



# Monte Carlo Simulations for the FLASH 2 Collimators

Aiveen Finn

MPY

6th September 2012

## Abstract

In the presented work, the programme FLUKA and its advanced interface *flair* were investigated in order to hence determine the occurrences within the FLASH 2 collimators and the collimators' effectiveness. With the theory and use of FLUKA and *flair* understood it was then possible to further the research to the FLASH 2 collimators. The FLASH 2 collimators were examined using two of FLUKA's unique scoring methods. The first scores the distribution of particles in a defined binning area independent of the geometry of the system and the second determines the fluence or current crossing a defined boundary.

# Contents

<b>1</b>	<b>Introduction and Theory</b>	<b>3</b>
1.1	FLASH and FLASH 2 . . . . .	3
1.2	The Collimator . . . . .	4
1.3	FLUKA and <i>flair</i> . . . . .	5
<b>2</b>	<b>Method</b>	<b>7</b>
<b>3</b>	<b>Results and Analysis</b>	<b>9</b>
3.1	Scoring Method: USRBIN . . . . .	9
3.1.1	All Charged Particles . . . . .	9
3.1.2	Electromagnetic Dose . . . . .	10
3.1.3	Electromagnetic Energy . . . . .	11
3.2	Scoring Method: USRBDX . . . . .	12
<b>4</b>	<b>Summary</b>	<b>13</b>
<b>5</b>	<b>Acknowledgements</b>	<b>14</b>
<b>6</b>	<b>References</b>	<b>15</b>

# Chapter 1

## Introduction and Theory

The aims of this project were to become familiar with FLUKA and *flair* and to determine what occurs within the new FLASH 2 collimators when an electron beam is present and also the collimators' effectiveness. With the construction of FLASH 2, it was necessary to discover what would happen inside its specific collimators and hence the programmes that would enable the research to be carried out had to be investigated also. Using the Monte Carlo techniques employed by FLUKA, the activity of the collimator and the beam was able to be determined, as well as the new collimators' efficiency. This was investigated by firing a  $1\text{ GeV}$  electron beam at the FLASH 2 collimator with varying impact points and starting distances. The data was collected under a range of parameters and from these different parameters it was possible to study the interactions of the new FLASH 2 collimators with a beam of electrons and thus the effectiveness.

### 1.1 FLASH and FLASH 2

FLASH: Free Electron Laser in Hamburg.

FLASH is the world's first free electron laser (FEL) and it generates radiation in the ultraviolet and soft x-ray regions. FLASH 2 is a major extension of FLASH [1].

An FEL consists of two parts: a linear accelerator (linac) and an undulator section. The linac begins with a laser which hits a cathode and excites electrons. These electrons travel as bunches and are accelerated to energies between  $600\text{ MeV}$  and  $1.25\text{ GeV}$ . As the electron bunches travel through superconducting cavities they are accelerated. This works via the principle of standing waves. These superconducting cavities are made up of nine pill boxes/cells and they are placed in modules with eight per module. These modules contain helium at  $4\text{ Kelvin}$  and it is this helium that cools the superconducting cavities, which are made of niobium. Once accelerated through the cavities the electron bunches are compressed via two bunch compressors. Beam optics consisting of quadrupole and sextupole magnets, focus the beam in both planes. The transverse collimators are downstream from the accelerating structures.

In the case of FLASH, the electron bunches pass through the energy dogleg, which

is required to have appropriate positions for the energy collimators. After the dogleg, the electron bunches travel through a series of undulators and it is in this section that synchrotron radiation is produced. In order to separate the radiation light from the electrons, the undulators are quickly followed by a massive dipole magnet which directs the electrons to the dump while the photons continue to the experimental hall.

The extraction arc for FLASH 2 occurs before the undulator section of the existing undulator beamline. It consists of four dipole magnets to bend the beam with angles of  $6.5^\circ$ ,  $-0.9^\circ$ ,  $3.2^\circ$  and  $3.2^\circ$ . In the extraction arc, there are also several quadrupole and sextupole magnets to further focus the beam. The extraction arc will also house the energy collimator. Like in FLASH, the beam then travels through an undulator sequence which produces synchrotron light and a massive dipole directs the electrons to the dump while the photons (produced in the undulator section) continue onto the new experimental hall. Every second bunch-train will be sent through the FLASH 2 beamline.

The main demand behind the creation of FLASH 2 was to provide five more user experiments [1]. Furthermore, the option to have a seeded FEL was desired. This seeding is HHG (High Harmonic Generation) which the electron beam is overlapped with a laser to impress an energy modulation on the electron bunches [1]. This energy modulation will then become a density modulation in the undulator and this helps to increase the quality of the synchrotron light for the users.

The existing FLASH undulators are fixed gap undulators while the new beamline will use variable gap undulators [1]. As a result of these different types of undulators FLASH can produce two varying wavelengths of synchrotron radiation simultaneously. The wavelength of the emitted photons can be changed by the electron beam energy or by varying the undulator gap sizes. The wavelength of FLASH 1 will be determined by the energy of the electron bunches while the wavelength of FLASH 2 can be adjusted via its variable gap undulators. Hence the FLASH 2 undulators allow the adjustment of the photon wavelength individually for each beamline.

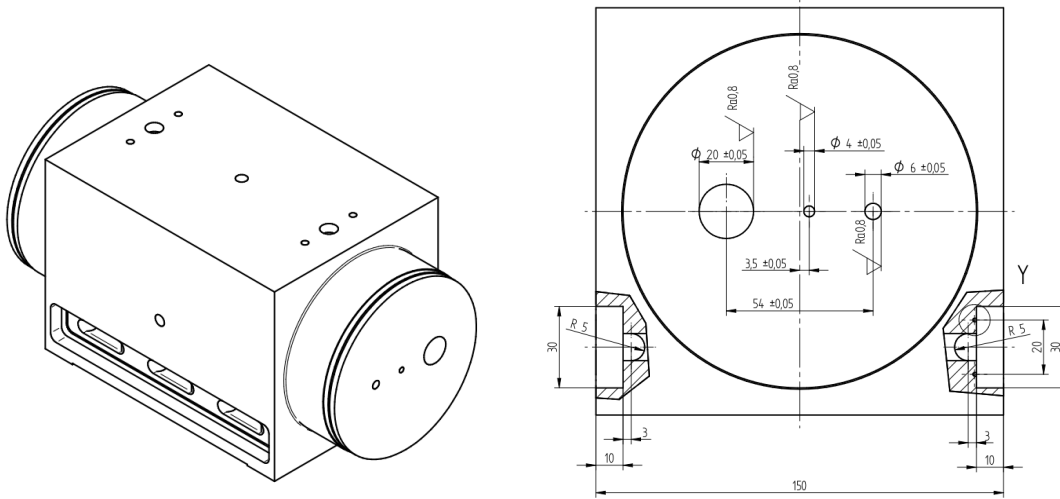
## 1.2 The Collimator

A collimating system is composed of three main parts; two transverse collimators followed by an energy collimator. The purpose of the system is to protect the rest of the machine, in particular the permanent magnet undulators. The objectives of the transverse and energy collimators of the system are for beam halo separation and energy collimation, respectively.

The new collimators in FLASH 2 are similar but not the same as FLASH, both are made out of copper moreover their designs differ. FLASH collimators are tapered. Their length is  $50\text{ cm}$  in total with  $20\text{ cm}$  of tapering at both sides and the main part of the collimator is  $10\text{ cm}$ , parallel to the beam axis [2]. The new FLASH 2 collimators will not be tapered because for the tapering to be of significant use the collimator would be

extremely large. The collimators used in FLASH 2 are 30 cm in total length with a square body of 15 cm and height of 15 cm. Running through the collimator parallel to the beam axis are three vacuum channels of diameter 20 mm, 4 mm and 6 mm from left to right when looking as if one was the beam travelling towards the collimator. Please see Figure 1.1.

Only the 4 mm and 6 mm channels are used in the collimation of the beam as if the 20 mm was selected due to its large size it would be the equivalent of no collimator being present. In this specific project, only the 4 mm channel was investigated.



**Figure 1.1:** The Collimator: A 3D image and a front on image depicting the size and positioning of the vacuum channels.

### 1.3 FLUKA and *flair*

FLUKA is a powerful tool based on Monte Carlo simulations [3]. It is used for the calculations of particle interactions with matter. It encompasses a large range of applications including detector design; proton, electron (and further particles) accelerator shielding; target design; accelerator driven systems and radiotherapy. FLUKA has the ability to work with about sixty different particles, from thermal energies into the TeV range. One of FLUKA's most desired feature, which has been included since the original programme, is its in-built scoring options e.g. USRBIN, USRBDX, RESNUCLEI and EVENTDAT. It contains these complex scoring algorithms which many users would not be able to compile themselves.

FLUKA originates from CERN and first began in 1962 when Johannes Ranft was working on hadron cascades [3]. While working at CERN, Ranft wrote the first high energy Monte Carlo transport codes, FLUKA. FLUKA grew with time. Each subsequent generation of the code was built upon its predecessor. However they all stemmed from the root, the first code composed by Ranft. Furthermore, the code known today as FLUKA is

very different from the Ranft's original code and is much more powerful.

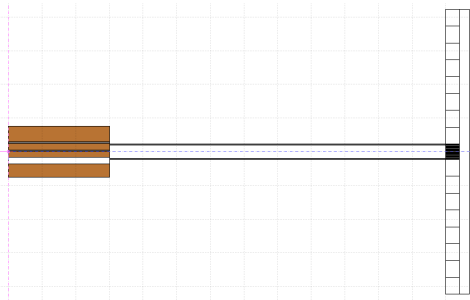
FLUKA became what is used today when it was decided to completely re-design the code structure [3]. Most of the effort in re-designing was put into numerical accuracy thus the whole code was converted to double precision, this would mean, for example, that energy conservation was ensured within  $10^{-10}$ . It is a Fortran programme composed of 'cards' and these cards are what make up FLUKA [4]. Each FLUKA card contains one keyword, six floating point values WHATs and one character string SDUM. WHATs describe the situation (e.g. energy values, coordinates, a region, particle type etc.) and all six may or may not all be employed when using a specific card. If more WHATs are needed further cards can be implemented.

*flair* is the FLUKA Advanced Interface authored by Vasilis Vlachoudis [5]. It was created in order to make the use of FLUKA much easier and friendly. It aids in the editing of FLUKA input files, the execution of the code and visualisation of the output files. The characteristics of *flair* include: front and back end interface, GeoEdit and monitoring the status of a run. GeoEdit is an interactive geometry editor which allows one to build the objects necessary for the simulations. The objects created by way of GeoEdit are then converted to FLUKA cards via *flair*.

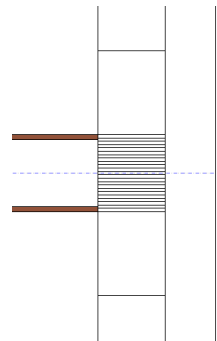
# Chapter 2

## Method

Using the geometry editor from *flair*, the collimator for FLASH 2 was drawn including a vacuum filled iron cylinder behind the collimator and a series of vacuums following the iron cylinder. These series of vacuums were arranged like a bullseye followed directly by a large cylindrical vacuum (the size of the entire bullseye). The two vacuums (the bullseye and large cylinder) were used in order to measure the particle fluence between two surfaces for the scoring method USRBDX. The bullseye target helps to locate the crossing position of the particles in the target, in order to differentiate between the particles which are on axis and those with an offset. The sections in line with the vacuum chamber were smaller because a higher resolution was wanted in that region and it was seen that most of the particles were there. The iron cylinder was implemented because some of the particles which leave the collimator will hit the main vacuum chamber and stop there, others will be reflected and will remain in the machine. Consequently the iron and vacuum cylinders were to guide the particles to the bullseye vacuum. It is thought that the iron cylinder with the vacuum change slightly the distribution of particles on the bullseye target. Please see Figure 2.1 and Figure 2.2.



**Figure 2.1:** An aerial view of the collimator, iron and vacuum cylinder, bullseye target and large cylindrical vacuum for USRBDX.



**Figure 2.2:** A zoomed-in view of the iron and vacuum cylinder with the USRBDX bullseye vacuum and accompanying large cylindrical vacuum.

A beam of 1 *GeV* of electrons was fired at the copper collimator for a range of in-

interaction points and firing distances. These distances and points were divided into four categories: *Near Start*, *Mid*, *Edge* and *No Angle*. For *Near Start*, *Mid* and *Edge* the cosine of the angle with  $z$  was set to a constant  $\cos(x) = 0.00833$ . *Near Start* was the setting whereby the electron beam would impact with the copper  $3.9\text{ cm}$  inside the  $4\text{ mm}$  channel. Its settings were  $x = 0.35\text{ cm}$ ,  $y = 0.0\text{ cm}$ ,  $z = -20.0\text{ cm}$ . In order for the electron beam to hit further inside the  $4\text{ mm}$  channel with the same angle as *Near Start*, *Mid* was used. *Mid* was defined as  $x = 0.35\text{ cm}$ ,  $y = 0.0\text{ cm}$ ,  $z = -8.9\text{ cm}$ . *Edge* was designed with settings,  $x = 0.35\text{ cm}$ ,  $y = 0.0\text{ cm}$ ,  $z = -23.9\text{ cm}$ , so that the beam would interact with the entry corner of the  $4\text{ mm}$  vacuum channel. The final setting, *No Angle*, enforced the particle to impact on the collimator  $2\text{ mm}$  away from the edge of the  $4\text{ mm}$  vacuum entrance between the  $4\text{ mm}$  and  $6\text{ mm}$  channel. Its settings were  $x = 0.9\text{ cm}$ ,  $y = 0.0\text{ cm}$ ,  $z = -23.7\text{ cm}$  and  $\cos(x) = 0$ . In the case of *No Angle* the value for  $z$  ( $-23.7$ ) was an arbitrary value.

For every setting of *Near Start*, *Mid*, *Edge* and *No Angle*, the programme was run for each of the varying particle types. The particle types chosen to be the examined in greatest detail were: ALL-CHAR, DOSE-EM and EM-ENRGY. ALL-CHAR shows the trajectories of all the charged particles present in the system. It is measured in  $pSv/s$  (pico-Sievert per second), the radiative dose per second [4]. DOSE-EM considers the electromagnetic dose and is measured in  $GeV/g$  (giga-electron volt per gram). EM-ENRGY calculates the electromagnetic energy of electrons, positrons and protons and it shows the amount of energy deposited in the system, also with units  $pSv/s$ .

The FLUKA scoring methods employed were USRBIN and USRBDX. The former scores the distribution of chosen particle types (ALL-CHAR, DOSE-EM and EM-ENRGY) in a regular spatial structure [4]. This spatial structure is not related to the geometry of the system. The latter measures the fluence or current crossing specific boundaries, in this case the fluence was determined [4].



# Chapter 3

## Results and Analysis

### 3.1 Scoring Method: USRBIN

USRBIN is a very useful scoring method and was implemented in this project in order to discover the intensities of different particle types during an interaction [4]. It works by dividing the desired area into a specific amount of bins and these bins gather the information within a designated region for the preselected particle types. In this project the main particle types under investigation were ‘All Charged Particles’, ‘Electromagnetic Dose’ and ‘Electromagnetic Energy’. The plots created and the data collected from USRBIN came from runs involving three thousand particles and five cycles.

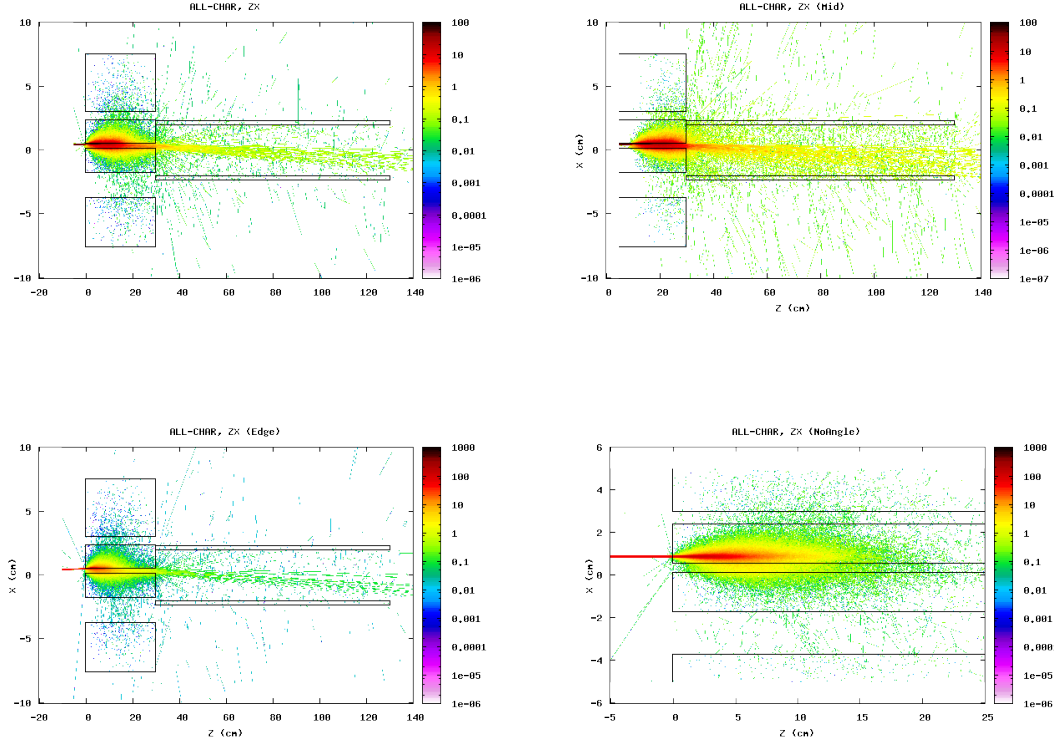
#### 3.1.1 All Charged Particles

Please see Figure 3.1.

‘All Charged Particles’ known to FLUKA as ALL-CHAR, shows the radiative dose per second of the trajectories of the charged particles in the system [4]. In this case, most of the charged particles are electrons, however if required, one can run simulations whereby the data for only one type of particle is collected. Comparing the plots for each of the settings (*Near Start*, *Mid*, *Edge* and *No Angle*), it was found that the first three settings were very similar in shape especially in regards to their ‘tails’. The ‘tails’ were of a similar density and at an almost identical angle. When the programme was run for *No Angle*, the USRBIN plot did not produce a ‘tail’. This was no doubt because the particles (from the original beam and also from the impact) were not guided into any of the vacuum channels as in the other cases. It must be noted that the beam penetrated quite deep into the copper of the collimator for this last case.

It can be seen that the *Mid* plot contains a lot of debris, more so than *Near Start* and *Edge*. It is also much yellower in colour and this yellow corresponds to a  $1 \text{ pSv/s}$  radiative dose. In contrast the *Edge* plot has much less debris and is more of a blue colour. The difference between the bluer and yellower colours is ten fold ergo the radiative dose per second for the *Edge* plot is  $0.1 \text{ pSv/s}$ . Hence the plot for *Near Start* acts like a halfway

point between *Mid* and *Edge*. This is unsurprising as for the *Near Start* setting the beam impacted with the collimator between that of the values of *Edge* and *Mid*.



**Figure 3.1:** ALL-CHAR Particles plots with varying impact parameters

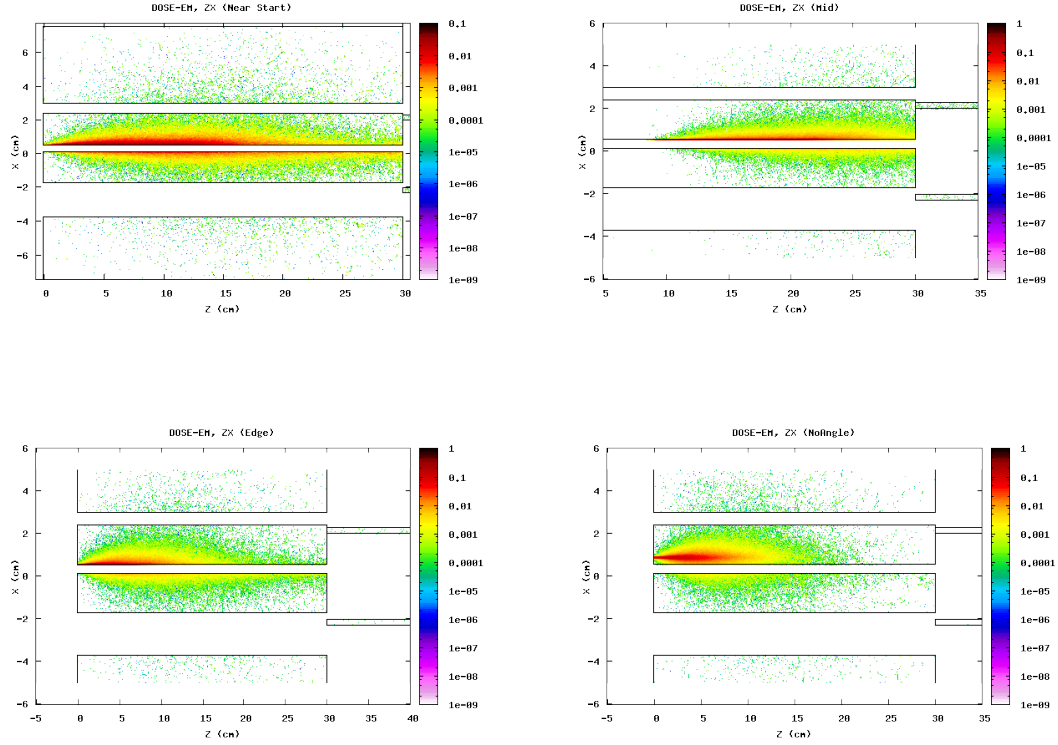
### 3.1.2 Electromagnetic Dose

Please see Figure 3.2.

DOSE-EM measures the electromagnetic dose in units of  $GeV/g$  [4]. These plots are quite different compared to their ALL-CHAR counterparts, except in the case of *No Angle* who's plot was quite similar to its ALL-CHAR plot.

*Near Start* and *Mid* produced USBIN plots that were very similar in terms of shape, both elongated. The same was true of *Edge* and *No Angle*. However *Edge* could be seen as a halfway point between the first two plots, *Near Start* and *Mid*, and *No Angle* but slightly closer to the latter.

It should also be noted, that the plot representing *Mid* settings expands the most into the iron cylinder. The reason for this was because of the beam's first interaction point with the copper collimator.



**Figure 3.2:** DOSE-EM plots with varying impact parameters

### 3.1.3 Electromagnetic Energy

Please see Figure 3.3.

‘Electromagnetic Energy’ recognised by FLUKA as EM-ENRGY, calculates the electromagnetic energy of the electrons, positrons and protons present within the system [4]. The EM-ENRGY plots exhibit the amount of energy deposited in the copper and iron. These plots are very similar to their DOSE-EM counterparts especially in regards to the *No Angle* plots. However it is paramount to note that the colour scales for the variety of particle types are measured with different units; DOSE-EM is represented by  $GeV/g$  while EM-ENRGY by  $pSv/s$ . Another departure between these plots are the colour scales; EM-ENRGY is a factor of ten times more intense than DOSE-EM. The *Mid* plot expands the most into the iron/vacuum cylinder but the clear reason for this was due to the position where the beam first interacts with the copper. The *Mid* setting causes the beam to impact on the copper at the furthest place from the start of the collimator in comparison to the other settings.

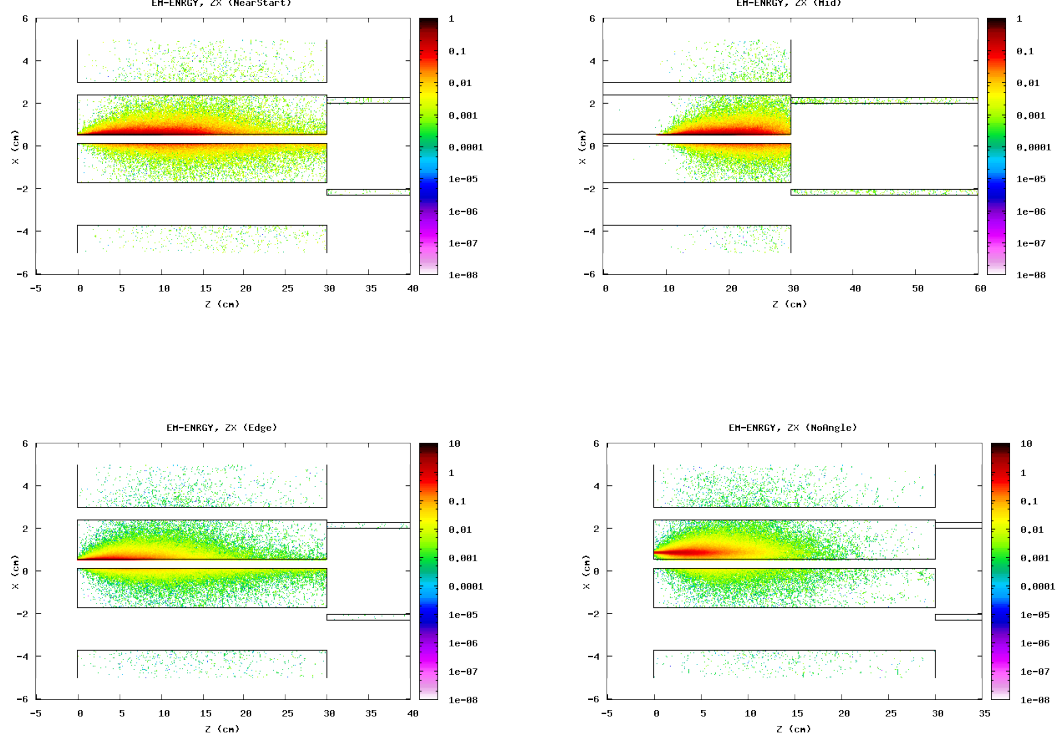


Figure 3.3: EM-ENRGY plots with varying impact parameters

## 3.2 Scoring Method: USRBDX

When using USRBDX, a boundary dividing two regions is decided and the fluence or current between those two regions is measured [4]. This technique was employed in this project in order to find the fluence created by the impacting beam on the collimator travelling between a series of cylindrical vacuums beginning  $1\text{ m}$  behind the copper collimator. The vacuums were originally divided into two parts each of  $3 - 4\text{ cm}$  in length. The first vacuum however was divided into a further amount of sections in order to represent a bullseye. In the centre these bullseye cylinders were of width  $0.2\text{ cm}$  and once the entire diameter was equal to  $4.6\text{ cm}$  (i.e. the diameter of the iron and vacuum cylinder combined), the bullseye cylinders became  $5\text{ cm}$  in width. The second part of the vacuum remained as one large vacuum of equal length to the whole bullseye vacuum.

Unfortunately, the USRBDX runs were not completed. This was because it was realised very late, that a *huge* amount of particles were needed to obtain reasonable results. A high number of particles is required because it is necessary to have many particles in each section of the target and moreover to differentiate between the particle quantities in the varying sections. In the current case, however many of the sections were empty and in the few sections that contained particles, only one or two were present. It is also thought that to increase the size of the sections of the bullseye could lead to more improved results.

# Chapter 4

## Summary

In regards to the aims of the project, both of the aims were achieved. Familiarity with FLUKA and *flair* was accomplished. The theory behind FLUKA and *flair* is now known, but most importantly the workings and composition of them. The occurrences within the FLASH 2 collimators when a 1 *GeV* beam of electrons was present and the collimators' effectiveness were analysed.

The USBIN data was processed and analysed for the four types of settings (*Near Start*, *Mid*, *Edge* and *No Angle*) under the different particle types (ALL-CHAR, DOSE-EM and EM-ENRGY). The trajectories of the charged particles for each of the four impact positions and firing distances were determined. It was observed that when the beam obeyed the *Mid* setting more debris was created and a higher radiative dose per second recorded. While the *Edge* setting produced the least amount of particle debris and had the least value on average in *pSv/s*. The electromagnetic dose of the copper collimator (and vacuum chamber) and the electromagnetic energy deposited within the system were also established.

For the use of the USBDX scoring method, an iron cylinder (vacuum chamber) with a vacuum centre and two large cylindrical vacuums were created via GeoEdit. These two large cylindrical vacuums were in order to employ the USBDX theory of measuring the fluence across a boundary. The first of the two vacuums was broken into sections to represent a bullseye, thus helping to locate the crossing positions of the particles. With further USBDX analysis, the effectiveness of the FLASH 2 collimators could be finally concluded.

# Chapter 5

## Acknowledgements

I wish to take this opportunity to thank DESY and the people behind the DESY Summer Student Programme for the wonderful and fascinating time I have had here. I would also like to thank A. Leuschner for his help with FLUKA and *flair*, without him I do not know if I would have any plots to show! Thank you also to J. Zemella for his help. Finally and most importantly a huge thank you to M. Scholz for the opportunity to work with FLASH II and for all the help and knowledge he has given me.

# Chapter 6

## References

- [1] [flash2.desy.de](http://flash2.desy.de)
- [2] Tesla Report 2003-17: Studies of the Collimator System for the TTF Phase 2,  
V. Balandin et al., DESY Hamburg
- [3] [www.fluka.org](http://www.fluka.org)
- [4] FLUKA Manual
- [5] *flair* Manual
- [6] [flash.desy.de](http://flash.desy.de)