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Simulation of undulator radiation for the recalibration of the sFLASH FEL energy monitor

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Abstract

Micro channel plates (MCPs) are a crucial part in the sFLASH experiment since they are telling us about the absolute radiation energy produced in the free-electron laser (FEL); the radiation that will be used in the different experiments. MCPs were installed years ago so we should concern about their functionality: are they working as the same way that they did at the beginning? This is what we have to investigate. Therefore, we perform simulations on spontaneous undulator radiation which will be used for the recalibration of the detector. For the recalibration, a detailed knowledge about the beam parameters and the detection geometry is mandatory, in order to get a precise calibration. This will allow in future seeding experiments to verify the absolute FEL pulse energy, making this project a success.

Contents

1 Introduction: A little overview about Undulator Radiation...

In the 70's the principle of the Free-Electron Laser (FEL) was invented by J.Madey, since then, many developments have been done in this frame; from the incoherent synchrotron radiation produced in bending magnets, to the modern synchrotron light sources where coherent synchrotron radiation is produced in wiggler or undulator magnets, giving the name of **Undulator Radiation (UR)**.

Wiggler or undulator magnets are periodic arrangements of many short dipole magnets of alternating polarity, this characteristic makes the electrons to move on a sinusoidal orbit through the magnet (Fig. 1). In contrast with the bending-magnet radiation, which has a continuous frequency spectrum, UR consists of narrow spectral lines concentrated in a narrow angular cone along the undulator axis, making this sort of radiation far more useful. Of particular interest, is the Self-Amplified Spontaneous Emission emerging from a Free-Electron Laser (SASE-FEL); this kind of source requires linear accelerators to provide a drive beam with small beam cross section, high charge density and low energy spread, that cannot be provided in storage rings. This kind of light is very appreciated; not only because it has the same properties as conventional laser light, but also because its nearly monochromatic, polarized, extremely bright, tightly collimated and its high degree of transverse coherence. Besides, this laser light is generated in high-power ultra-short pulses (femtoseconds) which is optimal for experiments with molecules and biology process in cells, as examples of their immense experimental capabilities. The peak luminosity of FLASH exceeds that of the most advanced synchrotron radiation sources, and we are interested in the number of photons that can reach the experiment. And we should not forget to mentioned the sFLASH (seeded FEL) improvement which solves the problem of the longitudinal coherence that the SASE-FEL presents, making these facilities even better. So now we have a glimpse about the possibilities of FLASH, but how to measure the number of photons that we are dealing with and that, ultimately, are used for the experiments?

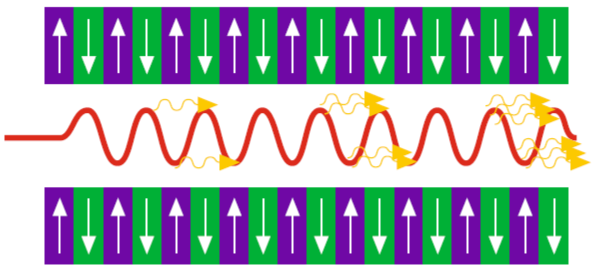

Figure 1: In this scheme, you can see the magnet arrangement in the undulator and how the radiation is emitted from the electron beam every time the beam is bent passing through the undulator.

Up to now, it is known that the SASE emission it is not very predictable, since it strongly depends of the beam electron density. Nevertheless, what it is very predictable, is the spontaneous emission that it is produced in the undulator and that gives way to the SASE when the electron density is high enough. How is this SASE radiation produced? The key word here is 'microbunching'. When the electron beam goes thought the undulator, due to the sinusoidal movement that it suffers inside, the beam is being accelerated and decelerated producing the spontaneous emission (it is important to remark that the spontaneous emission appears also without microbunching) and with it an electromagnetic field that, if there is sufficient electron density, interacts with the beam creating the SASE emission. The electrons in the beam are traveling at high velocity, almost the speed of light. Therefore, the photons from this emission are not in phase with the electrons [2], and here it is when a curious phenomena takes place, the electrons get retarded or accelerated in order to be in phase with the electromagnetic field producing the microbunching, an uniform electron cloud or individual charge disks separated by a single wavelength. All together make a chain, and it is possible to see the harmonics which follow the equation(1). In the Appendix (Fig. 8) you will find some graphics where this phenomena it is quite clear.

$$\lambda_{ph} = \frac{\lambda_{undulator}}{2i\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \tag{1}$$

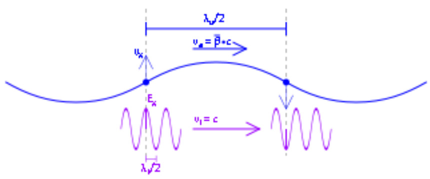

Figure 2: With this image, you will understand better the equation (1) since it shows the different phases that the photons and the electrons have at the same position and how it works the overlaping between them.

Where λ_{ph} is the wavelength of the emitted radiation and the distance between the electron clouds, $\lambda_{undulator}$ is the undulator period, γ is the ratio between the total energy (relativist one) and the electron energy ($m_e c^2$), K is the undulator parameter and finally, θ it is the observation angle with respect to the undualtor axis. You should do not forget easily this last factor since it tells you that the wavelength changes with angle, and as you will see later, that is very important in order to do good simulations.

2 A zoom in FLASH

2.1 How does it look like?

It is very useful to understand how the exact geometry of the photon beamline looks like (Fig. 3) in order to understand how much photons can be transported to the detector, especially with the existing mirrors and other apertures (Fig. 7).

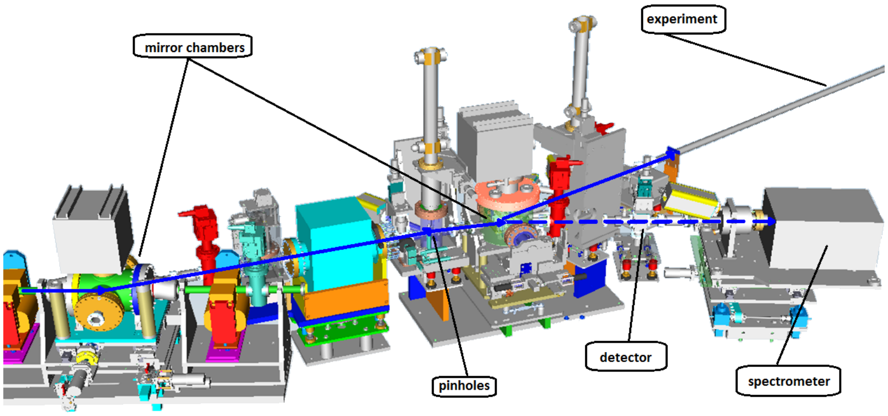

Figure 3: The radiation produced in the undulator is sent, by the first set of mirrors, to the second set of mirrors. Before the second set, there are the pinholes. In the second mirror chamber, two possible configurations are possible depending of the couple of mirrors you chose. Wich one of them, the photons are sent to the experiment, and with the other one to the detector (MCPs).

2.2 The Micro Channel Plates, also known as MCPs

This kind of detectors can detect impinging radiation including ultraviolet radiation and X-rays. It works intensifying photons by the multiplication of electrons via secondary emission. The MCP is made from a resistive material, very thick and a regular array of tiny tubes or microchannels which provides the spatial resolution that an electron multiplier, that follows a similar mechanism, does not. The microchannels are typically around the 10 micrometers in diameter and spaced apart by approximately 15 micrometers. They are parallel to each other and tilted 8° from the plate normal vector. So when the photons enter to the channels, they will hit the wall because of the angle to the plate. There is also a strong electric field inside the plate which gives a voltage difference between the two sizes of the plate, due to this fact, the impact starts a cascade of electron that propagates through the channel amplifying the original signal several orders of magnitude. When the process finish, the MCP needs some time to recover before it can detect another signal. When the electrons exit the channels they are detected by a single metal anode which gives the total current (Fig. 10). The MCP amplification gain can be tuned in a wide range just changing the voltage which is applied, these features make an MCP a perfect detector for monitoring XUV radiation. However, it is not a linear response, indeed the gain on the applied voltage is nearly exponential and about this topic special efforts have been done, to calibrate this dependence and then to make an automatic calibration, by the last years summer students [7] [8] [9]. So with this last work, and after check if our simulations correspond to a real situation, everyone should be able to perform experiments in ideal conditions.

3 Setting up; you already know why, now I am telling you how

We already know why to calculate the number of photons detected in the MCPs is that important, so we are ready to do the next step: How to proceed? The first thing that one needs is to get, somehow, the data corresponding to our situation for the further simulations. That is, a program where one can set up all the parameters like a linear accelerator, the length of the undulator, the gap in the undulator, the kind of source (in this case spontaneous emissions because of the reason explained above), the energy range and so on. For this purpose we will use SPECTRA [5], a very useful software that will be explained below. Then, to plot all the results, we will use MATLAB, due to its multiple capabilities for graphics, some other programs like OCTAVE could have been used, the only thing you need is a program that you be familiar with and where you have good tools for your graphics, interpolations, and other different arrangement needed to plot your results. For this particular, all the MATLAB files are already done, so in case that when the simulation be checked there will be not good results, the only thing to do, is to make new calculations in SPECTRA and import the data to the existing MATLAB scripts to get the new results. Finally, we have to take into account the reflectivity due to the mirrors. This point will be explained in the next sections with more details, now just remember that there is a factor very important for the simulations which up to now it is been missing in our explanations, you will find out why and how very soon.

3.1 SPECTRA, our new best friend

As I said, SPECTRA will allow us to get all the necessary data for the simulations since the program covers all the initial parameters needed. Besides, the program is very intuitive. So as you may see in the Fig. 11 the first parameters are related with the beam. To know which is the undulator constant K for the sFLASH undulator, we used a MATLAB script that calculates the constant for a given energy. The other parameters like the bunch charge or the electron energy we knew from before. Some others, like the beam's characteristics or the coupling constant we chose as simple as possible in order to simplify the problem; It was not necessary to set a non symmetrical configuration to get a more accurate result (Fig. 12).

I have chosen for the pictures one of the possible configuration. To be more precise, in Fig. 11 you can see the configuration that will give us the data for the partial flux going through one of the pinholes (the biggest one) at certain distance from the source. Probably, you have already realized that we are dealing with an ideal configuration and you may wonder if the distance is relevant (instead of set 4.5 m for instance), or why did we choose this pinhole instead of another one, or if is it right to make the beam going in a trajectory where the pinhole is perfectly aligned with the beam. Well, indeed all these things have been carefully considered. Step by step; about the distance between the source and the detectors, it is clear that the closest, the best since the photon density will be lower in the distance and we cannot have an infinite large detector. Unfortunately, because of the machine construction by itself, the minimum distance is the one you can see in the picture. We did not know from before if SPECTRA was considering the distance between the source and the detectors from the beginning or from the end of the source, so we set some different positions and we conclude that SPECTRA is taking the position from the end. The size of the pinhole we chose will have an enormous influence in the photons detected since, for the smallest one, the amount of them it is reduced dramatically (Fig. 13). And, to finish with, the position of the pinholes respect to the beam. As you can imagine, it is almost impossible to have a perfect alignment between the source and the pinholes. So, how does it affect if the pinhole is not exactly in the center? We did change the position to see the response of the flux due to this changes, of special interest is the fact that the response is not the same if we change the position in the horizontal direction or in the vertical, that is, the radiation is not in a cone-shape. Can you explain why? The answer can be found in the first section, but it is enough to remember that the electron beam, in an undulator, has its sinusoidal movement in the vertical or in the horizontal direction, instead of an helical movement in both horizontal and vertical directions. All these results are shown in the Fig. 14 where you can see in more detail all that have been explained above.

3.2 MATLAB innings

You have already seen why MATLAB has been used for. So here I am presenting a very important graphic that you should keep in mind. The power vs. the energy (Fig. 4). In principle, this graphic could be used as an example of the utility of MATLAB for converting the data from SPECTRA and to give a nice plot (and now it is a good moment to remember that you also can use all the MATLAB scripts built for this project to plot the result with other new data since they can be found in the public file), but also we are in a good point to introduce you to one of most important parts in this project: the mirror's role. As can be seen in Fig. 4, most of the radiation power is radiated in the higher harmonics of the undulator radiation. For the calibration of the detector at the wavelength of interest (which is at around 35 eV photon energy) this will give a huge background. Now a question for you: how to avoid the energy content in the high photon energy part (above 200 eV)?

3.3 Mirror, Mirror...

And here we have the answer. If you remember from the figures of the apparatus, the beam has to go through two arrangements of mirrors. In the first one, composed by three mirrors, the beam is bent to the detectors. In the second one, just after the pinholes, it is composed by two mirrors which send the beam to the experiment or to the energy monitor and the spectrometer. If you have a look to the Fig. 5, you can see the reflectivity due to the second set of mirrors. This reflectivity is so important since it absorbs the high energy that we did not want. To calculate the final flux and, with it, the power and the energy that finally reaches to the detectors, what we have is real data taken from a real experiment in the second set of mirrors. Because we did

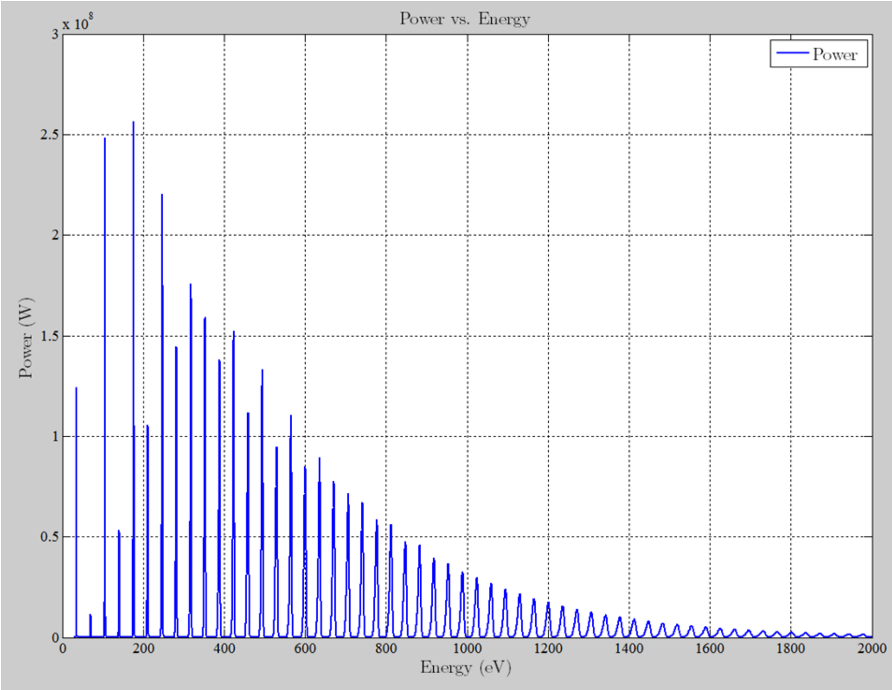

Figure 4: Most of the radiation energy is in the higher harmonics, instead in the fundamental wavelength, which we are interested in for the calibration of the detector.

not have any real data from the first set of mirrors, the logical step now is to find a way to reproduce the reflectivity due these mirrors. In order to get appropriate data for the 3.3° grazing incidence which was not measured, we will fit the measured data at 5° to the CXRO data tables for single layer coating, starting with the nominal values for the coating data. And for this purpose let me introduce you to a wonderful web site [6] from Lawrence Berkeley National Laboratory's which provides you the tools to simulate X-Ray interactions with matter. Once there, we chose a single layer which will give us the mirror layer reflectivity for certain mirror that we have to set since it is possible to select the kind of material you are dealing with, the thickness, the roughness, angles, energy range... In the Fig. 16 you can see the parameters that gave us a very acceptable result, that is, a curve very similar to the real curve. When you have set all the parameters, you can plot the curve using this program or, as we did here, export the data to plot the curve with the real one to make easier the comparison between them (Fig. 5). I strongly recommend you to have a look of the parameters used here since to find the correct parameters of the mirror was not an easy task, and they are unknown variables that have not been given by the manufacturers (Fig. 15).

4 Results and Conclusions

Finally, after have considered all the parameters, we are in the place that we wanted: we can simulate the amount of photons that reach the detector. You can observe in

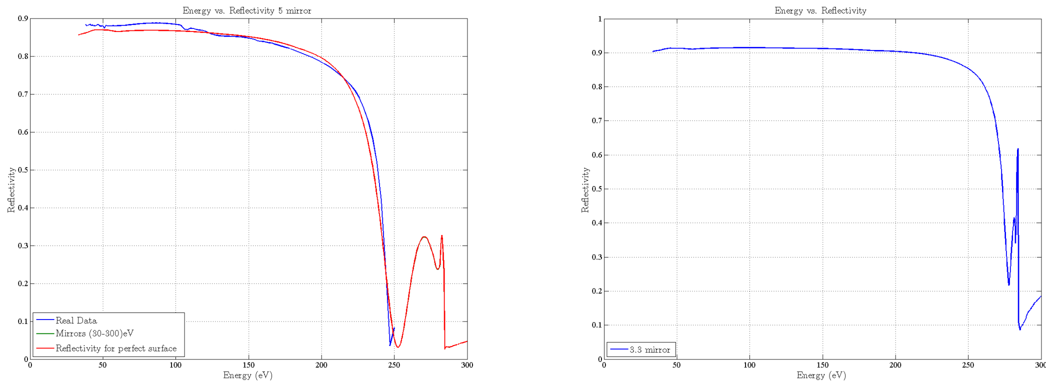

Figure 5: (a)In this first graphic you can see the real curve (in blue) compared with the built one (in red) for cero roughness. The one with the *real* roughness is in green, and the reason why you cannot see it, it is because it is almost the same than the red one telling us that this parameter is not that relevant. (b) This second figure shows you the curve for the mirror with 3.3° grazing incidence, which will be used to calculate the final flux and power that the monitor is detecting.

(Fig. 6) the total flux compared with the flux that it is detected considering the interaction of the mirrors. It is clear that the final flux has be reduced drastically when the mirrors have been considered, removing a wide range of energy that we did not want. And with this final result, we can plot the power and with it, calculating the energy that it is been detected in the MCPs (Fig. 7).

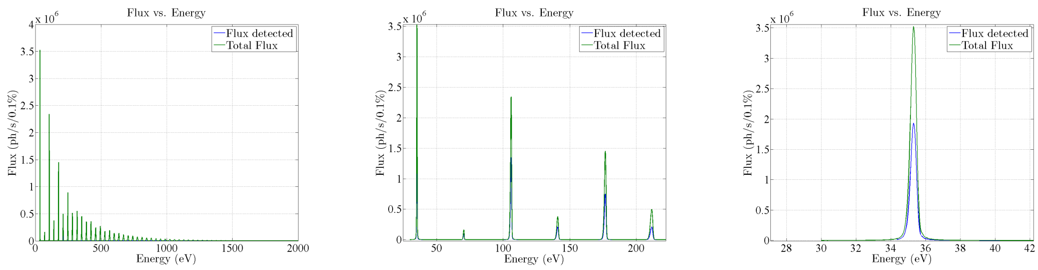

Figure 6: (a) The first graphic shows the total flux (in green) and the flux that is actually being detected in the monitor when the mirrors' interaction have been also considered. You can see the different between them in more detail in (b) and (c) for the energy range that we are interested in.

The conclusions can be summarized as follows:

- We will have to work with spontaneous emission since its behaviour is predictable, once we know how the detectors work with this kind of source, the problem it is solved. We are interested in the functionality of the MCPs, how many photons they detect, and for that it is not needed to use SASE. The detectors response to higher voltages has been studied already by the last years summer students.

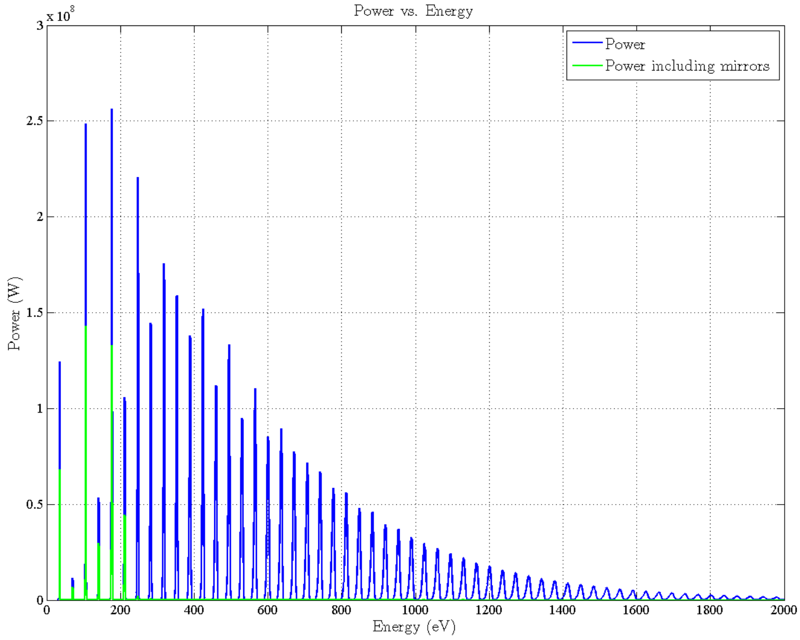

Figure 7: Power spectrum of the undulator radiation without taking the mirror reflectivity into account (blue). Including the reflectivity (green) reduces significantly the amount of power reaching the detector.

- To estimate the amount of photons that reach the detectors, it is important to consider several possible situations in order to study their corresponding responses in the detection; such as the position of the pinhole respect to the beam, the pinhole size, the distance between the source and the detector, the undulator length...
- Once we have the optimal parameters, the calculations can be done. This gives us the first view of what the detectors are working and shows us a non desired range of energy.
- The next step is to consider the effect that the mirrors, located in the beam path, and doing that we see that due to the reflectivity of all the mirrors, the energy gets reduce to the range of energy above 200 eV.

5 Outlook: What is missing?

This project has been done with the aim to give the researchers the numbers they need before set up the real experiments. The MCPs we are dealing with were installed years ago and we do not know if they still working as the beginning so, when they make the experiment in the future, it will be possible to check if this results correspond to the real ones get from the detectors. So the next task is to set the experiments, check, and then, if the numbers from these simulations do not fit with the real ones, change the possible sources of errors in the already built scripts to get some new simulations until the correct one be found, so the errors in the MCPs. With this, we will know how much FEL pulse energy we will have in absolute numbers. It is then possible to recalibrate the MCP detectors and get an absolute energy calibration for the energy monitor. Other thing to study is the signal that the MCPs generate for some range of wavelengths. For example for the wavelengths corresponding to the first harmonic and the second, to see if they are clearly separated or not. So study the MCP response via the output signal would be also very useful in order to make the comparison with the input and have a sight of what one would see in reality.

It is also important to calculate the energy from the power, which it is already known. So making the integral in the time interval once could know the energy arriving the detectors.

6 Acknowledgments

I would like to express my greatest gratitude to the people who have helped and supported me throughout my project. I am grateful to my supervisor, Jörn Bödewadt, who has taught me a lot in these two months, and who has made my day by day's work always interesting.

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And last, but not least, thanks to DESY and to the Summer Students Program's organizers, for their attention and welcome in this great program.

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7 Appendix

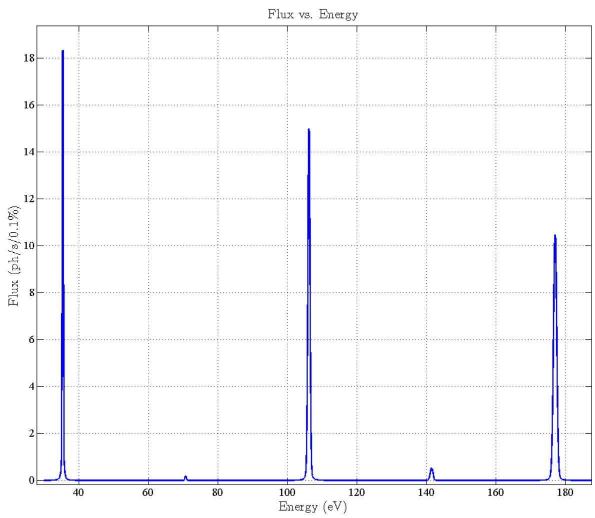

Figure 8: In this graphic, made for a 1mm-radio pinhole, it is clear the behavour of the harmonics produced in the undulator. Note that the odd harmonics are quite much higher than the even ones.

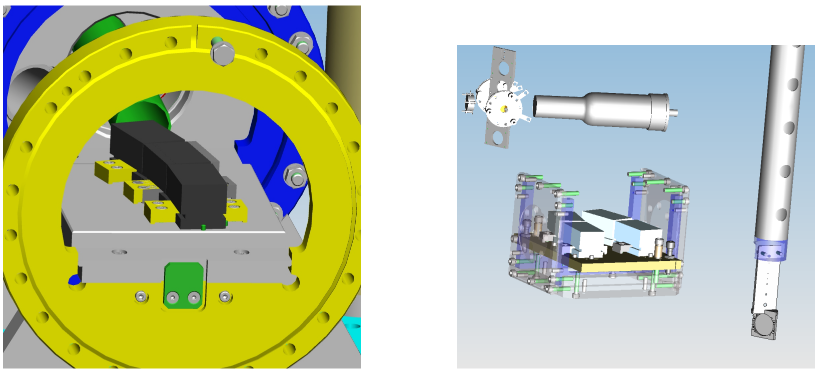

Figure 9: (a) This is the first set of mirrors. The first of them is tilted three degrees to the beam trajectory and the other two ones have also the same inclination between each other and the first. In this part of the accelerator, the beam is send to the second set of mirrors. Since there are not real data from the reflectivity due to this set of mirrors, in this work was simulated using the real data from the second set, as it is explained bellow.(b) In this second image, you can see in more detail the other elements that we have worked with. The pinholes, the second set of mirrors and, finally, the detector.

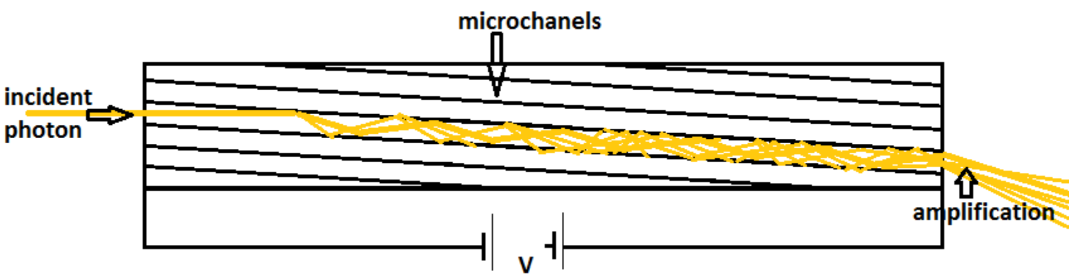

Figure 10: Simplified sketch of the MCP mechanism. The particle, electron or photon that comes normal to the plate's surface, hits the plate and starts smashing with the channels' walls due to the little angle between the plate and the channels. Every time this occurs, new electrons are produced and, because there is a potential difference between the inter and the outer of the MCP, the electrons keep moving until they go out from the MCP, so the initial beam gets amplified.

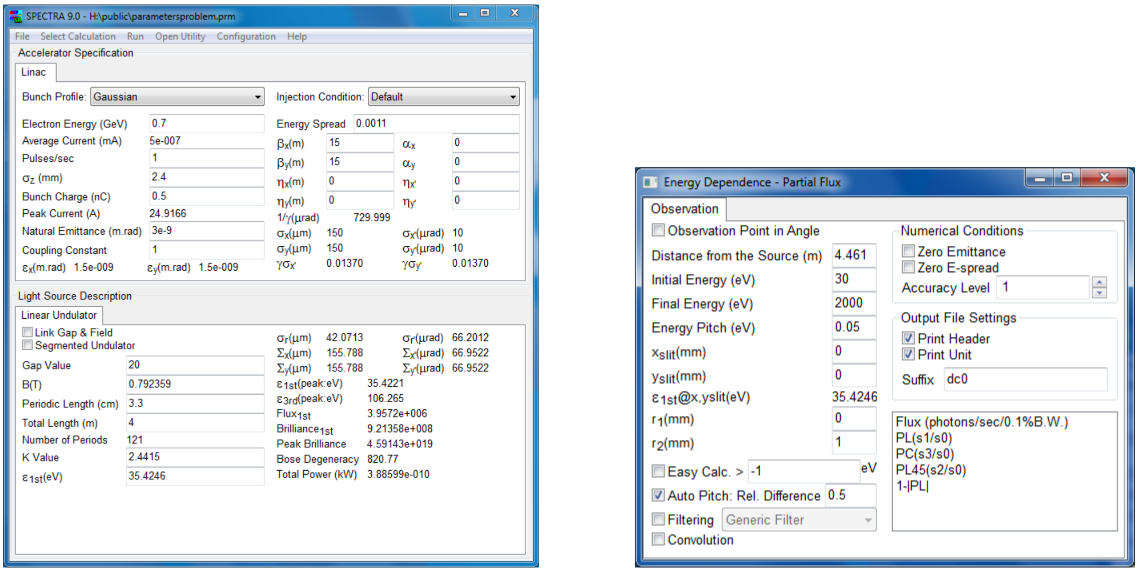

Figure 11: (a)These were the parameters used to the calculations made in SPECTRA. In case that the final results (the ones compared with the real experiences) do not fit with the simulations, you should go back here to change what be needed. (b)This is the window are set the parameters for the circular slit used.

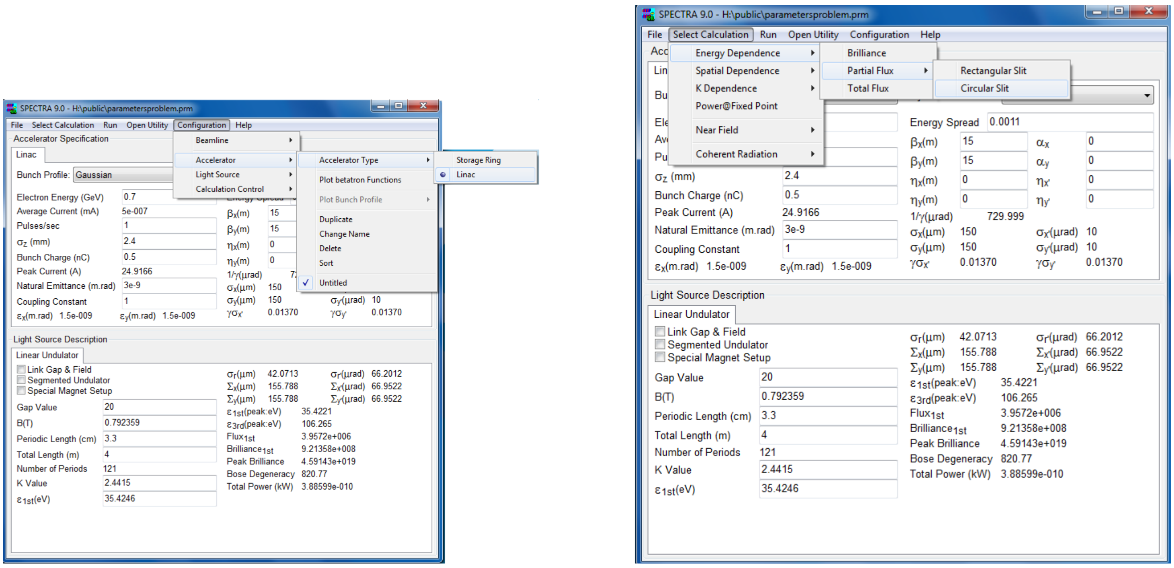

Figure 12: (a)These are the steps to select the kind of source we wanted to use, in this case, linac. (b)Here you also have the way to set the kind of slit that we are going to use. We used circular slits and, once there, you can also set the size of the slit, if you want a hole or a disk, and so on.

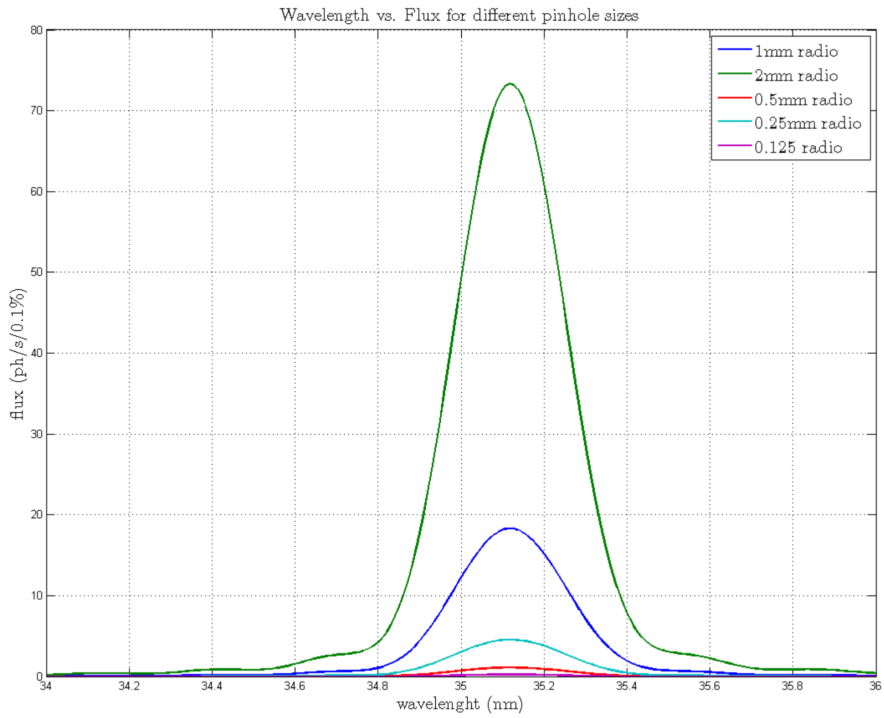

Figure 13: Here it is clear how the pinhole's size affect the radiation that arrives to the detector. For a very small pinhole it became close to zero. In the rest of the simulations made, we used the biggest one in order to get better results, since with a small amount of photons it is difficult to clear results.

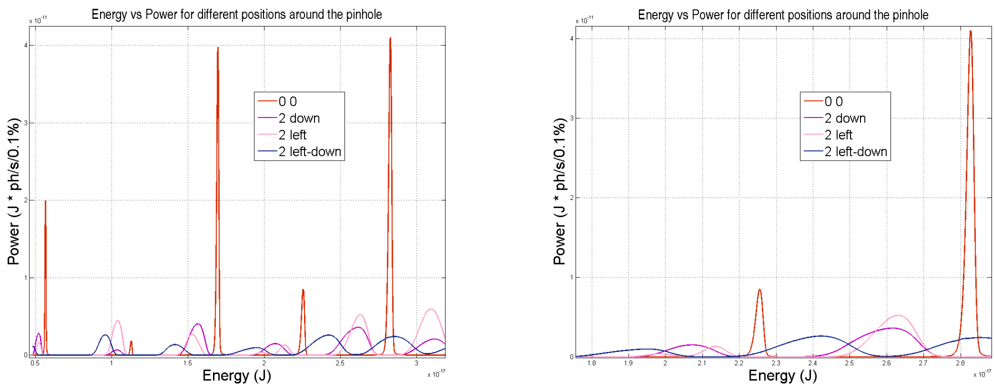

Figure 14: (a)Here it is clear how different can be moving the pinhole in the horizontal and the vertical direction from keeping it in the center. (b) In this you can see in more detail two of the harmonics and how they get displaced when the pinhole is moved.

Mirror Parameters		Units
Layer Material	C	-
Layer Density	1,65	gm/cm^3
Layer Thickness	40	nm
Top Surface Roughness	0,5	nm
Substrate Material	SiO2	-
Substrate Roughness	0,5	nm

Figure 15: In this table you find the optimal parameters to build the curve for the 3.3° mirror.

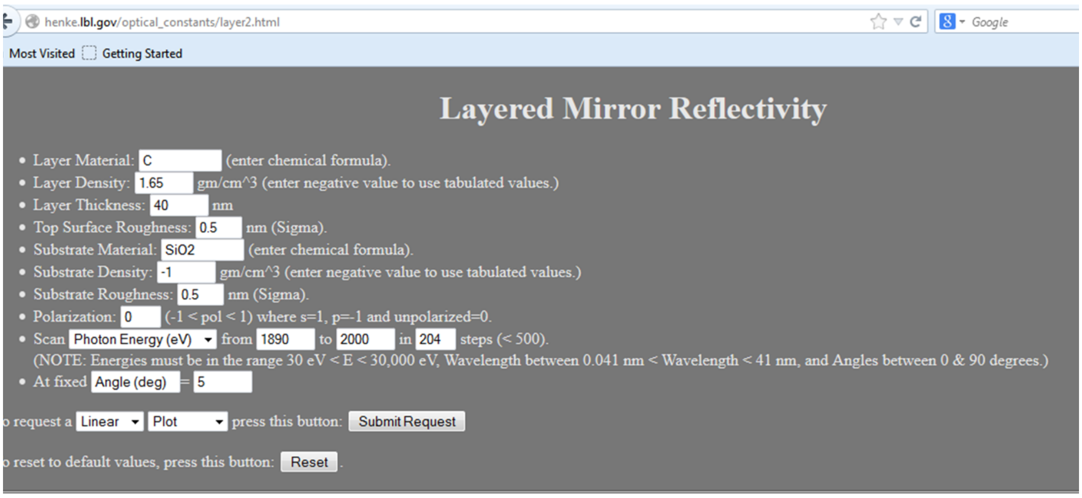

Figure 16: Here you have a view of the screen with the mirror proper parameters.