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MKI's alumina tube discrimination and optimisation

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Summary

The LHC's MKI (Magnet KIcker system) requires an alumina tube that holds screening conductors within slots. This setup shields the magnet from the beam that goes through the tube. The alumina tubes are not ideal as the thickness varies a lot at all angles along the length. These irregularities can cause breakdowns due to the aperture's high electric field during the kicking pulse. An optimiser for the tube's orientation was written using electrostatic simulations and python. An interface was created to make measurements sessions smoother and more efficient. Additional electrostatic simulations were ran to help with on going capacitance measurements used to determine the integrity of the tube.

Contents

1 Introduction

The alumina tube is a component of the MKI, used for its relative permittivity of roughly 10. The tubes are very complicated to manufacture. Due to the process of fabrication, the tubes inherit a problematic default: the alumina is not evenly distributed at all angles along the length. The tube posses slots to carry screening conductors [2] (kept at 0V) in order to protect the MKI ferrite from the beam, preventing heating of the magnet. A photo of the tube end can be seen in Fig 1. The aperture, shown in Fig 2, bears a strong voltage [1] (up to 50kV) along its walls during the kicking pulse which results in a strong electric field going through the tube. If parts of the tube, with a relatively small thickness, get near to a high voltage side of the aperture, the screening conductor could then be too close to a high voltage source which would result in a electric field strong enough to cause a breakdown of the alumina resulting in a puncture. This has already happened [1] and so appears the purpose of this work: the orientation of the alumina tube in the aperture can be optimised in order to limit the electric field magnitude dwelling inside it. Tubes may also be compared and discriminated based on certain criteria. Other problems concerns the fallacious tubes such as potential air bubbles present in the alumina, introduced from the fabrication. The creation of an optimiser using thickness measurements is proposed in a first time. More details are given on the obtaining of the weighting function (core element of the optimisation process). The brief description of a simple substitute measurement interface is then presented. Finally simulations results are proposed to help with the capacitance measurements used to detect holes in the walls of the tube. All figures are shown in the appendices at the end of the document.

2 Processing the data

2.1 Extracting information from the raw data

The data is composed of the thicknesses of the tube, each associated with two coordinates: an angle θ (the slot) and a longitudinal position z (as a length along the tube). We can make use of the very convenient cylindrical coordinate system in order to give the data points relative 3D positions in space: the thickness and fixed outer radius are used to obtain the radial component which completes the set of coordinates. It is then trivial to switch from these coordinates to Cartesian coordinates using the well known coordinate transform equations. The data would originally be displayed as thicknesses against length curves (one curve for each slot). It is quite difficult to extract information from this not very helpful representation. The 3D representation allows for a more intuitive visualisation of the data as shown in Fig 3. The coordinates attributed to each point also allows to perform an interpolation of the tube in 3D space. The tube is interpolated longitudinally and then in the angular θ direction at each "slice" of the tube. An interpolation with a custom thickness color map is shown in Fig 4. This interpolation is used in some optimisation methods and also to create the "discriminator", a python script that displays the interpolated cross section containing the smallest thickness for each tube given. A colormap indicates the expected field at each angle (from 0 to 360) and the normalised maximum electric field expected within the whole tube. For each case it also displays the cross section rotated at the optimal angle as calculated by a given method. This allows to discriminate between tube and optimisation methods at the same time. Fig 5 shows a typical output of the script.

2.2 Naive optimisation

2.3 Mathematical abstraction of the tube

A potentially useful mathematical abstraction for the tube (used in the optimisation process) is proposed in this section. The outer radius of the tube and the inner radius upon which lie the screening conductors are both fixed, implying a certain conservation of the amount of alumina for all cross sections of the tube. It is then possible to use the thicknesses to obtain coordinates, as described in section 2.1, and in turn use these to calculate an effective center for the screening conductors for each cross section. This effective center can then be positioned relative to the center in the ideal case, that is when it coincides with the center of the outer radius of the tube. The thickness information for this cross section would then dwell in the calculated effective center. These centers can be computed for each cross section and a 3D parametric curve passing through these points can be used to represent the tube and all its thicknesses. It is then no longer necessary to consider all thicknesses at all angles but rather simply this parametric curve. Rotating it in space would be equivalent to rotating the tube in space. Mathematically we can write:

$$\begin{bmatrix} x(z) \\ y(z) \end{bmatrix} \tag{1}$$

to describe the effective centers in the x–y plane, parameterised with z (the longitudinal coordinate for the tube). If we know a weighting function f such that:

$$f\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = E_{max} \tag{2}$$

where E_{max} is the maximum magnitude of the electric field in the alumina tube in the inputted configuration, then we can write down the following optimisation equation:

$$\frac{\partial}{\partial\theta}\left(f\left(R(\theta)\begin{bmatrix} x \\ y \end{bmatrix}\right)\right) = 0 \tag{3}$$

where $R(\theta)$ is the well known rotation matrix. A minimum is expected to be found from equation (3) considering the symmetry of the electric field within the aperture.

Two methods have been implemented to compute the described effective centers: calculation of the center of mass and the fitting of a circle to the data by moving it's center. Both method seem to give satisfactory results with a seemingly slight better performance for the first one. With this mathematical abstraction for the tube it is then necessary to obtain a weighting function such as described in equation (2). The search for weigthing functions is described in the following section 3.

3 The great search for weighting functions

3.1 Analytical approach

A simple analytical approach was used to get a test weighting function. The Laplace equation is solved for a rectangle approximating the aperture: 3 sides are set to a certain potential and 1 side is set to 0 (representing the grounded busbar above the aperture). The aperture is shown on Fig 2. A Fourier series is obtained for each boundary condition and are summed to obtain the complete solution. The potential obtained is shown on Fig 6. The corresponding analytical electric field can be obtained by taking the gradient as shown on Fig 7. A numerical gradient can also be taken (to get rid of instabilities caused by the non-smooth boundary conditions) as shown. The alumina tube can then be simulated by introducing a region of different permittivity: the material's polarisation is approximated as a linear response. This process could potentially lead to an interesting weighting function but it would require a lot of effort. The screening conductors have been ignored as they are the most complicated to include in this model. Since they also are the source of the strong field causing potential punctures, this method cannot be considered any other way than as a test weighting function.

3.2 Electrostatic simulations

As seen in section 3.1, the weighting function is hard to obtain analytically. It is however quite simple to use electrostatic simulations to extract information to construct one. The newest version of the Opera2D software is used for all the simulations. The software is almost completely controllable via python scripts. Two methods are considered to extract the coveted weighting function. One method consists in shifting the screening conductors radially and get values for the electric field close to the screening conductors in all directions which then allows to make linear fits for the electric field in function of the radial shift and this at all angles. The result of the fits for all angles is shown in Fig 8. The second method, which was chosen to be more reliable, consists in shifting the screening conductors with regards to their effective center as to simulate the varying thickness around the tube. It is then possible to obtain a weighting function which takes in the coordinates of the effective center of the screening conductors as inputs and outputs the maximum field calculated within the tube. Section 2.3 has more information about this weighting function, shown in Fig 9, and the effective center. The electric field close to the screening conductors can be measured at all angles, like in the first method, in order to compute another mapping used in the "discriminator"'s display. The discriminator is discussed in slightly more details in section 2.1 and section 4.

4 Optimisation results

The optimisation results are presented in the discriminator display shown in Fig 5. The results are as follows: clockwise rotation of 60°,60° ,15° and 105° of the MKI2B,LS1-1,LS2-2 and LS3-3 tubes respectively. The angles are multiples of 15 since the optimisation is made by rotating the tube in 15° steps, this angle corresponds to the angle between two slots. The

Tube name	Optimised clockwise rotation	Minimum thickness measured	Maximum normalised electric field predicted
MKI2B	60°	1.97 mm	1.076 V/cm
LS1-1	60°	1.75 mm	1.075 V/cm
LS1-2	15°	1.36 mm	1.101 V/cm
LS1-3	105°	2.03 mm	1.077 V/cm

Table 1: Table displaying the results of the optimisation. The normalised electric field is predicted for the tube after the optimisation rotation is applied.

minimum thickness for the LS1-3 and MKI2B tubes are 2.03 and 1.97 mm which makes the two tubes excellent candidates. The results are presented in Table 1.

5 Making a substitute interface

The thickness measurements of the tubes were made using a device called "Magna-Mike 8600". The device uses a serial connection with a computer. The user interacts with the device via an interface called "WINXL" [3] which is quite convoluted and not very practical. In order to make the measurement sessions go smoother, an interface was programmed using the well-known python basic GUI module Tkinter. Screenshots of the interface are shown in Fig 10 and Fig 11. The substitute interface was designed to be very specific to the task at hand: a set of parameters (thresholds, initial slot and others) are introduced. The thresholds are used to highlights measurement that are potentially wrong (values changing too quickly from on point to the next or values abnormally small). Plots show the thickness measurements as they are taken and the measurements are themselves all presented in a table with buttons that allow each measurements to be redone directly. Results can be saved and loaded from csv files in case the measurements are done over multiple sessions. The date (day/month/year and hours/minutes/seconds) is recorded for every single data point including redone measurements. The thickness values of redone data points are also stored in the output csv file. Temporary files are saved regularly as not to lose data upon an unexpected crash of the software or the computer.

6 Simulation of capacitance measurement

Additional electrostatic simulations were done to predict capacitance measurements using stored field energy and Gauss's law. The capacitance measurements would be used, in conjunction with the thickness measurements, to detect air bubbles defects in the alumina which would make the electric field stronger within the tube. Figs 12 and 13 show the predicted capacitance for different alumina thicknesses and Fig 14 shows the simulated capacitance for cases where the screening conductors don't fit exactly in the slots. The charge distribution on the edge of the screening conductor has also been investigated. A python script has been designed to extract charge distribution, with a chosen resolution, on the edge of any body modelled by the Opera2D software using the displacement field of the electrostatic solution and Gauss's law.

7 Conclusion

It is the author's conviction that some progress has been made regarding the MKI's alumina tube selection issue through this project. Measurements can now be read and saved smoothly to a computer directly via the new interface. These measurements can be directly fed into the optimiser to obtain a clockwise rotation to apply to the tube. The optimiser also generates plots and displays predicted electric fields and minimum thicknesses that allows to discriminate tubes by direct comparison. The simulated capacitance data will hopefully be useful to the on going investigation searching for potential air bubbles present in the tube. More work is also required to predict the electric field within the alumina tube during the rise of the kicking pulse and make sure the tube can withstand it post optimisation.

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References

[1] M. J. Barnes, W. Bartmann, C. Bracco, L. Ducimetiere, B. Goddard, G. Bregliozzi, L. Vega Cid, C. Yin Vallgren, V. Vlachodimitropoulos, and W. Weterings. MKI performance during 2016 and plans for EYETS. In *7th Evian Workshop on LHC beam operation*, pages 175–180, Geneva, 2017. CERN.

[2] M. J. Barnes, L. Ducimetiére, N. Garrel, B. Goddard, V. Mertens, and W. J. M. Weterings. Analysis of Ferrite Heating of the LHC Injection Kickers and Proposals for Future Reduction of Temperature. *Conf. Proc. C*, 1205201:2038–2040, 2012.

[3] Philip Graham. https://www.olympus-ims.com/en/insight/thickness-gage-how-to-videos/.

Appendices

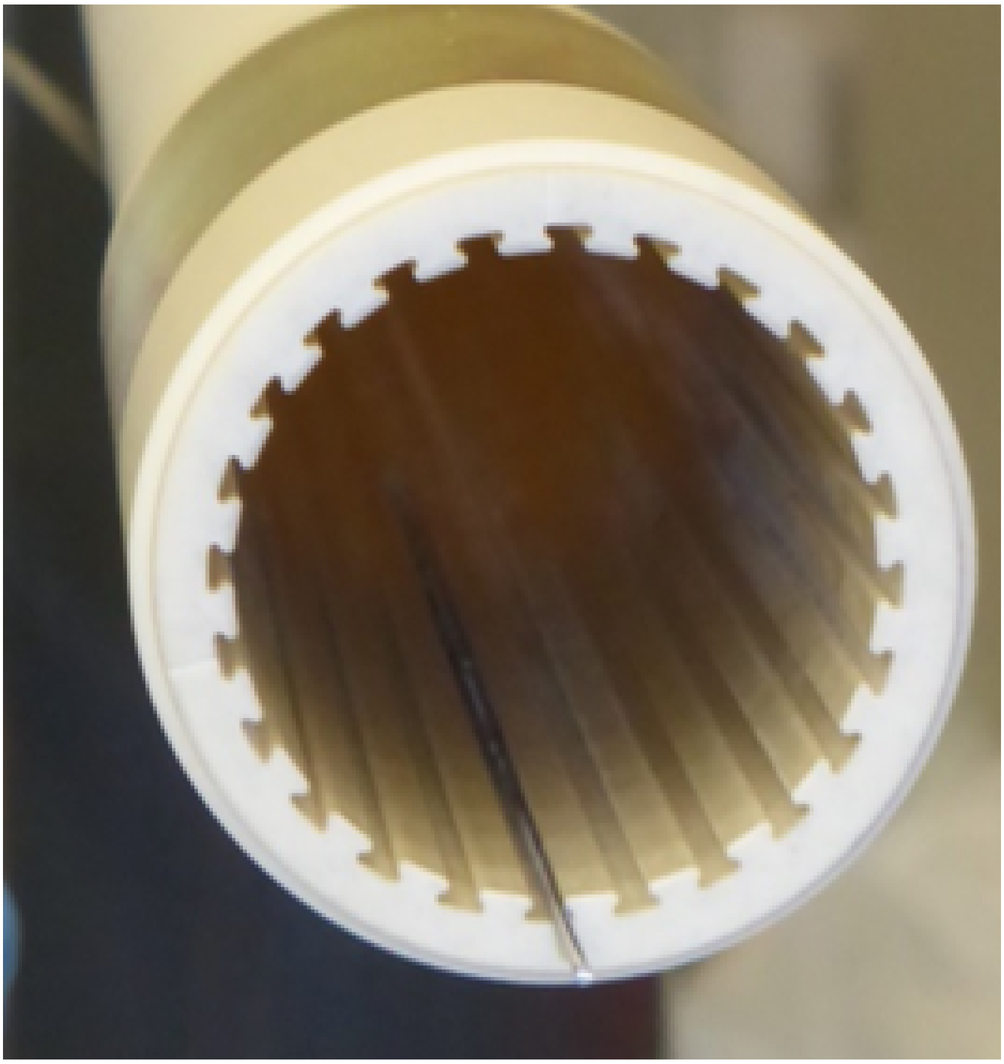

Figure 1: Picture of the alumina tube. The 24 slots in which the screening conductors are inserted are clearly visible. The wire used in conjunction with the "Magna-Mike 8600" to measure the thickness of the tube is also visible in one of the slot.

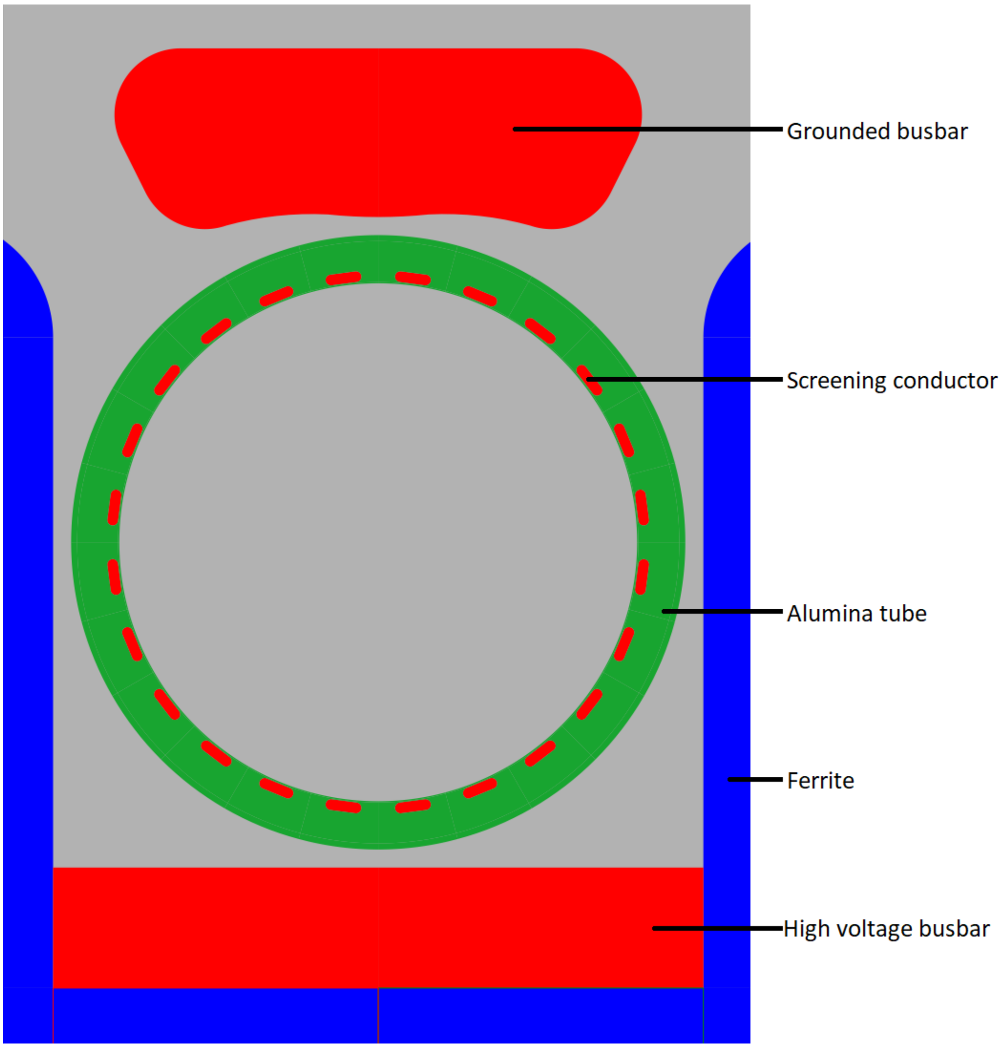

Figure 2: Screenshot of the Opera2D software showing the model of the MKI's aperture.

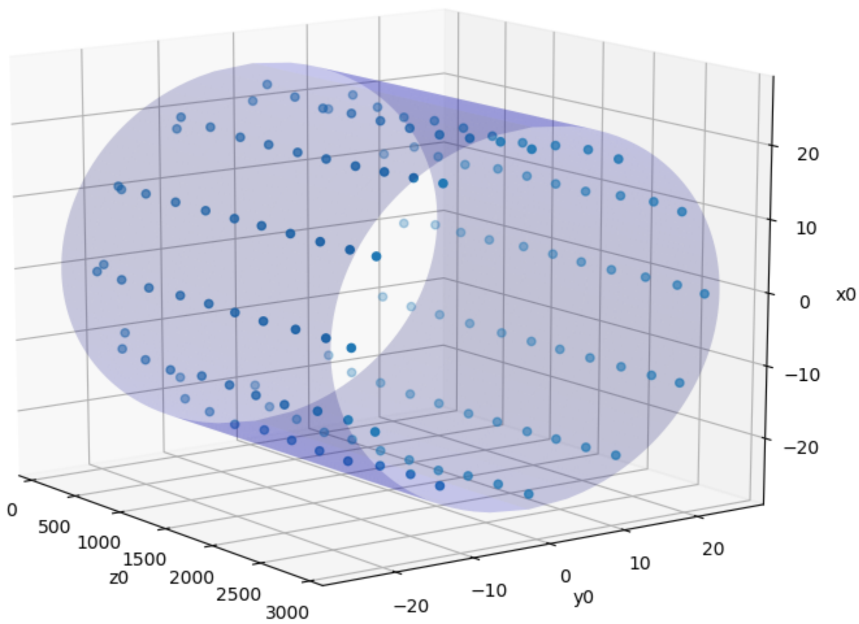

Figure 3: 3D representation of the LS1-2 tube. The thickness data is used to display the tube in 3D. The outer layer of the tube is represented by a transparent surface.

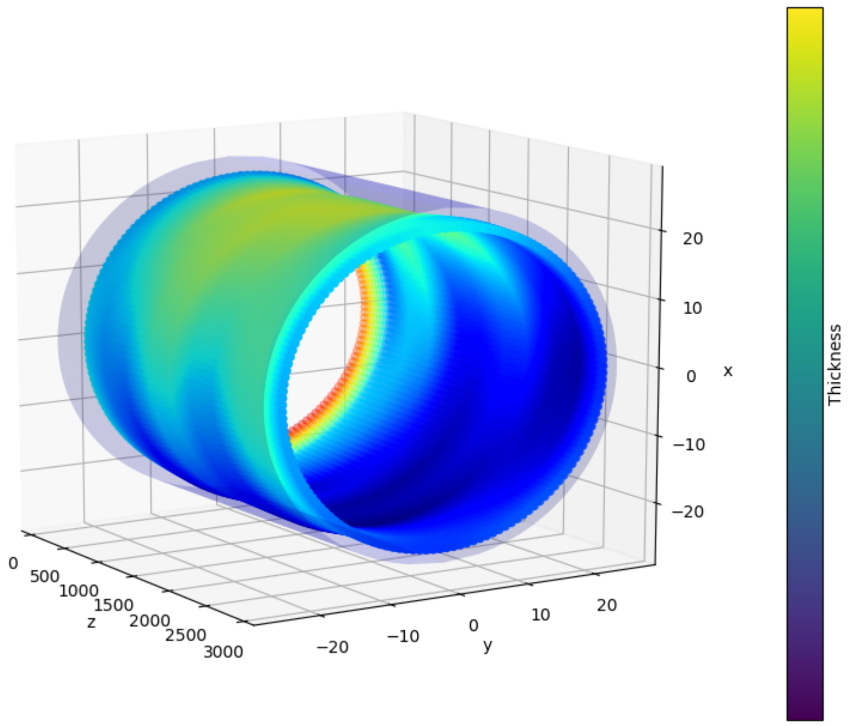

Figure 4: The data (from the LS1-2 tube) is interpolated longitudinally and around the z axis in order to obtain this representation. The colormap applied helps to show clearly the areas where the tube is the most thin.

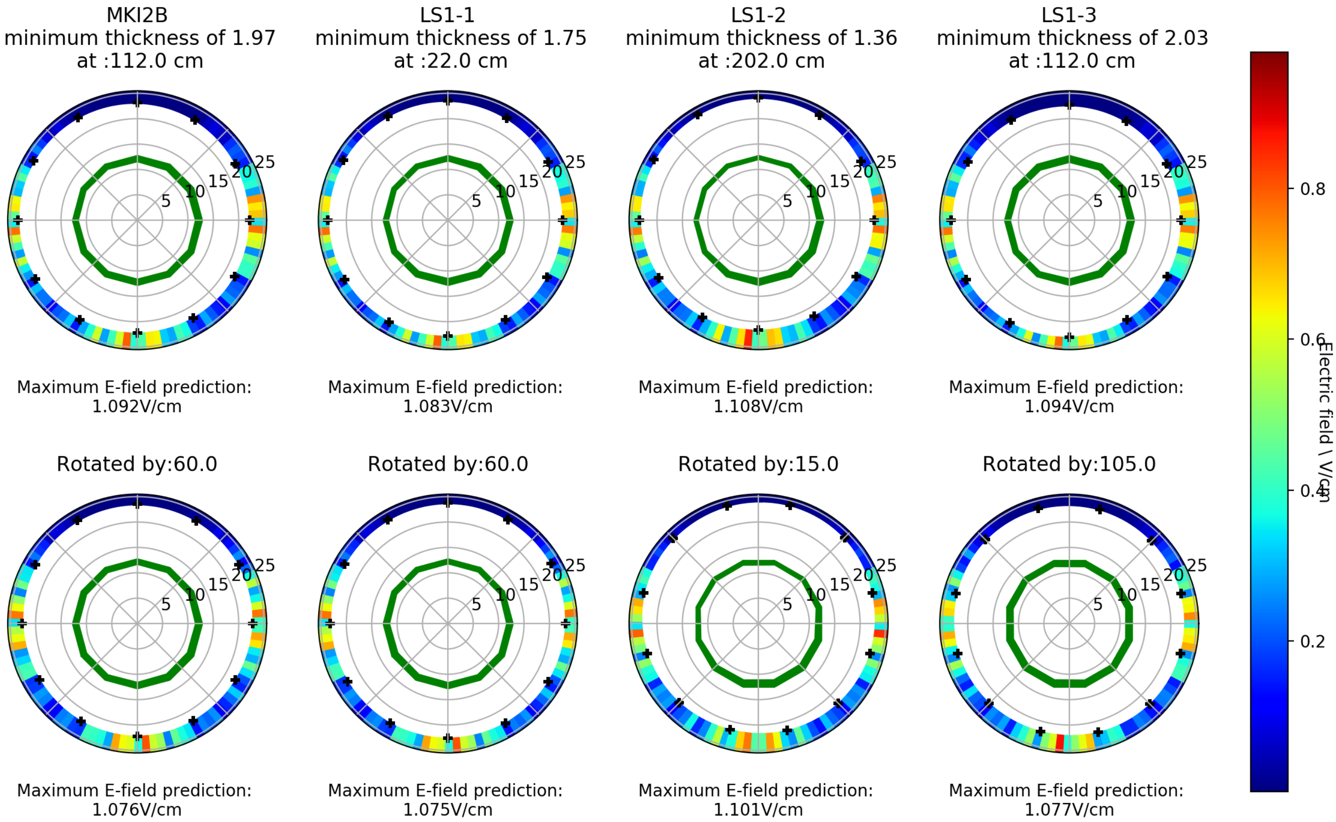

Figure 5: The discriminator output for the MKI2B,LS1-1,LS1-2 and LS1-3 tubes.. Each column corresponds to a different tube. The top row shows the orientation of the tube before optimisation (as chosen during Factory Acceptance Testing) and the bottom row shows the tube after optimisation. The rotation, to be applied clockwise, is shown as well as the maximum electric field expected within the tube. The cross section, at the length for which the minimum thickness has been measured, is shown in each case: in particular an interpolation of the tube thickness is shown with the black crosses representing the actual data (see section 2.1). The simulation data is also used to color the cross section plot with a color map that indicates the electric field close to the screening conductors at all angles. An inner green circle is displayed to represent the minimum thickness along the tube for all angles where thickness has been measured.

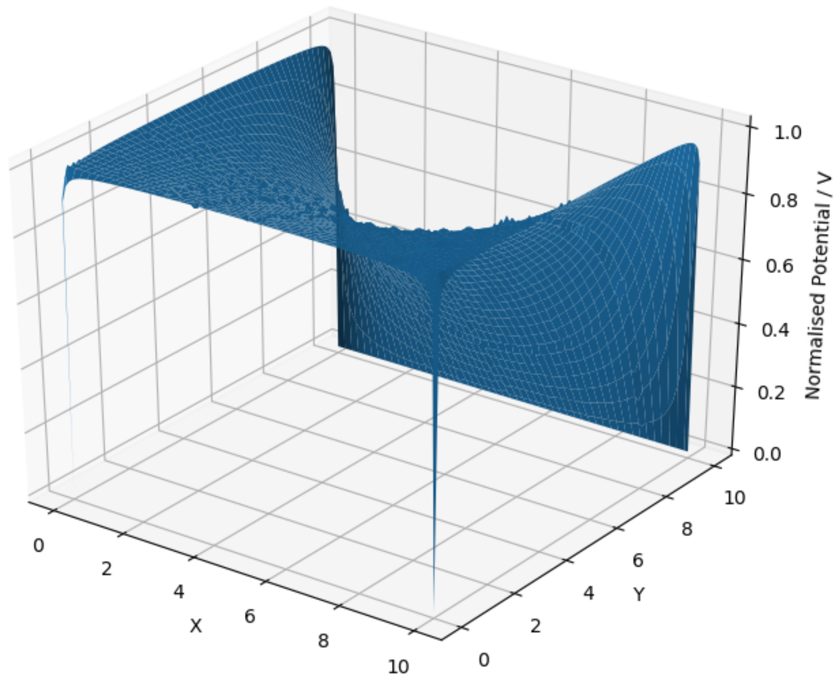

Figure 6: The analytical potential. The aperture is described by the x-y plane and the potential is plotted in the z direction. The Gibbs phenomenon can be observed (in particular at the corners) resulting in instabilities

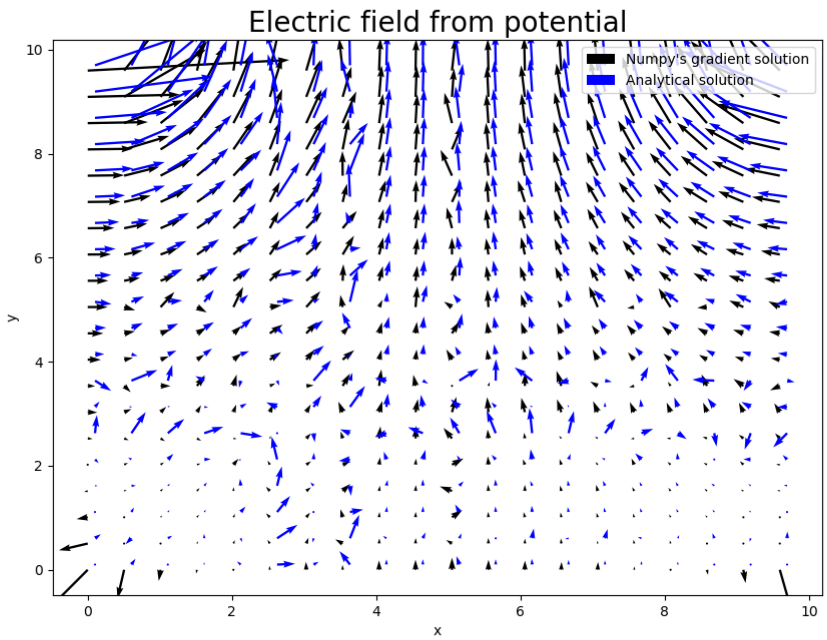

Figure 7: The analytical electric field in the aperture. The analytical electric field behaves oddly in some parts due to instabilities of the potential solution. However taking the numerical gradient results in a seemingly well behave electric field.

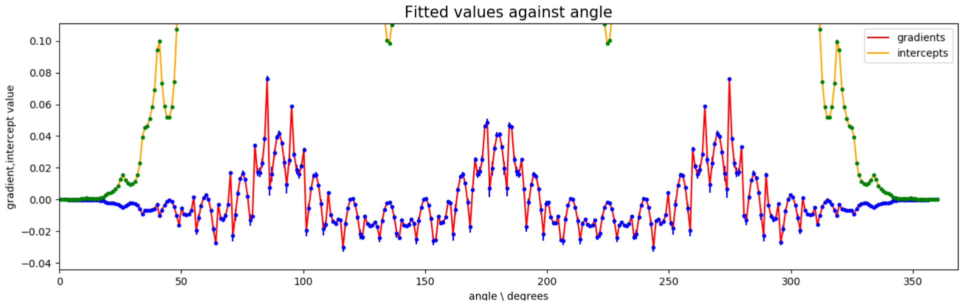

Figure 8: The first weighing function considered. A linear gradient and intercept are fitted for the electric field at each angle. The intercepts are not all shown to focus on the gradients. Some gradients have negative values due to the method used. (It corresponds to the angles in between screening conductors).

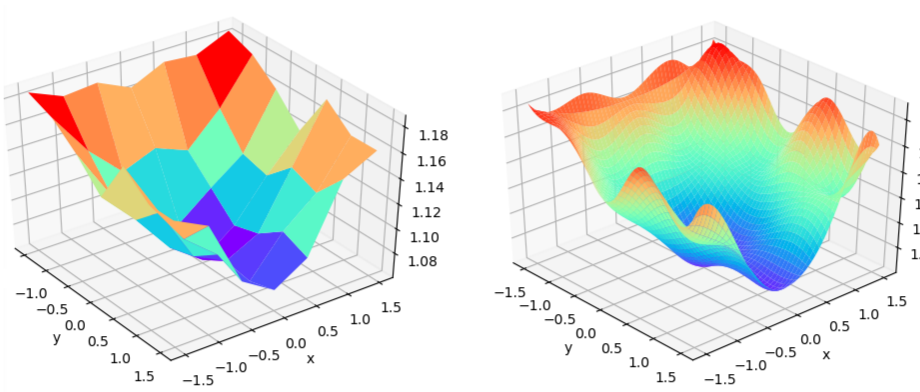

Figure 9: The second weighing function considered. The left graph shows to the data from the simulation and the right graph its cubic interpolation. The x and y coordinates represents the shifts of the screening conductors' effective center. The corresponding z coordinates represent the maximum electric field measured in the tube for that configuration. This is the weighting function chosen to be used in the optimisation process.

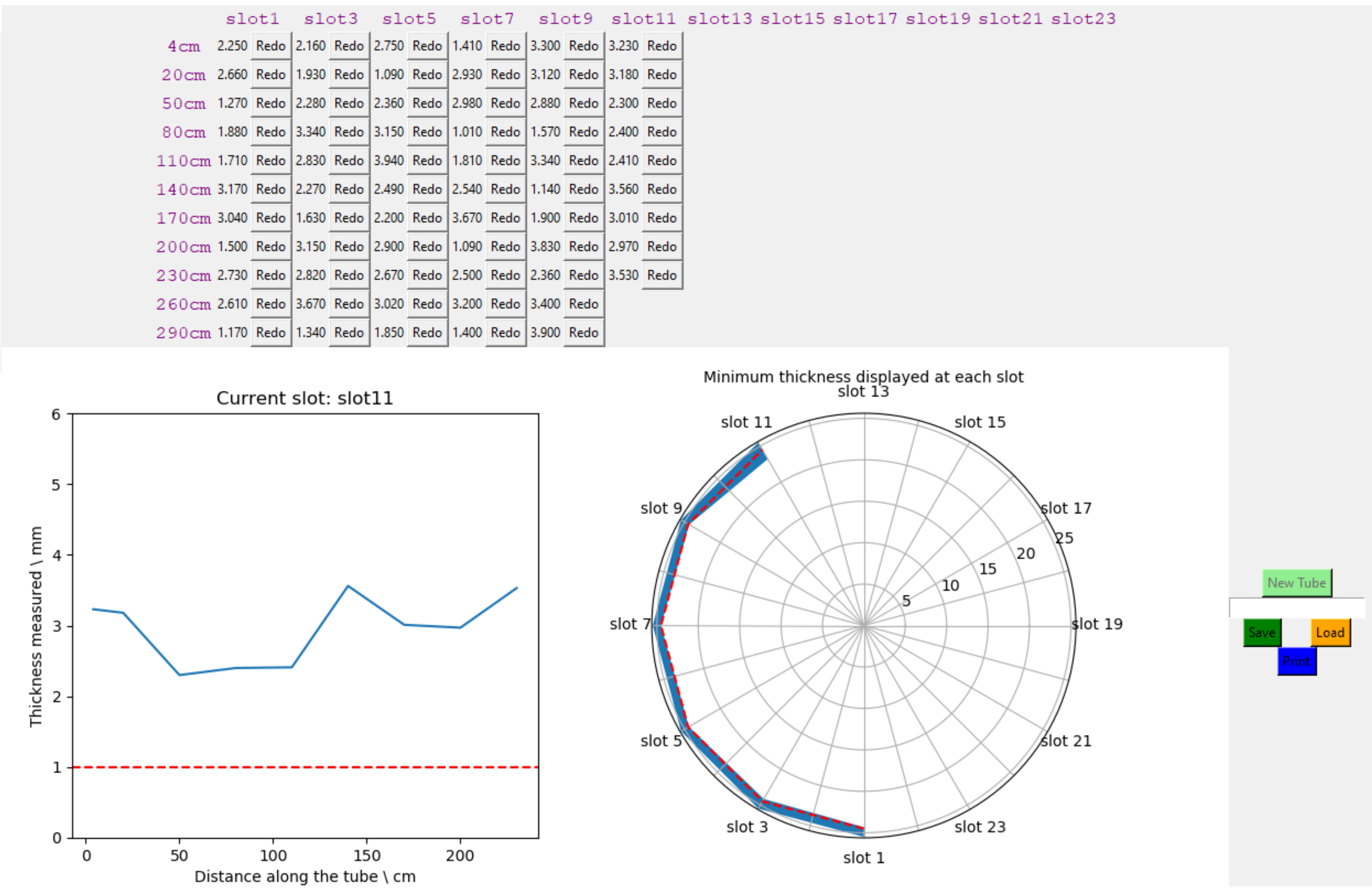

Figure 10: The main screen of the interface. The data is shown as a table where columns correspond to the slot number and rows correspond the length along the tube. Each point can be redone using the "Redo" buttons. Graphs are displayed showing the current state of the data stored. "Save","Load" and "New Tube" buttons are also implemented to make the usage of the software easier. (Fake random data is used in this screenshot)

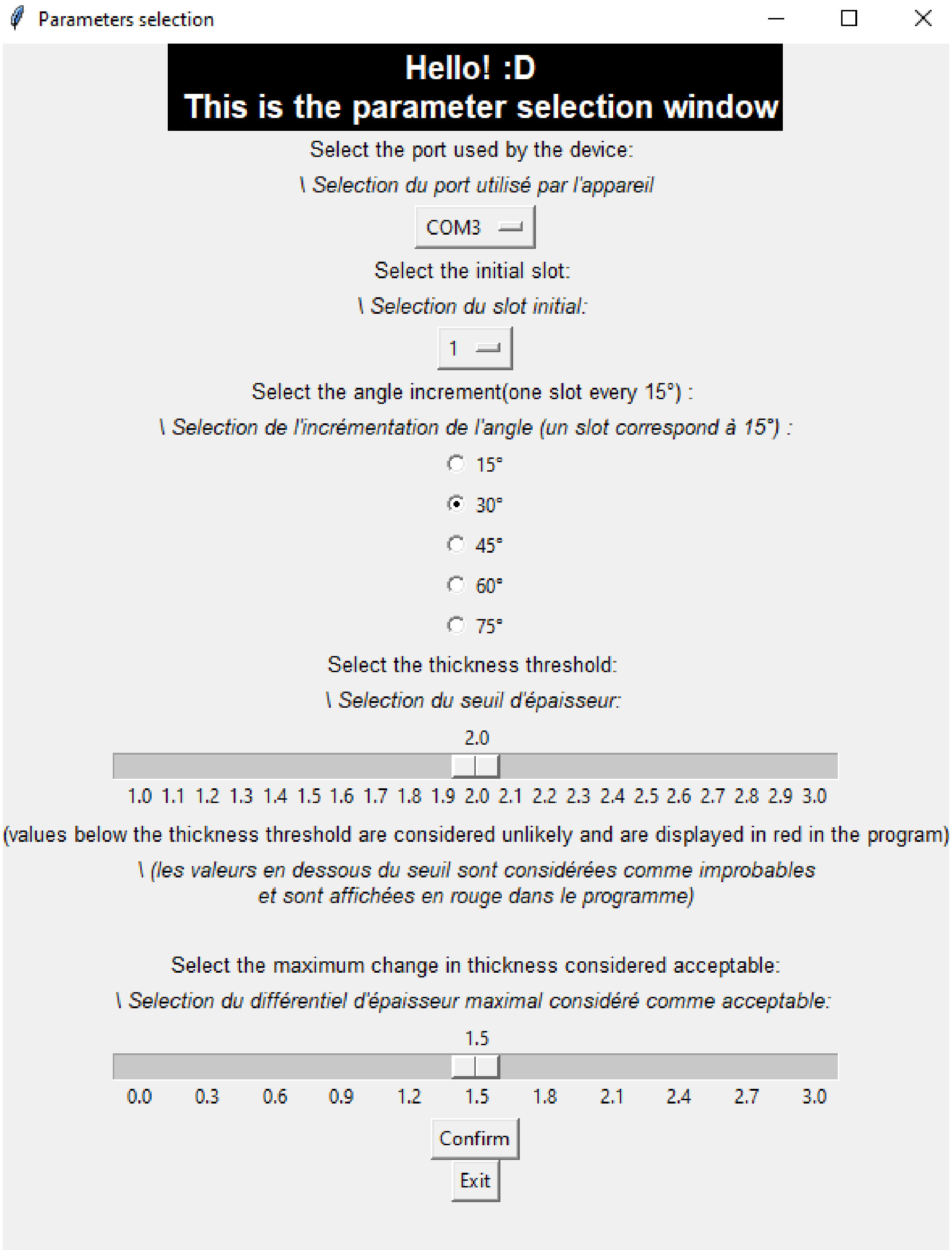

Figure 11: The parameter window of the interface. It opens first and prompts the user to obtain the parameters required to generate the other window amongst other things.

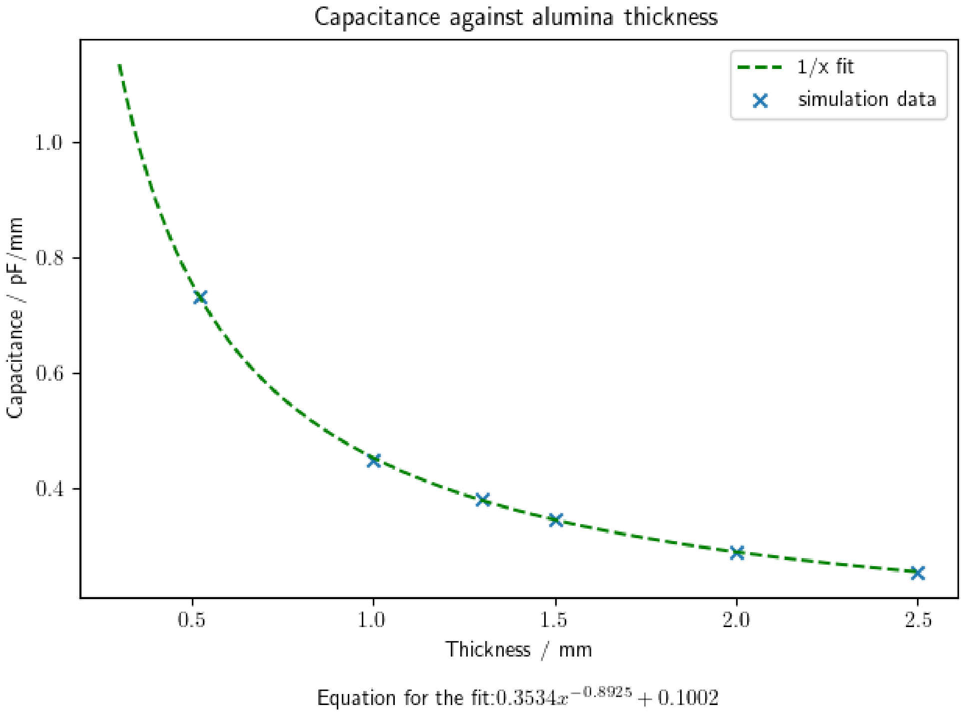

Figure 12: The simulated capacitance against alumina thickness is displayed with a fit.

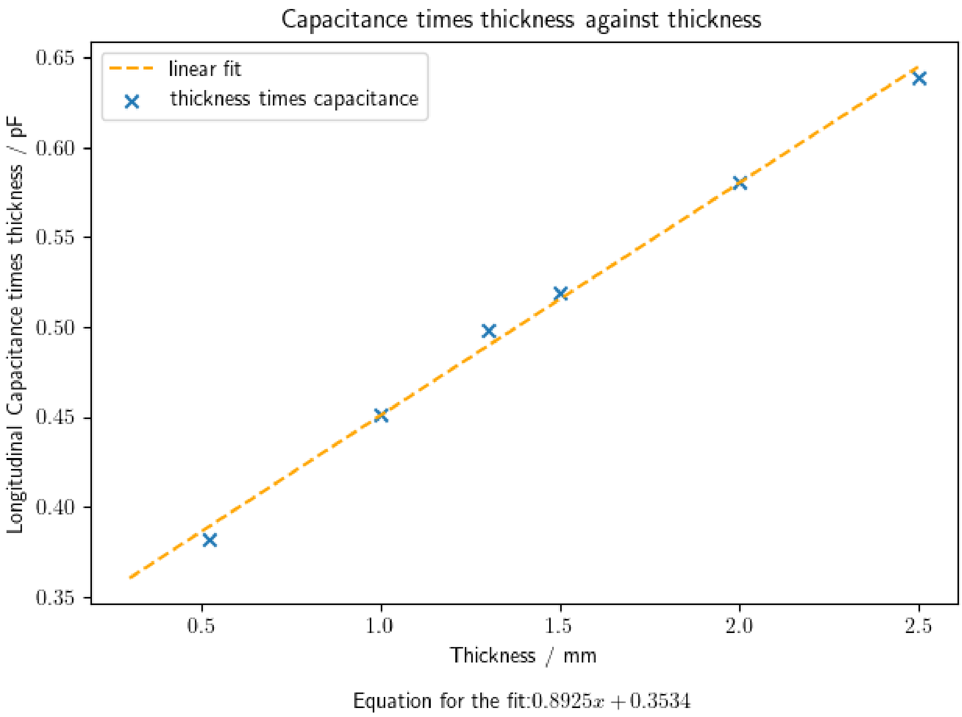

Figure 13: The capacitance values shown in Fig 12 are multiplied by thickness and a linear relation is obtained as expected.

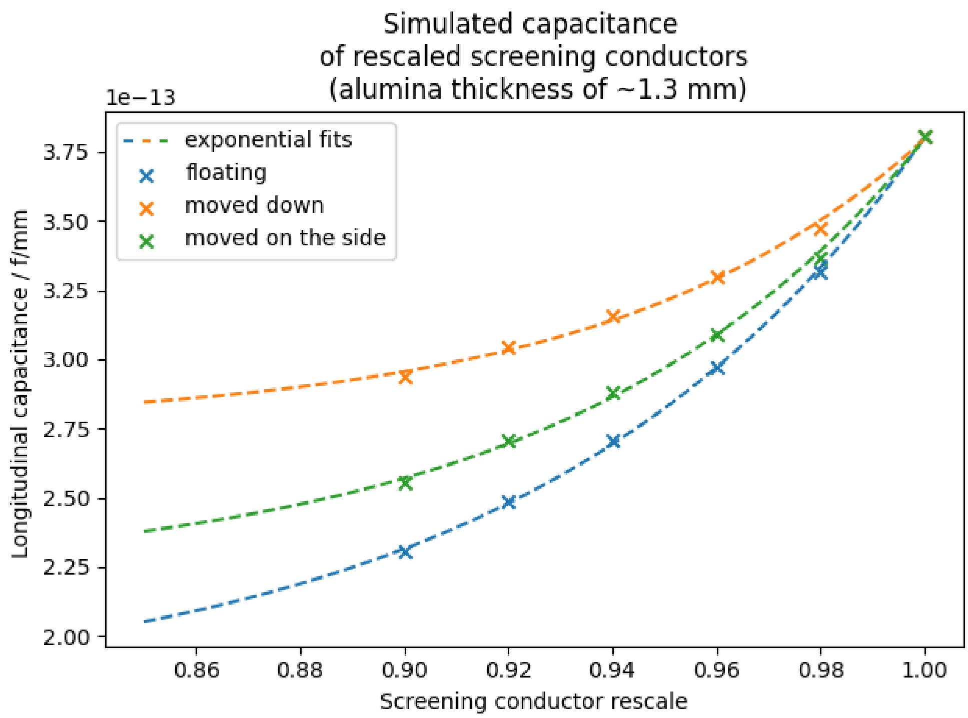

Figure 14: The capacitance is displayed as the screening conductors are rescaled by a factor. Three cases are studied: when the screening conductor "floats" in the slot, when the screening conductor is pushed on the side of the slot and when the screening conductor is pushed down in the slot. The first case can occur when the screening conductor is held in place, the second and third cases occur naturally due to gravity since the screening conductors do not fit the slot exactly. Exponential functions are fitted nicely to the data.