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Determining a more efficient stalk design for an IEC device using field and particle simulations

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Award date:
2018

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June 30, 2018

Abstract

Inertial electrostatic confinement (IEC) devices accelerate ions with static electric fields to fusion relevant energies. The fields are typically generated by spherical grid at negative potential which is suspended within a grounded vacuum vessel. However, the high voltage feedthrough (the stalk) connecting the cathode to an external power supply perturbs the field structure, leading to severe reduction in the number of fusion processes.

This thesis explores how the efficiency of the fusor (TU/e's IEC device) can be increased by optimising the stalk.

To this end, the fusor geometry is modelled in Comsol and the electric field is calculated for various stalk parameters: the thickness and materials of stalk insulators were varied, changes of the grid size were studied and a design using condensor bushing was implemented.

The performance is evaluated by using particle tracing simulations: particles are released uniformly at the edge of the fusor and the total number of passes through the central grid is calculated, particles colliding with the stalk are lost.

It is found that increasing the grid diameter has the biggest impact, increasing the number of passes by a factor of 17,1 compared to the current experimental design. The choice of insulating material has a negligible effect on the efficiency. The condenser bushing and the width of insulating material led to minimally increased and slightly decreased efficiency, respectively.

Contents

1 Introduction

When people think of nuclear fusion, they often envision large doughnut shaped machines that hold the promise of unlimited clean energy and perhaps rightly so. There is, however, a wide range of nuclear fusion technology that is less in the public eye but no less interesting.

One of these lesser known technologies is called Inertial Electrostatic Confinement or IEC. It is a technology that enables fusion reactions like its tokamak counterpart but has a practical utility that is very different from it.

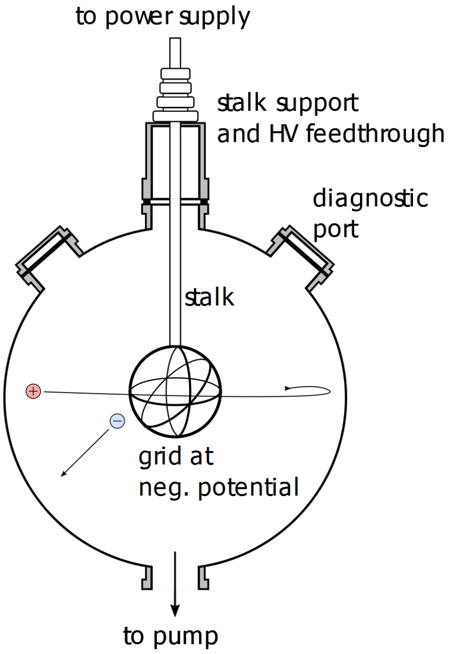

Figure 1: The basic function of an IEC device. Shown are the hull, the grid, the stalk and a particle that makes a trajectory (made by M.C.C. Messmer).

An IEC device in its simplest form consists of a combination of two concentric spheres that form a vacuum chamber and "the grid". This vacuum chamber is filled with a gas and kept at low pressure. The outer sphere is grounded while a large negative voltage is supplied to the grid via a high voltage feedthrough (commonly known as "the stalk"). This creates an electric field between the two spheres which causes ions to accelerate toward the inner sphere and collide with each other or the background gas to create fusion reactions.[1] This is also known as the Farnsworth IEC[2] and it is the one that will be discussed in this thesis for it is also the design used for the TU/e's IEC device (the fusor) see figure 1.

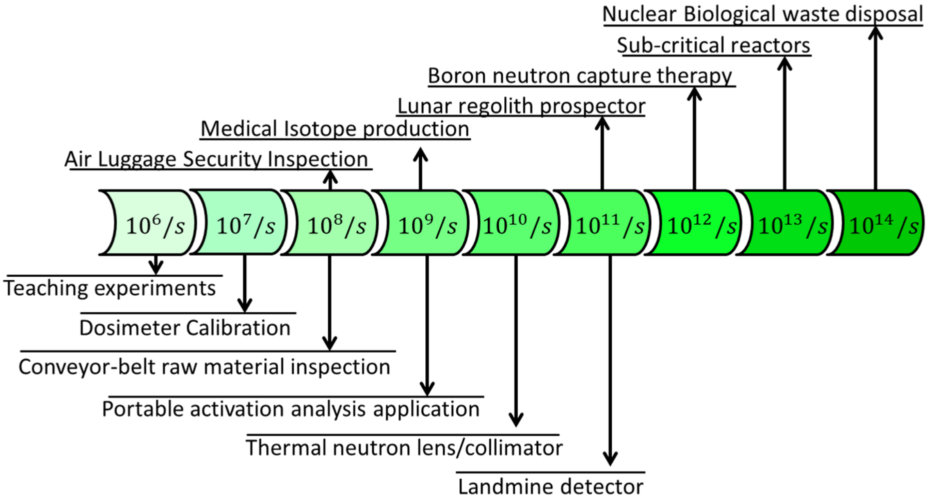

Figure 2: The number of possible uses of an IEC device increases with the number of fusion reactions per second.[1]

The efficiency of such a device is usually expressed as the 'rate of fusion reactions per second'.[3] Depending on the efficiency of an IEC device it can be used to: detect bombs in airports, create medical isotopes, dispose of nuclear waste and these are just a few of the applications.[3] It is worthwhile to investigate how to increase the efficiency of IEC devices as the range of possible applications in society increases with it, see figure 2.

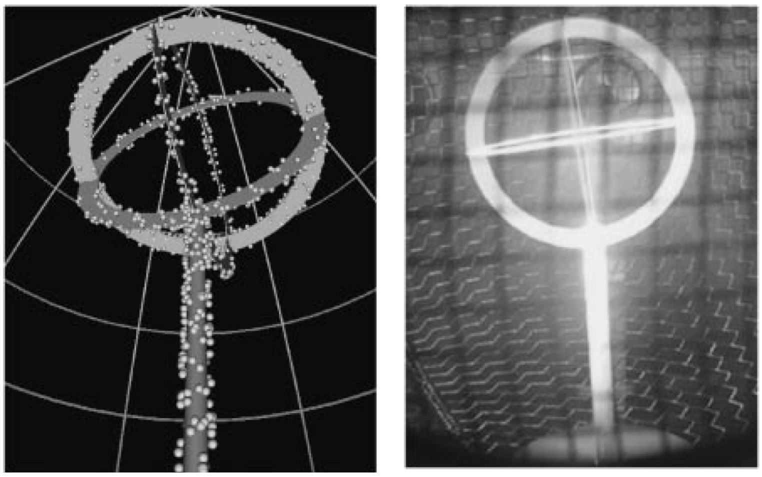

Figure 3: Image of ion bombardment on the cathode and the stalk.[4]

One of the biggest obstacles for increasing the efficiency is the high voltage stalk. The stalk is necessary to apply a voltage to the grid but in doing so it severely perturbs the electric field around it, introducing an asymmetry to the field. The perturbation of the field and the presence of the stalk causes a portion of the ions to accelerate towards the stalk and collide with it. Ions that collide with the stalk, see figure 3, can no longer cause fusion reactions. This phenomenon causes the efficiency to decrease. Prior research has shown that in current IEC devices more than 90 percent of ions pass the grid only two times before crashing into it or the stalk.[4]

In order to overcome this obstacle, the design of the high voltage stalk has to be examined and optimized. The stalk should be designed to minimize the field perturbation and simultaneously reduce the likelihood of ions colliding with it. It follows that the question this thesis seeks to answer is: How can the efficiency of the fusor (TU/e's IEC device) be increased by optimizing the high voltage stalk? As it would be very cost intensive to build and test every design, simulation software will be used to assess its effect on the efficiency.

To address this question properly the thesis will be outlined as follows. First there will be a discussion on several stalk designs and the most promising ones will be selected. Secondly there will be a brief explanation of the simulations used will be given along with some comments about their validity. Thirdly, all the results of the simulations will be given, compared and explained. Then there is a discussion on that validity of these results and their meaning and finally the conclusion.

2 Stalk Design

The introduction briefly touched upon the basic design and function of an IEC device. This chapter will take a closer look at the high voltage stalk in particular. Several stalk designs and their design parameters will be elaborated and their feasibility will be discussed. At the end of the chapter, a selection of the most promising designs and design parameters for optimization will be made.

There is a variety of stalk designs already tested by various groups throughout the world. A few that are relevant are those of: Institute of Advanced Energy (Kyoto University), Idaho National Environmental Laboratory, University of Illinois at Urbana–Champaign and the University of Wisconsin,[2] Technical University of Eindhoven.

The stalk design used at TU/e (see figure 4) is fairly simple but has some interesting design parameters which could be optimized. The stalk consists of three parts. An aluminium conducting cylinder is fed through the inlet and reaches to just above the grid. It is this cylinder that carries the voltage to the grid. The cylinder is coated with a layer of glass which serves as a dielectric. The last part of the design is a mechanism which allows a certain translation of the grid in the direction of the stalk. There are two thin rods, one is attached to the top of the cylinder. The other one is attached with a little spring to the first rod and with the other end to the grid. The spring allows the user to place the second rod with the grid to be placed higher or lower. These rods do not carry any electricity and are used only for the translation of the grid.

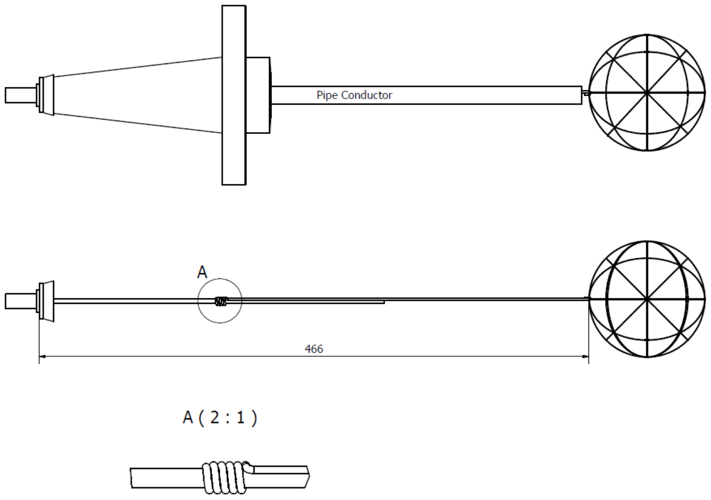

Figure 4: Schematic drawing of the current stalk used by TU/e, showing the stalk, the inlet and the grid (made by H.M. De Jong).

One of the design parameters that seems promising is the grid size. If the grid were to become larger, and the stalk consequently shorter, it could increase the homogeneity of the field and decrease the surface area of the stalk that particles could collide with.

The University of Wisconsin has a stalk design (see figure 5)that features layers of insulating material around a cylindrical conductor.[2] In this design quartz and alumina were used as insulating materials. The insulators were layered around the cylindrical conductor causing the stalk to be wider. This is likely because the dielectric materials reduce the field strength (otherwise known as electric stress) which reduces the chance of electric breakdown. The fusor does not have this as at the voltages being used, arcing is not yet a problem.

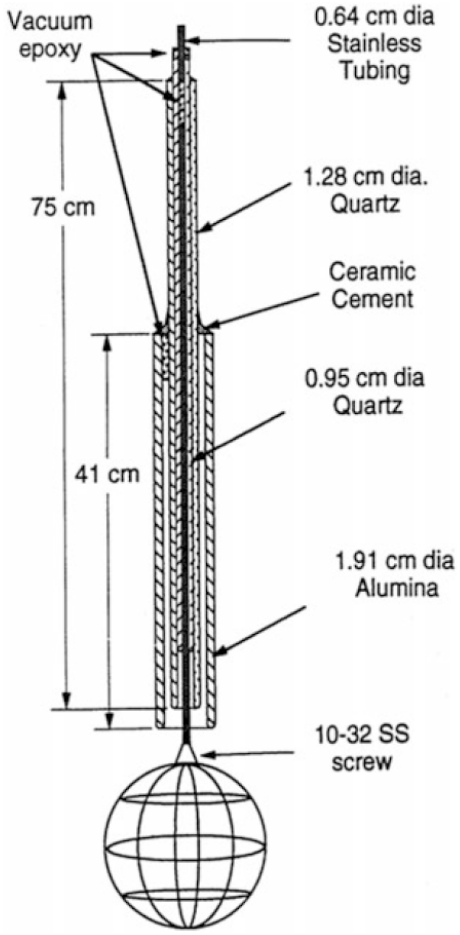

Figure 5: Stalk design of the University of Wisconsin featuring a conductive stalk layered with insulating material supporting the grid.[2]

The design parameters taken from this design will be the width of the insulating material and the choice of insulating material.

The design used by the Kyoto is particularly interesting as it does not use any form of insulating material around its stalk. They claim this minimizes the perturbation of the electric fields.[2],[4] This seems counter intuitive but can be explained from theory.

Function of the dielectric

When introducing a dielectric material in a capacitor, the electric field has to be calculated differently. This is because the relative permittivity (dielectric constant) of the dielectric material is different. Also, the dielectric material introduces a surface charge on both sides, this surface charge has to be taken into account when applying gauss's law. That is why gauss's law is modified for dielectrics, as can be seen below.

$$\oint K\vec{E} \cdot d\vec{A} = \frac{Q_{encl-free}}{\varepsilon_0}$$

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In figure 6 Is shown how the electric field changes by introducing a capacitor. The field between the condenser plates polarises the molecules inducing surface charges on both sides on the dielectric. These surface charges create their own field which is in the opposite direction. Adding these fields gives the resulting field which is weaker. Because of this the chance of breakthrough is diminished.[5]

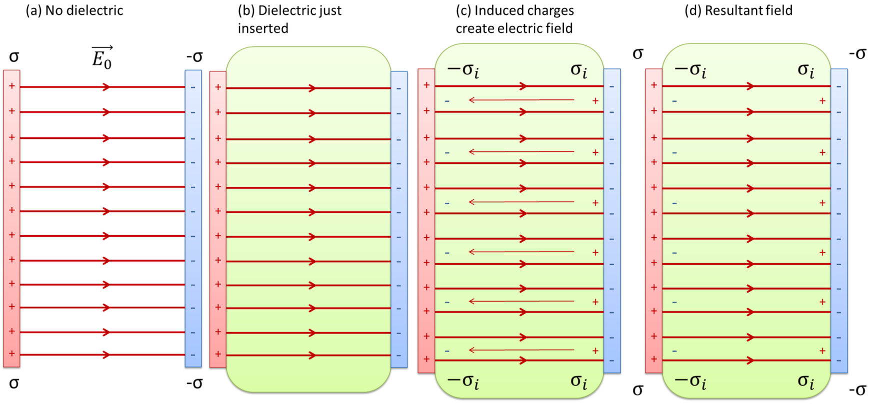

Figure 6: two capacitor with and without a dielectric. The figure shows how the field is altered by introducing the dielectric[5]

If the goal is to minimize the effect of the stalk on the electric field in an IEC device, a fast falloff of the potential is desired. The drop-off is correlated directly with the dielectric constant of the medium.[6] The closer the dielectric constant is to 0 the less the field and its symmetry will be disturbed. There are, however, no materials that have a dielectric constant lower than 1(the dielectric constant of a vacuum). This leads to the conclusion that for maximum drop-off air would actually be better than any kind of insulating material. This is the design parameter taken from this design: air for insulating material.

Another interesting suggestion from theory[2] is the implementation of a condenser bushing in an IEC device. A condenser bushing is a construction that aims to space the electric field lines more gradually (figure 7). To attain this goal, the stalk has a thin layer of insulation around its charge carrying wire that is in turn layered with floating potential screens. These screens make sure the field lines emerging from the condenser bushing are more evenly spaced.[6]

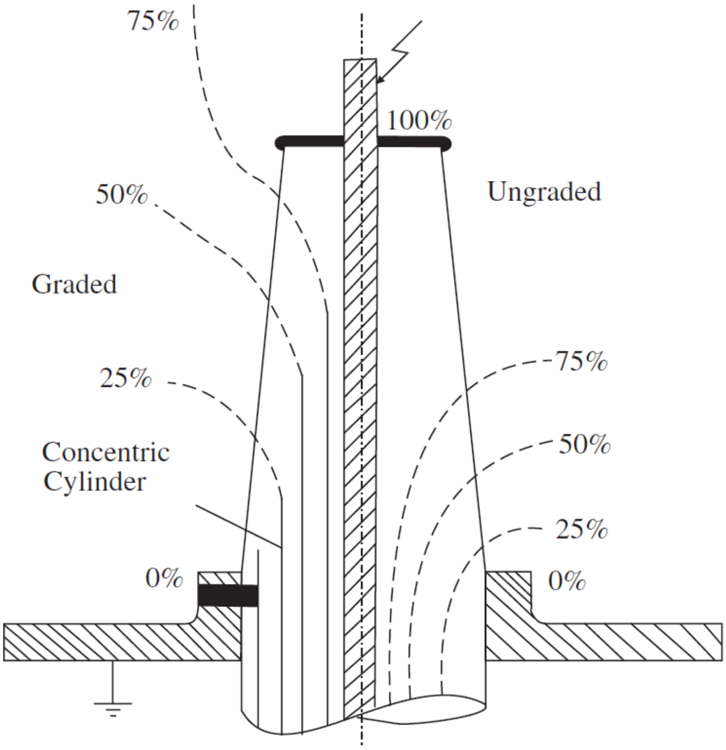

Figure 7: A schemetic drawing of a condenser bushing showing the potential lines for both a graded and non graded bushing .[6]

Considering the designs and design parameters explained in this chapter, this thesis will evaluate the design parameters that show promise: type of material used for insulation, the width of the insulating material, the grid diameter and the implementation of a condenser bushing.

3 Methods

This chapter will explain how the chosen designs and design parameters will be evaluated using finite element simulation software called COMSOL.

The chapter will describe the properties of the fusor geometry that will be used for the animations. Then it will elaborate on the field and particle simulations and finally there will discuss the validity of the simulation methods used.

3.1 fusor model geometry

The design of the fusor will be discussed as well as how this design will be implemented into the simulations. The different designs and design parameters that will be tested will be evaluated.

Then the simulations themselves will be discussed. A closer look will be taken at Insert expl

Two designs are going to be simulated. The current fusor design and the condenser bushing design. These designs will be explained below, starting with the current fusor design.

One of the main questions this thesis tries to answer is how to get a higher efficiency using the fusor with its current design. To be able to find an answer to this question a closer look has to be taken at the current design of the fusor.

3.1.1 Current fusor design

In order to do a worthwhile simulation of a high voltage stalk for an IEC device, the geometry in which this stalk will be placed should be well defined and relevant.

It would go beyond the scope of this thesis to outline all the design aspects of the fusor in great detail. Instead its most important design aspects will be discussed. There are certain design aspects that are not relevant to the simulation, these will be left out of the geometry.

The fusor is an IEC device that consists of two concentric spheres. The outer sphere will henceforward be referred to as "the hull" and the inner sphere as "the grid".

Attached to the grid is the high voltage stalk, which enters the hull through the port in the hull which will be called "the inlet"(see figure 8).

This particular stalk is also the stalk that is now implemented in the fusor. It consists of a hollow cylinder made out of aluminium which is encapsulated by a layer of glass.

The stalk carries the high voltage from the power supply to the grid. Because the hull is grounded and the grid carries a large voltage, a strong electric field emerges between the two.

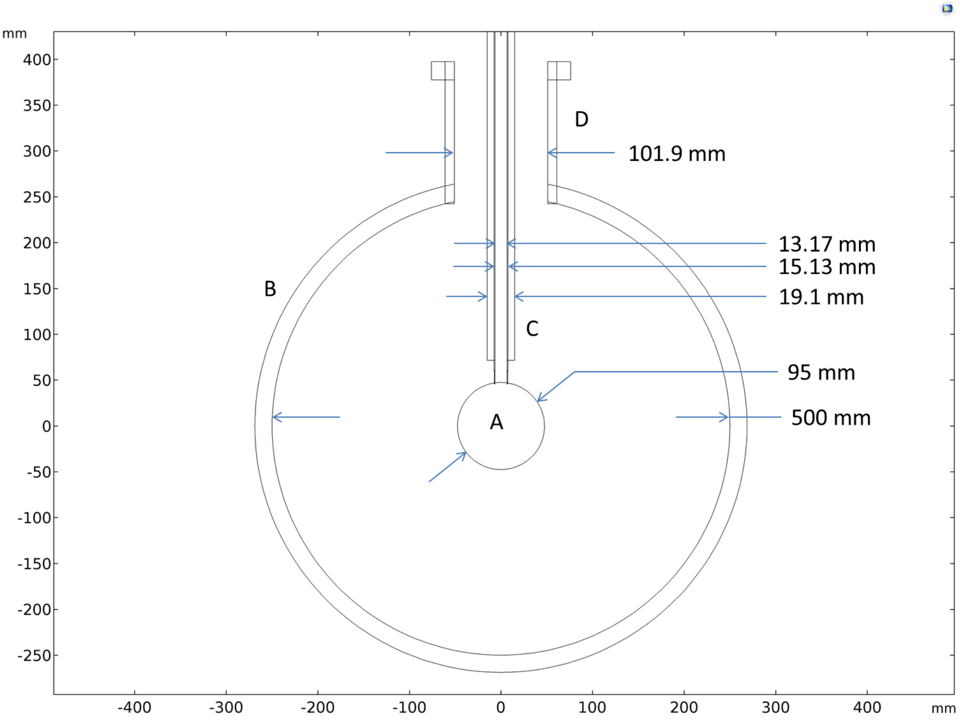

Figure 8: The simple stalk design fusor geometry as used in the simulations. A: the grid, B: the hull, C: the stalk, D: the inlet.

In order to make this design more efficient several of its design parameters will be tested.

The grid diameter To clearly see the effect of the increased grid diameter three different diameters will be simulated: the current diameter, twice the current diameter and four times the current diameter.

The width of insulating material This parameter will be tested for 3 different widths. The largest width is exactly the width needed to fill the entire inlet as shown in figure 10. The original width and the one just in-between those two will also be simulated.

The choice of material for the insulating layer Three materials are selected that are most relevant for the fusor. They are selected to be able to withstand the extreme conditions within the fusor and because they feature in other literature. The materials chosen are: glass, alumina and air.

3.1.2 Condenser Bushing Designs

Condenser bushings are used in high voltage technology to manage the electric field. A condenser bushing is an encapsulation of insulating material which goes around a high voltage carrying wire. The encapsulation is layered with floating potential screens. These screens alter the profile of the electric field lines and cause a more well-distributed potential gradient and a more uniform field distribution within the dielectric.[6] The condenser bushing design is quite similar to the current fusor design shown in figure 9.

As can be seen in figure 7 the condenser bushing spaces out the field lines more evenly, this could potentially be very useful as the field lines would behave more like the ideal case without the stalk. Also it could reduce the chance of breakdown as the dielectric with the floating screens decrease the electric stress.[6]

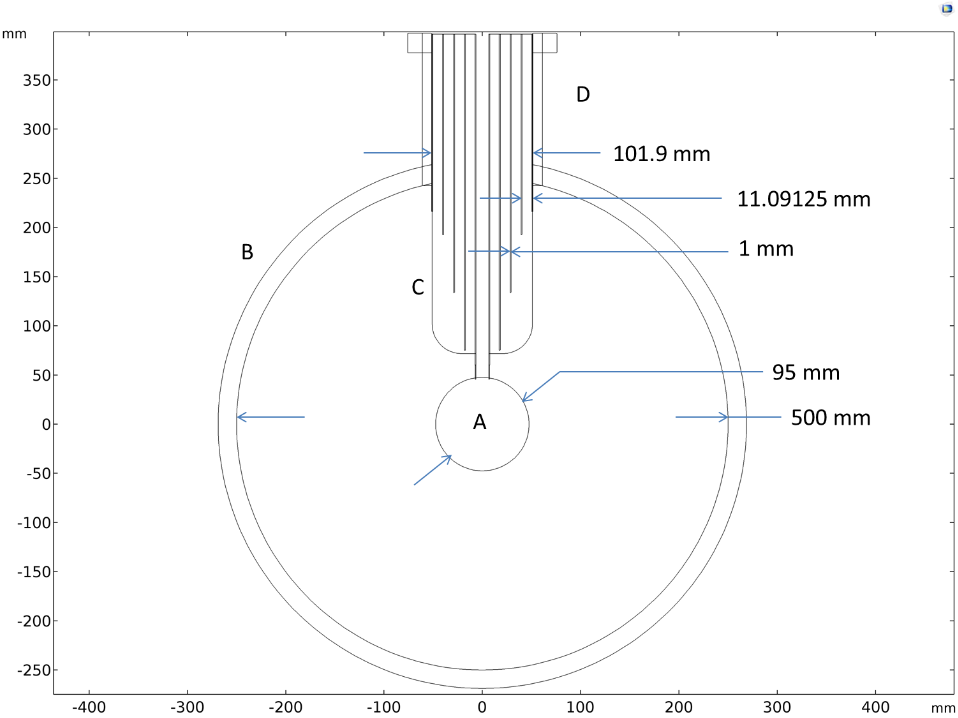

Figure 9: The condenser bushing design as used in the simulations. A: the grid, B: the hull, C: the stalk, D: the inlet.

The Condenser bushing design is implemented into the current fusor geometry. All the parameters are kept the same except the stalk. In the middle is still the same conducting cylinder. It is encapsulated by a very thick layer of glass. In the glass there a floating potential screens. These are layers of conducting material (aluminium in this case).

3.2 Simulations

Using computer simulations the potential in the fusor geometry can be simulated. Then charged particles can be loaded into the geomtry. They will be affected by the before calculated potential. They will accelarate gaining electric energy and making a certain trajectory through the geometry which can also be calaculated. Using all this data a measure of efficiency will be determined and used to evaluate all the different fusor designs and design parameters.

The simulations have to evaluate how well the different designs and design parameters work. In order to quantitatively state the performance of every design or design parameter, a single optimizable variable should be formulated. This variable will be called the efficiency and will be defined as described below.

In the simulation 100 particles will be initialized with 0 velocity on a circle close to the hull and a uniform spacing. The electric field in the system is calculated beforehand and is subsequently used to calculate the force exerted on the particles. Because of this force the particles will then accelerate inward and either pass through the grid or crash against the stalk and will be lost. The total number of passes made by all the particles will be the single optimizable variable and will be referred to as the efficiency.

Simulating and calculating the efficiency for each design and design parameter will give a quantitative verdict on their performance.

3.2.1 Electric field simulation

For the electric field simulations the "COMSOL AC/DC MODULE" will be used. This module uses Gauss's Law to solve for the electric field using the scalar electric potential as dependant variable.

$$\oint \overrightarrow{E} \cdot d\overrightarrow{A} = \frac{Q_{encl}}{\varepsilon_0}$$

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The electric field simulation is very important. It calculates the profile of the electric field throughout the entire fusor. This field will later be used to calculate the particle trajectories.

The electric field simulation will be done in 2 dimensions. There will be -60 kV applied to the grid and to the stalk. The hull will be grounded at 0 V. The material of both the grid and the hull are set to aluminum.

3.2.2 Particle simulation

For the particle simulations the "COMSOL Particle Tracing Module" will be used. This module allows for particle tracing in fluids, electric fields, magnetic fields and more.

To find the efficiency, the number of passes that all the particles make through the grid should be simulated. This is only possible by calculating all the particle trajectories.

The way that the module solves for the particle trajectories is as follows: The two components of the position vector of each particle is solved using newtons second law.

$$\overrightarrow{F} = m * \frac{d\overrightarrow{v}}{dt}$$

5

One for the x component and one for the y component of its position. The differential equations are solved iteratively, in time steps. At each iteration, the forces that act upon the particle are taken into the solving process. These forces are obtained by looking at the electric fields that were simulated earlier.

The particle simulations are very important as they help simulate and calculate the efficiency. As described above 100 particles released and accelerated using the information provided by the electric field simulation. When a particle passes through the grid it is unhindered as the grid does not have a collision condition. When a particle hits the stalk however it "crashes" and is removed from the simulation. The oscillation time of one particle, taken from one of the simulations, is about 0.3 microseconds. The simulation is run for 7 microseconds with time steps of 0.7 nanoseconds. The timesteps were chosen to be as small as possible as the contributes to the accuracy of the simulations. See appendix for validation. The simulation is done in 2 dimensions.

To determine the number of passes that each individual particle makes through the grid the derivative with respect to time of the kinetic energy of the particles is exported into matlab. It turns out that a pass through the grid gives a very distinct pattern in the derivative of the kinetic energy as can be seen in figure 10. One pass through the grid is characterized by a sharp peak up, then a flat line at zero and finally a sharp peak down. These peaks are exactly what would be expected from theory. When the particles are released from the hull they accelerate thus increasing their kinetic energy. When they enter the grid they are suddenly not being accelerated because there is no electric field inside the grid. This explains the first peak and its sudden drop to 0. The whole time the particle is moving through the grid, the derivative of its kinetic energy is 0 as it is not being accelerated. Then when the particle leaves the grid there is another peak because it is suddenly decelerated. This is why the peak is negative.

Using an algorithm that recognizes this pattern, the number of passes that each particle makes through the grid is computed. From this the total amount of passes through the grid can be computed which will serve as a measure for the efficiency of the fusor.

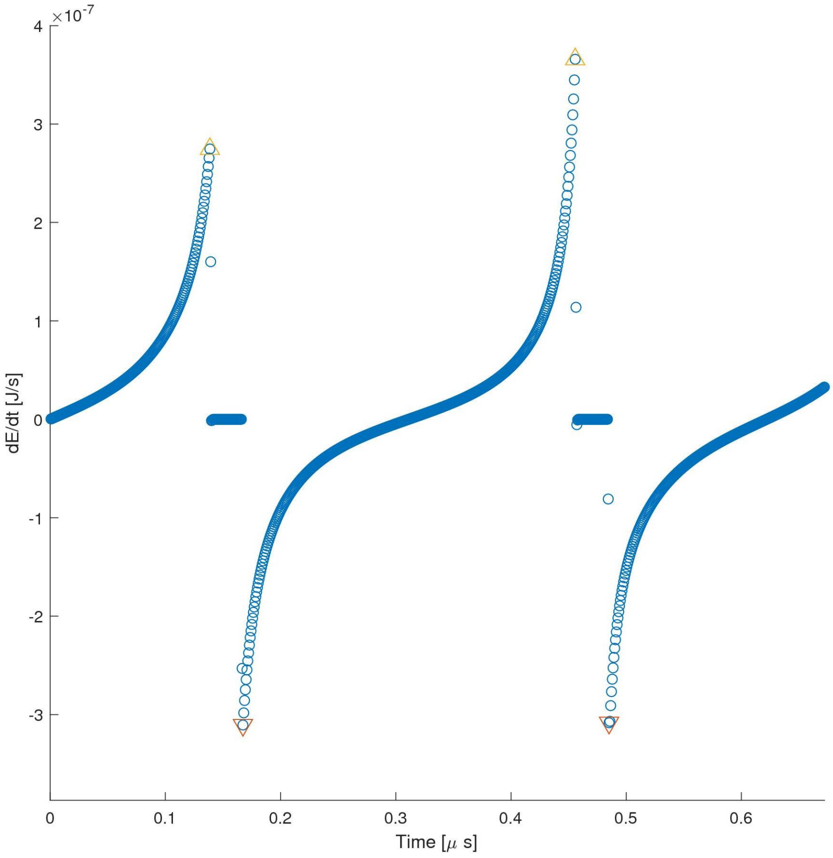


Figure 10: Derivative of kinetic energy over time, shown for a single particle. A pattern can be seen in the graph as well as marked maxima and minima.

3.3 Validation of FEM methods

An integral part of research involving computer simulations is the assessing the validity of these simulations. In the appendix there will be a section which addresses the validity of the simulations used making use of theory examples.

4 Analysis of the stalk designs

Using the methods described in the previous sections, the different stalk designs are simulated and performance indicators analysed.

4.1 Current fusor design

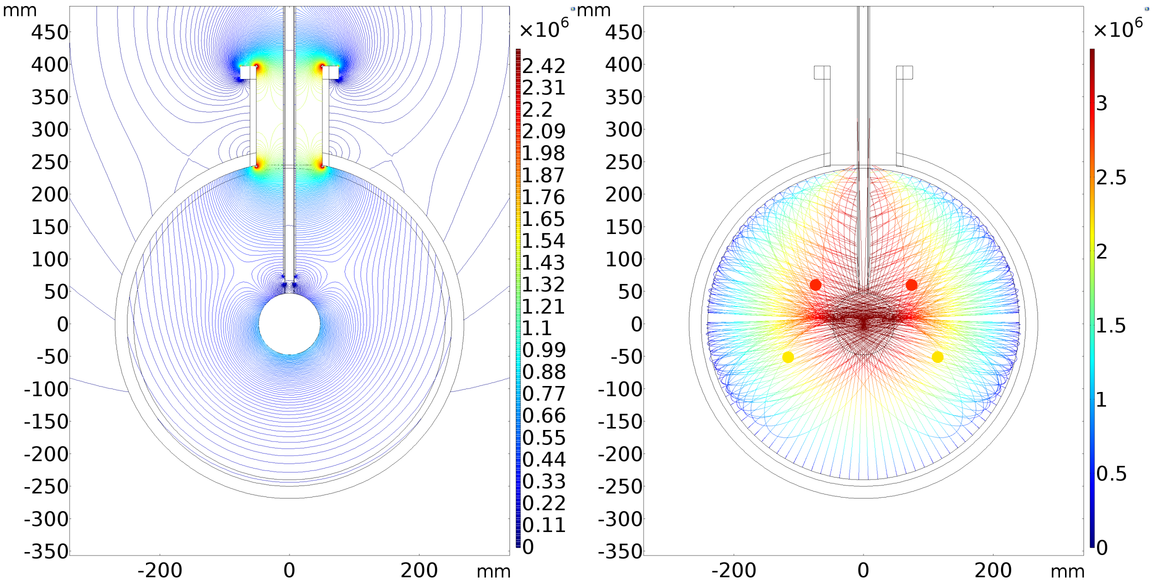
4.1.1 Effects of the insulator material on the field homogenity

In the afore mentioned current stalk design there is a thin layer of insulating material on the outside of the conducting part of the stalk. In this simulation the material paramater was tested. The simple stalk design was implemented inside the fusor geometry. The thin layer was set to be several different materials to test their effect on the efficiency of the fusor.The materials simulated here are: glass (current stalk), alumina and air. These simulations were done with an insulating layer width of 1.985 mm.

As described in section 3.2, the performance of the different materials will be analysed by evaluating the number of grid passes of the test particles released at the hull.

The electric field lines are shown for the simulations with glass insulators and the corresponding particle trajectories in figure 11 (a) and (b), respectively.

Figure 11 (a) below depicts the electric equipotential lines for a glass insulating layer of 1 mm. Figure 11 (b) next to it depicts the resulting particle trajectories for the same choice of material.



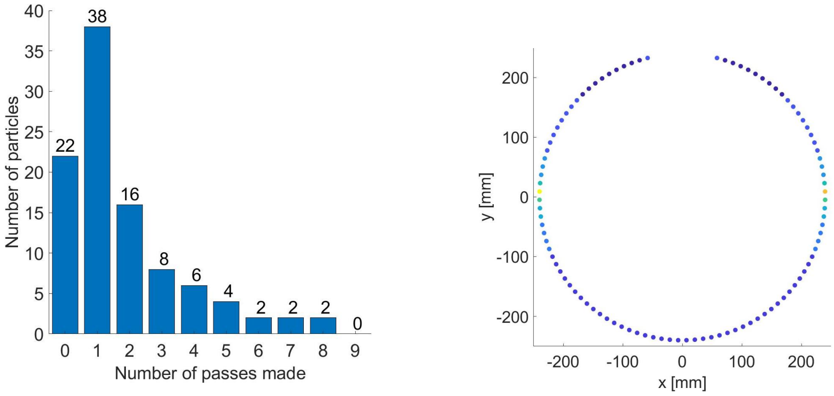
(a) Equipotential lines

(b) Particle trajectory lines

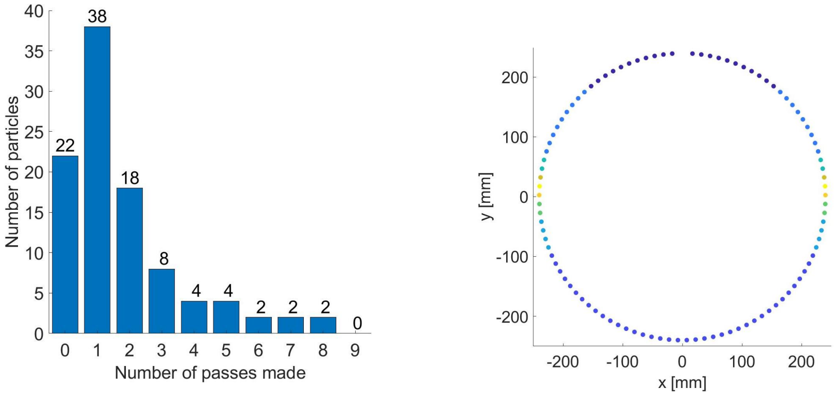
Figure 11: (a)Equipotential lines, glass stalk width 19.1 mm (b) Particle trajectories, glass stalk width 19.1 mm.

Figure 12 gives a measure for the efficiency of the fusor. They can be read as follows. The figure on the left is a histogram. It indicates how many particles made 0 passes through the grid, 1 pass, 2 passes, 3 passes.. etc.... The figure on the right show the initial position of the particles, the position from which the particles were released into the simulation. Each dot represents a particle and they are color coded for the numbers of passes they made.

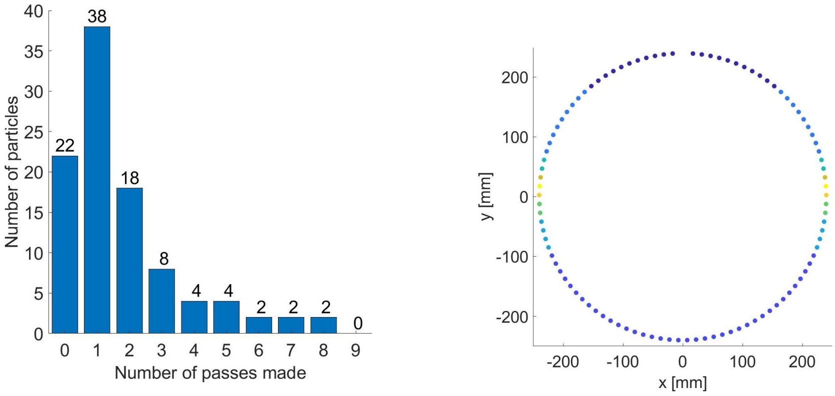
A number of interesting observations can be made when analysing the results. It is clear from the three histograms that each material has the same efficiency. The initial position graph shows that the particles released near the top and near the bottom, immediately hit the stalk. The particles that are released in the midplane, however, can oscillate for up to 8 passes.



(a) Material: air. Passes: 176



(b) Material: glass. Passes: 176

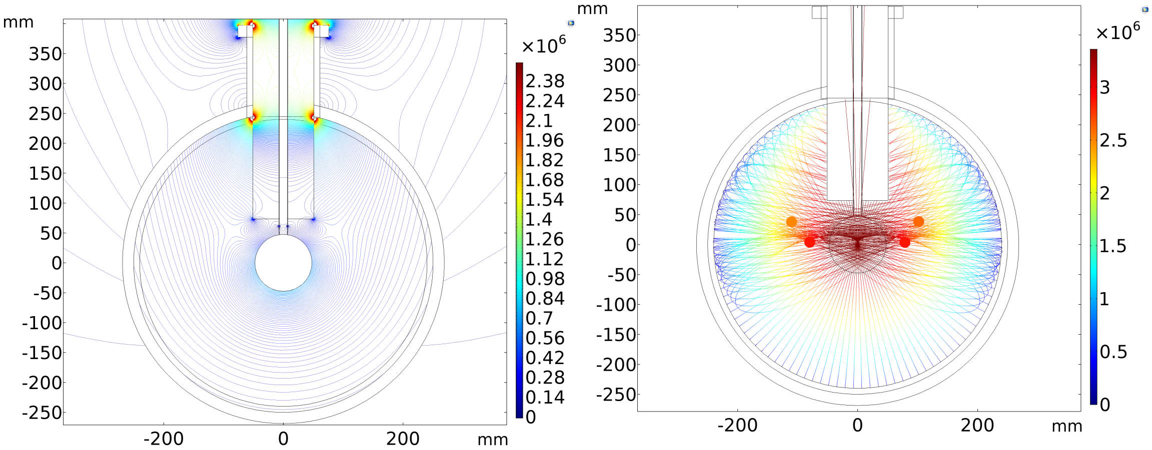


(c) Material: alumina. Passes: 176

Figure 12: Left figure: The histograms of the number of particles per number of passes. Right figure: The initial position of the particles color coded for the number of passes they make. The insulating material chosen is (a) air, (b) glass, (c) alumina.

4.1.2 Effects of the insulator width on the electric field homogenity

In the afore mentioned current fusor design there is a thin layer of insulating material on the outside of the conducting part of the stalk. In this simulation the effect of varying the insulator width is simulated. The current fusor design was implemented inside the fusor geometry. The thin layer was set to be several different widths to test their effect on the efficiency of the fusor. The simulated layer widths are: 1.985 mm (current stalk width), 22.685 mm and 43.385 mm. These simulations were carried out using glass for the insulating layer.



(a) Equipotential lines

(b) Particle field lines

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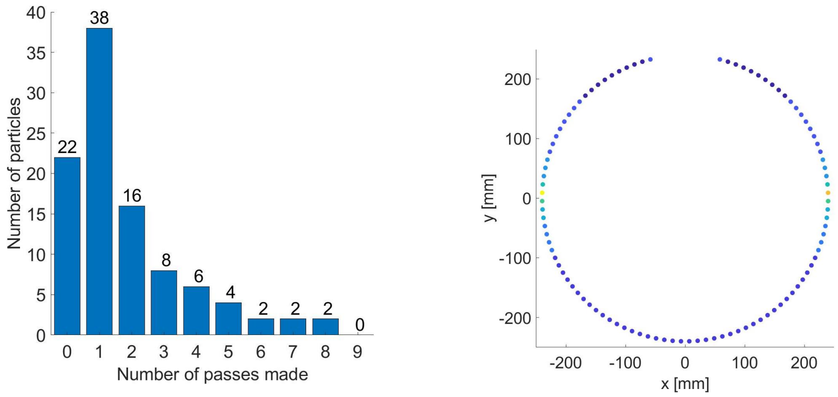
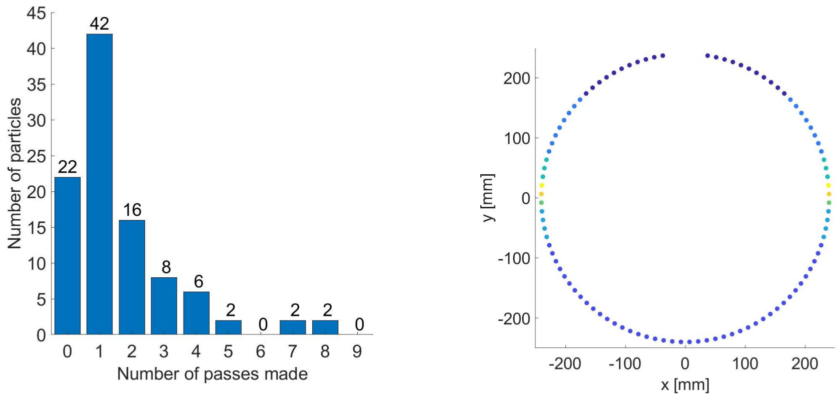
Figure 13: (a) Equipotential lines, glass stalk width 101.9 mm (b) Particle trajectories, glass stalk width 101.9 mm

Figure 14 gives a measure for the efficiency of the fusor, equivalent to the previous analysis.

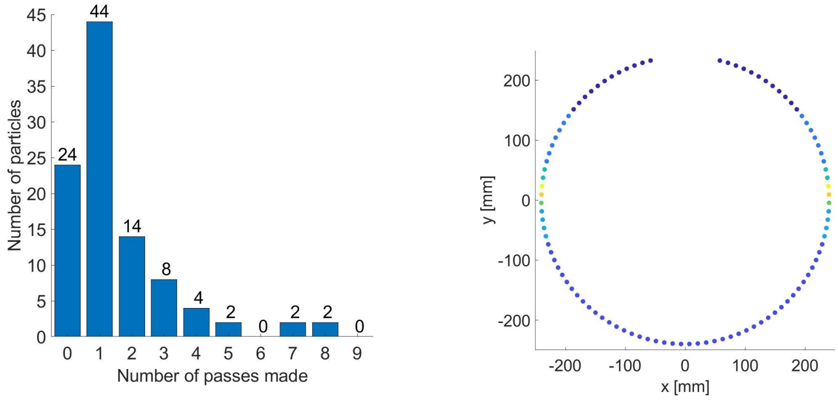
From the histograms it becomes apparent that an increase in insulating material width causes a decrease in the number of passes of all the particles. The initial position graph indicates that particles from the top and the bottom hit the stalk and only those that are released in the mid plane can oscillate equivalent to results found in previous section.



(a) Width: 1.985 mm. Passes: 176



(b) Width: 22.685 mm. Passes: 162

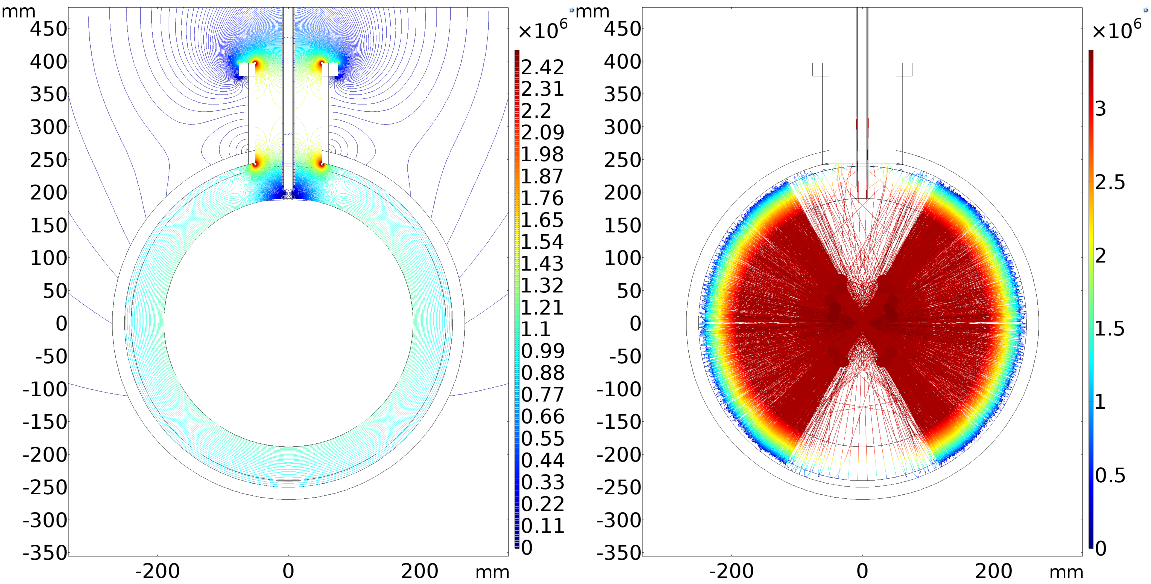


(c) Width: 43.385 mm. Passes: 152

Figure 14: Left figure: The histograms of the number of particles per number of passes. Right figure: The initial position of the particles color coded for the number of passes they make. The width of insulating material is chosen to be (a) 1.985 mm, (b) 22.685 mm, (c) 43.385 mm.

4.1.3 Effects on a larger grid size on the electric field homogenity

Another design parameter that was simulated is the grid size. Different grid sizes and their accompanying stalk sizes were chosen and implemented in the fusor geometry to test their effect on the efficiency of the fusor. The width of the insulating layer was set to be 1.985 mm (the current width) and the material of the layer was set to be glass (the current material). The grid diamters chosen in this simulation are: 95 mm (the current diameter), 190 mm and 380 mm.

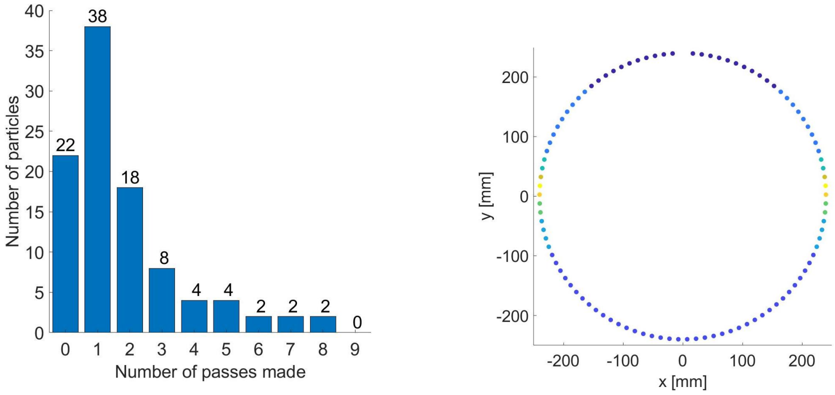


(a) Equipotential lines

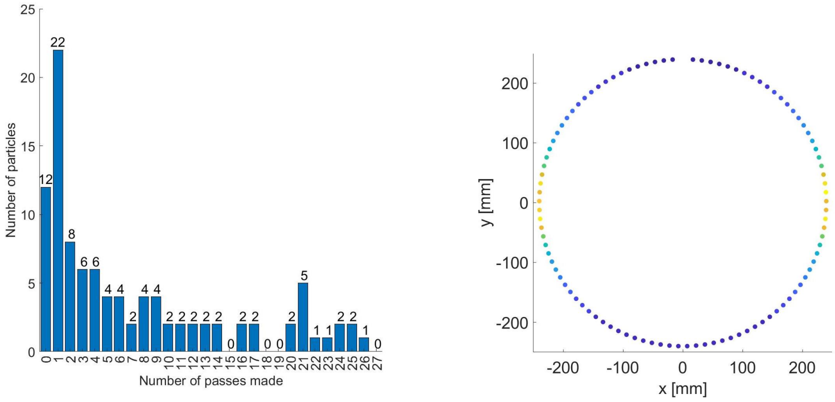
(b) Particle field lines

Figure 15: (a) Equipotential lines, grid diameter 380 mm (b) Particle trajectories, grid diameter 380 mm

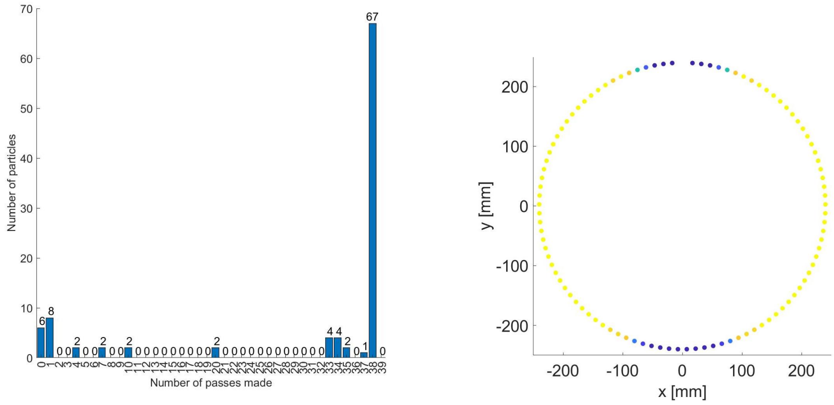
From figure 16 it can be derived that the altering of the grid size has a large effect on the fusor efficiency. For the largest grid size the efficiency is 17.1 times higher. The initial position graph shows that in this model a very large portion of the particles is free to oscillate and only the particles that are at the top and at the bottom collide quickly. This is supported by the histogram which states that 67 particles each make 38 passes through the grid.



(a) Diameter: 95 mm. Passes: 176



(b) Diameter: 190 mm. Passes: 706



(c) Diameter: 380 mm. Passes: 3011

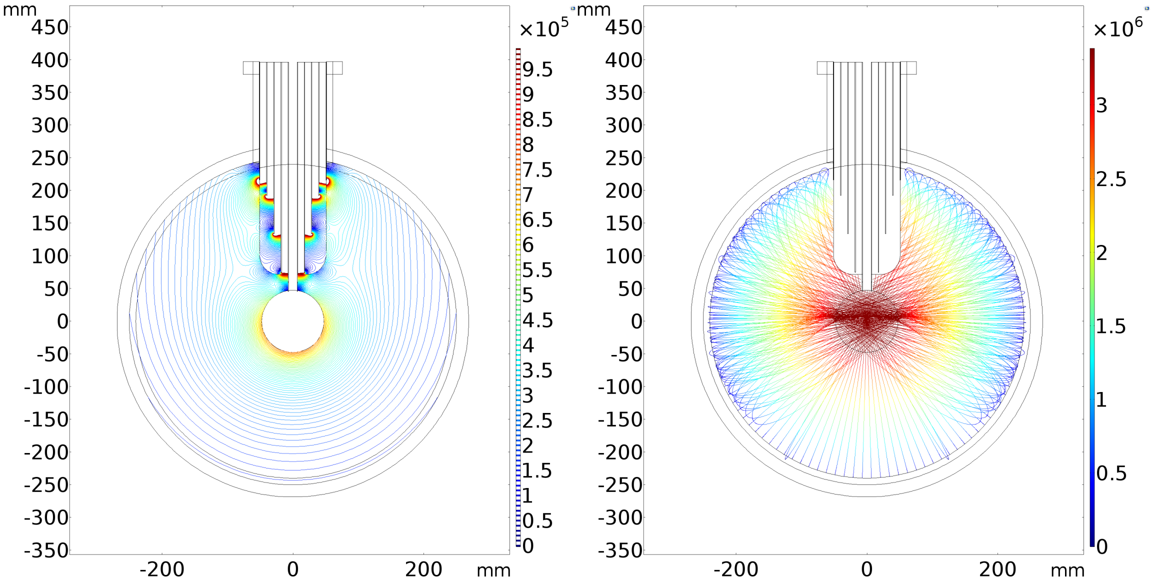
Figure 16: Left figure: The histograms of the number of particles per number of passes. Right figure: The initial position of the particles color coded for the number of passes they make. The grid diameter chosen is (a) 95, (b) 190, (c) 380.

4.2 Effects of the Condenser Bushing on the electric field homogenity

Previously, variations of the current stalk design were analysed. In this section, a more advanced design is evaluated; a stalk with a condenser bushing.

The condenser bushing has been described in chapter 2. In this simulation the condenser bushing was designed to have 3 floating potential screens and 1 grounded screen. The screens are evenly spaced and their material properties were set to aluminum. The insulating material was set to be glass.

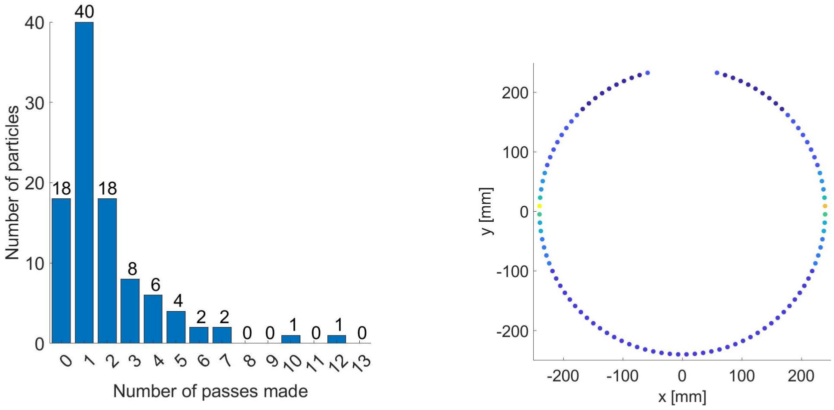
From the results it seems that the condenser bushing performs slightly better than the current fusor design. From figure **??** depicting the field lines it seems that the field lines are slightly more evenly spaced. The improved result is most likely a trade-off between the more optimal field lines and the bigger stalk which likely causes more particle collisions.



(a) Equipotential lines

(b) Particle field lines

Figure 17: (a) Equipotential lines, condenser bushing (b) Particle trajectories, condenser bushing.



(a) Condenser bushing. Passes: 192

Figure 18: Left figure: The histograms of the number of particles per number of passes. right figure: The initial position of the particles color coded for the number of passes they make.

4.3 Summary

In this chapter the results of the proposed simulations have been outlined. The efficiency of each simulation was evaluated according to the total number that particles passed through the grid.

From the simulations described in this chapter several inferences can be drawn. The design parameter with the greatest positive effect on the efficiency is the size of the grid. The efficiency of the largest grid size (380 mm in diameter) is 17,1 times larger than the efficiency of the simple design. This is partially because the stalk in this model is much shorter and so the particles are less likely to collide with it. Another reason is that as the grid grows larger and the distance between grid and outer hull decreases, the uniformity of the field grows stronger. At the same time the asymmetry introduced by the stalk becomes much less dominant in the model and is actually contained to a much smaller area (see figure 15).

The design with a large insulator width has the lowest efficiency. This is partially because the stalk takes up a substantial amount of space in the fusor. This increases the likelihood that particles will collide with it.

For the current fusor design it appears that there is no difference in the material that is used for the insulating layer. This maybe due to the fact that the layer is quite thin in this model.

In table 1 all the results are ranked from lowest to highest efficiency.

Table 1: A summary of all the simulation results ranked from lowest to highest efficiency.

Design	Design parameter	Efficiency [Total number of passes]
Simple stalk design	Insulator width 43.385 mm Insulator material glass	152
	Insulator width 22. 685 mm Insulator material glass	162
	Insulator width 1.985 mm Insulator material glass	176
	Insulator width 1.985 mm Insulator material air	176
	Insulator width 1.985 mm Insulator material alumina	176
Condenser Bushing	Condenser Bushing	192
Simple stalk design	Insulator width 1.985 Insulator material glass Grid diameter 190 mm	706
	Insulator width 1.985 Insulator material glass Grid diameter 380 mm	3011

5 Discussion

5.1 Limitations and suggestions for improvement

There are a number of issues to be considered when looking at the validity of the results and their relation to reality. A couple of factors have not been put into the model.

- The model does not account for particle to particle interaction. In the actual fusor there would be a background plasma for the fast ions to interact with. This could potentially alter the strength of the electric field as the positive particles would accumulate at the cathode parts creating what is known as a "Debye sheath". This sheath essentially decreases the electric field strength around it as it reduces the enclosed charge as seen in gauss's law.
- In the simulation the grid is chosen to be completely transparant. This means it carries the voltage but there is no actual matter for the particles to interact with. It is not clear what the effect of an increased grid size would be on the efficiency in terms of particles colliding with the grid itself. This might be an interesting topic for further research.
- An actual experiment was performed investigating the effect of grid size on fusion rate and this does not exactly agree with the simulation results. The research showed that at -60kV, multiplying the grid radius by a factor 2 (5 cm to 10 cm) affected the fusion rate by a factor 1,2. This is very different from the factor 4,1 found with the simulations.[7] This discrepancy could be because of all the physical phenomena that is not included in the model like the particle particle interaction and the collision with the grid.
- There has been no intensive study of the breakdown voltages in any of the simulations. Some basic calculations using the simulation results and the Passchen curve show that there will be electrical breakdown but a more thorough research of the particular aspect is needed.

Within the confines of the model the simulations are fairly accurate (see validation) and show some very interesting results. It could be worthwhile to experiment with larger grids in the future although a more detailed analysis of the new design would be advisable.

6 Summary and Conclusion

In this report we tried to answer the research question, how can the efficiency of the fusor (TU/e's IEC device) be increased by optimizing the high voltage stalk?

To answer this question, the TU/e fusor was modeled in 2 dimensions in COMSOL and the efficiency of various stalk designs and design parameters were analyzed. Evaluated were various different materials, several widths of the insulating layer around the stalk and the effect of a condenser bushing.

It is found that increasing the grid diameter has the biggest impact, increasing the number of passes by a factor of 17,1 compared to the current experimental design. The choice of insulating material has a negligible effect on the efficiency. The condenser bushing and the width of insulating material led to minimally increased and slightly decreased efficiency, respectively.

These findings provide insight in the effect of the stalk design upon the function and efficiency of the TU/e fusor. This insight could be used in the design and construction of a new high voltage feedthrough. For further designing of the fusor this thesis indicates that the stalk should be able to accommodate a larger grid.

7 References

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[2] George H. Miley and S. Krupakar Murali. *Inertial Electrostatic Confinement (IEC Fusion Fundamentals and applications.* ., 2014.

[3] S K Murali. Diagnostic study of steady state advanced fuel fusion in an IEC device. *PhD Thesis*, 2(December), 2004.

[4] Masami Ohnishi, Hodaka Osawa, Ryo Tanaka, and Naoki Wakizaka. Shape of electrodes for high performance of inertial electrostatic confinement fusion. *Journal of Nuclear Science and Technology*, 42(4):398–405, 2005.

[5] Sears, Zemansky, H D Young, and R A Freedman". *Sears and Zemansky's University Physics with Modern Physics Technology Update Thirteenth Edition.* ., 2014.

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8 Appendix

Validation of simulations

When doing simulation experiments it is important to assess the validity of the simulations used. In this section both the electric field simulation and the particle simulation will be validated

Validation of Electric field simulation

The electric field simulation will be tested using a model of a spherical concentric capacitor. The spherical concentric capacitor was simulated in comsol (see figure 19) and a line sample pas taken from the center of the capacitor along the z axis to the edge of the shell.

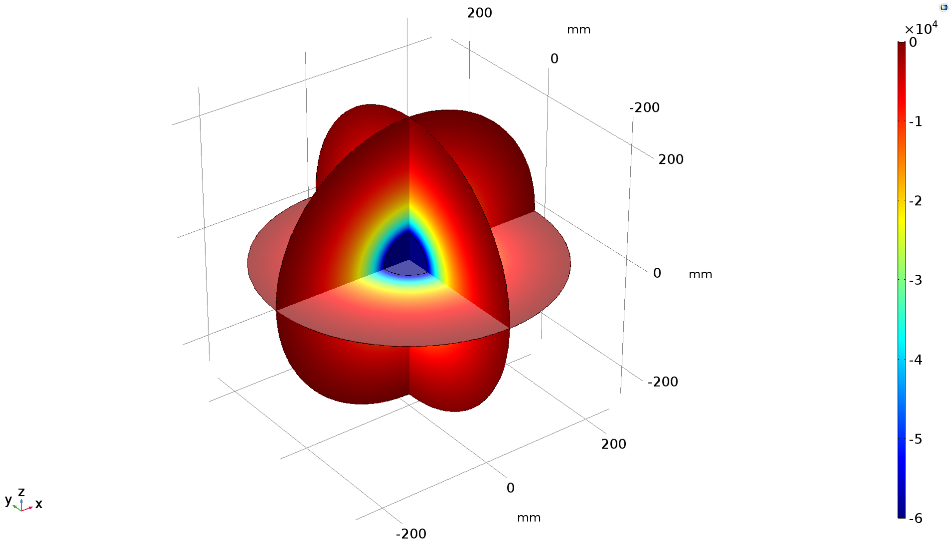

Figure 19: Spherical concentric capacitor. in 3 Different planes the potential is simulated.

On this line all the potential is simulated and exported to matlab. In matlab the simulated data is plotted against the theoretical solution for the potential. The theoretical solution states that the potential inside the spherical capacitor should go with:

$$V(r) = \Delta V(\frac{1}{r} - \frac{1}{rb}) * \frac{ra * rb}{rb - ra}$$

6

Below is the figure of both the simulation data and the theoretical solution. In figure 20 below that is the absolute difference of the two between the inner sphere and the outer sphere 21. From this graph it can be concluded that the error in the simulation is plusminus 20 volts.

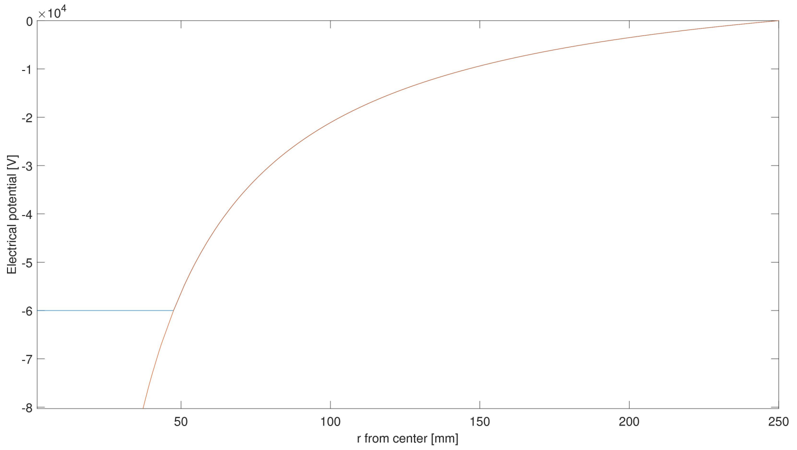

Figure 20: The simulated result of the potential (blue line) theoretical solution (brown line)

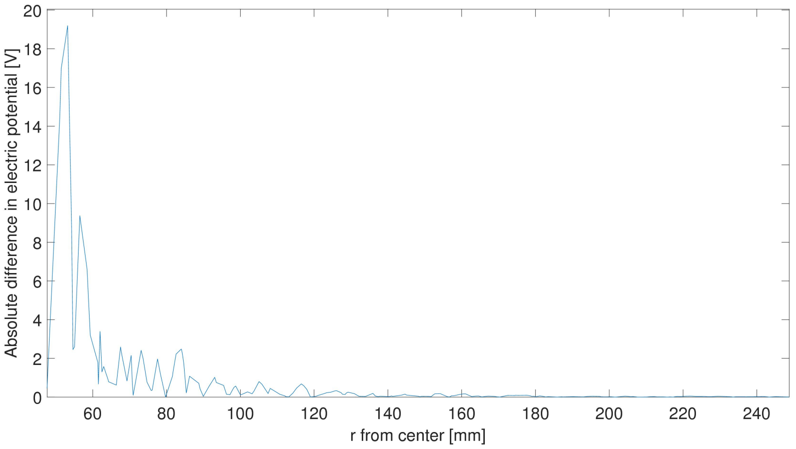

Figure 21: The absolute difference of the simulated solution and the theoretical solution

Validation of the particle simulation

In order to validate the particle simulation, a phase space diagram is made of a single particle in the current simple fusor model(see figure 22. This diagram plots the absolute magnitude of the velocity of the particle against the position of the particle in the x dimension. All the simulations shown in the thesis were made with a $7 \cdot 10^{-10}$ s timestep. In order to assess whether this was adequate the phase diagram will be made for timesteps of $7 \cdot 10^{-11}$ and $7 \cdot 10^{-10}$. If they are in good agreement then it can be concluded that the $7 \cdot 10^{-10}$ s timestep was sufficient.

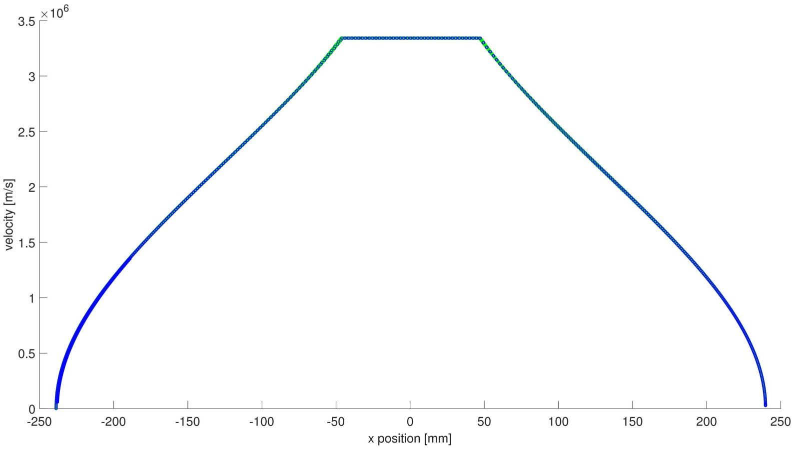

Figure 22: A phase space diagram of a single particle simulated in the current fusor geometry. Two solutions, blue for $7 \cdot 10^{-10}$ s time step and green for $7 \cdot 10^{-11}$ s time step

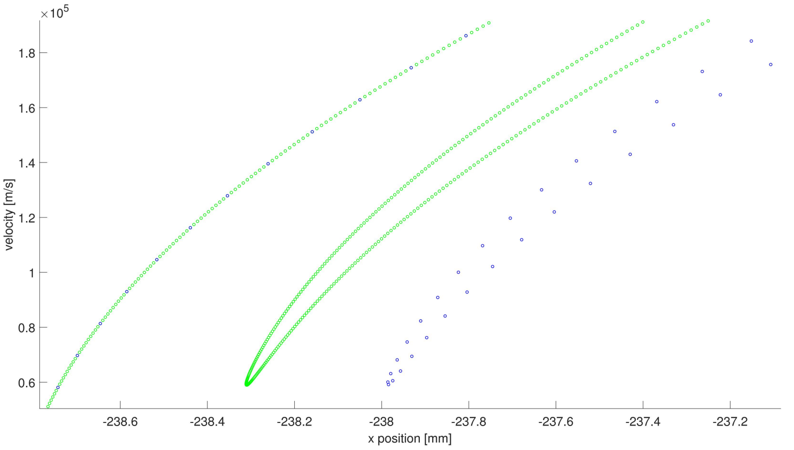

Figure 23: A close up of the phase space diagram of a single particle simulated in the current fusor geometry. Two solutions, blue for $7 \cdot 10^{-10}$ s time step and green for $7 \cdot 10^{-11}$ s time step

It is shown that the plots are in good agreement. Later in the diagram it can be seen that the lines do differ by less than 0.5 mm.

Pass counting script

```
%This script finds the number of passes that each particle makes trhough
%the grid by examining their kinetic energy. The kinetiec energy data is
```

```
%imported from comsol and analyzed.

%The innitial positions of all the particles are also imported from comsol
%and used to color code the particles in the begin position for how many
%passes they make during the entire simulation.


sizeofn=size(position)
split=((sizeofn(1,2)-1)/2)+1
xcoordinates=position(1,2:split)
ycoordinates=position(1,split+1:end)
sizeofm=size(energy());
histopass=zeros(1,100);
scatterdata=zeros(1,(sizeofm(1,2)-1));

for k=2:1:sizeofm(1,2)

maxvalue=max(energy(:,k));



[pks,locs] = findpeaks(energy(:,k),’MinPeakHeight’,maxvalue*0.07,’MinPeakDistance’,5);
x_peaks = energy(locs);


[minpks,minlocs] = findpeaks(-energy(:,k),’MinPeakHeight’,maxvalue*0.07,’MinPeakDistance
minx_peaks = energy(minlocs);
figure(1)
%plot(energy(:,1),energy(:,k),  minx_peaks,-minpks,’pg’,x_peaks,pks,’pg’);

mindistance=3;
bignesslocs=size(locs);
bignessminlocs=size(minlocs);
if bignesslocs>0 & bignessminlocs>0
for i=1:1:bignesslocs(1,1)

if minlocs(1,1)>locs(i,1)

mindistance= minlocs(1,1)-locs(i,1);
end
end
```

```
end

[pks,locs] = findpeaks(energy(:,k),'MinPeakHeight',maxvalue*0.07,'MinPeakDistanc
x_peaks = energy(locs);

[minpks,minlocs] = findpeaks(-energy(:,k),'MinPeakHeight',maxvalue*0.07,'MinPeak
minx_peaks = energy(minlocs);
figure(1)


plot(energy(:,1),energy(:,k),  minx_peaks,-minpks,'pg',x_peaks,pks,'pg')
grid
xlabel("Time (s)")
ylabel("Derivative of Kinetic energy (j/s)")
%sorting mechanism
% 1 pick first max, find closest min


pass=0;
nanvalues=find(isnan(energy(:,k))==1);
sizenanvalues=size(nanvalues);
if sizenanvalues(1,1)<= 0
    nanvalues(1,1)=sizeofm(1,1);
end
bignesslocs=size(locs);
bignessminlocs=size(minlocs);
i=1;

% if there are no maxima and minima
if bignessminlocs(1,1)<=0 && bignesslocs(1,1)<=0

     %the zero passings variable

    pass=0;

end

% if there is only one maximum and no minimum
if bignessminlocs(1,1)<=0 && bignesslocs(1,1)>0

     i=bignesslocs(1,1);
            avaragemax=energy(locs(i,1),k);
            zerotest=median(energy(locs(i,1):nanvalues(1,1)-1,k));
```

```
                    if zerotest<avaragemax*0.1

            pass=pass+1;

        end

end

%only apply if there are min and max
if bignessminlocs(1,1)>0 && bignesslocs(1,1)>0
for i=1:1:bignesslocs(1,1)

    for j=1:1:bignessminlocs(1,1)

        if locs(i,1)<minlocs(j,1)

        avaragemax=(energy(locs(i,1),k)+abs(energy(minlocs(j,1),k)))/2;
        zerotest=median(energy(locs(i,1):minlocs(j,1),k));

        if zerotest<avaragemax*0.1

            pass=pass+1;


        end
        break

        end
    end
end

%if there is one max left without a following min
if locs(end,1)>minlocs(end,1)
            i=bignesslocs(1,1);
            avaragemax=energy(locs(i,1),k);
            zerotest=median(energy(locs(i,1):nanvalues(1,1),k));

                    if zerotest<avaragemax*0.1

            pass=pass+1;

        end

    end
```

```
end

histopass(1,pass+1)= histopass(1,pass+1)+1;
scatterdata(1,k-1)=pass;
end

sizehistopass=size(histopass);

for i=sizehistopass(1,2):-1:0

    if histopass(1,i)>0
        cutoff=i+1;
        break
    end
end

y=zeros(1,cutoff);

for i=1:1:cutoff

    y(1,i)=i-1;

end


x=histopass(1,1:cutoff);
y=categorical(y);
totalpasses=sum(scatterdata)
a=num2str(totalpasses,5)
h = bar(y,x)
title(['Histogram of number of passes with total number of passes =',a])

text(1:length(x),x,num2str(x'),'vert','bottom','horiz','center');
box off


for i=1:1:cutoff

    x(1,i)=x(1,i)*(i-1)

end
```

```
figure(2)
scatter(xcoordinates,ycoordinates,50,scatterdata,'filled')
pbaspect ([1 1 1])
a=num2str(totalpasses,5)
title(['Innitial position of particles color coded for number of passes with total numbe
```