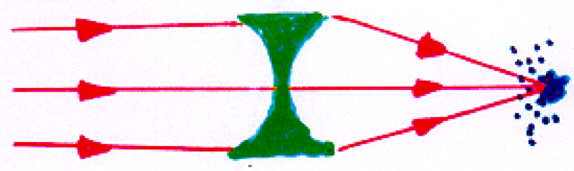
WG5 Summary Viewgraphs

A. Freund, ESRF

APRIL 6-9, 1999
ARGONNE NATIONAL LABORATORY, ARGONNE, IL U.S.A.

Report of Working Group V
(A. Freund)

PHOTON[1] OPTICS[2]



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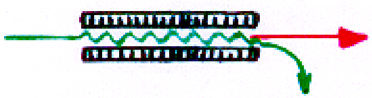

FUTURE LIGHT SOURCES[3]

1. X-rays, mostly hard.

2. - Crystal and multilayer monochromators
   - Mirrors
   - Zone plates (for focusing)
   - Refractive lenses (for focusing)

3. Ultra: - bright
   " - short
   " - coherent
   " - collimated pulses.

LCLS

TESLA FEL

Participants:

J. ARTHUR (SSRL), L. ASSOUFID (APS), A. FREUND (ESRF),
J. HASTINGS (BNL), M. HOWELLS (LBL), F. KRASNICKI (APS),
R. KHATCHATRYAN (APS), W. K. LEE (APS), A. MACRANDER (A
J. MASER (APS), D. MILLS (APS), C. NAVE (Daresbury),
H. SCHULTE-SCHREPPING (DESY), R. TATCHYN (SSRL), + ...

Working Group V: Photon Optics for Future Light Sources

Meeting Room: E1100/E1200 and B3100B
(see next page for details)

Group Leader:

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Objective:

The beams of fourth-generation light sources will raise new challenges for the optical elements needed for the optimization of phase space parameters according to the experimental requirements. The objectives of this working group are:

1. to pinpoint the relevant problems,
2. to evaluate them,
3. to propose strategies to solve them.

Working Group Activities:

The main optical elements are crystals, mirrors, gratings, multilayers and combinations of them, e.g., multilayer gratings, Bragg-Fresnel optics. All these devices have fundamental and technological performance limits in terms of their quality without and with heat load. These must be discussed in the light of the future extremely bright laser beams, both in the soft and in the hard X-ray regime.

The following topics are proposed for discussion by the working group members:

1. FEL beam interaction processes with materials constituting the beamline elements (including slits and absorbers/attenuators).
2. Matters related to the preservation of emittance/coherence, e.g., optical quality of surfaces:
    - Overview of coherence preservation of present-day optics.
    - Needs for improvements of optical performances.
    - Ways to upgrade existing devices for use in FEL beams.
    - New concepts.

3. Matters related to the preservation of brilliance, e.g., radiation resistance, heat load:
   - Overview of brilliance preservation of present-day optics.
   - Needs for optics that can withstand FEL beams.
   - Ways to improve upon existing schemes and limits.
   - New concepts.
4. Matters related to the time structure of FEL beams:
   - Pulse length preservation of optics.
   - Needs for optics to modify/control the time structure.
5. Possibilities to perform experiments on existing sources.

Working Group Input/Output:

We will get input from experts in the field of synchrotron X-ray optics who know the optics performance under the brightest presently available conditions and from other experts in the laser area who have experience with ultra-bright and ultra-short photon pulses. We will try to extrapolate from the existing knowledge to predict the performance of the optics for soft and hard X-ray FELs.

We will attempt to come up with an outline of R&D strategies to meet the future photon optics needs for FEL-based experiments.

Schedule of Presentations to the Working Group:

Tuesday, April 6: Session 0. 15:00 - 17:00, Group V.

Wednesday, April 7
Session 1: Joint Session of Working Groups I and V

Chairs: G. Materlik, A. Freund
Location: E1100 and E1200

10:30	Improving SASE Sources by Seeding	L. H. Yu
11:00	Atomic Resolution Holography	I. McNulty
11:30	Optics Needs for Future Light Sources (A summary and conclusions of the Stanford 97 Meeting)	J. Arthur
12:00	Lunch	
13:00	Overview of the Present LCLS X-ray Optics System	R. Tatchyn
13:30	Optics Needs for the DESY Project	H. Shulte-Schrepping
14:00	Multi-photon Methods	B. Adams
14:30	Break	
15:00	Outlook for Correlation Spectroscopy	S. Mochrie
15:30	Opportunities for Pump-Probe Methods	D. Umstadter
16:00	Working Group Progress Reports (plenary session in the Auditorium)	

Thursday, April 8
Working Group V, Sessions 2 and 3

A. – Imaging
B. – Multiphoton ....
C. – Correlation Spec
D. – Pump-probe

Chair: A. Freund

8:30 General participation with Working Group I sessions.
Special topic groups to be organized, if needed.

12:00 Lunch

Session 2 - Chair: A. Macrander
Location: B3100B (alternate: LOM438)

13:00 Addressing the Optical Needs for Various Techniques

14:00 Break

Session 2 (continued) - Chairs: J. Arthur, R. Tatchyn
Location: B3100B (alternate: LOM438)

14:~~0~~30 State-of-the-Art Optical Elements + R&D topics

L. Assoufid
A. Freund
M. Howells
A. Macrander
D. Mills
(T. Kuzay)

Session 3 - Chair: A. Freund
Location: B3100B (alternate: LOM438)

15:00 Optics R&D, (~~beamline scenarios, report writing~~,) and future planning

Information and Preparations Requested of Working Group Members:

Group members making presentations are requested to bring color copies and, if possible, electronic files of their presentation material for inclusion in the workshop proceedings.

Information Requested of This Working Group by Other Working Groups:

From Working Group I:

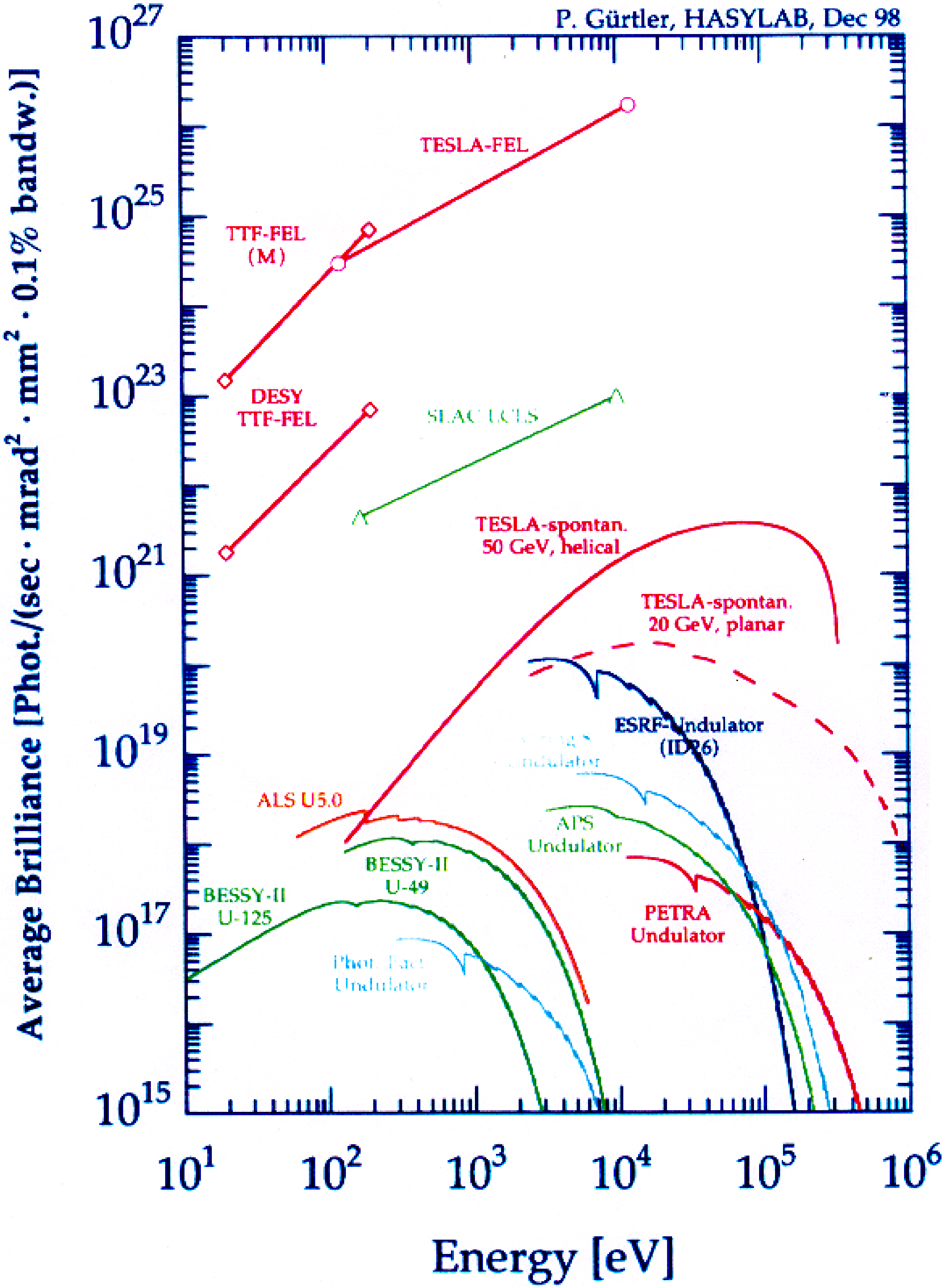
- Input on requirements for beamline optics to match the experimental needs and on the physics of FEL light-matter interaction mechanisms

From Working Groups II and III:

- Input on the beam properties

From Working Group VII (possibly):

- Input on testing and validating techniques



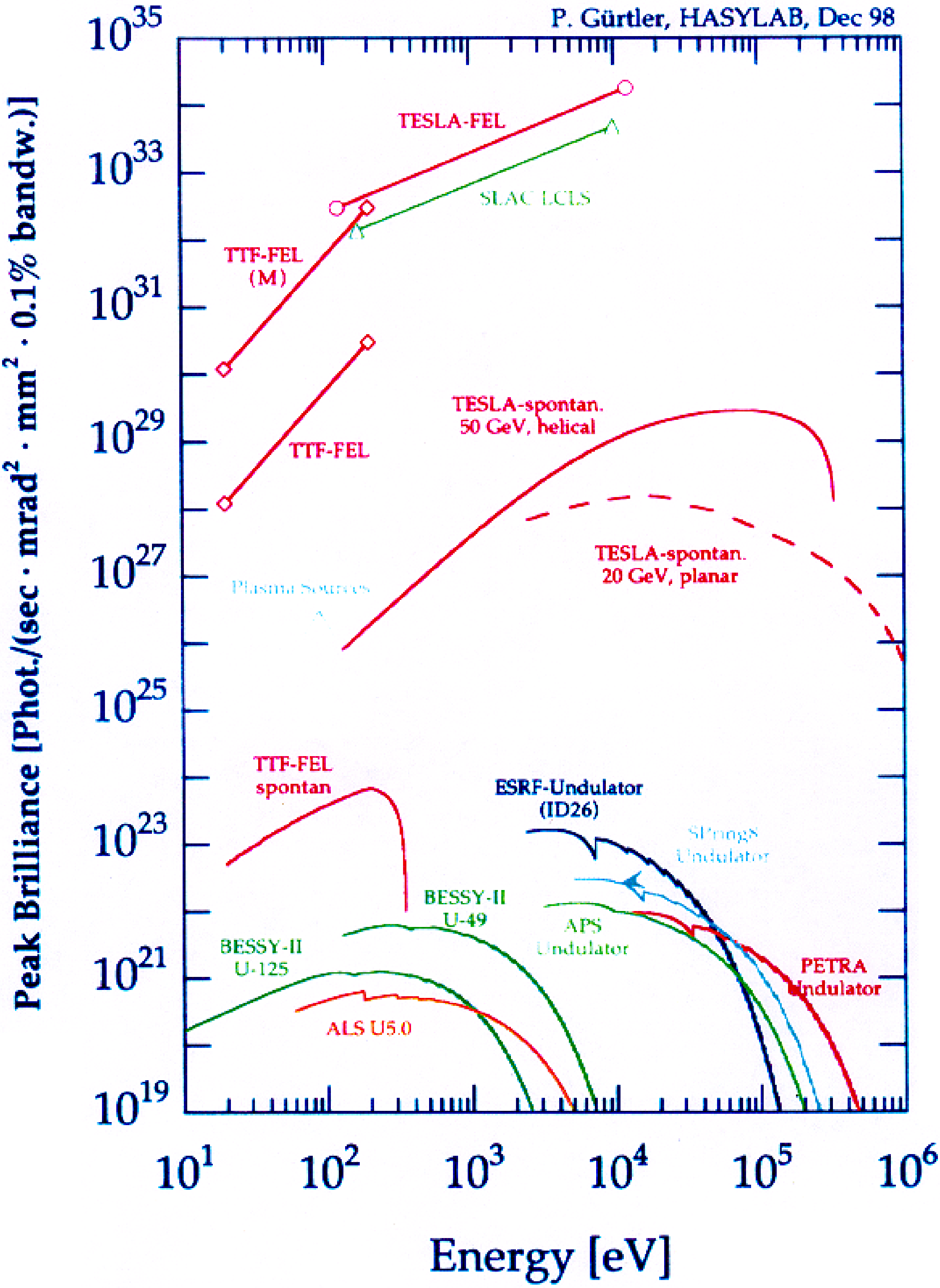
Spectral Brilliance (SB):

partially coherent source : $$SB = \frac{spectral\ Flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_z \Sigma_{z'}}$$

$$\Sigma = \sqrt{\sigma_e^2 + \sigma_p^2}$$

fully coherent source : $$SB = \frac{spectral\ Flux}{(\lambda / 2)^2}$$

$$\Sigma' = \sqrt{\sigma_e'^2 + \sigma_p'^2}$$



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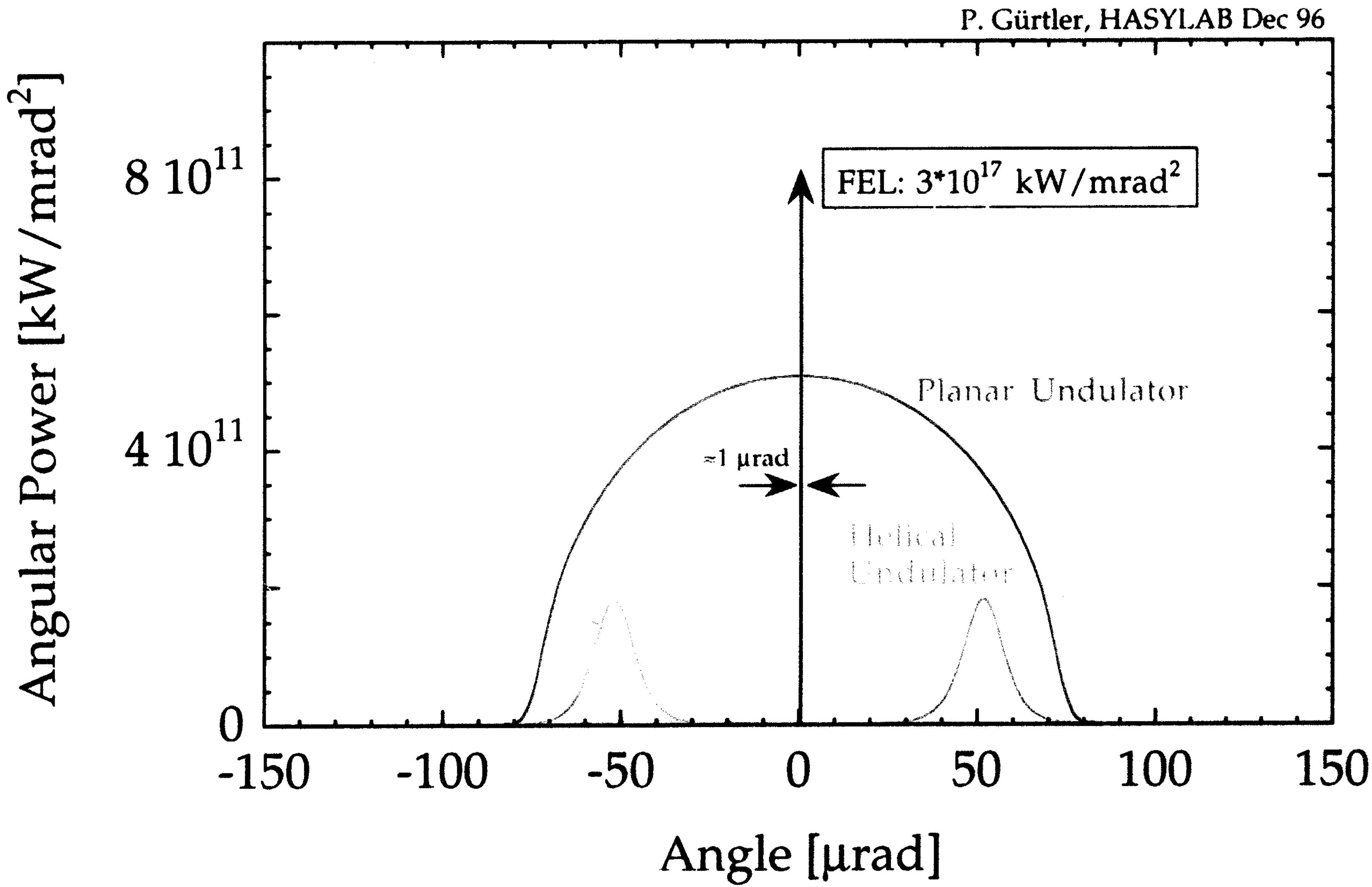
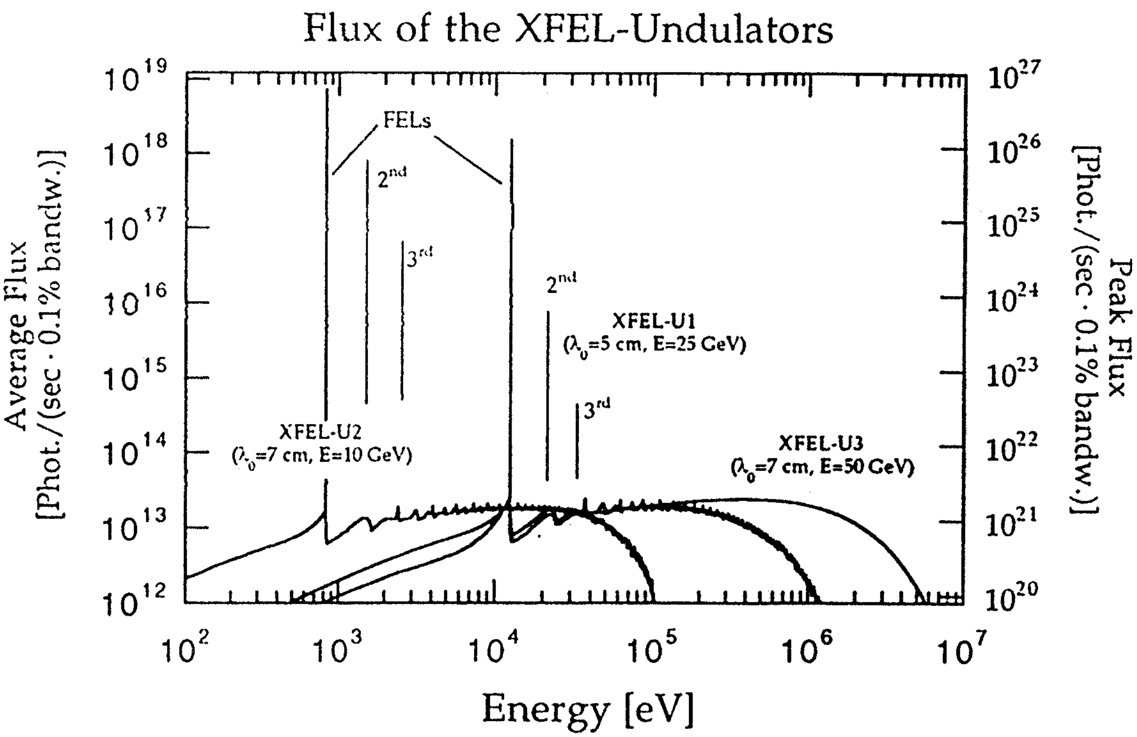


P. Gürtler, HASYLAB Dec 96
Angular Power [kW/mrad²]
8 10¹¹
4 10¹¹
0
FEL: 3*10¹⁷ kW/mrad²
Planar Undulator
≈1 µrad
Helical
Undulator
-150
-100
-50
0
50
100
150
Angle [µrad]

Summary of design parameters for the three X- FEL's

		Undulator 1		Undulator 2		Undulator 3	
Period Length	cm	5		7		7	
Field Type		Planar, Tapered		Planar, Tapered		Helical, Tapered	
Nominal Design Gap	mm	12		12		12	
Peak Field	T	0.887		0.85		0.785	
K-Value		4.14		5.55		5.13	
Energy Range	GeV	10	25	10	25	25	50
Radiative Wavelength	nm	0.625	0.1	1.5	0.24	0.4	0.1
Min. Device Length	m	33	95	35	87	45	95
External β-function	m	6	15	8	20	7.5	15
Peak Power	GW	74	65	85	85	280	280
RMS Beam Size	μm	18		20		12	



Average and peak flux for undulators 1,2, and 3 at the fundamental, second and third harmonic, respectively. The average values refer to TESLA parameters, while SBLC numbers are smaller by a factor of two.

- **LCLS source properties (preliminary studies)**

Table 1. Optical and physical parameters of the LCLS. Undulator K=3.67. N_u=3300 periods. Undulator period λ_u=3 cm.

Radiation wavelength [Å]	1.5	15
Norm. emitt. $\gamma\varepsilon$ [mm-mrad]	1.5	2.0
Electron energy [GeV]	14.35	4.54
Peak current [A]	3400	3400
Bunch duration [fs, FWHM]	277	277
Peak spontaneous power [GW]	81	4.9
Peak coherent power* [GW]	9	11
Average coherent power** [W]	0.31	0.35
Energy/pulse [mJ]	2.5	0.64
Coherent photons/pulse ($\times 10^{12}$)	1.9	23
Approx. Bandwidth (BW) [%]	0.1	0.1
Peak brightness*** ($\times 10^{32}$)	12	1.48
Peak degeneracy parameter [$\times 10^9$]	3.3	412
Average brightness*** ($\times 10^{21}$)	40	4.9
Transverse size [µm, FWHM]****	78	93
Divergence angle [µrad, FWHM]****	1	8
Spontaneous fundamental opening angle [µrad, FWHM]	4.9	15.5
Spontaneous fundamental transverse size [µm, FWHM]	82	131
Peak Power Density [W/mm^2]** ($\times 10^{12}$)**	**1.88**	**1.62**
Peak Field [V/m]**($\times 10^{10}$)**	**3.8**	**3.5**

*Output fully transversely coherent; **at 120 Hz pulse rep rate; ***Photons/s/mm^2/mrad^2/0.1%BW; ****At undulator exit

- **LCLS brightness & degeneracy parameter:**

$$B = \frac{N_{phot}/\sigma_\tau}{(2\pi)^3 \varepsilon_x \varepsilon_y \left(\frac{\sigma_f}{f}\right)}$$

$$\delta = \frac{(\lambda/2)^2 N_{phot}}{(2\pi)^3 \varepsilon_x \varepsilon_y \sigma_\tau \sigma_f} = B\left(\frac{\lambda^3}{4c}\right),$$

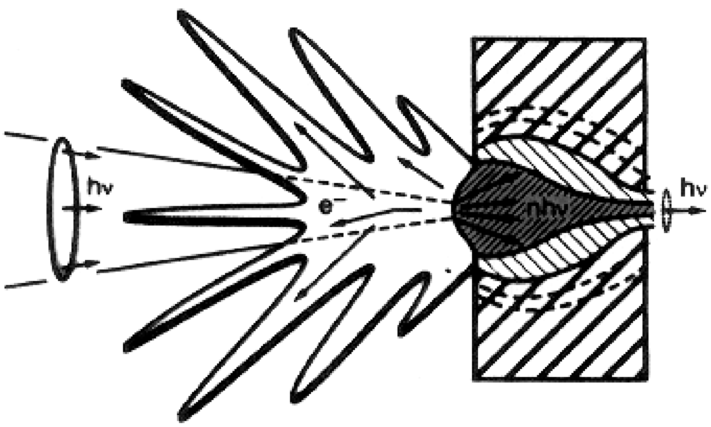
SLAC/DESY International Workshop
on
Interactions of Intense Sub-picosecond X-Rays with Matter

Stanford Linear Accelerator Center, Stanford, CA
January 23-24, 1997

Organization, Program, and Executive Summary

R. Tatchyn, G. Materlik, A. Freund, J. Arthur

SLAC-WP-12



Prepared for the Department of Energy
under contract number DE-AC03-76SF00515

STANFORD LINEAR ACCELERATOR CENTER
STANFORD SYNCHROTRON RADIATION LABORATORY
Stanford University • Stanford, California

Primary conclusion of workshop:

Much is not known about the interaction of an XFEL pulse with matter

Theoretical work and numerical simulation could help greatly in this area

Second conclusion of workshop:

XFEL optics will be different from 3rd-generation synchrotron optics

Development efforts should start immediately on XFEL optics and detectors!

Ionsec

TABLE 1.1

Evaporation fields calculated for some common ions by Southworth (1969, private communication) using a method devised by Brandon (1966a)

Element	F_1(V/Å)	F_2(V/Å)	Ion expected	Element	F_1(V/Å)	F_2(V/Å)	Ion expected
Be	5.4	4.6	Be^{2+}	Mo	6.5	4.0	Mo^{2+}
B	6.4	7.9	B^{+}	Ru	6.3	4.1	Ru^{2+}
C	14.2	10.3	C^{2+}	Rh	4.9	4.1	Rh^{2+}
Mg	2.0	2.5	Mg^{+}	Pd	3.7	4.1	Pd^{+}
Al	1.8	3.4	Al^{+}	Ag	2.3	4.4	Ag^{+}
Si	4.5	3.3	Si^{2+}	Cd	2.6	3.1	Cd^{+}
Ca	1.6	1.6	Ca^{2+}	Sn	2.6	2.3	Sn^{2+}
Ti	3.9	2.5	Ti^{2+}	La	3.1	1.9	La^{2+}
V	4.0	2.8	V^{2+}	Ta	9.6	4.9	Ta^{2+}
Cr	2.9	3.0	Cr^{+}	W	10.4	5.9	W^{2+}
Mn	2.8	2.8	Mn^{2+}	Re	8.2	4.3	Re^{2+}
Fe	4.2	3.4	Fe^{2+}	Os	10.8	4.4	Os^{2+}
Co	4.3	3.7	Co^{2+}	Ir	8.5	4.8	Ir^{2+}
Ni	3.5	3.5	Ni^{2+}	Pt	6.1	4.4	Pt^{2+}
Cu	3.1	4.3	Cu^{+}	Au	4.8	5.0	Au^{+}
Zn	2.9	3.5	Zn^{+}	Hg	2.9	3.7	Hg^{+}
Ga	1.6	3.9	Ga^{+}	Tl	1.1	3.6	Tl^{+}
Ge	3.5	2.9	Ge^{2+}	Pb	2.0	2.3	Pb^{+}
Zr	5.7	2.8	Zr^{2+}	Bi	(3.0)	2.6	Bi^{2+}
Nb	7.0	3.7	Nb^{2+}				

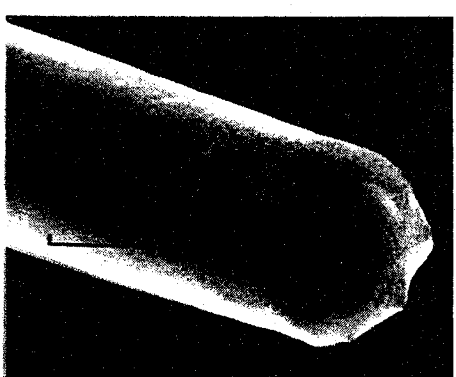


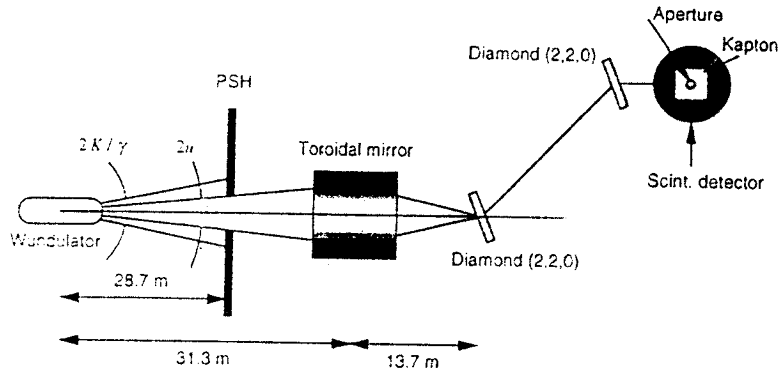
Fig. 1.7. Scanning electron micrograph of a field-ion specimen of tungsten that has fractured under the influence of the imaging field.

Bowkett & Smith, "Field Ion Microscopy"

Strongest heat load tests of a single crystal monochromator:

Diamond single crystal - the ultimate

heat load tests @ ESRF on wundulator source BL3/ID9

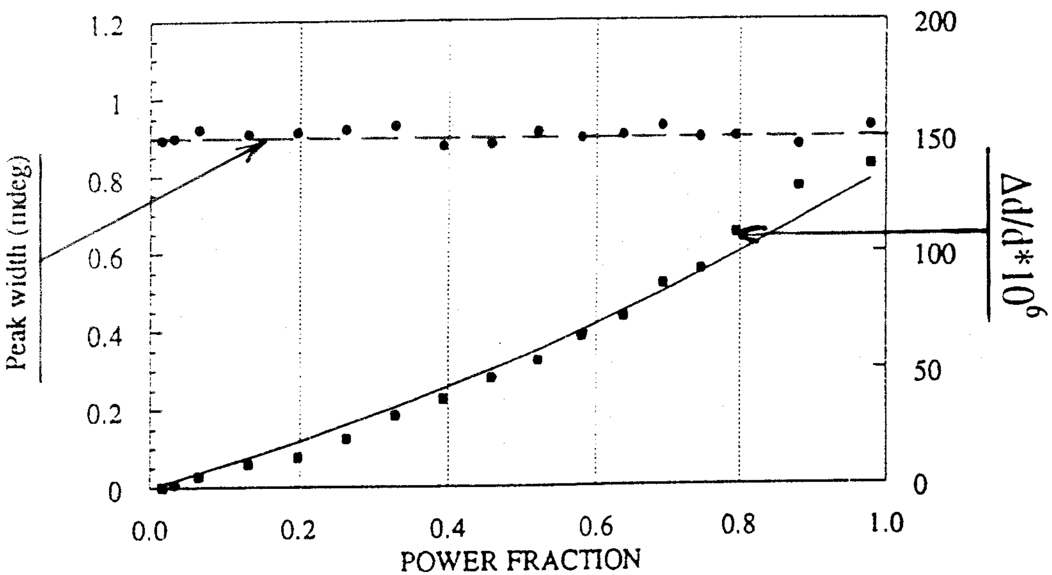


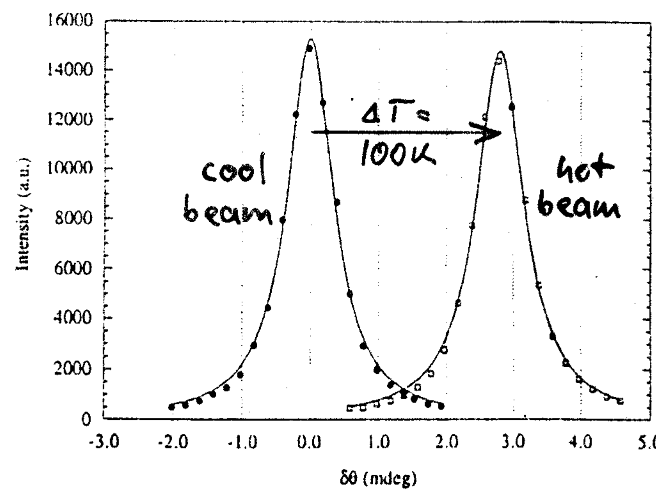
the beam is focused by the toroidal mirror onto a 4 x 8 x 0.1 mm^3 synthetic diamond crystal (Laue case)
(supplied by F. Sellschop, University of Johannesburg)

➡ incident [spot 0.2(h) x 0.4(v) mm^2]: P_t = 280W => **P_s = 3500W/mm^2** ↗ 3MW/mm^2 peak power density.

➡ absorbed : P_t = 8.7W (3.1%) and **P_s = 109W/mm^2**

Heat Flux 50x that on the sun's surface!!!





from J. Als-Nielsen et al. , NIM B, 94, (1994)

NEEDS EXPRESSED BY TECHNIQUES

- **BRILLIANCE:**

  should be preserved at maximum!

  → **R&D : Heat load, radiation damage.**

  ✓ Average heat load : a few Watts, no problem!

  ✓ Peak heat load : to be studied

  ✓ Interaction mechanism radiation-matter : to be studie[d]

  - simulation programs at LLNL : cost, manpower.

  Rough estimates:

  LCLS power → 1 V/Å a little below or equal to the damage threshold (D. Mills).

  Diamond better than silicon. (A. Macrander).

  If melting → recrystallization.

  Conclusions:

  - **Crystal optics should survive.**
  - **Peak heat flux is in the critical region, can be studied by varying power.**
  - **No real tests possible with existing facilities.**

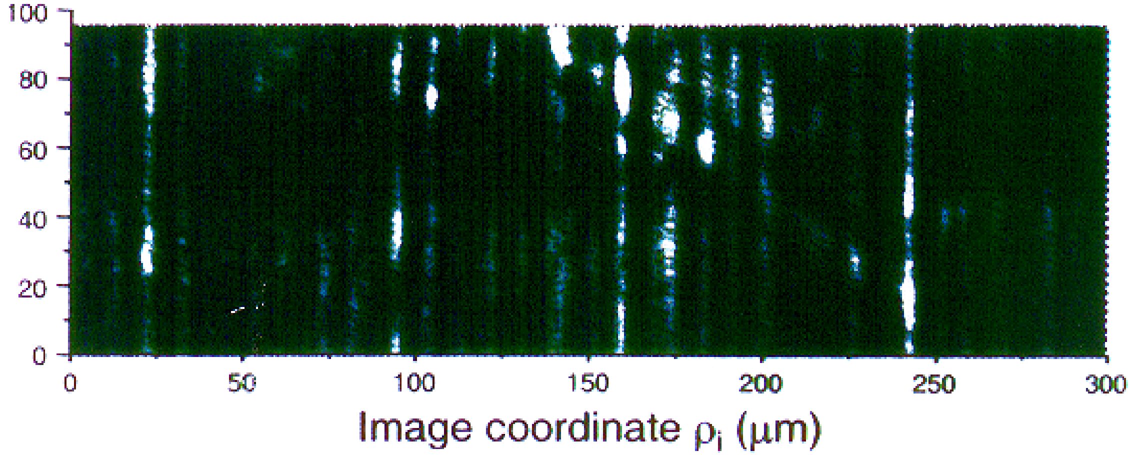
- **NOVEL OPTICS:**

  - **atom lattices produced by laser standing waves + atom beam.**
  - **"whispering gallery" (M. Howells).**

  → R&D: Increase density by 3 orders of magnitude to 10^{15} atoms/cm^3. Reflectivity tests.

Speckle pattern from a state-of-the art mirror

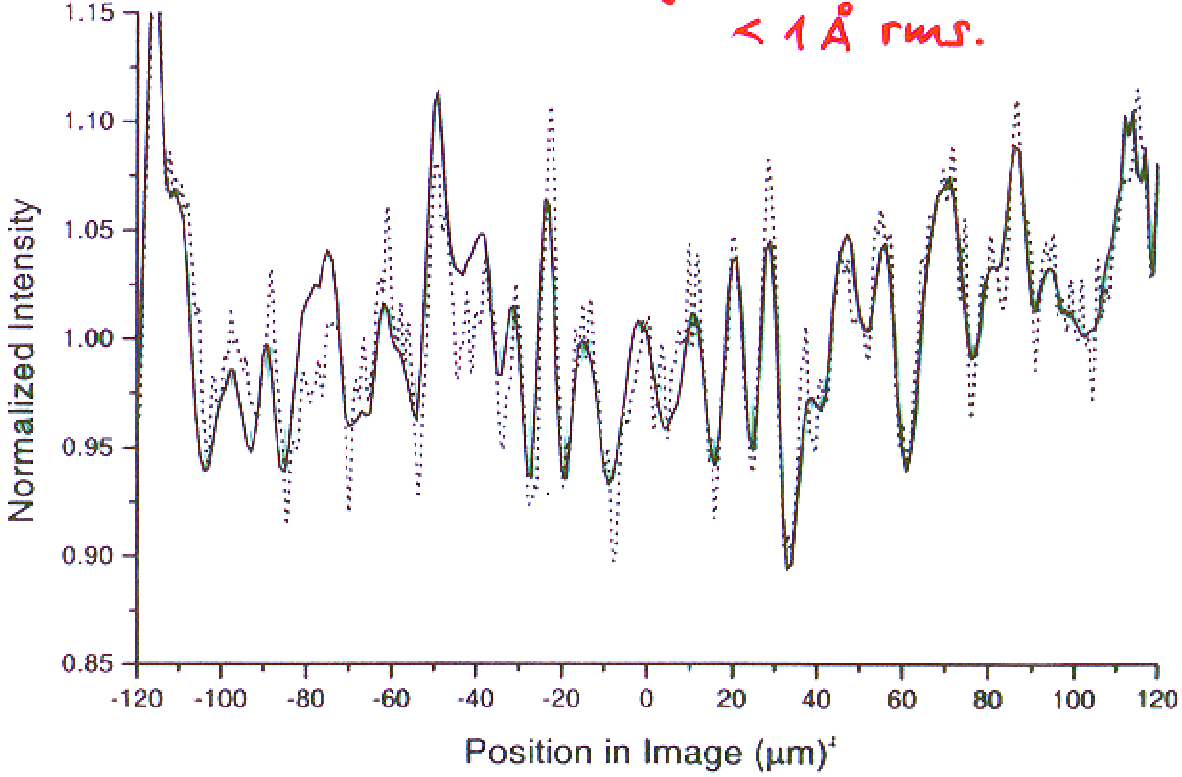
(Courtesy: A. Souvorov, ESRF)



a)

E = 16 keV ; - slope error (measured with LTA) ≲ 1 µrad rms.

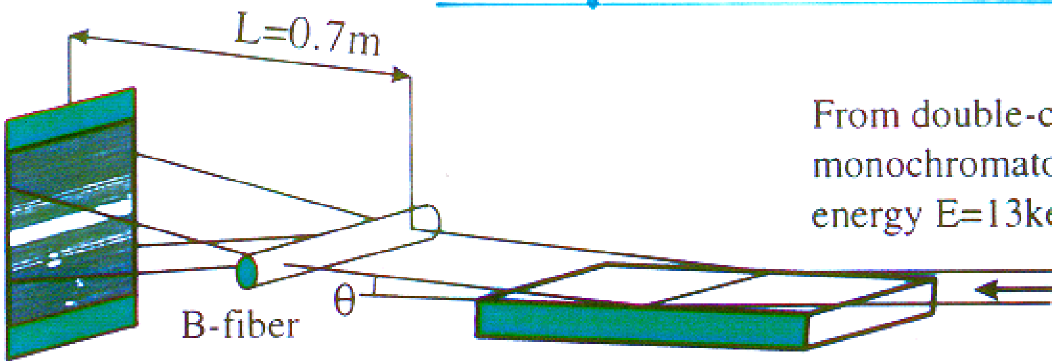
- roughness (measured with Promap) < 1 Å rms.



b)

Figure 3

Courtesy: A. Souvorov (ESRF)



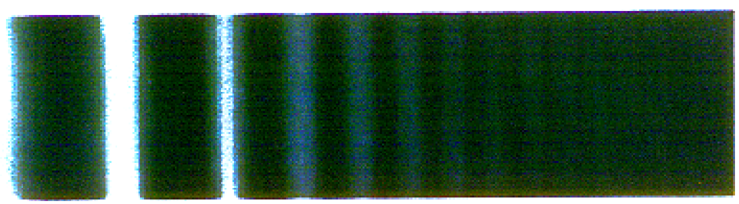
From double-crystal monochromator energy E=13keV

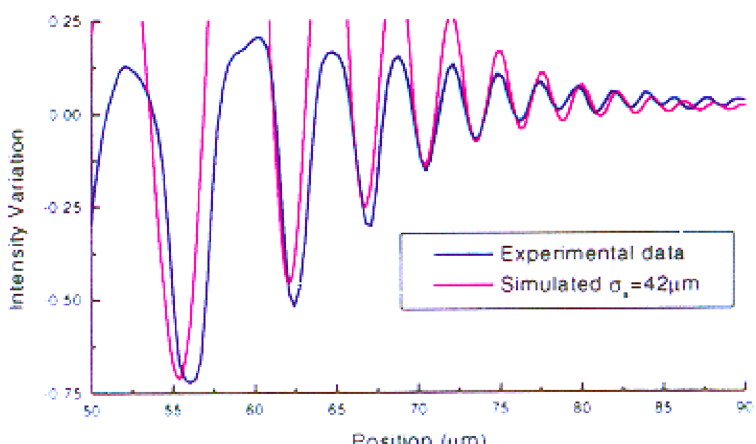
High resolution photo film or CCD camera

Ru/B_4C multilayer
period D=4nm, angle θ=0.69°
number of layers N=60
Length/Width 100×25mm

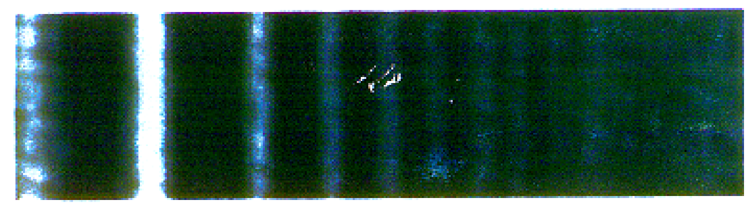
Intensity RMS~10.4%

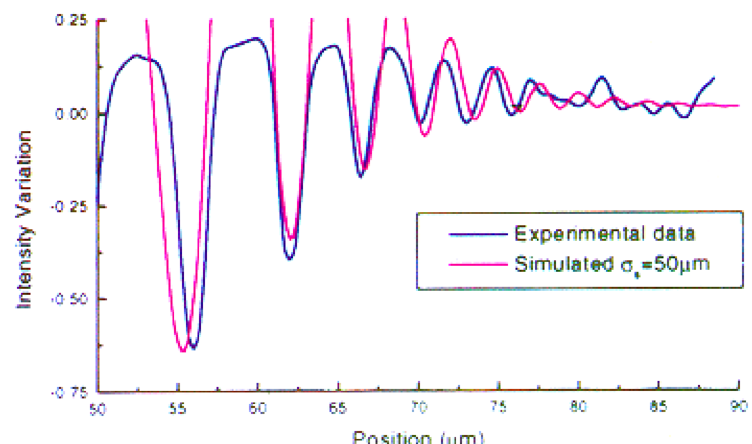
Incident beam





Reflected beam





Source size increment by 20%

Souvorov A.

NEEDS EXPRESSED BY EXP. TECHNIQUES (contd.)

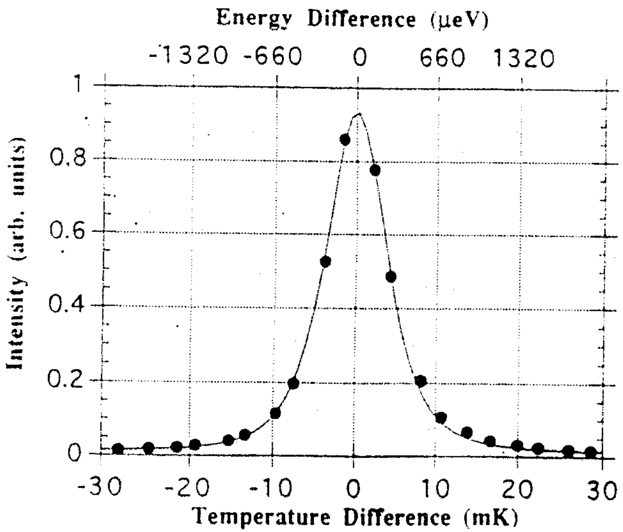
- **COHERENCE:**
- fully coherent or fully incoherent beams wanted!
  - → R&D:
    - Improve surface quality of mirrors & multilay
    - How to transform a coherent into an incoherent beam ???
    - Improve quality of diamond crystals. Be ?? Check if Laue (transmission case) is possible.
    - Silicon & germanium crystals OK.

- **BANDPASS + (tunable!) ENERGY RANGE** (-> gap scan
- range from very high resolution to 10^{-3} ($\Delta E/E$).
  - asymmetric Si & diamond needed. OK.
  - ! increase of beam divergence!
- 2x in E-range.

- **TIME STRUCTURE:**
  - pulse stretching and compression wanted!
  - variable spacing between pulses wanted!
  - → R&D:
    - Dispersive crystal or multilayer optics, chirp.
    - "Moving" optics

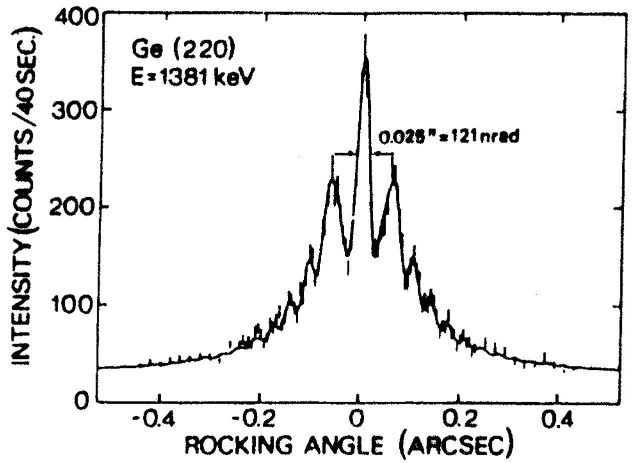
SINGLE CRYSTAL PERFECTION

SILICON



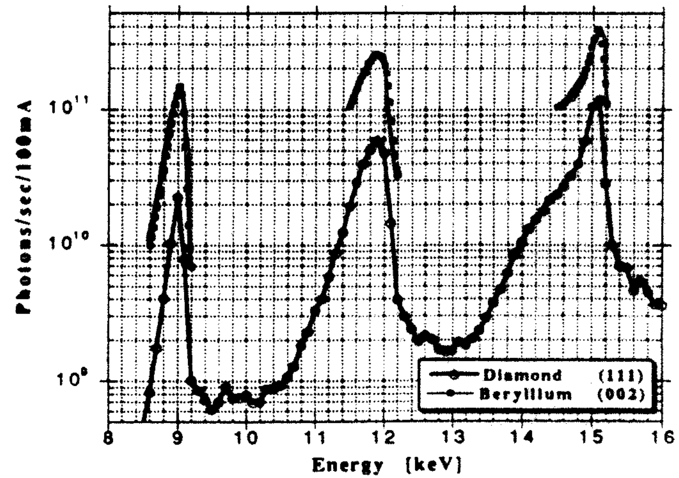
Backscattering Si (13,13,13)
rocking curve, T-scan at 26 keV
0.5 meV! **ΔE/E = 2·10⁻⁸ (FWHM)** ≈ Δd/d
(best value ever achieved)
Sette et al., ESRF Report (1995)
improved to $\Delta E/E = 9 \cdot 10^{-9}$!

GERMANIUM



Ge double crystal Laue
diffraction pattern at 1.4 MeV.
Excess width: $3 \cdot 10^{-8}$ rad.
(best value ever achieved)
Freund, RSI **63**, 414 ('92)
Dewey et al., PR **B50**, 2800 ('94)

BERYLLIUM, DIAMOND



ID10 undulator spectra
recorded with diamond
and Be single crystals.
0.5 x 0.5 mm² at 44 m.
Grübel et al. J.Phys. C9, 27 ('94)

EXAMPLES: Si AND DIAMOND AT 1.5 Å *

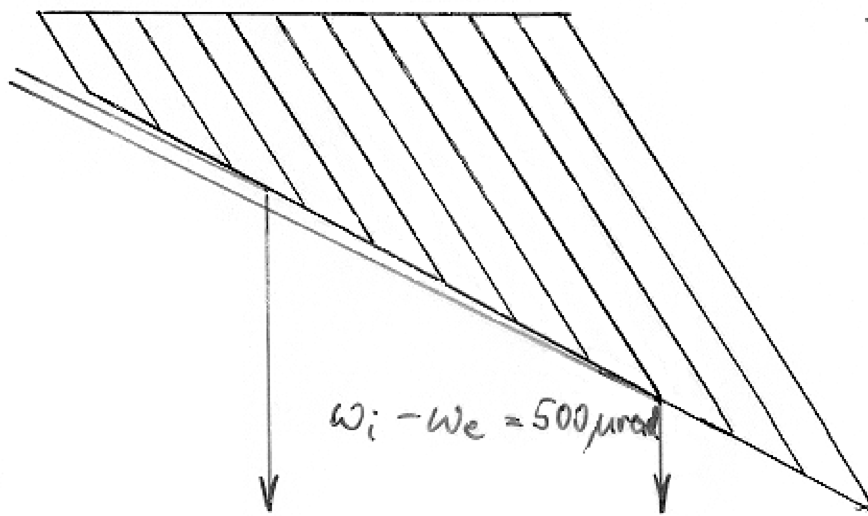
Crystal	d(Å)	θ_B	θ_i	θ_e	b	foot-print (mm)	$\Delta E/E$	t_{ext} (μm)	t_{abs} (μm)
Si(220)	1.9200	22.99°	0.1°	45.88°	411	85.9	1.2×10^{-3}	0.10	~~$3\cdot10^{-4}$~~ 0.124
C*(111)	2.0593	21.36°	0.1°	42.62°	388	85.9	1.2×10^{-3}	0.11	~~0.65~~ 2.33

↓ Power spreading factor: ≈ 600!

↓ full range reflected

Surface should be very smooth and precisely oriented: feasible!

* No refraction corrections of the Bragg angle included.

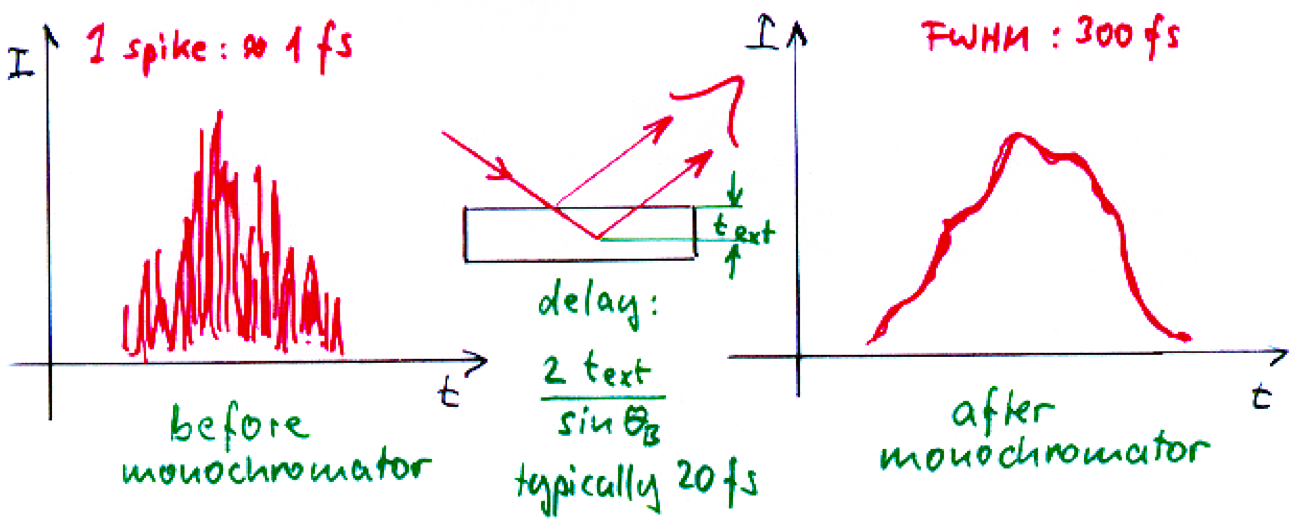


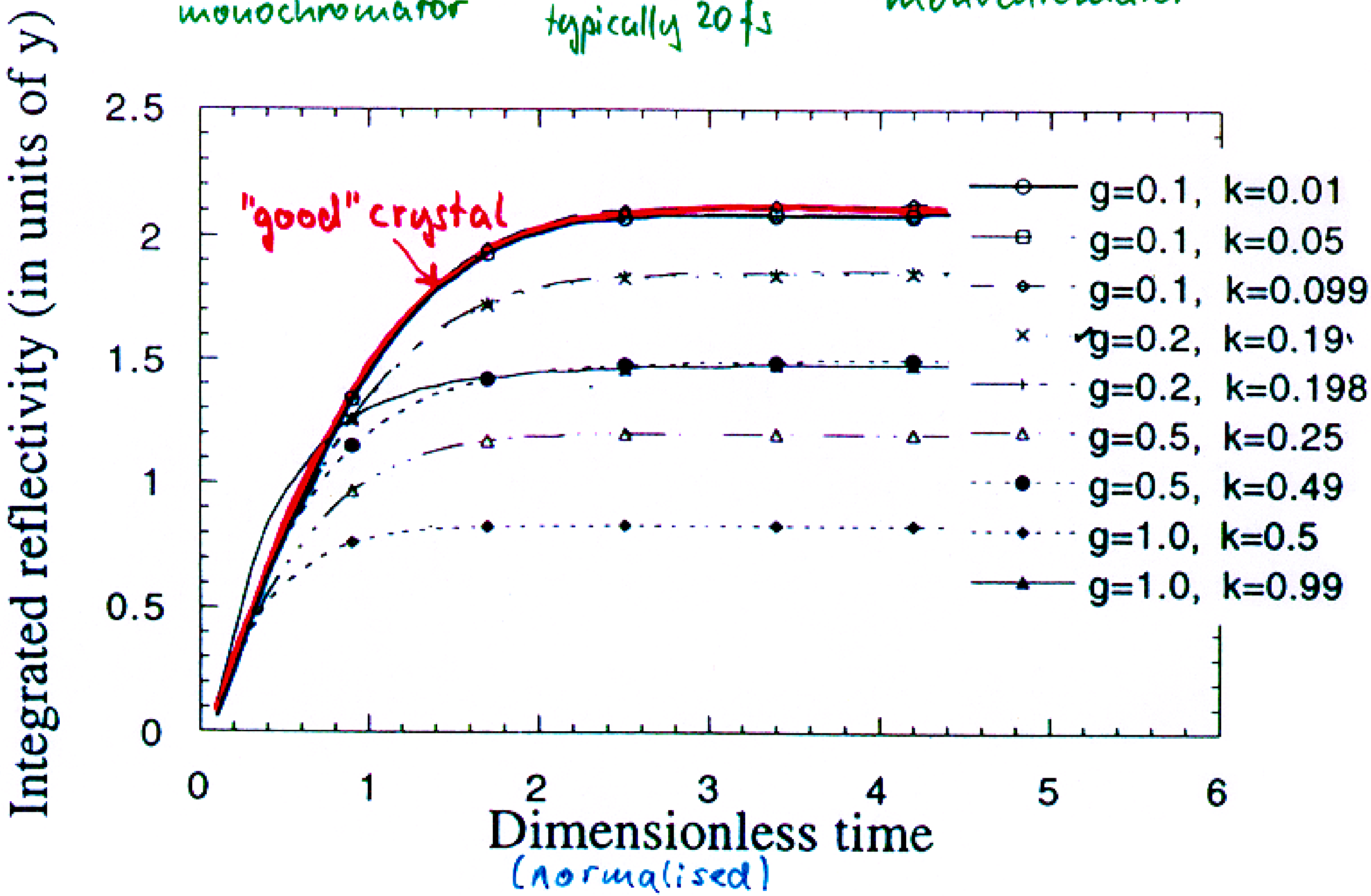
Further possibilities:

- inclined geometry
- Bormann effect (anomalous transmission)
- long beamlines

From:
A. Freund
SLAC Workshop (1997)

Advanced Photon Source (D. Mills)





Laser and Particle Beams (1994), *vol.* 12, *no.* 3, *pp.* 507–513
Printed in the United States of America

Subpicosecond X-ray diffraction

By J.S. WARK AND H. HE

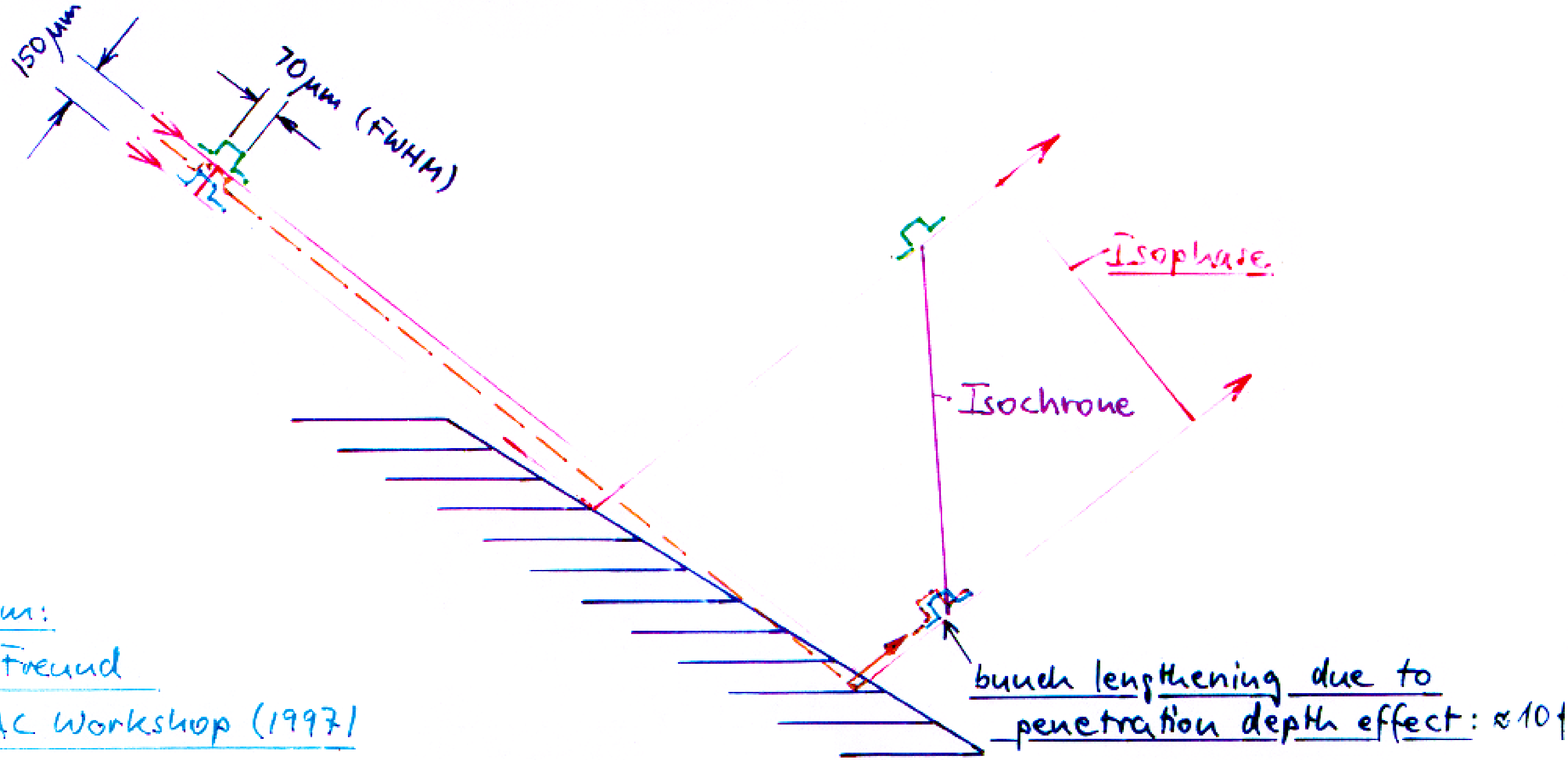
SOME CRYSTAL PARAMETERS AT 8 KEV

Material (h k l)	$d_H = \frac{1}{2}\lambda_{max}$ (Å)	$r_0 F_{Hr} e^{-M}/v_0$ (10^{-14} cm^{-2})	Darwin width ω_H (μrad)	energy resolution ε_H (10^{-6})	extinction thickness t_e (μm)	absorption t_a (μm)	
Be (002)	1.7916	5.59	10.7	22.8	5.0	1200	
Be (110)	1.1428	4.27	6.49	7.1	10.3	1874	
C* (111) (diamond)	2.0593	11.1	24.1	59.7	2.20	250	
C* (220)	1.2611	9.55	14.9	19.3	4.16	408	
Si (111)	3.1354	10.82	34.3	135	1.48	8.7	most
Si (220)	1.9200	12.29	25.3	57.7	2.12	14.2	commonly used
Ge (111)	3.2663	23.06	76.0	313	0.66	2.94	for high
Ge (220)	2.0002	27.51	58.5	140	0.91	4.79	energies

ISOPHASES AND ISOCHRONES

Possibilities:
- Time dispersion
- Time focusing
- Bunch lengthening
- Bunch compression

In connection with:
- Time-Energy dependence of source
- Gradient crystals



From:
A. Freund
SLAC Workshop (1997)

NEEDS EXPRESSED BY EXP. TECHNIQUES (ctd.)

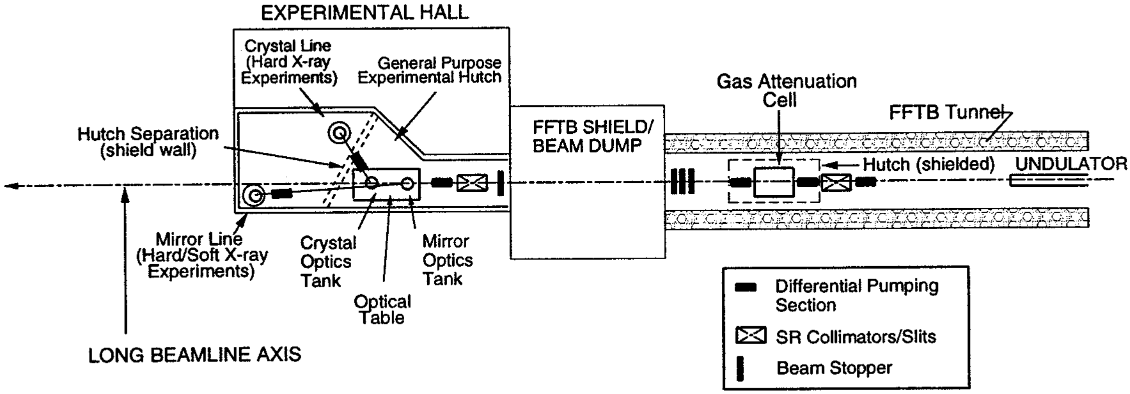
- **FOCUSING:**
  - sub-micron focal spot needed.
    possible with existing elements (zone plates, Kirkpatrick-Baez mirrors or multilayers)
  - but further decrease to 100 nm needs R&D
    → waveguides (1-dimensional ⇒ 2-dimensional).
    Warning: mirrors → coherence degradation!
  - maybe renewable optics required. (ZP, CRL ....)

  - multiple element system needed to record full information without turning sample in 1 shot.
    → R&D project required.

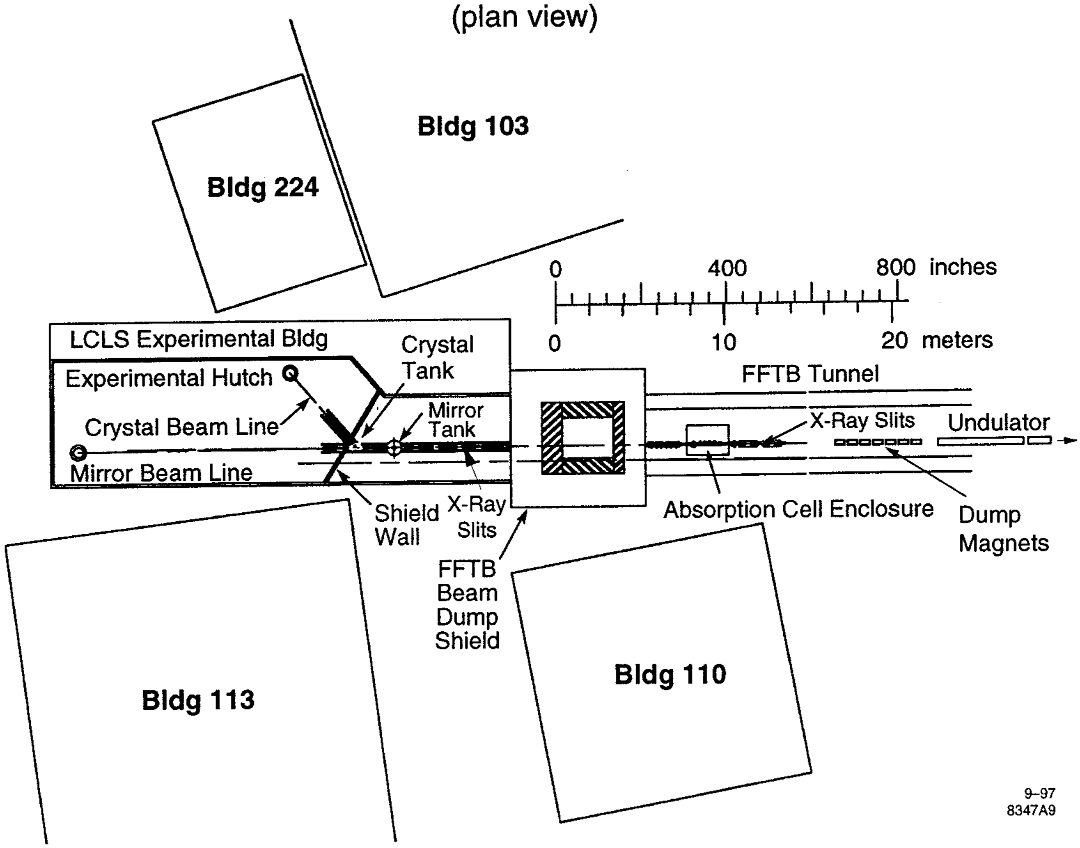
- **DETECTORS:**
  - very important (fast multielement APDs for example).
    → working group should be formed as soon as possible.

- **OTHER SUBJECTS TO BE ADDRESSED:**
  - stability
  - alignment
  - attenuators
  - slit systems
  - etc.
  - etc.

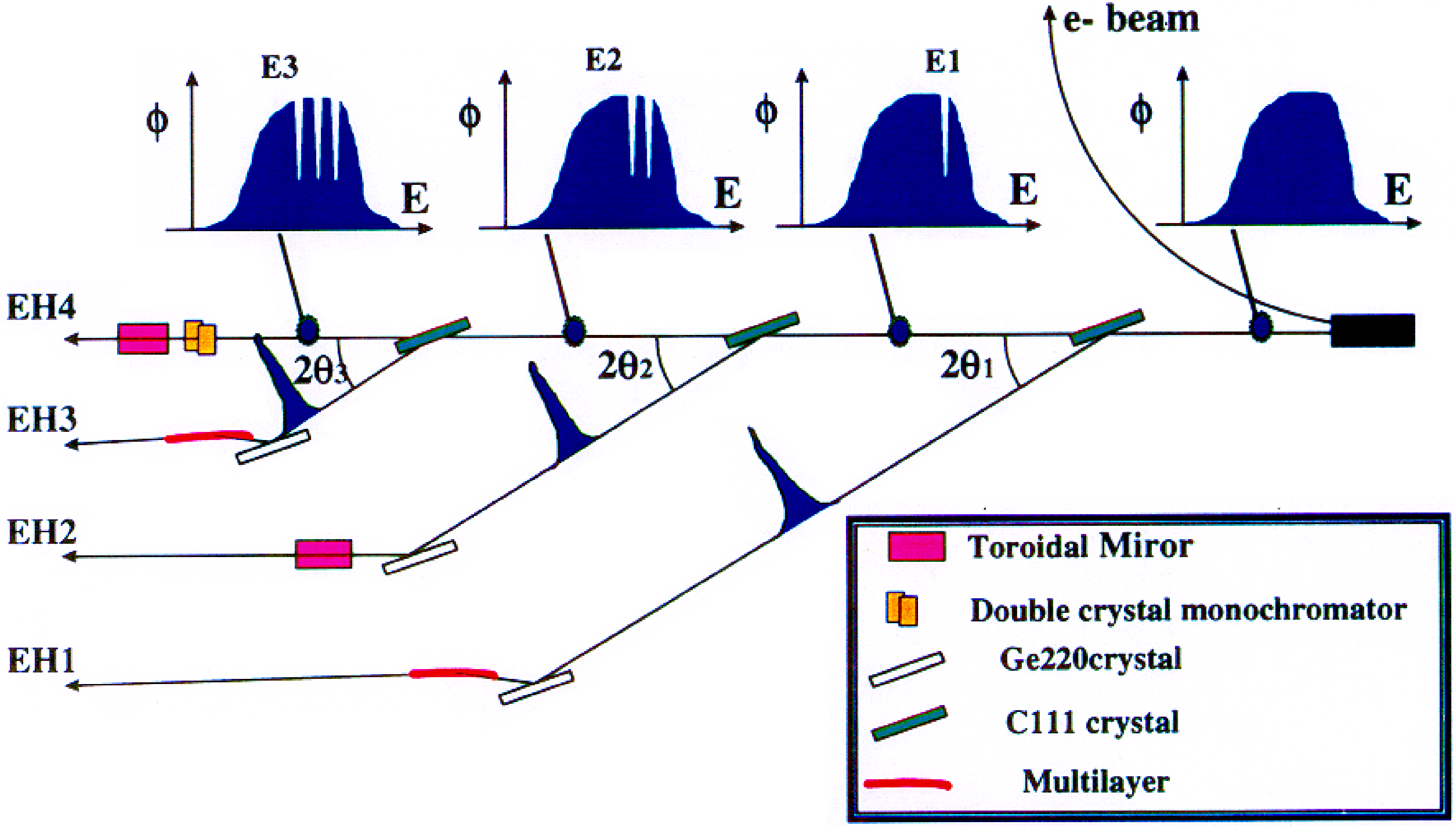
- **schematized LCLS X-Ray Optical system**



- **preliminary design**



ID14-Quadriga principle



Courtesy: S. WAKATSUKI (ESRF)

- **the absorption cell**

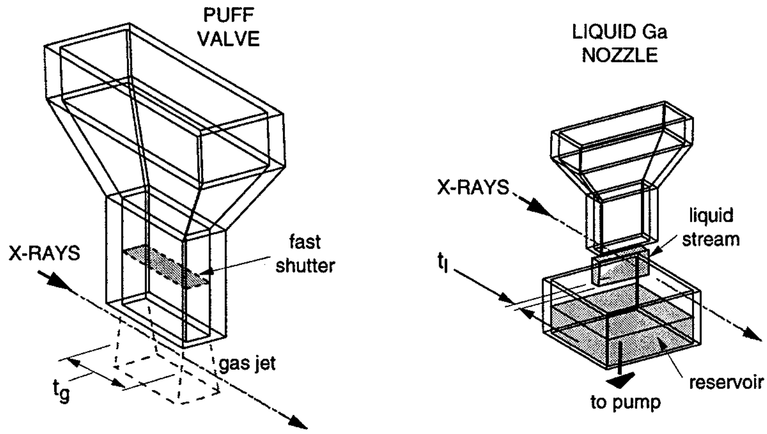


Figure 4.1.4.1. Schematized gas (left) and liquid (right) nozzle configurations for the LCLS absorption cell.

Table 4.1.4.1. Absorption cell valve and vacuum parameters. Valve orifice width 250 µm; t_g=1cm; gas jet height 1 mm.

Valve Rep Rate [Hz]	120	12
Valve Pressure [Torr]	7500	7500
Particles/Puff	6.65×10^{17}	6.65×10^{17}
Chamber Pump Capacity [l/s]	1800	1800
Gas Load Q [Torr-l/s]	2.25	0.225
Average Pressure [Torr]	1.25×10^{-3}	1.25×10^{-4}

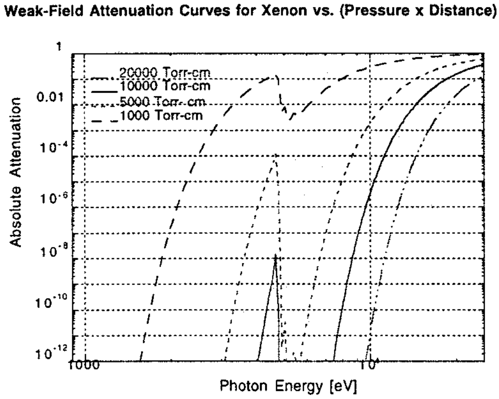


Figure 4.1.4.2. Weak-field attenuation curves for xenon.

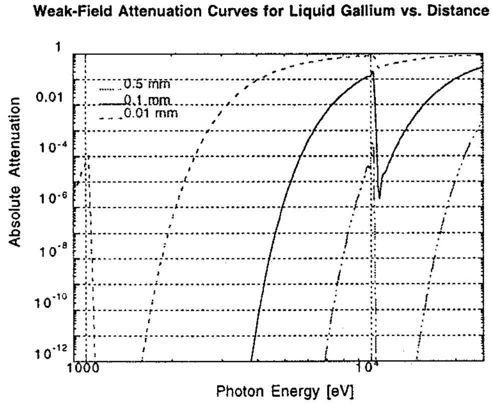


Figure 4.1.4.3. Weak-field attenuation curves for gallium.