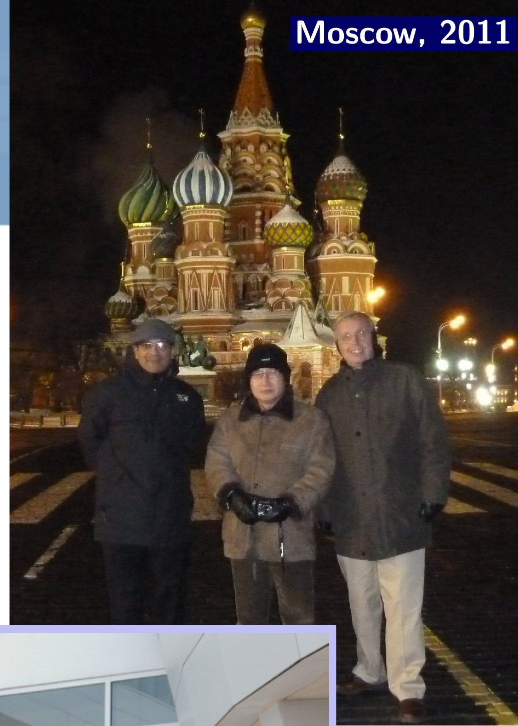
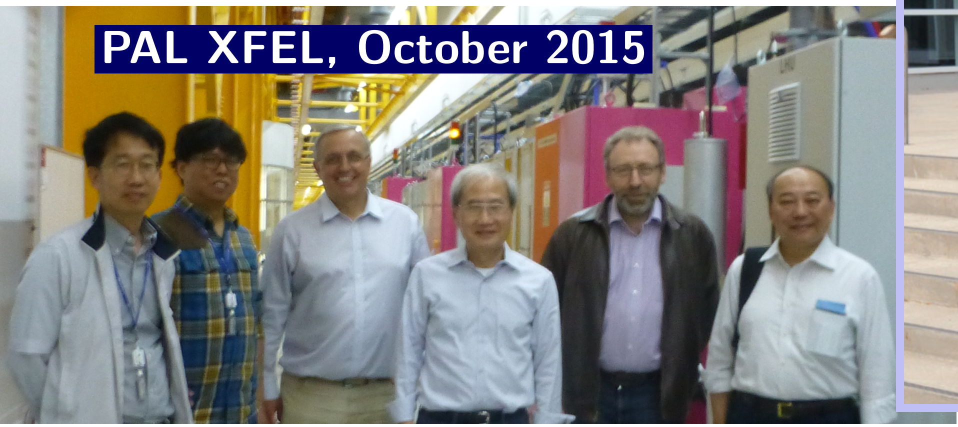
XFELO tunable cavities

Yuri Shvyd'ko



Moscow, 2011

Science Opportunities with an XFELO Workshop, APS, May 5th, 2010



PAL XFEL, October 2015

Celebrating Kwang-Je's distinguished career in science.

Coherence in particle and photon beams: Past, Present, and Future
March 15, 2019, APS

When this has started?

backscattering x-ray optics mailbox:///home/oxygen13/SHVYDKO/mail/Kim

Subject: backscattering x-ray optics
From: Kwang-Je Kim <kwangje@aps.anl.gov>
Date: 4/24/07, 3:38 PM
To: shvydko@aps.anl.gov
CC: "shastri@aps.anl.gov" <shastri@aps.anl.gov>, Anita Alamillo <alamillo@aps.anl.gov>

Hi Yuri,

There might be an exciting opportunity to raelize an x-ray FEL oscillator with much higher spectral brightness than from the SASE device under construction at SLAC. Critical for this is an x-ray optical cavity with a round trip loss less than, say 5%. Sarvjit started to do some calculation but he says that you are an expert on this topic. Can we meet to discuss this? When would be a convenient time for you?

I am available the rest of today and tomorrow anytime between 10 AM and 3 PM.

Kwang-Je

First XFELO APS seminar

date/time change - ASD/XSD Special Presentation: K.-J. Kim and Y. Shvydko, 7/27 10:00 a.m.

- *Subject*: date/time change - ASD/XSD Special Presentation: K.-J. Kim and Y. Shvydko, 7/27 10:00 a.m.
- *From*: Sara Hahn <hahn@aps.anl.gov>
- *Date*: Tue, 24 Jul 2007 09:40:06 -0500

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ASD/XSD Special Presentation

Name: Kwang-Je Kim and Yuri Shvydko

Title: "An X-Ray FEL Oscillator with ERL Beams."

Date Change: Friday, July 27, 2007

Time Change: 10:00 a.m.

Place: 401/A1100
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First XFELO APS seminar

date/time change - ASD/XSD Special Presentation: K.-J. Kim and Y. Shvydko, 7/27 10:00 a.m.

- *Subject*: date/time change - ASD/XSD Special Presentation: K.-J. Kim and Y. Shvydko, 7/27 10:00 a.m.
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Time Change: 10:00 a.m.

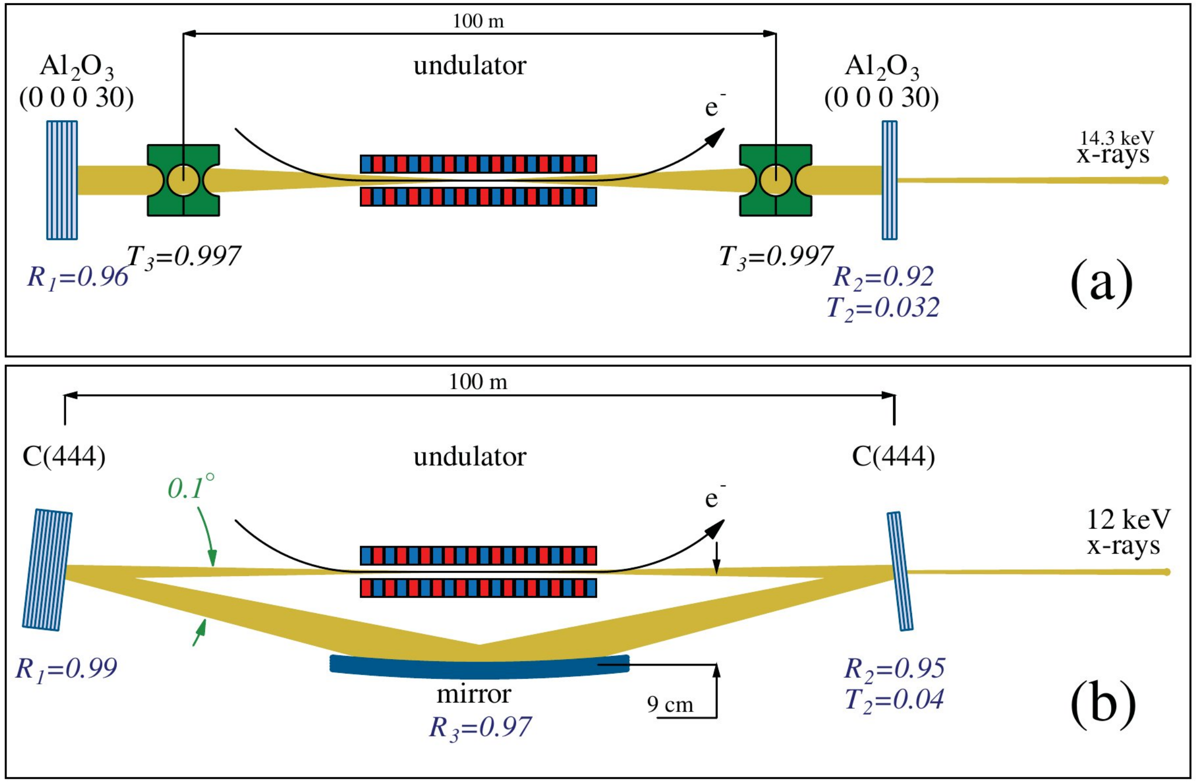
Place: 401/A1100

Kwang-Je approached me, regarding x-ray optics for the x-ray oscillator. I am very happy that he has initiated the discussion of this to my understanding very important project. Very many experiments, especially high-energy-resolution spectroscopies are suffering from the lack of photons and they need a special x-ray source with very high monochromaticity. At the beginning I was very sceptical, but we have started working and presently I am not so sceptical any more. This is what we can propose.

A Proposal for an X-Ray Free-Electron Laser Oscillator with an Energy-Recovery Linac

Kwang-Je Kim,[1] Yuri Shvyd'ko,[1] and Sven Reiche[2]
[1]Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, USA
[2]UCLA, Physics and Astronomy Department, Los Angeles, California 90095, USA
(Received 14 March 2008; published 17 June 2008)

We show that a free-electron laser oscillator generating x rays with wavelengths of about 1 Å is feasible using ultralow emittance electron beams of a multi-GeV energy-recovery linac, combined with a low-loss crystal cavity. The device will produce x-ray pulses with 10^9 photons at a repetition rate of 1–100 MHz. The pulses are temporarily and transversely coherent, with a rms bandwidth of about 2 meV, and rms pulse length of about 1 ps.



Tubale x-ray cavity

AAI-PUB-2008-004

A Tunable Optical Cavity for an X-Ray Free-Electron Laser Oscillator

Kwang-Je Kim

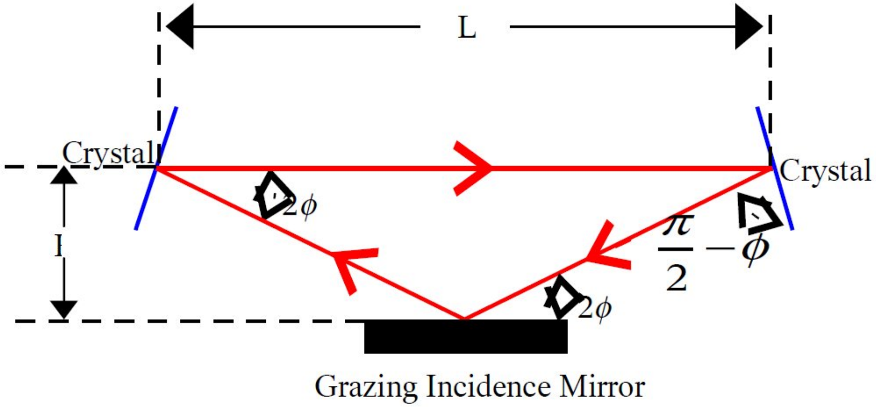


Fig. 1. An x-ray optical cavity configuration considered in Ref. [1]. This configuration
not practical for tuning as explained in the text.

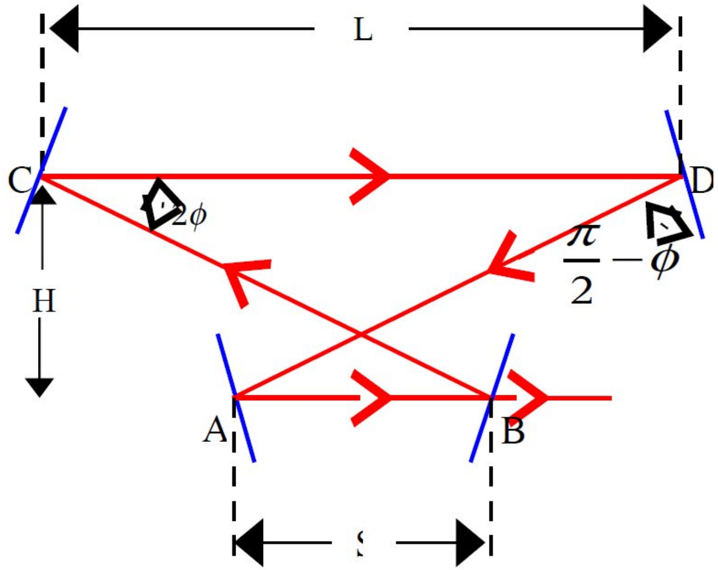
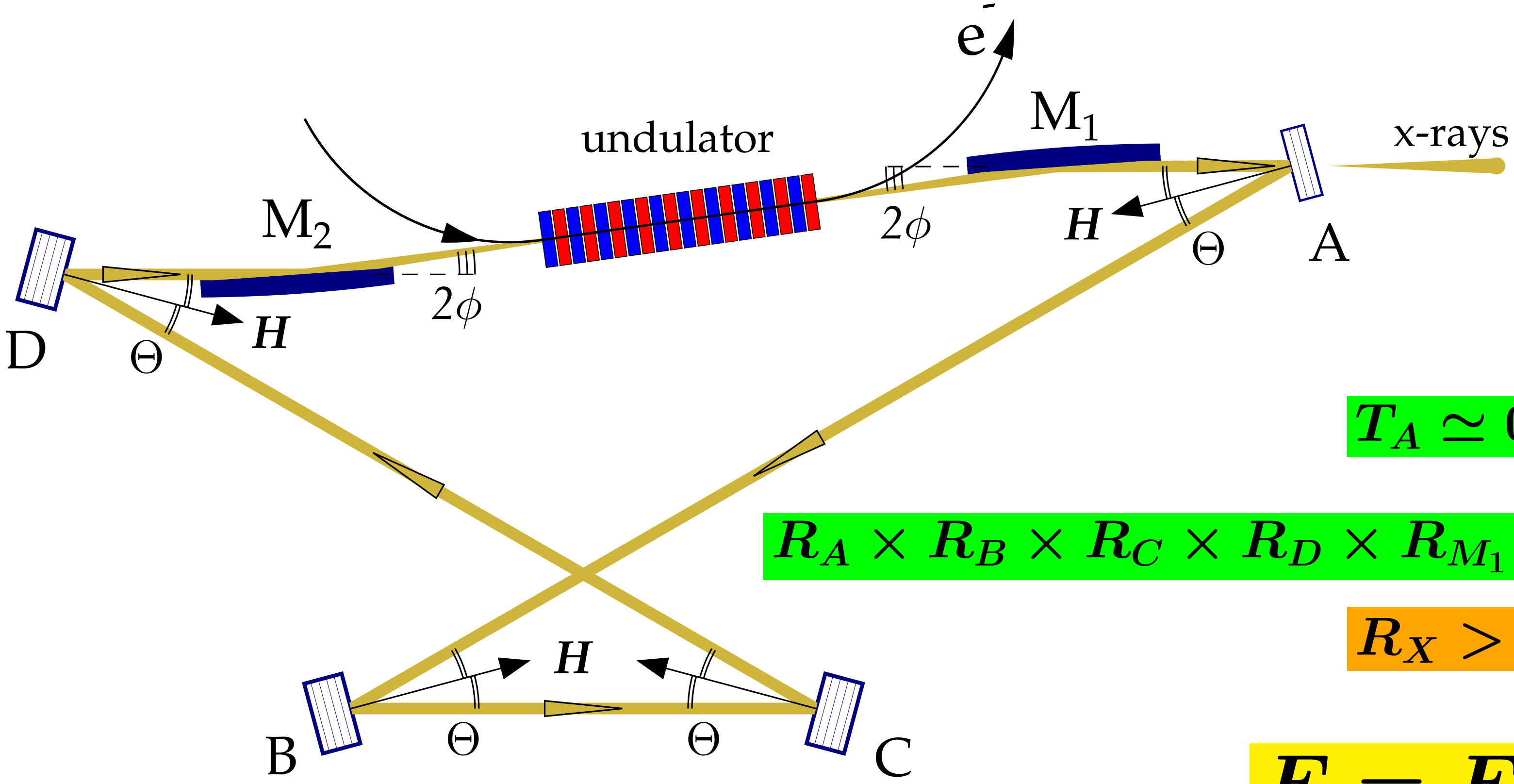


Fig.2. A scheme for x-ray optical cavity allowing a broad rage of tuning.

Tunable Cavity



$T_A \simeq 0.04$

$R_A \times R_B \times R_C \times R_D \times R_{M_1} \times R_{M_2} \simeq 0.9$

$R_X > 98\%$

$E = E_H \cos \Theta$

A four-crystal (A,B,C, and D) x-ray optical cavity allows photon energy E tuning in a broad range by changing the incidence angle Θ.

R.M.J. Cotterill, Appl. Phys. Lett., 12 (1968) 403

K.-J. Kim, and Yu. Shvyd'ko, Phys. Rev. STAB (2009)

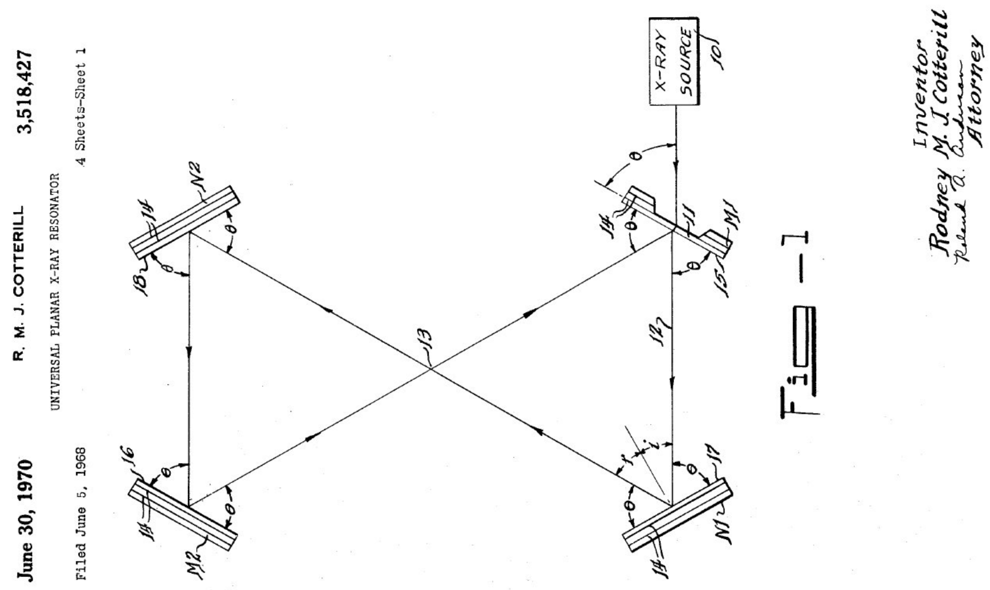
Cotterill's universal planar resonator

Volume 12, Number 12 APPLIED PHYSICS LETTERS 15 June 1968

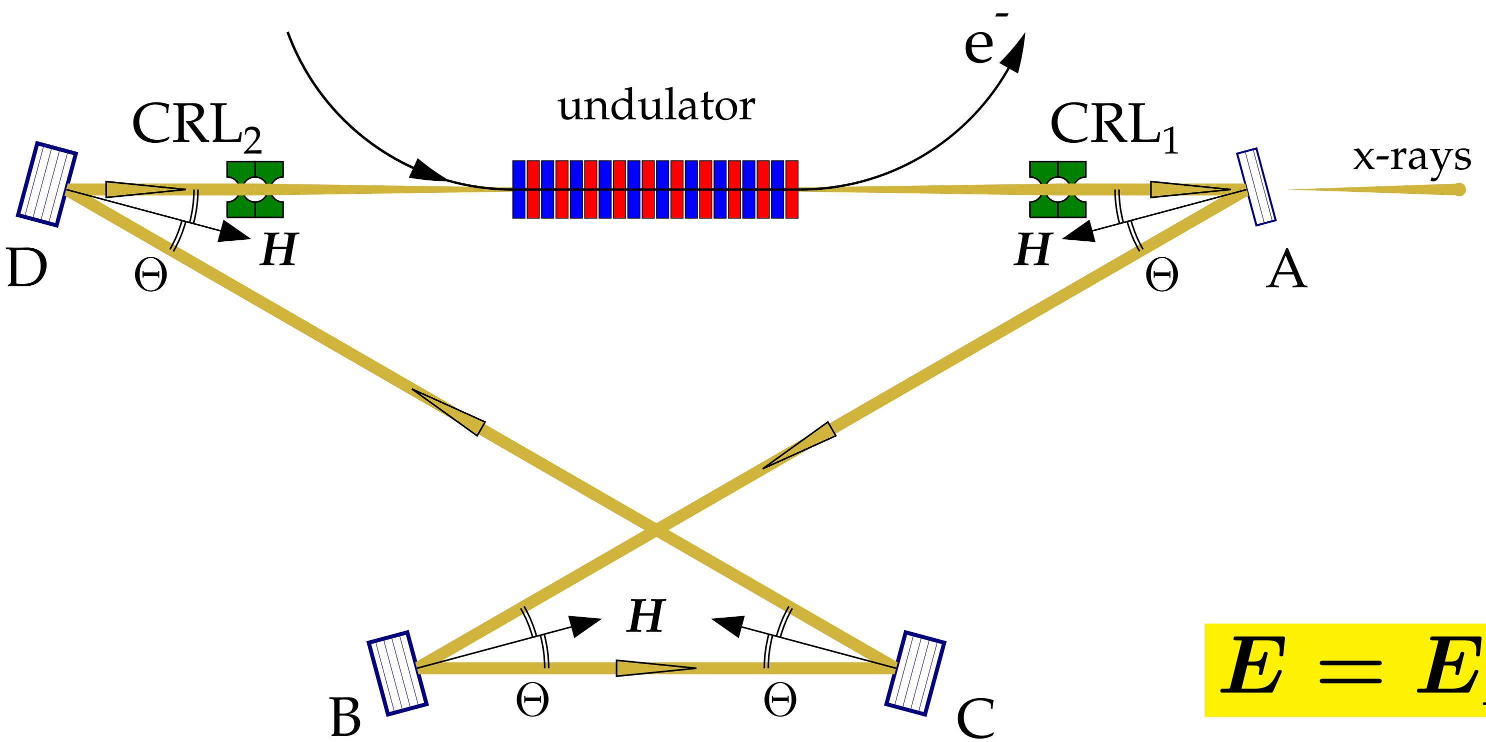
A UNIVERSAL PLANAR X-RAY RESONATOR*

R. M. J. Cotterill
Metallurgy Division
Argonne National Laboratory
Argonne, Illinois 60439
(Received 5 April 1968)

A planar x-ray resonator, the tuning of which is exact, can be constructed from a suitable arrangement of an even number of Bragg reflectors, pairs of which are parallel.



Tunable Cavity with CRLs

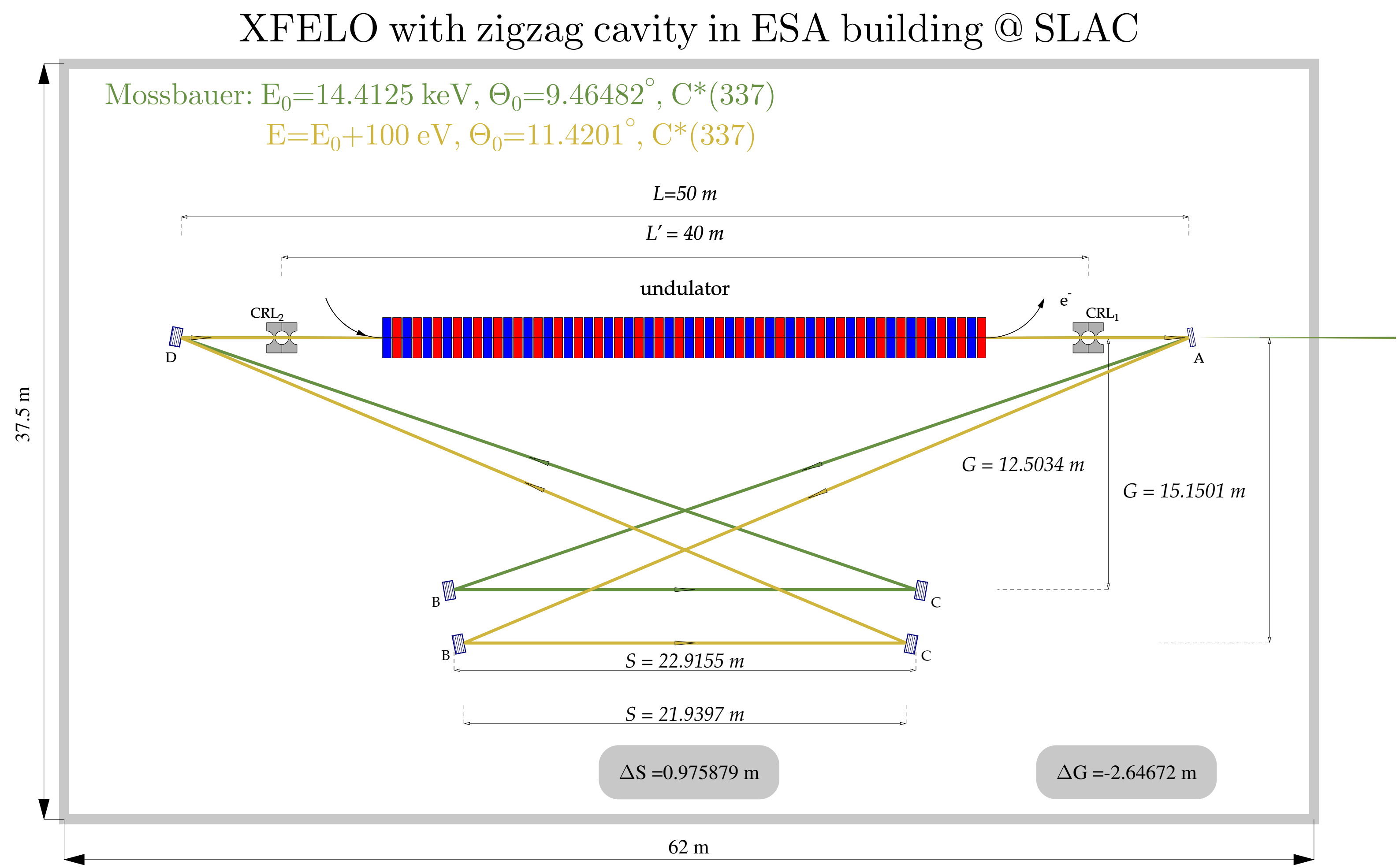


$$E = E_H \cos \Theta$$

A four-crystal (A,B,C, and D) x-ray optical cavity allows photon energy E tuning in a broad range by changing the incidence angle Θ.

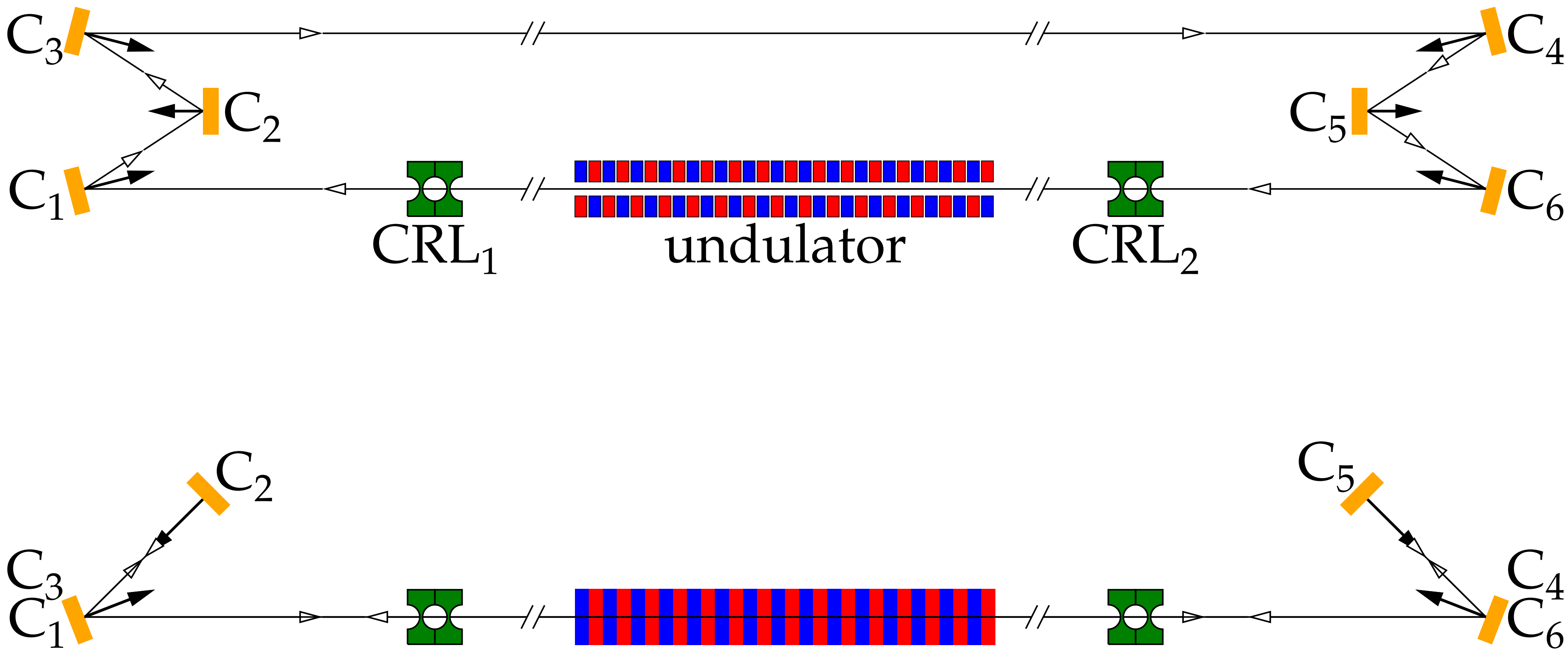
K.-J. Kim, and Yu. Shvyd'ko, Phys. Rev. STAB (2009)

XFELO Tunability



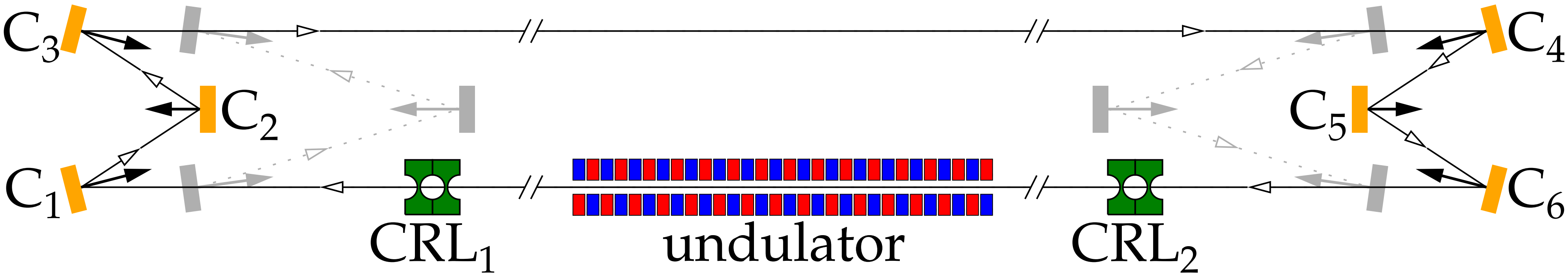
$\simeq \pm 100$ eV tuning range is feasible.

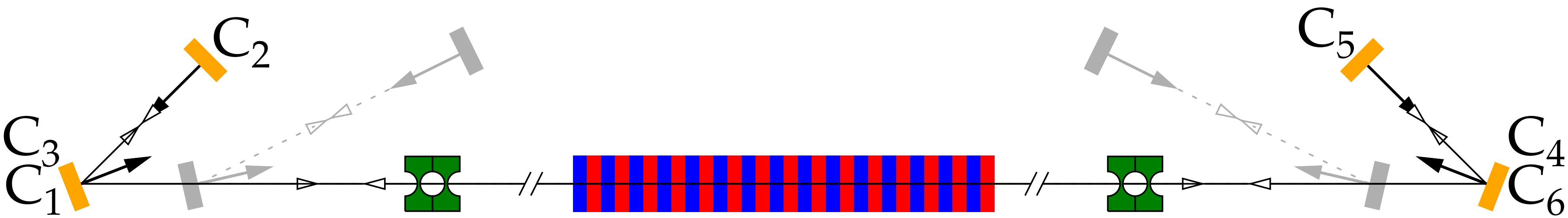
Tunable Compact Non-Coplanar Cavity



A six-crystal (C_1, C_2, ... C_6) x-ray optical cavity allows photon energy E tuning in a broad range by changing the incidence angle Θ.

Tunable Compact Non-Coplanar Cavity



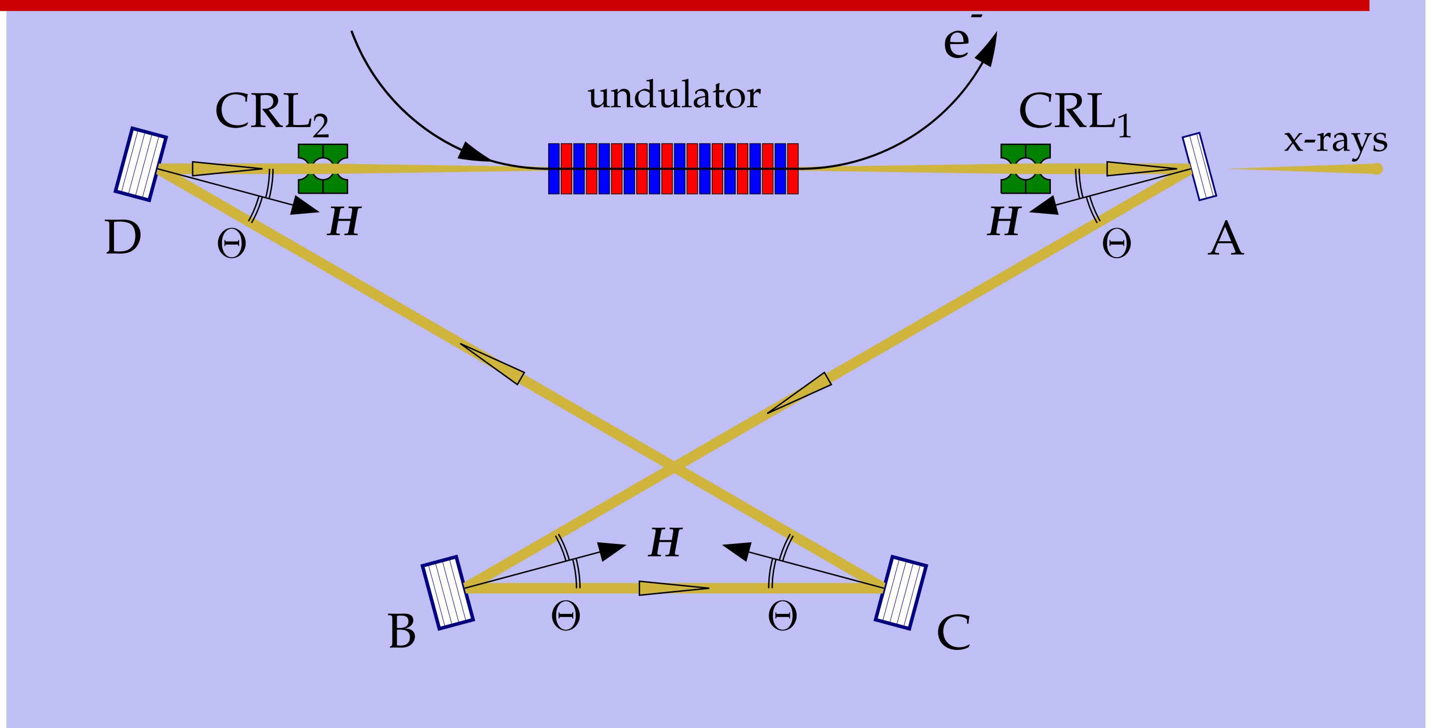


A six-crystal (C_1, C_2, ... C_6) x-ray optical cavity allows photon energy E tuning in a broad range by changing the incidence angle Θ.

Can be tuned easily by $\Delta E \simeq 1$ keV $E \simeq 14$ keV

Yu. Shvyd'ko, Beam Dynamics Newsletter No. 60, April 2013, 68-83

XFELO Cavity Technical Challenges



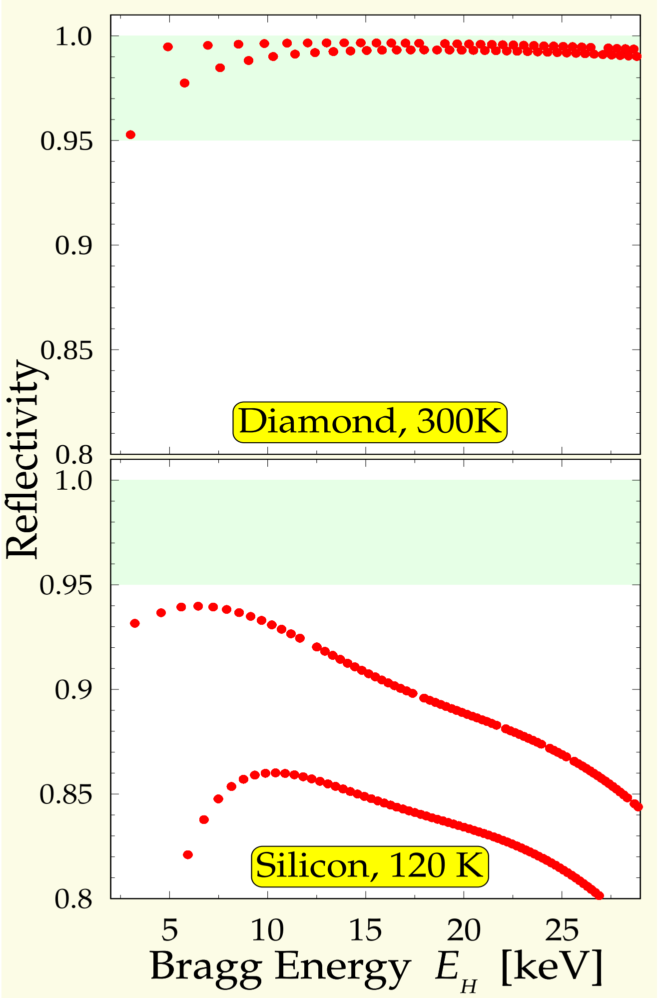
- Crystal reflectivity $> 98\%$ reflectivity in backscattering
- Crystal endurance to $\simeq 12$ kW/mm^2 irradiation.
- Efficient ($> 98\%$) & wavefront preserving focusing/collimating optics
- Heat load problem: reflection band instability due to thermal variations $\lesssim 1$ meV.
- Angular stability: $\delta\theta \lesssim 20$ nrad (rms)
  Spatial stability: $\delta L \lesssim 3\ \mu$m (rms) $\rightarrow$ $\delta L/L \lesssim 3 \times 10^{-8}$

Diamond: superlative physical properties

Record high reflectivity

for hard x-rays

Theory: $> 99\%$

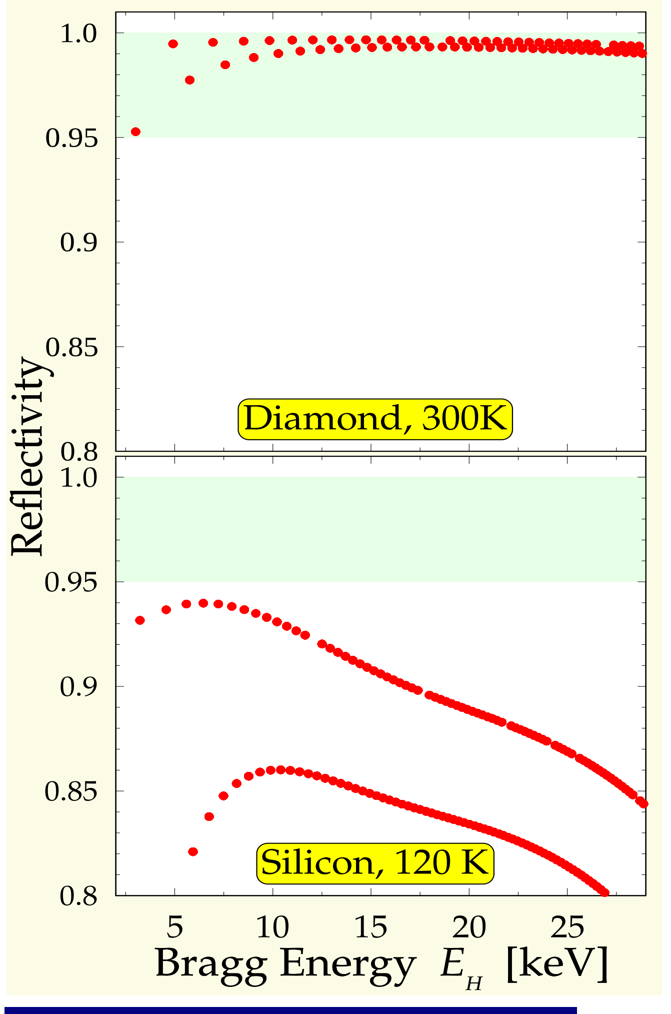


Yu. Shvyd'ko et al Nature Phys. (2010)

Diamond: superlative physical properties

Record high reflectivity for hard x-rays

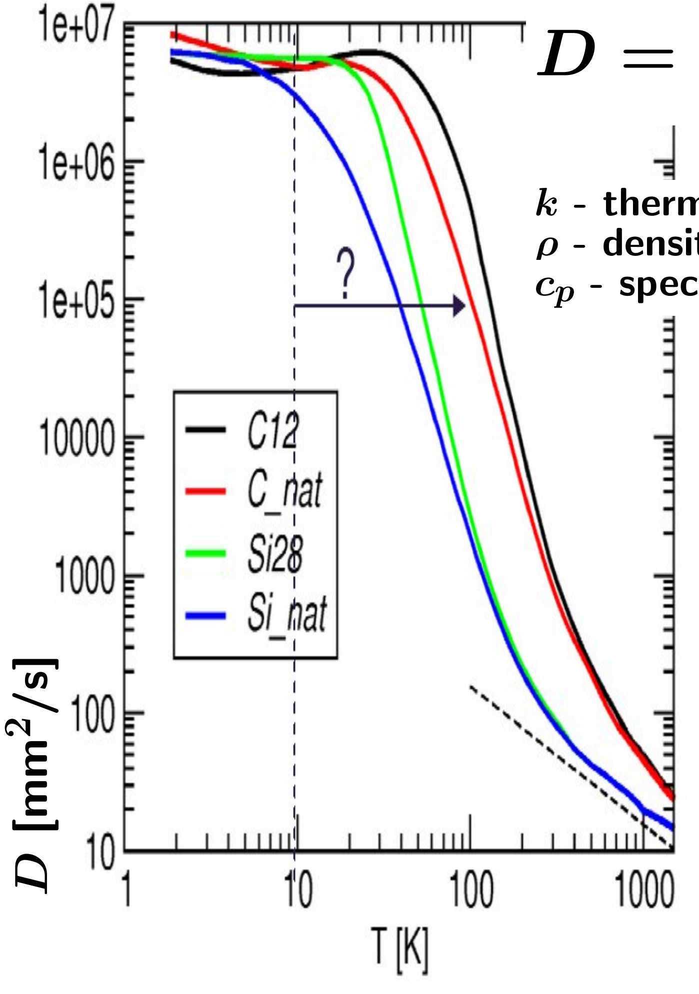
Theory: $> 99\%$



Yu. Shvyd'ko et al Nature Phys. (2010)

Ultra-high thermal diffusivity at low temperatures

$\simeq 10^5$ mm^{-2}s @ 100 K



$$D = \frac{k}{\rho c_p}$$

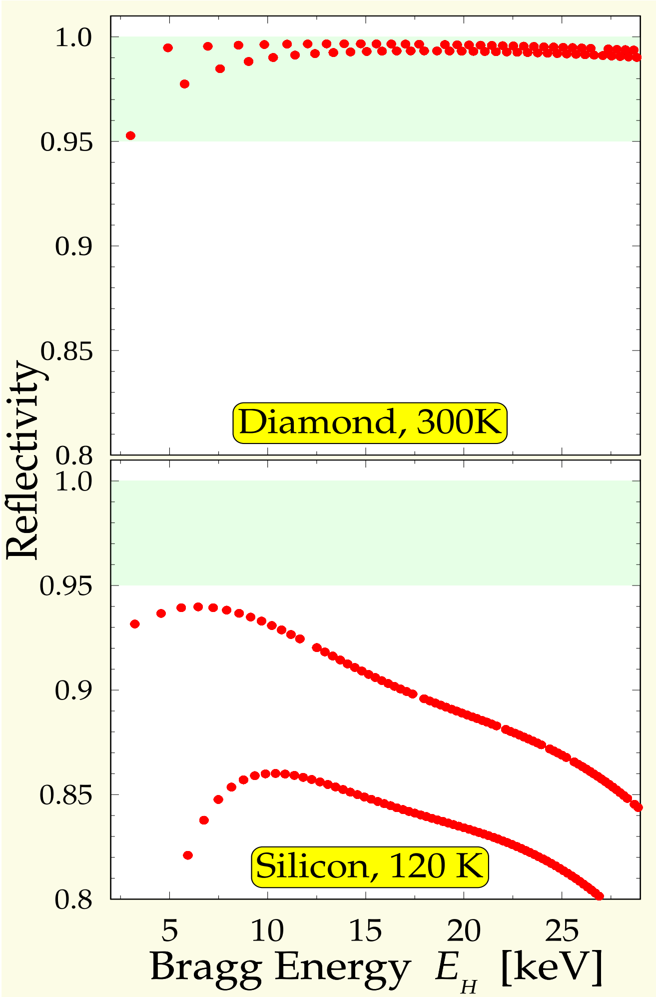
k - thermal conductivity
ρ - density
c_p - specific heat capacity

Courtesy of H. Sinn

Diamond: superlative physical properties

Record high reflectivity for hard x-rays

Theory: $> 99\%$



Yu. Shvyd'ko et al Nature Phys. (2010)

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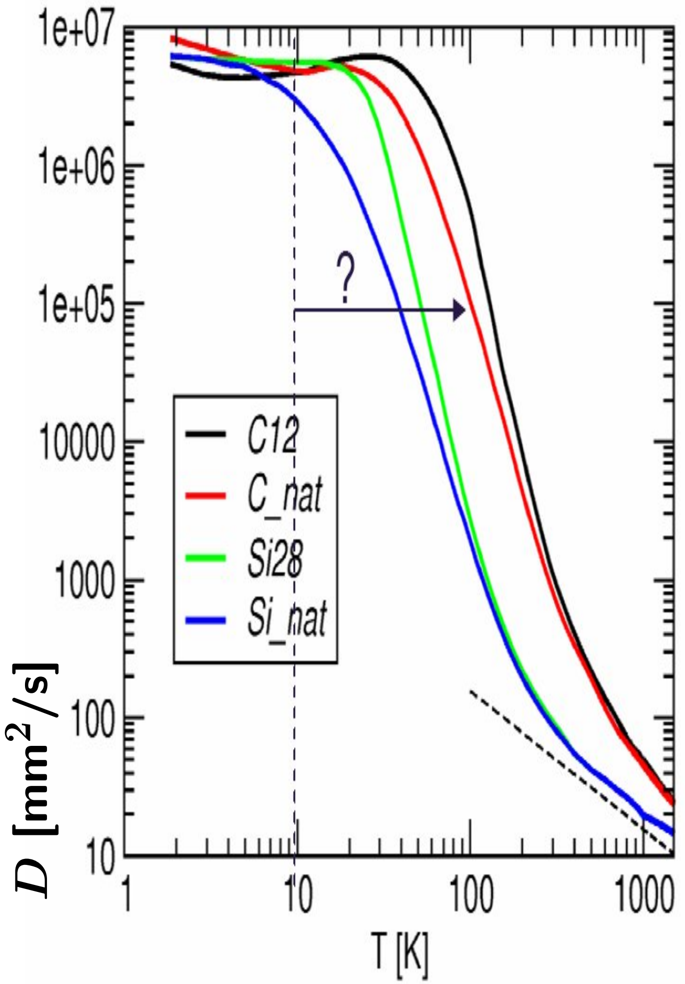
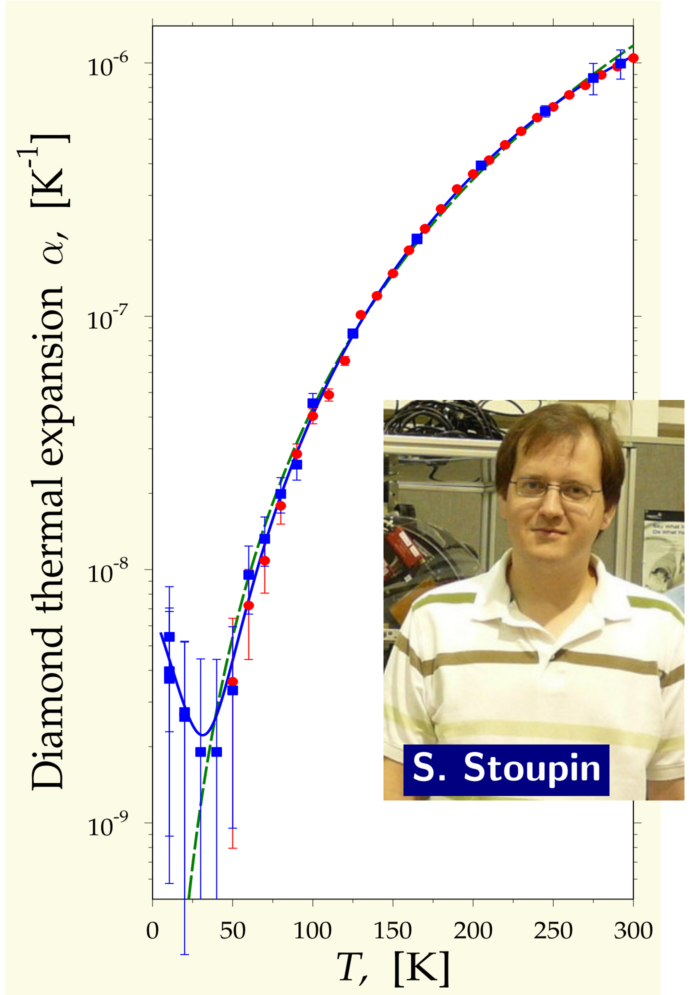


Courtesy of H. Sinn

Ultra-low thermal expansion at low temperatures

$\simeq 10^{-8}$ K^{-1} @ 100 K

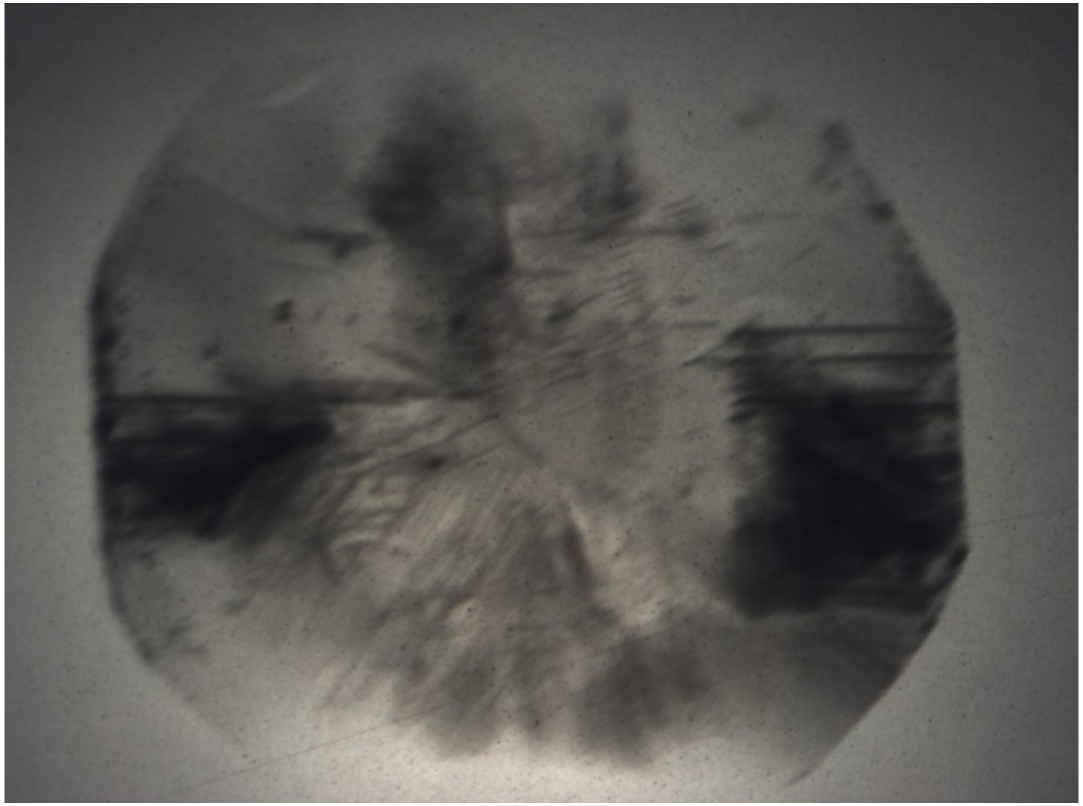


S. Stoupin, Yu. Shvyd'ko PRL (2010)

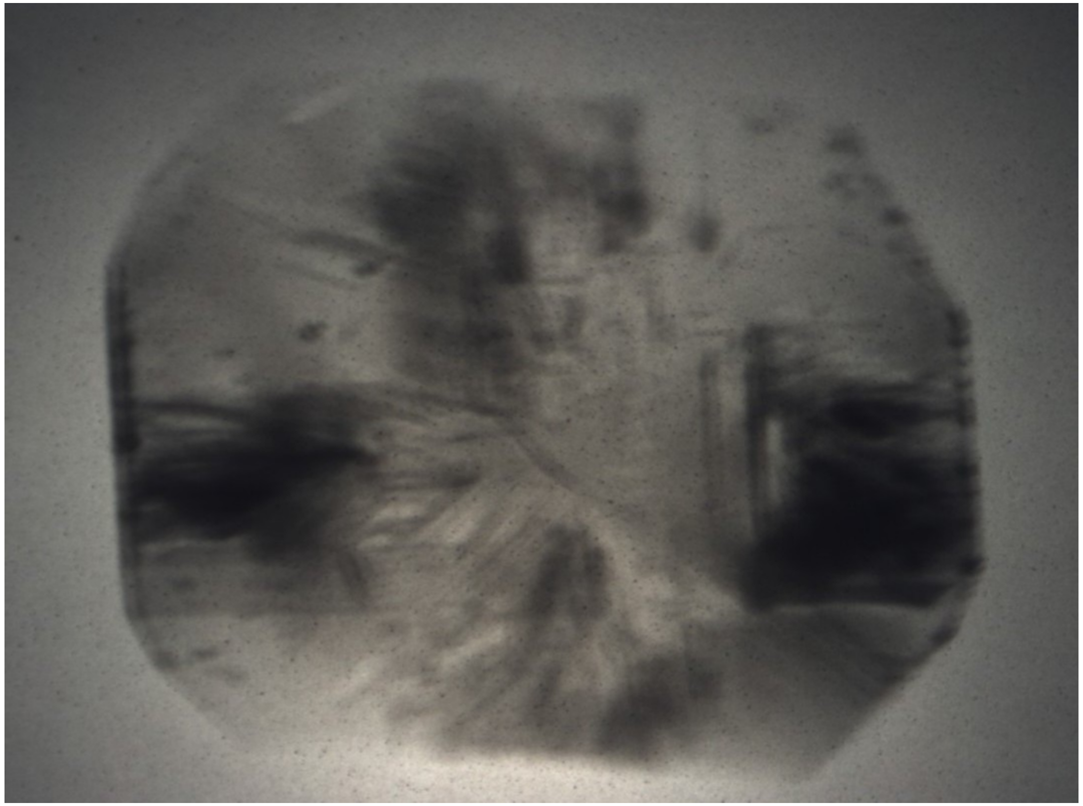
Quality and Reflectivity of Diamond Crystals

25-30 Years Ago ...

IIa, HTHP, from GE



(f) $\bar{3}\bar{1}1$



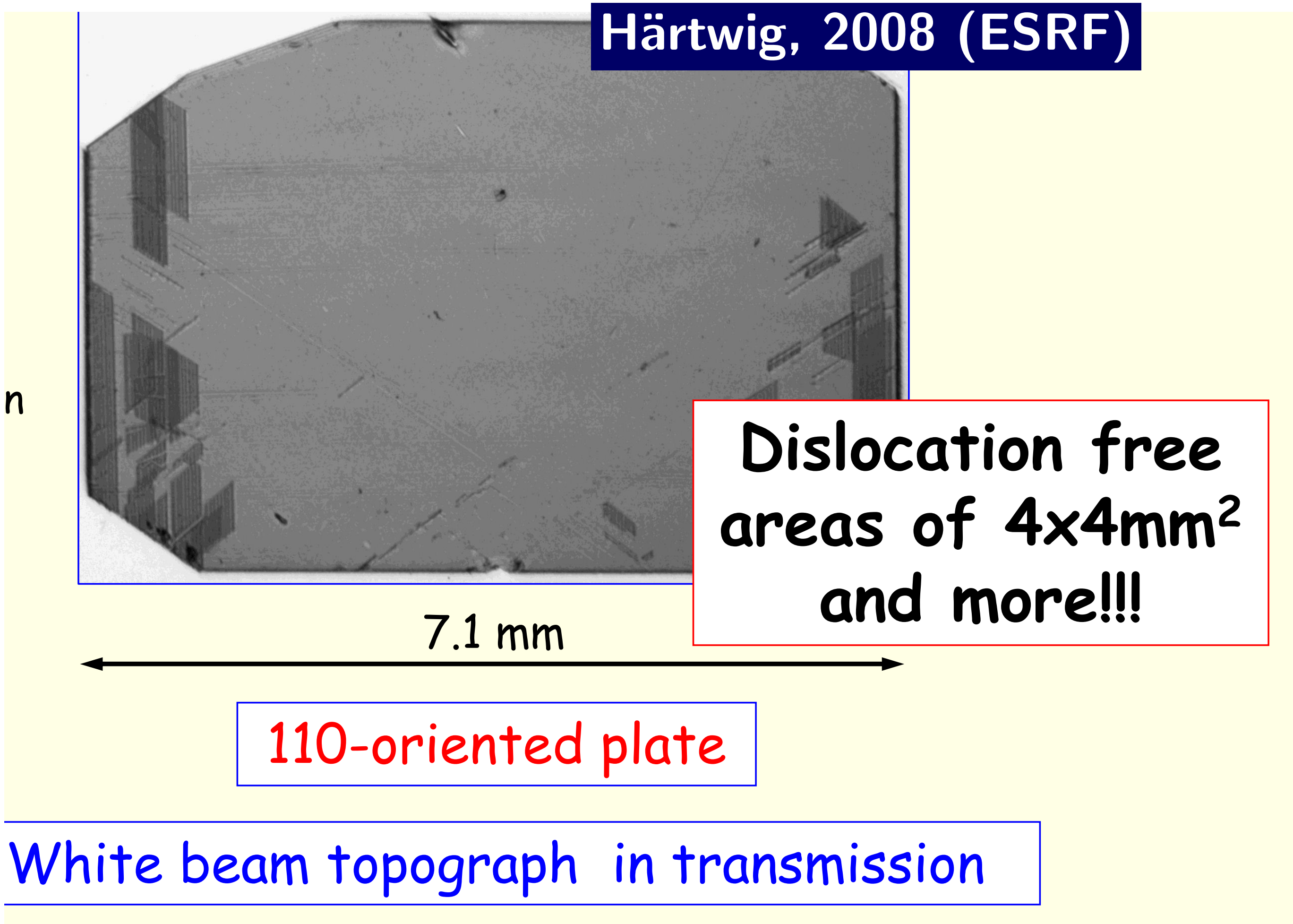
(g) $\bar{3}11$

x-ray white beam topography: Stoupin, 2011 (APS)

Diamond Crystal Quality. State of the Art

Progress in fabrication, characterization, and X-ray optics applications of synthetic high-quality HTHP diamond of type-IIa was substantial in the last two decades:
Pal'yanov et al. (1990), Berman et al. (1993), Freund (1995), Sumiya and Satoh (1996), Fernandez et al. (1997), Sellschop et al. (2000), Sumiya et al. (2000), Zhong et al. (2007), Yabashi et al. (2007), Burns et al. (2009), Polyakov et al. (2011).

Crystals with $> 4 \times 4$ mm^2 defect-free areas Burns et al. (2009), Polyakov et al. (2011) is the state of the art.



High Quality Diamonds from Sumitomo

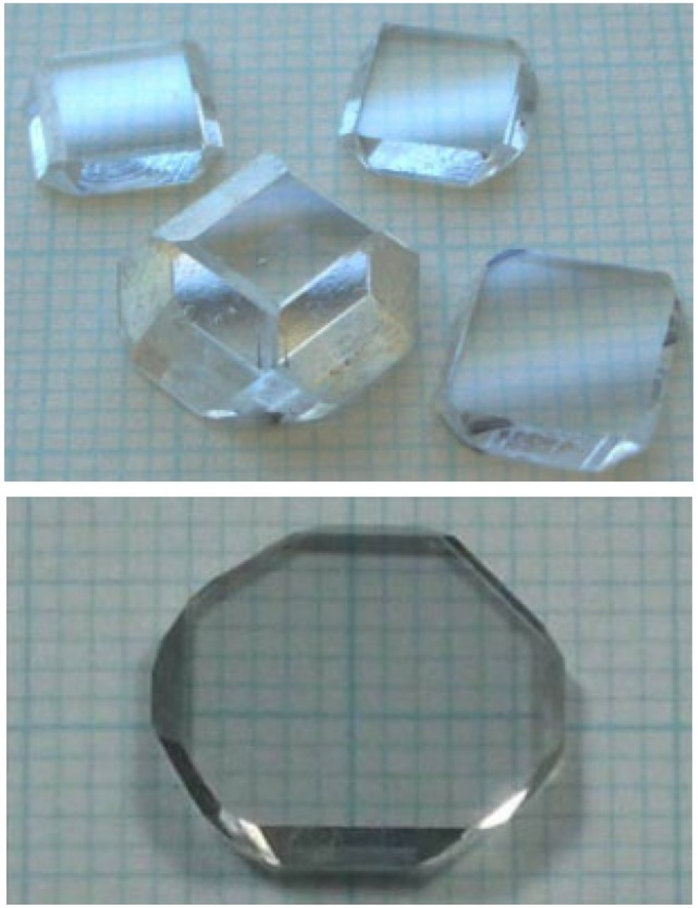


Fig. 3. (Color online) Large synthetic type IIa diamond crystals. Bottom: the largest diamond plate prepared from a large crystal of 12 mm diameter.

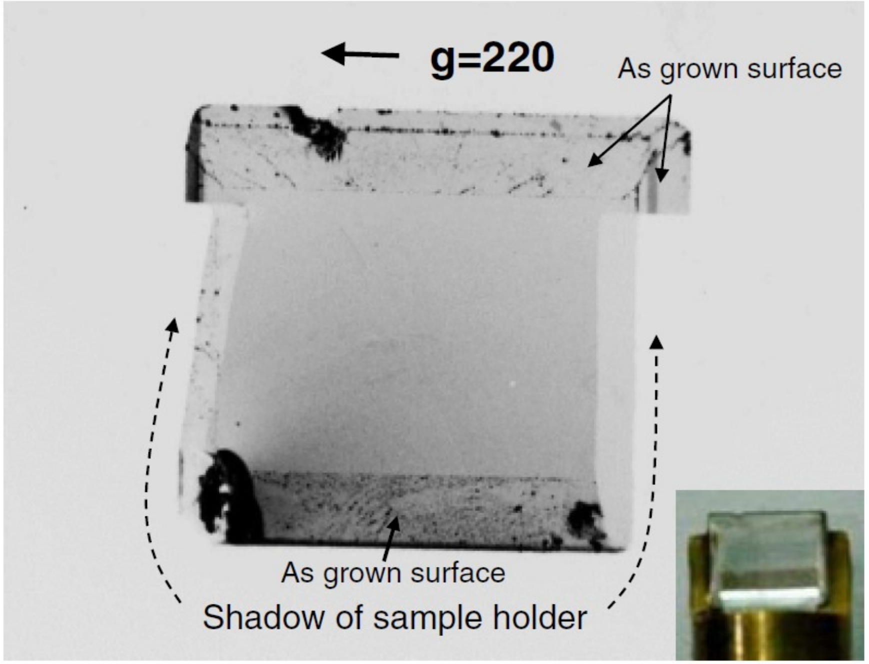


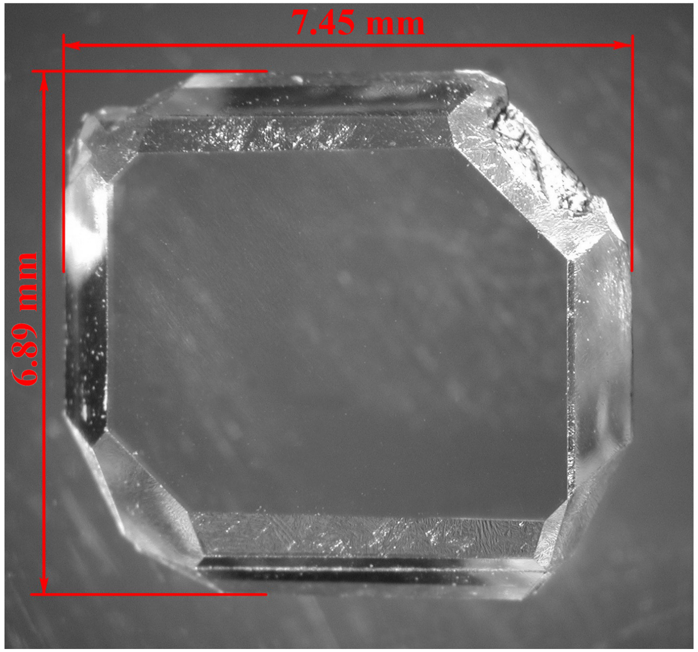
Fig. 5. (Color online) Transmission X-ray topograph of (001) diamond plate shown in Fig. 4(a) ($7.5 \times 6 \times 0.7\,mm^3$) cut from the upper region of a large synthetic type IIa diamond crystal. Bottom right shows the diamond plate attached to the sample holder for topography measurement.

Sumiya & Tamasaku JJAP 51 (2012) 090102

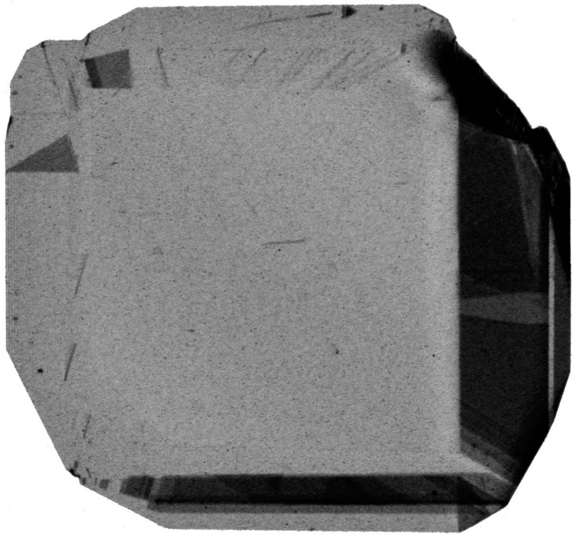
Courtesy of Kenji Tamasaku

Type-IIa, HTHP Diamond from TISNCM (I)

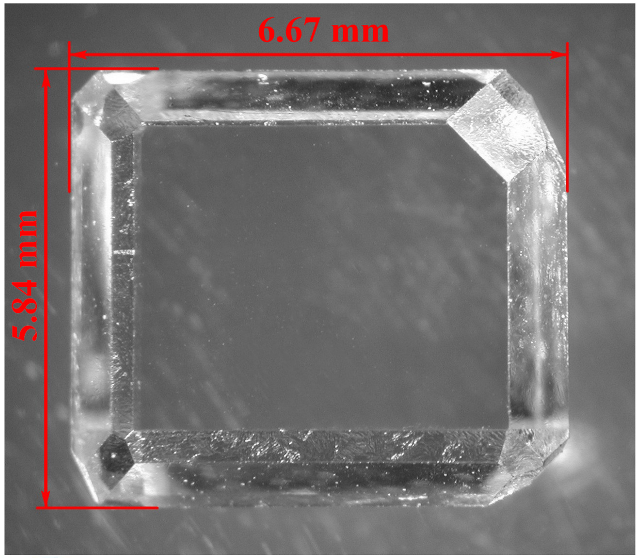
Visible light image

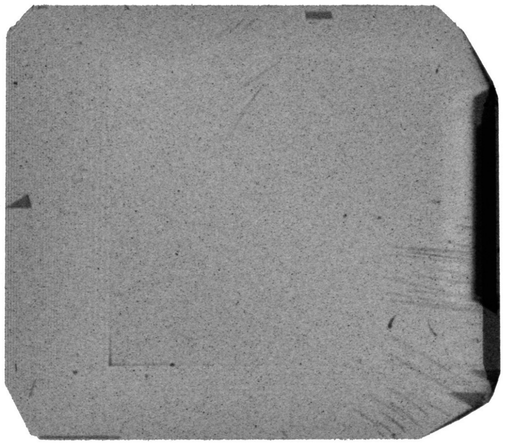


X-ray Lang topography in transmission



Technological Institute for Superhard and New Carbon Materials (TISNCM) Troitsk, Russia



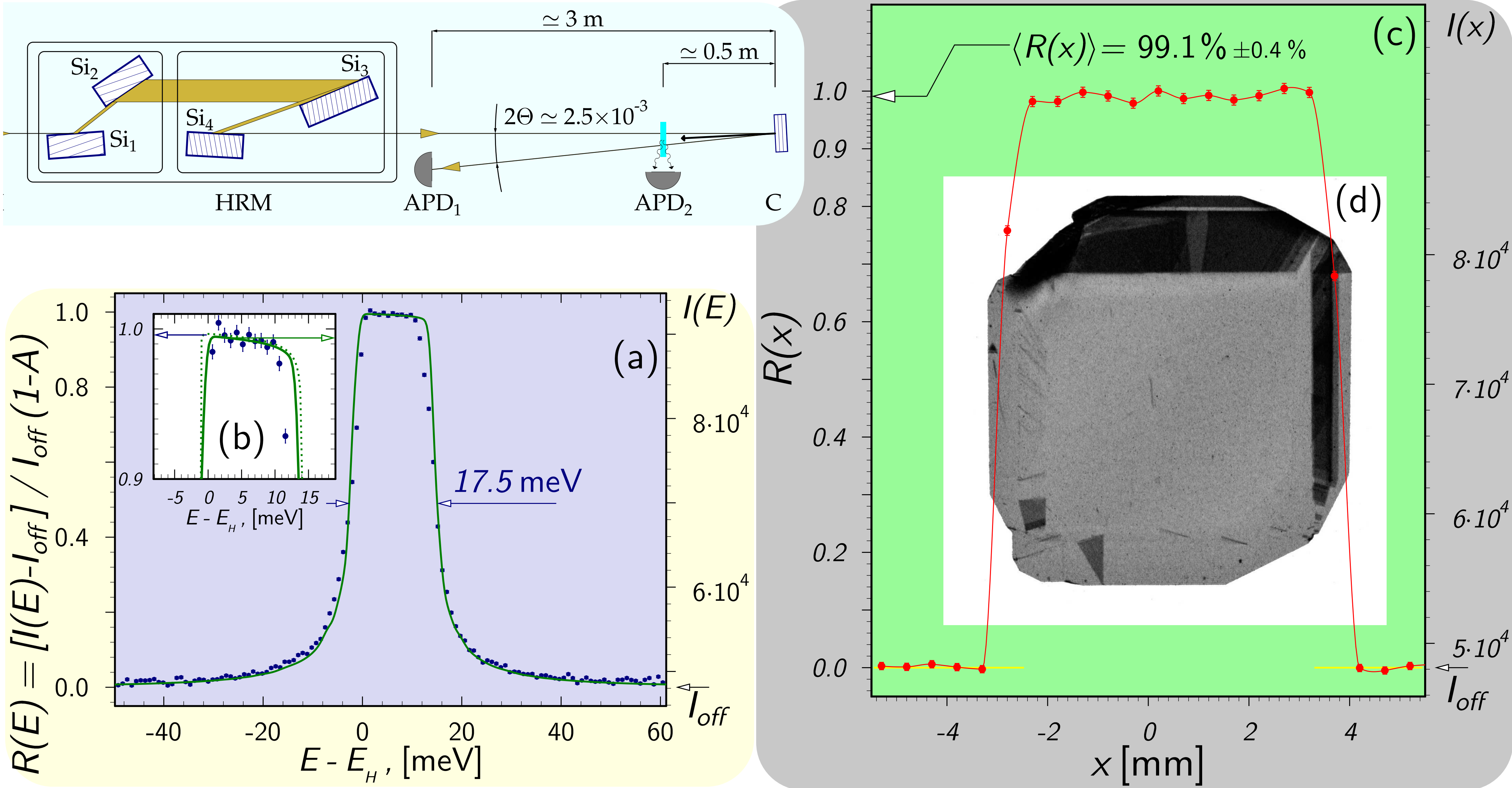


Preselected diamond plates:

(001) orientation, 1mm thick

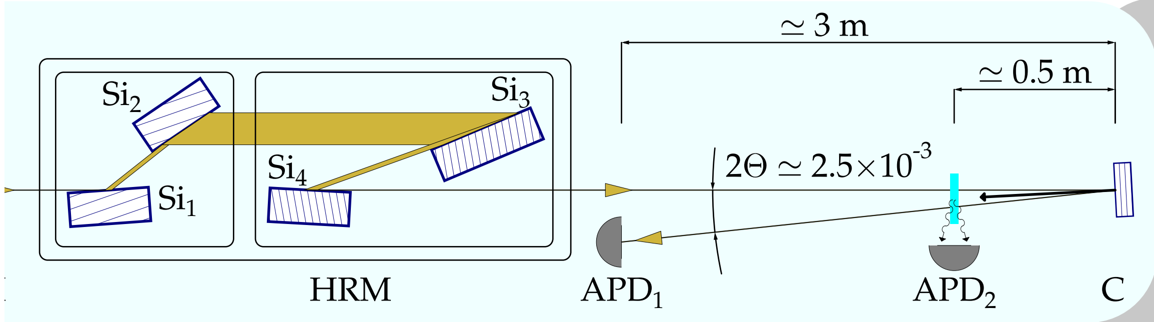
dislocation & stacking fault free areas $> 4 \times 4$ mm^2 and more

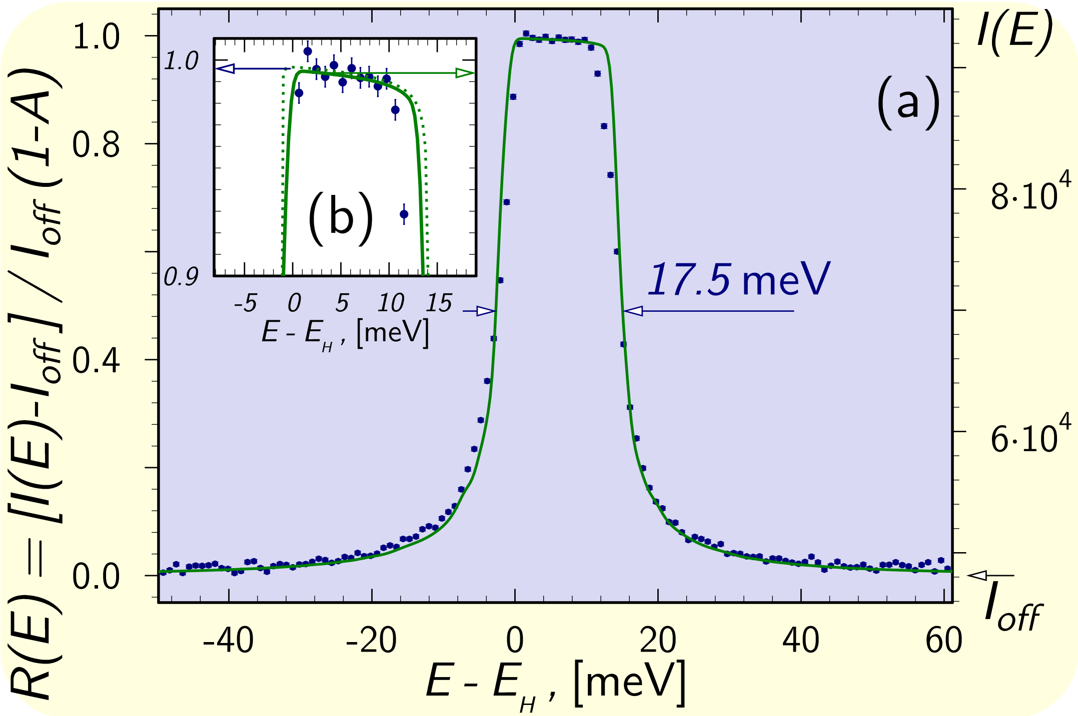
Diamond Reflectivity Studies: C(008) @ 14.3 keV

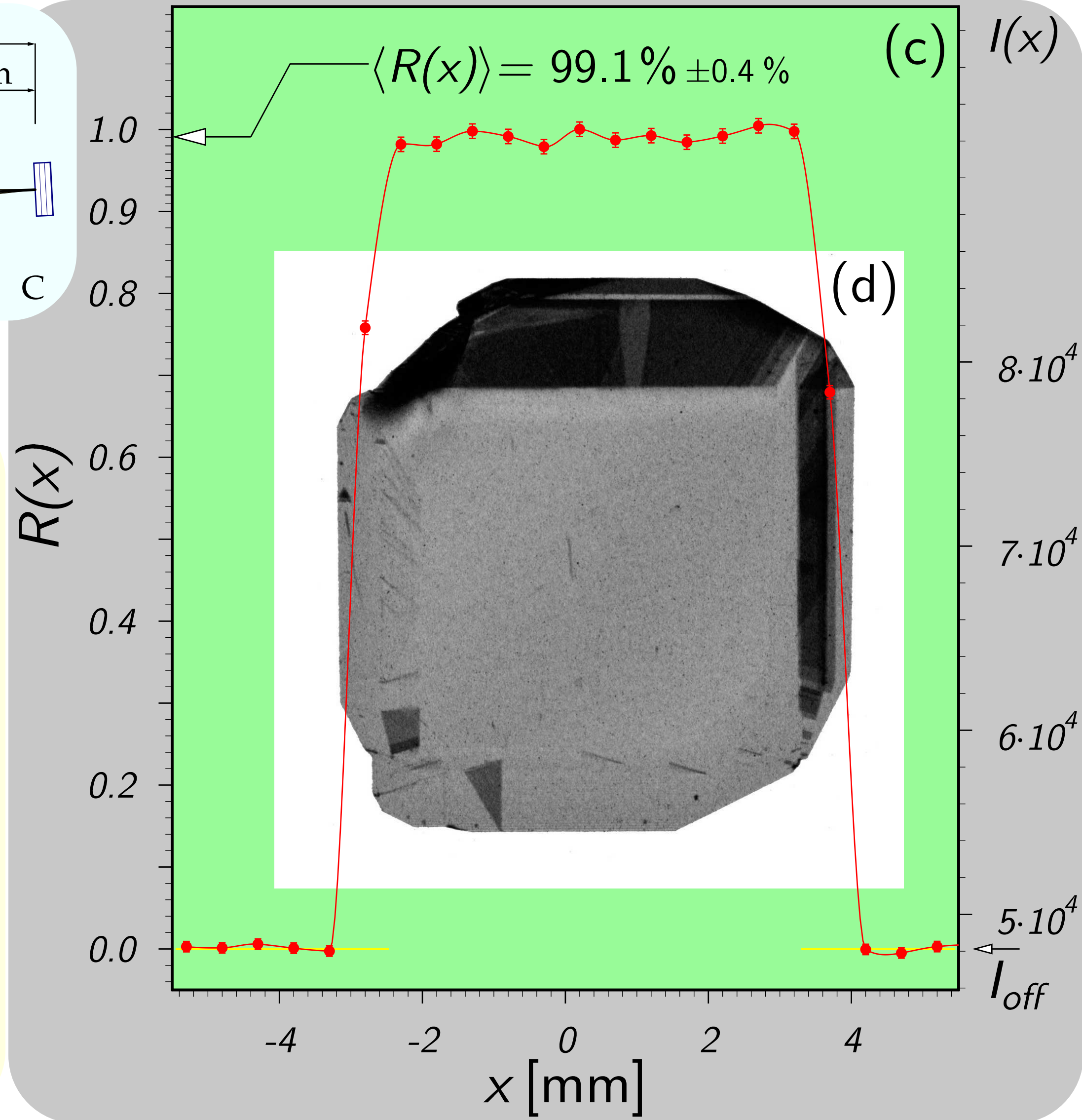


Shvyd'ko, Stoupin, Blank, Terentyev, Nature Photonics 5 (2011) 539

Diamond Reflectivity Studies: C(008) @ 14.3 keV







Shvyd'ko, Stoupin, Blank, Terentyev, Nature Photonics 5 (2011) 539

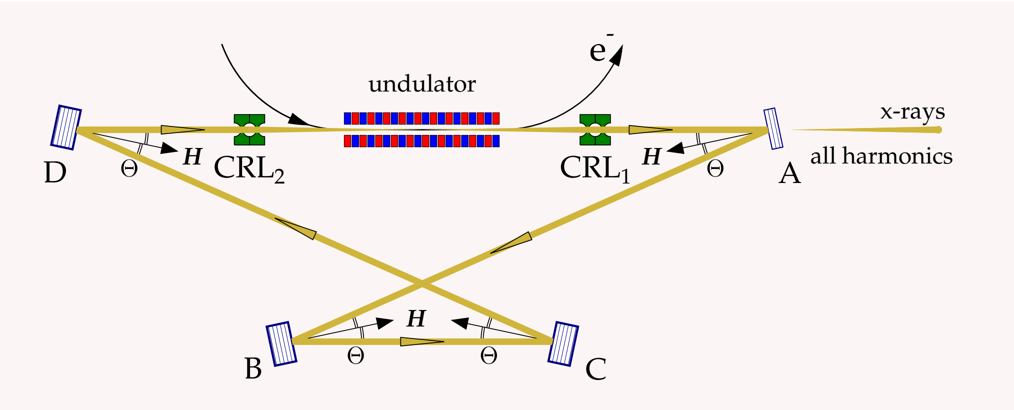
≃ 99% reflectivity and close to theoretical performance.

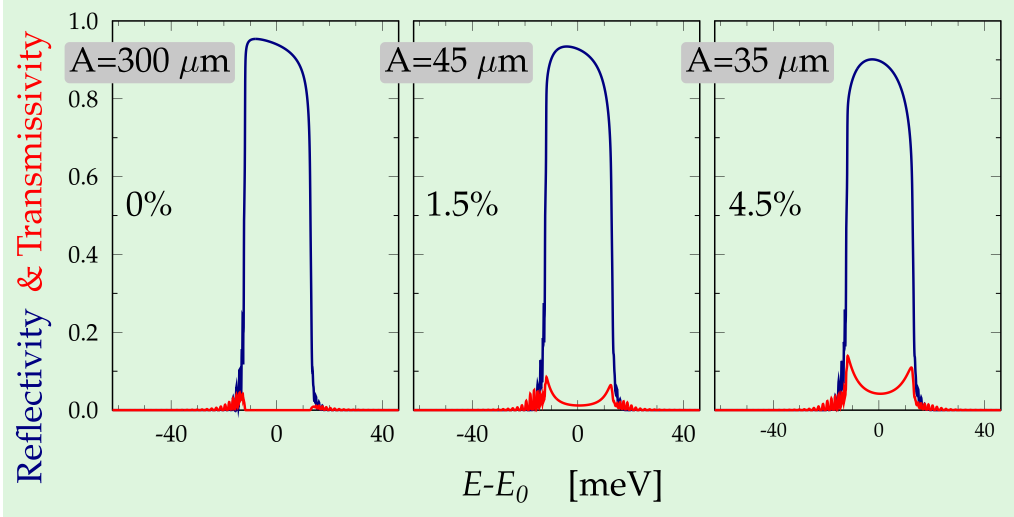
Outcoupling through Thin Diamond Crystals

Outcoupling: $I(0) \simeq 4 \times \exp(-A/\bar{\Lambda}_H)$

$H = (511)$, $\bar{\Lambda} = 7.8\ \mu$m, $E_0 = 9.1$ keV

$B = C = D > 300\ \mu$m; $A \ll B, C, D$

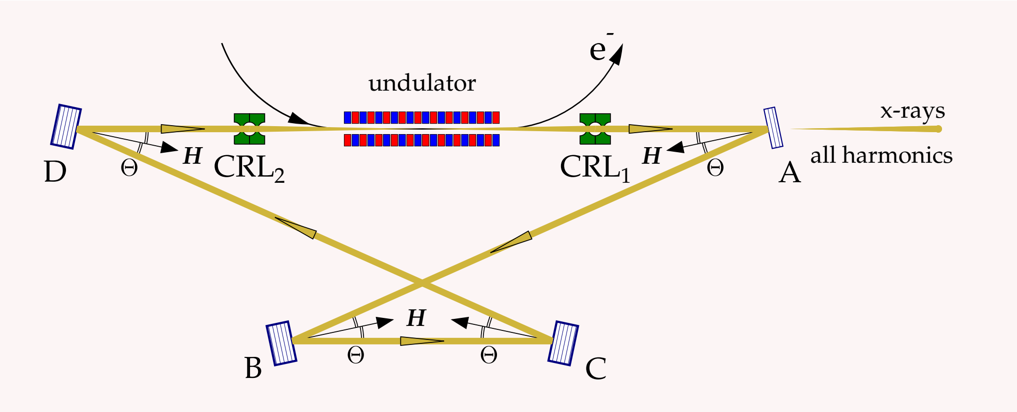




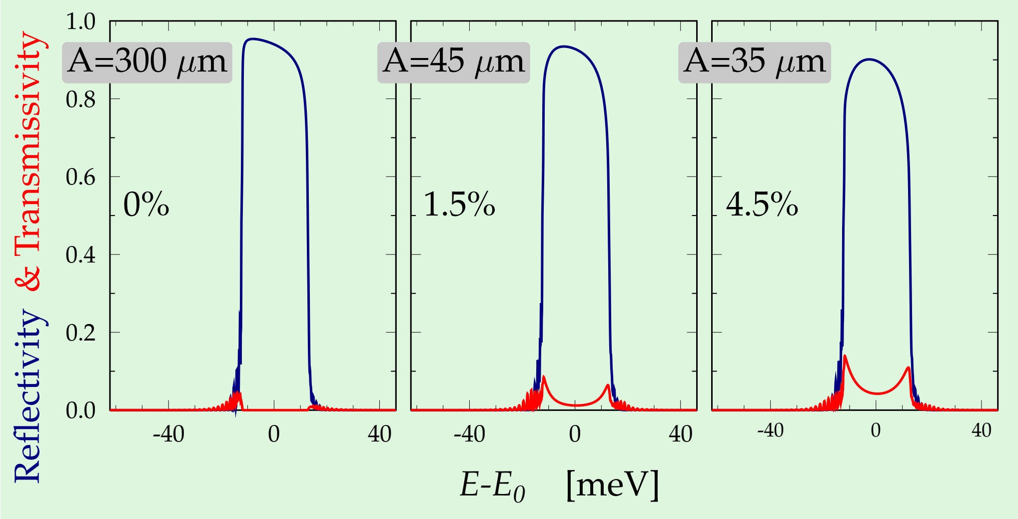
Outcoupling through Thin Diamond Crystals

Outcoupling: $I(0) \simeq 4 \times \exp(-A/\bar{\Lambda}_H)$

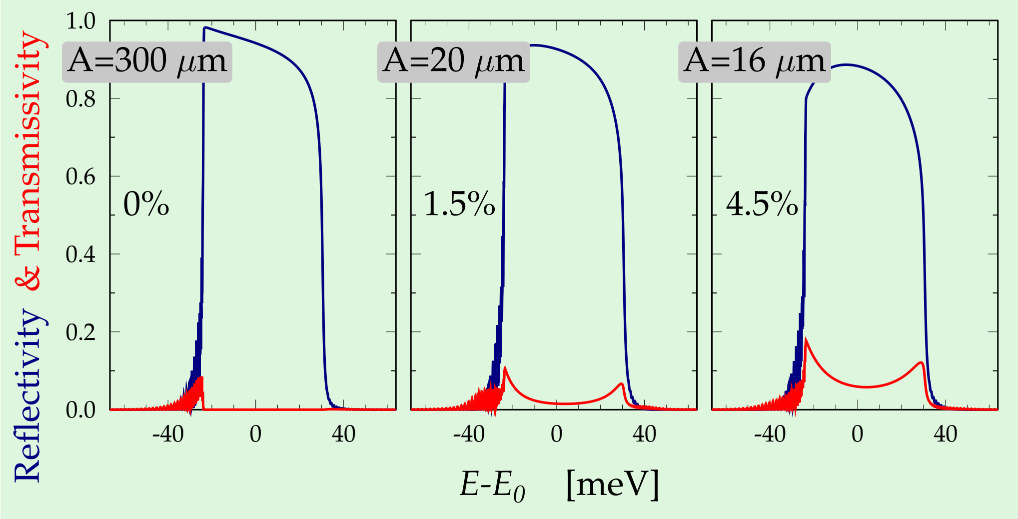
$$B = C = D > 300\ \mu\mathrm{m},\quad A \ll B, C, D$$



$H = (511),\ \bar{\Lambda} = 7.8\ \mu\mathrm{m},\ E_0 = 9.1$ keV

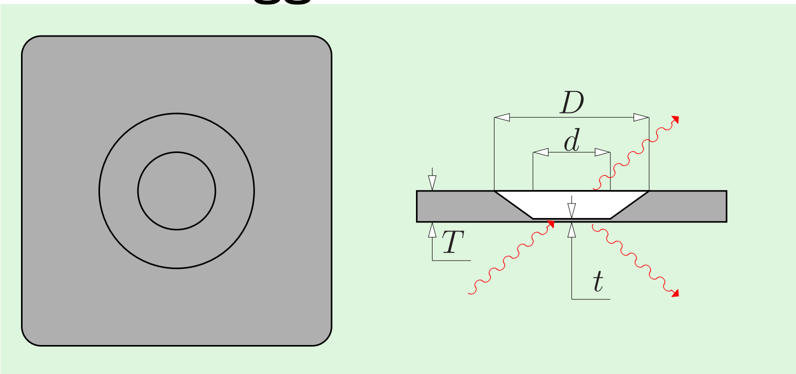


$H = (400),\ \bar{\Lambda} = 3.6\ \mu\mathrm{m},\ E_0 = 6.9$ keV



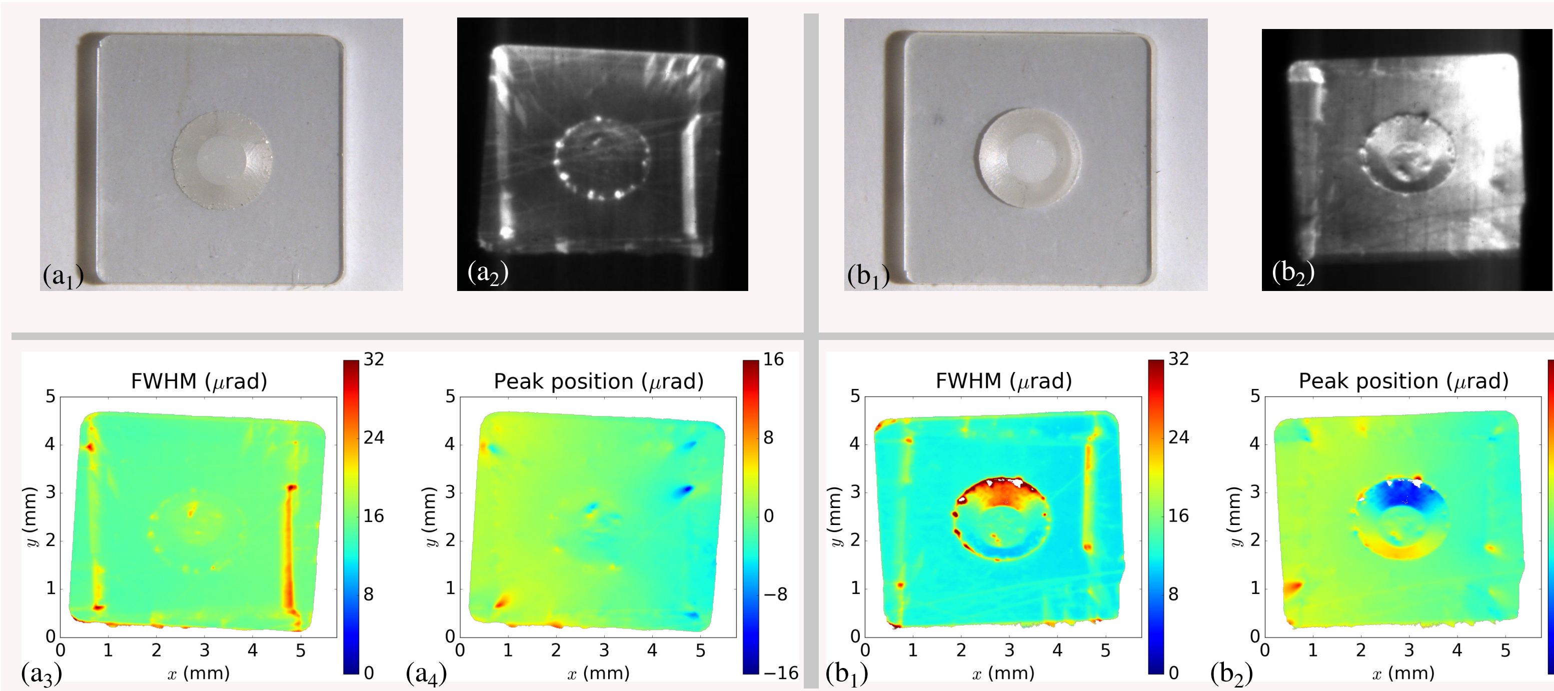
Outcoupling through Drumhead Crystals

A few tens of microns thick perfect diamond single crystals, properly functioning under Bragg diffraction conditions are required for outcoupling of x-rays.



Drumhead crystals, monolithic crystal structures comprised of a thin membrane furnished with a surrounding solid collar, are a solution ensuring mechanically stable strain-free mounting of the membranes with efficient thermal transport.

Almost flawless diamond drumhead crystal with a 25 μm thin membrane in the (100) orientation manufactured by picosecond laser milling.



Kolodziej, Vodnala, Terentyaev, Blank & Shvyd'ko (2016) J. Appl. Cryst. 49

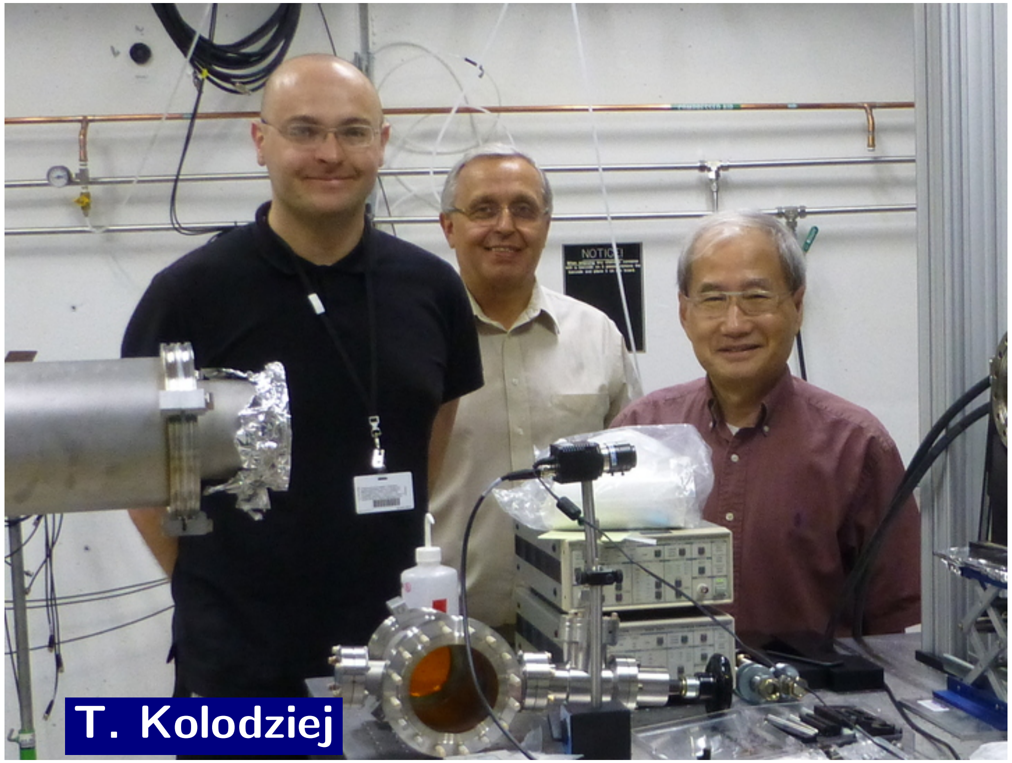
Endurance of Diamond to Radiation Damage

Endurance of Diamond to Radiation Damage

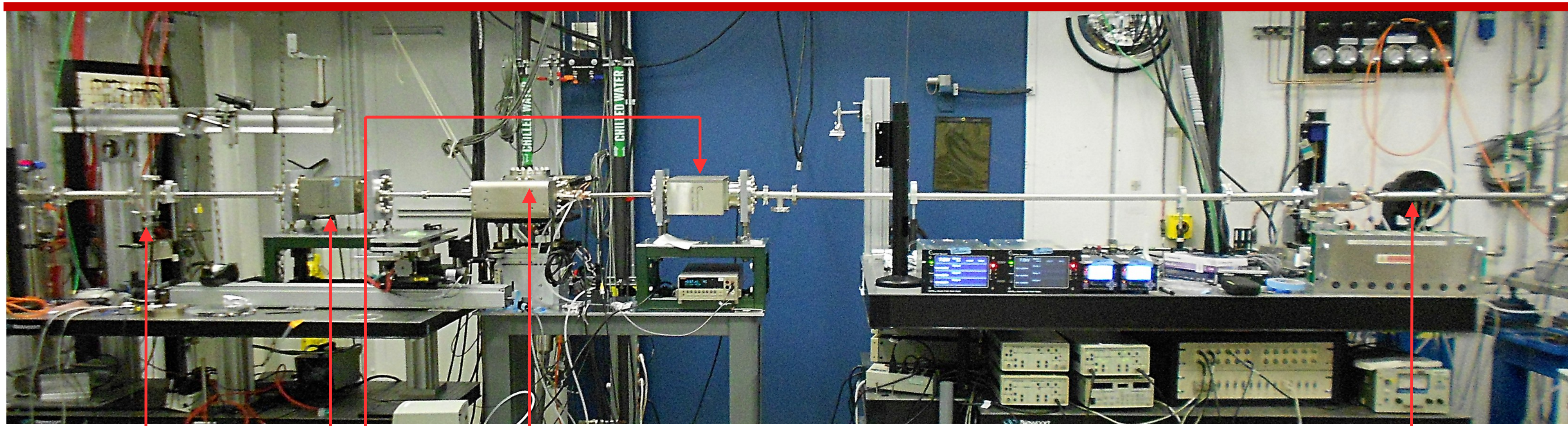
XFELO intracavity power: $\simeq 20$ W

XFELO intracavity power density: $\simeq 12$ kW/mm^2

Can diamond preserve crystal integrity under the $\simeq 12$ kW/mm^2 power-density loading in the XFELO cavity and preserve the very high Bragg reflectivity?



Endurance of Diamond to Radiation Damage Studies at the APS

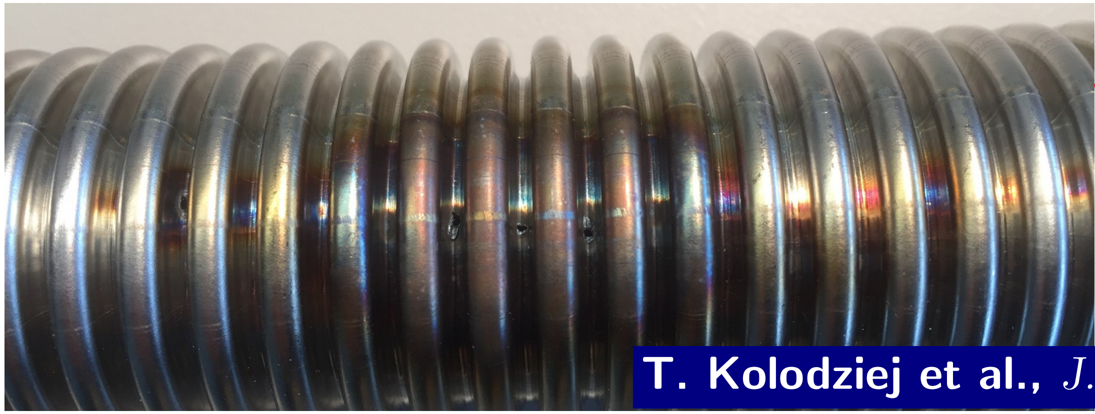


Scattering detector

Differential ion pumps

Irradiation chamber

Power: P = **12.5 W** (on the diamond)
Spot size: S = 50 μm * 20 μm = **$1\cdot10^{-3}$ mm^2**
Power density: P/S= **12.5 kW/mm^2**
Vacuum: **$1\cdot10^{-8}$ Torr**, ion pumps **ON**
$4\cdot10^{-6}$ Torr, ion pumps **OFF**, only turbo pumps



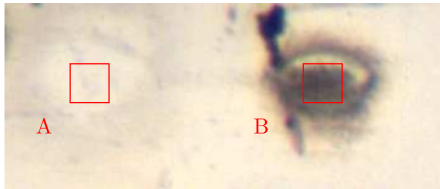
Unfocused beam burns a stainless steel bellow through in a few minutes.

T. Kolodziej et al., *J. Synchrotron Rad.* **(2018) 25, 1022**

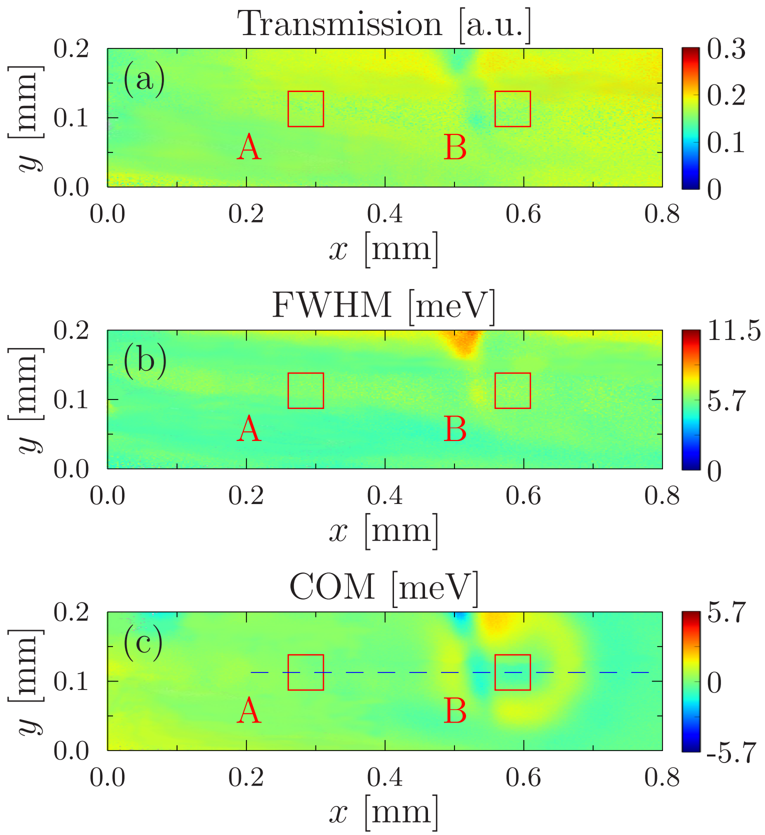
Endurance of Diamond to Radiation Damage Studies at the APS

Diamond crystal after 12 kW/mm^2 irradiation during 4 hours

Photograph



X-ray rocking-curve images



Spot A: The high Bragg reflectivity of the diamond crystals is preserved after the irradiation, provided it is performed at $\simeq 1 \times 10^{-8}$ Torr high-vacuum conditions.

Spot B: Irradiation under 4×10^{-6} Torr results in a $\simeq 1$-meV shift of the Bragg peak, which corresponds to a relative lattice distortion of 4×10^{-8}, while the high Bragg reflectivity stays intact.

Diamond crystals survive the power loading in the XFELO cavity and preserve very high reflectivity.

T. Kolodziej et al., *J. Synchrotron Rad.* **(2018) 25, 1022**

Summary

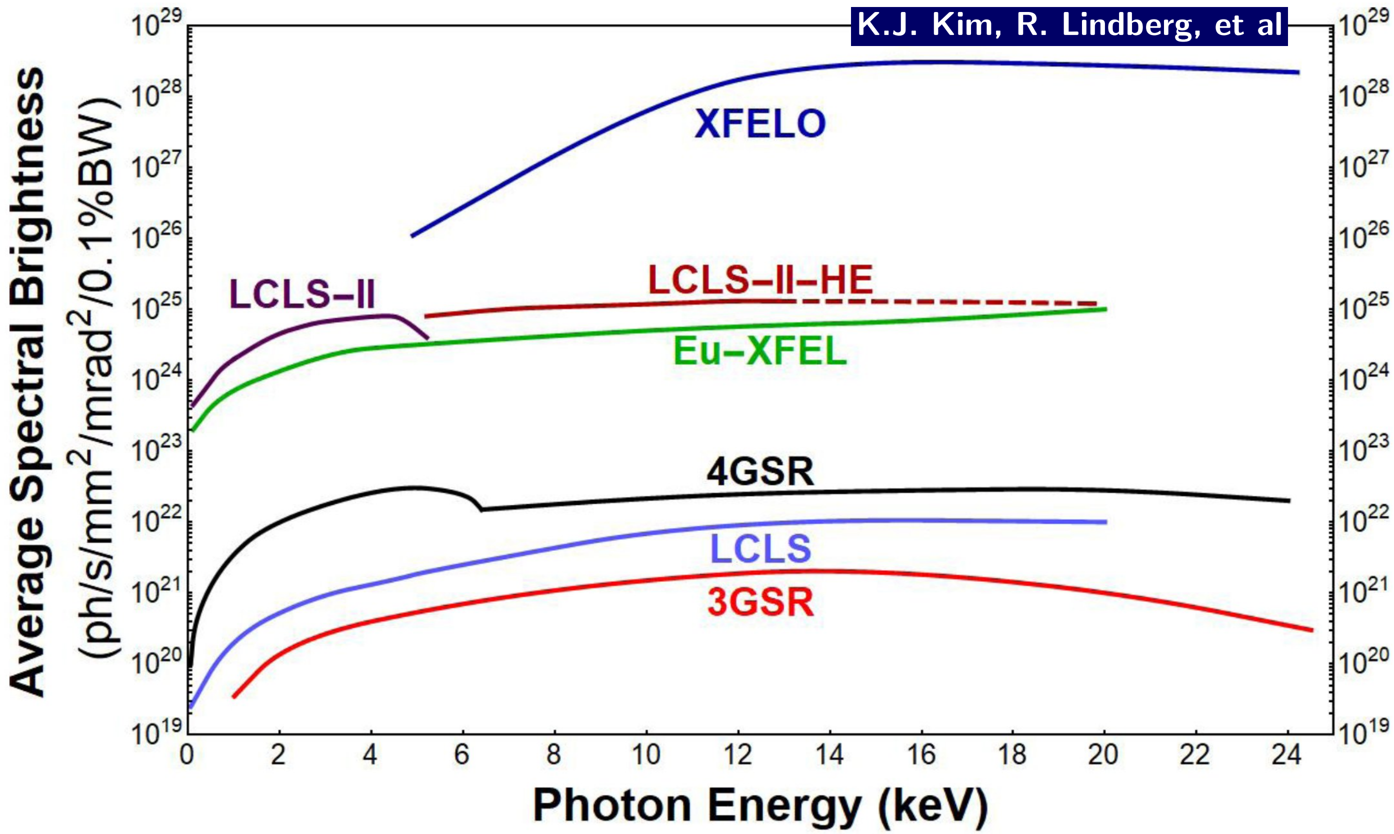
XFELO optical cavities are feasible:

- Tunable XFELO cavities can be constructed.
- High-quality diamond crystals are available featuring $\simeq 99$% reflectivity.
- Coupling x-rays out of the cavity through a thin drumhead crystal is possible.
- Diamond crystals survive $\simeq$ 12 kW/mm^2 power loading expected in the XFELO cavity and preserve high reflectivity.
- Focusing mirrors/lenses appropriate for XFELO cavity are commercially available.
- Heat load problem: simulations indicate that Bragg reflection region variations can be $\lesssim 1$ meV.
- Angular stability $\simeq 20$ nrad (rms) can be achieved.

XFELO Performance

Performance:

- fully coherent hard x-ray source
- highest average spectral brightness
- meV spectral bandwidth
- ps pulses
- 10^9 photons/pulse ($\simeq 1\ \mu$J)
- 1 MHz repetition rate.



XFELO Performance $\Longrightarrow$ Applications

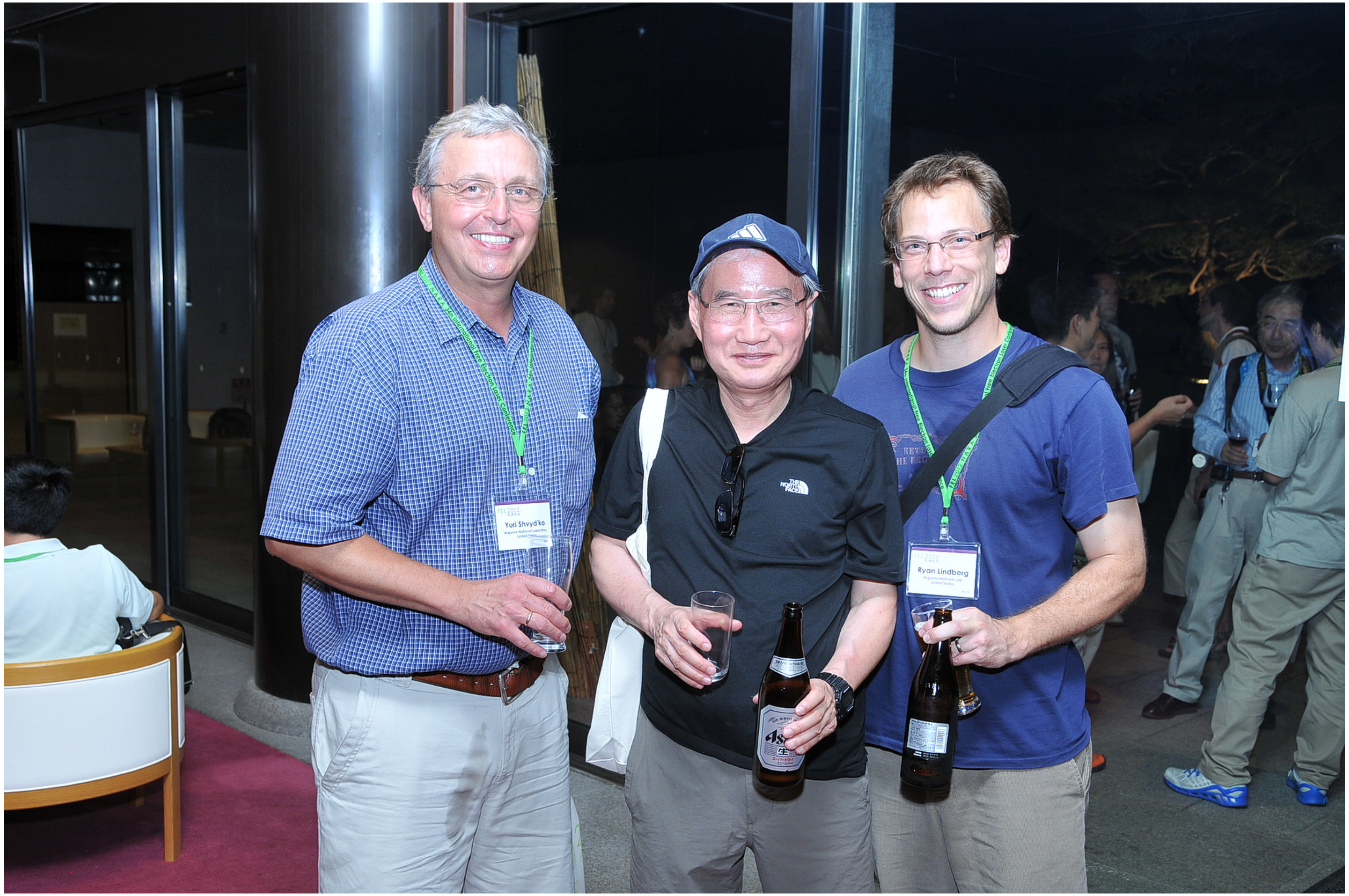
Performance:

- fully coherent hard x-ray source
- highest average spectral brightness
- meV spectral bandwidth
- ps-pulses
- 10^9 photons/pulse
- 1 MHz repetition rate.

Applications:

- inelastic X-ray scattering (IXS)
- nuclear resonant spectroscopies
- photon correlation spectroscopy
- non-linear x-ray optics and spectroscopy
- imaging at near-atomic resolution ($\simeq 1$ nm)
- x-ray comb generation

Happy Birthday, Kwang-Je!
and Many More to Come



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