Optics needs for the DESY-XFEL project

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HASYLAB

DESY

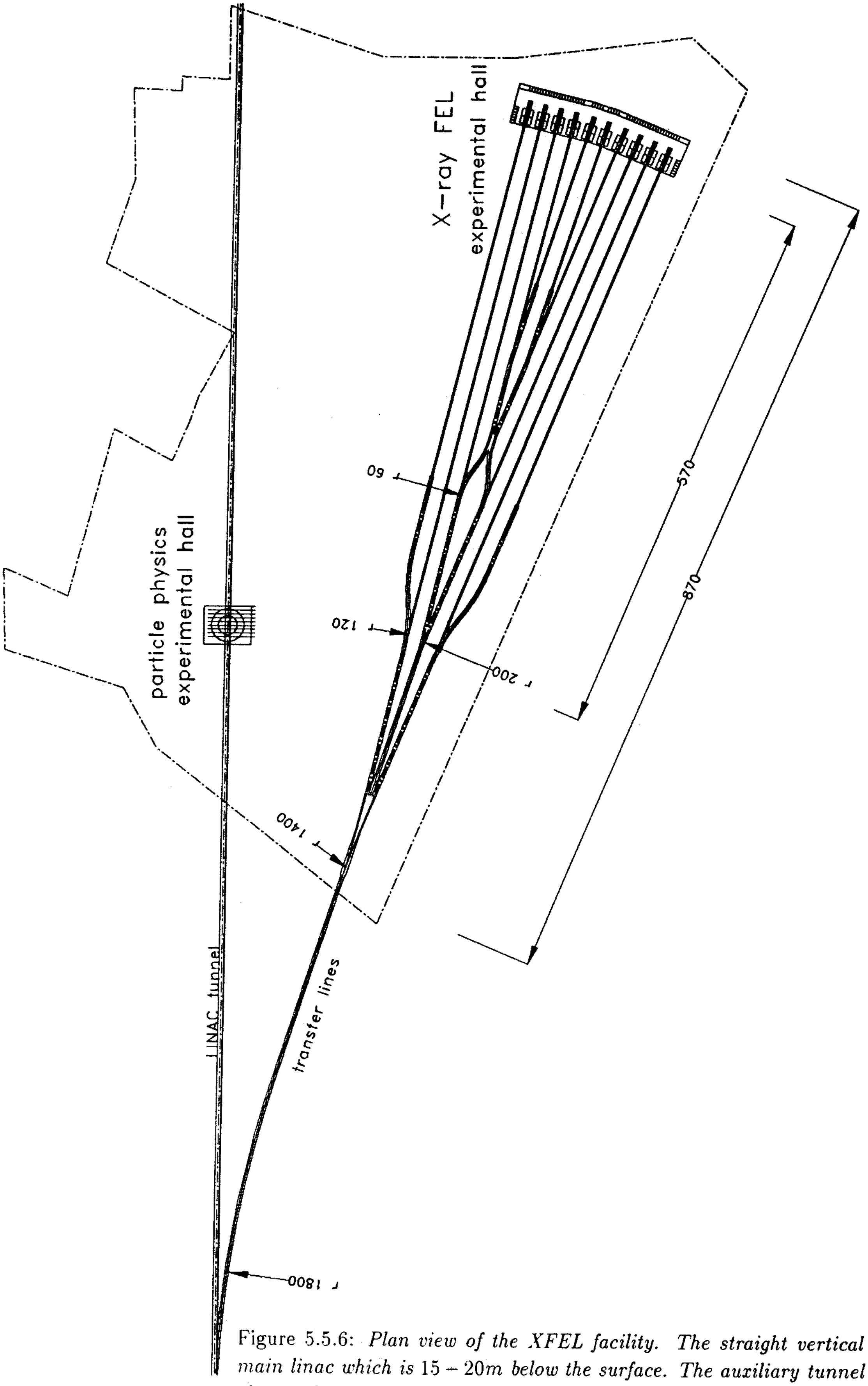
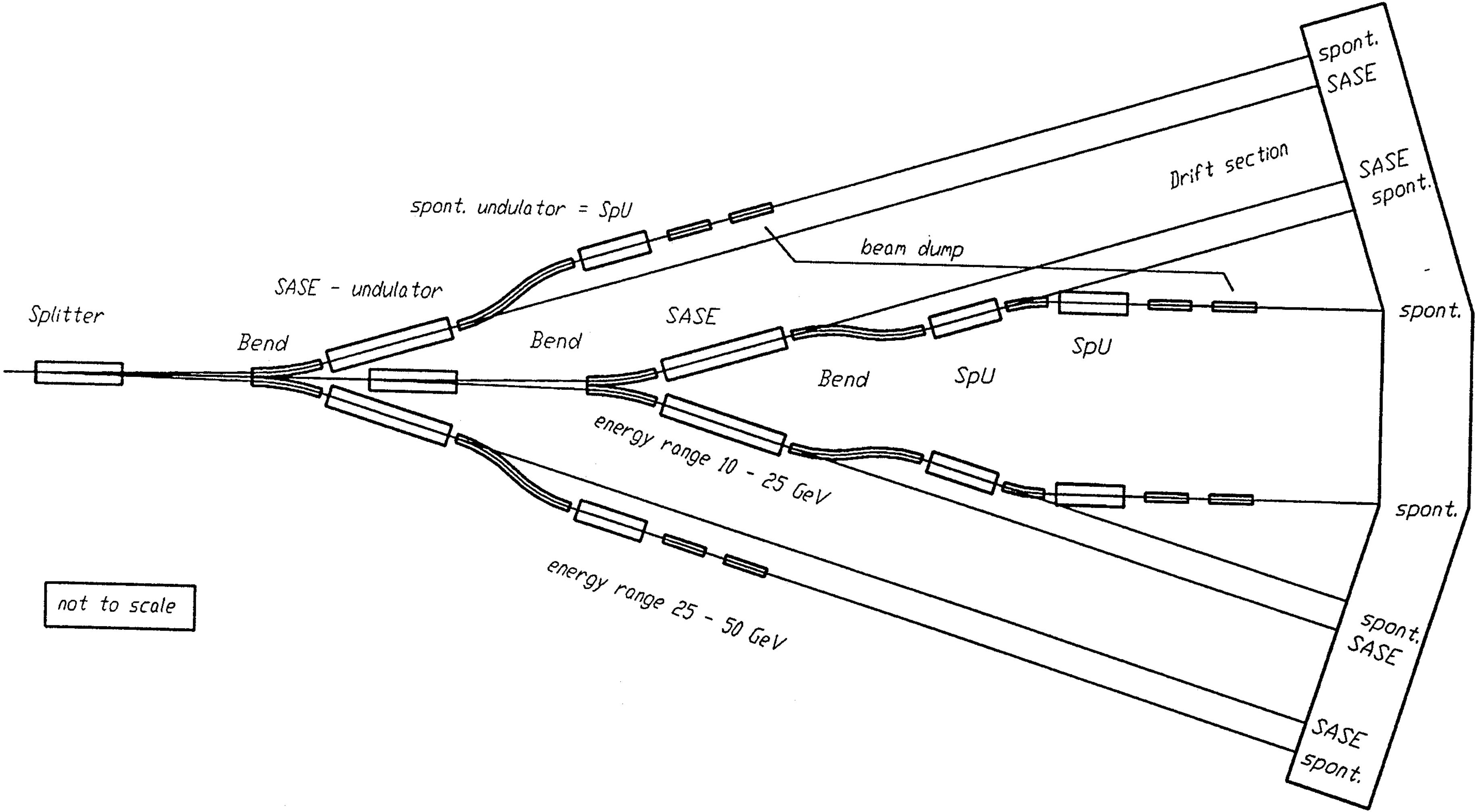
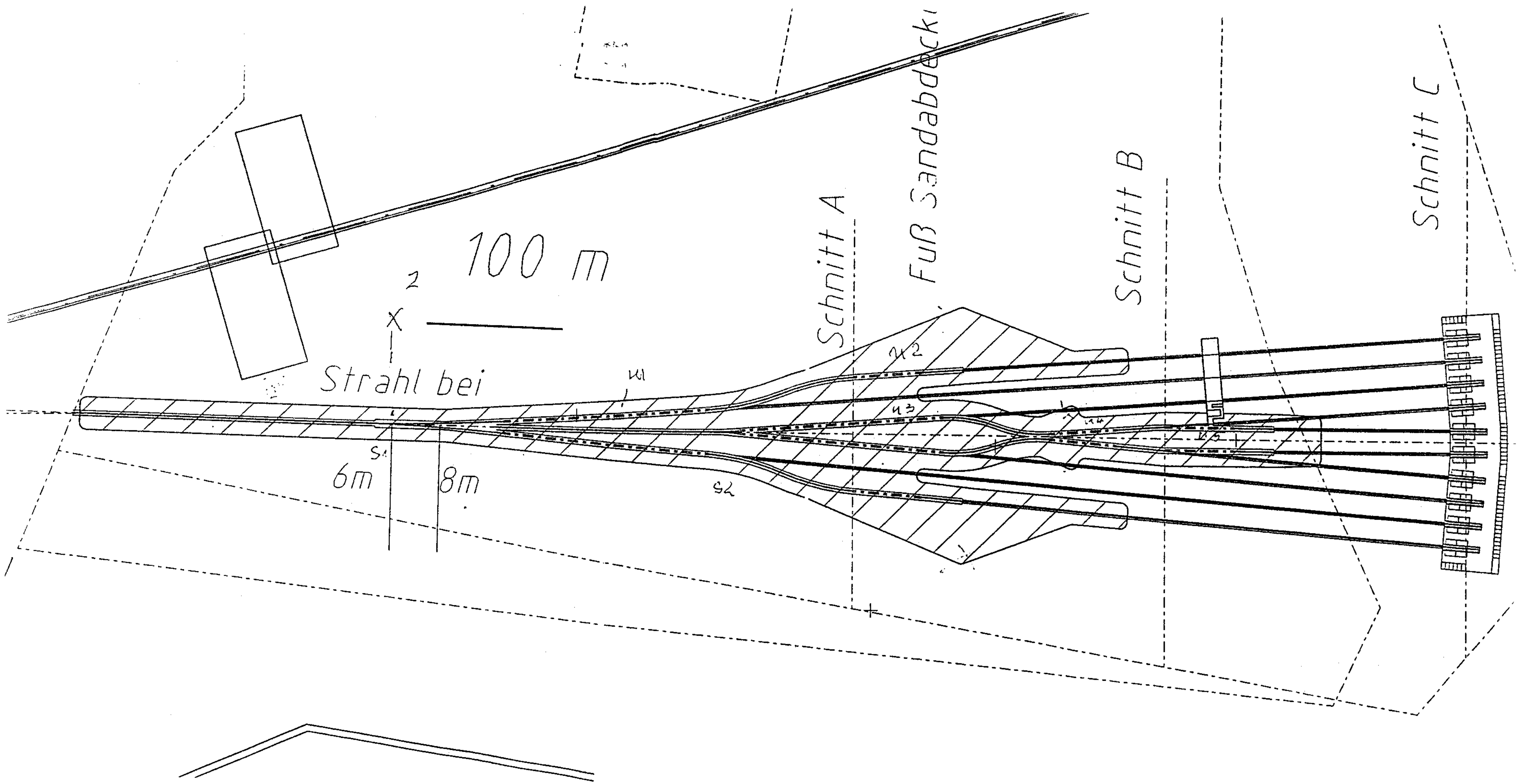
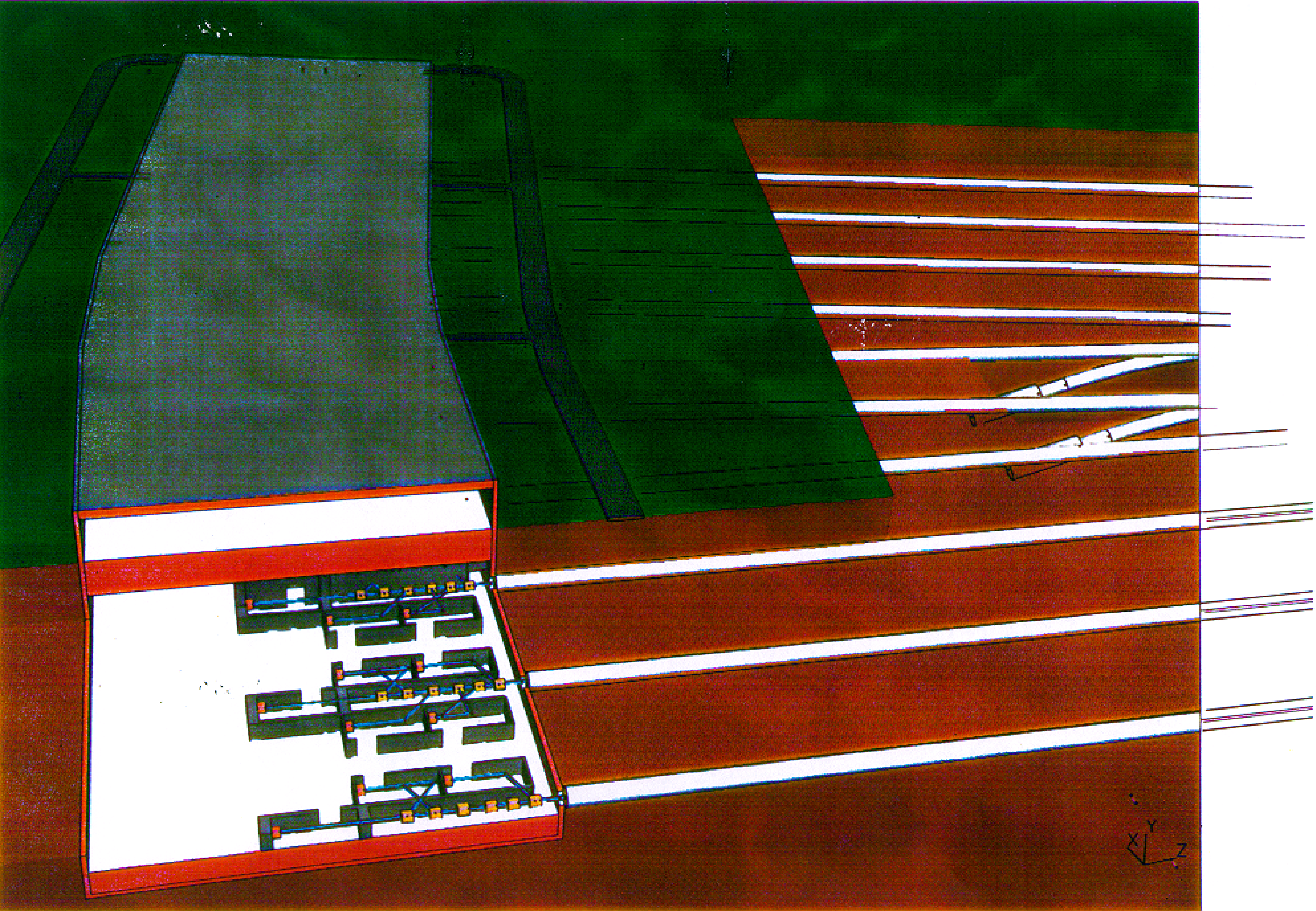


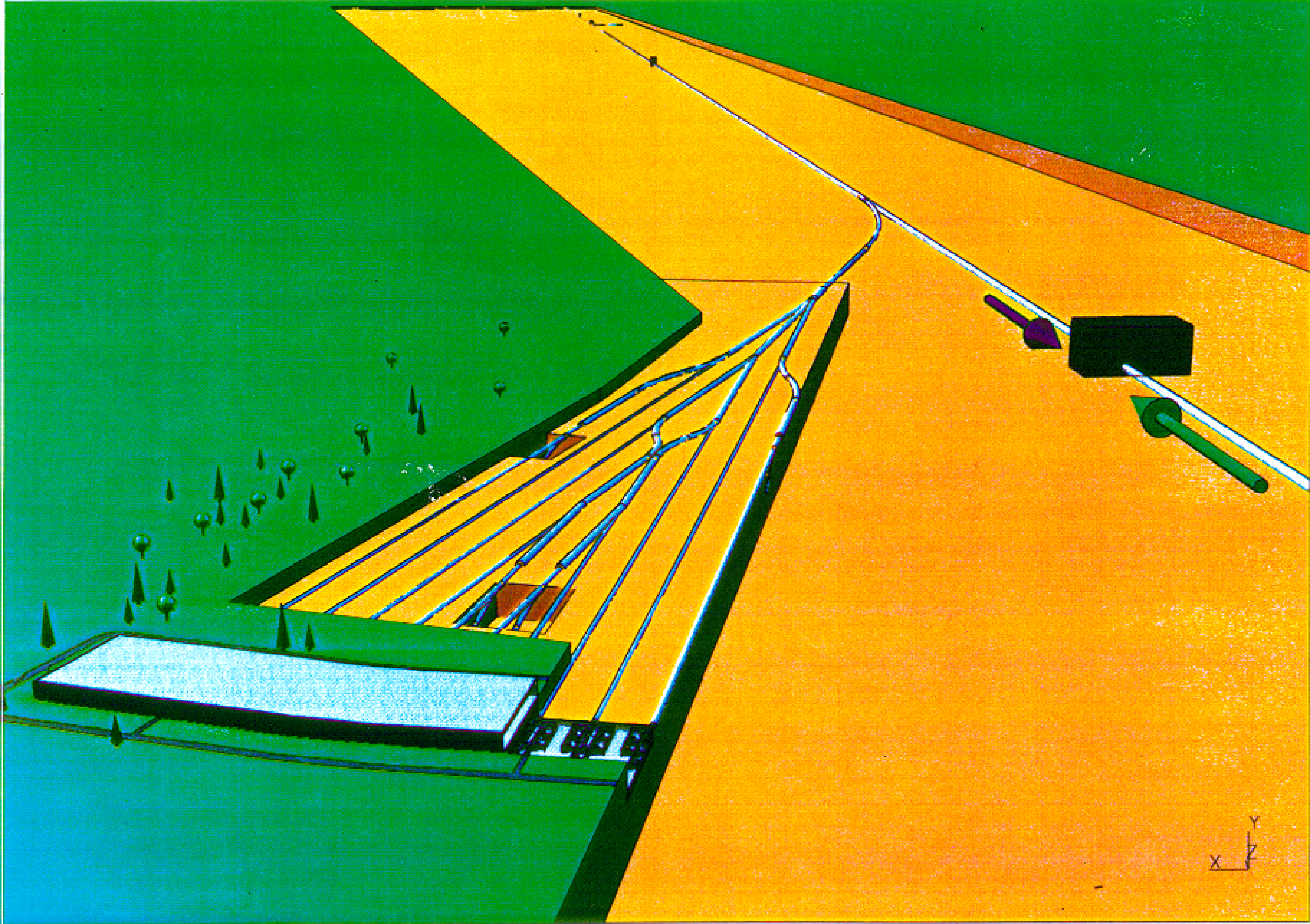
Figure 5.5.6: *Plan view of the XFEL facility. The straight vertical line represents the main linac which is* $15 - 20m$ *below the surface. The auxiliary tunnel to guide the XFEL electron beams to the undulators already leaves the main linac tunnel outside the laboratory site. Its horizontal angle with respect to the main linac is* 18°. *On the laboratory site, this tunnel comes close enough to the ground surface so that the following tunnels (tunnels housing the switch yard and the undulators etc.) can be built in cut-and-fill technique. The overall size of the site is approx. 900 m in length and 200 m in width.*



Splitter
Bend
SASE - undulator
spont. undulator = SpU
Bend
SASE
Bend
SpU
SpU
beam dump
Drift section
energy range 10 - 25 GeV
energy range 25 - 50 GeV
not to scale
spont.
SASE
SASE
spont.
spont.
spont.
spont.
SASE
SASE
spont.


100 m
Strahl bei
6m
8m
Schnitt A
Fuß Sandabdeck
Schnitt B
Schnitt C


X
Y
Z



Y
Z
X

Undulator beamlines at TESLA

SASE-FELs at :	630 m
	460 m
spontaneous undulators at :	420 m
	290 m
	190 m
pre-optics position at :	200 m

from experimental stations

X-FEL Beamline Components

source

planar undulator, helical undulator

- SASE-Fel
- incoherent Undulator

attenuators

- absorption cells

beam shaping

- primary slits for planar undulators
- "pinhole" for helical undulators
- mirrors
  - multi-bounce
  - collimation
  - defocusing
  - background reduction

crystal optics

- coherent undulator with diamond crystal (arrays)
- incoherent undulator with Si-optics

(re)-focusing optics for final focus at sample position

- mirrors
- bent crystal optics
- bragg-fresnel lenses
- compound refractive lenses

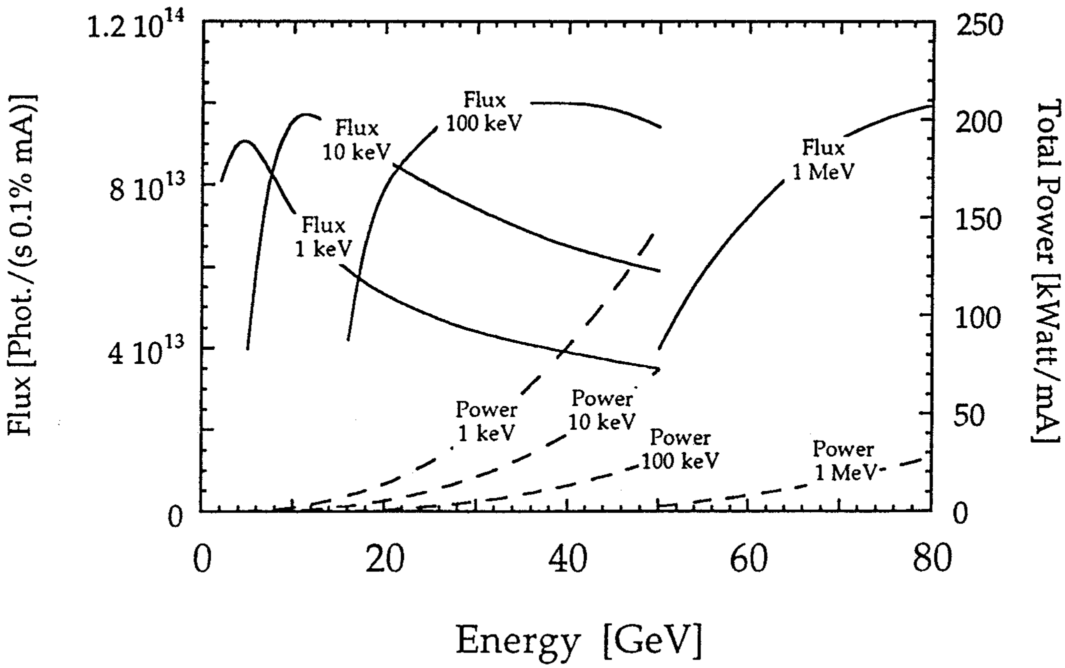
beamstop

- white beam
- monochromatic beam

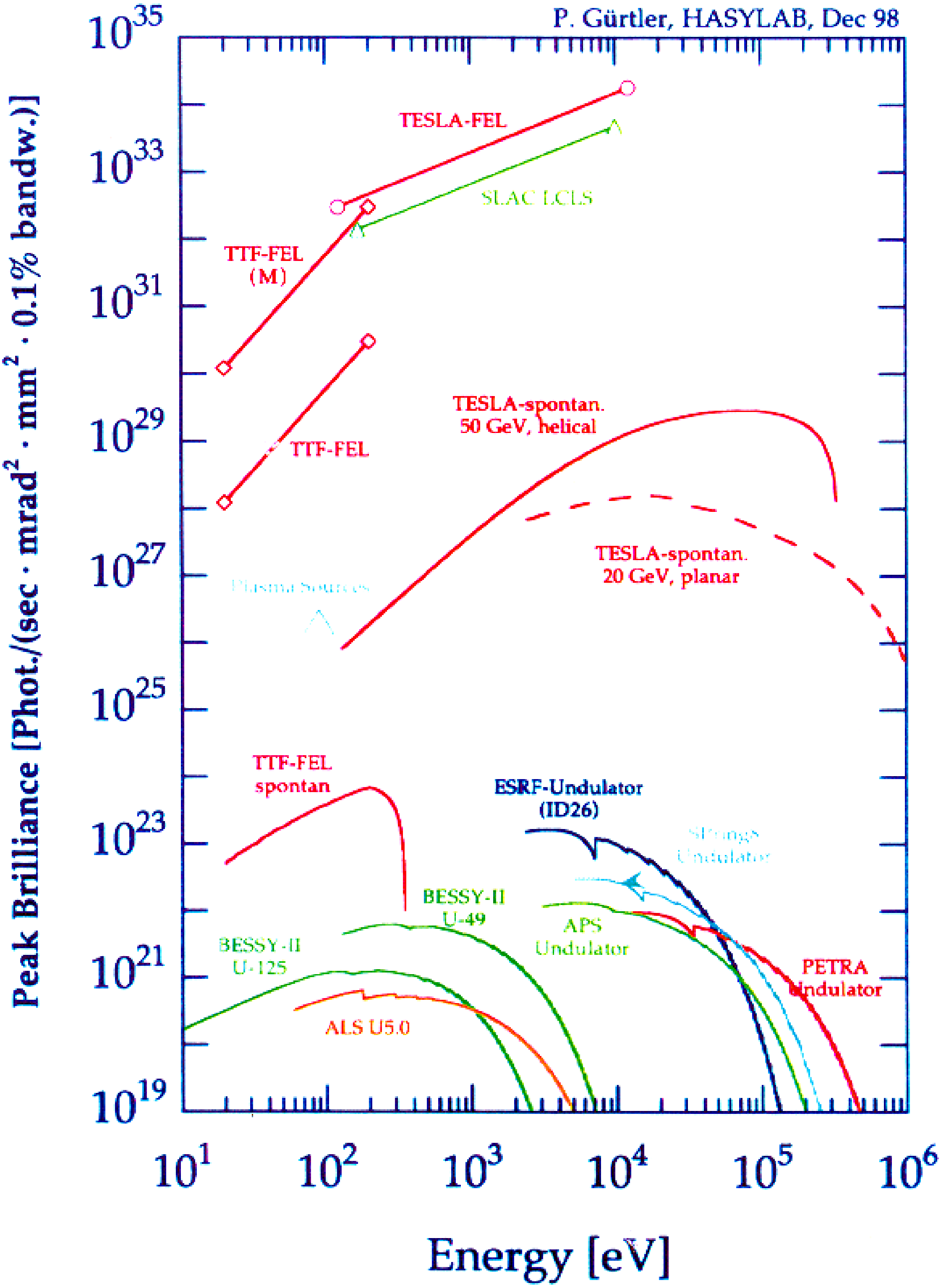
Parameters	Device 1	Device 2	Device 3	Device 4
Photon energy [keV]	1	10	100	1000
Electron energy [GeV]	5	12	40	100
Electron beam divergence [μrad]	2.6	1.7	0.9	0.59
Electron beam size [μm]	39	25	14	8.9
Total Length [m]	30	30	30	30
Periodic length [cm]	4.3	3.81	3.90	3.50
Number of periods	697	787	769	857
Magnetic field [Tesla]	0.75	0.65	0.66	0.57
Undulator Parameter	3.01	2.28	2.41	1.85
Total average Power emitted [Watt]	16	68	806	60812
Peak-Flux of 1. Harmonic*	$4.69 * 10^{20}$	$5.05 * 10^{20}$	$5.02 * 10^{20}$	$5.19 * 10^{20}$
Peak-Brilliance of 1. Harmonic**	$2.58 * 10^{25}$	$4.66 * 10^{26}$	$8.42 * 10^{27}$	$4.86 * 10^{29}$

* [Phot./(sec· 0.1%)]

** [Phot./(sec · mrad²· mm²· 0.1%)]



Flux and total power of undulators optimized for 4 different photon energies (1, 10, 100 and 1000 keV) as a function of electron energy.



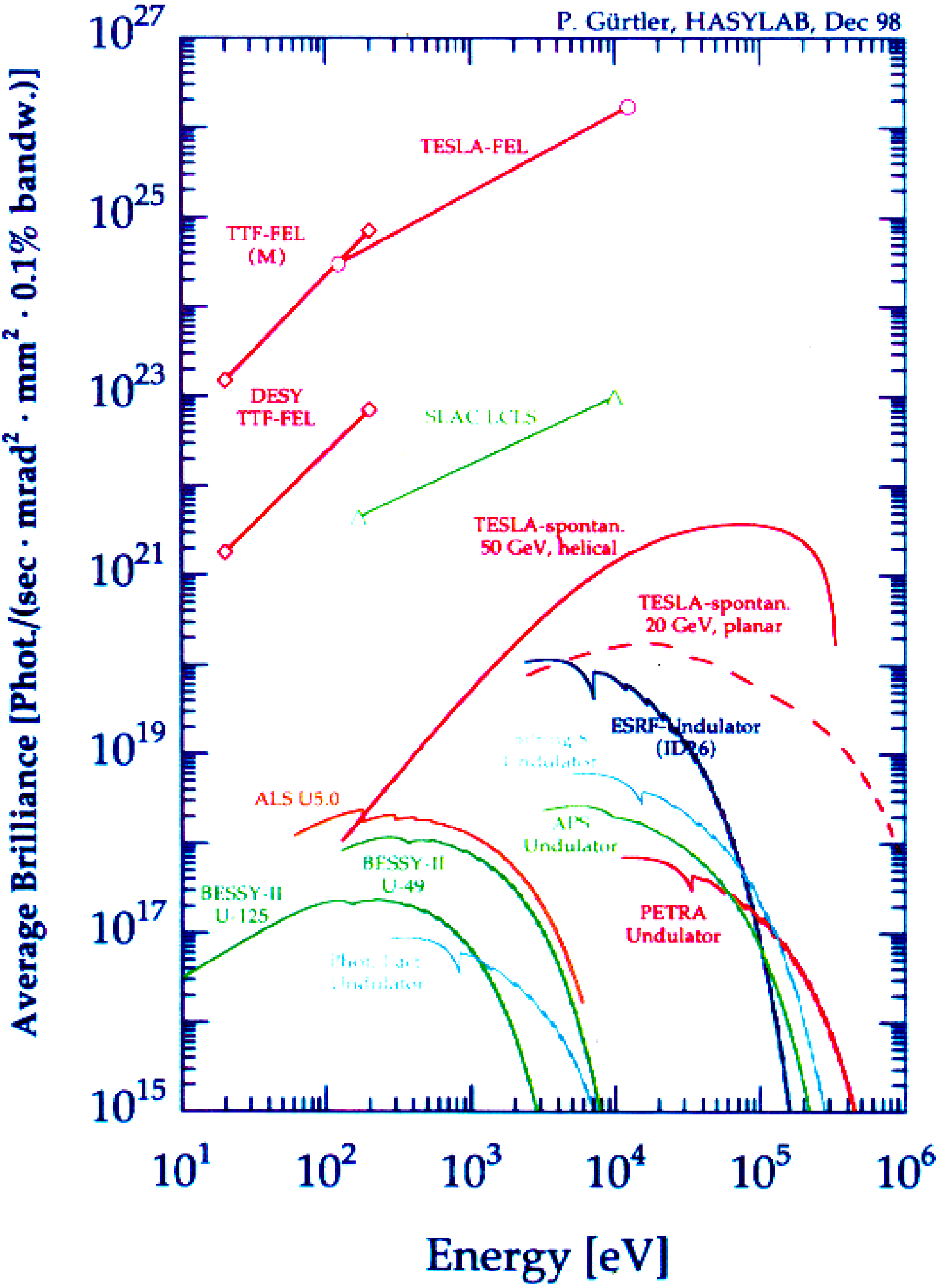
Spectral Brilliance (SB):

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

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

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

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



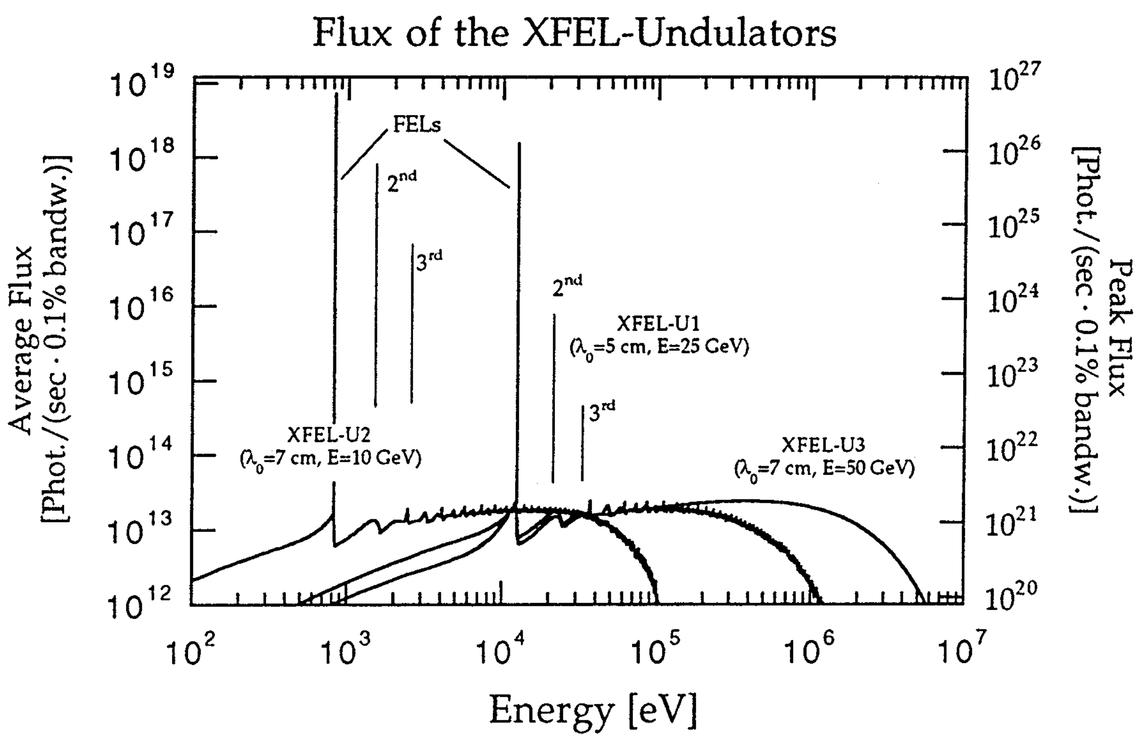
Spectral Brilliance (SB):

partially coherent source : $SB = \dfrac{spectral\ Flux}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_z \Sigma_{z'}}$ | $\Sigma = \sqrt{\sigma_e^2 + \sigma_p^2}$

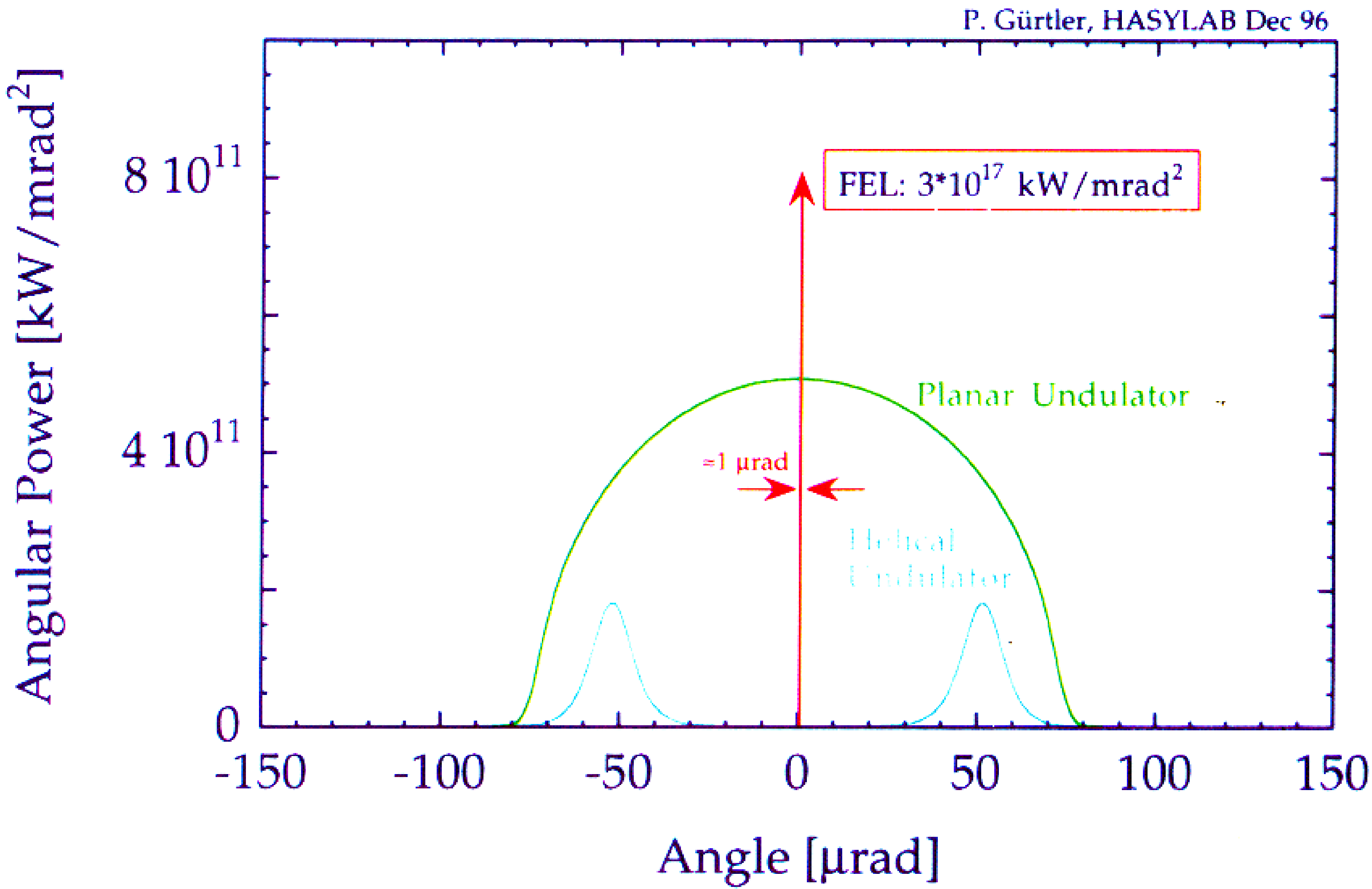
fully coherent source : $SB = \dfrac{spectral\ Flux}{(\lambda/2)^2}$ | $\Sigma' = \sqrt{\sigma_e'^2 + \sigma_p'^2}$

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.


P. Gürtler, HASYLAB Dec 96
FEL: 3*10^17 kW/mrad^2
Planar Undulator
≈1 µrad
Helical Undulator
8 10^11
4 10^11
0
-150
-100
-50
0
50
100
150
Angular Power [kW/mrad^2]
Angle [µrad]

FEL photon beam parameters. The maximum tolerable average power density absorbed by a monochromator crystal is of the order of 20 kW/cm² for diamond and 1 kW/cm² for silicon.

	undulator period (cm)	λ (Å)	rms radius at z = 0 m (μ m)	rms radius at 600 m (μ m)	peak power density at z = 0 m (W/cm²)	peak power density at z = 600 m (W/cm²)	av. power density at z = 0 m (MW/cm²)	av. power density at z = 600 m (kW/cm²)
1	5	6.25	27	2160	$1.6 \cdot 10^{15}$	$2.5 \cdot 10^{11}$	20	3.1
2	5	1	25	450	$1.7 \cdot 10^{15}$	$5.1 \cdot 10^{12}$	20	62.9
3	7	15	28	3600	$1.7 \cdot 10^{15}$	$1.0 \cdot 10^{11}$	20	1.2
4	7	2.4	28	840	$1.7 \cdot 10^{15}$	$1.9 \cdot 10^{12}$	20	22.6
5	7 hel.	4	21	1920	$1.0 \cdot 10^{16}$	$1.2 \cdot 10^{12}$	123	14.7
6	7 hel.	1	17	480	$1.1 \cdot 10^{16}$	$1.4 \cdot 10^{13}$	132	165.8

Average energy, ε, transferred to an atom immediately behind the undulator ($z = 0$ m) and at a distance of 600 m due to absorption of the FEL photon beam.

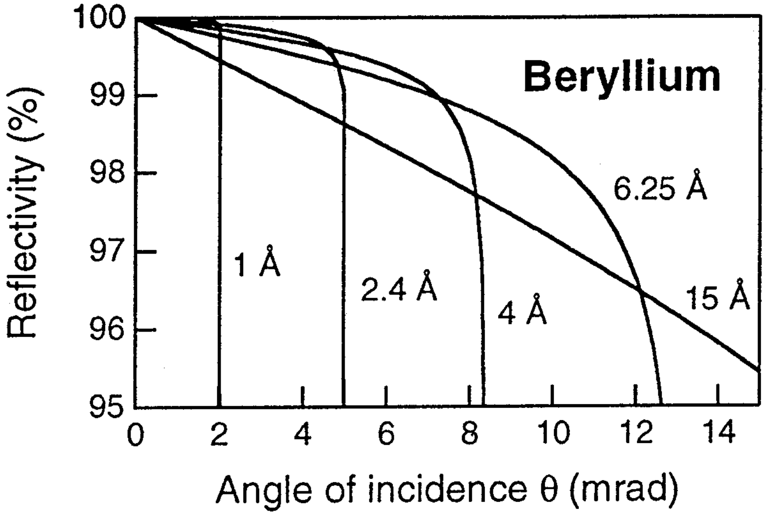
	λ (Å)	*Be* atom at z = 0 m (eV)	*Be* atom at z = 600 m (meV)	*C* atom at z = 0 m (eV)	*C* atom at z = 600 m (meV)	*Si* atom at z = 0 m (eV)	*Si* atom at z = 600 m (meV)	*Au* atom at z = 0 m (eV)
1	6.25	2.2	0.34	11.7	1.82	249	39	708
2	1	0.01	0.02	0.04	0.12	1.6	5	108
3	15	32.2	1.95	154.6	9.35	268	16	4949
4	2.4	0.11	0.13	0.68	0.76	20	22	423
5	4	3.4	0.41	19.2	2.30	493	59	7818
6	1	0.04	0.05	0.26	0.3	10.4	13	708

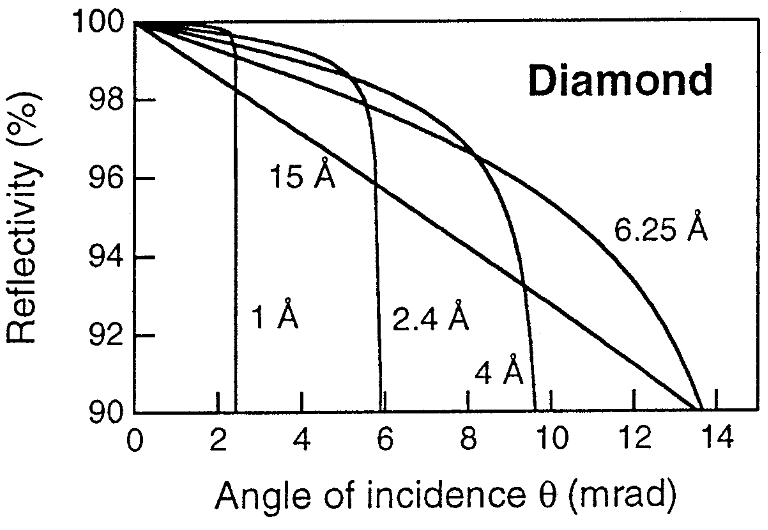
Properties of possible monochromator crystals and mirror coatings.

	Be (002)	diamond (111)	*Si* (111)
d-spacing (Å)	1.792	2.059	3.136
density (g/cm³)	1.85	3.52	2.33
thermal conductivity (W/cmK)	1.93	23	1.5
thermal expansion (10^{-6}/K)	7.7	1.2	2.4
1/e absorption length at 1 Å(μm)	25100	2800	250
1/e absorption length at 2.4 Å(μm)	1420	165	20
1/e absorption length at 4 Å(μm)	280	35	4.8
1/e absorption length at 6.25 Å(μm)	70	9	1.5
1/e absorption length at 15 Å(μm)	5	0.8	1.6

Power density absorbed by beryllium, diamond and silicon mirrors at 2 mrad angle of incidence.

	λ (Å)	*Be* atom at z = 0 m (W/cm^2)	*Be* atom at z = 600 m (W/cm^2)	*C* atom at z = 0 m (W/cm^2)	*C* atom at z = 600 m (W/cm^2)	*Si* atom at z = 0 m (W/cm^2)	*Si* atom at z = 600 m (W/cm^2)
1	6.25	96	0.02	291	0.05	3183	0.50
2	1	41	0.13	69	0.21	1023	3.16
3	15	225	0.01	589	0.04	471	0.03
4	2.4	37	0.04	122	0.14	1437	1.60
5	4	380	0.05	1212	0.15	12442	1.49
6	1	264	0.33	449	0.56	6638	8.33





Angular dependence of the reflectivity of beryllium (top) and diamond (bottom) for different X-ray wavelengths.

The X-FEL beam

coherent beam from planar X-FEL $\sigma = 1\text{-}6\mu\text{rad}^2$
incoherent beam from planar X-FEL $\sigma = 50\mu\text{rad}^2$
(1μrad = 0.2 arc sec)

no optical elements

+ no optical elements, best coherence preservation

− incoherent background of same order in much larger angle, only intrinsic linewidth monochromatization of 0.2%, white-beam beamstop in experimental hutch

aperture (primary slits, (pin)-hole)

+ no optical elements, reduced incoherent background

− incoherent background below coherent line still present, total reflection and scattering at aperture, only intrinsic linewidth monochromatization of 0.2%

The helical X-FEL beam

coherent beam from helical X-FEL $\sigma = 1\mu\text{rad}^2$
incoherent beam from helical X-FEL AT $50\mu\text{rad}^2$

no optical elements

+ no optical elements, best coherence preservation

− incoherent background of same order AT much larger angle, only intrinsic linewidth monochromatization of 0.2%, white-beam beamstop in experimental hutch

aperture (primary slits, pinhole)

+ no optical elements, most of the incoherent background removed

− total reflection and scattering at aperture, only intrinsic linewidth monochromatization of 0.2%

Monochromatizing the X-FEL beam

trimmed coherent beam from planar or helical X-FEL $\sigma = 1\mu\text{rad}^2$

diamond crystal(s) in Laue-geometry at largest possible distance

$+$ monochromatic beam

$-$ R&D regarding peak power, ionisation of crystal

incoherent beam from planar X-FEL $\sigma = 50\mu\text{rad}^2$

diamond crystal in Laue-geometry at largest possible distance

$+$ monochromatic beam

$-$ R&D regarding total power, large diamonds required 10mm^2, need to to re-focus the beam

Spreading a X-FEL beam

trimmed coherent beam from X-FEL $\sigma = 1\mu\text{rad}^2$

$1\AA = 12.34$ keV, intrinsic Si-111 = 4 arc sec
Spread the beam to reduce the power density at the crystal, but stay inside the rocking curve width.

Be-(coated) mirror at 200m from mono and 200m (400m) from undulator at lowest usable glancing angle $<= 2$mrad.

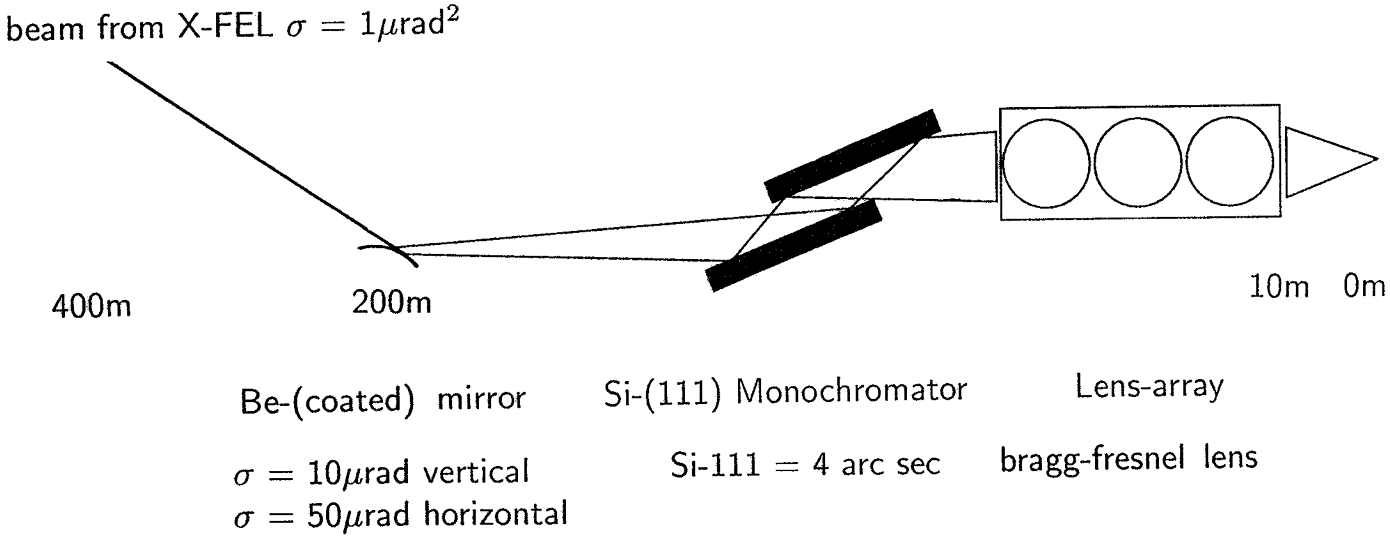
spreaded beam $\sigma = 10\mu$rad vertical (* 10)
spreaded beam $\sigma = 50\mu$rad horizontal (* 50)

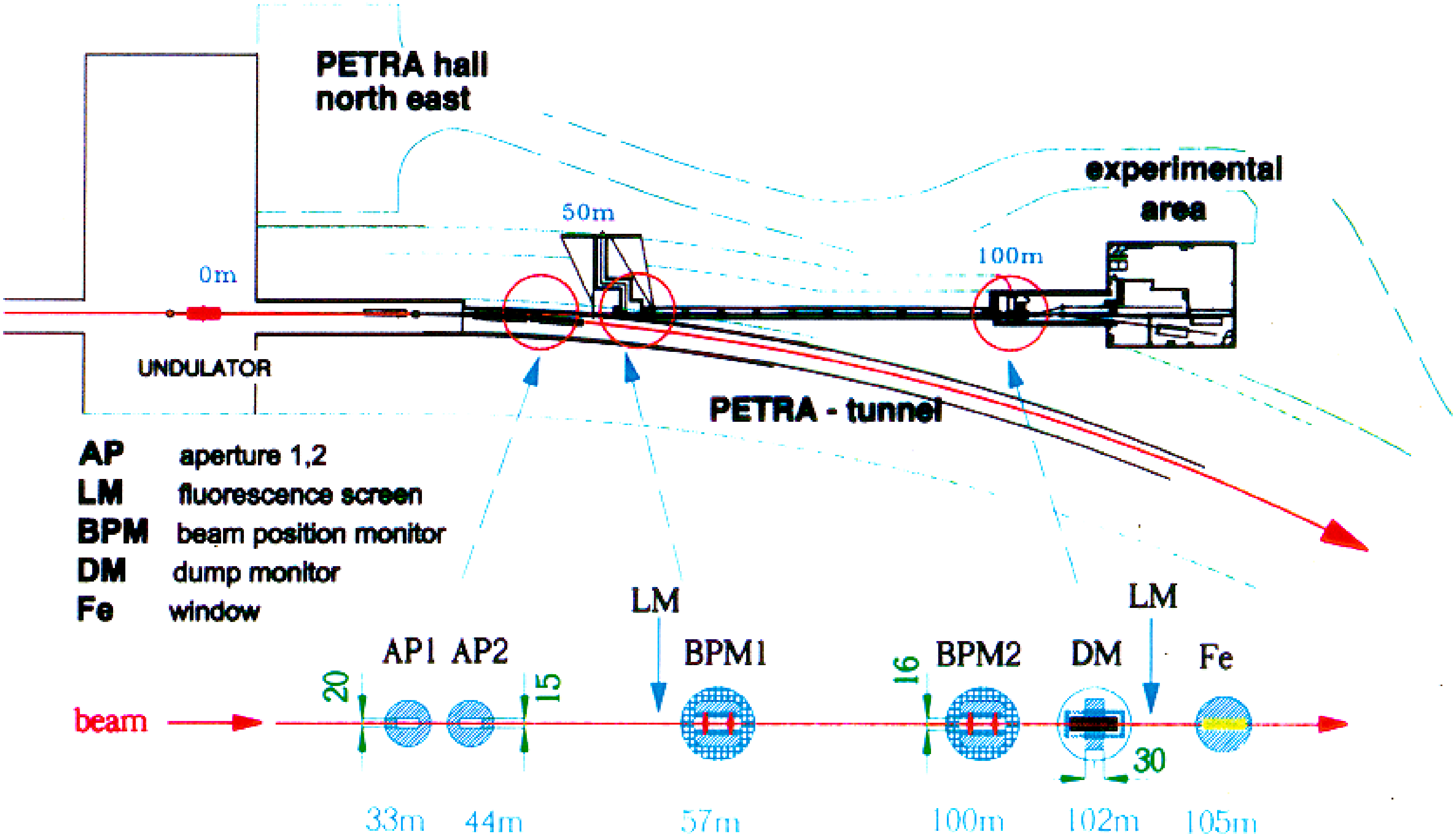
Si-(111) Monochromator

Lens-array or bragg-fresnel lens re-focuses the beam onto sample at a distance of up to 10m.

+ use of known optical elements, monochromatic beam

− additional optical surfaces, quality of coherence, additional convergence at sample


beam from X-FEL $\sigma = 1\mu\text{rad}^2$
400m
200m
10m
0m
Be-(coated) mirror
$\sigma = 10\mu\text{rad}$ vertical
$\sigma = 50\mu\text{rad}$ horizontal
Si-(111) Monochromator
Si-111 = 4 arc sec
Lens-array
bragg-fresnel lens



PETRA hall
north east
experimental
area
50m
100m
0m
UNDULATOR
PETRA - tunnel
AP aperture 1,2
LM fluorescence screen
BPM beam position monitor
DM dump monitor
Fe window
LM
LM
AP1 AP2
BPM1
BPM2
DM
Fe
20
15
16
30
beam
33m
44m
57m
100m
102m
105m

PETRA undulator beamline

@60 mA, 12 GeV, 14mm gap

total power	:	7.5 kW
power density	:	500 $kW/mrad^2$
power density at 26.5m	:	700 W/mm^2
power density at 100m	:	50 W/mm^2

PETRA undulator with (test) mirror

ring current 1mA, single bunch

aperture size 50μrad * 180μrad at 110m
Au-coated Si-mirror at 6mrad glancing angle
1W total reflected power (1st harmonic)

focusing 110m : 6m = 18.3
in both directions = factor of 340

source size 2.6mm * 0.3mm
power density in focal spot = 435W/mm^2

optimum case peak power density:
$435W/mm^2 * 10mA * 54857 = 2*10^8 W/mm^2$