

Designing and implementation of electron monochromator

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Abstract

At the upgrade in 2018, ALICE plans to replace the inner tracking system (ITS) with silicon pixel detectors. In order to characterize the pixel detector prototypes minimum ionizing particles (MIPs) are used.

My assignment at CERN was to design and implement an energy selector for electrons, also referred as an electron monochromator. With an energy selection, one can have minimum ionizing electrons from decay electrons of Sr-90. Electrons of different energies are spatially separated with a magnetic field. The strength of the magnetic field density and the location and width of output slit can be chosen in a such a manner that only electrons of the chosen energy region remain.

I calculated the necessary characteristics for the electron monochromator, decided the dimensions physical dimensions of the produced parts and performed verification measurements for the output of the electron monochromator. The output of the energy monochromator was estimated with theoretical calculations.

In the verification measurements it was found that the amount of low energy electrons is suppressed. Otherwise, the output of the electron monochromator agrees with the rough, theoretical predictions.

1 Introductory

At the upgrade in 2018, ALICE plans to replace the inner tracking system (ITS) with silicon pixel detectors. This is the first time at Large Hadron Collider (LHC) at CERN that monolithic active pixel detectors are the base line technology. In order to characterise the performance of the pixel detectors either radioactive sources or test beams are used.

As the usage of test beam requires travelling with the measurement setup to an available test beam location and that takes effort from the actual development work. Sr-90 emits electrons of minimum ionizing particle (MIP) energies. As the beta decay is three body decay, the electron energy distribution also possess significant amount of low energy electrons, which are not minimum ionizing particles. Monochromatic Sr-90 source would be a considerable substitute for test beams in some situations.

Aim of this work is to design and implement a monochromatic electron source. The monochromatic electron source is produced by using a magnetic field as energy filter. After the production the characteristics of the produced electron monochromator are tested.

2 Monochromator characteristics and specifications

The estimation of the characteristics of the electron monochromator consisted of estimating the necessary energy accuracy, magnetic field density, electron trajectories, count rates and slit dimensions. Also dimensions and characteristics of an old electron monochromator were estimated and they were found to agree with the done estimations.

The electron energy selection of the electron monochromator is demonstrated in figure 1a.

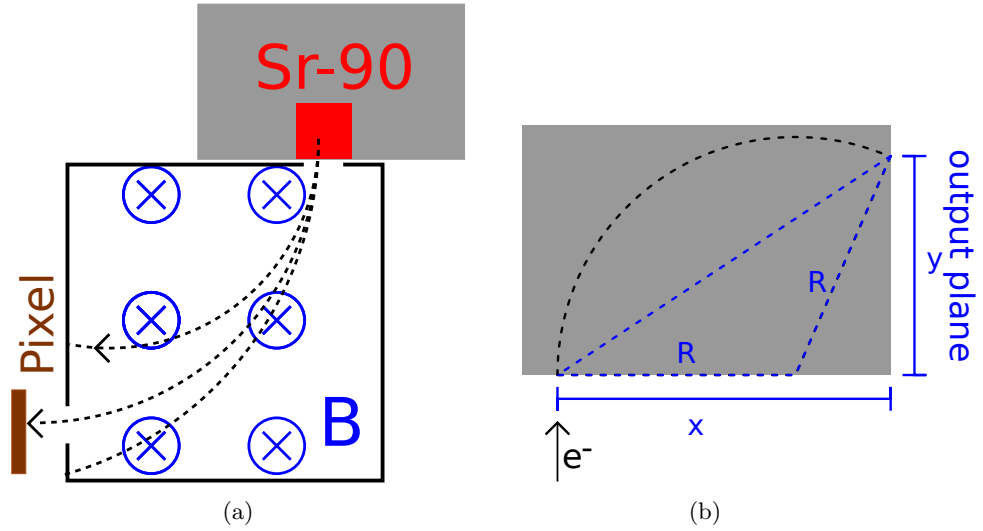
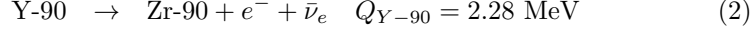
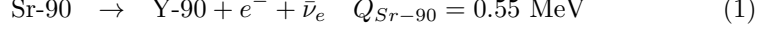


Figure 1: 1a: Diagram of the energy selection of the electron monochromator. The “B” stands for magnetic field and “Pixel” for the silicon pixel detector. 1b: Diagram of the electron trajectory calculations. The black dashed curve represents the trajectory of the electrons. Blue notations are for the trigonometrical calculations. R is the radius of the electrons, x and y are the locations of the input and output slits.

2.1 Necessary characteristics of the electron monochromator

The necessary energy accuracy was defined as under 10 percent fluctuation of electron behavior in the silicon detector. Particles are detected in the silicon detector by the electron-hole-pairs produced by the energy loss of the particles. The mean energy loss was calculated from the stopping power of electrons in silicon using continuous slowing down approximation. The given energy accuracy condition was found to be satisfied for all electrons with kinetic energy, T_e , between 0.7 and 2.3 MeV (the maximum kinetic energy of electron from Sr-90 source).

The decay chain of the Sr-90 is



where the Q -value of the reaction is the maximum kinetic energy of electron. The distribution of available electrons from the Sr-90 source was approximated with the Fermi theory of the beta decay. It was found that 35 % of the decay electrons of the Sr-90 source have enough energy to be minimum ionizing particles.

The curvature, r , of electrons with energy, T_e , can be achieved from the Lorentz force

$$R = \frac{p}{Be} = \frac{\sqrt{(T_e + m_e c^2)^2 - m_e^2 c^4}}{Be} \quad (3)$$

where m_e stands for the rest mass of the electron, c for the speed of light, B for the magnetic field density ($[B]=1 \text{ T}=1 \text{ Vs/m}^2$) and e for the unit charge. The necessary magnetic field density was estimated with the most probable electrons satisfying the energy accuracy condition ($T_e \in [0.7, 2.3] \text{ MeV}$). The necessary magnetic field density can be achieved with an electromagnet consisting of a coil and a C-shaped iron yoke with a narrow air gap. The magnetic field produced into the air gap is almost constant besides the very edges of the air gap.

The count rate distribution in the output side plane was calculated by assuming uniform magnetic field in the air gap and parallel input electron distribution. The calculation of the electron trajectories is illustrated in the figure 1b. The electron count rate density in the output plane can be achieved by applying both electron decay probabilities and the electron curvatures

$$\frac{dPr}{dy}(y) = \frac{dPr}{dT_e}(T_e(y)) \frac{dT_e}{dy}(y). \quad (4)$$

By integrating the electron count rate density over the output slit one get the count rate fraction of the output of the total decays. The energy resolution of was considered to be sufficient when the non-parallel electrons were unable to make it to the output with a margin of 1 mm.

2.2 Optimisation

In order to find theoretical number for the optimal operating point of an electron monochromator an iteration method was derived. This is necessary because the term $dT_e/dy(y)$ is found to be monotonically increasing. Therefore, the highest output count rate density is not at the location of the most probable electrons.

After implementing the first plans for the monochromator there was time to do further calculations. An iteration method to find the optimal main radius for minimum ionizing electron monochromator was found. This was applied for monochromator configuration of 90° where electrons bend full 90° . The output rate of 21 % of all Sr-90 source decays was achieved with 3 mm diameter output slit. As this is 60 % of the theoretical maximum for MIP electron monochromator there is no sense to search maximums with other bending angles because the 90° enables the easiest usage.

2.3 Production of electron monochromator

The main objective of my assignment was to produce the electron monochromator. Therefore, the monochromator was implemented as soon as it felt reasonable.

At the consultation of the Magnets, Superconductors and Cryostats (MSC) group at CERN it was found out that the production of the coil is the longest delay in the production process. Therefore, an existing coil was selected and other characteristics were adjusted to according the one's of the coil. The main bending radius of electrons was selected to be 45 mm, corresponding magnetic field density of rough 0.1 T. The technical drawings for the monochromator are shown in figure 2a and the actual monochromator in figure 2b. 10 mm aluminium was chosen as the output shield because the mean range of electrons in aluminium is rough 6 mm according the continuous slowing down approximation (CSDA) [1, 2]. The slits and mechanics to attach the Sr-90 source were done by Detector Technology (DT) department.

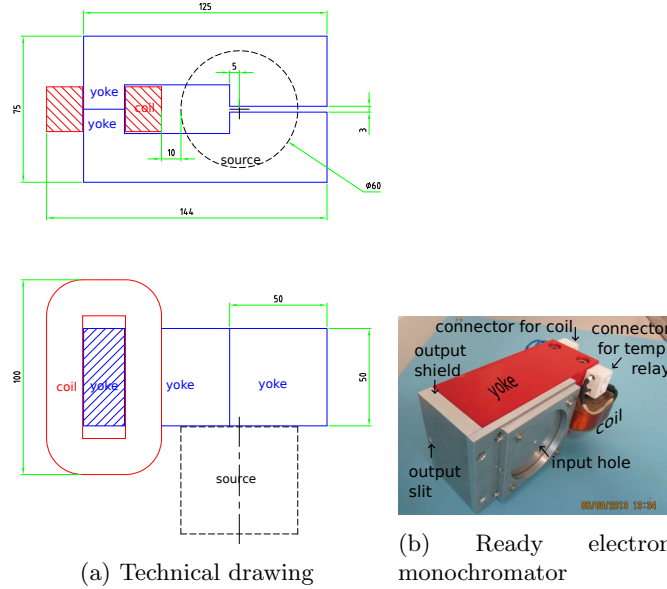


Figure 2: Technical drawing and picture of the ready electron monochromator.

3 Experimental results

The operation of the electron monochromator were verified with count rate measurement with both scintillation counters and a silicon pixel detector. The measurement data with theoretical predictions based on chapter 2.1 are shown in figure 3.

The scintillation counter measurements were done with integration time of 180 seconds for the first scintillation counter measurement and 120 for the second and third. The pixel detector measurement was done with pALPIDE pixel detector with 512×64 matrix of $22 \times 22 \mu\text{m}^2$ pixels. During pixel detector measurement the integration time was 100 μs and number of recorded events was

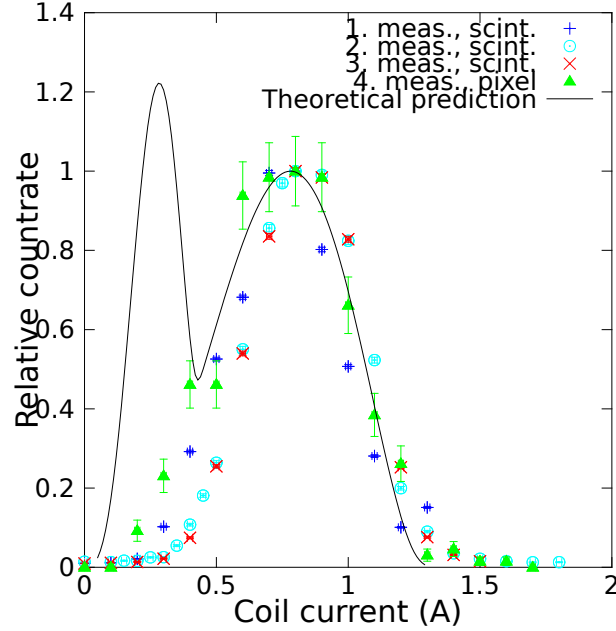


Figure 3: Measured data of the electrons from the electron monochromator with both scintillation counters and pixel detector.

100 000. The statistical errors of the count rates are minor for scintillation counter but significant for pixel measurements. The granularity of the current source was assumed to be the error of the current source.

We see that the data agrees the rough theoretical predictions by the position of the peak of the higher energy. The shape of the measured peak is narrower than the expected. We can also see marks from gaussian-like resolution function because the measured spectra have gaussian tails. Therefore, with this limited amount of data it can be assumed that the actual peak is even narrower.

From data we see that peak corresponding the low energy particles is missing. This could be at least partially explained by the $50\ \mu\text{m}$ encapsulation layer of steel of the Sr-90 source. This layer absorbs electrons with energy equal or less than 0.2 MeV, according CSDA approximation and data from [1, 2].

4 Summary

I performed designing and implementation of electron monochromator. The designing was started from needed energy accuracy, the under 10 % electron behavior fluctuation in silicon detector. The estimations for magnetic field density, electron trajectories, count rates and physical dimensions were done.

The implementation of the electron monochromator was done relatively soon in order to enable ready device within 10 weeks of stay. The characteristics of the monochromator were based on an existing coil which expedited the production significantly. The main radius of the electron trajectory in the monochromator

is 45 mm.

The verification measurements of show that the electron monochromator is functional. the electron monochromator suggest that low energy part of the Sr-90 output is strongly suppressed. This might be due the steel encapsulation of the Sr-90 source.

References

- [1] National Institute of Standards and Technology, Stopping powers and range tables for electrons, <http://www.nist.gov/pml/data/star/index.cfm>
- [2] The Engineering toolbox, cited 15.8.2013
http://www.engineeringtoolbox.com/density-solids-d_1265.html