Miniature Particle Accelerator Simulation, Design and Fabrication

A Thesis

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Master of Science

by

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ABSTRACT

X-rays were first discovered in 1895 by Rontgen. Since then, various applications, such as computer tomography, radiotherapy, and X-ray microscopy, have been developed. The size of the X-ray source remains too big for portable use. The objective of this research is to explore the technology of a miniature particle accelerator that can be used as an X-ray source. Such a miniature particle accelerator can store an electron beam using a storage ring. The storage ring in this thesis is designed to store electrons of the MeV energy range. The MeV electrons can be used to generate X-rays by Bremsstrahlung and Inverse Compton Scattering. This type of miniature X-ray source could be used in the battlefield or at an accident site.

Several analytic and computational techniques were used to simulate the storage ring. The design of the storage ring was simulated using Opera and Autodesk Inventor. Results of the simulation in Opera show that the charged electrons circulate the storage ring 1000 turns without leaving the equilibrium trajectory. The kinetic energy of the charged particles is 100keV. The simulation structure was fabricated using cast iron and permanent magnets. The fabricated storage ring has a diameter of 114mm and a height of 57mm. The angle of the center cone inside the Betatron structure is 43.36^0 which was found through design to be optimum for implementing a storage ring.

BIOGRAPHICAL SKETCH

JuneHo Hwang was born in Seoul, South Korea on February 5, 1983. He moved to La Paz, Bolivia for three years and then moved back to Seoul. After three years he moved to Vancouver, Canada for three years and came back to Seoul for three years. After his fourth grade he moved out to Paris, France.

In 2002, he began studying physics at Yonsei University. While there, he was the team leader of a search engine project. In 2006, he joined the Korean army and served until 2008. In the army, he was a squad leader and driver for the battalion commander. During his undergraduate studies, he learned quantum mechanics, electrodynamics, and computer programming languages such as Visual Basic, C, C++, Fortran, and structured query language. In 2010 he received a Bachelor of Science degree in Physics from Yonsei University, and in August 2010, he began studying Applied Physics as a Master of Science student at Cornell University.

ACKNOWLEDGMENT

I deeply appreciate having Professor Amit Lal as my thesis advisor. His suggestions and comments have made my thesis more concrete and successful and he helped me understand ‘the forest and the trees’ of the project. I also feel deep gratitude for Professor Manfred Lindau, my committee chair. He has continually helped me to build the big picture of the thesis. He also gave me suggestions and helped me finish my degree.

I am also grateful to Serhan Ardanuc and Yue Shi for helping me design and fabricate the results shown in the thesis. They taught me to simulate computer software such as Opera and also trained me in using the LPKF tool in Duffield Hall. I would also thank Hamidreza Vajihollahi for teaching me Autodesk Inventor and basic machine shop skills, and Justin Kuo for helping me design the circuit boards that were used in the storage ring and Betatrons.

I would also like to thank my parents and my brother for encouraging me and helping me achieve my goals. Thank you.

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Chapter 1

Introduction

1.1 Historical Overview of Particle Accelerators

X-rays were first discovered by Rontgen in 1895. In 1901, he was awarded the first Physics Nobel prize in recognition of his discovery. Since then, X-rays have been developed for applications in computer tomography, radiotherapy, and synchrotron source for condensed matter physics. Along with the development of X-ray applications, scientists have constantly reduced the size of the X-ray source. The energy of the accelerated particles also increased.

There are various types of particle accelerators which can be classified by their design and method of acceleration. The major conventional particle accelerators are electrostatic accelerators, cyclotron, Betatron, and linear particle accelerators [1]. They will be shortly introduced in the next paragraphs.

Electrostatic accelerators use static high voltage to accelerate particles. A Van de Graaff generator is an example of an electrostatic accelerator, but it has limitations due to its electrical breakdown. Cathode ray tubes like those inside televisions are another type of widely used electrostatic accelerator.

Cyclotron, Synchrotron, Betatron, and linear particle accelerators use oscillating electromagnetic fields for acceleration. They were demonstrated by Ernest Lawrence(1932), Edwin McMillan(1945), Donald Kerst(1940), and Rolf Wideroe(1928) [1], [2].

Cyclotron accelerates particles in a spiral path, from the inside smaller radii towards an outside larger radii corresponding to higher energies obtained through acceleration. Both magnetic and electric fields are used in a cyclotron. The magnetic field is used to hold the particle in its trajectory by bending it and the time varying electric field is used to accelerate the particles. Ernest Lawrence was the first scientist to make a cyclotron [2].

A synchrotron is a cyclic particle accelerator that originated from the cyclotron. It has a time varying magnetic field that changes according to the kinetic energy of the particle being accelerated. In a synchrotron, there are quadrupoles that focus the particles and dipoles that bend the particles. Synchrotrons are normally built in large dimensions. The first synchrotron was built in 1945 by Edwin McMillan. A storage ring is a device that stores accelerated particles and can be used like a synchrotron to produce synchrotron radiation [2].

A Betatron uses a time varying magnetic field that both bends the particle path and accelerates the particles. It is also a cyclic particle accelerator that was made by Donald Kerst. Before Kerst, Rolf Wideroe had the idea of a Betatron which he failed to manufacture. For the Betatron to accelerate particles, the magnetic field inside the Betatron needs to vary in time. Time varying magnetic field induces an electric field along the path of the particles by Faraday's law.

After going through successive improvements, larger particle accelerators were built for particle collisions. The Tevatron and Large Hadron Collider are examples of such big particle accelerators in modern times realized by ever longer accelerating structures.

1.2 Principles of Particle Accelerators

The mechanisms of particle accelerators can be explained by classical electrodynamics and physics. A particle accelerator is a device that accelerates charged particles using electromagnetic forces. The forces from electrodynamics such as electric potentials, oscillating electric fields and magnetic fields are capable of accelerating charged particles. All accelerating methods use the electromagnetic force shown in Equation 1.1. The force is equal to the mass times the acceleration. In Equation 1.1, q is charge, v is velocity, B is magnetic field, and E is electric field. Equation 1.1 shows that the force depends on the cross product of the velocity and the magnetic field, where force is orthogonal to particle motion, resulting in no work being done on the particle. Hence magnetic fields can only be used to guide, while electrical forces are used to impart higher energy.

$$\begin{aligned} F &= ma \\ &= q(v \times B + E) \end{aligned} \tag{1.1}$$

Electric fields can be more effective to accelerate electrons than to accelerate protons. The mass of the electron is 9.109×10^{-31} kg and the mass of the proton is 1.673×10^{-27} kg which is 1836 times the mass of the electron. The total energy of a particle is given in equation (1.2). In equation (1.2), m is the mass, c is the speed of light, m_0 is the rest mass, and KE is the kinetic energy.

$$\begin{aligned} Total\ \ Energy &= Rest\ \ Energy + Kinetic\, Energy \\ &= mc^2 \\ &= \frac{m_0 c^2}{\left(1 - \frac{v^2}{c^2}\right)^{1/2}} \\ &= m_0 c^2 + KE \end{aligned} \tag{1.2}$$

A proton that has the same total energy as an electron will have a much slower velocity than the electron. This means that protons will be much less affected by magnetic force than electrons. Because of this fact, magnets are used to bend the electrons and other methods such as electric quadrupoles are used to bend protons.

Another factor that should be considered in designing a particle accelerator is the velocity of the particle. As the kinetic energy of particles exceeds 500keV, their velocity approaches 80% of the speed of light. Thus, for particles that have a kinetic energy larger than 500keV, their speed can be approximated as the speed of light as shown in Figure 1.1. This is important as the term v in the Lorentz force can be approximated to be equal to c at higher energies greater than 512keV.

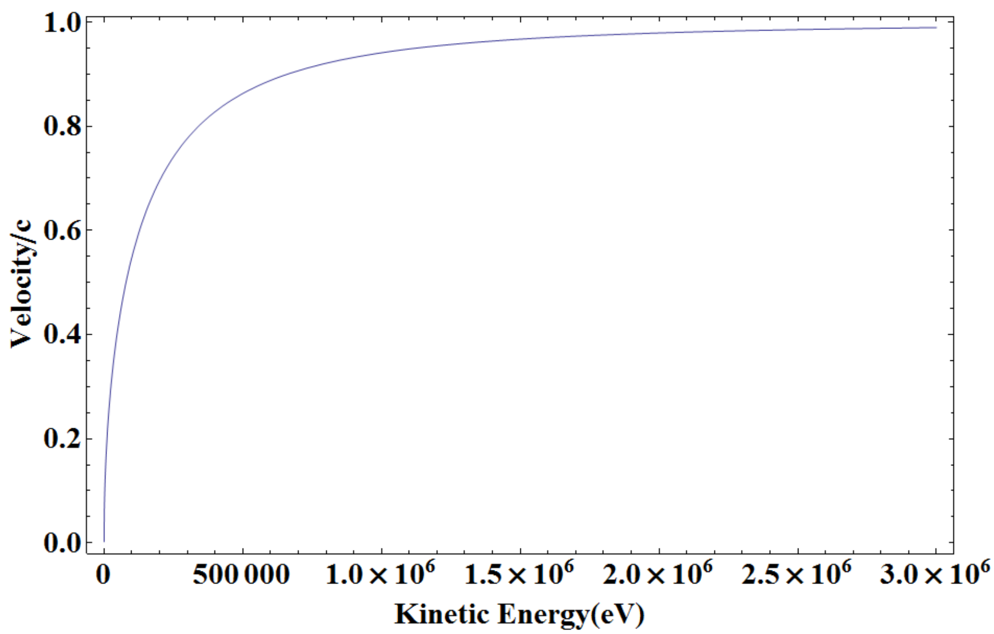

Figure 1.1 An electron’s kinetic energy and velocity normalized to the speed of light

1.3 Objective of the Research

The major objective of this thesis is to explore the technology of a miniature particle accelerator that could be used to general X-rays. A portable X-ray source could be convenient for patients who need immediate diagnosis away from hospital. The energy of the accelerated particles needs to be in the range of 20 to 150keV for medical uses [3]. In addition to the accelerator, a device is needed to store the accelerated particles. The storage ring used for this purpose will be presented and simulated in Section 4. Also, a simulation in Opera that uses microfabricated microgaps will be shown. Such microgaps will be used to apply high electric field inside the storage ring, which will provide better control of the charged particles. Finally, electron beam detectors made from FR4 plates will be installed inside the storage ring to see the actual trajectory of the particles.

Chapter 2

Opera Simulation

2.1 Electric and Magnetic Field Lenses

Electrostatic and magnetic lenses are devices used to bend and focus the beam. They use electromagnetic forces and work in a similar way to optical lenses, but they are sometimes more complicated due to complex electrostatic potential distributions. Normally an optical lens has a constant radius of curvature, but an electrostatic lens can have a varying radius. This makes the calculation and prediction of an electrostatic lens difficult. There are several ways to calculate the trajectory of the beam. One way is to fit the potential curve of the Einzel lens to a function and use it to predict the trajectory of the electrons. Another way is to use a simulation program such as Opera, which uses finite element method to solve for electron trajectories.

Several computational techniques were used in this thesis to design the lenses. Simulation programs such as Mathematica, Matlab, and Opera were used to design the electric and magnetic lenses. In this thesis, Opera simulation was used to design an accurate electrostatic lens. Before designing the lenses, it is necessary to understand the physical concept of the electrostatic lenses.

Electric and magnetic field lenses are used to focus the beam. The Einzel lens is one type of lens that focuses the beam while conserving the energy of the electron. An Einzel lens has at least three electrodes that are aligned along the optical axis. Because an Einzel lens is symmetric along the optical path, the energy of the particles remains the same.

Figure 2.1 shows the trajectory of the beam in an Einzel lens as it passes through the device. The electric field lines emanate from the high voltage electrode to the lower voltage electrodes. A particle entering the left encounters a diverging and converging electric force field that results in a focusing effect. The trajectory of the particles tends to bend outward as it passes through the first two electrodes, but as it passes through the second and the third electrodes, it bends inward giving a focal point at the other end. This bending is due to particles moving to a lower potential energy state. The distance between the electrodes and the voltage applied are the factors that define the focal point of the beam [4], [5].

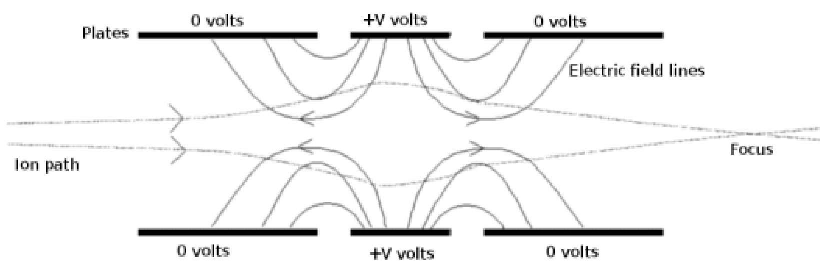

Figure 2.1 Einzel lens and the ion path being focused[1]

In addition to the Einzel lenses, there are other different electric and magnetic field lenses in particle physics: aperture lenses; cylinder lenses; and dipole, quadrupole, and sextupole lenses [4]. The electrostatic quadrupole lens is one of the most common lenses that have strong focusing. It has at least two quadrupoles that are 90 degrees shifted in respect to each other [6]. As the beam passes through one of the lenses, it is focused on one axis while the other is defocused. But as the beam passes through multiple quadrupoles the final effect on the beam is a strong focusing. The different lenses and Opera simulations are presented in the following sections.

2.1.1 Einzel Lens Simulation in Opera

There are several different types of electrostatic lenses that could be used to bend electron beams. Different lenses could be used inside the storage ring. Lenses

[1] http://en.wikipedia.org/wiki/Electrostatic_lens

inside the storage ring will give a better control of the electron beam. For the storage ring presented in section 2.2, the Einzel lens will be used to control the electrons.

Figure 2.2 shows an example of an Einzel lens. It consists of six electrodes. The center electrode has a higher applied voltage compared to the other electrodes. As the electron passes through the first two rows of electrodes, it gets defocused, but as it passes through the last two rows of electrodes, it gets focused [7]. The different colors represent the relative scale of the electrostatic field. The green region has a stronger electric field than the blue region. The purple arrows are the direction of the electric field on the horizontal plane.

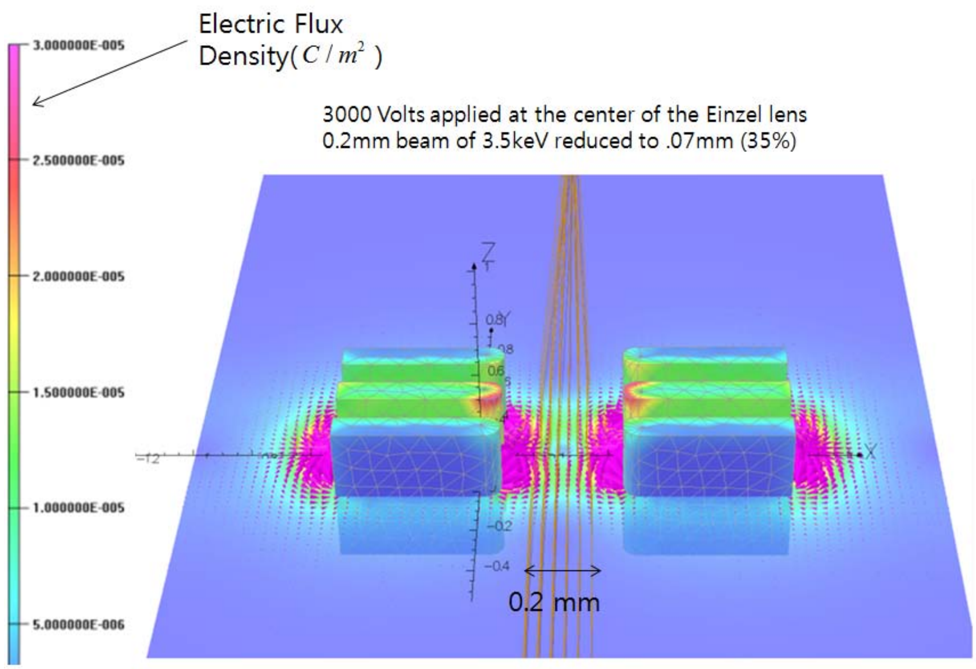

Figure 2.2 Einzel lens

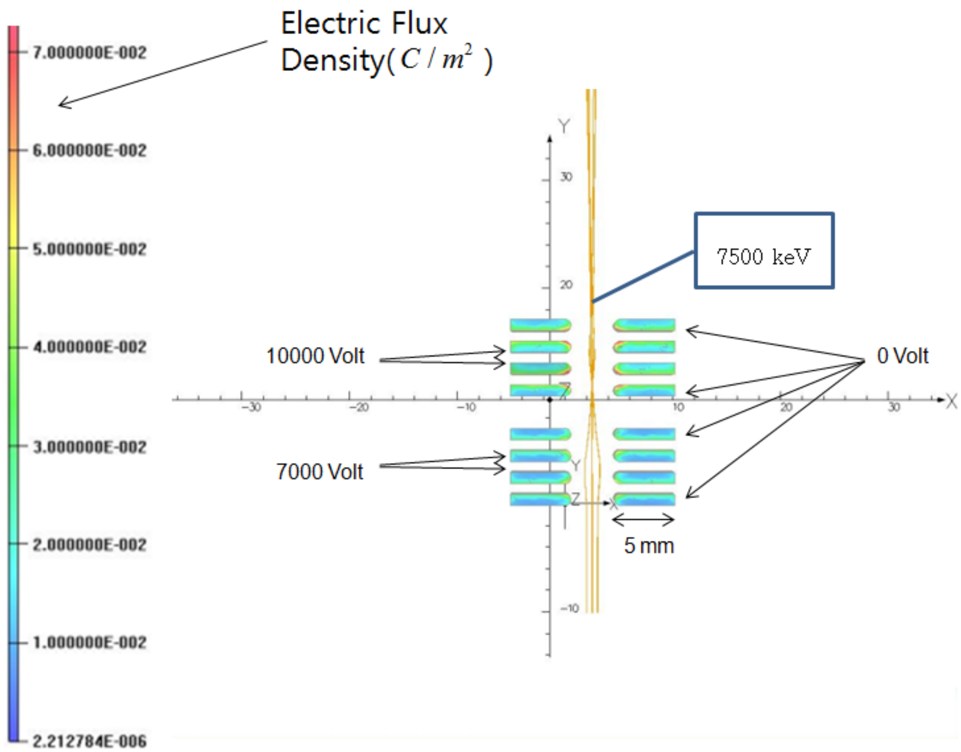

Figure 2.5 Two Einzel lenses

One set of Einzel lenses need high voltage to focus the beam to a close focal point. Rather than using only one Einzel lens, multiple Einzel lenses with a lower voltage could be used. Figure 2.5 shows a case where two Einzel lenses are used to focus the beam twice. The second Einzel lens is situated near the focus point of the first Einzel lens to bend the beam efficiently.

Also, multiple Einzel lenses can be used in an array as in Figure 2.6. This would curve the electron path with higher energies with less voltage applied to the electrodes. Figure 2.6 is a case where 14keV electron is effectively bent using 7000 Volt electrodes. A beam of 2mm horizontal width was focused to a 1mm spot. Einzel lenses presented in this thesis focus the beam horizontally, but the quadrupole presented in the subsequent section focuses the beam both horizontally and vertically.

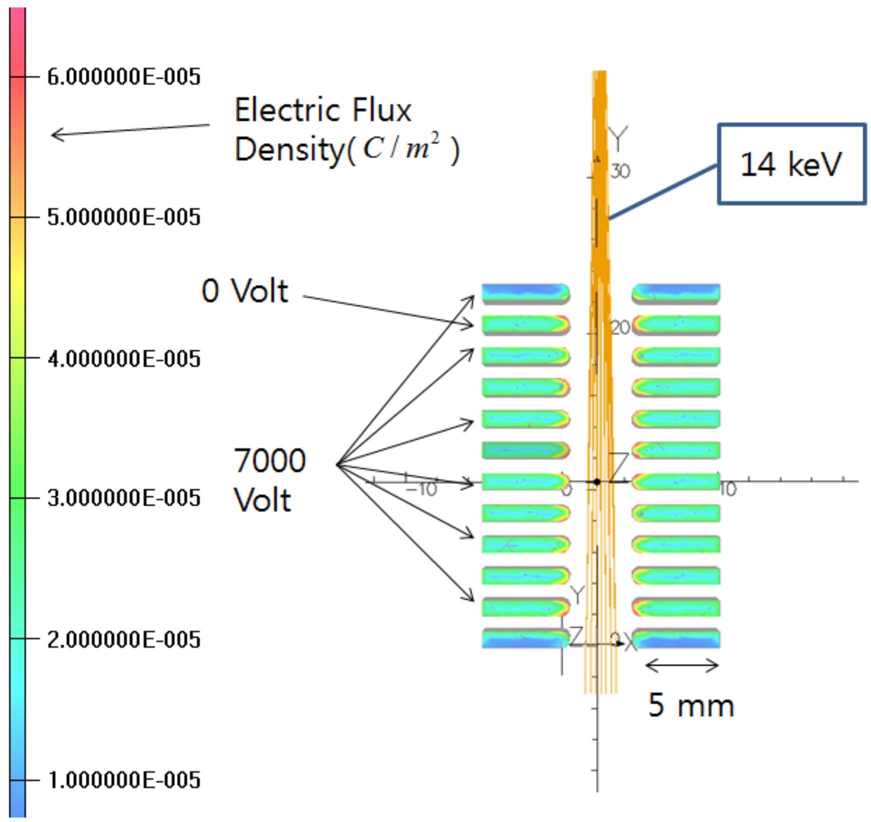

Figure 2.6 Multiple Einzel lens

2.1.2 Quadrupole Lens and Periodic Focusing System

A quadrupole is another type of electron lens that focuses a beam as shown in Figure 2.7. A quadrupole has a strong focusing compared to other lenses and is thus widely used in large particle accelerators [8]. There are two types of quadrupoles, electrostatic quadrupoles and magnetic quadrupoles. In this section, both magnetic and electrostatic quadrupoles were simulated.

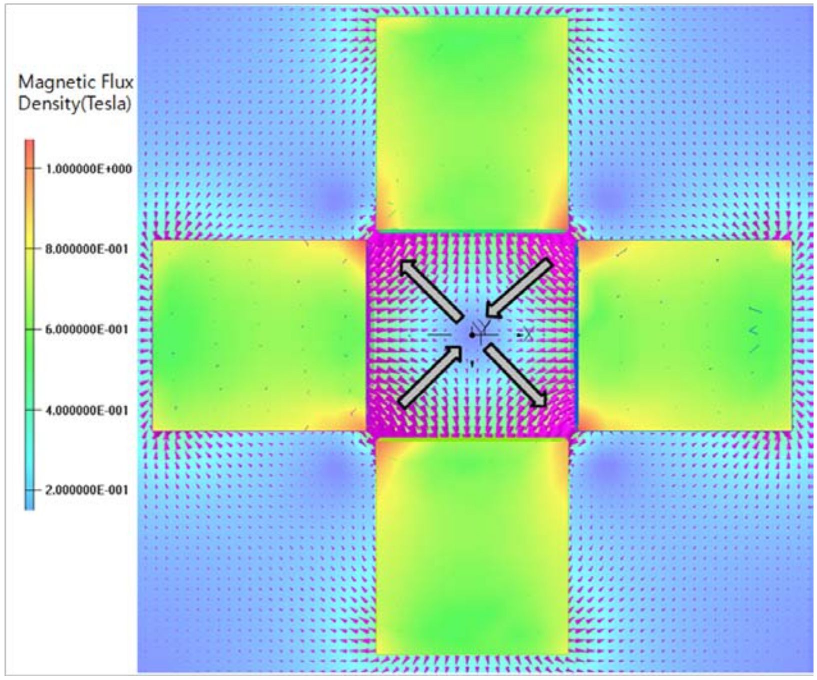

Figure 2.7 Quadrupole magnet

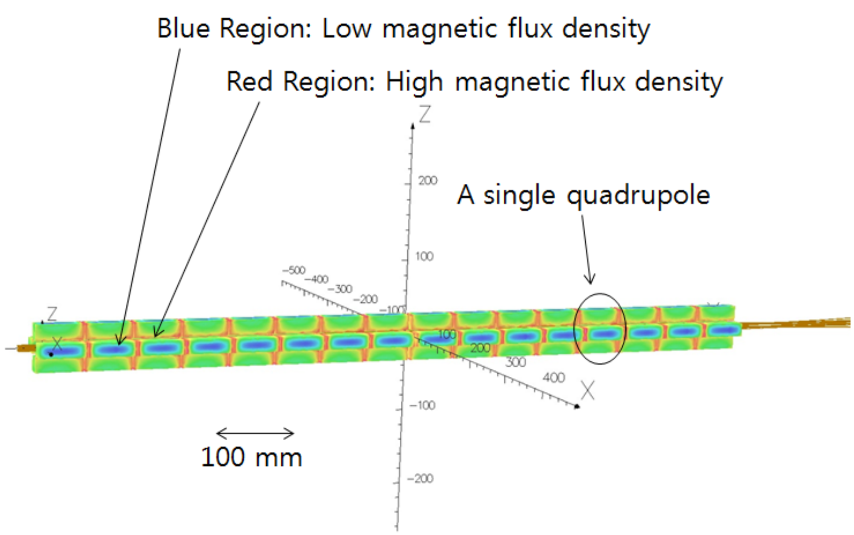

Figure 2.8 Multiple quadrupoles

The electrostatic quadrupole in Figure 2.8 shows that the beam is being focused. After entering the array of quadrupoles, the beam is focused by the FODO(focusing quadrupole, drift, defocusing quadrupole, and drift) quadrupoles [9]. The electrons leave the quadrupoles after being focused. To have a stable electrostatic quadrupole, the voltage applied on the electrodes and the distance between them must meet the stability conditions. Otherwise the quadrupole will lose the electron beam.

The particle inside a quadrupole gets focused on one axis and gets defocused on the other axis as shown by the arrows of Figure 2.7. But as the particle passes through multiple quadrupoles, the overall effect is a strong focusing. The oscillation of the particles can be seen in Figure 2.9. In Figure 2.10 the electron path along the optical axis is shown. The vertical axis represents the relative x position of the electron and the horizontal axis represents the distance along the optical path. The injected electrons oscillate while being focused towards the center of the optical axis. These quadrupoles can be inserted inside the storage ring to provide better control over the electron beam.

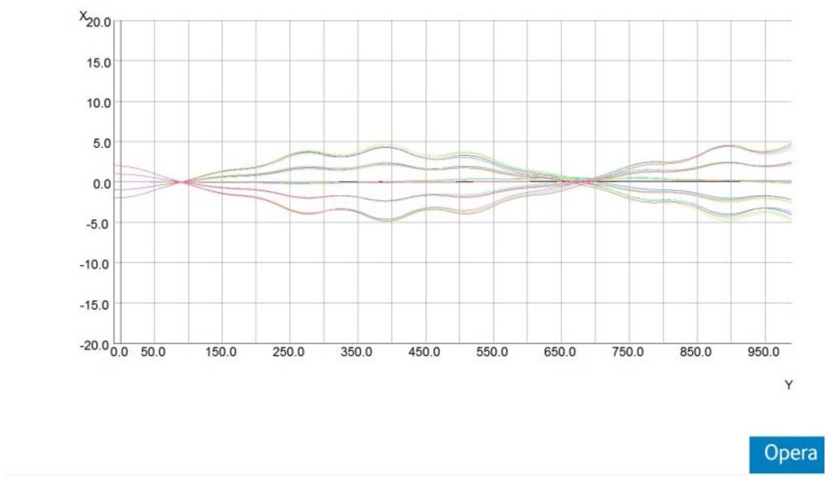

Figure 2.9 Electron trajectories along the quadrupole

2.1.3 Combination of Electrostatic Lenses

The final objective is to put a combination of electrostatic lenses inside the storage ring to achieve electron containment around the ring. Curving electrodes and quadrupoles should be combined to give maximum focusing. Figure 2.10 is a curving electrode that could be used in combination with the Einzel lens. It has two walls stacked with three layers. Such a device can have a horizontal focusing and can also curve the particle towards the center. As the particle is accelerated, a higher voltage is applied accordingly, but the voltage should not exceed the breaking voltage.

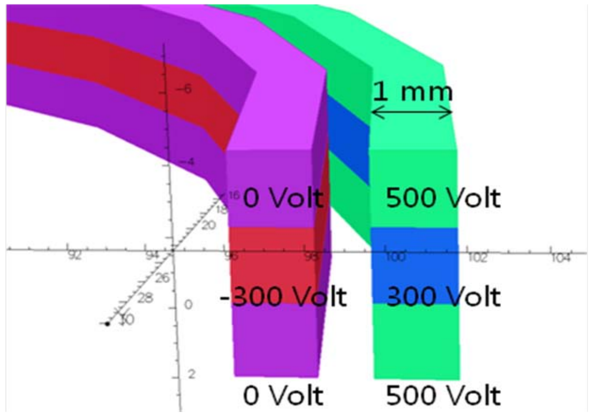

Figure 2.10 Curving electrodes

In order to have both vertical and horizontal focusing, combinations of the Einzel lens and the curving electrodes are used as in figure 2.11. In such a combination, the optimized voltage should be found using a simulation tool. Not only the voltages, but also the location and number of Einzel lenses, factor in creating effective confinement.

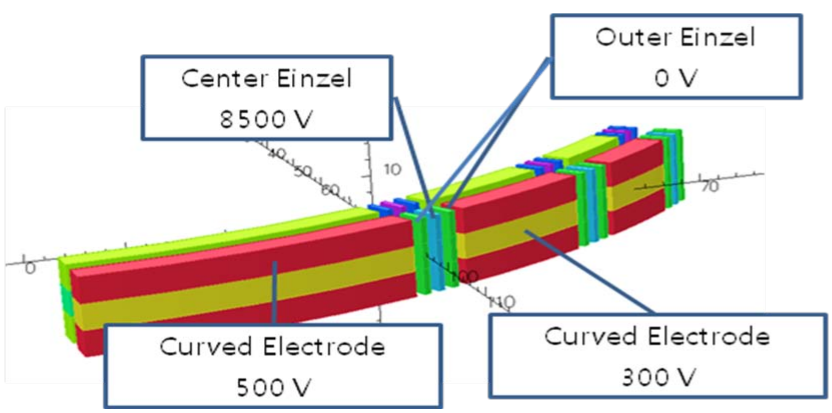

Figure 2.11 Combination of curving electrodes and Einzel lenses

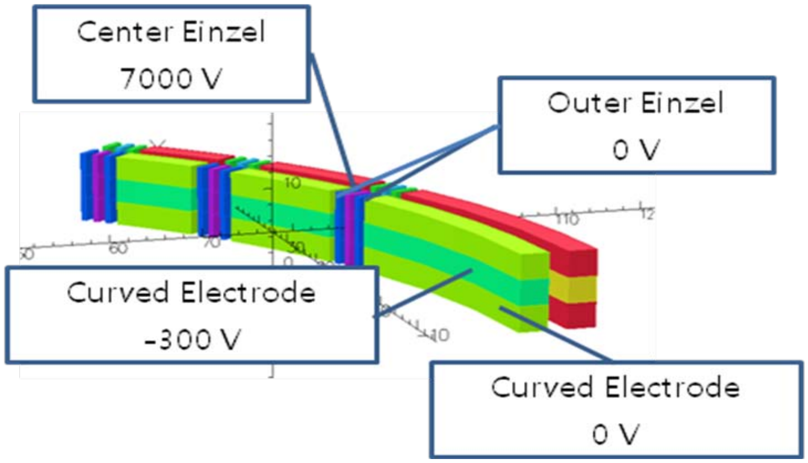

Figure 2.12 Combination of electrodes

Figure 2.12 is the inner view of the electrodes. It consists of three Einzel lenses that are located near the focus point of one another to have a maximum focusing. As seen in Figure 2.13, the beam that comes in from the bottom would eventually be both curved and focused horizontally and vertically. Such a complex design would be hard to make with simple hand calculation, since the function of the potential would consist of higher polynomials. Opera on the other hand can mesh the device and calculate the field from the divided parts of the device. The advance of modern computational physics has allowed such complex simulation.

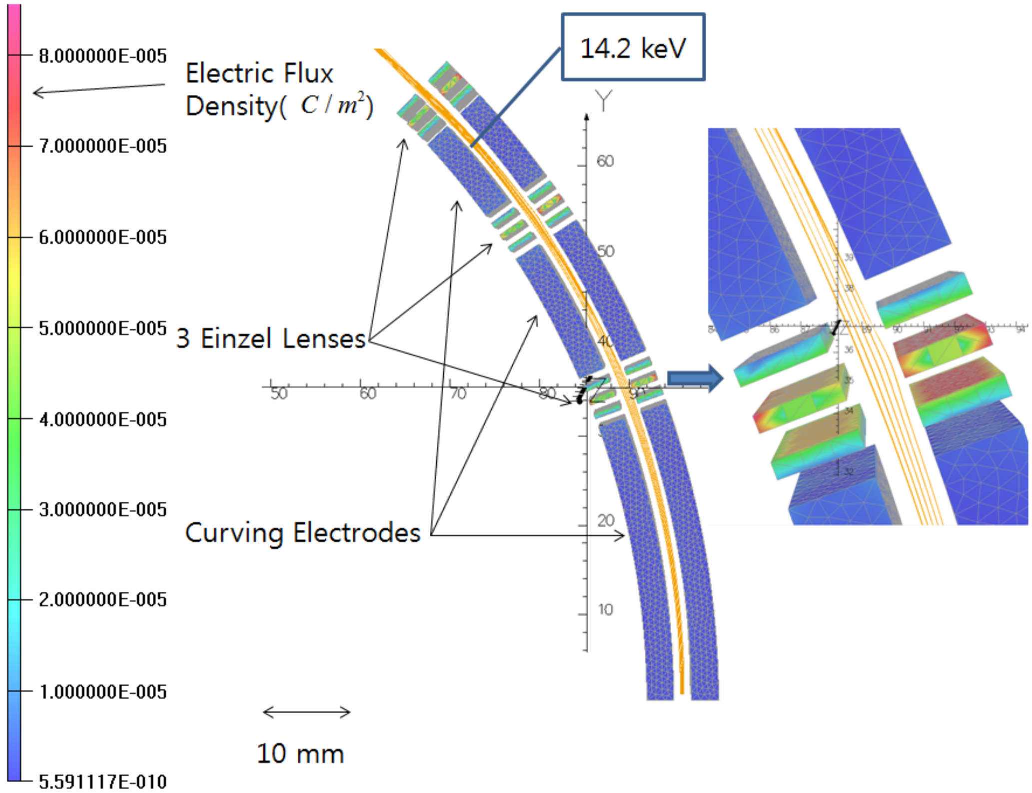

Figure 2.13 Top view of the electrodes

2.2 Storage Ring

A storage ring is a device that stores the charged particles in a confined space. The particles stored in a storage ring could be kept from seconds to a few hours. The design of the storage ring largely depends on the mass, charge, and energy of the particles.

There are several conditions for a storage ring to keep charged particles in their trajectory. A low vacuum tube, and exact injection and extraction of particles are necessary for a stable storage ring. Since the electrons kept in a storage ring travel at a speed close to light, they will have numerous collisions with the atoms inside the vacuum. Hence a low vacuum tube is one of the most important factors for a good storage ring. As for the injection, a Faraday cage and electrostatic electrodes are used.

The charged particles were injected using electrostatic electrodes, which were turned off when the injection was complete.

2.2.1 Magnetic Fields

Dipole magnets are used to steer the beam in a storage ring, but a quadrupole and sextupole can also be used for strong focusing and aberration correction. A FODO structure is the most common shape of a quadrupole. Sextupoles fix the difference in chromaticity given by dipoles and quadrupoles.

The previous examples of storage rings had several different parts to steer and store the beam. But we can also make a storage ring using a Betatron design. A Betatron shaped storage ring has the same shape as the Betatron, but it has a constant magnetic field. The constant magnetic field inside the storage ring has both vertical and horizontal focusing.

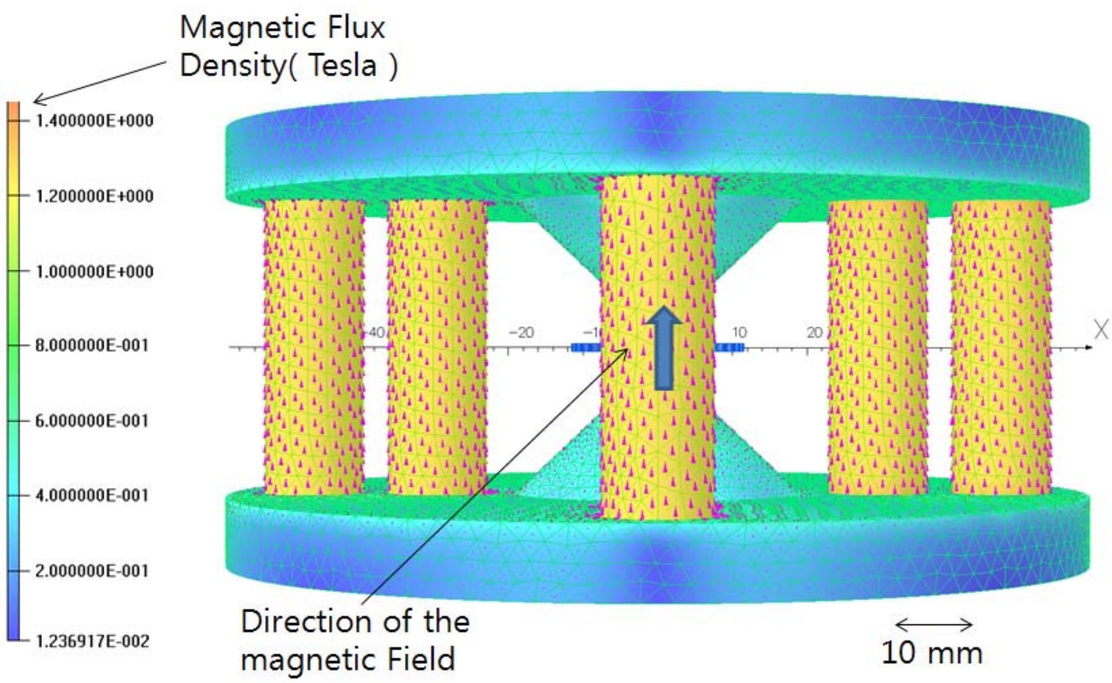

Figure 2.14 Magnetic fields inside the storage ring

Figure 2.14 shows the magnetic flux inside the storage ring. Opera lets one see where the magnetic flux is high and also where the magnetic fields are flowing. The little purple arrows are normalized to a small size. The flux that comes out of the magnetic dipoles flows through the cast iron towards the center. Also, to see how well the simulation matches the measured value, a graph was plotted for both the measured B field and the simulated B field in Figure 2.15. The x axis represents the distance from the center of the storage ring and the y axis shows the magnetic field in Tesla. We can further match the measured value with the simulation by changing the magnetic property of the magnets in Opera.

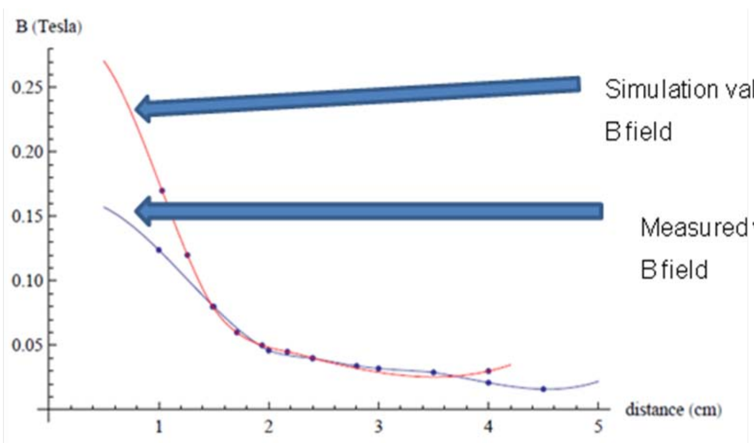

Figure 2.15 Measured and simulated B field inside the storage ring

2.2.2 Electrostatic Force and Charged Particle Confinement

The objective of this thesis is to make a storage ring and a particle accelerator with good control of an electron beam. To get better control of the beam inside the storage ring, different lenses made of electrodes can be incorporated inside the device. Figure 2.16 shows a storage ring that has three layers of electrodes. The large structure, hence the bottom iron plate and the six magnetic dipoles, contains magnetic fields to curve the electrons. The purple and orange electrodes inside the storage ring would bend the electrons further when sufficient voltage is applied.

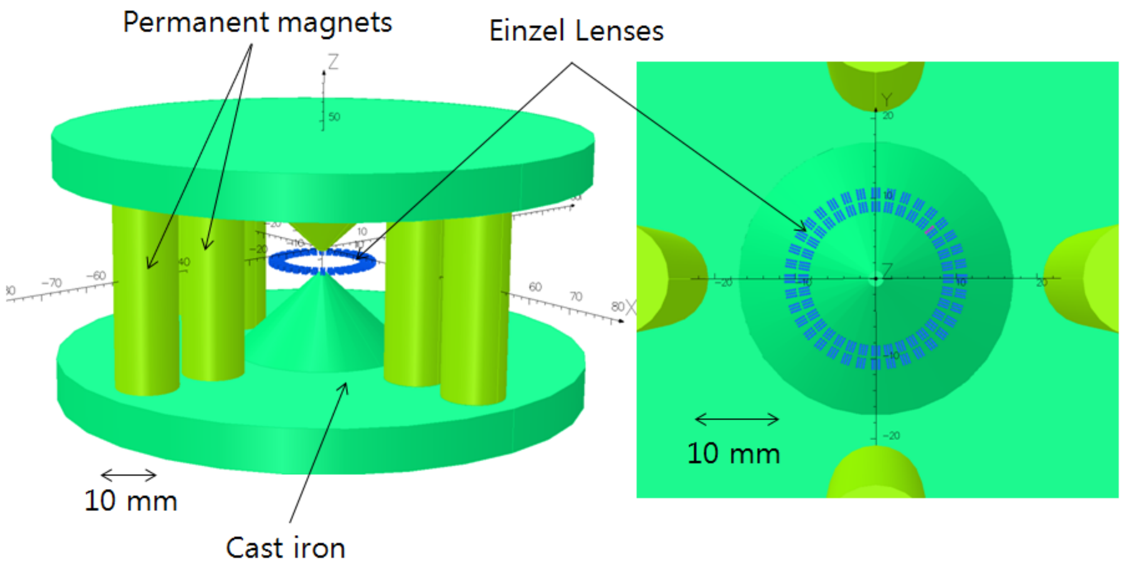

Figure 2.16 Storage ring with electrodes.

Figure 2.16 (right panel) is a top view of the storage ring and the electrodes. The electrodes inside the storage ring are closely packed to the trajectory of electrons to provide better control of the electrons. This structure is a case where both the electric and magnetic fields are used to control the particles.

Figure 2.17 is a closer view of the electrodes. The center electrodes have negative 2000 Volts applied to the walls. The red and blue materials in between the layers are the insulating parts. These different layers can not only bend the electron horizontally, but also vertically.

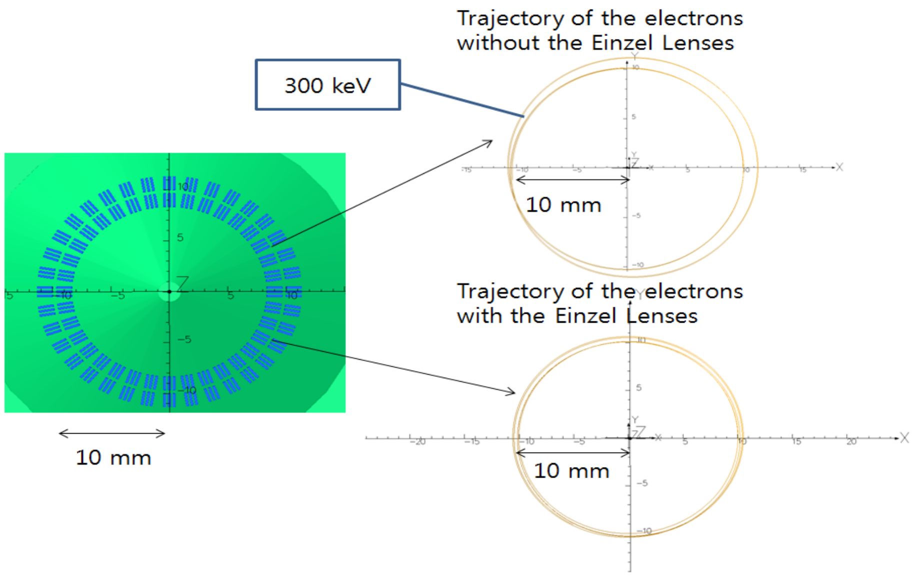

Figure 2.17 Storage ring and three layers electrodes

A storage ring that has a well defined electron beam needs strong magnetic dipoles, Einzel lens, curving electrodes, and quadrupole lenses. The combination of magnetic forces from the magnetic dipoles and the electrostatic forces from different lenses will provide better control of the electron beam inside the storage ring. A summary of this concept is shown in Figure 2.18.

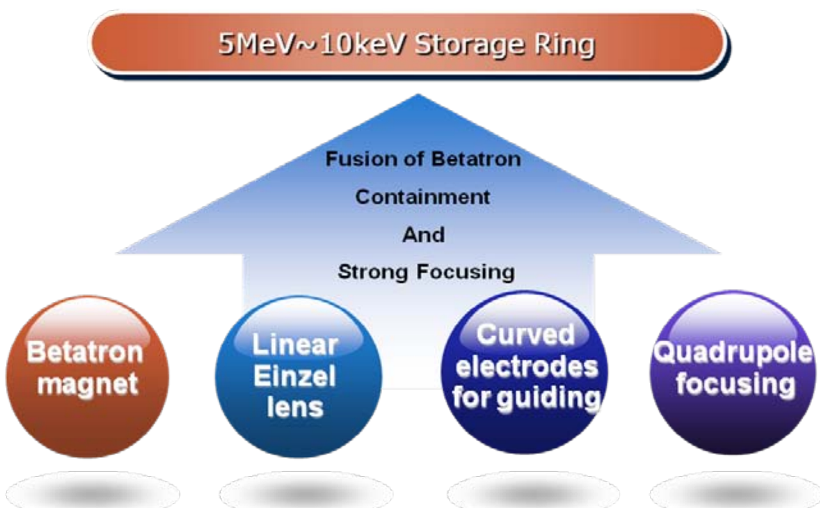

Figure 2.18 Integrated system of the storage ring

Chapter 3

Fabrication Results

3.1 Printed Circuit Board for the Einzel lens

The storage ring in this thesis uses the magnetic field to focus the electron beam. Additional Einzel lenses are incorporated inside the device in the Opera Simulation to increase control of the beam. Micro-fabricated electrodes inside the Betatron or a storage ring would bend the beam further. Electrostatic electrodes that are located inside the storage ring will provide better control of the charged particles.

Figure 3.1 shows an example of a Printed Circuit Board (PCB) for the Einzel lens that goes inside the storage ring. The PCB contains copper connections to the electrodes. The design in Figure 3.1 contains 39 Einzel lenses. As mentioned before, each Einzel lens consists of three sets of electrodes to bend the electrons.

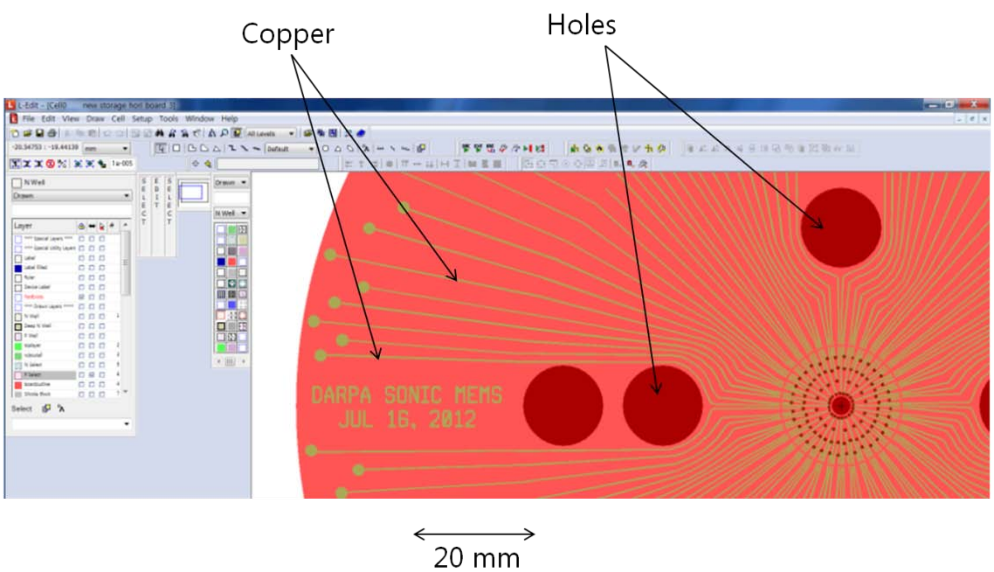

Figure 3.1 PCB for the Einzel lens

Figure 3.2 is the layout of the PCB for the storage ring. The layout was made using L-edit and the fabrication process was done using a 1.5mm thick FR4. Due to the fine (25um) resolution of the laser cutter it was possible to make an accurate Einzel lens PCB. The right side of Figure 3.2 is a closer view of the PCB. The little holes connect the electrodes to the backside of the PCB.

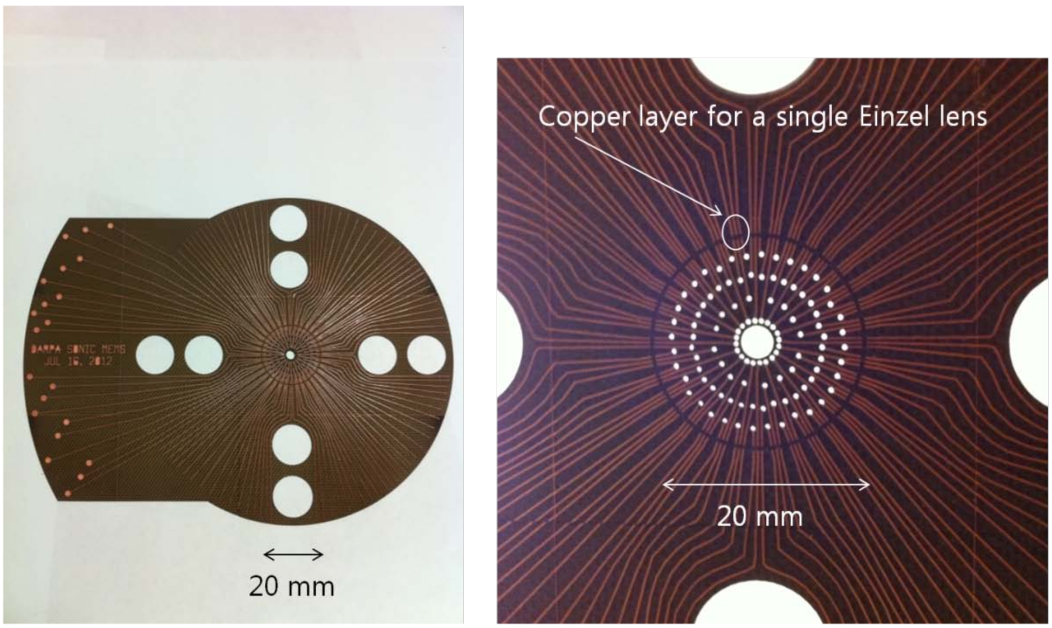

Figure 3.2 Einzel lens PCB that goes inside the storage ring

3.2 Storage Ring and Detectors

The design of the storage ring simulated in section 2.2 was fabricated. Figure 3.3 shows the first and second generation storage rings. The first generation storage ring has a diameter of 7 cm. It consists of two pieces of cast iron on the top and bottom and six permanent magnets that hold the iron plates. The particles would be injected through the permanent magnets and circulate inside the storage ring at a radius of 1.2 cm. There are holes inside the Betatron to make the assembly easier. The diameter of the second storage ring is approximately 12 cm and could contain up to eight permanent magnets.

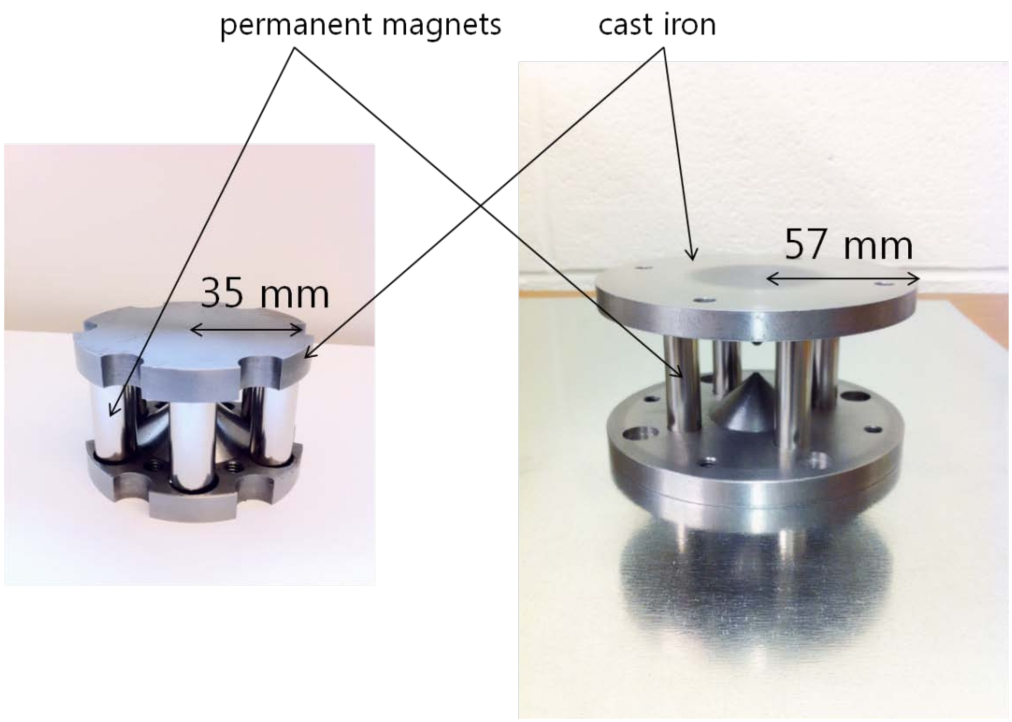

Figure 3.3 The first and second generation storage rings

In order to make sure that the magnetic field inside the storage ring matches the Opera simulation, the Hall effect sensor was used to measure the magnetic field. The Hall effect sensor generates 5Volts for 1 Tesla. Figure 3.4 shows the Hall effect sensor mounted inside the storage ring. The sensor tip is brought inside the storage ring and the change in voltage is shown on the oscilloscope. The higher readings in the oscilloscope signify a larger magnetic flux. For future research, magnetic Hall sensor chips that have different precision could be mounted inside the storage ring to get a better measurement of the magnetic field. After the measurement of the exact magnetic field inside the storage ring, it is possible to predict the trajectory of the particles.

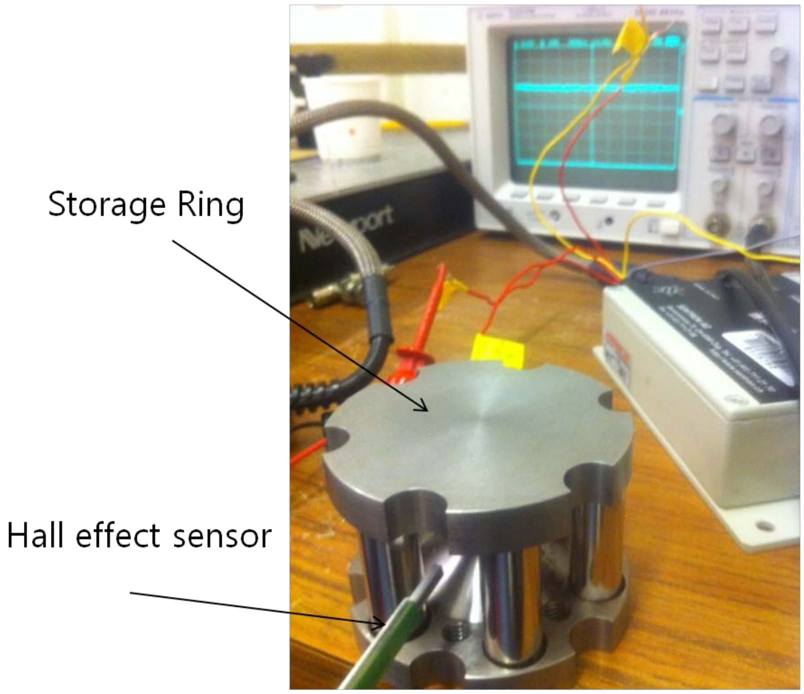

Figure 3.4 Measurement of the magnetic field inside the storage ring

After measuring the magnetic field inside the storage ring, the device can be tested with an electron gun to see the trajectory of the electron beam, but a detection mechanism is required to track the electron path. Conventionally, large particle accelerator facilities use phosphorous plates as one way to detect the beam. Whenever a particle hits the phosphorous plates, it generates a photon that can be seen on camera. Another way of detecting a particle is to have an electromagnetic radiation detector. Neither method is easily embedded inside a small storage ring. The phosphorous plate could be mounted inside the storage ring but it would be hard to put a camera on every path to see the particles. As for the electromagnetic radiation detector, the precision of the detector would be too small for a compact storage ring.

One solution is to place a PCB inside the storage ring. As the electrons hit the PCB, a current will be generated which can be amplified for detection. Figure 3.5 is an example of a PCB cut for the first generation storage ring. The green part is where the copper is left and the purple hole is where the electron is expected to pass. If the electron is deflected to the first quadrant, the green copper board would detect the current generated by the beam. The different colors in the picture depict the different layers.

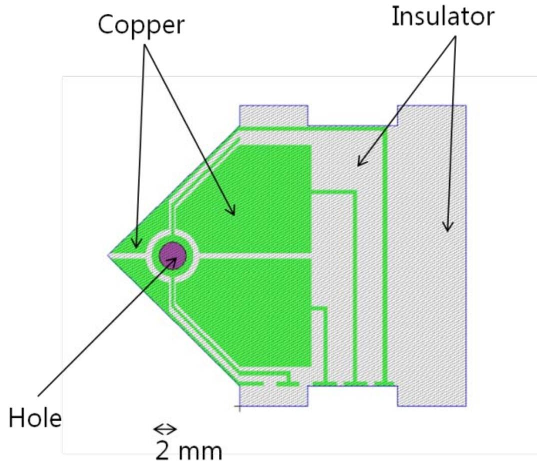

Figure 3.5 Vertical detector

Figure 3.6 shows a horizontal board that goes inside the storage ring. It is designed to hold the vertical detectors. The green part is the copper where the current flows. The magnetic poles and the iron plates of the storage ring pass through the circular purple holes and the vertical detectors go through the rectangular purple holes.

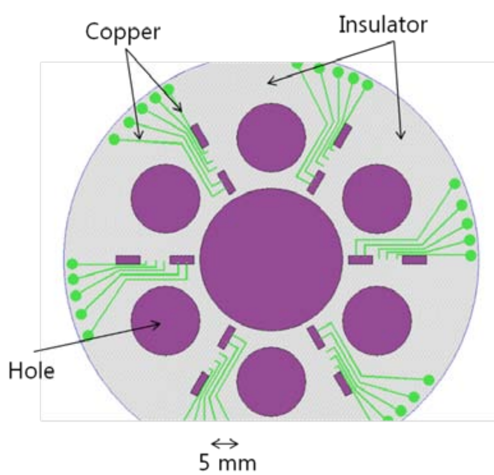

Figure 3.6 The horizontal plate that holds the vertical detectors

Figure 3.7 is the storage ring before and after assembly. The storage ring consists of two iron plates. They are the top and bottom structures. The magnetic poles fit between the top and bottom structures to give the magnetic flux. The detectors also go in between the top and bottom structures. If the electron goes through the expected equilibrium trajectory of the detector holes, no current will be read, but if the electrons deviate from the stable orbit, they will hit one of the detectors inside the storage ring and a current will be generated.

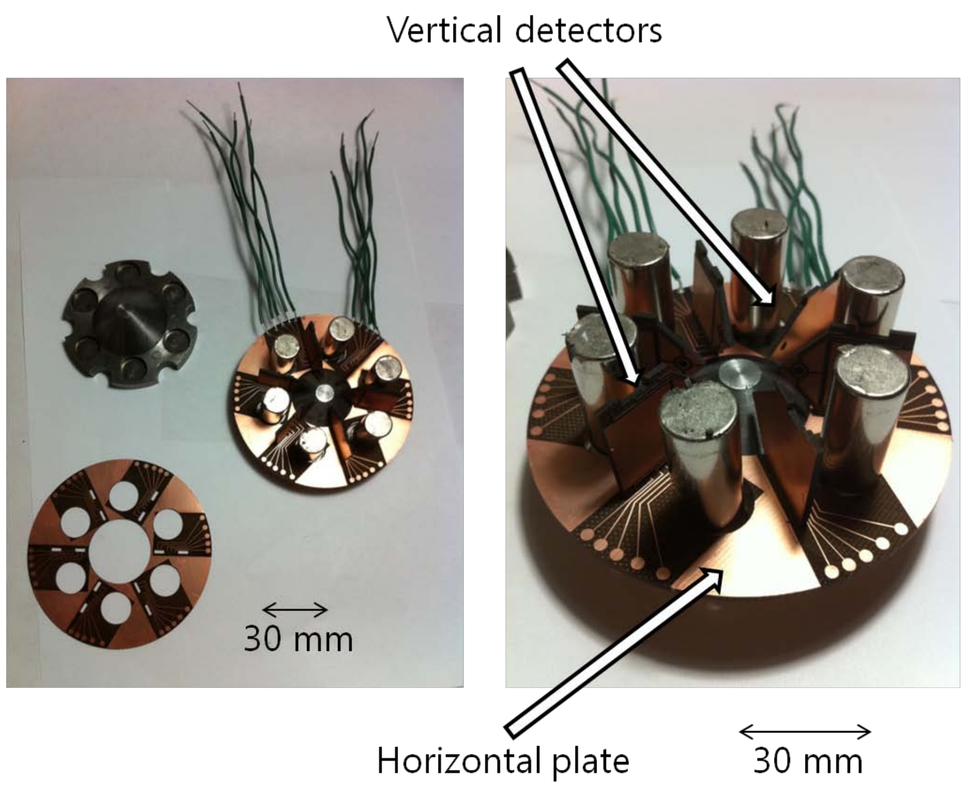

Figure 3.7 Detectors and the storage ring

The second generation detector has a different design with 100um precision in detecting the position of the electron. It can only read the vertical or horizontal position of the particle. Figure 3.8 shows the second generation detector that fits inside the storage ring. It has a horizontal strip of copper (100um) with a gap of 100um.

Therefore, it has a vertical resolution of 200um. The same design with vertical strips can be made to analyze the horizontal position of the beam.

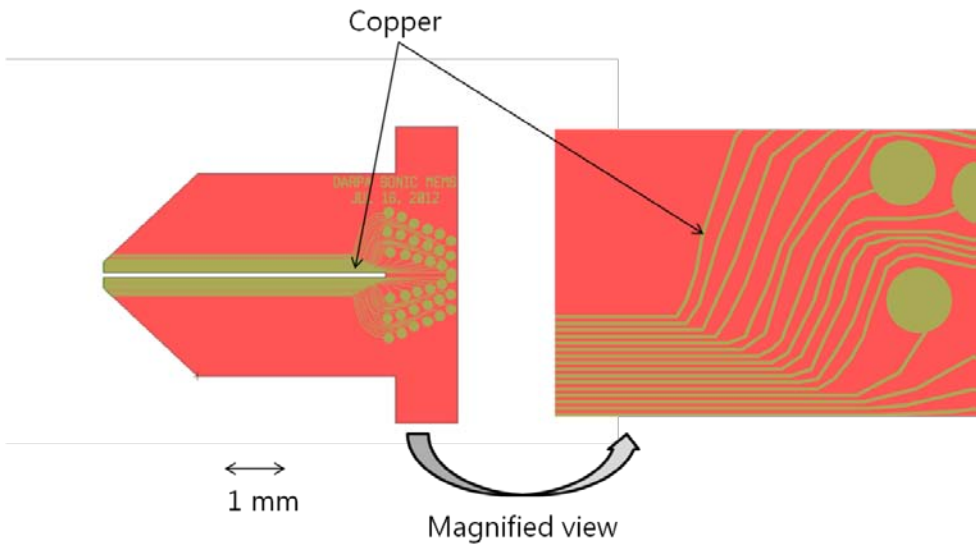

Figure 3.8 Second generation detector for the new storage ring

Chapter 4

Summary and Conclusion

The objective of this thesis is to explore the technology of a miniature particle accelerator which can be used as an X-ray source for chest X-rays and computed tomography scanning. A miniature particle accelerator can store an electron beam using a storage ring. Such a storage ring was simulated using computational and analytic techniques.

Autodesk Inventor and Opera were used for the simulation of the storage ring and the Einzel lens. The Opera simulation of an Einzel lens that is 100 micrometers in width shows a focusing of 0.2mm diameter beam to 0.07mm. The electron beam energy is 3.5keV and the voltage applied to the electrodes is 3000V. Furthermore, storage rings were simulated in Opera and the simulated structure was fabricated along with the detectors. The fabricated storage ring has a diameter of 114mm and a height of 57mm.

The storage ring confines an electron beam in its equilibrium orbit in the Opera simulation, but the simulated structure still needs to be tested inside the vacuum chamber. The detectors made from the FR4 inside the storage ring would detect the trajectory of the electron beam. Once the storage ring works experimentally, other particle accelerator devices for the Bremsstrahlung and Inverse Compton scattering can be designed for applications.

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