Simulations of the Electron Current Spectrometer Setup in Geant4

Exploring the Physics Limitations of Compact High Gradient Accelerating Structures

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Abstract

The high field gradient of 100 MV/m that will be applied to the accelerator cavities of the Compact Linear Collider (CLIC), gives rise to the problem of RF breakdowns. The field collapses and a plasma of electrons and ions is being formed in the cavity, preventing the RF field from penetrating the cavity. Electrons in the plasma are being accelerated and ejected out, resulting in a breakdown current up to a few Ampères, measured outside the cavities. These breakdowns lead to luminosity loss, so reducing their amount is of great importance. For this, a better understanding of the physics behind RF breakdowns is needed. To study these breakdowns, the XBox 2 test facility has a spectrometer setup installed after the RF cavity that is being conditioned. For this report, a simulation of this spectrometer setup has been made using Geant4. Once a detailed simulation of the RF field and cavity has been made, it can be connected to this simulation of the spectrometer setup and used to recreate the data that has been collected at XBox 2, before and after a breakdown has occurred. In this way, we hope to be able to look further into the RF breakdowns occurring in high field gradient accelerator structures.
1 Introduction

The Large Hadron Collider (LHC) at CERN is scheduled to run at least until 2035. After this period, there will be a need for a new collider, to further explore the nature of our world. Many proposals for future colliders have been made, one of them being CLIC. CLIC stands for "Compact Linear Collider". It is a 50 km long linear collider, placed in front of the Jura mountains, which will eventually accelerate electrons and positrons up to 3 TeV. To be able to accelerate electrons and positrons up to 3 TeV, one needs a very high field gradient in the accelerator cavities. At the moment, radiofrequency (RF) pulses with a field gradient of about 100 MV/m can be reached [1]. For comparison, the LHC accelerator cavity has a field gradient of 5 MV/m [3] and the ILC, another possible future linear collider located in Japan, would have a field gradient of 31.5 MV/m [4]. CLIC can reach these high gradients compared to other accelerators, because it has normal-conducting cavities instead of superconducting cavities, which allows for pushing the limits of the field gradients, without having to fear for excessive cooling power, as would be needed for superconducting cavities having such high field gradients.

However, when applying these high field gradients, a problem arises: that of RF breakdowns. If a breakdown happens, the RF power must be taken out of the cavity as quickly as possible, and loss of luminosity will occur. Therefore, a reduction of the amount of breakdowns is desirable. However, the physics of breakdowns and what exactly triggers them is still not well understood. In order to reduce the amount of breakdowns, a better understanding of RF breakdowns is needed.

To accomplish this, it would be useful to make a simulation of the RF breakdowns, and compare them with the data that has been obtained in the CLIC test facilities, mainly XBox 2. For this, one would need a detailed simulation of the accelerator cavity with an RF field, and a simulation of the measurement setup that is built to collect the data. For this report, the spectrometer setup in XBox 2 has been simulated, using the simulation toolkit Geant4 [2].

2 RF Breakdowns

In an accelerator, electrons get accelerated in a cavity filled with a radiofrequency (RF) field. This RF field will in general extract electrons from the surface of the cavity, accelerate them and eject them out of the cavity. This current is called a dark current, and happens at all field strengths. When an RF field with a high field gradient is applied to the cavity, such as in CLIC, the field can collapse due to an RF breakdown. Neutral particles and electrons get extracted from a local point on the cavity surface. The electrons ionize the neutral particles, forming a plasma. If the RF field is not turned off, more particles will get extracted from the surface, and the plasma's density will rise. The growth of the plasma happens rapidly: within nanoseconds one can go from an ultrahigh vacuum of about $10^{-10}$ mbar, to $10^{16}$ ions, which are highly localized within the cavity.

The electrons in the plasma can get accelerated and ejected out of the cavity as well. This breakdown current is usually over one order of magnitude higher than the dark current. While the dark current contains electrons from many sites along the cavity, a breakdown is localized and only affects one cell in the cavity, if stopped rapidly enough.

When the density of the plasma becomes high enough, the RF field that is sent into the cavity cannot penetrate the cavity anymore. Instead, it will be reflected, as can be seen in figure 2 in section 3. Without an RF field in the cavity, it will no longer accelerate the electron beam. This means the beam will lose energy, and that it will no longer be synchronized with the magnetic field, since the synchronization is calculated supposing the beam gets accelerated in each cavity. The beam might receive kicks from the breakdown current itself as well as from the magnets downstream. This will result in beam quality loss.

If a breakdown happens, it should be stopped as quickly as possible by taking out the RF field, and preventing any (further) damage. However, this will affect the luminosity of the accelerator. To keep the luminosity loss within reasonable limits of one percent, the amount of breakdowns should be brought back
to about $10^{-7}$ breakdowns per RF pulse per meter [5]. To reduce the amount of breakdowns, further understanding of the origin and triggering of breakdowns is necessary. Therefore, the behavior of the RF field and the dark current and breakdown current before and after a breakdown are being studied during the conditioning of the accelerator cavities.

3 XBox 2

One of the test facilities for CLIC is called XBox 2. It is currently being used to condition the RF cavities before they can be used in the accelerator. During this conditioning period, where RF pulses are sent into the cavity, but no electron beam is present, there will occur many RF breakdowns. A spectrometer setup has been built after the cavity, and elements to measure the RF field have been installed around the cavity. This allows for detecting and measuring what is happening before, during and after a breakdown. This might lead to a better understanding of the RF breakdowns, which can be used to further reduce future breakdowns. This can lead to a better and faster conditioning of the cavities. Since CLIC will have about two hundred thousand cavities, there is a strong need for faster conditioning.

Figure 1a shows XBox 2, and figure 1b shows a schematic overview of the setup. Around the cavity, there are two elements to measure the RF field. One measures the incoming and the reflected field, and the other the transmitted field. These parameters provide a strong breakdown signal. As explained in section 2, the RF field cannot penetrate the cavity anymore during a breakdown. This results in the transmitted field dropping to zero. The field gets reflected instead, and this can be seen by a rise in the reflected field. Both reflected and transmitted field values are shown in figure 2, where the rising and dropping of the parameters can clearly be seen.

![Figure 1a: The XBox 2 test setup](image1a)

![Figure 1b: A schematic overview of XBox 2](image1b)

Figure 2: Transmitted (red) and reflected (blue) RF field after an RF breakdown [6]
Furthermore, the setup exists of two Faraday cups, to measure the dark current and the breakdown current. A tungsten collimator is placed after the RF cavity, which can contain a slit or a pinhole. After the collimator, a dipole magnet is being placed and at the end, a YAG:Ce fluorescent screen. The screen is slightly tilted and shows the distribution of the electrons hitting it. A CCD camera is being placed under a ninety degree angle with the screen, and a mirror is being used to direct the light from the screen to the camera [5].

4 Geant4

For this report, a simulation of the spectrometer setup described in section 3 has been made, using Geant4. Geant4 is a simulation toolkit based on C++, which allows the user to create a (complex) detector geometry, after which particles can be traced and detected while they pass through the geometry materials. It is a form of Monte Carlo simulation. A source is created, and can be adapted to the user’s needs. The particle type, energy, momentum etc. of the source can be changed, and the user can choose the number of particles that will be initiated per ‘run’. The individual particles will be recorded step by step while they pass through the geometry. They will interact with the geometry materials according to predefined physics lists, which contain a wide range of particle interactions and long-lived particles.

The geometry can also include multiple sensitive detectors. They can be set to record part of the information of a particle when it ‘hits’ this detector. For example, one can record a particle’s position, its energy, if it was being stopped in the detector volume et cetera. The user can define what parameters are being recorded by which detector. This information can be stored in ntuples or histograms, and can be read out and analyzed using various programmes. For this report, the programme ROOT is being used for this purpose [2].

5 Simulation of the spectrometer setup in Geant4

From the measurements of the RF field and from an increase in the electrons being detected in the Faraday cups, it is possible to detect a breakdown right after it took place. However, little is known about what triggers a breakdown, and how one may reduce their frequency. To further investigate the origin, it might be useful to simulate the XBox2 test facility, and to try to recreate the breakdowns using this simulation. For this, a detailed simulation of the RF field and cavity and a simulation of the spectrometer setup are necessary. For this report, a simulation of the spectrometer setup has been made, using the programme Geant4, as explained in section 4.
Firstly, the geometry of the spectrometer has been defined. It exists of a collimator, a uniform magnetic field in three dimensions, two beampipes and a screen, as can be seen in figure 3. The collimator is made of tungsten and can have a narrow slit or a pinhole in the middle, allowing electrons to pass through. Inside the magnetic field, which is placed behind the collimator, is a 3 mm wide beampipe. A second beampipe is placed before the collimator, as a connection between the electron source and the collimator. At the end of the setup, a screen is placed, which is tilted by 30 degrees. The screen is divided into rows and columns. The number of rows and columns can be altered. The whole setup is placed in vacuum.

The screen is set as a sensitive detector (see section 4). It records the row and column number of each hit, the deposited energy on the screen per hit, the spatial position of the hit and if it was a primary or secondary particle that hit the screen. This information per hit is stored in an ntuple, which can be read out and analyzed using a programme such as ROOT.

The row and column numbers indicate where the particle hit the screen and give a distribution of the particles. By changing the amount of rows and columns, one can change the resolution of the screen, making the position more or less precise. In this way, the camera taking a picture of the screen in the XBox2 spectrometer setup is being mimicked. The spatial position is redundant, when one also records the row and column number of the hit. However, it provides a helpful check to see if the sensitive detector is working properly, and if every hit is indeed a particle hitting the screen.

It is thought that mostly primary particles, the electrons in the breakdown or dark current, contribute to the distribution on the screen. However, the simulation can be used to check this assumption, by recording the row and column numbers for primary and secondary particles separately. Then the distribution on the screen of the primary and secondary particles can be plotted, and compared to one another and to the full particle distribution.

For the electron source, the class General Particle Source in Geant4 is being used. This class allows one to fully customize the electron source. To obtain the results as shown in this report, two types of sources were being used. A monoenergetic beam of electrons at 100 MeV, with different radii and angular dispersions, and a monoenergetic annulus-shaped plane of electrons at 100 MeV, with different radii and angular dispersions.
6 Results

Multiple simulations have been run, using two types of sources: a beam and an annulus-shaped plane of electrons, each with different widths and variations in angular momentum. The 100 x 50 mm screen is divided into 1000 rows and 1000 columns, which means each row has a width of 0.05 mm and each column a width of 0.1 mm.

6.1 Influence of the collimator

Simulations were run using a slit, a pinhole or no collimator at all. The value of the magnetic field was set to 0 T. Figures 4a, 4b and 4c show the distribution recorded on the screen of a 1 mm wide beam consisting of monoenergetic particles with an energy of 100 MeV and an angular variance of 0.1 degrees, with respectively no collimator, a collimator with a slit and a pinhole.

Figure 4: Distribution on the screen of a 1 mm wide, monoenergetic electron beam of 100 MeV and 0.1 degree angular dispersion, without a magnetic field.

If a wider beam is used, the distribution becomes more smeared out, especially for the slit. This can be seen in figure 5 and 6.

Figure 5: Distribution on the screen of a monoenergetic electron beam of 100 MeV and 0.1 degree angular dispersion, with a slit and without a magnetic field.
The slit results in a more spread-out distribution for a wider beam, while the pinhole mainly blocks a large part of the beam, when a wider beam is being used.

6.2 Influence of the magnetic field

The magnetic field is in this case applied in the z-direction. The axes are defined such that positive z is upwards, and positive x is in the direction of the beam/setup. Figure 7 gives the distribution of a 1 mm wide monoenergetic beam of 100 MeV when a magnetic field of different field strengths is applied. A collimator with a pinhole was placed in between the beam and the field.
Figure 7: Distribution on the screen of a monoenergetic electron beam of 100 MeV and 0.1 degree angular dispersion, with a pinhole and different magnetic field strengths.

The figures show a displacement of the beam when a magnetic field is applied in the z-direction. It moves to the right when a positive field is applied, and to the left if a negative field is applied. If we look at the raw data of the camera taking a direct picture of the screen in XBox 2, figure 8, the beam moves to the left when a magnetic field is applied. This means that in the simulation, the axes are defined slightly differently. One should either apply a negative field in the z-direction, or change the orientation of the axes.

Figure 8: Photo of the distribution of particles hitting the screen in XBox 2 with a pinhole in the collimator, with and without a magnetic field [6]

When a magnetic field is applied, the distribution also smears out. This is not visible in the simulation, since we use a monoenergetic beam. When a beam consists of particles with different energies, each
particle will get bent differently by the magnetic field, which leads to a smeared-out distribution on the screen.

6.3 Different electron sources

The simulation has been run using two different electron sources: a beam and an annulus-shaped plane of electrons, both with an energy of 100 MeV and with different radii. The annulus-shaped plane should be a better projection of the dark current coming from the accelerator cavity, since it mimics the electrons being extracted from the surface of the cavity. So we expect the annulus-shaped plane electron source to better correspond to the XBox 2 data. In figure 9, the outcome of the simulation using different annulus-shaped sources can be seen.

![Annulus-shaped monoenergetic plane of electrons at 100 MeV with different widths](image)

Figure 9: Annulus-shaped monoenergetic plane of electrons at 100 MeV with different widths

We see that this does not compare well to the data found at XBox 2. This means that our dummy source is not very realistic, and there is a need for a simulation of the RF cavity and field itself, so that we can use the outcome of that simulation as a source for the simulation of the spectrometer setup.

6.4 Difference between primary and secondary particles

The difference between the primary and the secondary particles hitting the screen has been looked into. The results can be seen in figure 10.
As one would have suspected, the primary particles are more located and their distribution is of the same shape as the distribution of all the particles. The secondary particles however have a more homogeneous distribution, which resembles the background noise better. Still, also in the distribution of the secondary particles, we can distinguish the shape of the distribution of all the particles, only less well-defined.

7 Conclusion

A simulation of the spectrometer setup of XBox 2 has been made, containing a collimator, a magnetic field, two beampipes and a screen. The collimator can either have a slit or a pinhole in it, and the screen is set as a sensitive detector which records the distribution of the particles hitting the screen, their energies and if it is a primary or a secondary particle. This mimicks the setup of XBox 2, where only the camera and the mirror guiding the light from the screen to the camera has been left out, since in the simulation the screen records everything. The axes of the magnetic field in the simulation are defined differently than the axes in XBox 2, which means that one would need a negative magnetic field in the z-direction to get the same beam displacement on the screen as data from XBox 2 shows.

One can see a clear difference in the distribution of the particles hitting the simulated screen when a comparison is being made between no collimator, a collimator with a slit or a collimator with a pinhole. When this is compared to the data of XBox 2, we see that a wider beam matches the data better. When we compare different electron sources, an annulus-shaped plane of electrons and an electron beam, we see that the annulus-shaped source does not seem to match the data we have of XBox 2. A small annulus (1mm wide) gives a distinct ring shape when a pinhole is used, which is not seen in the XBox 2 data. A wide annulus (3mm wide) gives two symmetric dots when a slit is used, a feature that also is not represented in the data of XBox 2.

When we look at the difference between the distribution on the screen of primary and secondary particles, we see that it is mostly the primary particles contributing to the total distribution on the screen. The secondary particles produce a more uniform distribution, which can be seen as background noise. Thus, it seems so far that the secondary particles are of lesser influence, but one could investigate if this holds for all secondary particles, or only certain types of particles or particles of certain energies.

It can be concluded that there are some similarities to the data of XBox 2. However, the sources being used now are only dummy sources and not representative for the dark or breakdown current coming from the RF cavity. A detailed simulation of the RF cavity and field would be needed to create a dark or breakdown current. Then the energy, momenta and spatial distribution of these electrons can be used as the electron source for the spectrometer setup simulation. This will make the simulation more realistic and better comparable to the data.
8 Discussion

To use this simulation to study RF breakdowns, a detailed simulation of the RF cavity and field is needed. In the future, one would like to couple these two simulations, and try to match the outcome of the simulations to the data obtained from XBox 2. In order to accomplish this, one could save the energies, position and momenta directions of the particles from the RF field simulation in histograms, and use them as input for the General Particle Source (see section 5 of the spectrometer simulation. In this way, the outcome of the spectrometer simulation will be more realistic and more comparable to the XBox 2 data than when using a dummy source, as was the case for this report.

Other improvements on the spectrometer setup simulations can be made. First of all, the storage of the spatial position of the particles hitting the screen can be removed. As explained in section 5, this information is redundant and serves merely to check if the sensitive detector works properly. This would make the simulation run faster. One could also implement cuts on the secondary particles, to see which particles contribute most to the distribution of the breakdown current as displayed on the screen. This will also make the simulation run faster. Furthermore, the simulation can be used to make an energy resolution calibration and an energy calibration.

The simulation of the spectrometer setup could be made more realistic by implementing (small) geometrical misalignments and non-uniform magnetic field. One could test how this influences the simulation and compare the results with the XBox 2 data, to see if it contributes significantly. The effects of charging up of the collimator or screen for example by the dark and breakdown current could also be investigated in the future, and implemented in the simulation.

References


