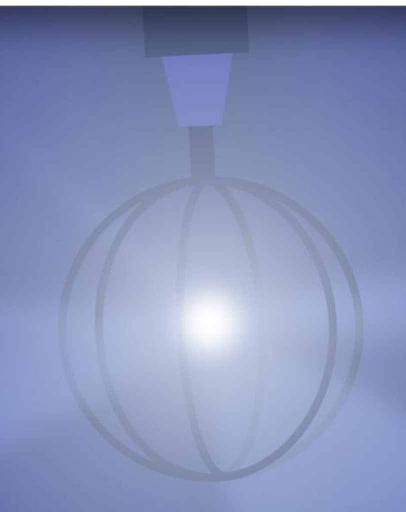
THE FUNDAMENTALS AND CONSTRUCTION OF IEC FUSION DEVICES



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THE FUNDAMENTALS AND CONSTRUCTION OF INERTIAL ELECTROSTATIC CONFINEMENT (IEC) FUSION DEVICES

This paper illustrates the ‘simplicity’ of achieving fusion reactions versus the difficulty of generating a sufficiently high fusion energy output gain from said reactions for utilization in electrical power plants.

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Abstract

In the current media, nuclear fusion startups are often publishing exaggerated headlines, commonly stating the high temperatures needed for fusion, as an example. In this paper, research into whether achieving nuclear fusion itself is headline worthy, or just a way of attracting investors is published.

There exists an extraordinarily simple system called the Farnsworth fusor invented by Philo Farnsworth in the 1900s which is capable of fusion, the replicating of which is the goal of this paper to prove our point. Thus, research into the security and precautionary measures needed to make a safe, simplified version of the Farnsworth fusor is published, alongside the development of the experiment bound to this paper, the RSR-1 (Rietveld Simple Reactor 1). It is not our goal to produce a net-energy system, but rather to document the construction of a fusion-enabled object. Even though the construction of a fusor is legal, it is, at least in The Netherlands, illegal to operate a fusion device without a license since the radiation emitted from the device exceeds the $1.00\ MeV$ limit, which in the case of a deuterium-deuterium fusion reaction, which is used in the fusor, radiation with energy levels higher than $3.00\ MeV$ is emitted. Due to the absence of a permit in this project, the necessity of which was discovered later in the project, we will more closely look at the potential to build a fusor ignoring the need for a permit. Thereby, our research question is as follows: “How can nuclear fusion reactions take place with respect to safety and cost?”, while ignoring positive energy gain. To make things clear, the goal of constructing a fusion capable device was not reachable in this project, and a demo fusor was constructed instead. Though, the material discussed in this paper is about constructing a functioning neutron-producing fusor. The paragraphs outside of the theoretical material differ in the way that it is about a demonstration fusor, RSR-1.

To conclude, building a nuclear fusion reactor without spending millions of dollars is entirely possible, though huge amounts of research must be conducted to make its construction and operation safe. When unfunded by third parties or sponsors, a lot of time must be spent looking for second-hand or surplus equipment, when a low budget is desired.

About this paper

This work is a collaborative research paper written in the final year of pre-university education or ‘profielwerkstuk (PWS)’ in Dutch. The project started as a joke from team member S. Harmsma to supervisor J.J.H.M. Kövi, where he asked him if it would be possible as a project to construct a nuclear reactor, in which he responded ‘yes’, after which we took the project proposal quite serious.

This project has taught us a multitude of things, under which the handling and workings of high vacuum equipment and attempting to settle deals and sponsorships with dozens of companies are examples of experiences we had. This way, each team member had a taste of a variety of areas of expertise.

This project has been carried out in cooperation and assistance with:

TNO innovation for life

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We wish you much reading pleasure,

Thijs Hampsink, Stefan Harmsma, and Jan Spekman

2023, February 10

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CHAPTER

A

General introduction

RSR-1 (Rietveld Simple Reactor-1) is the first nuclear fusion experiment developed by students at the Gerrit Rietveld College therefore nicknamed Rietveld Simple Reactor-1. This paper is targeted at those who have gained interest in the experiment. For further information on how this type of fusion reactor is designed, please visit the 'fusor.net' forums and the references in chapter G, as it contains results and findings of many fusor experiments carried out by enthusiasts, and heaps of information regarding the matter.

Our research question is as follows: "How can nuclear fusion reactions take place with respect to safety and cost?".

A.1. The history of nuclear research

The concept of nuclear fusion was first proposed by the works of physicist Arthur Eddington and theoretician Hans Bethe among others in the 1930s, the fundamental principles of which are discussed in chapter B.1. They proposed that the sun's energy was generated by the fusion of hydrogen into helium (McCracken & Stott, 2005), (Wijers, 2007). After the concept was first introduced, in the 1940s and 1950s, scientists around the world began to experiment with nuclear fusion (Meade, 2010). In 1952, a team at the University of California, Berkeley, was able to achieve the first controlled nuclear fusion reaction in a laboratory setting. However, the process was not yet practical for generating electricity on a large scale (Thomas, 1959).

Over the next several decades, scientists and engineers continued to work on developing nuclear fusion as a practical energy source. In the late 1970s and early 1980s, several experimental fusion reactors were built and operated, including the Joint European Torus (JET) in the United Kingdom (Keilhacker, 1999) and the Tokamak Fusion Test Reactor (TFTR) in the United States (Young, et al., 1984). These experimental reactors helped scientists understand the complex physics of nuclear fusion and made significant progress toward the goal of achieving practical fusion energy, which as of the writing of this paper, has not been reached.

Philo Farnsworth (1906-1971), the inventor of the first television, was one of the first to design a fusion apparatus: the Farnsworth fusor, which is a system built on the concept of inertial electrostatic confinement which is thoroughly discussed in this paper. The fusor, although producing fusion reactions, could never produce net-energy and is currently used as a viable neutron source instead (Miley & Sved, 2000), mainly for medical applications. This matter is further discussed in chapter B.3, while the fusor's design principles are discussed in chapter B.2.

In the decades since, numerous research programs have been carried out around the world to advance the field of nuclear fusion. While significant progress has been made, the technical challenges of achieving practical fusion energy remain formidable and scientists and engineers continue to work on developing viable fusion energy systems (World Nuclear Association, 2022). Recently, a new milestone was reached in December 2022. Nuclear fusion with a net-energy yield of 154% took place in the United States for the first time at the Lawrence Livermore National Laboratory (LLNL). With an input of 2.05 MJ, an output of 3.15 MJ was achieved (U.S. Department of Energy, 2022).

CHAPTER B

Theory

B.1. Principles of fusion and approaches

Atoms are made up of nuclei containing protons and neutrons, of which the proton has a positive charge, while the neutron is neutral. These nuclei are surrounded by electrons, which are negatively charged, resulting in a net-charge of zero, as the number of protons and electrons in atoms are equal. When an atom does not have an equal number of electrons as it has protons, it is considered an ion. The number of protons in an atom determines the atom's corresponding element (Landa, Schouten, Valk, & De Zoon, 2019). Furthermore, the corresponding element of an atom can simply be changed by for example splitting the atom in two new, smaller atoms. This process is called nuclear fission.

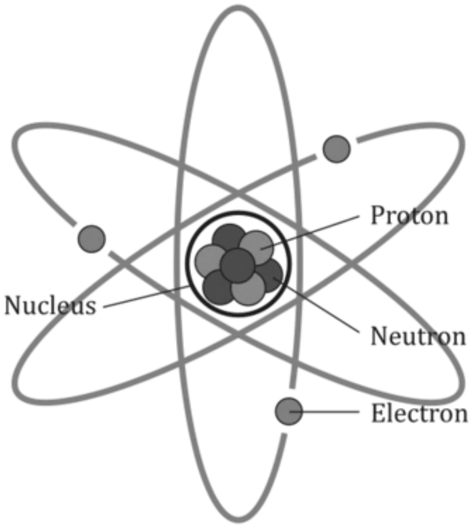

Figure B.1: Illustration demonstrating a simplified non-quantum-mechanical interpretation of an atom (Landa, Schouten, Valk, & De Zoon, 2019).

Instead of splitting atoms like in nuclear fission, which is used in all currently active commercial nuclear power plants, nuclear fusion is the act of combining two atoms together resulting in a single, heavier atom, which is lighter than the two former atoms combined. As there exists a law of conservation of energy and mass, the mass defect is converted into pure energy to make up for the lost mass in accordance with Einstein's mass-energy equivalence equation:

$$ {}_{1}^{2}H + {}_{1}^{3}H \rightarrow n(14.1\ MeV) + \alpha(3.5\ MeV) \tag{B.1} $$

$$E = mc^2 \tag{B.2}$$

Given that $c = 3.0 \times 10^8\ ms^{-1}$ one can see that the conversion of slight amount of mass (m) can result in tremendous amounts of pure energy (E), the harvesting of which is an objective in both commercial fission and fusion power plants. Just like in fusion, during a fission reaction a mass-energy conversion takes place to make up for the lost mass in accordance with eq. (B.2).

A well-known fusion reaction is the fusion of deuterium and tritium:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow\ n(14.1\ MeV) + \alpha(3.5\ MeV) \tag{B.3}$$

In this reaction, both the tritium $(^{3}_{1}H)$ and deuterium $(^{2}_{1}H)$ nuclei form a new nucleus $(^{4}_{2}He)$, better known as an alpha particle, while a single neutron is emitted with 14.1 MeV of kinetic energy and therefore has a higher speed than its surrounding particles, which is classified as a fast neutron (United States Nuclear Regulatory Commission, 2021). Nuclear fusion has the potential to be a virtually limitless and clean source of energy. However, this is a technical and challenging process, and scientists and engineers around the world are still working to develop practical fusion energy systems with a sustainable power output as is discussed in chapter A.1.

The reaction desired in this project, however, is not the reaction as mentioned in eq. (B.3), but the reactions between two deuterium nuclei, or the D-D fusion reactions (EUROfusion, 2023). There exist two possible fusion reactions between two deuterium nuclei which can take place:

$$\begin{aligned} D + D &\rightarrow\ ^{3}_{2}He(0.82\ MeV) + n(2.45\ MeV)\ |\ 50\%\ | \\ D + D &\rightarrow\ ^{3}_{1}H(1.01\ MeV) + p(3.02\ MeV)\ |\ 50\%\ | \end{aligned} \tag{B.4}$$

From eq. (B.4) it can be concluded that there is a 50% chance that a fast neutron production takes place when deuterium-deuterium fusion occurs.

There are multiple known ways to achieve fusion reactions, under which the most known approaches are magnetic confinement, inertial confinement, magnetic or electric pinches, and inertial electrostatic confinement. Gravitational confinement, however, as is utilized in stars, cannot currently be reproduced by humans as the amount of gravitational force required for such a fusion-supporting environment is enormous. Gravitational confinement alongside magnetic and inertial confinement can be considered the three main ways of achieving fusion. All fusion environments require at least $150\ K$ for fusion to occur (Letcher, 2023). To illustrate, with magnetic confinement, a vessel is created in which plasma is heated to fusion levels. As the plasma will simply melt the walls of the fusion vessel, a magnetic field holds the plasma away from the walls. With inertial confinement, powerful lasers aimed at a single pellet of fuel bombard it with high-energy photons, causing the pellet to heat up and collapse in on itself, after which nuclear fusion will occur (Wikipedia, 2023c).

One problem with a fusion is that, just like with quantum mechanics, there is just the chance of things to fuse. This means that there is no absolute certainty that atoms will fuse, just the probability. One would like the circumstances for atoms to fuse to be as favourable as possible, since that would theoretically maximize the number of fusion reactions taking place. The probability of a fusion reaction happening is called the cross-section (Letcher, 2023).

As stated before, the fusion environment requires high temperatures to support fusion reactions. There is an approach, however, that allows fusion to take place at room temperature called muon-catalysed fusion. Net energy production has been unsuccessful with this approach due to the high energy costs of generating muons, their short lifespan, and the high chance muons will bind to the newly generated alpha particles (Chem Europe, n.d.; Wikipedia, 2022).

RSR-1 uses a simpler way of achieving fusion that is not targeted at generating energy but rather achieving nuclear fusion itself, in the form of inertial electrostatic confinement or IEC. With this method, a nuclear accelerator is used which ionizes and accelerates fuel using a negatively charged high-voltage inner grid which creates an electric field. This field is not linear in our design but is rather a spherical shell in which the ions collide at high speeds in the centre of the electric field inside the reaction vessel, where the so-called inner grid is located which generates the electric field. Upon arriving in the centre of the vessel, the ions have a very small chance to collide with other high-speed ions which gives them the opportunity to fuse under high temperatures. A system which incorporates this type of fusion is called a fusor.

B.2. Inner workings of a Farnsworth fusor

B.2.1. The ‘demo-fusor’

Simple fusor devices can currently be divided into two types of fusor systems: demo-fusors and deuterium-fusors. A demo-fusor can be a demonstration or test of a fusion device, system, or experiment planning to do deuterium fusion in future experiments, though demo-fusors are often made of glass vessels, not intended for fusion and act as a look-alike replica of IEC fusor systems (Spangler, 2013).

Figure B.2: An example picture of a demo-fusor at work (Spangler, 2013).

Furthermore, the glass vessel will not protect operators against X-rays emitted by deuterium fusion if proper deuterium fusion is desired, and it is therefore unsafe to conduct fusion experiments in non-steel thick shelled vessels, unless additional radiation shielding is put in place (Hull, 2012b). Radiation safety measures are discussed in chapter B.2.6. Demo-runs are not intended to produce sustained fusion reactions. These types of systems are merely plasma generators which replicate fusors, therefore named ‘demo-fusors’. No deuterium fuel is used in these types of experiments, and non-fusion fuels like plain atmospheric air or standard helium or argon is used to generate the plasma (Hull, 2007).

As stated in chapter B.1, fusors use an inner grid with a high negative voltage. When the power supply is turned on, electrons will travel from the negatively charged inner grid to the positively and grounded outer shell. When these electrons are travelling at high speed to the outer shell, they have a chance to hit atoms in the air. The atom then loses one of its own electrons according to the following reaction:

$$N + e^{-} \rightarrow N^{+} + 2e^{-} \quad \text{(B.5)}$$

N in this case does not stand for nitrogen but stands for an arbitrary particle. This means that this reaction applies to all ionization reactions that happen in a fusor. The ionised positively charged particle is formed somewhere between the inner grid and the outer shell, from which point it will start accelerating to the inner grid. This also means that when a deuterium atom ionizes somewhere between the outer shell and inner grid, it does not reach full fusion potential, due to the shorter oscillation path it receives (Messmer, 2019). To illustrate: an ion forms halfway in between the outer shell and inner grid, while the full potential generated between the grid and shell is $50\ kV$. As this ion travels to the inner grid, where the ion's fusion potential is at its maximum, it only receives $25\ keV$ of energy. See ion a Figure B.3. This is opposed to ion b in Figure B.3, which has formed at the outer shell, and receives $50\ keV$ of energy, and thus a higher fusion potential. Most ions however are formed close to the inner grid. This means that most ions do not receive maximum kinetic energy for fusion. The positively charged fuel ions accelerate to the centre, where they have a chance to collide with atoms, other positively charged ions, the non-transparent areas of the inner grid, get neutralized by an electron, or oscillate through the system until another event occurs (Messmer, 2019).

The ions mainly collide with one another or an atom inside the inner grid since the concentration of fast-moving ions is highest inside the inner grid. All positively charged ions oscillate through the inner grid, as depicted in Figure B.3 on the next page, and ion a and ion b both move through the centre even though they have a different oscillation direction. When these collisions occur, they can form a plasma in the centre of the inner grid. Plasma is superheated matter. It is so hot that the atoms and the electrons are split, forming an ionized gas. It can be regarded as a soup of positively charged ions and negatively charged electrons (Massachusetts Institute of Technology, n.d.).

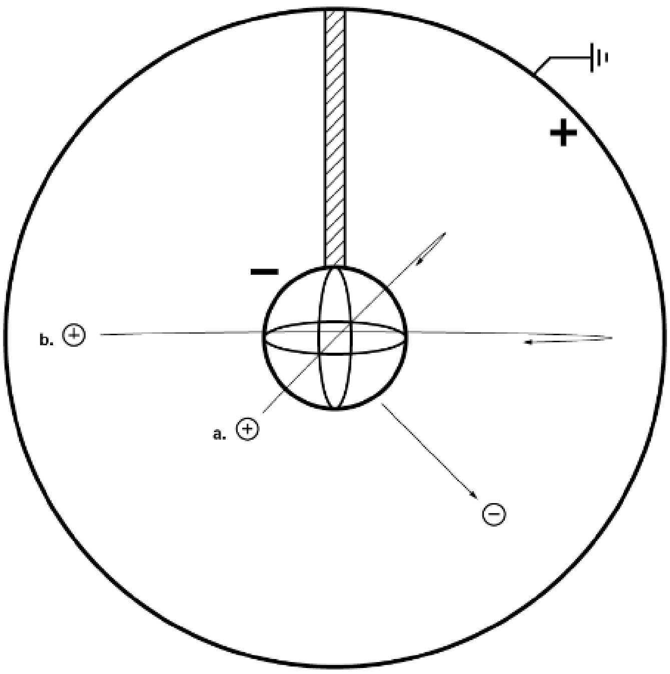

Figure B.3: General illustration of the path of charged particles in a spherical fusor. Deuterons are accelerated towards the center inner grid, while electrons are shot towards and absorbed in the grounded outer shell. Deuterons can have oscillating paths through the system with their oscillation length determined by the position of ionization. A shorter path (a) to the inner grid means the fusion potential is lower than when an ion forms at the longest possible path (b) to the inner grid.

The colour that is emitted by the fusor is determined by the gas that mainly forms the plasma. The photons get released when the plasma changes state from plasma to gas. The particles that become gaseous are not charged and thus take one or more electrons with them. It is called deexcitation when an electron falls back into its original shell. This emits energy in the form of photons since the potential electric energy of the electron gets lowered. The wavelength of the emitted photon is dependent on the element, because different elements have a different number of protons and thus a different electric field in which the electrons can exist (Wikipedia, 2023b).

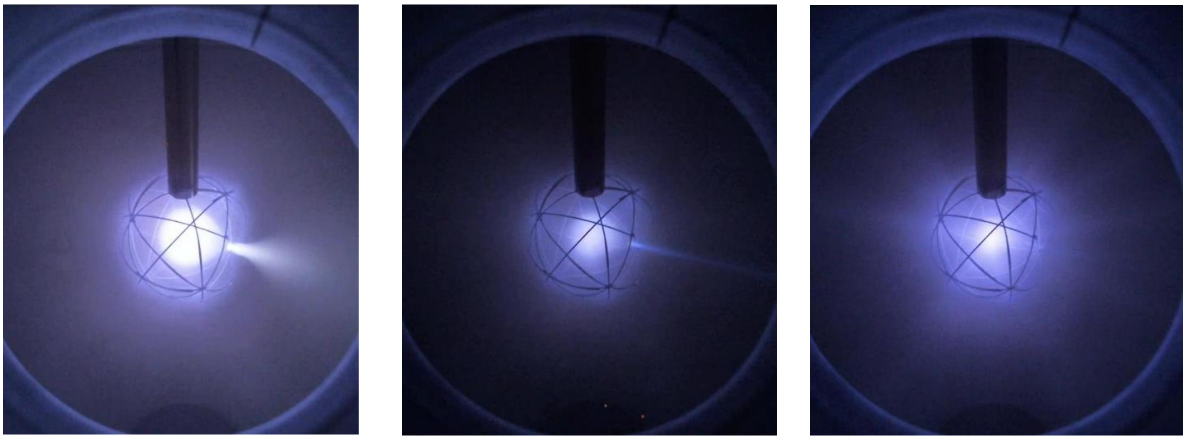

Figure B.4: From left to right: jet mode, mini-jet mode & star mode (Van Limpt, 2013).

In fusors, three states of the plasma or 'modes' have been defined: glow mode (see Figure D.11 for an example of glow mode), jet mode, and star mode. During glow mode operation, a uniform glow is observed around the inner grid region. During jet mode operation, a beam or 'jet' is visible originating from the centre plasma sphere consisting out of electrons escaping the inner grid region at the largest opening between the wires, dragging ions along with them. This is visible in the left picture of Figure B.4. When achieving star mode, the oscillatory trajectories of the ions can be observed as jets or beams through all the inner grid openings. There is also a transition period between jet mode and star mode. This period is called mini-jet mode and it is visible in the middle of Figure B.4. This phase can be recognised by the straight jet (Van Limpt, 2013).

B.2.2. How fusion is achieved in a deuterium-fusor

Deuterium-fusors work in a similar way to demo-fusors but are often more sophisticated than a common glass-vessel system. In a deuterium-fusor, deuterium is used as fusion fuel according to eq. (B.4). It is commonly used as fuel in fusion systems as it is abundant and relatively easy to work with, as it is a non-radioactive isotope of hydrogen, though highly flammable.

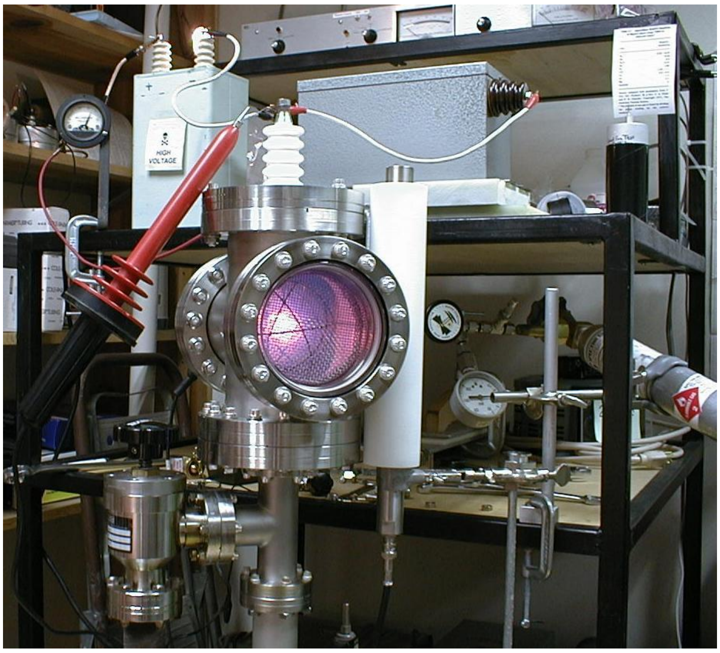

Figure B.5: An example picture of a more sophisticated deuterium-fusor at work (Earthtech, 1999).

For a clean reaction in a deuterium-fusor, air present in the system must be removed as it is seen as an obstruction in the path of acceleration of a deuteron (deuterium ion) to the inner grid, and thus a contaminant. Therefore, a vacuum system is required for fusion operation to increase the mean free path of ions and enable fusion between deuterons. This works in the same way as in the demo fusor.

B.2.3. Functions of main fusor hardware units

This section explains what equipment is needed to construct a deuterium-fusor. All equipment is connected using vacuum flange systems like Conflat (CF) and Klein Flansche (KF), with KF also being known as QF, NW or DN. CF fittings are one of the most widely used ultra-high vacuum fittings, making use of metal-on-metal seals utilizing copper O-rings compressed with bolts. The copper O-rings are 'used' after flange disconnection, as the knife edges of the flanges will have pressed a permanent groove in the copper O-ring. KF fittings make use of malleable O-rings, which are compressed using clamps. They have a lower vacuum rating but are still good enough for use with fusors. These O-rings, unlike the copper CF variant, can be reused. Although, when baking vacuum systems, which is the process of heating up the system to remove for example water molecules in the walls of the vacuum system, the utilization of KF flanges lowers the maximum temperature these systems can be baked on. There do however exist multiple materials out of which these KF O-rings can be manufactured, each having their own specific properties including a maximum baking temperature and durability (Dabrowski, 2022; Leybold, n.d.).

B.2.3.1. Reaction vessel

The reaction vessel is the vacuum container or chamber in which the fusion reactions take place in a fusor. The reaction vessel is typically made of a material that can withstand the high temperatures and low pressures of the fusion reactions. In some fusors the reaction vessel is made of a transparent material such as glass or quartz, which allows scientists and engineers to observe the plasma and measure the characteristics of the fusion reactions. However, glass and other transparent materials can be fragile and may not be suitable for use in high-pressure or high-temperature environments as is mentioned in chapter B.2.1. They can also shatter or break if they are subjected to too much pressure or stress, which can be immensely dangerous. An overpressure in the chamber can occur for example when using high-pressure bottled deuterium. If the operator incorrectly operates the valves which manage the flow of deuterium resulting in a high flow of gas into the chamber, there exists a risk that the glass viewports can shatter and explode when vacuum pumps shut down for unknown reasons (Van Elswijk, J.I.M., personal communication, 2022, September 6).

Though, even a steel-shelled fusor must be equipped with some sort of glass viewport, which gives operators a key insight in what is happening in the chamber utilizing cameras or spectrometry systems to avoid X-ray exposure when doing deuterium fusion (Hull, 2007).

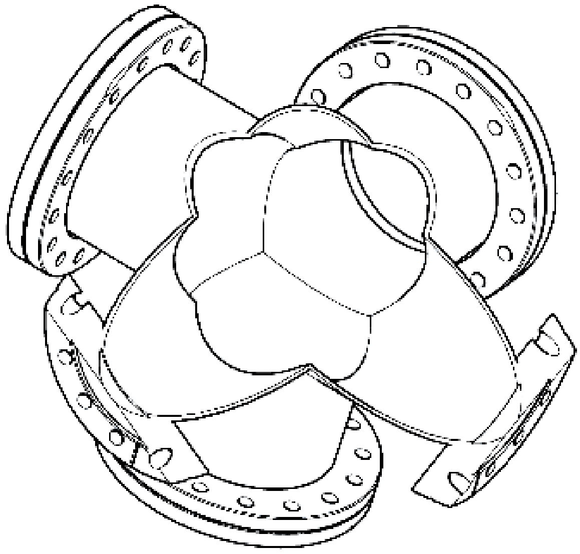

Figure B.6: A cross section of the steel-shelled vacuum chamber which is used in the RSR-1. It is not a spherical shape, but rather a 6-way CF-flanged cross on which pumps, feedthroughs, gauges or other diagnostic systems can be attached.

A steel-shelled vessel, spherical or not, can also act as the outer grid of the fusor, which acts as the ground potential of the electric field generated in the chamber (Hull, 2012a). A glass reactor, however, needs a custom outer grid placed inside of the reactor alongside with the inner grid to act as ground potential, to generate the electric field. The shape of the grounded steel chamber influences the acceleration path of the deuterons, which is further discussed in chapter D.4 and is backed by simulation figures. However, an outer grid could be used, which would be attached to the inside of the chamber, which is grounded on the outside, but as the bulk of ions are generated very close to the inner grid, the increased fusion count is negligible (Messmer, 2019).

As stated before in chapter B.2.1, and discussed in chapter B.2.6, any glass in a fusor is a major source of X-ray radiation, and thus glass vessels are inappropriate for fusion reactions unless additional radiation safety measures are taken, as a fusor requires higher voltages than a demo-fusor does and thus generates higher energy X-rays. A demo-fusor requires a lower voltage, since the only goal of a demo-fusor is to produce a look-alike, while a deuterium-fusor attempts detectable fusion, which can theoretically be achieved with voltages as low as $20\ kV$ but require expensive neutron detection gear (Hull, 2011b).

B.2.3.2. Vacuum pumps

As the deuterons are shot at incredibly high speeds to the negatively charged inner grid at the centre of the reaction vessel, no other particles must be present in the reaction chamber that could interfere with the path of the high-speed ions. Because of this, the fusion reactions will only take place in a vacuum environment where the mean free path of the ions is increased. To be more specific, fusion reactions in our type of setup will require a vacuum of $2.6 \times 10^{-2}\ mbar$ to $1.3 \times 10^{-3}\ mbar$ (Hull, 2011b). At higher pressures, the voltages required for detectable fusion reactions cannot be achieved without melting the inner grid due to high currents. At lower pressures, no amount of voltage applied will result in detectable fusion, as there is an insufficient number of ions able to potentially fuse.

The low pressures are achieved with two pumps. A so-called backing or roughing pump, and a high vacuum pump, like a diffusion or turbo pump. Two pumps are needed since the high vacuum variant will not function at atmospheric pressure and therefore most of the gas must be removed using a conventional vacuum pump that does function at atmospheric pressure. In this project, problems arose with the high vacuum pump, which are discussed in Chapter **Error! Reference source not found.**. The backing pump used in the RSR-1 experiment can t heoretically achieve $2.4 \times 10^{-3}\ mbar$ which at first glance seems to be more than enough for fusion, but that is not the case. When pumped down to $2.4 \times 10^{-3}\ mbar$ from atmospheric pressure, the reaction vessel is still filled with a lot of atmospheric gases that will contaminate the fusion environment. To combat this, the pressure must be reduced to $1 \times 10^{-6}\ mbar$ or lower using a high vacuum pump which will remove those contaminants. After this operation, the pressure is increased back to fusion levels of $1.3 \times 10^{-3}\ mbar$ to $2.6 \times 10^{-2}\ mbar$ by injecting deuterium gas at a constant flow into the vessel while keeping the high vacuum pump running at a throttled speed by utilizing a vacuum flow control valve mounted on the input of the high vacuum pump, as to not waste too much potential fusion fuel. Controlling variables such as the flow control valve throttling ratio and the flowrate of deuterium creates a pure deuterium fusion-ready environment at the correct fusion-level pressure. This also explains why a demo-fusor utilizing atmospheric gases instead of deuterium fuel does not require a high vacuum pump, as the gases used in the demo-fusor already exist in the chamber when no vacuum is present, and contaminants are not an issue as detectable fusion is not desired here (Hull, 2014).

B.2.3.3. Measuring pressures in a high vacuum system

There are many ways to measure the pressure in a vacuum chamber. Vacuum gauges can be subdivided into 4 main categories, all responsible for their own pressure ranges:

1. **Mechanical gauges** use some form of mechanical deformation to measure the differences in pressure. Most of these designs make use of a reference vacuum. One side of the meter is subjected to the unknown vacuum, while the other side is subjected to a known and stable reference pressure. The difference in mechanical deformation can be calculated and thus the pressure in the chamber can be determined. Bourdon gauges and McLeod gauges are examples of mechanical gauges (VAC aero International, 2019).

2. **Absolute pressure gauges** measure the pressure over the full vacuum range. Absolute pressure remains accurate and precise, even when the ambient surrounding or process temperature changes. When measuring with these gauges, the current atmospheric pressure is the baseline. This means that it is slightly off, since the current atmospheric pressure can fluctuate a bit depending on where the gauge is located. This is however still considered to be the most accurate gauge with a large pressure range (VAC aero International, 2019).

3. **Thermocouple or Pirani gauges** are the most widely used gauges available. These gauges rely on thermal conductivity to measure the pressure. A wire (usually made of tungsten) gets heated by an electrical current. The heated wire gets cooled down when it gets hit with gas molecules inside the air, since they carry away some of the heat when they hit the heated wire. When the pressure gets lowered, the number of collisions with the wire decreases. This means that the wire cools down slower. The problem with these gauges is that the thermal conductivity for each gas is slightly different. This means that the gauge is inaccurate unless it gets calibrated accordingly for the gas being measured. This is also problematic when the chamber is contaminated since the gauge will show a higher pressure than is achieved. A thermocouple gauge measures the temperature of the wire, while a Pirani gauge measures the resistance of the wire (VAC aero International, 2019).

4. **Ionization cathode gauges** can only be used at low pressures. There are two types of these ionization gauges: cold and hot cathode gauges. These gauges create a crossed electric and magnetic field to trap electrons. The hot cathode gauges then make use of a heated filament to discharge the electrons quicker than the cold cathode can. These electrons are then ionizing the residual gas with help from the magnetic

field. Lastly these ions are collected and measured to calculate the pressure of the gas (VAC aero International, 2019).

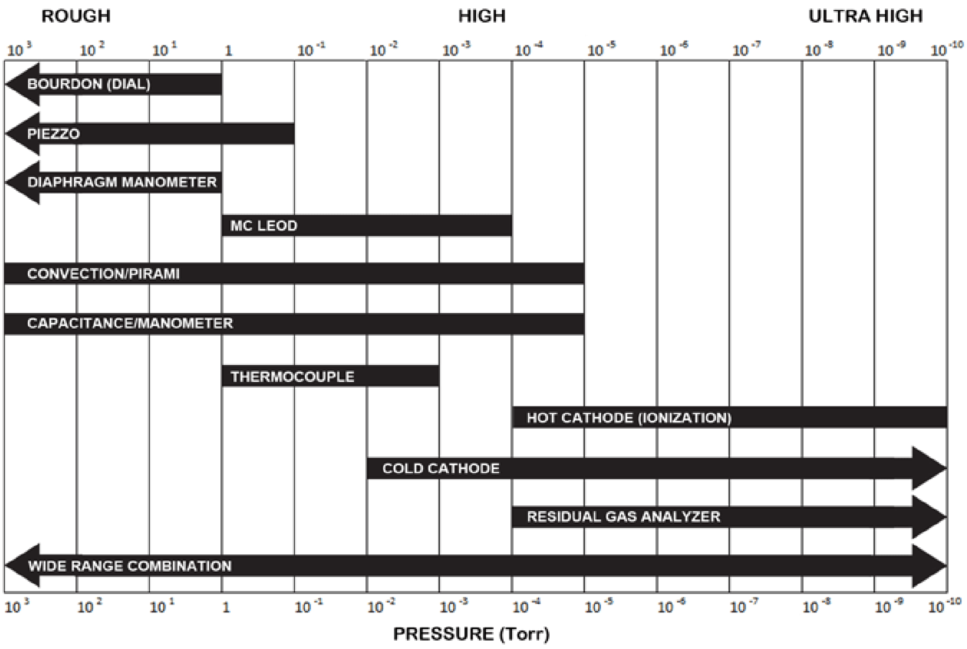

Figure B.7: A rough visualization of the different operation ranges of different kinds of vacuum gauges (VAC aero International, 2019).

These types of gauges all have different operating pressures (Figure B.7). Most often one vacuum gauge is used for measuring high pressures, and another for low pressures, as is the case for the use of two vacuum pumps both responsible for their own pressure range. One must make sure that most of the vacuum spectrum where experiments are conducted can be observed. Some of these gauges entail their own constraints or inaccuracies, as mentioned before.

B.2.3.4. Inner grid and high voltage electrical vacuum feedthrough

To apply a high voltage inside the vacuum chamber to the spherical inner grid, a specialized electrical lead must be used which is separated from the grounded shell, while also maintaining vacuum levels and thus a so-called electrical vacuum feedthrough is used. The feedthrough conductor is insulated from the steel reactor vessel using an insulator, most often aluminium oxide, which is a type of ceramic. This ceramic has a vacuum-tight connection with the flange in which the feedthrough is housed, as well as the conductor which passes electricity through the flange into the vacuum side of the chamber. This is where the inner grid is mounted (Hull, 2011a).

In a fusor, there exists a balance between the voltage applied and the pressure of the fuel inside the chamber. Finding the optimal values for these two variables is essential in obtaining a fusor capable of doing detectable fusion. The voltage required is determined by the distance the ions can accelerate into the inner grid. A lower distance results in a higher required voltage. The potential required in most fusors range from $20\ kV$ all the way up to $100\ kV$. Above $35\ kV$, X-rays will start to penetrate the steel outer vessel due to bremsstrahlung, and proper shielding is required, as will be explained in chapter B.2.6 (Hull, 2011b).

B.2.3.5. High voltage power supply

As the fusor requires a strong electric field to both ionize and propel ions to the inner grid, a high negative voltage potential must be utilized which can be generated by a high voltage power supply. There exist three main types of power supplies: ‘positive hot’, ‘negative hot’, and ‘floating’ power supplies. The types of supplies have their negative lead, positive lead, and no leads grounded, respectively. A fusor device requires that its power supply must be ‘negative hot’ or ‘floating’, so that the positive lead can be connected to the fusor’s outer shell and ground potential. Often standard and high voltage power supplies are built to be positive hot, which is not suitable for fusor operation, as the inner grid must be negatively charged as to attract positively charged ions.

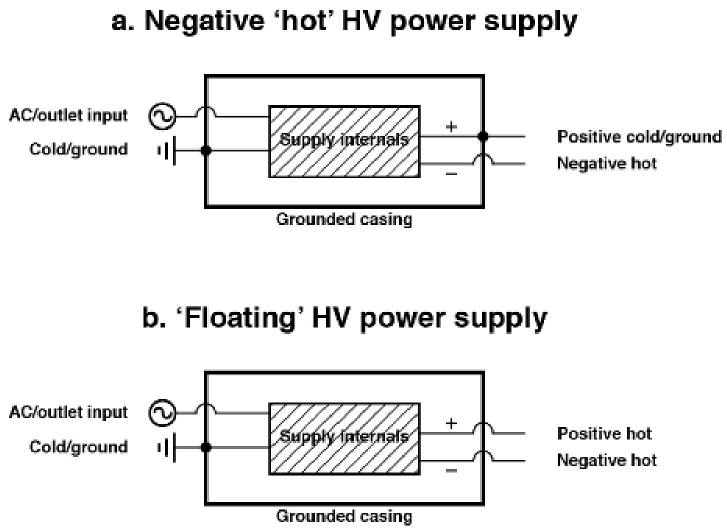

Figure B.8: The two types of high-voltage power supplies suitable for fusors. The figure interprets a dot as an electrical connection, while a half-circle bridge represents an insulation point. Supply inputs are illustrated on the left, while outputs are on the right. Notice that the only difference between the two is whether or not the positive lead is grounded.

A positive hot power supply cannot be used for a fusor operation, because it requires that the outer vessel is not connected to the ground, thus creating a highly dangerous environment around the fusor, since lethal currents, which overcome the breakdown voltage of a sufficiently small airgap between the operators and fusor, can flow through the operators, potentially causing casualties. Another downside is that diagnostic systems connected to the 'hot' vacuum vessel, will potentially be damaged or destroyed as unwanted currents will flow through them, unless additional electric isolation is used between the vessel and diagnostic systems.

Whether or not the high voltage power supply is built in a 'negative hot' or any other configuration, can be checked in the following manner if it is unknown to the operator: the resistance between the two poles can be measured with respect to the power supply's grounded electrical plug lead with a resistance meter, when the power supply is disconnected. The pole which results in a value that is close to $0\,\Omega$ is grounded. Poles that result in a resistance value of $\infty\,\Omega$, are not grounded or 'hot'. If the negative pole is grounded, the power supply is not suitable for use within a (safe) fusor setup, depending on whether the grounding of the poles can be manually changed. If the two poles are floating, the positive lead must be grounded manually (Harmsma. P.J., personal communication, 2023, February 8).

B.2.3.6. Fuel injection in a demo-fusor versus a deuterium-fusor

The main difference in fuel injection between a demo-fusor and a deuterium-fusor is the absence of deuterium fuel in a demo-fusor. A system built for deuterium fusion is also able to operate as a demo-fusor. Instead of incorporating a deuterium gas or deuterium ion source, the fuel injection system is simply non-existent, as the demo-fusor relies on the backing pump's ultimate pressure. This way, the remaining air that cannot be evacuated by the roughing pump can be used as 'fuel' in producing a plasma. Though undetectable using basic equipment, very small amounts of fusion take place. Deuterium fusion is much easier to both achieve and detect, and therefore the go-to fuel in a fusor. Deuterium-tritium fusion would be even better, but as tritium is highly regulated due to its radioactivity, it is considered unobtainable in the scope of this project (Hull, 2007).

There are multiple ways to inject fuel into the fusor reaction chamber, the first of which is to make use of high-pressure research-grade bottled deuterium gas. The advantage of this method is that the deuterium is of high purity. Though, implementing such a system is costly, and requires multiple pressure gauges, valves, and capillary tubing, as the high pressure of the deuterium must be brought down such that it is suitable for vacuum use. Glass viewports can explode when the high pressure is incorrectly handled and creates an above-atmosphere pressure in the vessel (Van Elswijk, J.I.M., personal communication, 2022, September 6). To combat this, one can make use of the electrolysis of heavy water or D_2O, which results in low-pressure deuterium gas and oxygen, of which the oxygen is disposed of. The low-pressure fuel can be fed into the reactor directly with just a couple of gas valves, including a needle valve, without risking a huge increase in pressure in the chamber, as the pressure of the deuterium gas originating from the cell is at atmospheric pressure, instead of high pressure. Unfortunately, the PEM cell cannot be connected directly to the gas input, without risking vacuuming the PEM cell and destroying it. While the PEM cell can be modified by incorporating a safety system in the form of an oil reservoir described in Figure B.9, an easier method is to use simple plastic syringes to enable the transport of gas from the fuel generator and reactor fuel input. The result of this is two disconnected systems that do not risk breaking the other. A disadvantage is that the syringes have a small so-called 'dead volume' of plain air in the tip which must be vented out of the gas input before initializing deuterium fusion (Clagwell, 2021; Sandbakken, 2014).

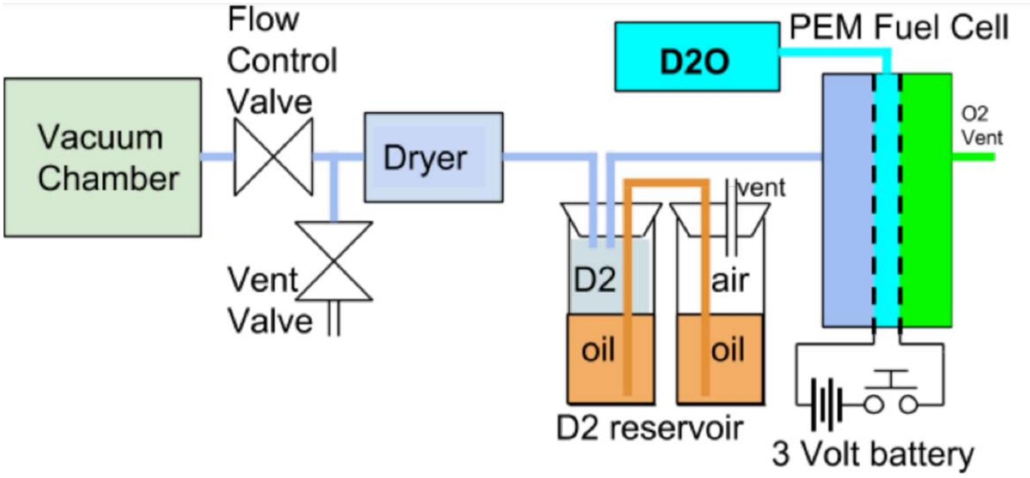

Figure B.**9**: Figure illustrating the working principle of a connected PEM system incorporating a gas overdemand safety system. When the reactor demands too much deuterium gas, the oil level in the rightmost oil reservoir will lower, until atmospheric air bleeds into the vacuum system to prevent vacumizing and damaging the fuel cell. The generated deuterium gas is removed of moisture by a gas dryer (Sandbakken, 2014).

B.2.3.7. High vacuum pump flow control valve

A flow control valve is used in between the main reaction chamber and the high vacuum pump if the latter cannot be throttled internally, which is different from the flow control valve illustrated in Figure B.9. This is done since a lot of costly deuterium gas will be ejected out into the atmosphere without giving the gas a chance to ionize and fuse, if throttling is neglected. This way, the fusion cross-section is increased. An alternative for a flow control valve would be to simply inject more deuterium gas into the chamber, but as deuterium is an expensive asset, it is preferred to simply throttle the flowrate of the high vacuum pump rather than wasting deuterium.

There are many types of vacuum valves available, and one must pay attention to their type and usage. A vacuum shutoff valve could technically be used, but as the flow rate through the valve with respect to the amount the valve has been closed is not linear with these types of valves, it is rather undesirable to use shutoff valves for throttling. A second disadvantage is that most shutoff valves require a quarter turn of the valve handle to fully open or close the valve, which cannot be used for precise control of flow through the valve (Hull, 2017).

B.2.3.8. Approach to observing the reaction

As stated before, massive amounts of X-rays will penetrate the glass during a fusion reaction. Because of this, operators are unable to peek through the viewports to observe the reaction without exposing themselves to X-ray radiation.

Without a visual confirmation that a plasma is forming and doing fusion in the centre of the reaction chamber, the operator is unable to verify if everything is under control. This visual confirmation is also a must-have to control the fusor to achieve higher fusion levels. A common way to observe the reaction is by utilizing (digital) cameras. The advantage of using cameras is that they can be replaced cheaply (and your eyes sadly cannot). One example of cheap camera's is the camera from the Raspberry Pi Foundation, which can easily be connected to a Raspberry Pi microcomputer on which the reaction can be viewed digitally.

B.2.3.9. Proving that fusion is taking place

There are multiple ways to prove that fusion is taking place. One way is to use a bubble dosimeter. A bubble dosimeter is a type of radiation detection device that is used to measure the dose of radiation that an individual or object has received. The bubble dosimeter is filled with superheated droplets of liquid trapped in gel. When such droplets are hit with high energy neutrons, they will turn gaseous and become visible bubbles inside the gel. These gas bubbles can be counted and the number of fusion reactions happening per second can be calculated when measuring the number of bubbles per second (Bubble Tech Industries, n.d.).

To use a bubble dosimeter to prove that fusion is occurring in a fusor, the bubble dosimeter must be placed in the vicinity of the fusor, so it is exposed to the radiation produced by the fusion reactions. If the bubble dosimeter indicates that a significant amount of radiation has been received, it can be used as evidence that fusion is occurring in the fusor. However, it is important to note that a bubble dosimeter is only one of several methods that can be used to confirm the presence of fusion in a fusor, and other methods may be needed to fully confirm the occurrence of deuterium fusion, like the presence of high energy neutrons.

This concludes the closer look at all the main parts used in a Farnsworth-Hirsch-Meeks fusor.

B.2.4. General description of the path of a fuel particle

In a deuterium fusor, deuterium atoms are used as the fuel for the fusion reactions. Deuterium is a stable isotope of hydrogen with one proton and one neutron in its nucleus. When two of these deuterium particles collide, there is a 50% chance that they form ${}^{3}_{2}He$, releasing one neutron. The other 50% chance is that they form ${}^{3}_{1}H$ (also known as tritium), releasing one proton according to eq. (B.4).

Deuterium atoms are injected in their gaseous state into the reactor, in which they ionize due to the electric field generated between the reactor shell and inner grid. After this plasma has formed, electrons will be pulled from the plasma to the outer shell. The nuclei are shot toward the centre of the inner grid since the grid is negatively charged, while the nuclei are positively charged. As the deuterium ions change their state to plasma in this point, their density increases, which increases the chance of fusion reactions taking place (Messmer, 2019).

B.2.5. Effects of fingerprint vacuum contamination

According to Danielson (2001), fingerprints have an enormous impact on the pump down of the entire system. One single fingerprint contains about 1019 molecules and loads of about $1.3 * 10^{-7}\text{atm. L}/sec$. It would take between 24-36 hours to pump away the fingerprint. This means that the pump will reach a higher pressure than it is rated for (Figure B.10). This means that a few fingerprints can already have a large impact on the maximum vacuum that is achieved in a fusion experiment (Danielson, 2001).

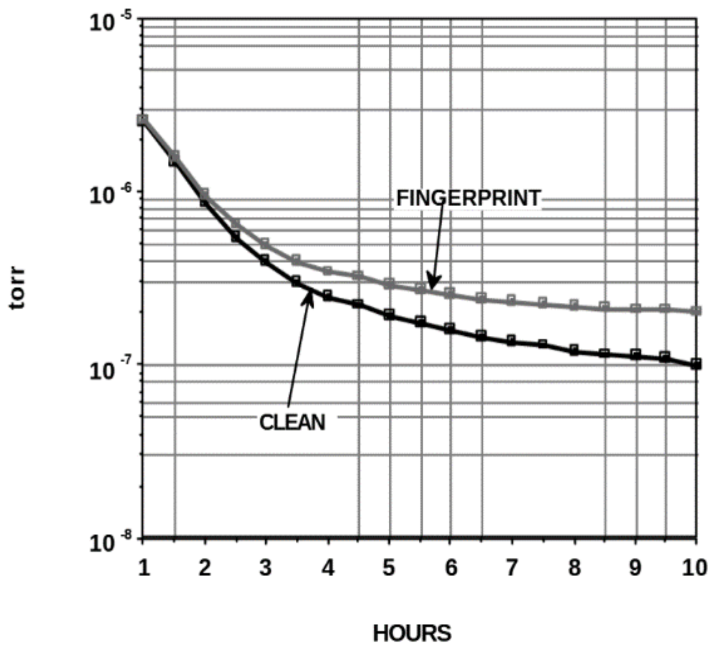

Figure B.10: *Graph showing the impact a fingerprint has on a vacuum system's ultimate pressure.*

Most high vacuum pumps use oil to achieve low pressures. Vacuum pumps are mechanical; they have a lot of moving parts. They spin and to make sure that air doesn't get back in the chamber, there is oil seal. This oil though can evaporate, and the oil vapor is able to slither past the seal, into the chamber. If the chamber is still at high pressure, a lot of air molecules are leaving the chamber, so the oil vapor is being pushed back. Once there is low pressure though, a problem arises. There is only a little air leaving the chamber and this isn't enough to push back all the oil particles. These oil particles can interfere with the fusion, and this means that fusion might not take place if the parts are contaminated by oil or fingerprints (Danielson, 2001).

B.2.6. Radiation emittance and safety measures

During the operation of a fusor or other type of fusion devices, high-energy particles and radiation are produced because of the fusion reactions. These particles and radiation can pose a potential health and safety risk if they are not properly contained and controlled. This is also why the Dutch government does not allow the release of radiation in particle accelerators with more than $1.0\ MeV$ of energy without a permit (Nederlandse Overheid, 2021).

As mentioned before, electrons move from the negatively charged inner grid to the positively charged shell, because of the potential difference between them. Some of these electrons hit atoms that were floating around in the vacuum, the following reaction occurs:

$$N + e^- \rightarrow N^+ + 2e^- \tag{B.6}$$

Where N represents an atom. An electron fired from the inner grid hits the atom and rips one of the electrons out of its shell. This turns the atom into a positively charged ion. The two electrons combined have a lower speed then the higher energy electron fired from the inner grid. The speed of the electron fired from the inner grid can be determined according to the following set of formulas:

$$\Delta E_{el} = qU \tag{B.7}$$

$$E_k = \frac{1}{2}mv^2 \tag{B.8}$$

$$qU = \frac{1}{2}mv^2 \rightarrow v = \sqrt{\frac{2qV}{m}} \tag{B.9}$$

With eq. (B.7), the increase in electric energy can be determined when a unit is subjected to an electrical field. With eq. (B.8), the kinetic energy can be determined, since the amount of electric energy that one electron gets from the electrical field is equal to the kinetic energy the electron has when it leaves the inner grid ($E_k = \Delta E_{el}$). The other sides of these equations are equal too, resulting in eq. (B.9). With the eq. (B.9), the speed of an electron released by the inner grid when it arrives at the outer shell can be determined (Beck, 2020).

Knowing the speed of an electron, it is possible to calculate the bremsstrahlung. Bremsstrahlung (break radiation) is electromagnetic radiation in the form of X-rays. This radiation gets emitted when a charged particle gets slowed down by an oppositely charged particle. With fusors, this is usually an electron that gets slowed down by the positively charged nucleus of an atom (Figure B.11). This means that the electron in position E_2 has a lower speed than the electron in point E_1. The kinetic energy of the electron gets turned into radiation. The photon released is directed perpendicular to the movement.

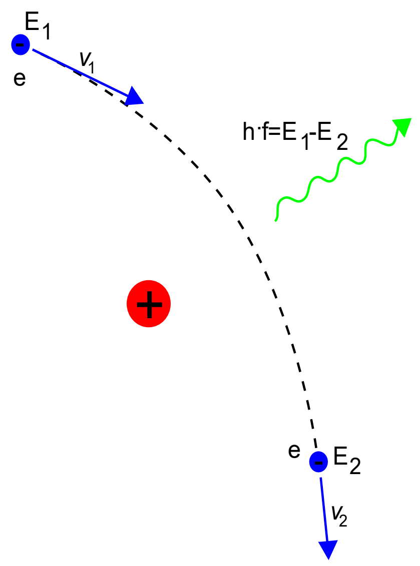

Figure B.11: Bremsstrahlung being produced by an high energy electron when interacting with the electric field of an atomic nucleus (Wikipedia, 2023a).

Usually, like depicted in Figure B.11, the electrons do not lose all their kinetic energy when they pass through the electric field of an atomic nucleus. This means that one electron can emit multiple lower energy photons. Lower energy photons (such as visible light or so-called soft X-rays) get emitted more often than high energy photons (such as hard X-rays), since it is likely that the electrons will pass through the electric field at a larger distance to the atomic nucleus. It is possible to calculate the maximum frequency of the photons that get released, using the following formulas:

$$E_{radiation} = hf \tag{B.10}$$

$$E_{rad} = E_k \quad \rightarrow \quad f = \frac{mv^2}{2h} \tag{B.11}$$

The previously established kinetic energy will be turned into radiation when the electron hits the outer vessel. The electron will lose all its kinetic energy, but, as stated before, this usually **does not** happen in one go. The calculated frequency of the released photon will for that reason be much higher than is radiated (Boon, T., personal communication, 10/02/2023).

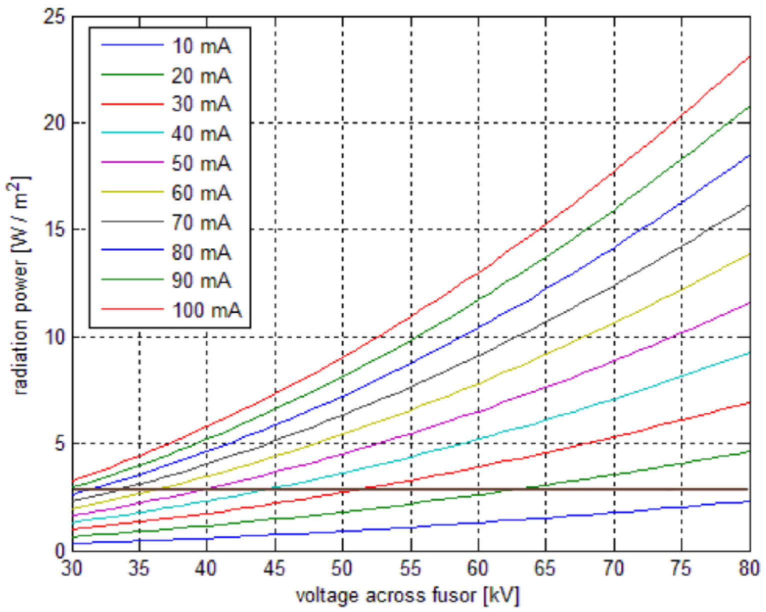

Figure B.12: Graph of the radiation power produced by bremsstrahlung when electrons hit stainless steel. The radiation power per square meter is plotted as a function of the voltage across the fusor. The brown line represents the amount of background radiation that hits the earth per day (Minderhout, 2014).

The X-rays that get released when the fusor is turned on, can be dangerous for the human body. Radiation with a low frequency is not dangerous to the human body. Demo-fusors normally do not send out much radiation (Minderhout, 2014). Bremsstrahlung only becomes dangerous after it comes close to the amount of background radiation. Figure B.12 shows the amount of Bremsstrahlung that is released when running a fusor. It is important to make sure to stay under the background radiation for safety reasons, or to make sure that proper shielding is put in place and a safe distance is kept at all times. When doing deuterium fusion though, high energy neutrons get emitted. Since neutrons pass through almost everything, it is hard to be safe from these neutrons. A thick layer of lead or a large distance from the chamber are solutions to the problem of neutron radiation (Hull, 2012b).

Glass windows can be a safety hazard since glass is easily penetrated by radiation. Photons can pass right through, so X-rays do not get stopped or even slowed down when moving through the glass. As unshielded glass viewports on a reactor are dangerous, these viewports must be aimed at the ground while making sure no person is beneath the lab floor. Additionally, lead shielding can be put in place as an extra precautionary measure, which is a must on vessels doing fusion (Wikipedia, 2023a).

One other safety aspect that must be kept in mind when working with fusors is the usage of high voltage. Since it costs a lot of energy to overcome the electromagnetic repulsion, all fusion devices that use electrostatic confinement will need to have a high voltage power supply. This high voltage can also be lethal for the human body and when talking about high voltage, everything is a wire. Since the voltage wants to be spread evenly, the high voltage will even go through the air and create sparks to oppositely charged objects. To make sure the high voltage is handled safely, the outer shell should be grounded to avoid sparks to other objects outside the chamber. Other high voltage objects should be insulated properly (Hull, 2013).

The chamber should also be covered with high voltage stickers to make sure that even unknowing passers-by know that the chamber is potentially deadly to touch. There also needs to be a failsafe system put in place for when something goes wrong, like a big red switch which clearly says, “power off”, so that even people without knowledge of the experiment that is conducted will know how to turn it off. People also need to be at a safe distance from the potentially charged chamber (Hull, 2013).

B.3. Producing net-energy

If a nuclear fusion machine that can produce net power is built, there will come a (at least the promise of) never-ending energy due to the abundance of hydrogen atoms. There are multiple main approaches to pursue this goal. The most complex concepts are designed to fuse two heavy hydrogen isotopes. Most often, deuterium-tritium fusion is used to try to produce energy from the fusion of those atoms, according to the following reactions:

$$D + T \rightarrow {}^{4}_{2}He(3.5\ MeV) + n(14.1\ MeV) \tag{B.12}$$

The energy the helium isotopes get is kinetic. The kinetic energy can be turned into electric energy in multiple ways. One way to turn the kinetic energy from the neutrons into electric energy is to make use of a steam engine. Around the vacuum chamber is a bath of water. When a water molecule gets hit with a high energy neutron, it will get most of the kinetic energy from the neutron and try to change state from liquid to gas (U.S. Department of Energy, 2021).

As visible in Figure B.13, the water will warm up at the reactor vessel but is unable to turn into gas. This is because a gas takes up more space than a liquid. The hot water gets pulled from chamber 1 by a water pump through a series of pipes that run through another chamber with water. The pipes with hot water that run through the chamber have a circular shape, so they have as much surface area as possible. The water inside chamber 2 gets the heat from the pipes and turns into steam. The steam moves to a turbine which starts to turn, and this generates electricity. Figure B.13 also depicts how most nuclear fission reactors create energy (U.S. Department of Energy, 2021).

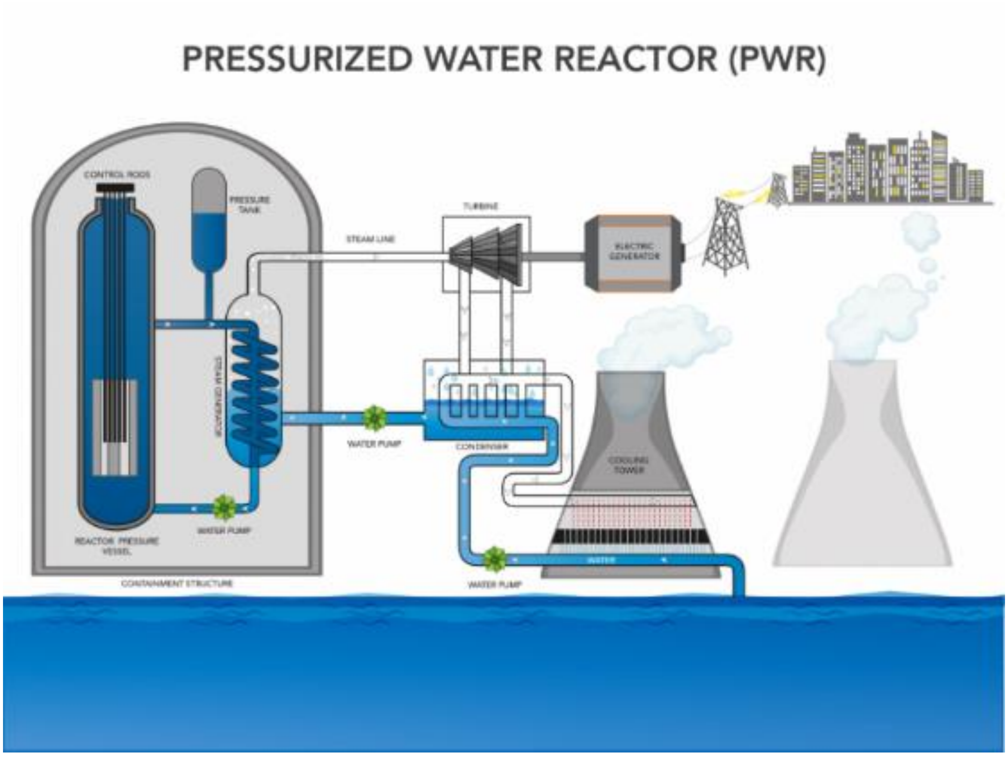

Figure B.13: Turning kinetic energy into electric energy (U.S. Department of Energy, 2021).

The challenge with creating net energy is to get more energy than one must put in. For the deuterium-tritium fusion to occur, the temperature of the plasma will need to be around 150 million Kelvin. Hydrogen has the lowest electromagnetic repulsion of all elements, since it has the lowest number of protons in the nucleus. The temperature needed to fuse and the number of protons per nucleus scales proportionately. Boron for example would need to be heated to around $600{,}000{,}000\ K$ since it has 4 times the number of protons as hydrogen has. This is one of the reasons why deuterium-tritium fusion is so fruitful (Letcher, 2023).

On December 5th, 2022, researchers from the Lawrence Livermore National Laboratory (LLNL) (for the first time ever) got a positive power output while doing nuclear fusion. This breakthrough happened at LLNL's National Ignition Facility (NIF). The fusion that happened in the reactor generated more energy than the lasers used to drive the fusion. There was more than 60 years of research and development that ultimately led to the crossing of this threshold. To pursue a concept from the 1960s, LLNL built a series of powerful laser systems. This ultimately led to the creation of NIF, which is the largest and most energetic laser system in the world. 192 lasers delivered $2.05\ MJ$ to a capsule with hydrogen nuclei. This resulted in a positive output of $3.15\ MJ$ (U.S. Department of Energy, 2022). This might sound like a lot of energy, but this amount of energy is only enough to bring a kettle to a boil. There still needs to be a lot of research done to get a stable flow of almost infinite amount of clean energy available.

B.3.1. Fundamental net-energy problems in IEC systems

Overcoming the Coulomb repulsion between two ions is the main obstacle of fusion physicists attempting to achieve a net-energy gain from nuclear fusion, which requires large amounts of kinetic energy for them to come close enough to make nuclear fusion possible. In a fusor, this is achieved by electrostatic confinement. There exist several issues which make it fundamentally impossible to achieve a positive net-energy gain in fusor systems.

The first issue is the escape of electrons. When deuterium is ionized, electrons will be accelerated towards the outer shell where their kinetic energy is simply absorbed by the walls of the vessel in the form of bremsstrahlung, which in turn generate X-rays. The electrons are then absorbed by the walls, and the energy that could be used to both ionize deuterium and accelerate the formed electrons is wasted.

Secondly, due to the nature of the inner grid, there exists a chance that ions collide with the non-transparent parts of the inner grid, and their potential fusion energy is lost. If the path of ions is not a straight line and keeps altering, their paths will eventually intersect with the inner grid, and thus the ions proceed to collide with the grid, after which their energy is lost.

Another problem lies in Coulomb scattering between deuterium ions. In a perfect situation, all deuterium ions will be infinitely oscillating in a perfectly straight line through the electric field until a fusion event occurs, as can be seen in Figure B.3, and no energy is lost by accelerating ions. The problem, however, is that ions interact with each other. Thus, according to the second law of thermodynamics, which states that the state of entropy of an isolated, irreversible system will always increase over time (National Aeronautics and Space Administration (NASA), n.d.), a high-speed, high-energy moving ion capable of fusion will cause another slow, low-energy ion to change its direction and/or velocity, thereby transferring energy. This transfer of energy causes the previously high-energy ion to have an insufficient amount of energy to do fusion, and thus the fast ion can no longer fuse, but the slow ion does not gain enough energy to fuse. This leads to thermal equilibrium: the fast ions (hot ions) lose their speed (temperature) to other slow ions (cold ions), and their chance to collide with the inner grid approaches 100%. What is important to remember here is that, as previously mentioned in chapter B.2.2, most deuterium ions are formed close to the inner grid. This means that when looking at the temperature of the entire system, the average temperature of each ion is lower than the minimal required amount of energy for fusion, which is approached by the system and results in massive energy losses.

To elaborate in a more mathematical approach: to obtain fusion, two ions must get very close, and it takes energy to overcome the Coulomb force that drives them apart. The Coulomb force is given by

$$F = \frac{q_1 \cdot q_2}{4\pi \cdot \varepsilon_0} \cdot \frac{1}{r} \tag{B.13}$$

Where constant ε_0 is the permittivity of free space, q_1 and q_2 represent the two charged particles, and r represents the distance between the two charges.

The minimum distance between ions to obtain fusion is in the order of $2 \cdot 10^{-15}$ meters. The cross-sectional area of the ions is equivalent to

$$\sigma = \pi \cdot r^2 \tag{B.14}$$

With r being the minimum distance between ions to obtain fusion.

The probability P that an ion collides with another ion is equal to

$$P = \frac{N \cdot \sigma}{A} \tag{B.15}$$

Where N is the number of ions in a volume and A is the cross-sectional area of the volume. This can be written as

$$\frac{n \cdot V \cdot \sigma}{A} = n \cdot dx \cdot \sigma \tag{B.16}$$

Where n is the ion density, and V is the volume of the reactor.

If $P = 1$, the average distance an ion will travel before fusing with another ion is obtained, and thereby

$$dx = \lambda_m = \frac{1}{n \cdot \sigma} \tag{B.17}$$

As an estimate, $\sigma = 4 \cdot 10^{-30}$. In one cubic meter air at $1\,atm = 1 \cdot 10^5\,Pa$, the number of atoms in the volume is approximately $1 \cdot 10^{26}$, so at $1\,Pa$, $n = 1 \cdot 10^{21}$. Therefore, when plugging these values in equation (B.17), the path length λ_m is approximately $2.5 \cdot 10^8\,m$. If the fusor is for example $5 \cdot 10^{-1}\,m$ in diameter, the ions would have to oscillate $5 \cdot 10^8$ times back and forth through the inner grid to have an efficient process. However, the inner grid is not sufficiently transparent, and the probability that an ion will hit the inner grid or get neutralized in some other way resulting in energy losses during its $5 \cdot 10^8$ passes is almost one, and therefore the output energy of a fusor is considerably lower than the input energy on a fundamental basis. Because of this, fusors are mainly used as neutron sources and research environments for plasmas and nuclear fusion (Harmsma, P.J., personal communication, 2023, February 10; Jaspers, R.J.E., personal communication, 2023, January 11; Messmer, 2019).

CHAPTER

C

Method

Due to a variety of problems discussed in the beginning of this paper (e.g. the license requirement), this chapter will only describe the method of constructing a demo-fusor, with the potential for it to be upgraded to a deuterium-fusor. The design of the constructed RSR-1 fusor closely resembles the bare-bones deuterium systems built by the fusor.net community, which are variations of the original Farnworth-fusor.

An unprecedented large amount of research had been done from the ground up, as we barely had any knowledge of high vacuum systems and nuclear fusion, let alone fusors. It is essential to not rush the research stage of a project of this scope and costs, as mistakes are easily made resulting in wasted money and crushed expectations. It is also best kept in mind that there does not exist a step-by-step instruction manual in which the construction of a fusor is explained in high detail, due to the variety of options the constructor has regarding diagnostic systems, vacuum pump types among other things. This chapter will only describe a general approach to building a fusor, and it is recommended to thoroughly read chapter B of this paper, which gives a basic introduction regarding the subject, and the fusor.net forums linked in the references.

After a considerable amount of research had been done, due to extreme system costs, we needed sponsorship to even begin considering building a fusor, which succeeded thanks to the cooperation of TNO and Gimex, while the Eindhoven University of Technology assisted with theoretical principles and fusor demonstrations. When working with a limited budget, it is best to work hard to get institutes or relatives to cooperate and help with project funding.

From the received parts from TNO, a lot of time had been spent optimizing the cheapest, most efficient way to construct a fusor from all sponsored parts utilizing 3D illustration software and dozens of drawings and sketches. Additional required parts were ordered from our budget, and even a sponsorship deal with Gimex was established, after which the final system design was built. A parts list consisting of all the parts used in the RSR-1 system can be found in Table D.1.

CHAPTER

D

Results

D.1. RSR-1 project costs

High vacuum equipment among other things were necessary for the construction of RSR-1. The costs of which have been put in Table D.1 below.

Table D.1: RSR-1 parts list and prices per part according to Kurt J. Lesker (https://www.lesker.com/), neglecting aluminium foil and glove usage, as well as cleaning materials.

General parts	RSR-1 parts	Costs for project funds (€)	Approximated market value (€)
CF tightening bolts, spacers, and nuts	M8 bolts (104), M8 spacers (104), M8 nuts (96), M6 bolts (12), M6 spacers (12)	Sponsored by Gerrit Rietveld College	-
Backing vacuum pump	Leybold Trivac D8B	Sponsored by TNO	2,900.00
Pump oil filter	D8B exhaust filter	Sponsored by TNO	838.00
Vacuum chamber	CF-100 6-way cross	Sponsored by TNO	1,470.00
HV electrical feedthrough	CF-40 12kV feedthrough	142.75	142.75
Feedthrough stalk insulation	25.4x7.0x120.0mm aluminium oxide tube	Sponsored by Gimex	150.00
Inner grid/feedthrough connection	Collets (2)	32.06	32.06

Inner grid wire	10m tungsten 0.5mm wire	27.29	27.29
Viewports	CF-100 viewports (2)	Sponsored by TNO	955.50
Flanges and adapters	CF-100 blank flanges (2)	Sponsored by TNO	297.70
	CF-100/CF-40 adapter	Sponsored by TNO	143.55
	CF-100/CF-63 adapter	Sponsored by TNO	180.40
	CF-63/CF-40 adapter	Sponsored by TNO	97.85
	CF-40/KF-40 adapter	Sponsored by TNO	137.55
	KF-40/KF-25 adapters (2)	Sponsored by TNO	59.30
	KF-40/KF-25 conical adapter	26.45	26.45
	KF-40/KF-16 adapter	Sponsored by TNO	28.60
	KF-16 Bellows hose	Sponsored by TNO	125.00
	KF-40 4-way cross	Sponsored by TNO	134.50
	KF-25 4-way cross	100.65	100.65

CF gaskets	CF-100 copper gaskets (10)	Sponsored by TNO	55.85
	CF-63 copper gaskets (10)	Sponsored by TNO	43.40
	CF-40 copper gaskets (10)	Sponsored by TNO	19.20
KF gaskets	KF-40 gaskets (5)	Sponsored by TNO	26.50
	KF-25 gaskets (7)	Sponsored by TNO	41.65
	KF-16 gaskets (2)	Sponsored by TNO	9.20
KF clamps	KF-40 clamps (5)	Sponsored by TNO	24.00
	KF-25 clamps (7)	Sponsored by TNO	30.10
	KF-16 clamps (2)	Sponsored by TNO	7.50
Valves	KF-25 bellows angle valve	75.07	248.00
	KF-40 venting valve	21.11	21.11
Gauges	Edwards CP25-K cold cathode	Sponsored by TNO	279.50
	Edwards APGX-M NW25 ST/ST Pirani Gauges (2)	Sponsored by TNO	1,210.00

Camera setup	Raspberry Pi Zero W	Sponsored by L.W. Assink	18.50
	Raspberry Pi camera modules (3)	13.74	68.64
	Raspberry Pi SD	5.29	5.29
	Raspberry Pi adapter	2.70	2.70
Power supply	10 kV power supply	Borrowed from Gerrit Rietveld College	-
Total		391.64	9,958.299,958

According to Table D.1, the project, market value wise, is ~4% funded by Gerrit Rietveld College, while sponsors contributed ~96% of the project value.

D.2. RSR-1 construction timeline

The project started with the idea that we were constructing a fully functioning deuterium-fusor, and the best place to start at the time was getting our hands on a high vacuum pump, which is necessary for a deuterium-fusor. For elaboration why this was necessary, visit chapter B.2.3.2. Coincidentally, the Technasium department had a dismantled Pfeiffer TVP-250 turbomolecular pump on display originating from a retired particle accelerator, which we set out to fix. After months of trying to find the right people willing to fix such a pump, including the manufacturer and a hobbyist who repaired the exact same pump model before, we ultimately decided to scrap the idea of repairing the pump and moved on to gathering other essential parts, like a vacuum chamber.

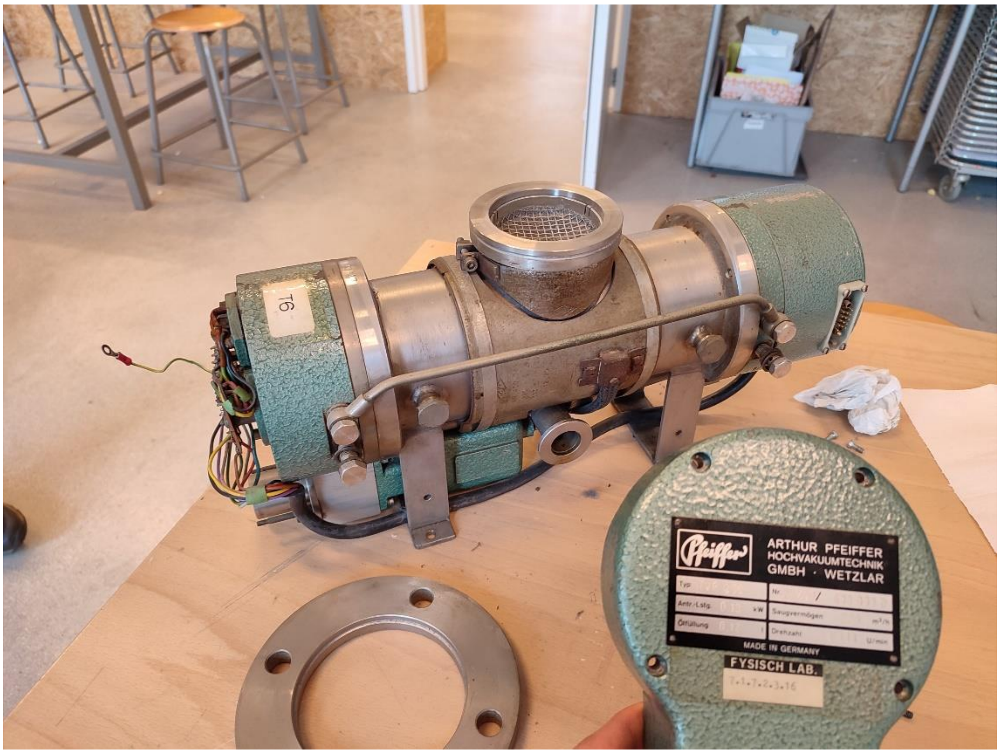

Figure D.1: Dismantled Pfeiffer TVP-250 turbomolecular pump of which many repairing attempts failed.

One of our team members, S. Harmsma, together with supervisor P.J. Harmsma, managed to cooperate with TNO Delft, and we were lent high-end vacuum equipment which gave the project a huge boost. At the time, we had not done research into storing high vacuum equipment, and no aluminium foil wrapping was used to ensure cleanliness of the vacuum parts, which ultimately led to a deep cleaning operation in the school's lab, this is further clarified in chapter **Error! Reference source not found.**.

Figure D.2: A collection of the first batch of parts which was kindly lent out to us by TNO.

After receiving this equipment, we started to investigate what the most efficient way to construct the fusor was. We were at first convinced that the backing pump received by TNO was sufficient to reach pressures required for deuterium-fusor, and a secondary high-vacuum pump was unnecessary. We did not know that the pressure requirement reachable by the backing pump was of a pure deuterium-environment, and a high vacuum pump was indeed necessary to eject most of the atmospheric gasses before injecting deuterium, as described in chapter B.2.3.2. This was discovered later in the project. TNO had a spare turbomolecular pump, though the controller for it was used elsewhere, and thus could not be used for our project. Multiple designs have been modelled in 3D software to check the clearances and to showcase the necessary parts.

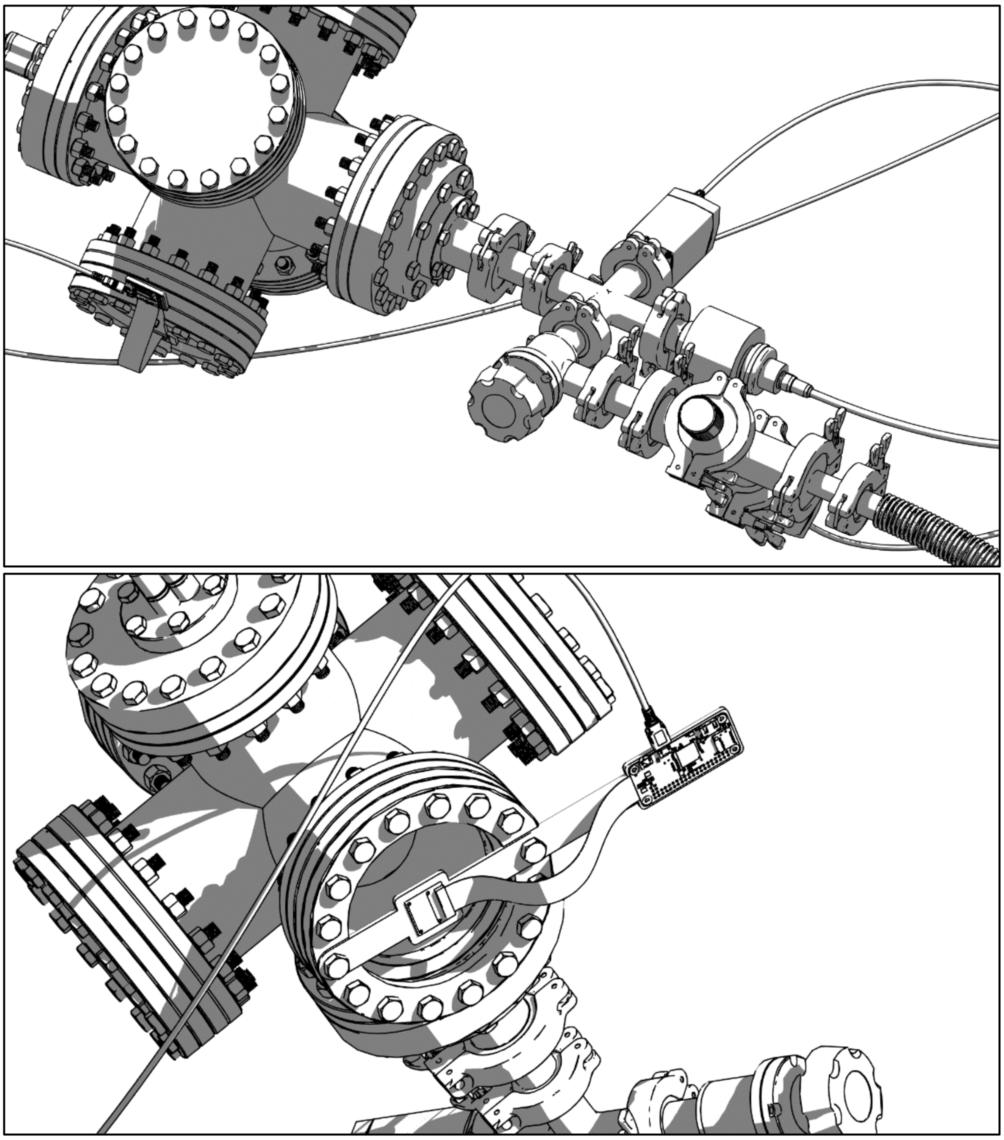

Figure D.3: Renderings of the final RSR-1 system which was designed in 3D software.

Next, additional vacuum parts were bought which allowed us to pump down the system for the first time. We did not have a venting valve at that time, and the throttling valve which was supposed for a high vacuum pump was used for ventilation instead, which was deemed 'unsafe' according to surveillants after a closer examination at our setup. High vacuum was considered 'dangerous' due to the high-pressure difference between the inside and outside of the chamber. Though, the maximum achievable pressure difference in a vacuum system is $1\ atm.$, opposed to high-pressure systems where the pressure difference can be far above $1\ atm$. The first pump down was an investigation whether the vacuum gauges were not defect, and whether the pump was working as expected.

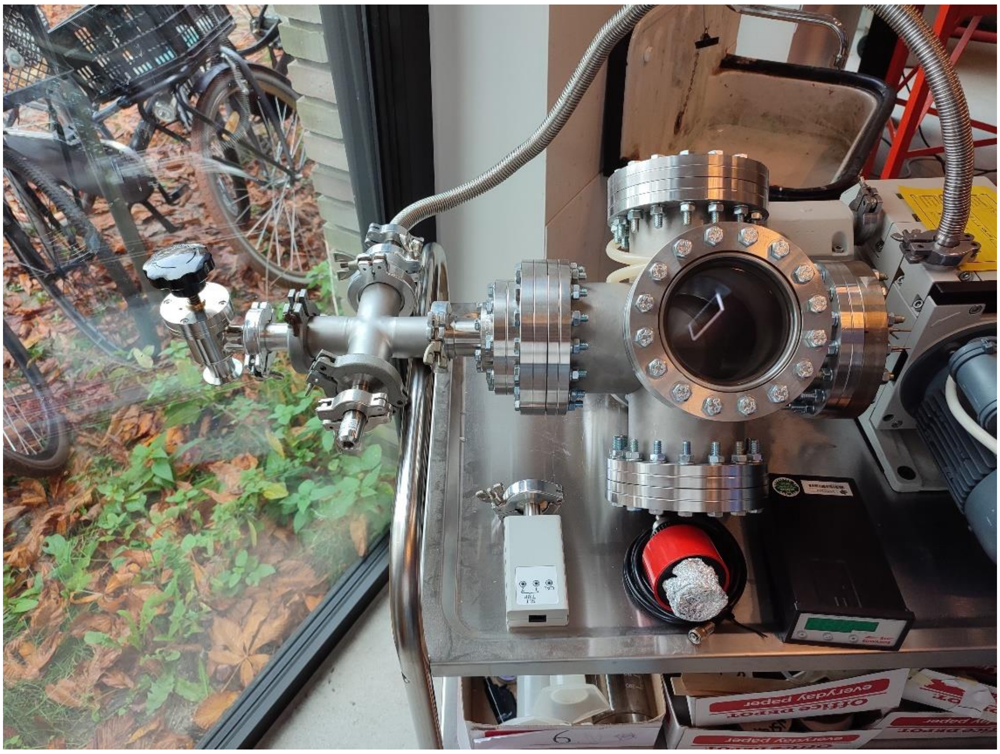

Figure D.4: The first configuration which was pumped down for testing the vacuum pump. At the leftmost side of the system, a bellows angle valve with a black knob can be seen, which was used for ventilation.

After the first test, we were fortunately able to continue with the experiment. After our first test we ordered a few new parts, including a new feedthrough rated for a high voltage, a venting valve, and a 4-way KF-25 splitter. We received the news from Eindhoven University of Technology that we were not allowed to fuse deuterium, since it would emit neutrons (e.g. radiation) with energy levels higher than $1\,MeV$ and would then be considered a particle accelerator, and thus a deuterium fusor would require a permit. It was at this point that we decided to scrap the idea of constructing a system producing detectable fusion and focussed on building a demonstration variant instead which could easily be upgraded for deuterium fusion if a permit was obtained. Obtaining a permit was out of the scope of this project, since it would take a lot of time to get approved and the chances to get a permit were slim.

The inner grid sections had been constructed from the ordered tungsten wire. It consisted out of multiple rings which were bent in 60-degree angles to avoid overlapping three rings over each other at the outermost inner grid point, which happens when trying to fit multiple rings into each other to form a sphere. Welding was avoided in this way.

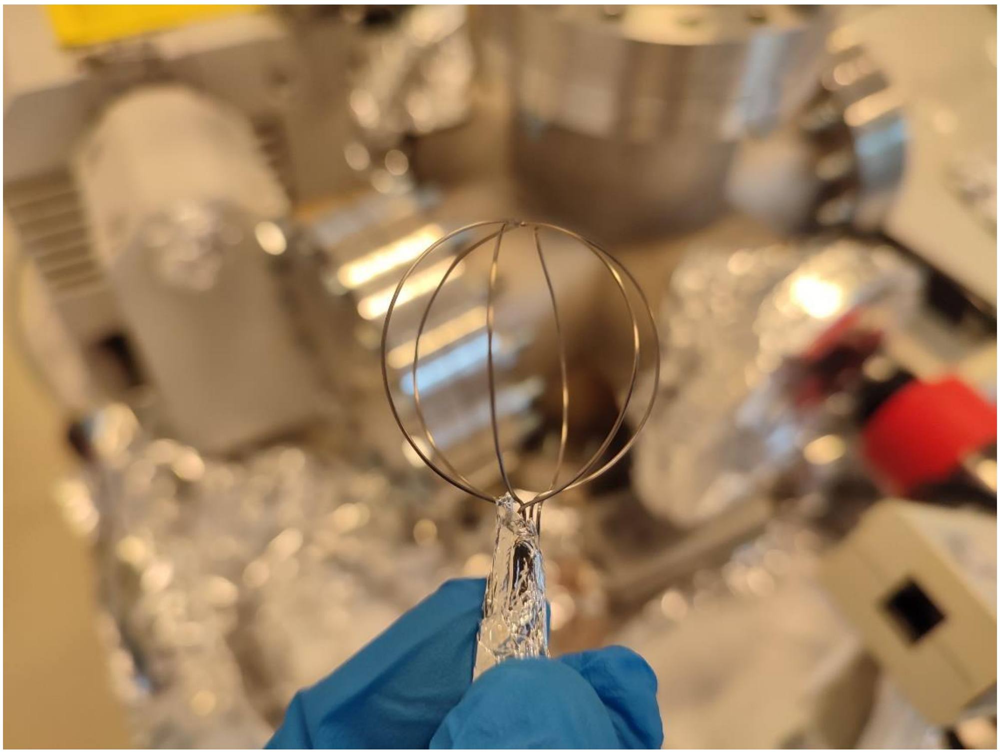

Figure D.5: Inner grid arrangement protoype.

After many attempts at obtaining a high voltage power supply, we ended up using a $5\ kV$ supply from the school lab. TNO had $12.5\ kV$ power supplies lying around, but due to the danger of high voltage, we could not borrow them as TNO did not want responsibility if something were to happen to us. The school lab had a $10\ kV$ power supply, though it was constructed to be positive hot, and thus not suitable for the fusor. We still ended up using this power supply. The reason is discussed later in this paragraph.

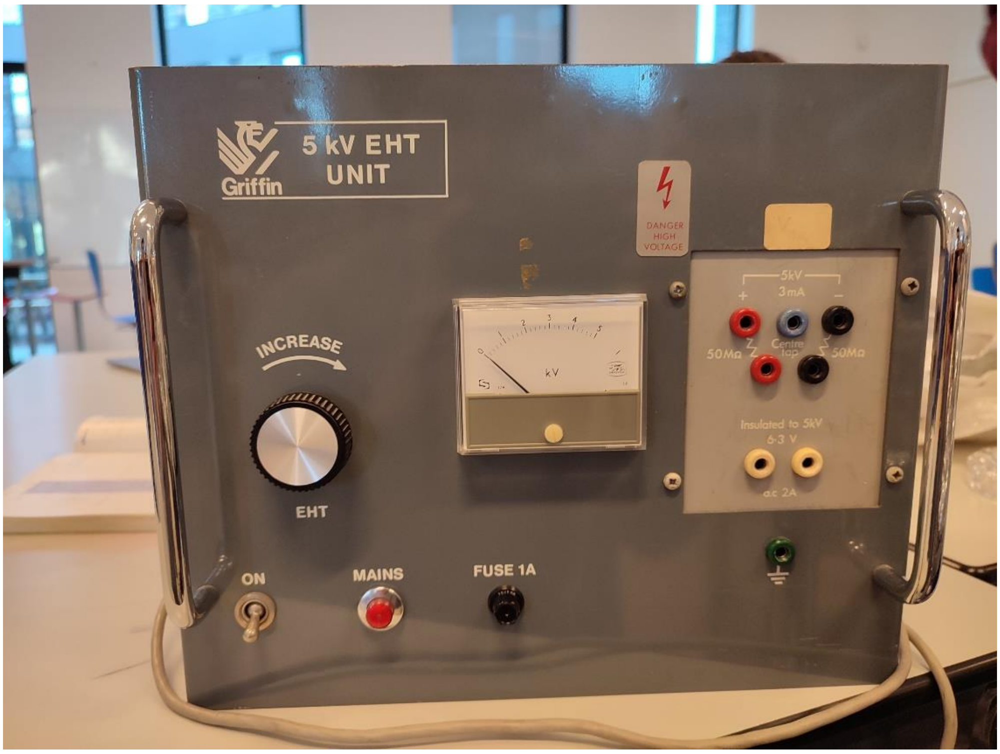

Figure D.6: The high voltage power supply we ended up using, which was able to output $5\ kV$.

Due to global supply issues an essential (not freely tradable) part (the high voltage feedthrough) almost did not arrive in time. Luckily, after many emails back and forth to the Kurt J. Lesker Company, from whom we had ordered essential vacuum components, together with their customer support we managed to obtain our feedthrough just in time for the deadline, and the final system could be constructed and tested. The adapter was necessary to be able to test the entire vacuum setup, which we could not do at first since there was no way to attach diagnostic systems to the chamber without the adapter. Firstly, a pump-down test was conducted with the old feedthrough installed checking for leaks, which were minor enough to proceed with constructing the final inner grid mounted on the newly arrived feedthrough.

As the feedthrough is simply a stainless-steel rod, it had to be threaded to be able to bolt down and hold the ceramic insulator, which failed. Multiple tapping attempts at both TNO and at home failed, and a bolt was welded on top of the feedthrough instead with the assistance a neighbour of our team member T. Hampsink.

Figure D.7: Picture of the ceramic insulator held down by a welded bolt.

After the welding was complete, the individual inner grid sections could be attached to the bolt. The three sections were held down in place by winding copper wire around the extended bases of the inner grid sections and binding it with aluminium foil. The result of which can be seen in Figure D.11 and Figure D.12, in which the resulting plasma can also be observed. The first plan was to use a small collet which would hold all the inner grid sections in place. However, there was no way in which this collet could be attached to the feedthrough, as the thread in the base of the collet was unconventional, and we could not find a bolt which would fit in this collet.

This concluded the construction of the feedthrough. We proceeded to swap the newly built feedthrough with the old placeholder feedthrough and tested the system but ran into issues. The $5\ kV$ power supply did not seem to work as intended. The voltage kept dropping at random intervals and we suspected that an electrical short had been the culprit. Though after removal of the housing, no sparks could be observed and we needed an alternative, which was to transform the positive hot $10\ kV$ power supply into a negative hot $10\ kV$ power supply.

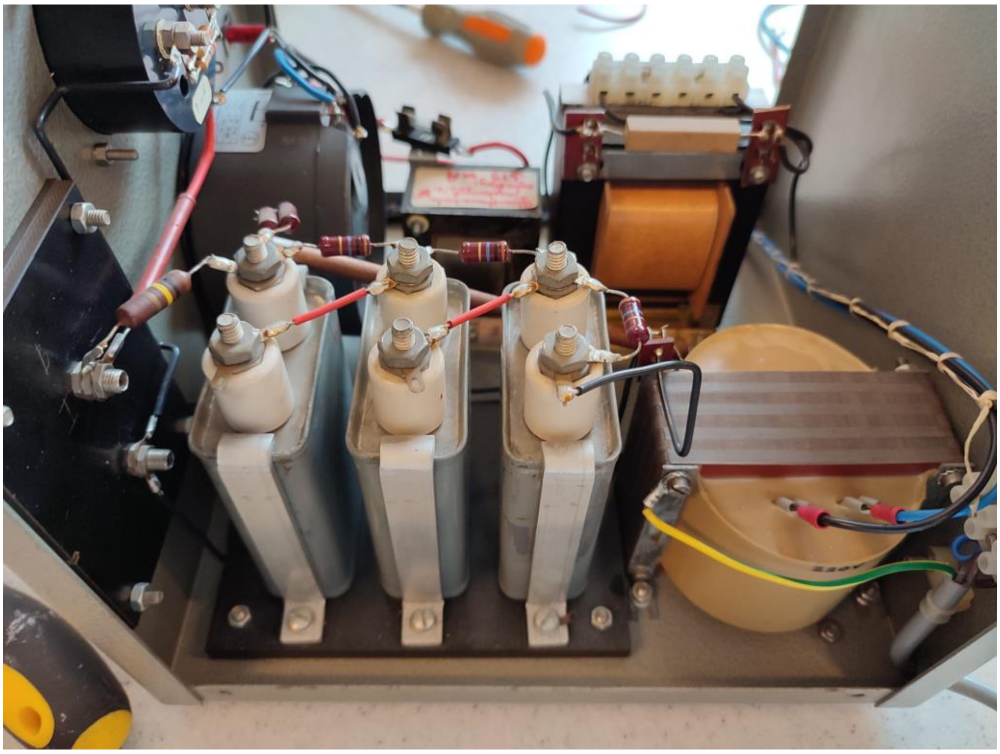

Figure D.8: The inside of the $10\ kV$ power supply before its negative hot conversion.

Before attempting anything inside the power supply, it was made sure that the high voltage capacitors had been discharged by placing an insulated screwdriver across each of the poles. First, the yellow/green coloured grounding wire had simply been disconnected from the $220\ V$ transformer and was attached to the positive lead at the left side of the capacitor bank, on the left of Figure D.8. As the $220\ V$ transformer was connected to the chassis, it had to be insulated from the chassis using a wooden baseplate. The chassis was then reattached to ground, resulting in a negative hot power supply, where the chassis was safe to touch.

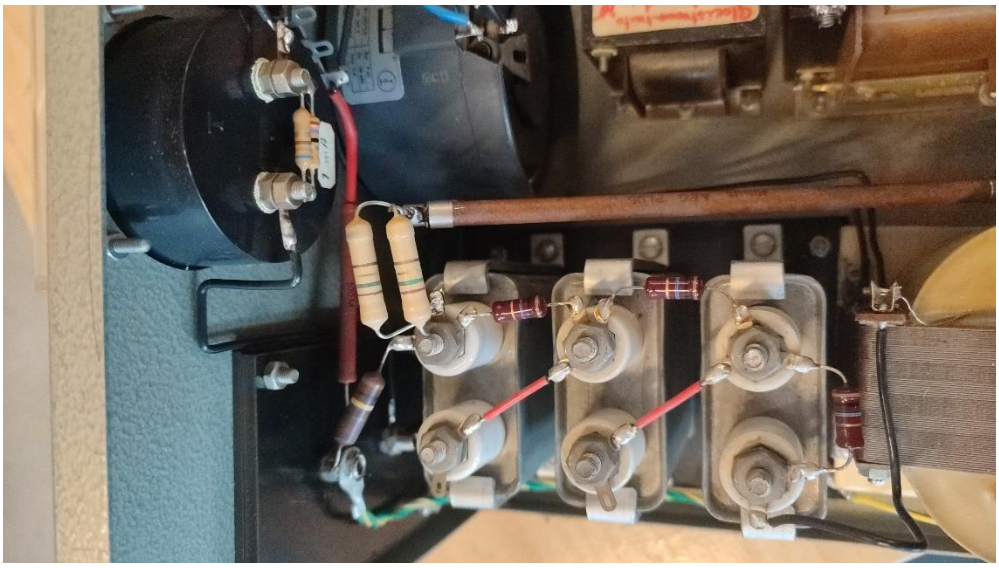

Figure D.9: The inside of the $10\ kV$ power supply after its negative hot conversion. Note the rerouted yellow/green grounding lead in the bottom-left and the insulated wooden baseplate on the bottom-right.

After testing the converted power supply in the final vacuum system, the first plasma was observed. Additional observations are made in chapter D.3.

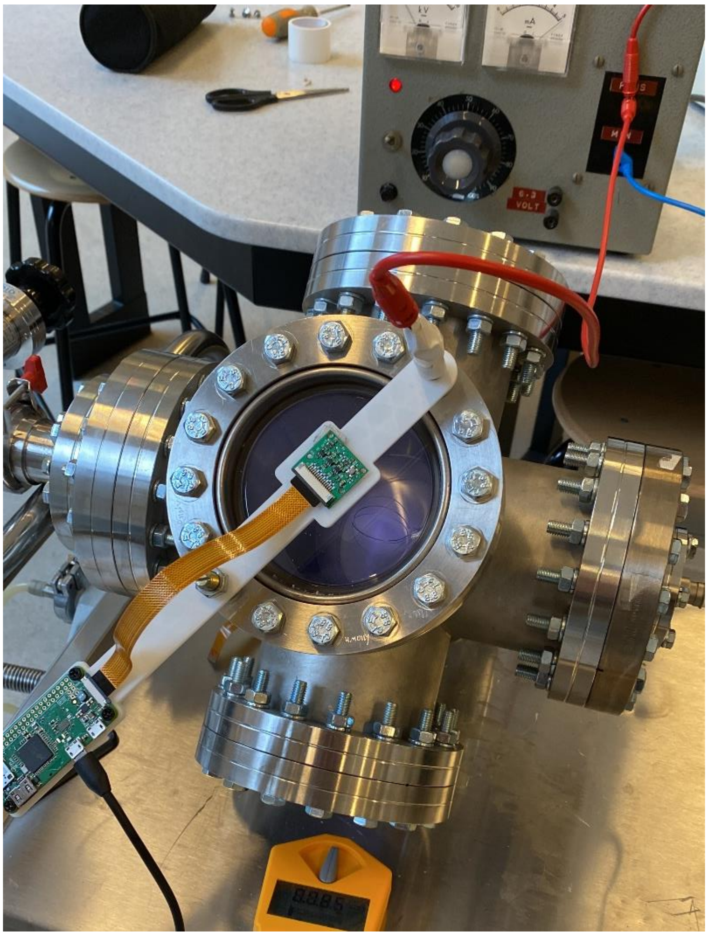

Figure D.10: Picture showing the first plasma ever recorded in the RSR-1 system.

D.3. RSR-1 plasma states

Jet mode was achieved in the RSR-1, but star mode was not reached due to the relatively low vacuum achieved in the system, and therefore no stable oscillatory trajectories could exist. Additionally, the power supply was not able to output more than $4\ kV$. We suspected this was the case due to the relatively high current flowing through the system as a high number of ionizations took place. This can be reduced by pumping down to a higher vacuum, but due to the absence of a second stage high-vacuum pump, this was not achieved.

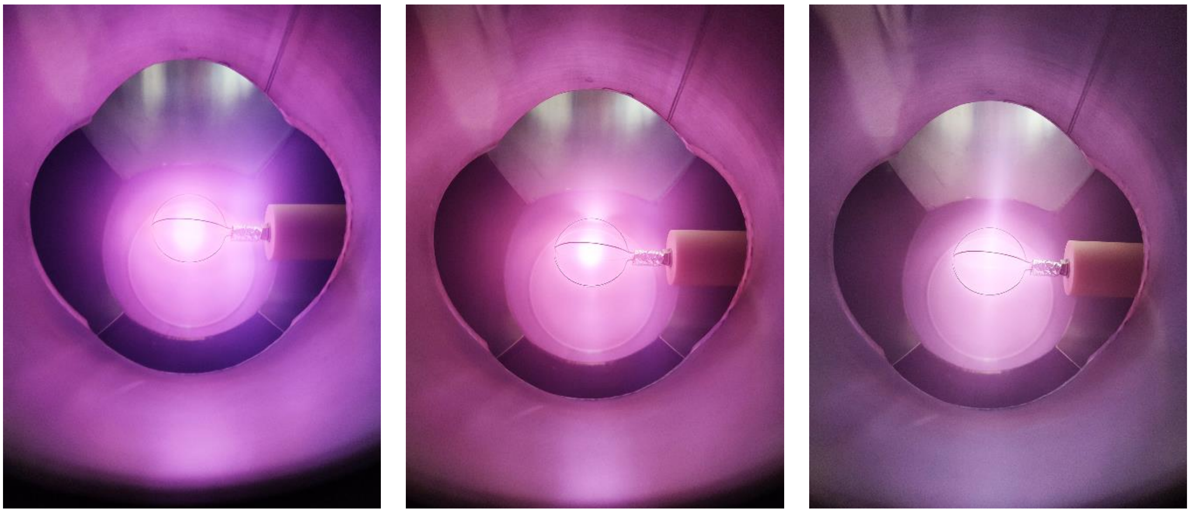

Figure D.11: From left to right: glow mode, jet mode, mini-jet mode. Note the beams of light streaming out of the inner grid region during jet mode, hence its name. A gradual colour change can be observed throughout the modes.

Around the vacuum level where the plasma is able to ‘ignite’, a plasma can be observed which is strongly attracted to the inner grid wires, and there exists less of a centred ball of plasma inside of the inner grid, as is seen in Figure D.12 below.

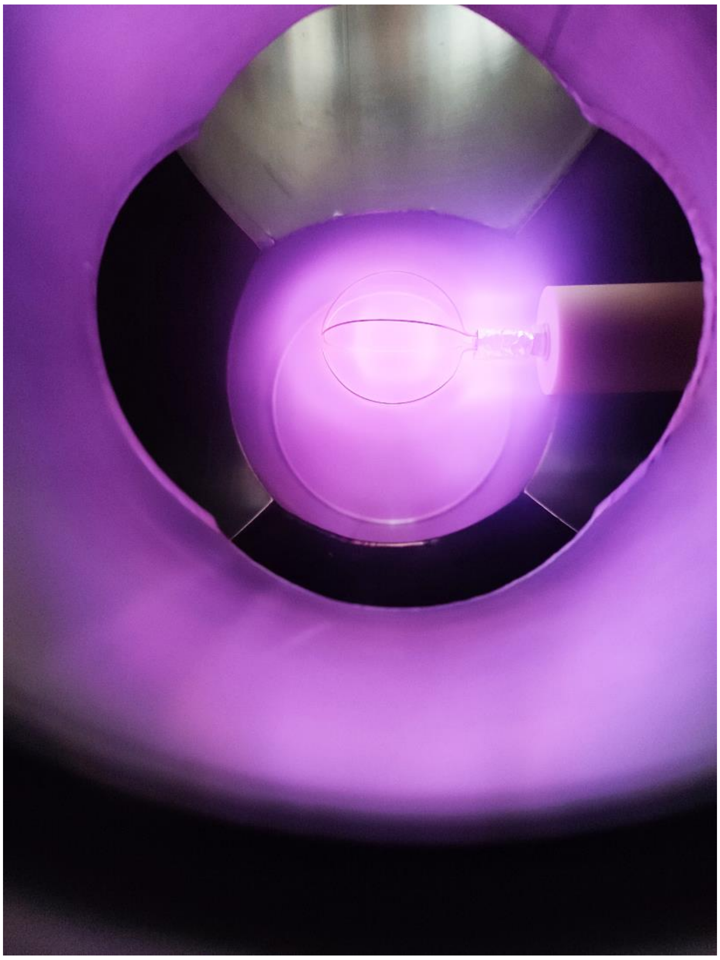

Figure D.12: Picture showing the vacuum level at which plasma is first able to form, which we called *'ignition'. No confined 'plasma ball' can be observed yet. Note that there is no plasma observable* around the ceramic insulator.

D.4. Chamber shape electric field homogeneity

We were able to research if the shape of our vacuum chamber has an influence on the path of ions using software. A 2D representation of our chamber and a perfectly spherical chamber were simulated in Agros2D. Note that during this simulation, the feedthrough stalk is neglected so only field deviations by the shape of the chamber can be investigated. The inner grid is represented as a solid sphere, due to software limitations.

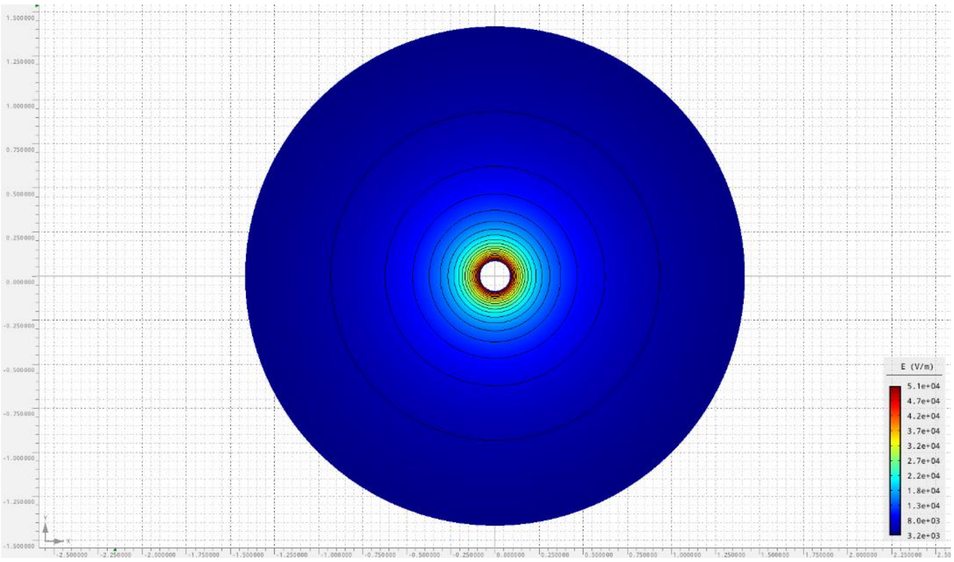

Figure D.13: An electric field simulation of a perfectly spherical vacuum chamber. All field lines are perfectly homogenous.

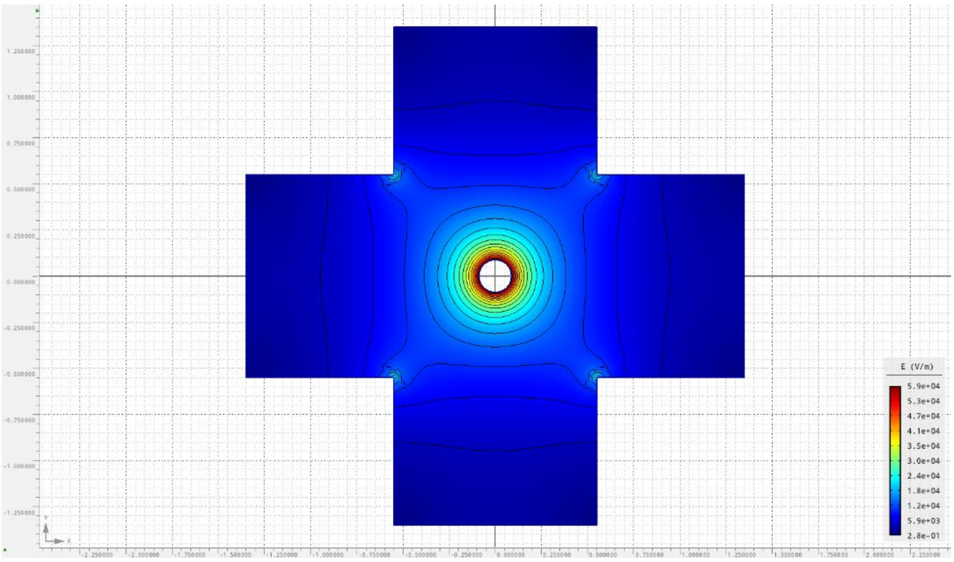

Figure D.14: Electric field simulation of the RSR-1 reaction chamber. Note that around the inner grid, there exists a slight deviation the the homogenity of the electric field lines, and the field is warped.

As can be seen in Figure D.14, the paths of the ions are influenced, and there is a possibility that there exist fewer stable oscillation paths for the ions to oscillate in, resulting in a reduced fusion cross-section and a higher ion loss is measured. Conclusions cannot be made with absolute certainty, and additional research is required, which is outside of the scope of this project.

D.5. Estimated bremsstrahlung by fast electrons

The speed of an electron can be calculated using formula (D.1:

$$v = \sqrt{\frac{2qV}{m}} \tag{D.1}$$

Where q is equal to the elementary charge, which is equal to $1.602 * 10^{-19}C$. V is equal to the voltage difference measured in volts. With the power supply used in this system, the maximum theoretical achievable voltage was $10\ kV$. The m stands for mass and is equal to the mass of one electron: $9.10938 * 10^{-31}kg$. This leads to the following equation:

$$v = \sqrt{\frac{2 * (1,60218 * 10^{-19}) * 10000}{9.10938 * 10^{-31}}} = 5.931 * 10^{7}ms^{-1} = 0.14c \tag{D.2}$$

The maximum frequency of the radiation is calculated using formula (D.3. Using this, it can be determined which kind of radiation is emitted when running the fusor.

$$f = \frac{mv^2}{2h} \tag{D.3}$$

Where v is equal to the calculated speed with formula (D.2 and h is the Planck constant, so it is equal to $6.6261 * 10^{-34}Js$. This leads to the following equation:

$$f = \frac{(9.10938 * 10^{-31}) * (5.931 * 10^{7})^2}{2 * 6.6261 * 10^{-34}} = 2.418 * 10^{18}\ Hz \tag{D.4}$$

This means that the maximum frequency that a photon released from bremsstrahlung gets, is well within the X-ray spectrum. As explained in B.2.6, most photons that get released get a lower frequency than is calculated above.

CHAPTER

E

Conclusion

In this part we will answer our research question: "How can nuclear fusion reactions take place with respect to safety and cost?".

E.1. Safety

According to equation D.2, the maximum frequency of the photons released from this fusor is $1.2089 * 10^{18}$ Hz. This means that the radiation which could potentially be dangerous, in practice will not reach harmful levels. After all, the calculated frequency of the released photons is the absolute maximum and can only be reached if every electron frontally collides with the outer shell. The actual emitted radiation is low and, according to B.2.6, even lower than background radiation, so when building a demo fusor, radiation precautions do not strictly need to be taken. This all changes when the bremsstrahlung becomes greater than the background radiation. The dangerous bremsstrahlung can be blocked by using thick lead plates around the fusor. The high energy neutrons that get released when running a deuterium fusor are also dangerous and pass through almost everything. This is why it is safer to keep a distance from the chamber when fusion is happening. When both the lead plates are in place and a safe distance is kept at all time, operators can be safe around a working high voltage fusion device.

For a safe high voltage environment, it is important to have a failsafe for when things suddenly go wrong. It is important to have this failsafe clearly labelled as such. Another crucial thing to do is to let your high voltage setup get checked by a professional. This is to make sure that there are no mistakes in the setup and that lives are not unnecessary at risk.

E.2. Cost

The market value of the entire setup estimated to be €9,958.29. It does not cost millions of dollars to achieve fusion reactions. The cost we made totalled to just €391,64. This means that we spend a little under 4% of the worth to get all the parts. Some of these parts were lent out to us and needed to be returned after the project was finished. To buy these parts, more costs would need to be made. It is possible to obtain better prices for parts by looking for second-hand components, but due to time constraints all our own spendings were made on new products. If one has the time to wait until good second-hand deals become available, this will greatly reduce the cost of building a fusion capable device.

E.3. Reproduction by other amateurs

If one has the time to wait around and do extensive research into what parts are best for usage with fusors and into the available second-hand parts, this will make the task of making a fusion reactor straightforward. It is always important to think before you act, especially when working with expensive and potentially dangerous equipment. Modelling and drawing system designs are essential to make sure that no mistakes are made. This is especially true for the most dangerous part of the fusor: the high voltage power supply. Since the requirements for making a plasma are much lower, it is recommended to first try to build a demo fusor, before going for fusion. This creates an achievable goal where one can manage the safety aspects without the need of guidance from a professional. The price of making a demo fusor is also much lower and can be much simpler than the RSR-1, simply consisting out of a crude vacuum tube with a cheap pump and an inner grid made from stainless-steel wire.

Even though we were not able to achieve fusion, our system was largely fusion capable. Due to the absence of a license, we were unable to make use of its fusion capabilities. It is possible for nuclear fusion to take place on a budget by keeping a close eye on the second-hand supply of vacuum parts. When doing fusion though, more safety measures need to be taken. Neutron radiation and Bremsstrahlung need to be considered to guarantee the safety of the operator. For high voltage safety it is crucial to let a professional control the setup, this can even be done via the internet using sites like fusor.net.

CHAPTER

F

Discussion

There were a few mistakes made when doing this project. Firstly, we did not know that fingerprints would have such a great impact on the maximum achievable vacuum. Because of this, we did not use gloves for the first few weeks working with our vacuum equipment and did not get lower than $6.0 * 10^{-3}$ mbar when running the pump for 5 minutes. This is almost the same as the maximum vacuum achievable with the gas ballast turned with our pump (which is $5.0 * 10^{-3}$ mbar). The only problem was that the pressure went up fast when the pump was turned off. At first, we thought we had a leak, but after conducting additional research that the outgassing of fingerprints could also be the problem, we tried to tackle that problem first. We went to the lab at our school and gave all the parts used in the experiment a few baths. First, we rinsed everything with bio ethanol (~95%). Acetone is the industry standard, but acetone was not something we had at the time. We proceeded to put the vacuum components in a bath with detergent and water. After flushing away all the soap with deionized water, we gave the parts a final bath of isopropyl alcohol (>99%) and finally cleaned it with a hairdryer.

After doing this, we started to wear gloves when we worked on the fusor. In that way the contamination was reduced, but because we for example did not start to wear facemasks, there is still a possibility of some contamination in our current chamber. Furthermore, the vacuum components we received from TNO were contaminated themselves with unknown material. We suspect that most parts are contaminated with vacuum pump oil and some parts were labelled with ‘Sn contamination’ (tin). Due to all these contaminants, we might not have reached the maximum vacuum that was achievable with our vacuum pump.

The power supply we used was only able to output $10\ kV$, which is insufficient to fuse deuterium atoms together. This makes it harder for our system to become a fusion capable system, since more parts would need to be upgraded. This means that it is not recommended to use a power supply below $25\ kV$ when building a demo fusor, because it is harder to upgrade to a fusion capable fusor. Above this, fusion reactions become easier to detect.

As for follow-up research, the next step in developing RSR-2 would be to obtain a permit for conducting high-energy fusion reactions.

CHAPTER

G

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G.2. Table of Figures