Ion tracking simulations for the WITCH experiment

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1 Introduction

The WITCH experiment (standing for **W**eak **I**nteration **T**rap for **CH**arged particles) is dedicated to high-precision measurements of fundamental properties of electroweak interaction. Its first goal is to indirectly determine the electron-neutrino correlation coefficient in β decay by measuring the energy spectrum of the recoiling nuclei. For this, a set-up consisting of two Penning traps, a retardation spectrometer and an MCP (Microchannel Plate) detector was designed and coupled to REXTRAP at ISOLDE/CERN. Schematic drawing of the experiment is presented in Figure 1.

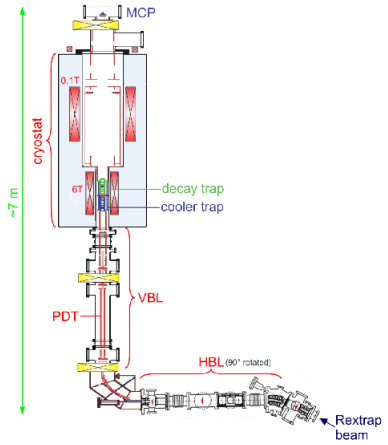


Figure 1: WITCH experiment set-up. Ions pass from REXTRAP through two beam lines: horizontal (HBL) and vertical (VBL) and reach Penning traps. Then they are released to the spectrometer, accelerated and detected by the MCP detector.

2 Motivations

My task at the WITCH was related with the spectrometer. This element is responsible for creating a potential barrier and reflecting ions, which energy is lower than the barrier. The ions that go through the spectrometer are registered by the MCP detector which measures their energy and builds energy spectrum that is further analysed in order to recover the electron-neutrino correlation coefficient.

Although all the data gathered during the experiment is analysed in detail, there is still a result that is not yet fully understood. The position distribution of ions at the MCP detector is

presented in Figure 2. The most puzzling fact is that the peak is not in the middle. If the system is fully cylindrical symmetric, the distribution should be peaked in the center of the detector.

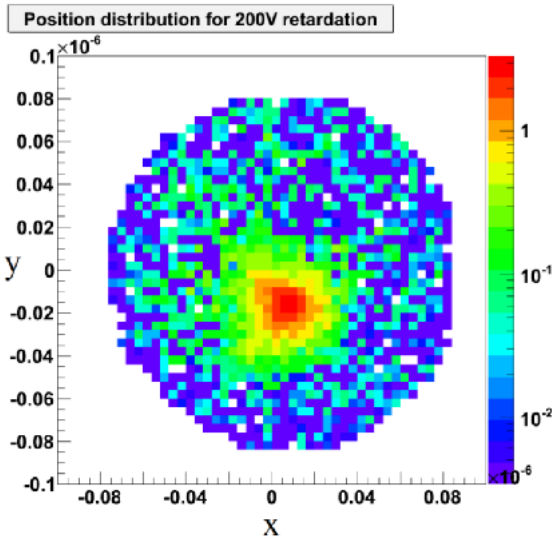


Figure 2: The typical position distribution of ions detected by the MCP detector [1].

This feature of the position distribution can be caused by two factors. First, the ions in the Penning trap might not be located precisely in the center, but there might be shifted. To rule out this factor a test measurement was done with all the electrodes at ground potential. The deflection of ions at the MCP detector was about 1 mm – too small value to explain the observed position distribution spectrum. Second, in the spectrometer there are two elements that are breaking axial symmetry: a wire and an arm. The wire sits in the middle of the retardation section of the spectrometer and it is responsible for removing the electrons from the system. The arm is holding a test MCP detector, which is used during the set-up phase of the experiment. While measurements, the arm is rotated as far as possible from the spectrometer's center.

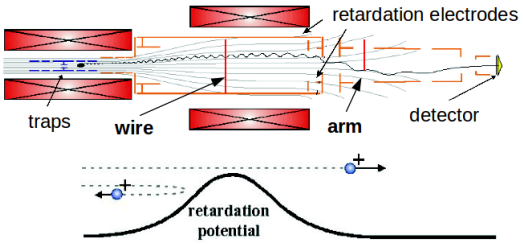
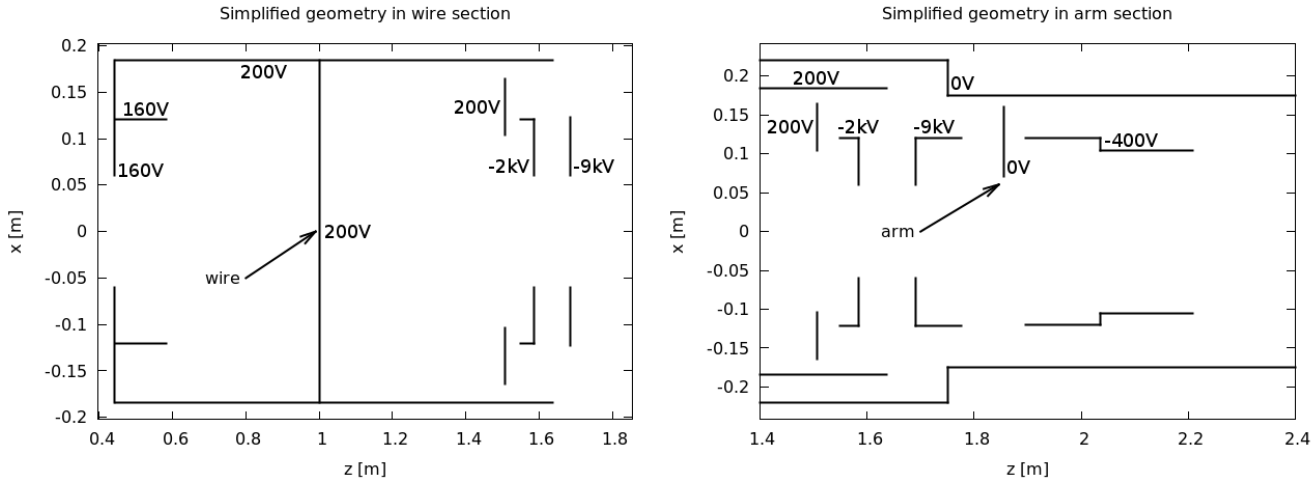


Figure 3: Schematic drawing of the WITCH spectrometer and its principle of operation. All the electrodes (except the wire and the arm) are cylindrical.

Precise simulations of ions going through the spectrometer are required in the data analysis. Each ion is tracked and the electric potential and field are calculated along its path. By the time I started my work these quantities were calculated with routines that assume axial symmetry of the system. The azimuthal angle is not considered, so these calculations are 2D. My task was to introduce the dependence on ϕ angle (3D) and run the ion tracking simulations with the presence of the wire and the arm.

3 Potential calculations

The 2D calculations with the cylindrically symmetrical system are providing reliable values of electric potential and take into account all electrodes in the set-up. Since the symmetry is broken, the dependence on the azimuthal angle has to be considered. This fact increases the number of segments in which the system has to be divided. Because of this the 3D calculations can not be done with the whole geometry and I had to divide the spectrometer in two sections and make some further simplifications. Electrodes that was chosen to calculate the potential using 3D routines are presented in Figures 4a and 4b. They were divided into segment which number was at the limit of available computer memory.



(a) wire section (b) arm section

Figure 4: Simplified geometry of the spectrometer's sections near the elements. The potential values of the chosen electrodes were labelled.

The 3D calculations can be done in two ways: with and without the non-symmetric element (wire, arm). The first type of computation is essential in comparing the results obtained with 3D routines with 2D calculations. The latter is providing potential influenced by the presence of the element which is necessary for ion tracking simulations.

In Figure 5 the comparison between 2D calculations and 3D ones with the wire is shown. In the whole wire section the difference introduced by this element is small, but significant. The wire is located in the middle of the retardation electrodes and therefore it influences the height of the potential barrier. Even small changes in this value may cause significant differences in the energy spectra of ions, so precise calculations of the potential value introduced by the wire are necessary.

In Figure 6 the difference between potential calculated with 3D routines for the system with and without the arm is presented. The arm is rotated from the center by 52^o which is the maximum angle. The change in potential value in the system caused by the arm is deflecting the ions, which is discussed in Section 5.

4 Interpolation

The most important part of the simulation is tracking of ions going through the spectrometer. Each ion is guided step by step through the system and the potential and electric field at each point are calculated. The 3D potential calculations are really slow in comparison to 2D – it takes 2000 times longer to do tracking of an ion in 3D than in 2D. To overcome this problem I came up with an idea of using potential map and 3D interpolation method. A map is a grid of equidistant points with a potential value calculated in each of them. Computation of a map is time-consuming,

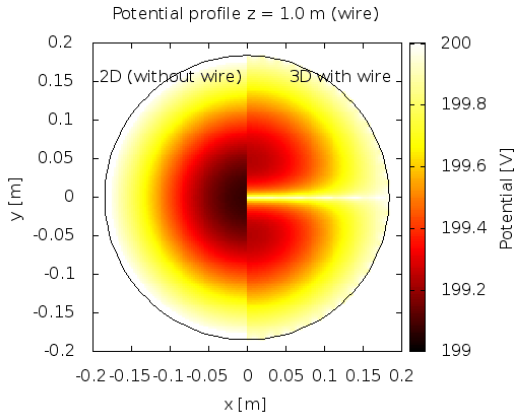


Figure 5: The potential profile at $z = 1.0$ m (wire position) calculated with 2D (left) and 3D (right) routines.

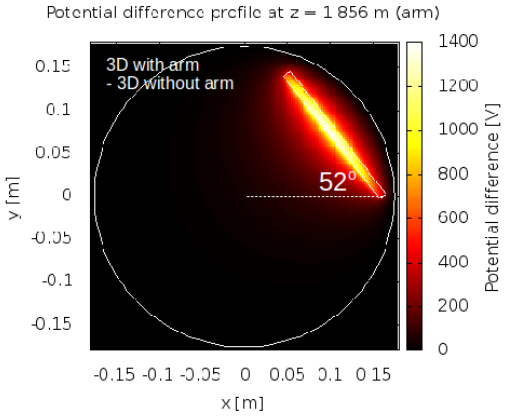


Figure 6: The profile of potential difference between 3D calculations with and without the arm at $z = 1.856$ m (arm position).

but it is done once, before the simulations. Then, if a potential value is needed in a certain point, fast 3D interpolation algorithm is used.

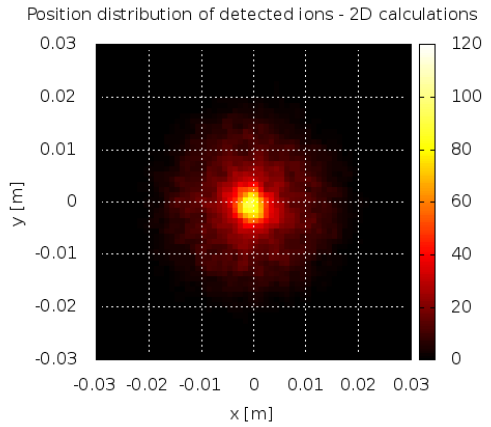
Another important idea is to model the influence of the wire or arm on the system by taking the difference between 3D calculations with the element and without it. This value is non-zero only in the vicinity of the element and it is approximately zero away from it. The potential gradient is also reduced by applying this method, which is important for 3D interpolation. Using this concept the potential difference can be added to 2D calculations combining precision and speed of 2D and taking into account the influence of the elements of interest. As it was observed, the difference between 3D with and without element is close to zero at the sides, so neglecting this value and taking into consideration only 2D calculations is not introducing significant error. The regions of only 2D and combined 2D and 3D calculations can be defined and the fast simulations can be run – they take only 20% more time than pure 2D tracking.

5 Simulations

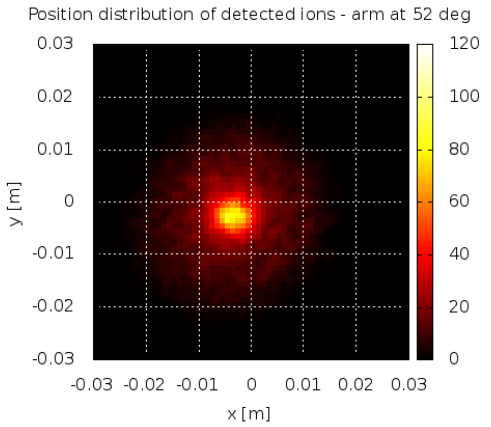
After implementing the fast 3D potential calculations with the wire and the arm the ion tracking simulations can be done. Two important studies were made during this project: the dependence of the peak position at the MCP detector with respect to the arm rotation angle and the arm position.

At first, the reference simulation was done using 2D routines to calculate the potential. The arm was not in the system. The result is presented in Figure 7a. Then, the arm at 52° was added to the spectrometer, the potential map was computed and tracking was done. The position distribution of ions is presented in Figure 7b. The conclusion is that the arm is deflecting the ions and the shift of the peak is of the order of magnitude of what was seen during the experiment (compare Figure 2). The simulations for different arm's angles was done and it was observed that the lower the angle the more deflected are the ions.

The second observation was made by changing the arm's location in z. The simulations described in the previous paragraph were done with the arm at the position as in Figure 4b – in two thirds of the distance between the two electrodes. In Figures 8a and 8b the position distributions for different arm's positions are presented. It can be deduced that the peak at the MCP detector is more shifted when the arm is closer to the electrode on the left. This is because the potential difference between the left electrode and the arm is higher than between the right one and the



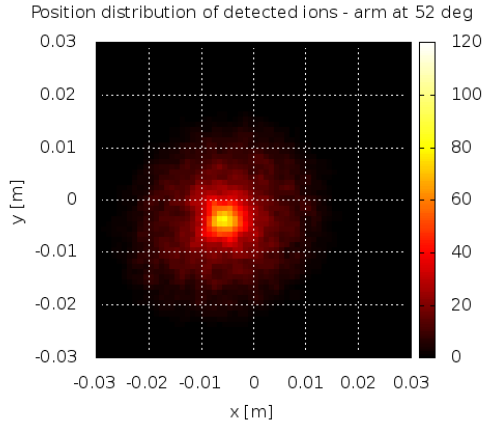
(a) 2D calculations without the arm



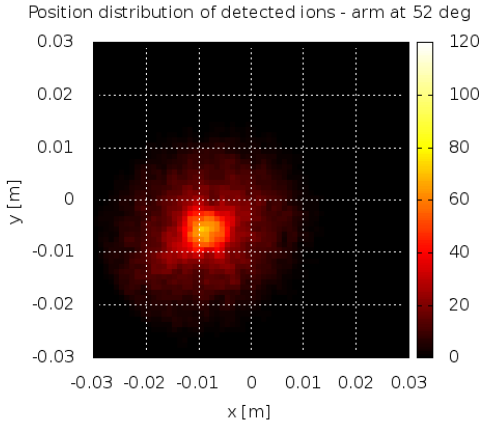
(b) 3D calculations with arm at 52°

Figure 7: Position distribution at the MCP detector coming from tracking simulations.

arm.



(a) 3D calculations with the arm at 1.856 m



(b) 3D calculations with the arm at 1.816 m

Figure 8: Position distribution at the MCP detector coming from tracking simulations.

6 Conclusions and outlook

To conclude, I managed to successfully implement 3D potential calculations and tracking into existing code. The idea of 3D interpolation improved the time efficiency of the calculations. Its further development may bring even faster simulations.

The tracking simulations showed that the introduction of the arm may cause the peak shift which is seen in the position distribution at the MCP detector. The deflection of ions depends both on the angle of the arm and its position along the z axis.

References

[1] Elisabeth Wursten, *Searching for Exotic Weak Currents with the WITCH Experiment*, Master thesis, KU Leuven, 2013