Radiation protection study for the X-FEL[*]

updated version

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Abstract

After passing an undulator section, where electron and photon beam are almost collinear, the electron beam is being separated from the photon beam by an electromagnetic dipole for a further lasing process, while the photons travel down the beampipe until they reach the experimental hall. In case this magnet fails, some safety installations are being discussed at the moment, most of them resulting in a quality loss of the photon beam due to optical beam manipulations. It was my task to find out, whether it is feasible and reasonable to install a permanent magnet right after this beam distribution. The results of this estimation and recommendations for the permanent magnet, as well as for appropriate shielding measures are displayed here.

1 Introduction

The X-FEL is a free electron laser that is going to be build in Hamburg at the DESY-site. It's goal is to produce X-rays of wavelengths between $0,1$ nm and $1,6$ nm with the highest brilliance ever achieved. It benefits from the experience gained from the already operational Free Electron Laser Hamburg (FLASH) and the superconducting accelerator technology that was developed for the (never built) Linac TESLA.

The electrons are being accelerated in a 2km long linear accelerator to an energy of $17,5$ GeV and then distributed in a 1.2 km long beam-distribution-system to three different undulator sections, where the lasing processes (SASE) take place.

Another 219 m after the end of the undulator SASE 1 (see figure 1) the already mentioned electromagnetic dipole is installed. The designated position for the permanent magnet of yet unknown specifications is another 10 meters further down the photon-beampipe. This gives a 153 m long tunnel-section between the safety installation and the next hall-segment (XS3) where people are considered

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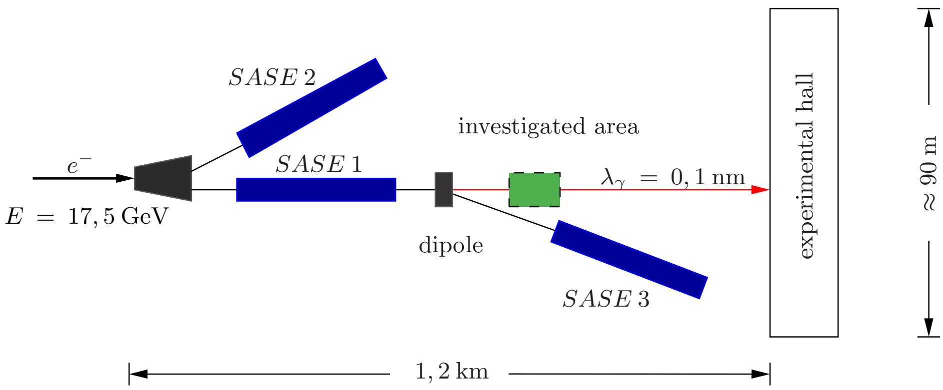


Figure 1: beam-distribution-system (relevant parts only)

to work when the electron beam is being deflected into another tunnel and the photons are being blocked by a tungsten-shutter.

The breakdown-scenario discussed is a complete and instantanious failure of the electromagnetic dipole. Emergency systems have a delay, such that one complete train of $1,9 \cdot 10^{13}$ electrons at 17, 5 GeV is likely to accidentally fly uncontrolled through the photon-beampipe before the electron injection can be stopped. To illustrate this, the energy in one such train is about 55 kJ which is enough energy to melt 160 g of stainless steel or even more dramatically, the energy of about 100 fired pistol bullets.

1.1 Deflection of the electron beam by a magnetic field

For the following calculations, it is essential to have an expression for the deflection of the electron beam caused by a magnetic field perpendicular to it. In order to do so, one can exploit the equality of centrifugal and Lorentz force, giving the radius R of the electron-trajectory:

$$R = \gamma \cdot \frac{m|\vec{v}|^2}{|\vec{F}_L|} = \gamma \cdot \frac{m_e\,|\vec{v}|}{q_e|\vec{B}|\sin\zeta} \tag{1}$$

This radius can now be used in order to calculate the deflection of the beam x perpendicular to its original direction due to the presence of a homogeneous magnetic field:

$$x(L, |\vec{B}|) = R \cdot \left(1 - \sqrt{1 - \left(\frac{L}{R}\right)^2}\right) \tag{2}$$

After passing the permanent magnet, the beam will continue its movement on a linear trajectory but deviated from its original direction by the angel α, given

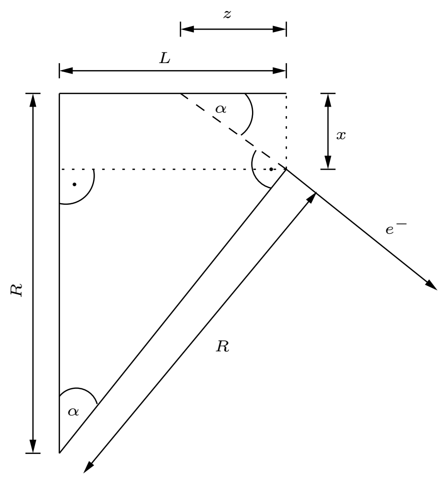


Figure 2: radius of the electron trajectory

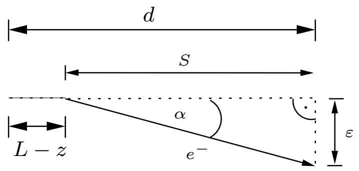


Figure 3: deflection of the electron beam

by:

$$\alpha = \arccos\left(\frac{R-x}{R}\right) = \arccos\left(1-\frac{x}{R}\right) = \arccos\sqrt{1-\left(\frac{L}{R}\right)^2}$$

As one can learn from figure 3, the deflection ε is given by $\varepsilon = S \cdot \tan\alpha$. With the help of figure 2 this can be expressed in terms of the length and the intensity of the magnetic field L, $|\vec{B}|$ as well as the distance d between the start of the magnetic field and the expected impact at hall XS3:

$$\varepsilon\,(L, d, |\vec{B}|) \;=\; (d \;-\; L) \cdot \tan\alpha \;+\; x \qquad (3)$$

See equation(2) for an expression of the quantitiy x.

2 Permanent magnet

It is a common demand for safety installations that they have to exceed external effects at least by two orders of magnitude, thus the deflection of the beam caused by the magnetic field of the permanent magnet has to be at least 100 times greater than that of the most relevant external fields. In this section the two strongest external fields are being discussed. These are the earth's magnetic field and the one caused by the Hamburg S-Bahn, which runs on continuous current.

2.1 Earth's magnetic field

Luckily, the *GeoForschungsZentrum Potsdam* operates a measuring facility in Wingst, just 50km east of the DESY-site. They measure the (local) components of the earth's magnetic field once every second. Their data is accessible to the public[1].

The components measured are defined as follows:

- horizontal component H: tangential to earth's surface, pointing towards magnetic north pole
- vertical component Z: perpendicular to earth's surface, positively pointing downward
- declination D: angle between magnetic and geographic north pole

The values of H and Z used for the actual calculation are displayed in table 1. They are derived from a data sample covering 81 days, representing the value of the field components during night, which means in absence of solar influences. The latter are included in the errors given in the table. They contain the differences of these components between night and day, which are about 150 nT each, as well as the greatest solar influence measured so far that took place during the so called 'Halloween-Storm' a solar storm in october/november 2003 of about 1000 nT. Also another 10 % buffer covering the differences between Wingst and Hamburg is included in these numbers.

The coordinate system used and the geometry of the X-FEL tunnel in it are shown in the figures 4 and 5. In Hamburg, the magnetic north pole is situated east of the geographic north pole, thus the vector of the magnetic field has the following structure:

$$\vec{B} = \begin{pmatrix} Z \\ -H \cdot \cos D \\ -H \cdot \sin D \end{pmatrix}$$

From figure 5 one can derive the strucure of the vector of the electron's velocity:

$$\vec{v} = \begin{pmatrix} 0 \\ v_y \\ v_z \end{pmatrix} = |\vec{v}| \cdot \begin{pmatrix} 0 \\ -\sin\eta \\ \cos\eta \end{pmatrix}$$

The LORENTZ force is given by $\vec{F}_L = q \cdot \vec{v} \times \vec{B}$ which gives:

$$\vec{F}_L = -e\,|\vec{v}| \cdot \begin{pmatrix} H \cdot [\cos\eta \cdot \cos D + \sin\eta \cdot \sin D] \\ Z \cdot \cos\eta \\ Z \cdot \sin\eta \end{pmatrix}$$

This is a vector with negative components only, since the following inequalities hold:

$$0 < \eta; \qquad D < \frac{\pi}{2}: \qquad H,\ Z\,, |\vec{v}| > 0$$

This can be used to qualitatively derive the deflection of the electron beam, which is according to the coordinate system used (figure 4) to the top right of the endcap wall, if seen from the viewpoint of the incoming particles.

[1] `http://www.gfz-potsdam.de/pb2/pb23/index.html`

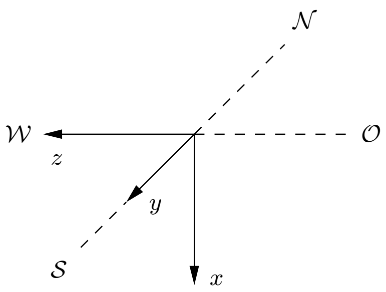


Figure 4: coordinate system

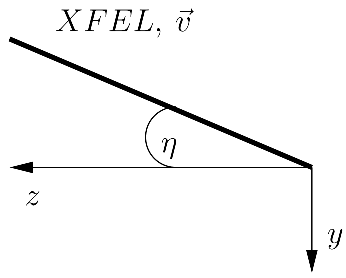


Figure 5: position of the X-FEL, top view

Quantity	Value	Unit
H	18200 ± 1820	nT
D	68 ± 20	$'$
Z	45900 ± 4590	nT
η	$23,02 \pm 2,35$	$\circ$
E	$17,5 \pm 0,0015$	GeV
d	153 ± 1	m
L	$2,0 \pm 0,2$	m

Table 1: properties of earth's magnetic field and the X-FEL

The norm of $\vec{F}_L$ is given by

$$|\vec{F}_L| = e\,|\vec{v}| \cdot \sqrt{H^2 \left[\cos\eta \cdot \cos D + \sin\eta \cdot \sin D\right]^2 + Z^2} \tag{4}$$

As mentioned before, the resulting radius of the electron trajectory can now be calculated by taking advantage of formula (1) using the result from equation (4):

$$R = \gamma \cdot \frac{m}{e} \cdot \frac{|\vec{v}|}{\sqrt{H^2 \left[\cos\eta \cdot \cos D + \sin\eta \cdot \sin D\right]^2 + Z^2}}$$

With formula (2) and the values found in table 1, the expectable deflection ε of the electron-beam after passing $d = 153\,\text{m}$ of the beampipe is:

$$\underline{\varepsilon = (0,992 \pm 0,013)\ \text{cm} \qquad \frac{\Delta\varepsilon}{\varepsilon} = 1,3\%}$$

This means, that in order to satisfy the demand for an effect of two orders of magnitude greater than that of external fields, the permanent magnet must at least deflect the electron beam by 1 m.

2.2 Influence of the S-Bahn

Since the S-Bahn Hamburg runs on continuous current ($I = 1250\,\mathrm{A}$) and the S1 (Blankenese ↔ Poppenbüttel) being situated almost parallel to the X-FEL-tunnel, a rough approximation of the resulting magnetic field at the location of the X-FEL can be gained by the use of Ampere's law applied on the problem of a straight conductor of infinite length and negligible cross section:

$$|\vec{B}(r)| = \frac{\mu_0 I}{2\pi r}, \qquad \mu_0 = 4\pi \cdot 10^{-7} \frac{T}{A \cdot m}$$

The closest distance between the tracks and the tunnel is about $2\,km$, giving a magnetic field of

$$|\vec{B}_{SBahn}(XFEL)| = 125\,\mathrm{nT}$$

This magnetic field is two orders of magnitude smaller then earth's magnetic field, hence the influence of the S-Bahn will be neglected for this problem.

2.3 Magnetic field intensity needed

In order to exceed the effects discussed earlier by two orders of magnitude, we can now use equation (3) to estimate the strength of the magnetic field needed. The length of the magnetic section is assumed to be $L = 2\,\mathrm{m}$. The results of this calculation are shown in figure 6 for different qualities of the magnetic field.

3 Radiation protection simulations

All the simulations werde done using FLUKA[2], a Monte Carlo tool that has first been introduced in 1962 and whose capabilities have since then permanently been expanded by INFN and CERN. It is widely used in dosimetry and high energy physics especially for the designing of detectors and safety installations.

The geometry was modeled using specifications given in the X-FEL's Technical Design Report[3]. Simulations with FLUKA are very demanding in CPU-time, therefore, only the most relevant parts were considered (see figure 7 and table 2). This was done for two cases, on the one hand considering secondaries produced directly at the beampipe only, which leads to about two thirds of all electrons escaping the simplified geometry shown in figure 7b and on the other hand considering the secondaries produced in the 'complete' geometry shown in figure 7a causing $99,8\,\%$ of all electrons to generate secondary particles.

3.1 Secondary particles

For deflections ranging from 75 cm to 275 cm simulations with 10000 beam particles have been performed. The statistical summaries of these FLUKA-runs

[2] `http://www.fluka.org`
[3] X-FEL TDR, July 2006

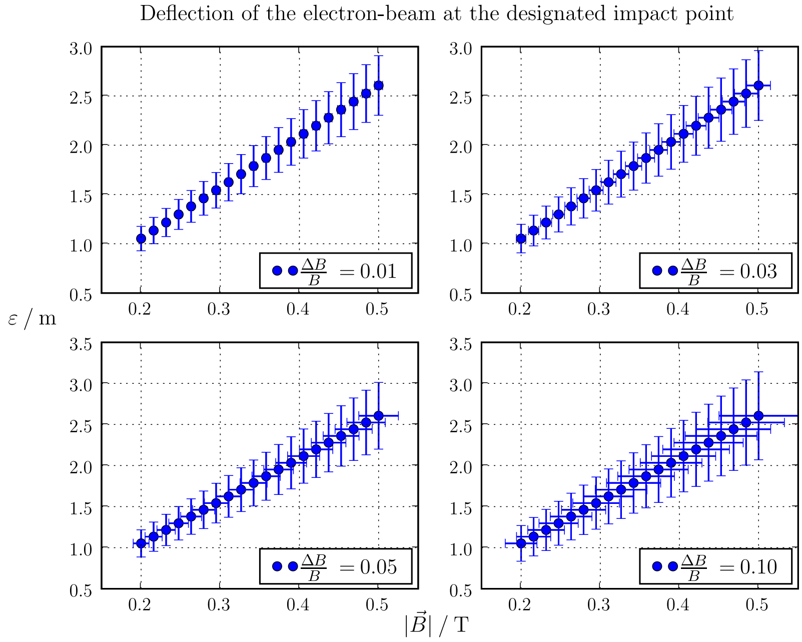
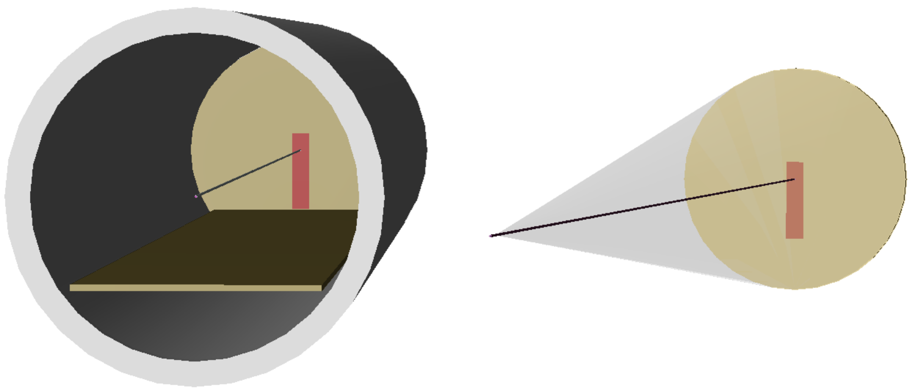


Figure 6: Deflection results for 2 m long magnets of different qualities

Component	length / cm	outer ∅ / cm	inner ∅ /cm	Material
tunnel sections	15570	600	520	heavy concrete
end cap walls	135	600	4	heavy concrete
beampipe	15570	4	3,6	stainless steel
	lenght /cm	width /cm	heigth /cm	
floor	15300	400	10	concrete
persons	12	180	40	tissue equivalent M-20

Table 2: Components modeled for the FLUKA-simulations



(a) Complete geometry (omitting front wall) (b) Simplified geometry

Figure 7: Geometries used for FLUKA-simulations

have been used to investigate the number and the kind of secondary particles produced as prompt radiation.

Production at beampipe

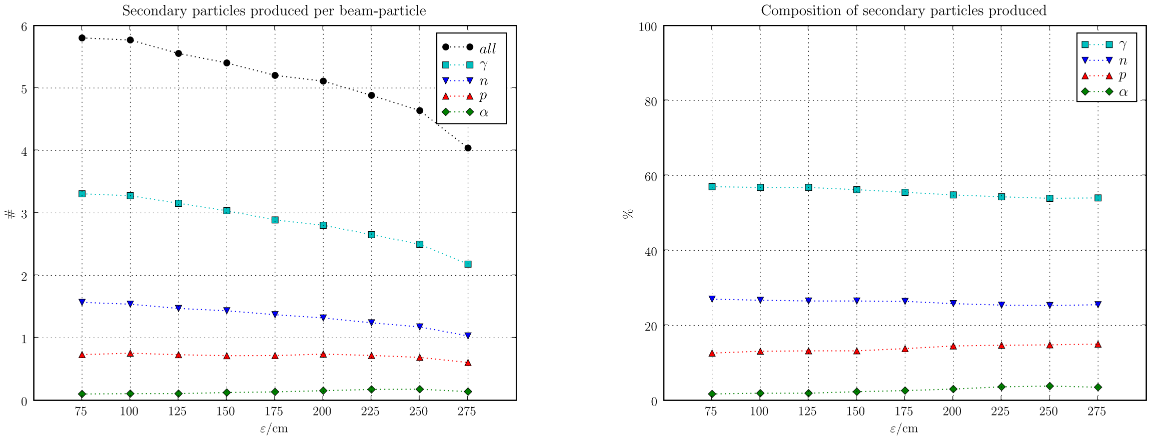
It might be of interest to know about the secondaries produced directly at the beampipe, so that further shielding measures (if composed appropriately) might be able to stop the particles as soon as they appear.

From the simulations one observes, that the number of secondary particles being produced decreases as the deflection of the beam increases (see figure 8a). This can be understood by taking into consideration that a larger angle of incidence results in less material the electrons 'see' and therefore an increasing escape probability of the electrons from the beampipe.

Also, the composition of the secondary particles changes slightly. A greater deflection results in a somewhat smaller amount of photons and neutrons, while the fraction of protons and α-particles becomes slightly larger. The latter one being unproblematic.

ε/cm	$\Phi_{n,before}/10^3$ cm^{-2}	$\Phi_{n,behind}/10^3$ cm^{-2}	$\Phi_{\gamma,before}/10^5$ cm^{-2}	$\Phi_{\gamma,behind}/10^5$ cm^{-2}
100	9,0	3,5	59,2	2,7
150	37,2	7,4	64,2	5,4
200	70,8	8,3	86,5	5,2
250	69,7	21,4	93,3	4,4

Table 3: neutron and photon fluxes appearing on persons before and behind endcap wall, extrapolation for a complete train of electrons



(a) Secondaries produced ...

(b) ... and their composition

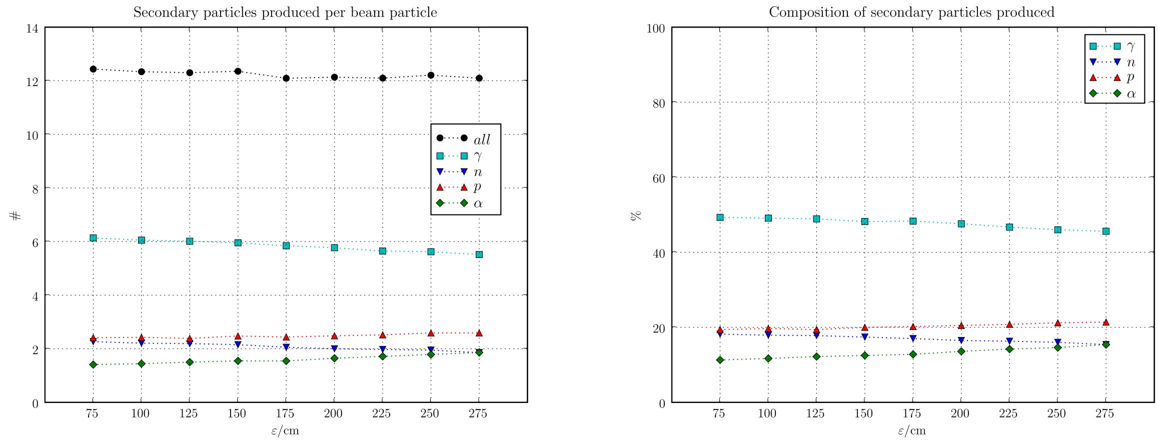
Figure 8: Production occuring directly at the beampipe as a function of the (virtual) deflection of the beam at the endcap wall

Production at complete eometry

The same holds if one considers the whole tunnel (geometry as shown in figure 7a) as a target for the electron beam, except the fact, that the number of secondary particles produced per beam particle appears to be constant.

3.2 Particle fluxes

For a total number of 500000 electrons per run, the resulting particle fluxes appearing on a person (for specifications see table 2) in front of and behind the endcap wall have been recorded from simulations using the simplified geometry (figure 7b). Extrapolations for a complete train from these samples are shown in table 3 for several deflections of the electron beam. Please note that these numbers do not include fluxes caused by reflections at the tunnel segments or the floor.



(a) Secondaries produced ...

(b) ... and their composition

Figure 9: Production at complete geometry as a function of the (virtual) deflection of the beam at the endcap wall, 0, 2 % of beam particles escape

4 Conclusion

Simulations have shown that every beam particle is likely to cause about 12 secondaries, including 6 photons as well as 2 neutrons and 2 protons, the latter one's fraction slightly increasing with growing deflection, while the fraction of neutrons and photons slightly decreases. Even for a spatially isotropic particle production in the center of momentum system (CMS), most of the particles are likely to deposit their energy at or after the endcap wall if no proper precautions are made, since the CMS of a 17, 5 GeV electron colliding with a proton at rest, moves with almost a quarter of the speed of light with respect to the lab-frame.

Specifications of the permanent magnet

The external magnetic fields have been found not to be of much concern. Apparently, already comparably small magnetic field intensities like 0, 3 T could satisfy the minimum demand for a beam deflection by at least 1 m as it was discussed earlier.

On the other hand, we know that the beampipe will melt after a few bunches (see example ahead). From another simulation we know, that an electronbeam that hits the 1, 35 m long heavy concrete endcap wall unhinderedly, results in $\approx$ 3% of all beamparticles passing the wall without causing electromagnetic showers and thus whithout energy-loss. So in order to minimize the risk of beam particles passing the wall and entering XS3, the deflection should be at least 2, 15 m, so that the beam will hit the ground floor first.

This could already be achieved with a 2 m long permanent magnet of 0, 5 T.

Shielding

From a simple calculation we know that a 100 μm long piece of the beampipe is very likely to melt after 1 % of all particles in one train. This means, that about 99 % of all the electrons will not 'see' the beampipe. This already takes into account, that the probability of an interaction between a beamparticle and the beampipe is about one third.

a) just after the electrons hits the beampipe

Knowing this and following the discussion above, one could draw the conclusion that the beampipe should be comparably thin at the designated impact point to avoid wild showering (1 % of all beamparticles cause production of $\approx 10^{11}$ neutrons) in the first place and that the beam should rather hit a heavy concrete beamdump, followed by a heavy concrete wall that provides photon and proton shielding in one go.

Behind this wall an almost hermetically enclosing paraffin/plastic-wall should be installed in order to cope with the vast number of $4 \cdot 10^{14}$ neutrons produced in total, especially the low energetic ones that are able to 'sneak around' any object.

The also vast number of α-particles produced is of no concern since they can be stopped completely by a sheet of paper.

b) at the endcap wall

From the study of the particle fluxes, that will appear on a plane of the size of a person, we learnt, that the heavy concrete endcap wall does a good job in the shielding the photons, because it damps their flux by a factor of 20. This could easily be improved by a thicker endcap wall.

However, the flux of neutrons is only damped by a factor of 3, so that additional neutron shielding measures have to be considered. The simplest way would again be the installation of a plastic/paraffin wall.

further remarks

During experimenting with the software it was observed, that a greater wall thickness of the beampipe results in significantly less particle fluxes at the wall at hall XS3 due to more material shielding the radiation and preventing particles produced from escaping the beampipe. This could also be considered in further studies.

Acknowledgement

I would like to thank my supervisor Dr. Martin Sachwitz as well as Dr. Harald Sinn[4] for their continuous support and patience. Also a big thank you to Dr. Hans-Joachim Linthe[5] for his comments on the earth's magnetic field.

[4]DESY/HH, work package leader hard photon beamlines for X-FEL
[5]GeoforschungsZentrum Potsdam