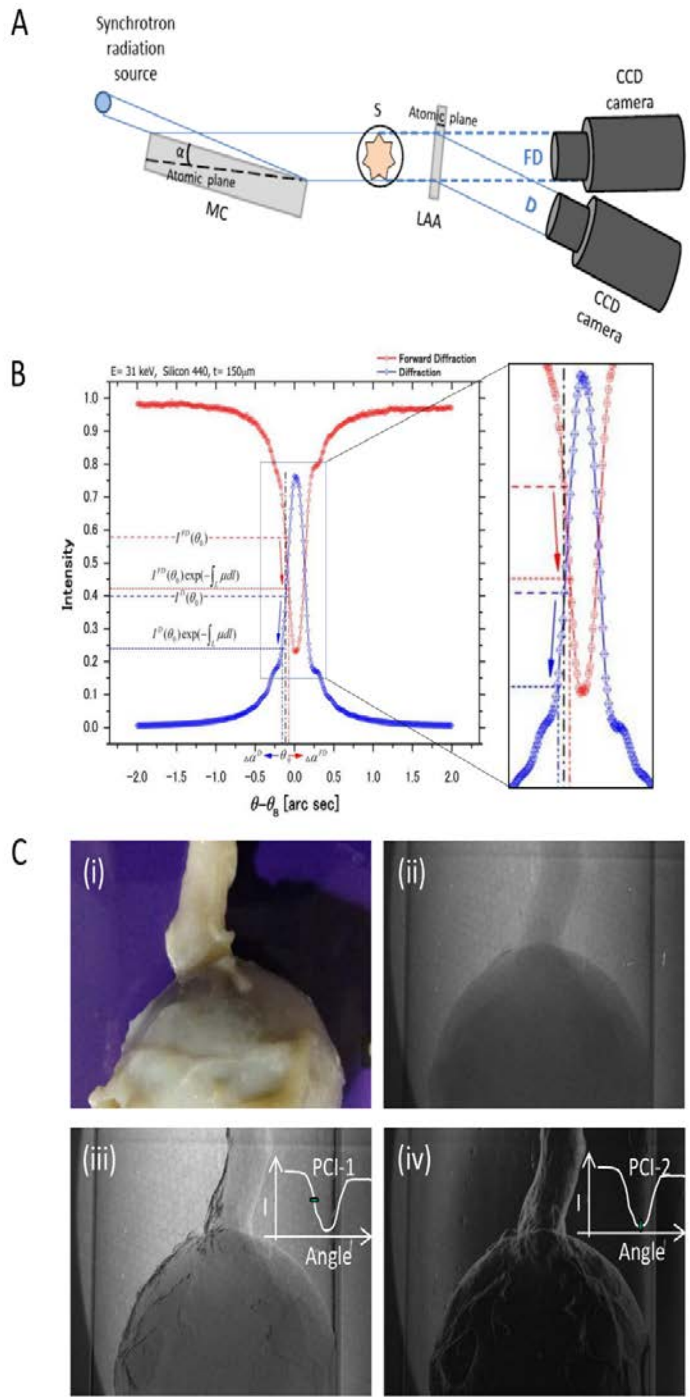


Initial tomogram
$f^{(1)}(x,y)$
Radon Transform & differentiation
$f^{(n+1)}(x,y)$
$n=n+1$
$p^{(n)}(\xi,\theta)$
Constraint:
Fill zero outside a sample
and TV minimization
Constraint:
$\int_{-\infty}^{\infty}\tilde{p}^{(n)}(\xi,\theta)d\xi=0$
$\tilde{p}^{(n)}(\xi,\theta)$
$\tilde{f}^{(n)}(x,y)$
ART after Sign-function convolution
CT Space
Sinogram Space

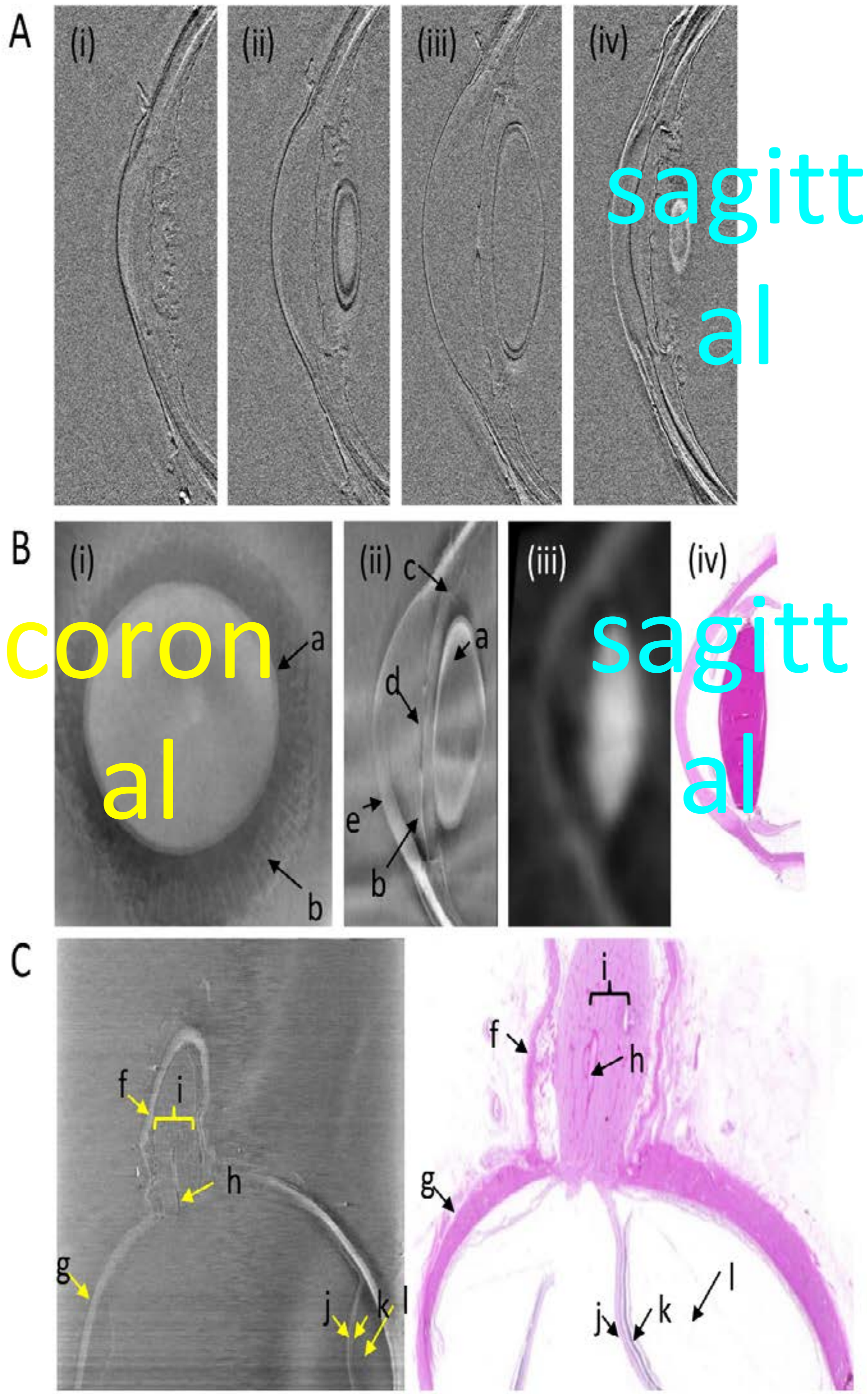


H. Sato, M. Ando, D. Shimao

Radiation Protection Dosimetry 145 (2011) 1-3.



- Experimental system and rocking curve for the Laue-case angle analyser. (A) Experimental system. MC: Bragg-type monochromator-collimator; LAA: Laue-case angle analyser. (B) Rocking curve for the 150-μm-thick LAA used in this study; the arrows show the displacement of operating points on the dark and bright field images due to tissue absorption. (C) Projection images of an eye specimen showing the posterior globe and optic nerve insertion: (i) photographic image, (ii) diffraction or bright field image, (iii and iv) forward diffraction or dark field images obtained at two



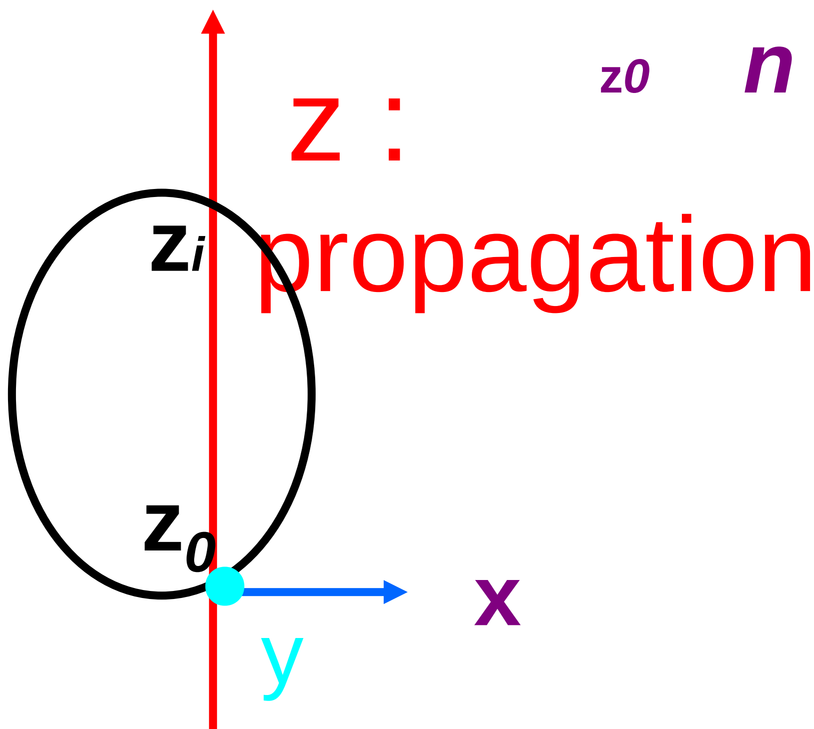
•Anterior and posterior chambers of an eyeball imaged with XDFI. (A) Tomographic slices (sagittal plane) of the differential phase map of an anterior chamber ((i)-(iv)). (B) Refractive index images in the coronal (i) and sagittal (ii) planes, a matched absorption image from conventional MDCT (iii), and a histological H&E slide showing this specimen (iv); the difference in the imaging and histological appearance are due to tissue retraction during histological processing and sample preparation. (C) Globe and optic nerve insertion of the same specimen. a: lens; b: iris muscle; c: ciliary body; d. pupil; e. cornea; f. optic nerve sheath; g. sclera; h. central retinal artery; i.

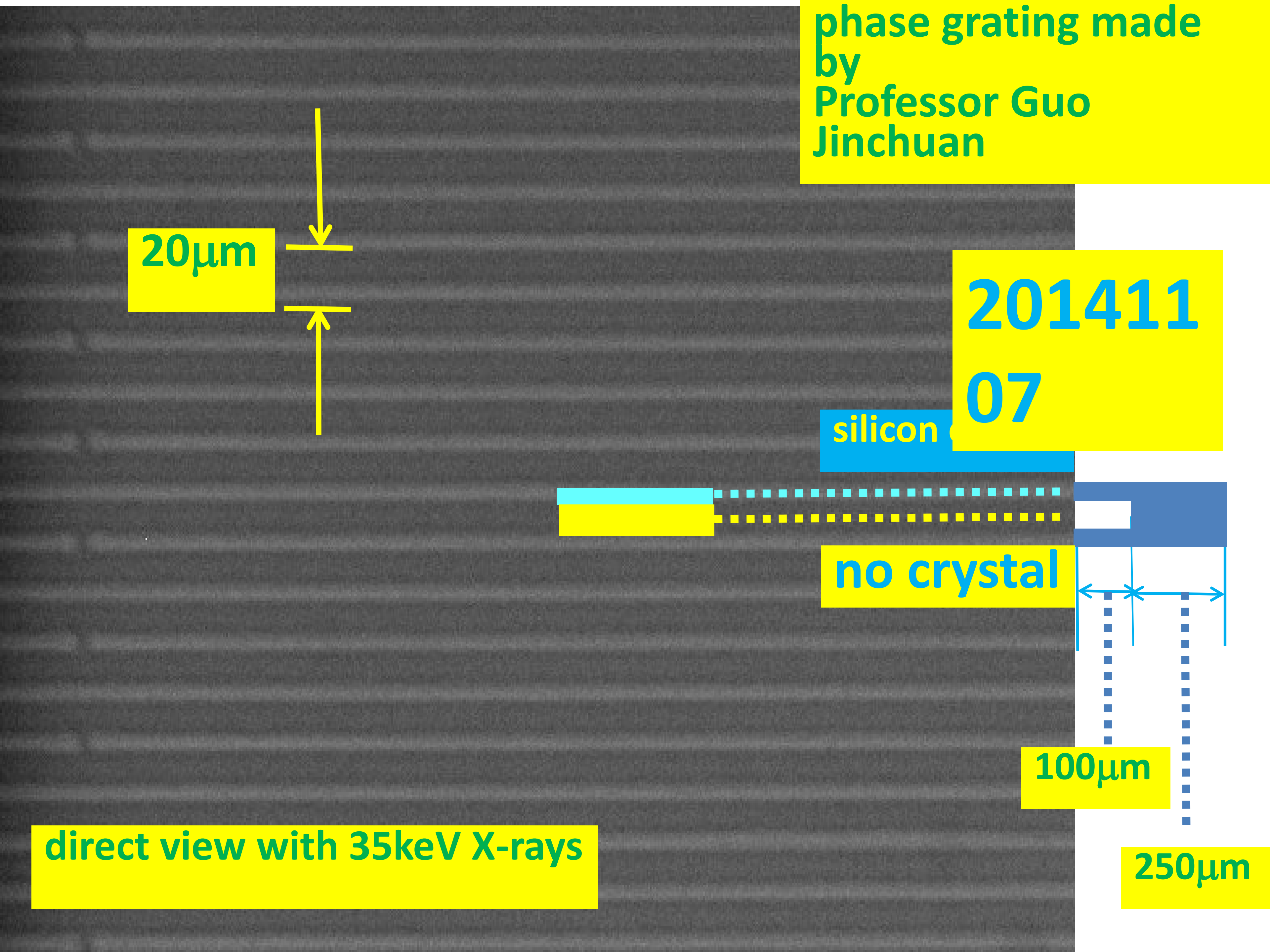
refraction angle: α

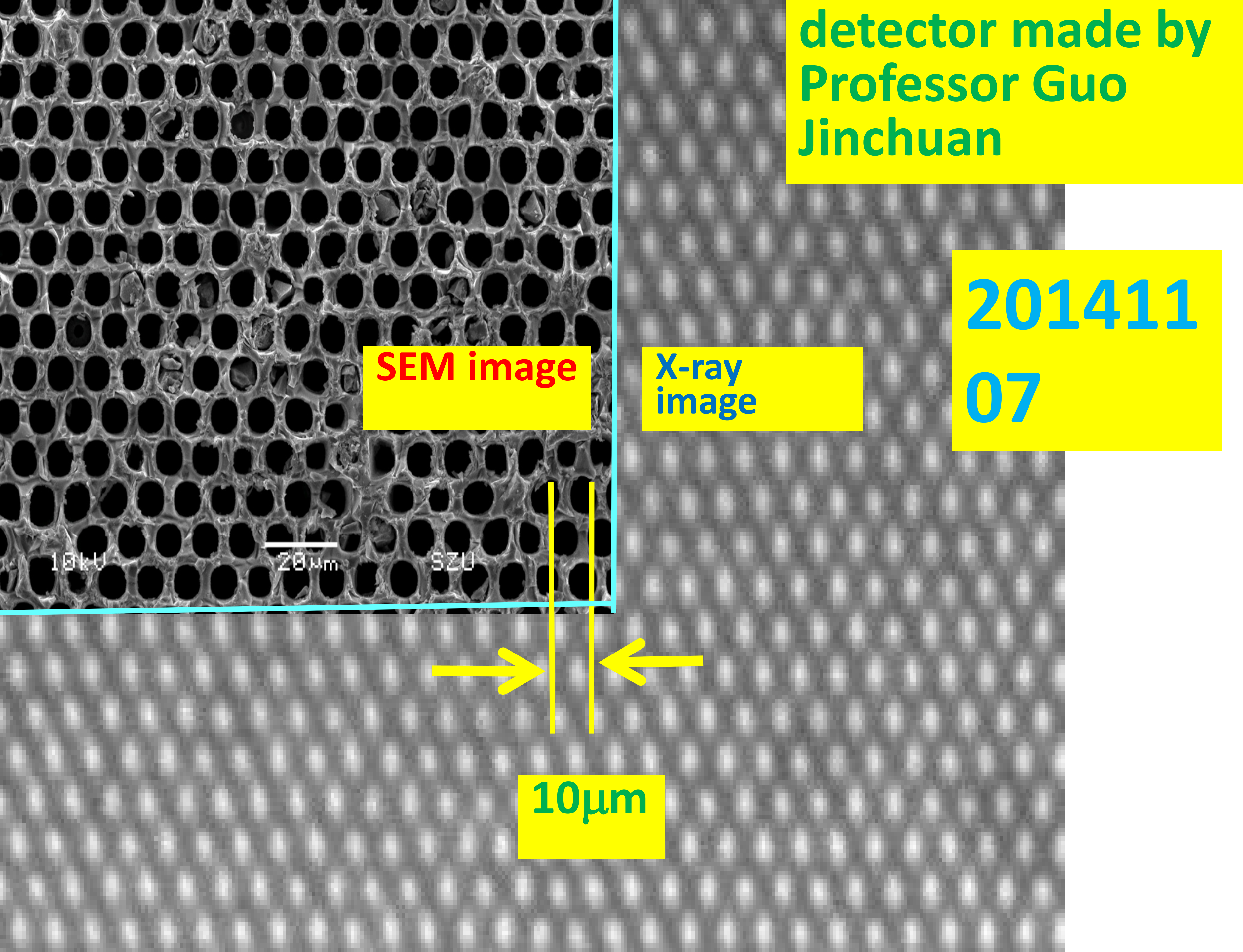
$$\alpha = r_e h^2 c^2 / E^2 \, 2\pi \int_{z_0}^{z_i} \partial n(\mathbf{r}) / \partial x \, dz$$

$$n = 1 - \delta$$

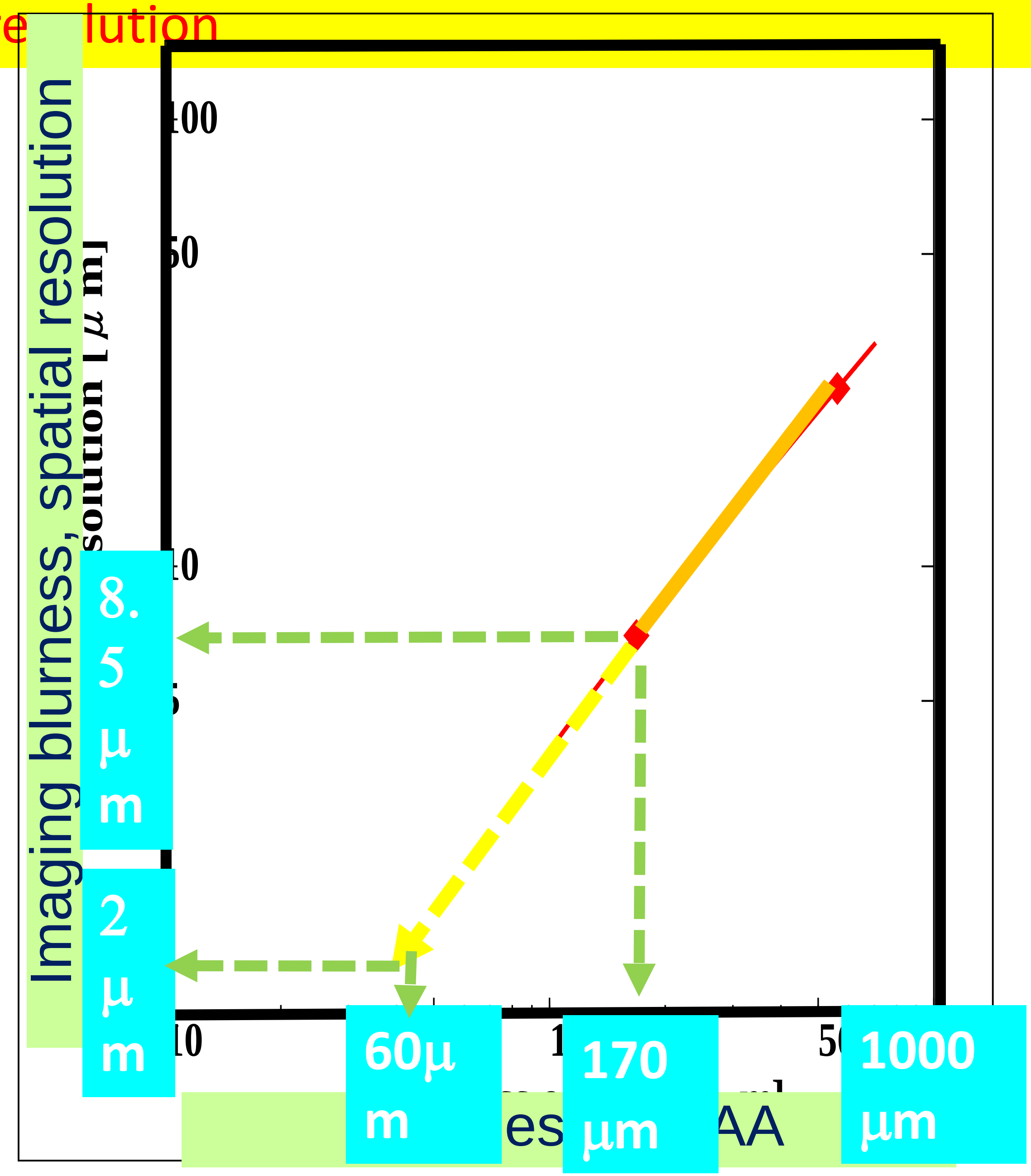
object




phase grating made by
Professor Guo Jinchuan
20μm
201411
07
silicon
no crystal
100μm
250μm
direct view with 35keV X-rays


detector made by Professor Guo Jinchuan
201411
07
SEM image
X-ray image
10kV
20μm
SZU
10μm

LAA thickness and spatial resolution

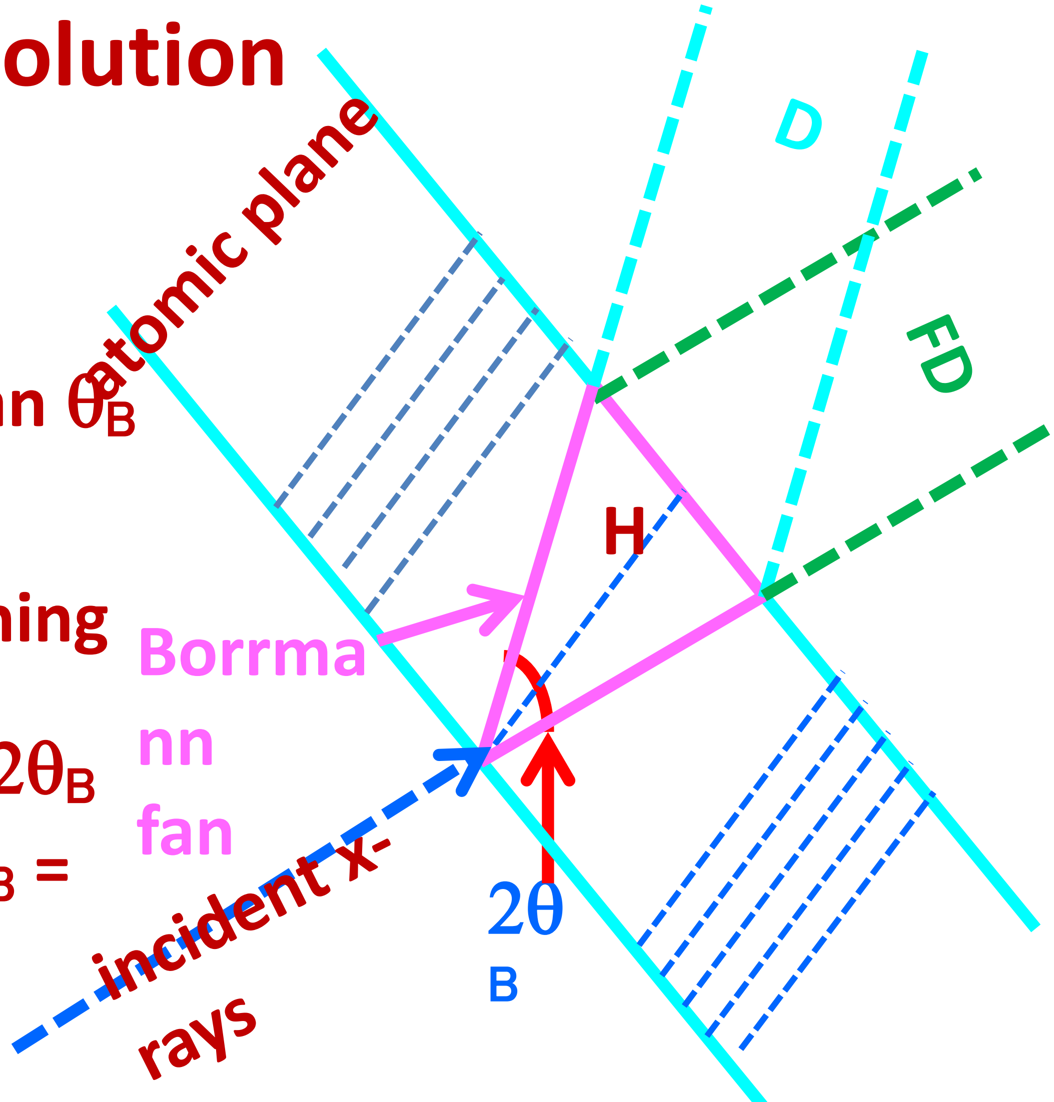


towards micrometer spatial resolution

$\delta = 2H\tan\theta_B$

(i) thinning H

(ii) less $2\theta_B$ by $\sin\theta_B = 1/dE$



approaching to 2-3μm spatial resolution

Towards future

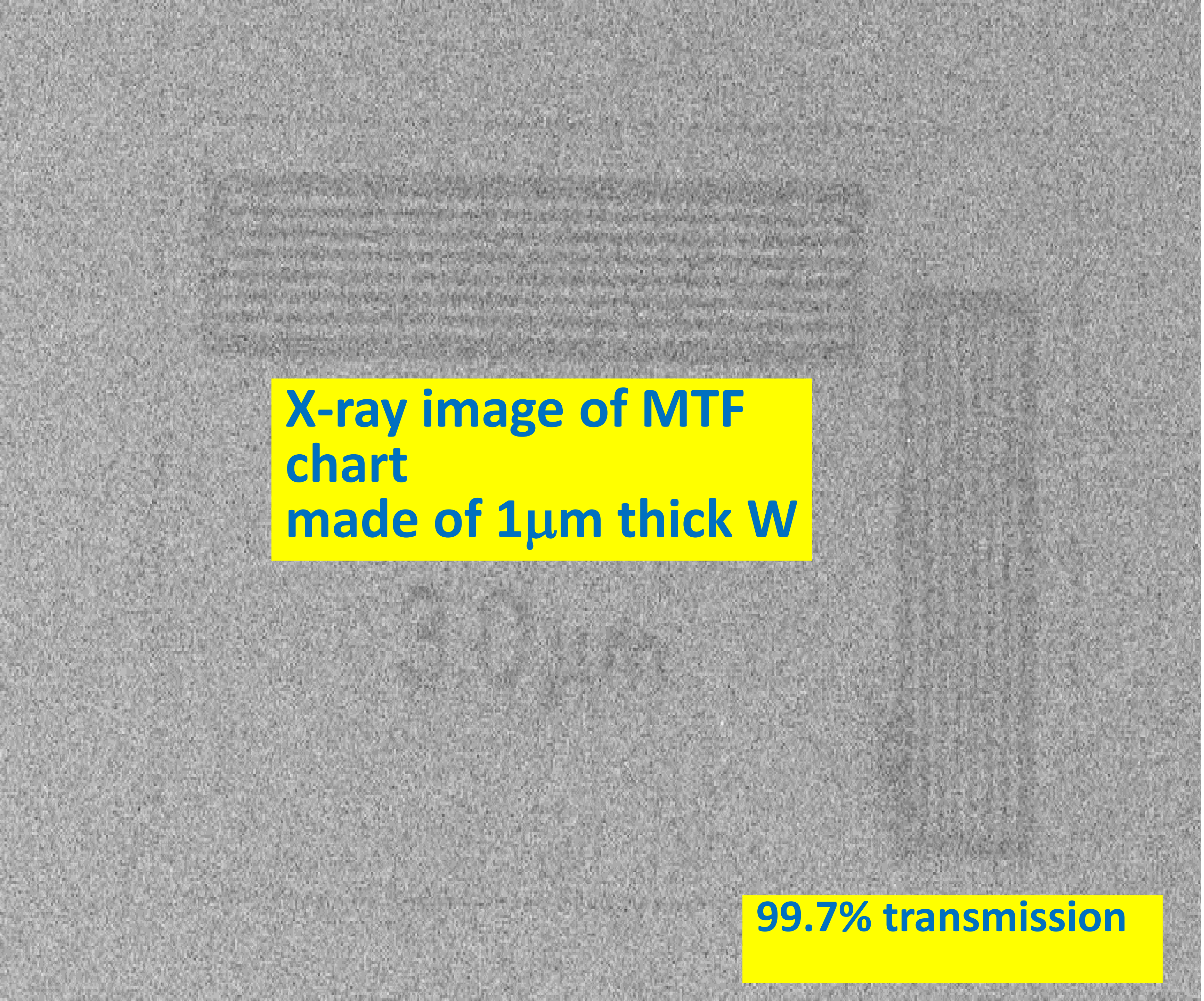
Needing development

(b)pathology：high resolution 3D像

(c)clinical：large FOV

Thank you for listening

measurement of spatial resolution without x-ray optics in a hutch BL6C **20141112**


X-ray image of MTF chart
made of 1μm thick W
99.7% transmission

vertical polarization at BL14 by 5T horizontal magnetic field at Photon Factory

To: in Korea

Pohang Accelerator Laboratory

VACTRON Co., Ltd.

In relation to Leading Industry Development for Economic Region Program by the Ministry of Trade, Industry & Energy (MOTIE),

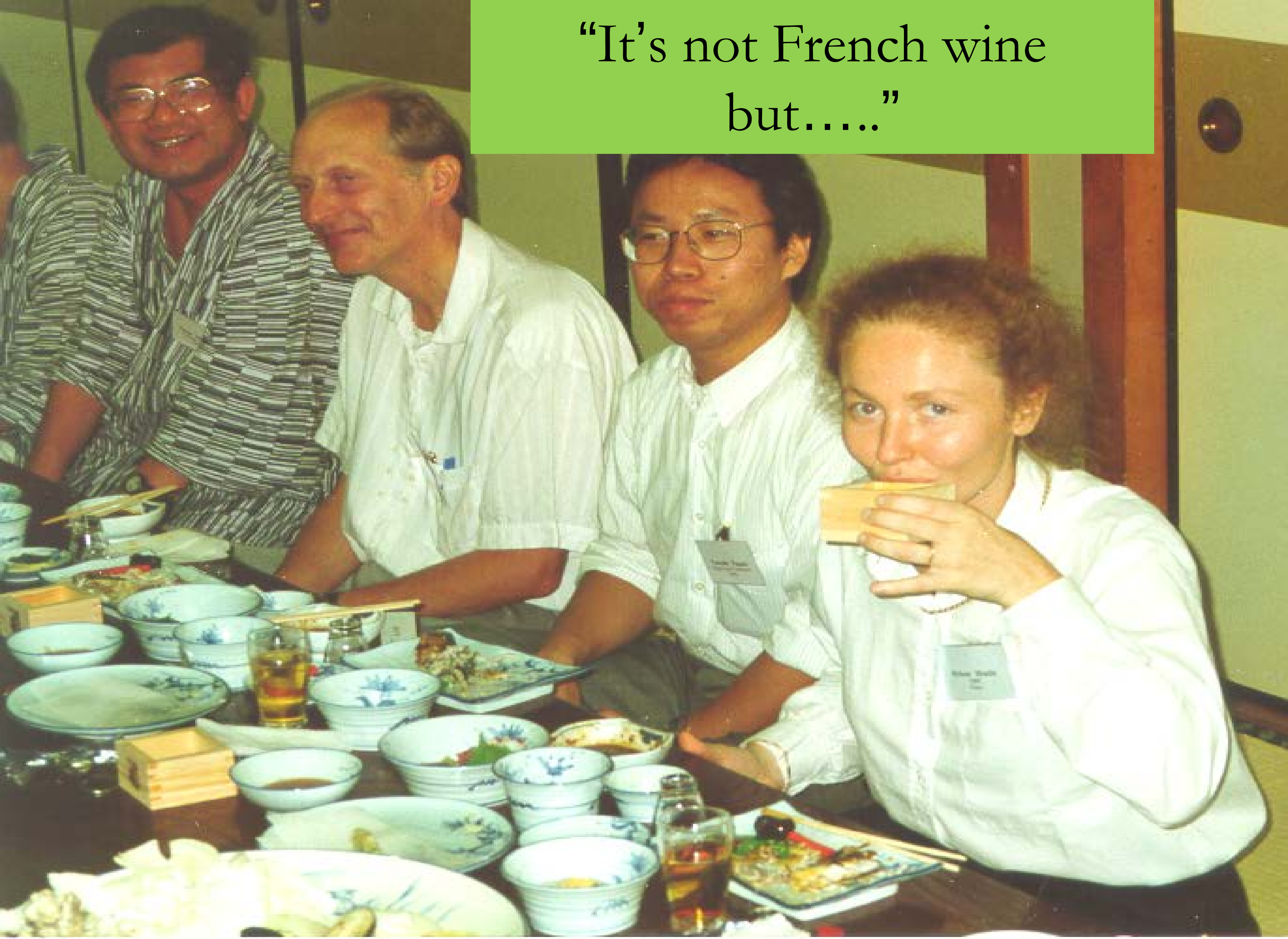
Korea Institute for Advancement of Technology (KIAT)

Daegyeong Institute for Regional Program Evaluation (DGIRPE)

To: in Japan

MEXT (Ministry of Education, Culture and

"It's not French wine but….."



Haga in 1997

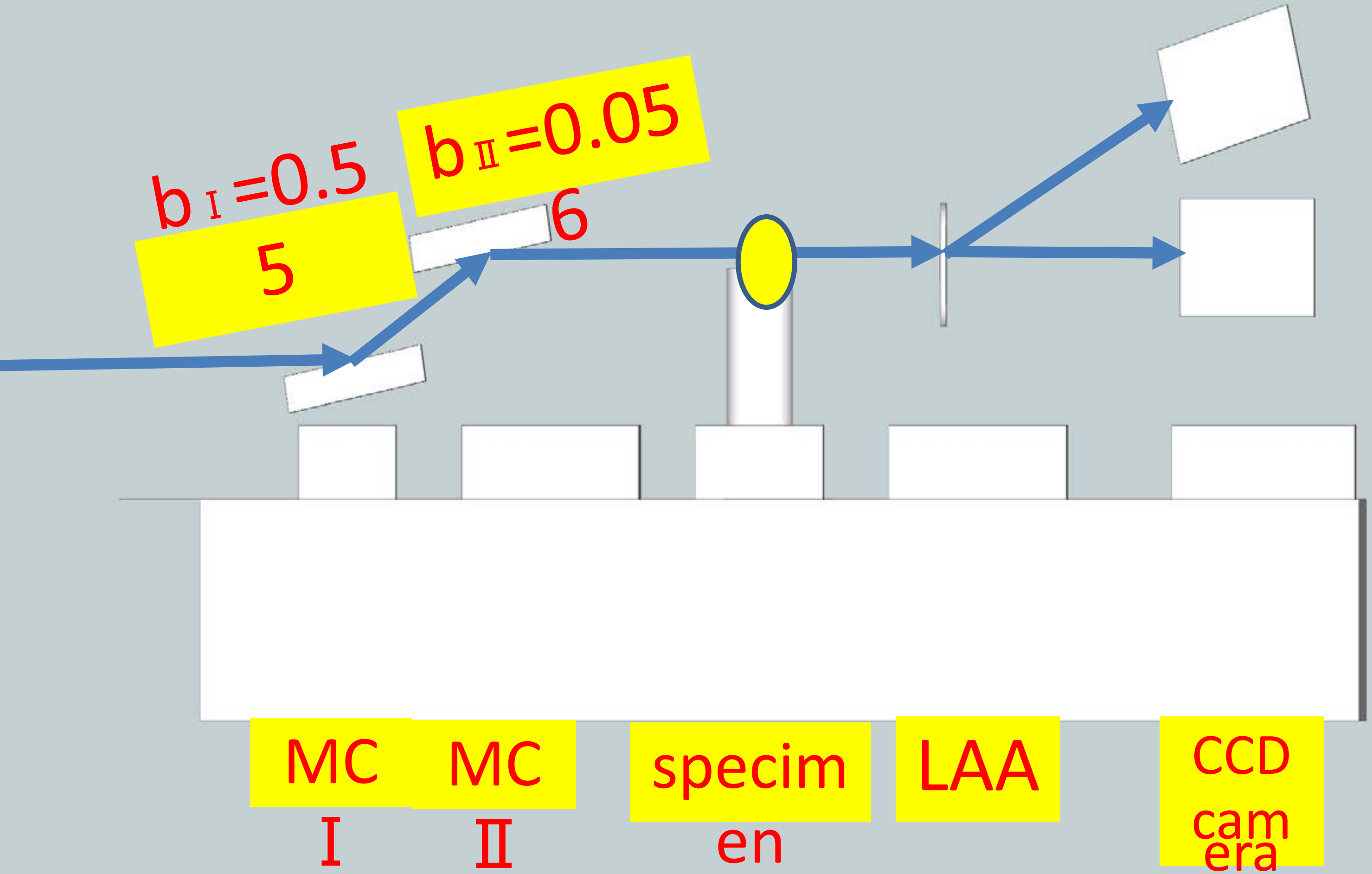
HAGA '97

Morning Work

Afternoon Work

Evening Work

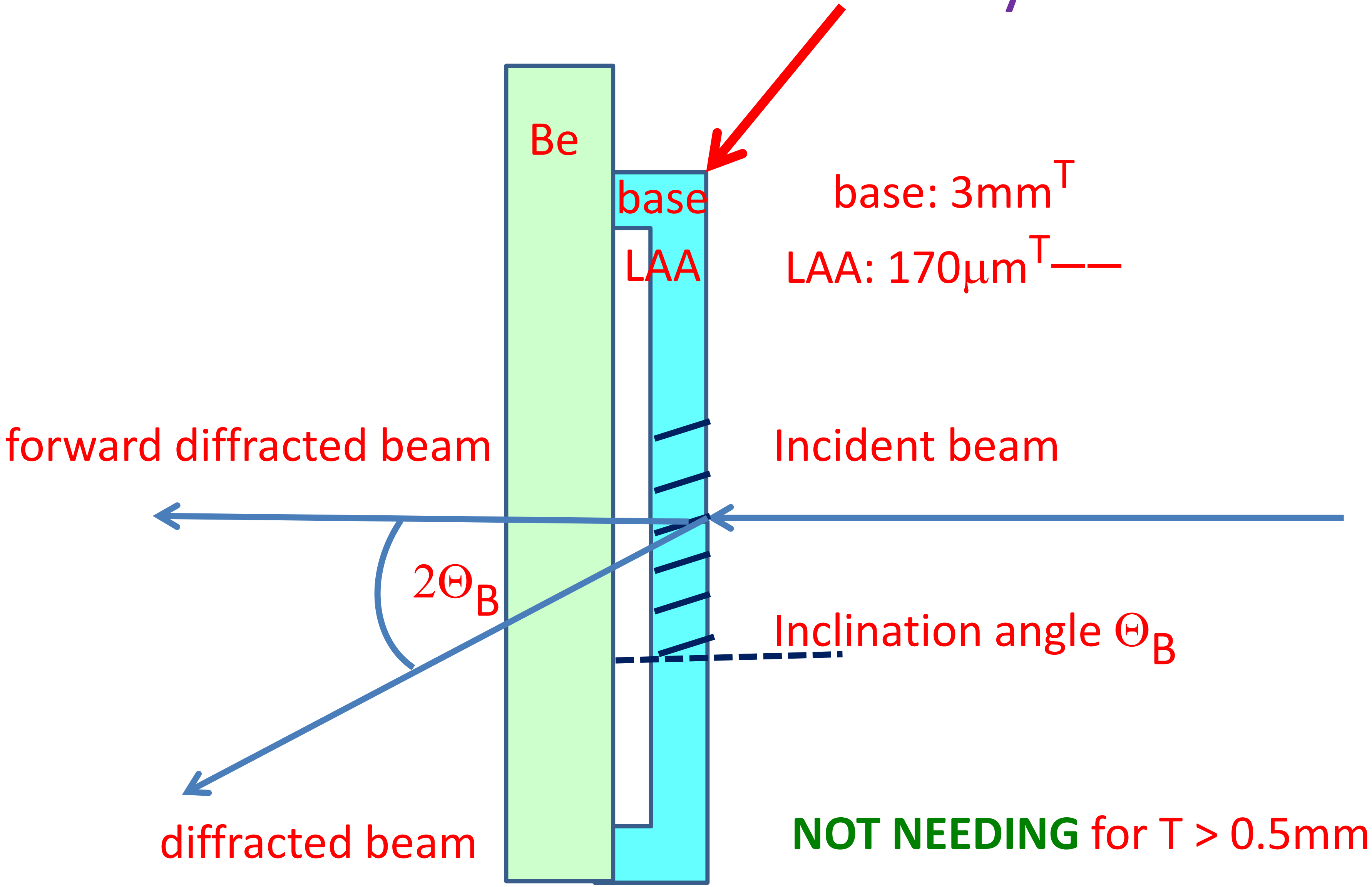
Monochromator-collimator in an experimental hutch



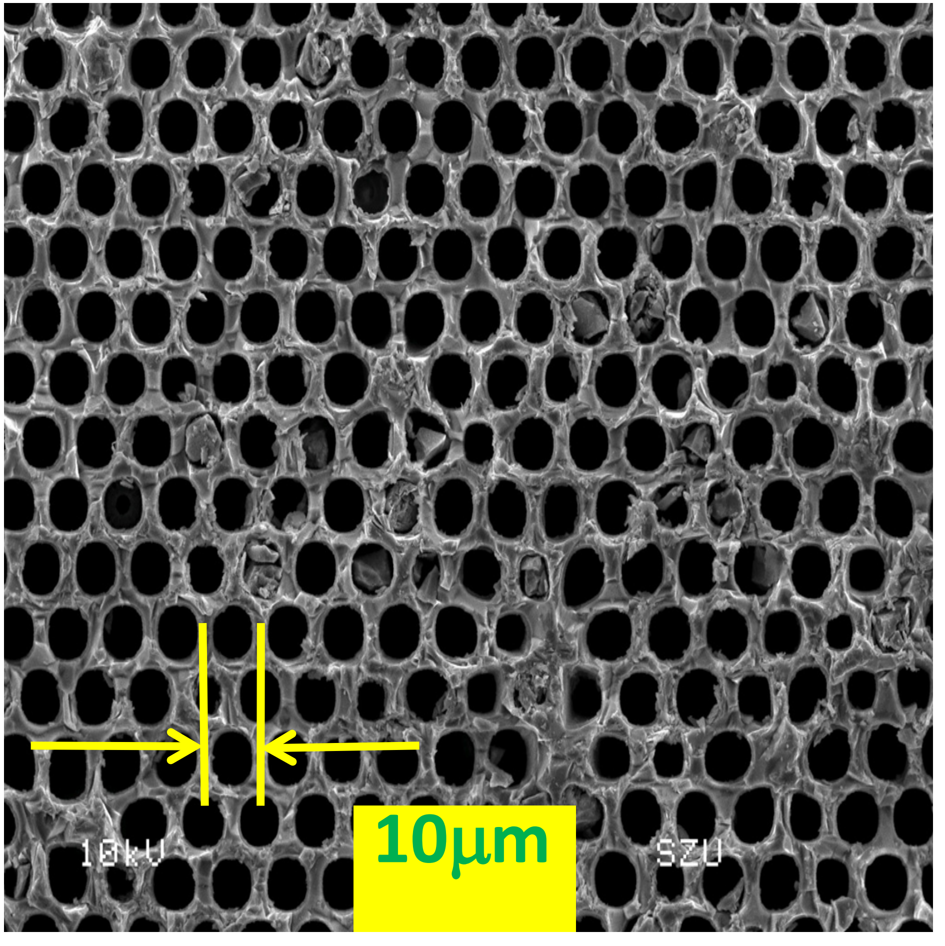
side
view

Designed by Dr.

Asymmetric LAA that stands vertically



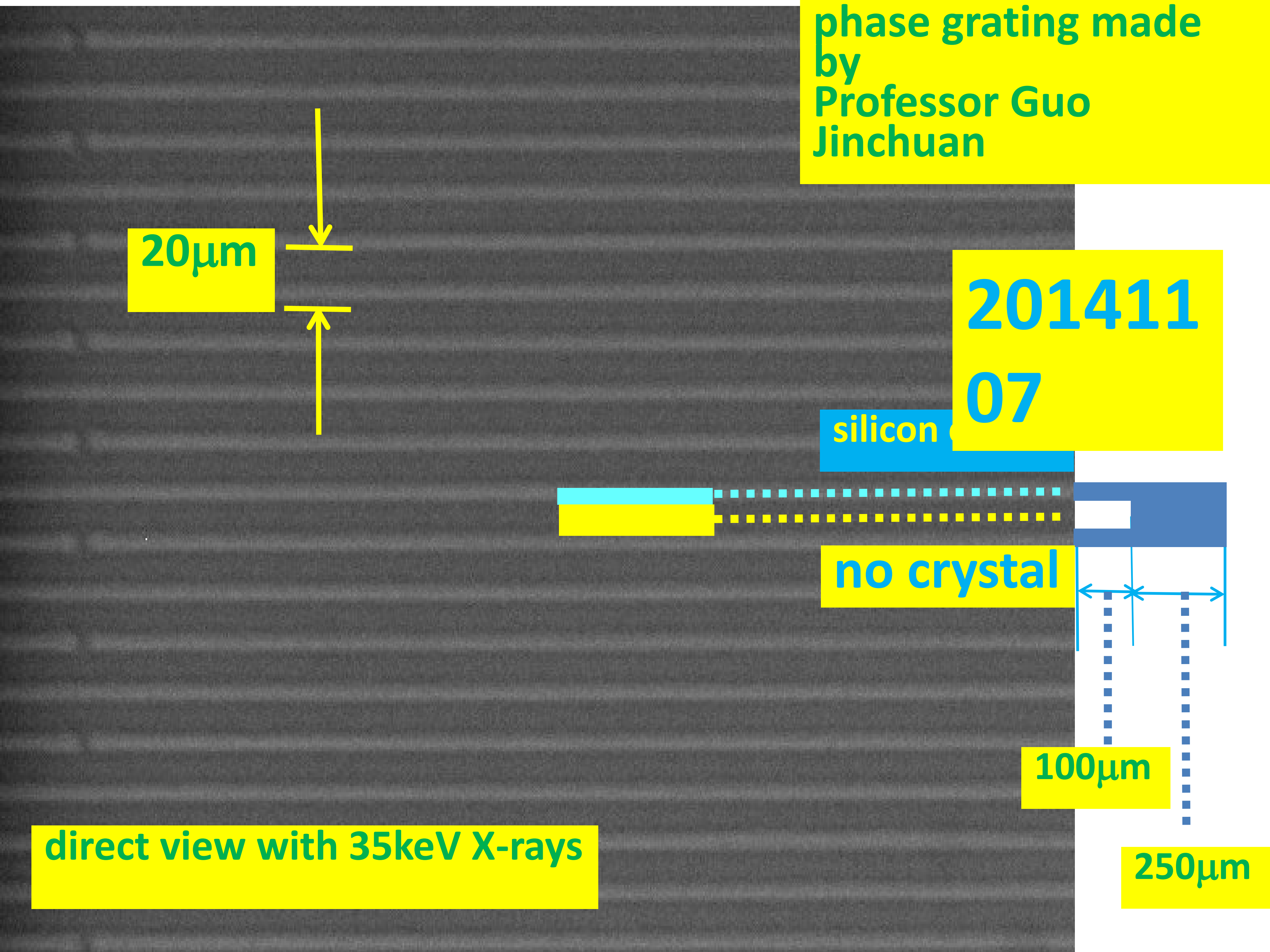
detector made by Professor Guo Jinchuan



Daigo in 1992

DAIGO '92

Mrs. Rubenstein serenading Ed!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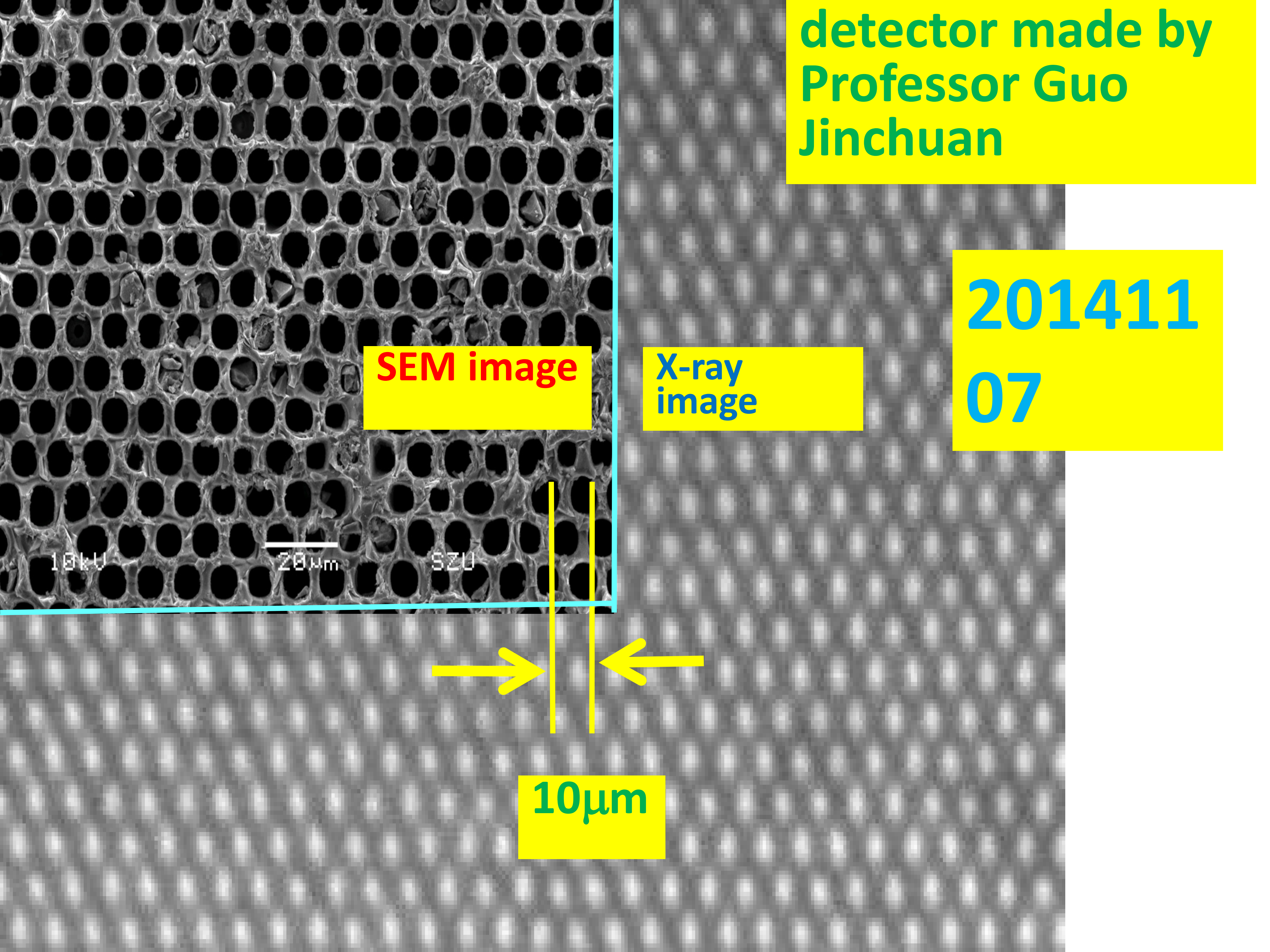
detector made by Professor Guo Jinchuan
201411 07
SEM image
X-ray image
10kV
20µm
SZU
10µm

towards micrometer spatial resolution

$\delta = 2H\tan\theta_B$

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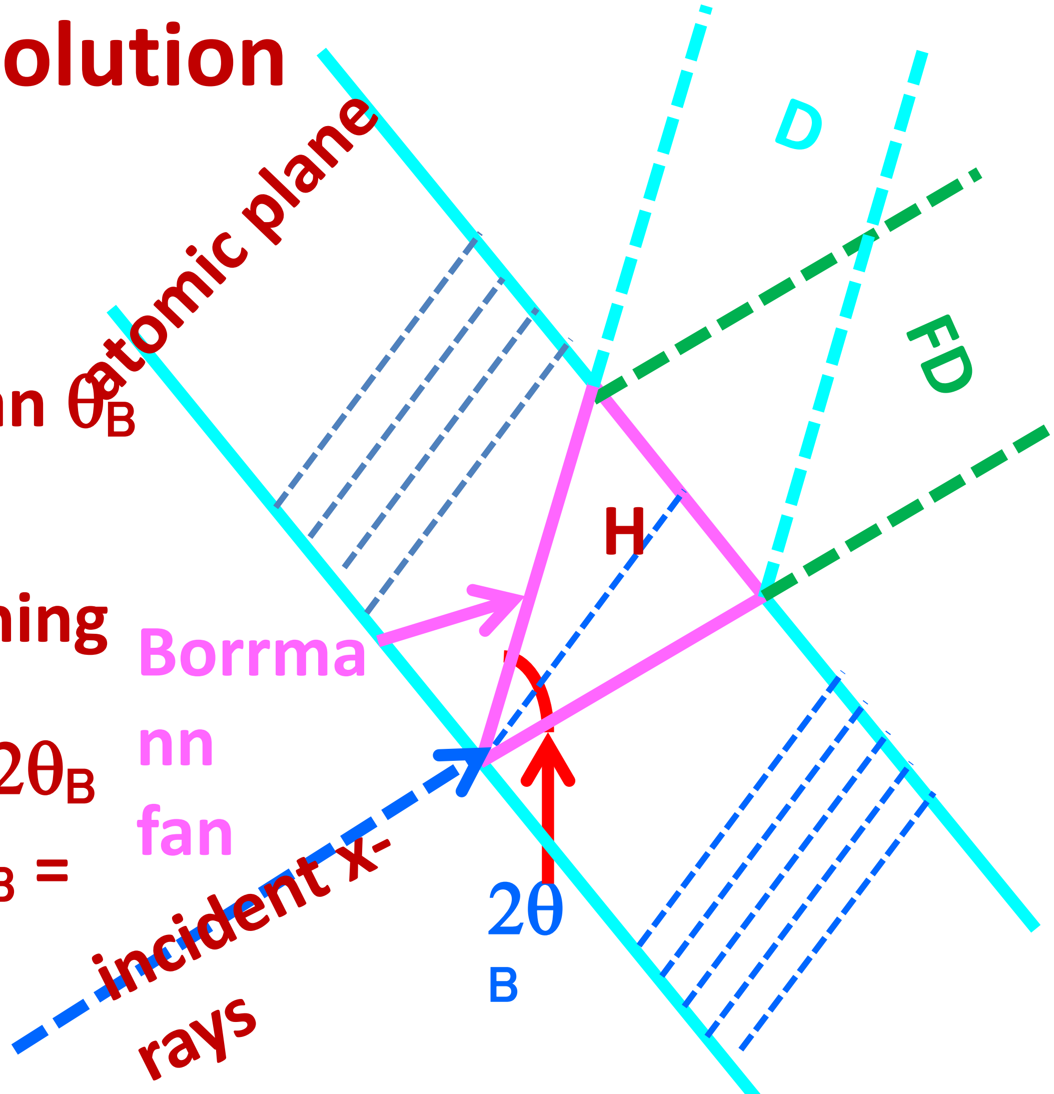
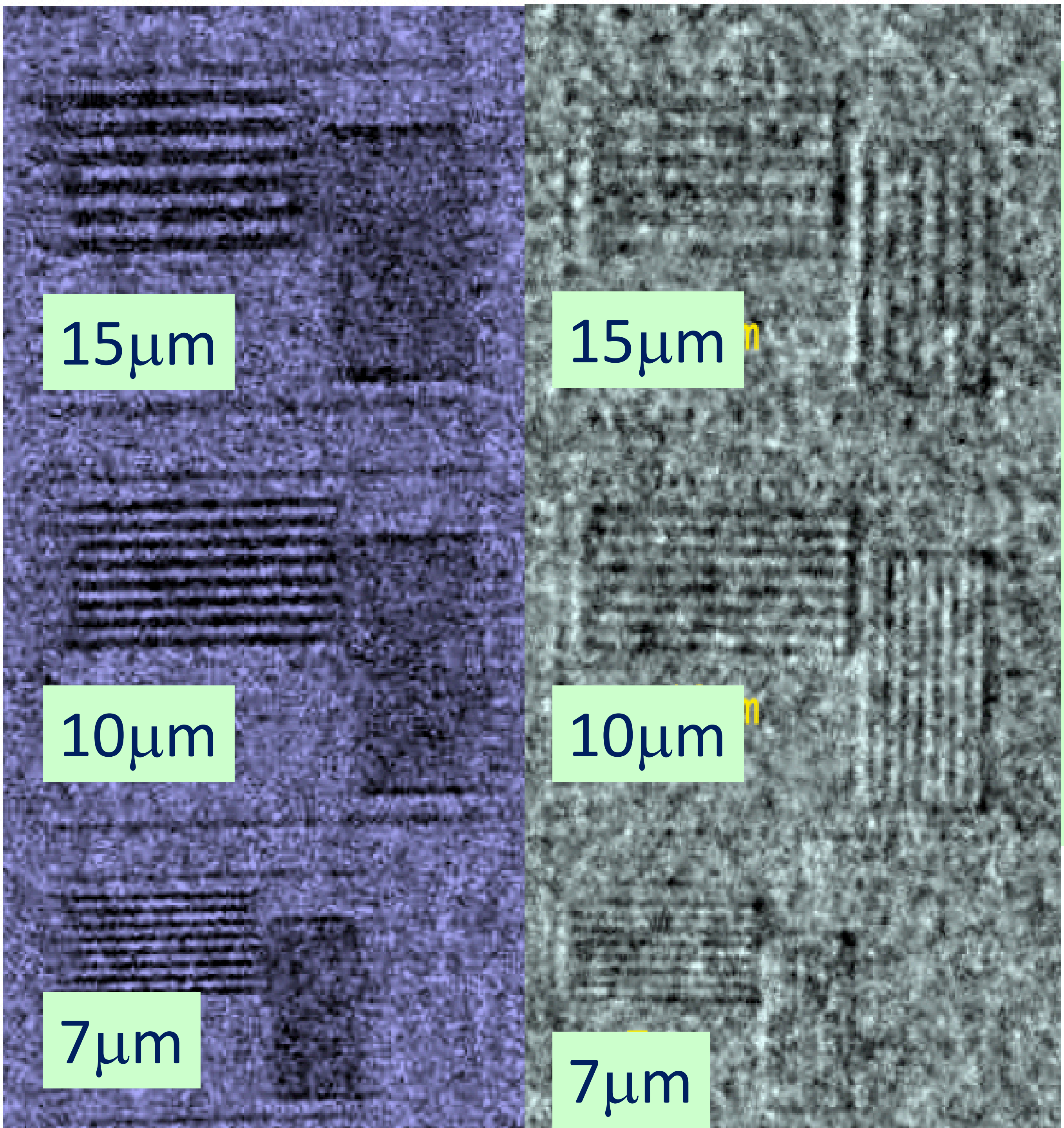


approaching to 2-3μm spatial resolution



JIMA RC-02B

1μm^T W

left:

without MC

right:

with MC

31keV

150μm

thank

- Organizing committee, Professor Kulipanov,
  Old friends

- Special thanks to Professor Vazina

- Today