

FEL X-RAY BACKGROUND RADIATION

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Yerevan, June 2010

CANDLE-PSI Collaboration 2010

Workpackage L

L-2 Startup of hard X-ray background calculation (bremsstrahlung)

Bremsstrahlung radiation is generated when electron beam is interacted with collimators, beam diagnostic devices and residual gas. Bremsstrahlung radiation overlaps with the FEL radiation. Bremsstrahlung causes beam energy losses and widens beam energy spread. The study should be carried out to distinguish bremsstrahlung contribution into radiation at the undulator exit.

L-3 The study of the spontaneous background radiation

In the long chain of the undulator sections installed to ensure FEL radiation growth development spontaneous radiation is being emitted providing essential background to FEL radiation. Spontaneous background radiation increases beam energy spread and drives out part of the beam from the FEL resonant condition due to energy losses thus degrading FEL radiation growth. Numerical simulation study along with analytical calculations allows estimation of the spontaneous background radiation role.

SPONTANEOUS BACKGROUND RADIATION

- increases beam energy spread
- drives out the beam from the FEL resonant condition
- provides essential background to FEL radiation

The spontaneous radiation in the long chain of the undulator has been simulated by SPECTRA code [2]. Analytical methods has been used [3,4].

FEL main specifications

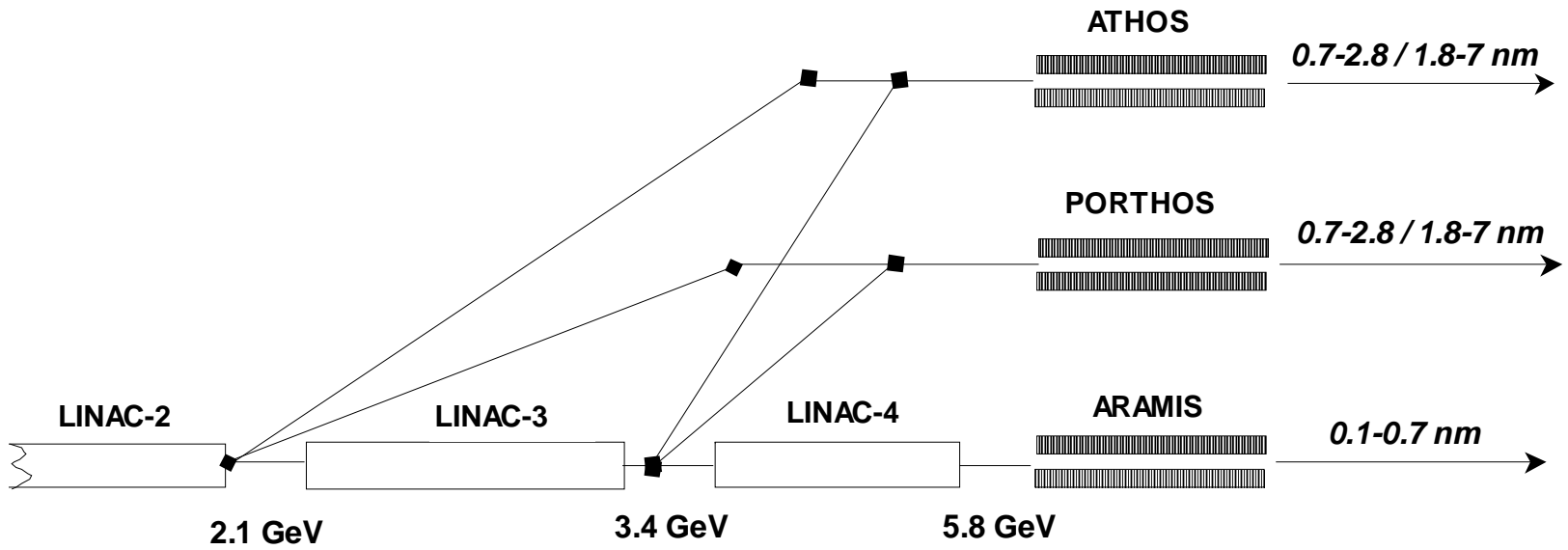
Undulator	Athos	Porthos	Aramis
Beam Energy [GeV]	2.1 /3.4	2.1 /3.4	5.8
Wavelength [nm]	0.7-2.8/1.8-7	0.7-2.8/1.8-7	0.1-0.7
Wavelength tuning	energy and gap	energy and gap	Gap
Polarization	Variable	variable	Linear

Beam parameters

Undulator	Athos	Porthos	Aramis
Energy [GeV]	2.1 / 3.4	2.1 / 3.4	5.8
Bunch charge [pC]	200	200	200
Emittance [mm-mrad]	0.43	0.43	0.43
Energy spread [MeV]	0.35	0.35	0.35
Peak current [kA]	2.7	2.7	2.7
Bunch length rms [mm]	8.9	8.9	8.9

SwissFEL undulators design parameters

Undulator	Athos	Porthos	Aramis
Energy [GeV]	2.1 /3.4	2.1 /3.4	5.8
Wavelength [nm]	0.7-2.8/1.8-7	0.7-2.8/1.8-7	0.1-0.7
Undulator type	APPLE II	APPLE II	planar/invac.
Magnetic material	SmCb/NdFeB	SmCb/NdFeB	NdFeB
Operation mode	SASE	SASE	SASE
# Modules	14	14	14
Undulator period length [cm]	4	4	1.5
Undulator periods	100	100	265
Active undulator length	4 m	4 m	3.975 m
Effective drift length	70 cm	70 cm	72.5 cm
Gap [mm]	6.5 - 50	6.5 - 50	4.2 – 20
K value	1-3.2	1-3.2	1.2 (peak)
Quadrupole max gradient	50 T/m	50 T/m	50 T/m
Quadrupole nominal gradient	35 T/m	35 T/m	35 T/m
Quadrupole length (effective length)	75 mm	75 mm	75 mm
Average beta function [m]	10	10	15
FODO period [m]	9.4	9.4	9.4



SwissFEL chematic layout

Wavelength and photon energy

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2} (1 + K^2 / 2) \quad \varepsilon_n [keV] = 0.94963 \frac{nE^2 [GeV]}{(1 + K^2 / 2)\lambda_u [cm]}$$

Band Width

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{nN}$$

Flux on axis

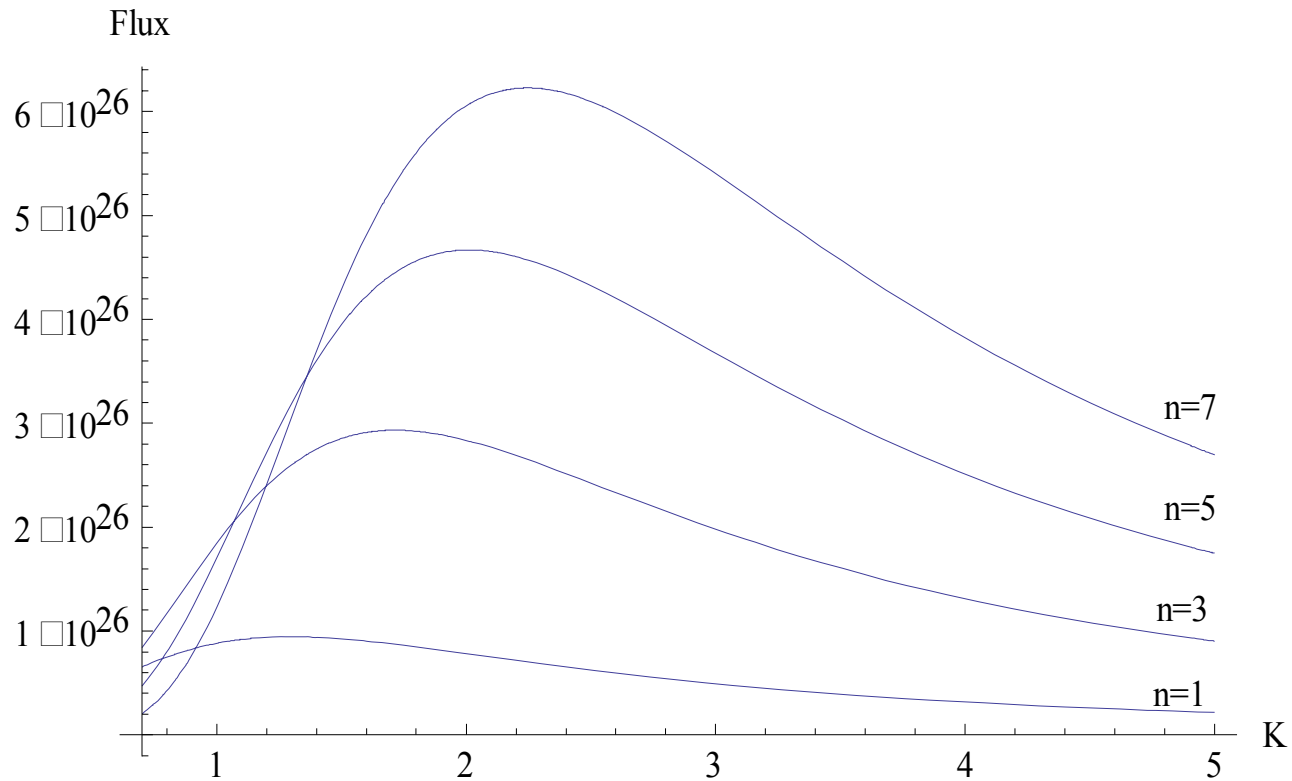
$$L \neq N\lambda_u$$

$$\left. \frac{d^2 F_n}{d\vartheta d\psi} \right|_0 = \alpha N^2 \gamma^2 \frac{\Delta\omega l}{\omega e} f_n(K)$$

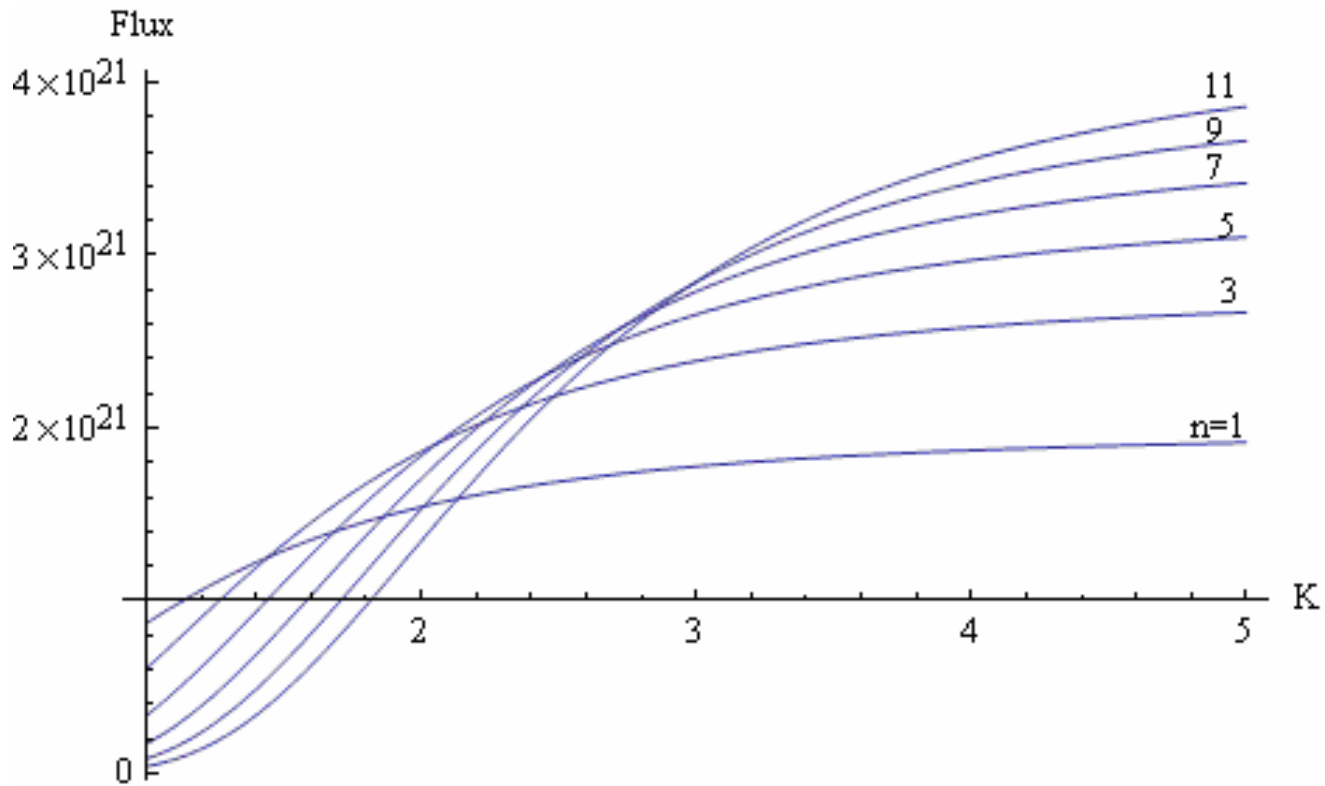
$$f_n(K) = \frac{4K_1^2}{K^2} \left[J_{\frac{n-1}{2}}[K_1] - J_{\frac{n+1}{2}}[K_1] \right]^2$$

$$K_1 = \frac{nK^2}{4(1 + K^2 / 2)}$$

Units: [photons/(s/mr²/0.1%bw)]



Flux [photons/(s mr^2 0.1%bw)] at the central axis for ARAMIS undulator. Curves corresponding to the fundamental and odds harmonics are presented ($n=1,3,5,7$); note that flux is 0 for even harmonics. Tuning range of the undulator strength K is 1.2 – 4.7;



Flux [photons/(sec x 0.1%bandwidth)] integrated over central cone versus undulator strength K for ARAMIS undulator. Curves corresponding to the fundamental and its odds harmonics are presented (n=1,3,5,7); note that flux is 0 for even harmonics.

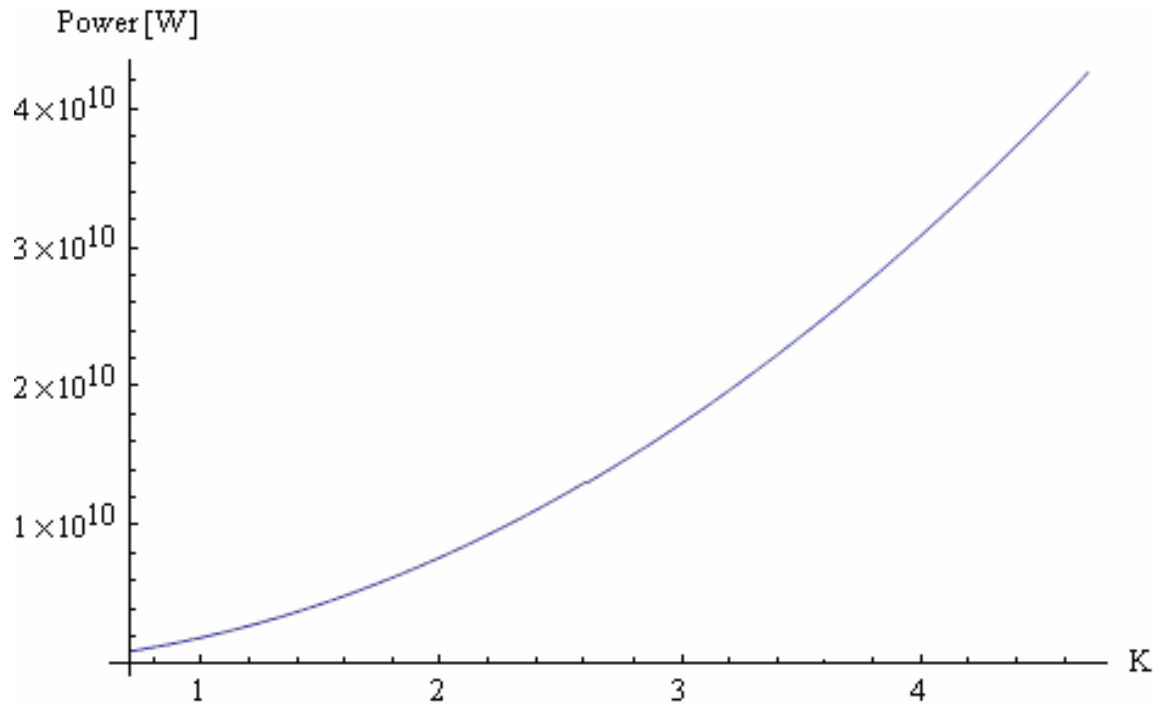
Central cone $\sigma_{r'} \approx \sqrt{\frac{\lambda_n}{L}}$

Halo rings $\vartheta_{n,i} = \sqrt{\frac{i(1 + K^2/2)}{n\gamma^2}}, (i = 1,2,3,...)$

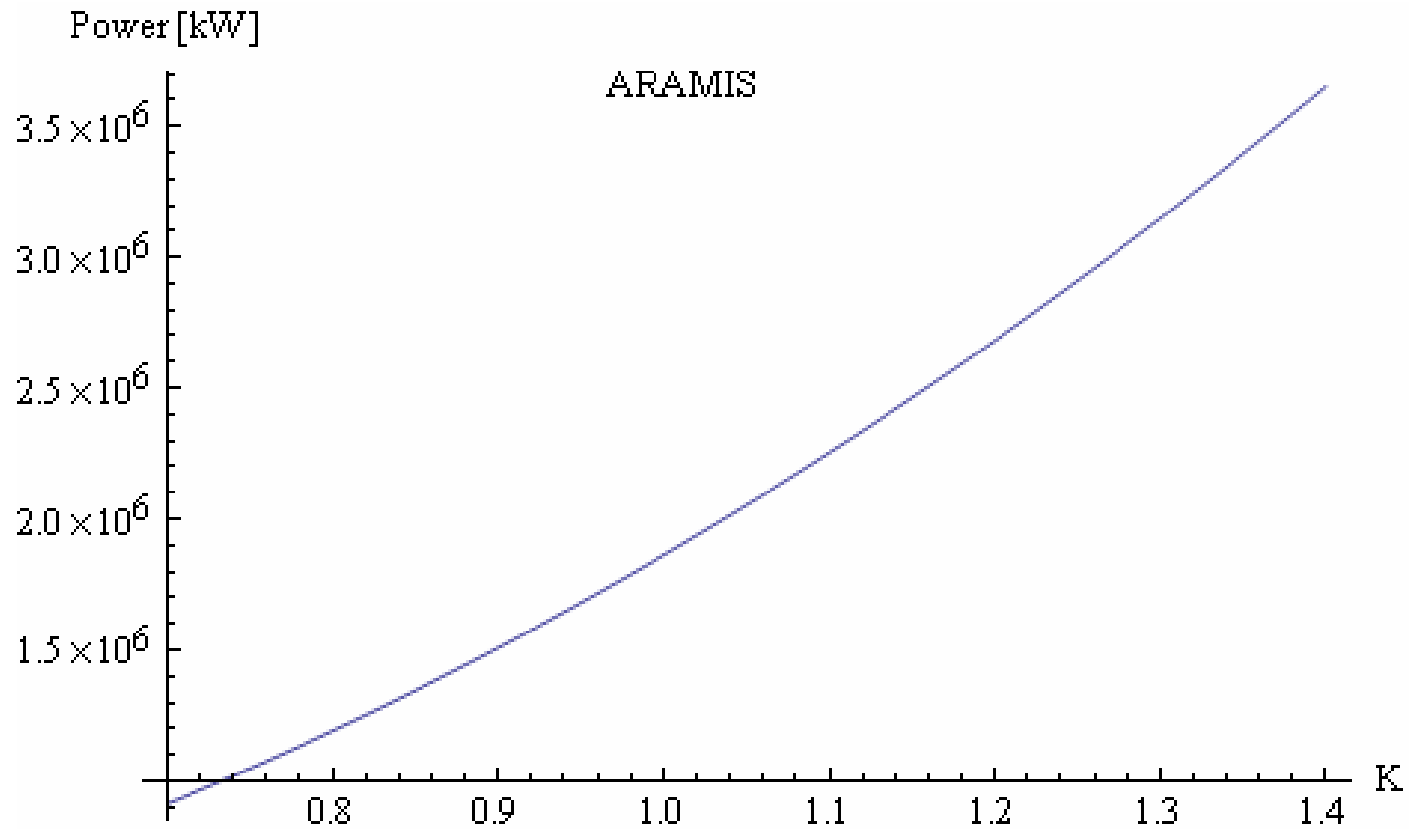
The flux integrated over the central cone $F_n = \pi\alpha N \frac{\Delta\omega}{\omega} \frac{I}{e} Q_n(K) = 1.431 \times 10^{14} N Q_n I [A]$
 $Q_n(K) = (1 + K^2/2) f_n / n$

total power

$$P = \frac{\pi c}{3\lambda_u} NZ_0 I e \gamma^2 K^2$$



ARAMIS undulator radiation total power versus K parameter



ARAMIS undulator radiation total power versus K parameter.

Spectral brightness is the photon flux in the phase space volume (usually is given in the units of photons/s/mrad²/mm²/0.1%bw)

$$B_n = \frac{F_n}{(2\pi)^2 \sqrt{(\sigma_r^2 + \sigma_x^2)(\sigma_r^2 + \sigma_y^2)} \sqrt{(\sigma_{r'}^2 + \sigma_{x'}^2)(\sigma_{r'}^2 + \sigma_{y'}^2)}},$$

$\sigma_x, \sigma_{x'}, \sigma_y, \sigma_{y'}$ are the electron beam sizes $\sigma_x = \sigma_y = \sqrt{\epsilon\beta/\gamma}$ $\sigma_{x'} = \sigma_{y'} = \sqrt{\epsilon/\beta\gamma}$

$\sigma_r = \frac{1}{4\pi} \sqrt{\lambda L}$ $\sigma_{r'} = \frac{1}{4\pi} \sqrt{\lambda/L}$ are the sizes of the single electron radiation from an axially extended source

For the ARAMIS at the 0.1nm $B_1 = 1.1 \times 10^{28}$

Accelerator Specification

Linac

Bunch Shape:	Gaussian	Energy Spread	6.03e-5		
Electron Energy (GeV)	5.8	$\beta_x(m)$	15	α_x	0
Average Current (mA)	2e-05	$\beta_y(m)$	15	α_y	0
Pulses/sec	100	$\eta_x(m)$	0	η_x'	0
σ_z (mm)	0.00886	$\eta_y(m)$	0	η_y'	0
Bunch Charge (nC)	0.2				
Peak Current (A)	2699.77	$1/\gamma(\mu rad)$	88.1033		
Natural Emittance (m.rad)	0.87e-10	$\sigma_x(\mu m)$	25.54	$\sigma_x(\mu rad)$	1.703
Coupling Constant	1	$\sigma_y(\mu m)$	25.54	$\sigma_y(\mu rad)$	1.703
$\epsilon_x(m.rad)$ 4.35e-11		$\gamma\sigma_x'$	0.01933	$\gamma\sigma_y'$	0.01933
$\epsilon_y(m.rad)$ 4.35e-11					

Light Source Description

Linear Undulator | Segmented Undulator

<input type="checkbox"/> Link Gap & Field		$\sigma_r(\mu m)$	8.40088	$\sigma_r(\mu rad)$	0.948505
<input checked="" type="checkbox"/> Segmented Undulator		$\Sigma_x(\mu m)$	26.89	$\Sigma_x(\mu rad)$	1.94927
<input type="checkbox"/> Special Magnet Setup		$\Sigma_y(\mu m)$	26.89	$\Sigma_y(\mu rad)$	1.94927
Gap Value	20	$\epsilon_{1st}(peak:eV)$	12376.9		
B(T)	0.85678	$\epsilon_{3rd}(peak:eV)$	37133.7		
Periodic Length (cm)	1.5	Flux _{1st}	3.48101e+09		
Total Length (m)	3.975	Brilliance _{1st}	3.20935e+16		
Number of Periods	265	Peak Brilliance	4.33226e+27		
K Value	1.2	Bose Degeneracy	1813.53		
$\epsilon_{1st}(eV)$	12382	Total Power (kW)	1.73893e-05		

SPECTRA GUI with ARAMIS undulator parameters

SIMPLEX - D:\SpontanRad\Aramis01b15.prm

File Configuration Run View Help

Accelerator | Undulator | Wakefield | Seed | Foc ◀ ▶

Basic Parameters

Electron Energy (GeV)	5.8
Bunch Length (m)	8.86e-06
Bunch Charge (nC)	0.2
$\epsilon_x(\pi\text{mm.mrad})$	0.43
$\epsilon_y(\pi\text{mm.mrad})$	0.43
Energy Spread	6.03e-05
$\beta_{xAv.}(m)$	14.9976
$\beta_{yAv.}(m)$	14.9962
γ	11350.3
Peak Current (A)	2699.77
$\sigma_x(\text{mm})$	0.0238364
$\sigma_y(\text{mm})$	0.0238353
$\sigma_x(\text{mrad})$	1.5893e-03
$\sigma_y(\text{mrad})$	1.5894e-03
Bunch Shape	Gaussian

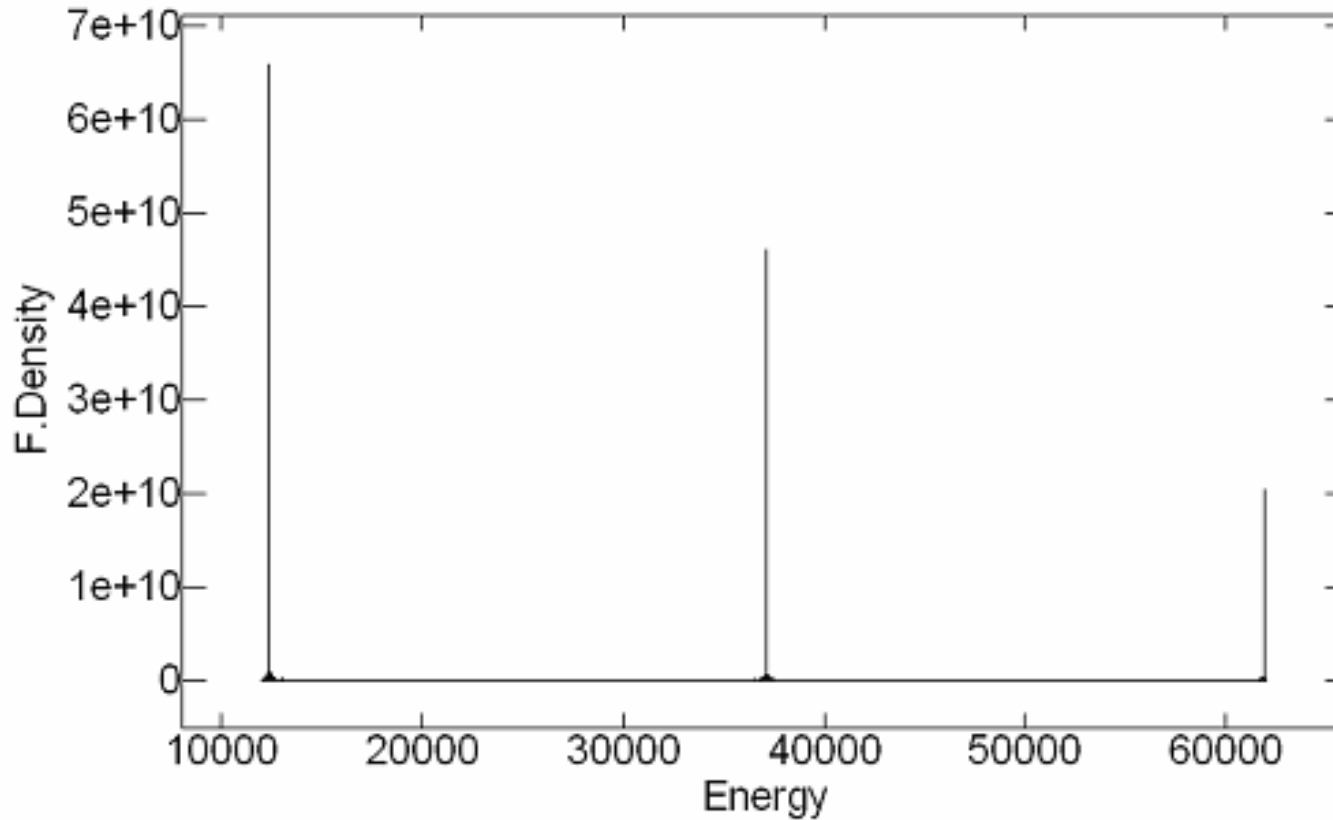
FEL Output

ρ	4.2475e-04
$L_{g1D}(m)$	1.62251
$L_{g3D}(m)$	2.22462
$L_{\text{sat}}(m)$	41.0124
$P_{\text{sat}}(\text{GW})$	5.6607
Energy/Bunch (J)	4.1935e-04

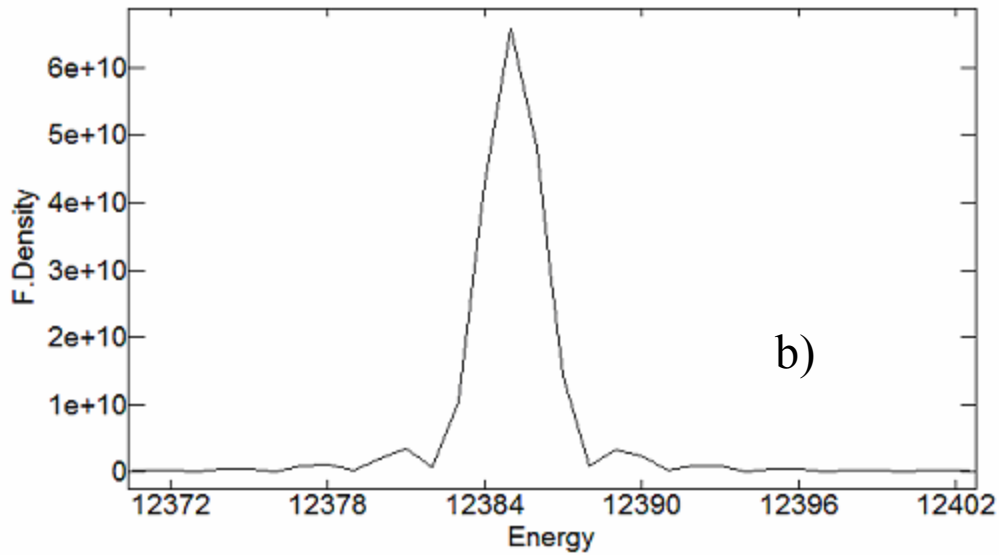
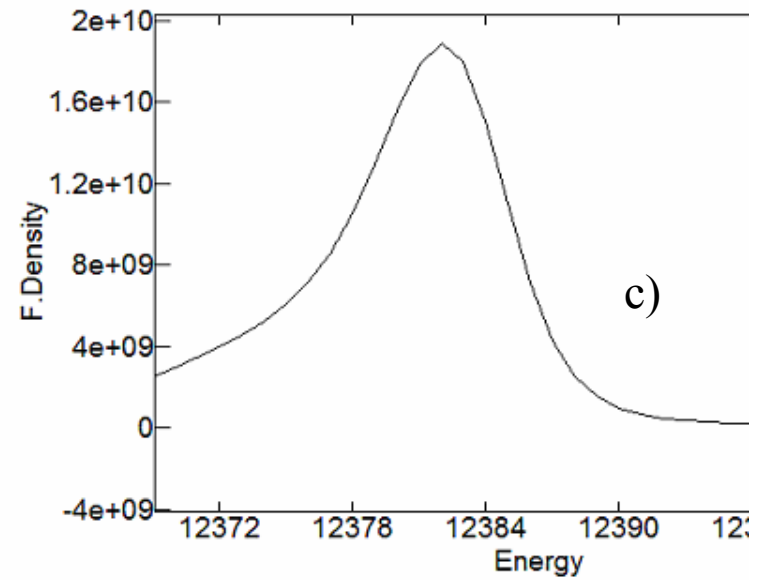
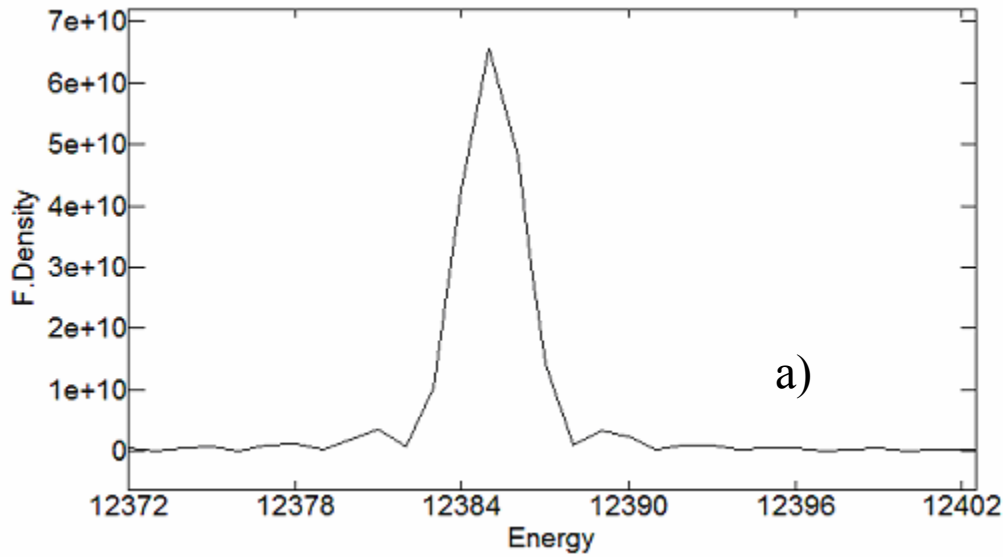
Radiation Characteristics

$\epsilon_{1\text{st}}(\text{eV})$	12382.1
$\lambda_{1\text{st}}(\text{nm})$	0.100132
$\Delta\lambda/\lambda$	9.3353e-04
Peak Flux	2.87181e+24
Brilliance	1.14569e+33
Degeneracy	4.796e+08
Peak Photons	2.12745e+11
Total Photons	2.11406e+11

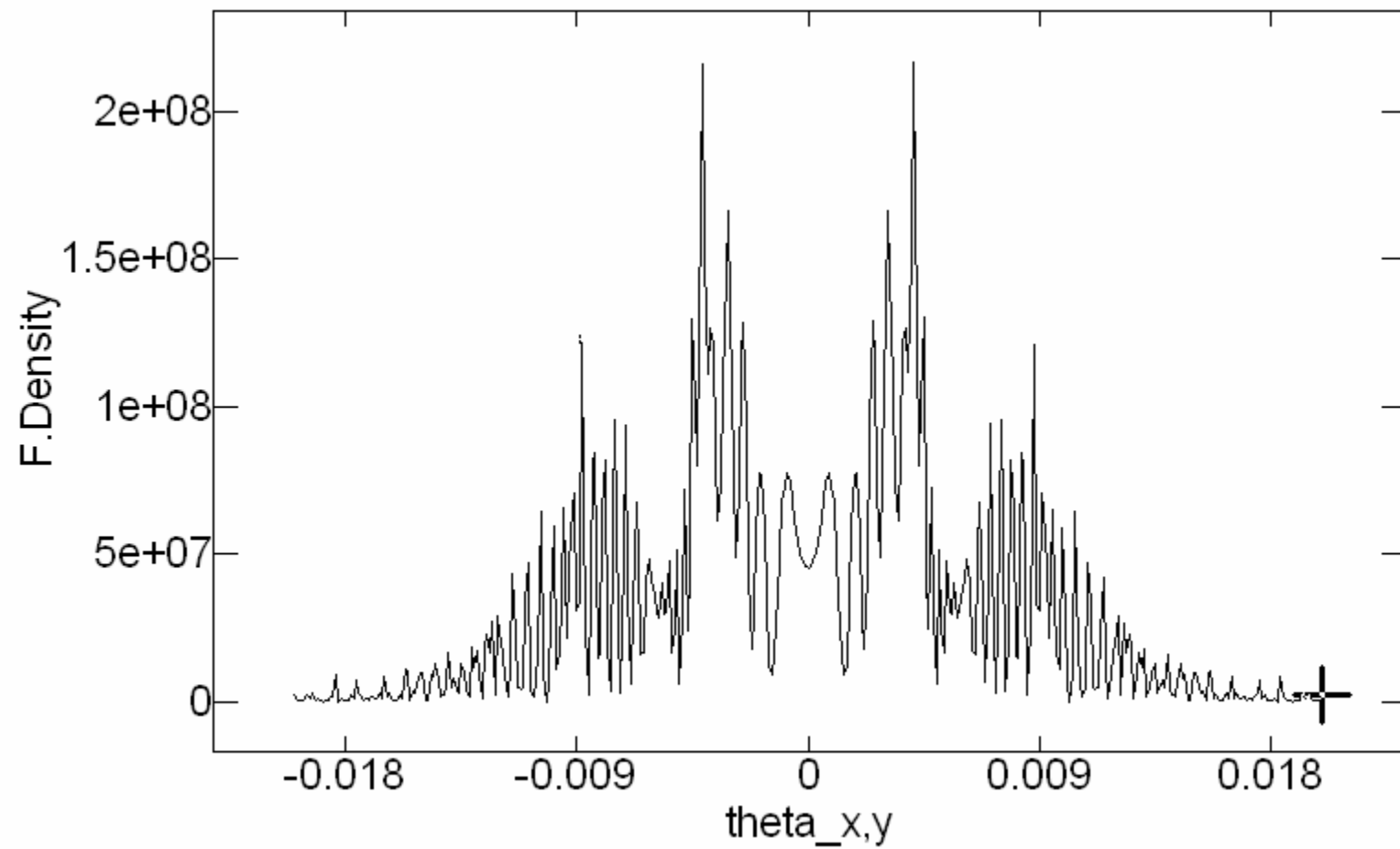
SIMPLEX GUI with ARAMIS undulator parameters



Flux density on axis (Photons/s/mm²/(0.1%bw)) vs. radiated photon energy. The fundamental (12.4MeV) 3rd and 5th harmonics are presented. Electron beam emittance and energy spread are 0. (SPECTRA)



Flux density on axis
 (Photons/s/mm²/(0.1%bw)) vs.
 radiated photon energy.
 a) Electron beam emittance and
 energy spread are 0; b) Electron
 beam energy spread is 0.

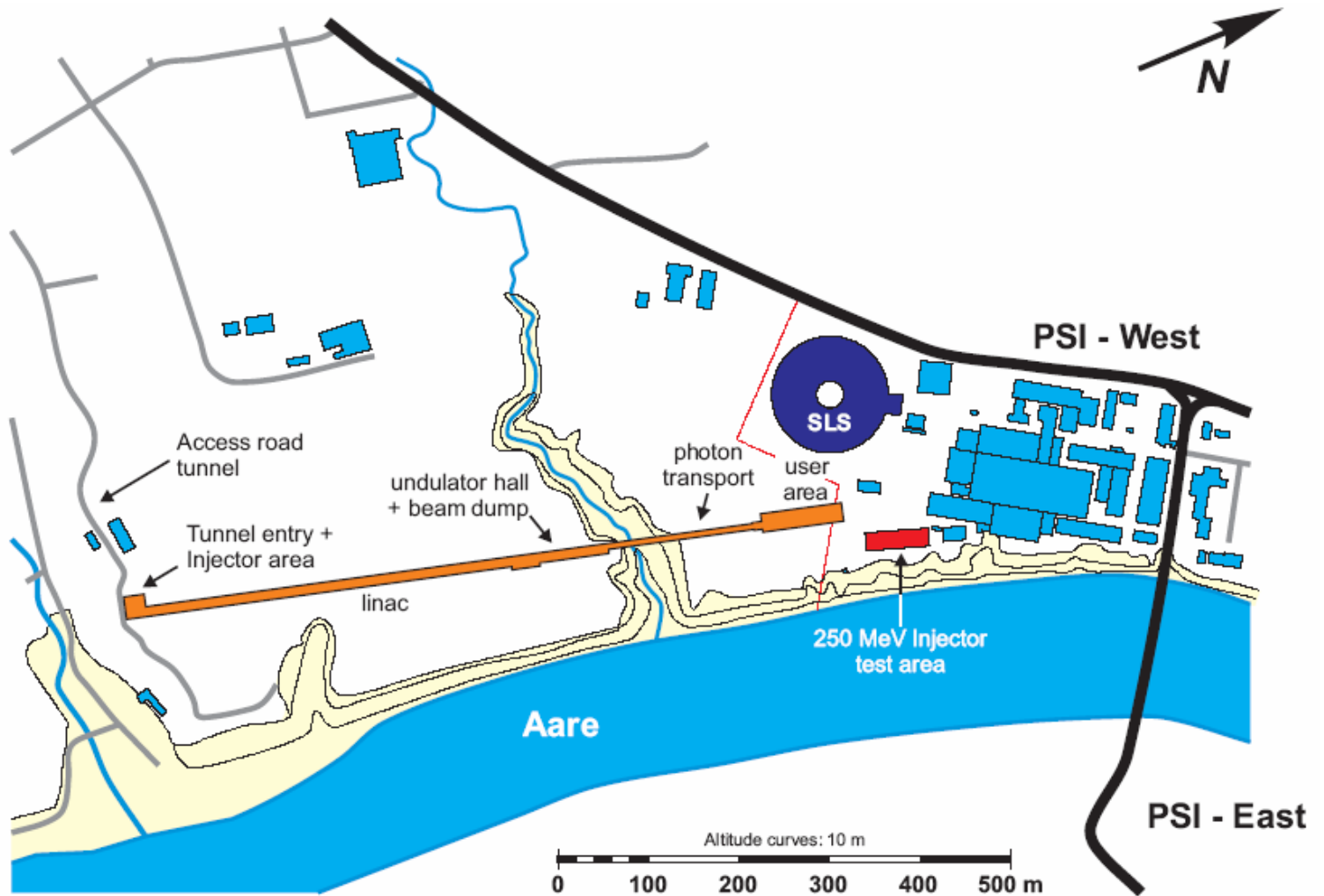


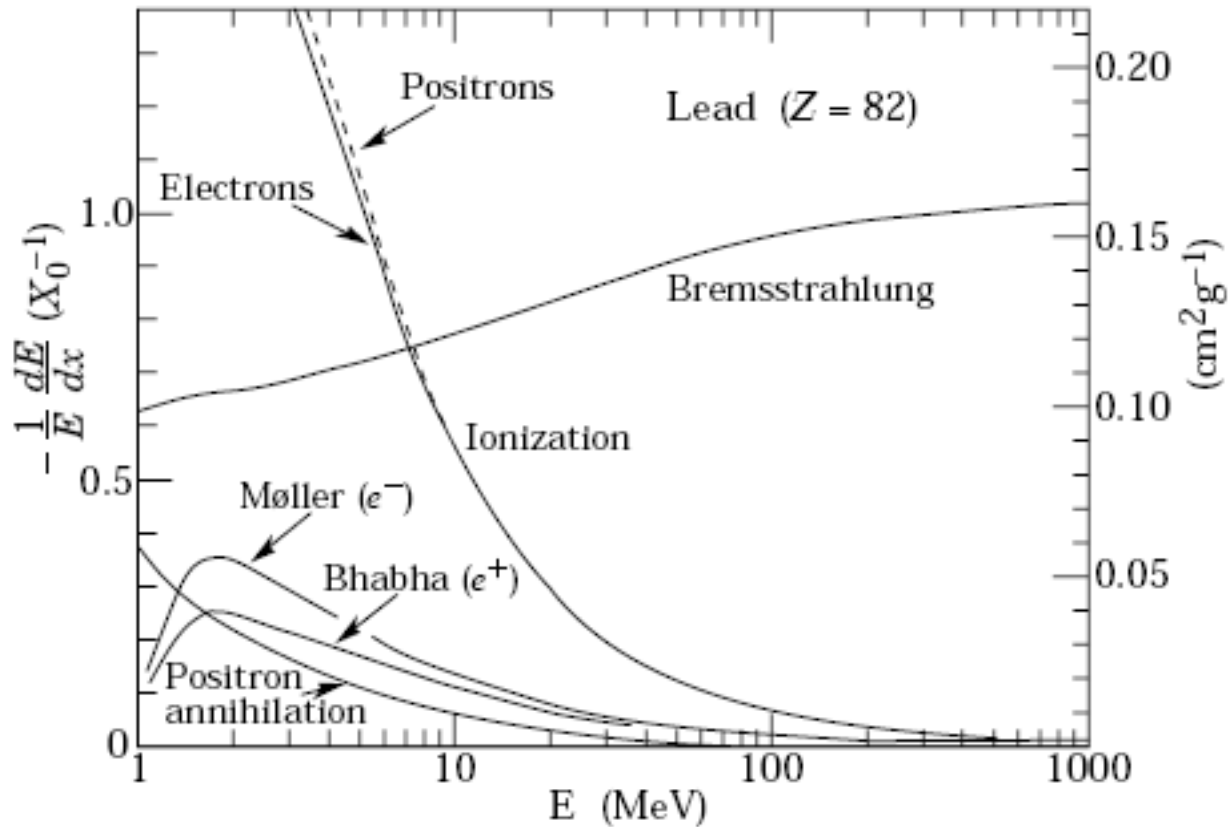
CONCLUSIONS

Peak brilliance SPECTRA value is 4.3×10^{27} , while FEL brilliance is 1.1×10^{33} in (Photons/s/mm²/mrad²/0.1%bw)

SPECTRA allows precise calculations of spectral, angular and spatial distributions as well as polarization parameters of the radiation produced by long chain of the undulators taking into account finite beam emittance and energy spread.

Bremsstrahlung on the residual gas





(Fig. 27.10 from PDG report 2008, [2]); Energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above [2].

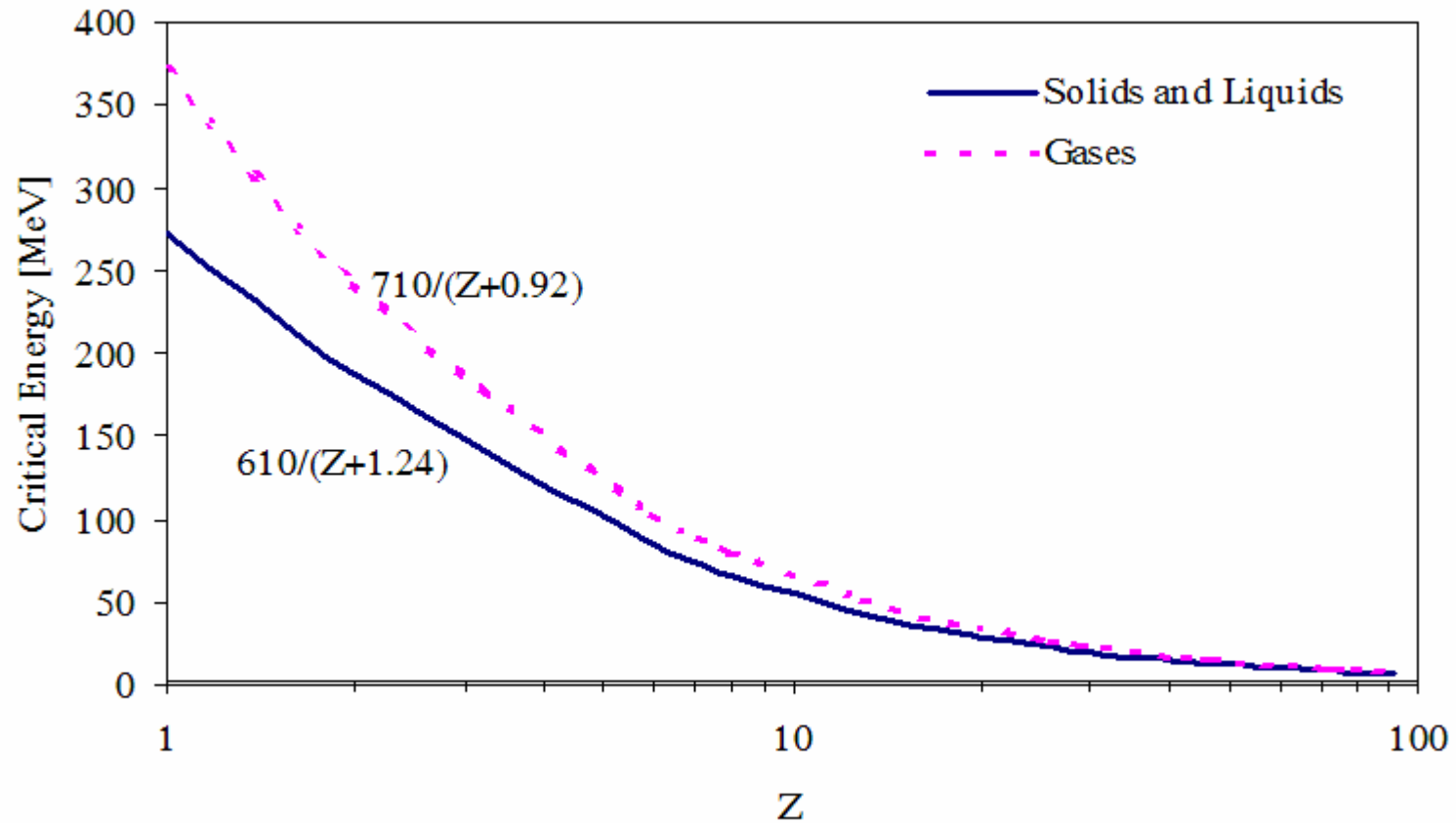
Bremsstrahlung on residual gas

Residual gas	CO
Atom. Weight	28
Effective Z	7.14
Density	$1.25 \cdot 10^{-3} \text{ g/cm}^3$
Rad. Length	37.4 g/cm^2
Beam pipe strait length	$>\sim 100\text{m}$

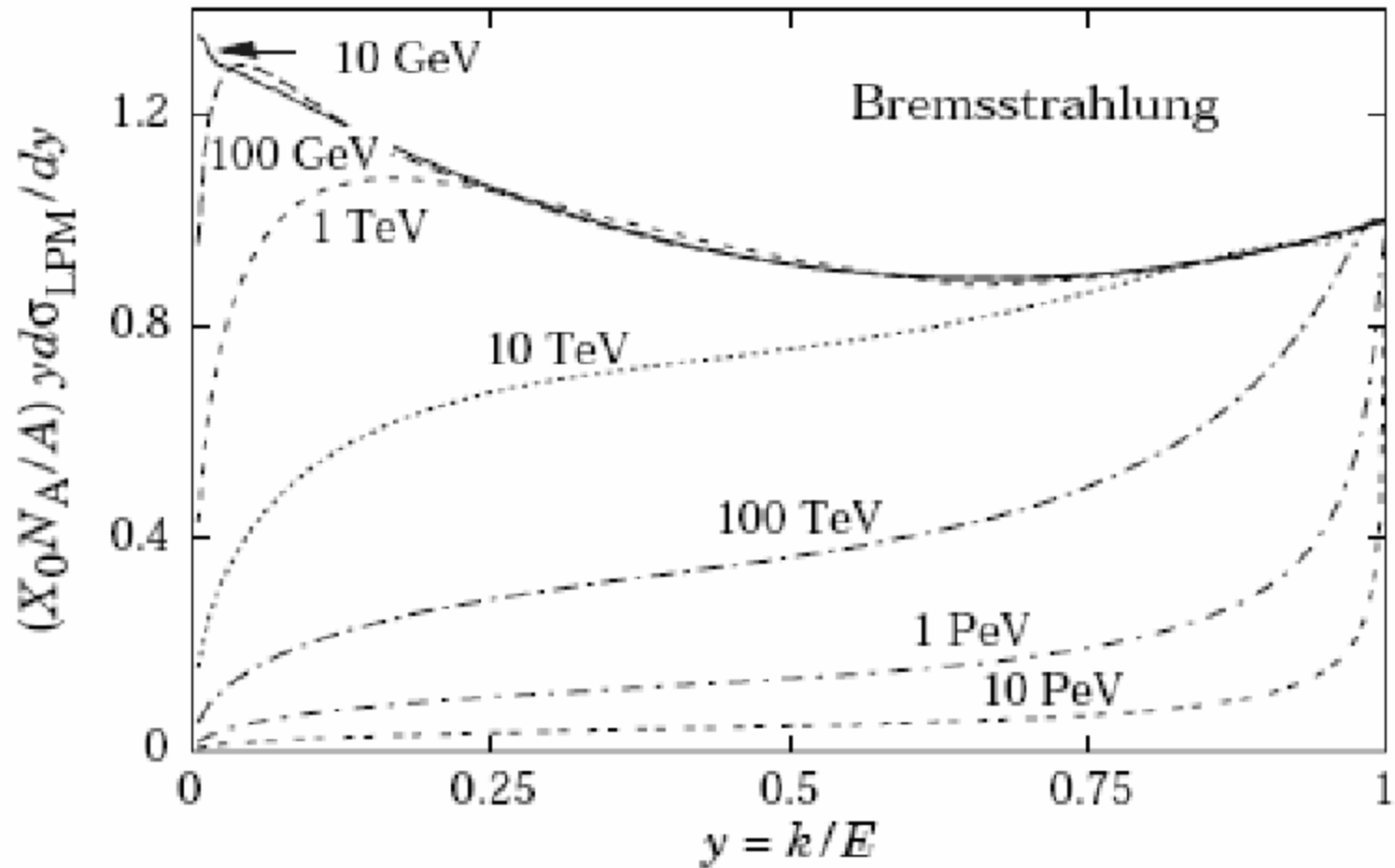
Radiation length

O. I. Dahl fit to the data

$$X_0 = \frac{716[g - cm^{-2}]A}{Z(Z+1)\ln(287/\sqrt{Z})}$$



Electron critical energy dependence on the atomic number of the chemical elements, for solids and liquids (solid line) and gases (dashed line). At energies above critical one bremsstrahlung prevails over ionization.



(Fig. 27.11 from PDG report 2008, [2]): The normalized bremsstrahlung cross section $k d\sigma_{\text{LPM}}/dk$ in lead versus the fractional photon energy $y = k/E$. The vertical axis has units of photons per radiation length.

Gas pressure is measured in mbars (1bar = 100000 Pa) or Torrs (1Torr = 133.322 Pa). Note that normal atmospheric pressure is equal to 101325 Pa (760 Torr), it also is being used as a gas pressure unit (atm).

Full screening limit in the bremsstrahlung process for CO gas is 36 MeV (Formula 8). Beam pipe strait section length adjacent to the undulator section is about 200 m (Fig. 6) and calculated travel distance of electron beam (in the units g/cm²) under the modest vacuum pressure 10⁻⁶ Torr would be $d = 3.29 \times 10^{-8}$.

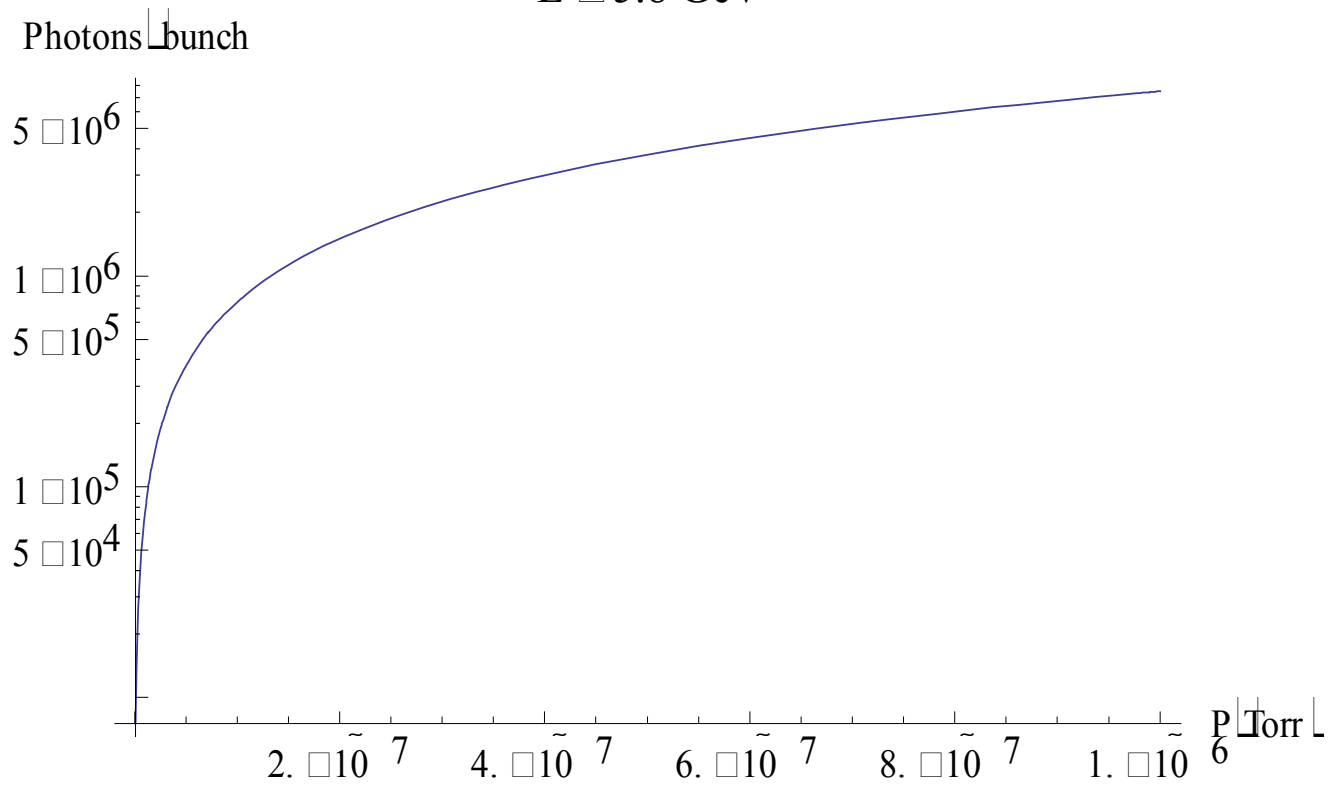
The number of photons with energies between k_1 and k_2 radiated by an electron traveling a distance $d \ll X_0$ is

$$N_\gamma = \frac{d}{X_0} \left[\frac{4}{3} \ln \left(\frac{k_2}{k_1} \right) - \frac{4(k_2 - k_1)}{3E_e} + \frac{k_2^2 - k_1^2}{2E_e^2} \right]$$

photon emission angle is $\bar{\theta} = \frac{m_e c^2}{E_e} \quad 0.88 \times 10^{-4} \text{ for } 5.8 \text{ GeV}$

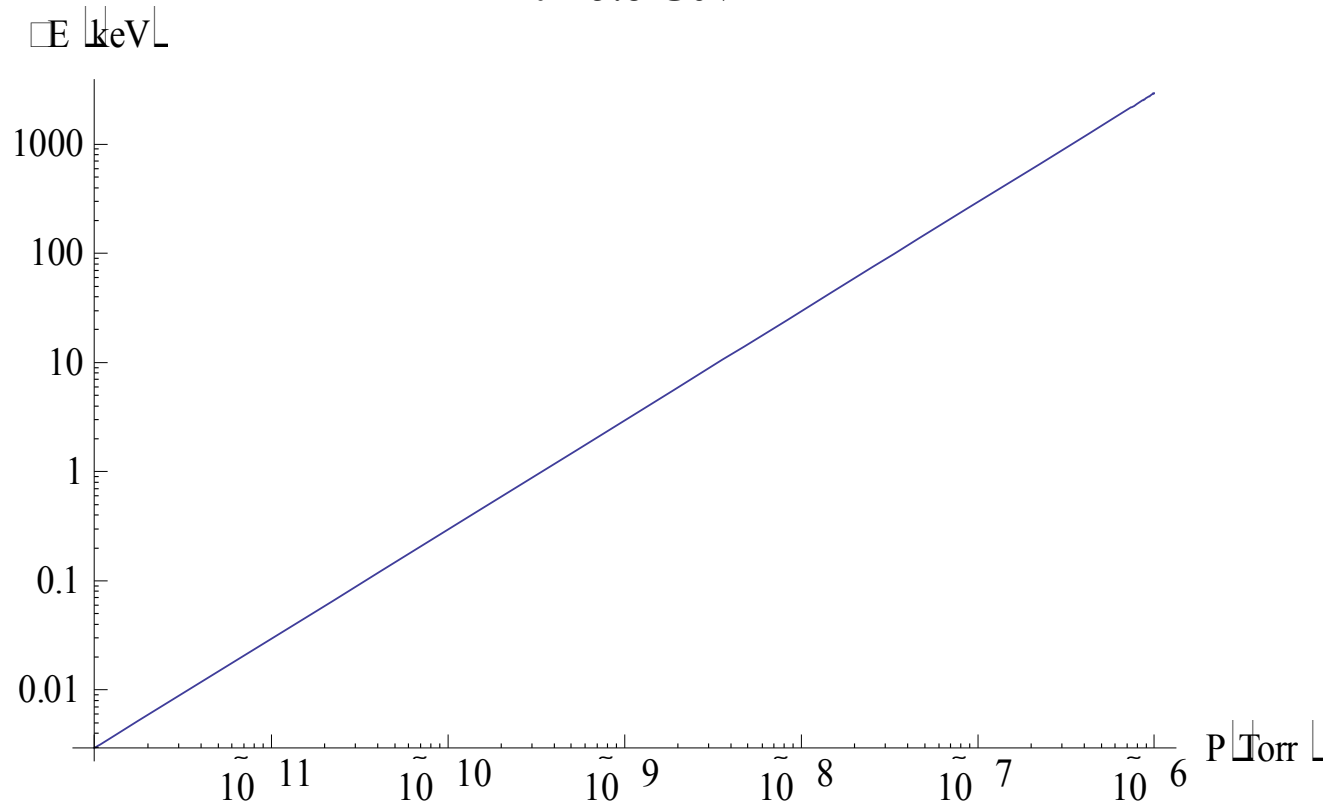
Electron energy [GeV]	Photon angle [mrad]	Energy loss rate[MeV/(g/cm ²)
5.8	0.088	155
5.6	0.091	150
5.4	0.095	144
5.2	0.098	139
5	0.102	134
4.8	0.106	128
4.6	0.111	123
4.4	0.116	118
4.2	0.122	112
4	0.128	107
3.8	0.134	102
3.6	0.142	96
3.4	0.150	91
3.2	0.160	86
3	0.170	80
2.8	0.183	75
2.6	0.197	70
2.4	0.213	64
2.2	0.232	59

$E \approx 5.8 \text{ GeV}$

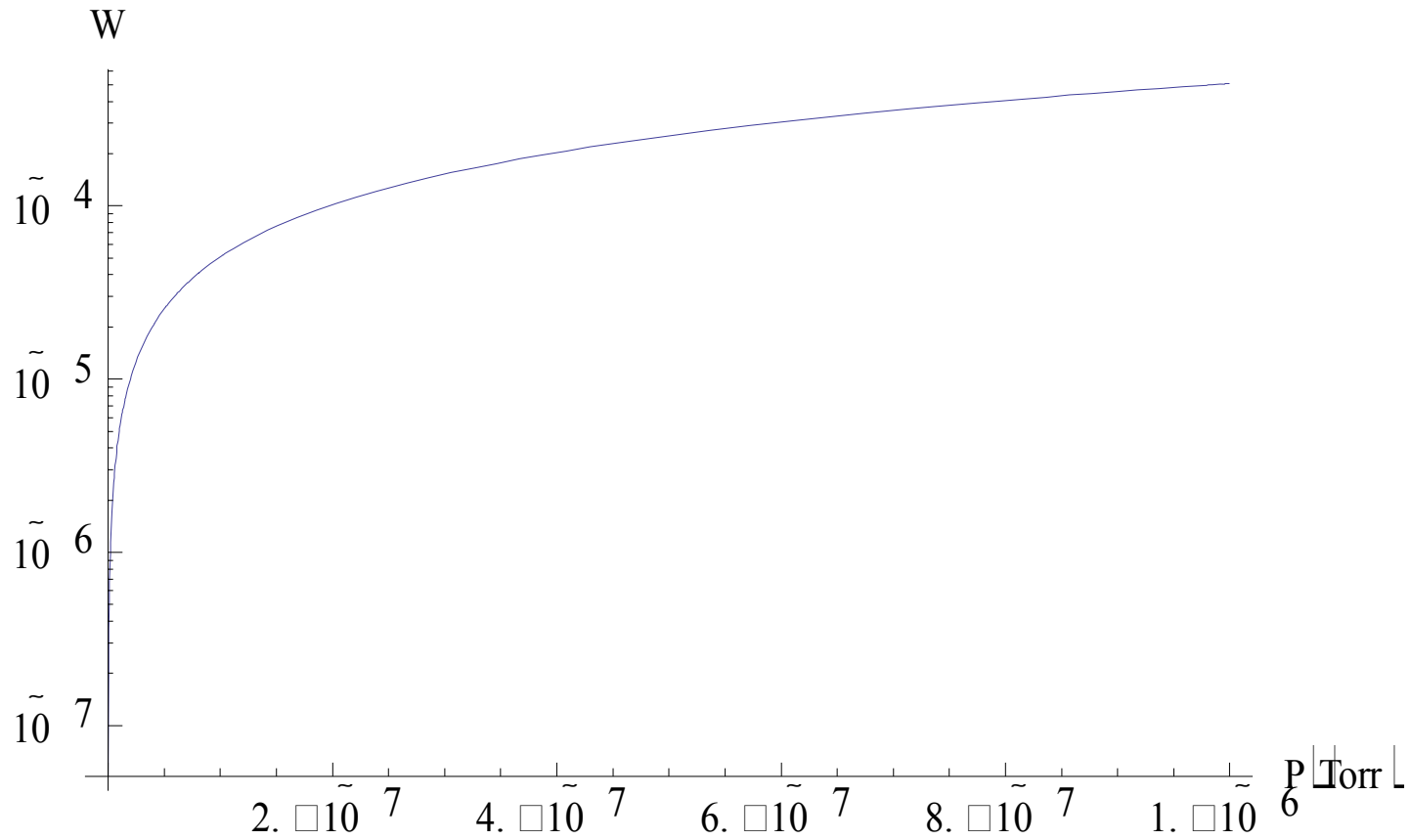


Number of radiated photons per bunch with the energies versus residual gas pressure.

$E_0 = 5.8 \text{ GeV}$



Mean energy loss for the electron traversed strait section of the vacuum chamber. Under the pressure $p=10^{-7}$ Torr mean energy loss is equal to RMS energy spread 300keV.



Bremsstrahlung radiation probability for the electron traversed strait section of the vacuum chamber. Under the pressure $p=10^{-7}$ Torr radiation probability is 5.1×10^{-5} .

CONCLUSIONS

For the certain technology of beam pipe (stainless steel vacuum chamber with Titanium-Nitride (TiN) inner coating) the residual gas predominantly consists of CO. If another technology is chosen calculations should be repeated for new gas.

Bremsstrahlung radiation opening angle is large and photons can hit the walls of beam chamber. Photons emitted by 5.8 GeV electron travel 9mm in transverse direction in 100m path.

There are always very energetic photons in radiation spectrum with energies up to energy of the primary electron that can cause electromagnetic shower when they hit the vacuum chamber walls.

For the 200 PC bunch charge there are 1.25×10^9 electrons in the bunch. In the moderate vacuum 10^{-8} Torr 7.5×10^4 photons (with the energies more than 300 keV) per bunch are being radiated. Thus about 0.6 % of 5.8 GeV electrons energies are being changed by the greater value than initial energy spread.