JOINT INSTITUTE FOR NUCLEAR RESEARCH
Flerov Laboratory of Nuclear Reactions

SUMMER STUDENT PROGRAM FINAL REPORT

Design of gaseous detectors for charged particle detection

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ABSTRACT

Out of many interesting issues of nuclear physics it can be distinguished light exotic nuclei investigations. Exotic nuclei are artificially produced isotopes, characterized by the ratio of neutron number N to proton number Z significantly different than in nuclei occurring in the nature. Because of low separation energy light exotic nuclei are located near the border of stability and easily decays through different channels. Research carried out in Flerov Laboratory of Nuclear Reactions focused among others on study of these nuclei which decays with β-delay proton emission. FLNR is equipped with facilities enable to conduct whole experiment of nuclear reactions. From the synthesis light exotic nuclei with cyclotron U-400M, then selection of desirable isotope from all produced nuclei by ACCULINNA fragment separator and finally set of devices designed for decay products detection. Very useful in that study is gaseous detector with optical readout named Optical Time Projection Chamber.

The subject of the presented project was assembly, electronic and mechanical tests of OTPC chamber and design of small chamber for new gaseous test detector.

Contents

1 Introduction

Flerov Laboratory of Nuclear Reactions (FLNR) is known mostly from synthesis of super heavy elements, artificially produced transactinides which have very short half life time. Here in the late sixties were synthesized element 105 named after location of the Joint Institute for Nuclear Research as dubnium. In recent years heavier nuclei were synthesized and currently known periodic table was filled completely. In previous year 2016 The International Union of Pure and Applied Chemistry honoured Yuri Oganessian, the leader of the laboratory where super heavy elements were created, by naming the heaviest element 118 as oganesson.

However superheavy elements are not the only one FLNR's area of interest. Other important field of research are light exotic nuclei and that will concern the report presented here. There is investigated radioactivity with proton emission and recent discoveries have confirmed theoretically predicted exotic channels of decay with emission of two or even three protons. These discoveries were possible thanks to the use of novel technique of charged particle detection which is Time Projection Chamber with optical readout (OTPC). Discussed OTPC is gaseous detector and its principle of operation based on signal, which comes from gas ionization inside the chamber volume. Electrons signal is amplified due to usage of Gas Electron Multiplier (GEM) foils system. There are collected two types of data: CCD camera pictures and PMT signals, what enable to reconstruct trajectories of implanted ions and emitted protons.

It is exactly construction and operation principle of OTPC was topic of the project within the Summer Student Program at JINR. The tasks included getting acquainted with the structure of OTPC, electrodes installation inside the detector chamber and test of the insulation in GEM foils and the main part was to design new chamber for test detector, which will be smaller than its predecessors.

1.1 Exotic nuclei study

Each element is defined by its atomic number Z, which corresponds with number of protons in nucleus and is also equivalent the number of electrons in unionized atom. Thing that may vary in atomic nucleus is number of neutron N, hence the elements with the same atomic number but different neutron number are called isotopes. As elements could be ranked in periodic table also the same isotopes can be line up into nuclide chart (Figure 1).

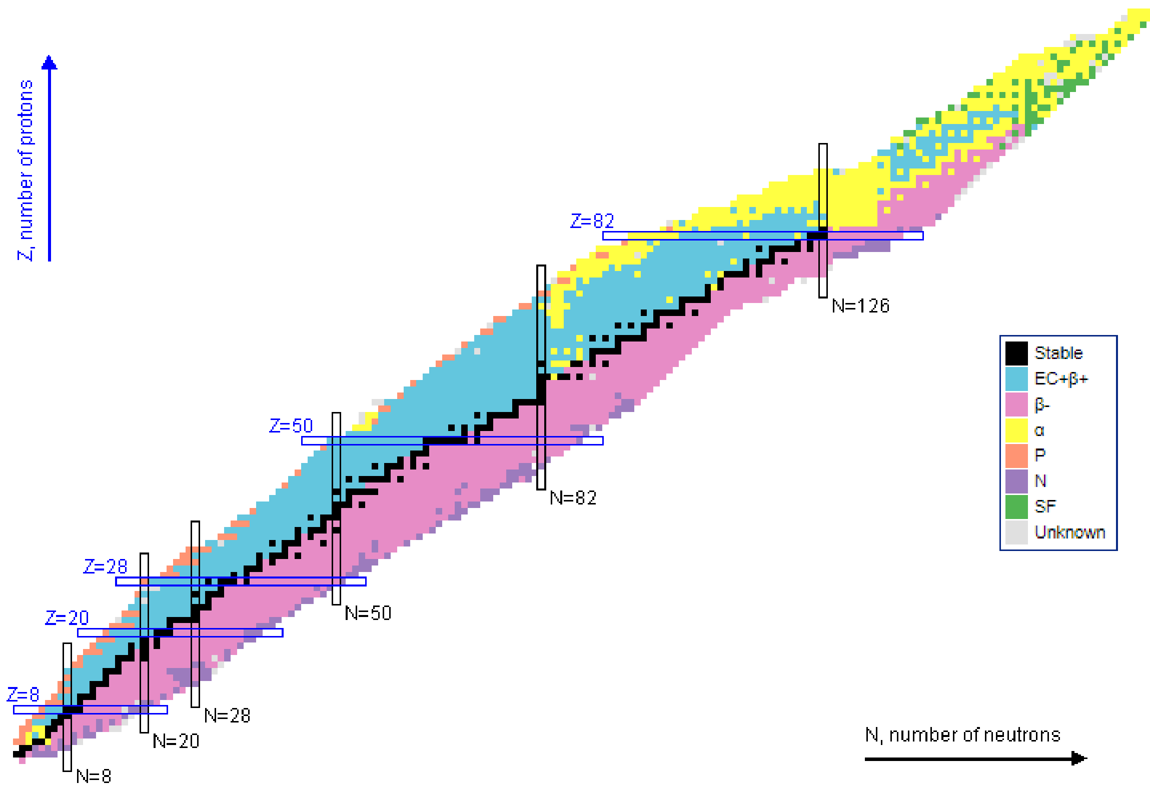


Figure 1. Chart of nuclides taking into account all existing decay channels [1]

The path of stability, marked by black line, represents isotope with optimum proton to neutron ratio, where the energy of the nucleon separation is the largest. With the receding away from stability path separation energy decreases until it becomes negative. The borders of nuclide chart are called accordingly proton and neutron drip lines. Exotic nuclei, which are located above stability path have more protons than neutrons inside nucleus, so they are defined as neutron-deficient isotopes. These nuclei undergo $\beta+$ decay, that is positron emission, or electron capture (EC).

Initial nucleus, called precursor, disintegrates in $\beta+$ process which leads to the formation of the product in excited energy state. If the excitement energy of the formed nucleus is higher that proton separation energy after $\beta+$ decays one or even more protons could be emitted. That process is termed as β-delayed proton emission and is one of research subject carried out by ACCULINNA group. An interesting issue is search for 3 protons emission in light exotic nuclei. It is extremely rare channel of decay, as far observed only in three cases: ^{45}Fe, ^{43}Cr and ^{31}Ar [3]. 3 protons decay channel is also theoretically predicted in ^{27}S and that isotope is actually one of FLNR's research subject.

1.2 ACCULINNA fragment separator

Exotic nuclei does not occurring in the nature, so they must be formed artificially. Nuclear reaction is performed by projectile of one nuclei hitting thin target made from another nuclei. Primary beam is made by acceleration appropriate nuclei in the cyclotron. In case of FLNR study cyclotron is U-400M. As a result of the collision there are produced many different fragments and secondary beam is not homogeneous. In order to study particular isotope features, special device to fragments separation must be used. Nuclei can be split according to their mass to charge ratio A/q and by atomic number Z. In the discussed energy range atomic number is equivalent to the charge $Z = q$, because ions are deprived of electrons. Selected fragments reaches to detection section where is measured their time of flight (TOF), energy loss (dE) and finally decay products are recorded. All mentioned steps of nuclear reaction experiment accomplishment are presented on the scheme below.

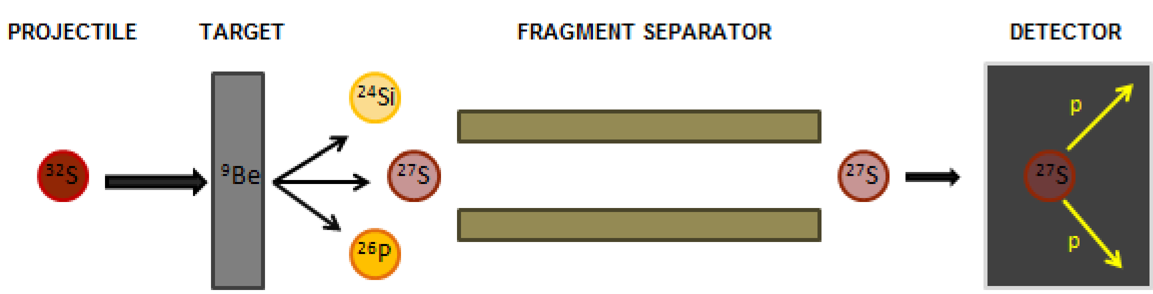


Figure 2. All stages of the experiment with exotic nuclei on the example of ^{27}S.

Important and the biggest equipment of Flerov laboratory is fragment separator ACCULINNA (*Figure 3*). As each separator it consists of many elements intended for various purposes. Quadruple magnets (green elements) orders to focus beam along all its path. In the first focal plane ($F1$) is located target and it is place of exotic nuclei production. Dipole magnets ($D1$ and $D2$) are used to split beam according to A/Z ratio, wedge degrader with slits (placed in focal plane $F2$) enable to select fragments by its charge Z. The physical principle of the first ions separation is based on radius ρ of the charged particle track dependence on mass to charge ratio:

$$B\rho = \frac{p}{q} = \frac{\gamma m v}{q}$$

where B is induction of applied magnetic field and γ is Lorentz factor. With good approximation $m = A \cdot u$ (u is unit of atomic mass) and knowing that $q = Z$ results:

$$\rho \sim \frac{A}{Z}$$

By appropriate setting of slits on the exit of dipole magnet desirable radius is chosen and primary ions separation is obtained. In the next step wedge degrader is used to disperse beam by fragments velocities. After passing through degrader ions with different Z have different velocities, because atomic slowing down of the ions is proportional to Z^2/v^2 [4]. ACCULINNA's separation method is called *in-flight* because generally products of nuclear reaction are not stopped in the target.

In last two focal planes are located scintillation detectors to measure time of flight and energy loss of ions which were chosen in the process of separation.

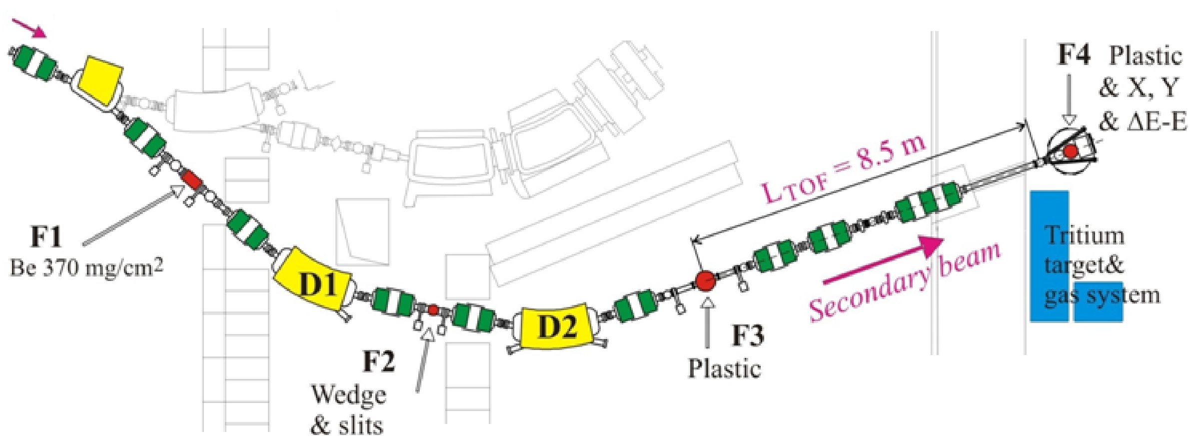


Figure 3. ACCULINNA *in-flight* fragment separator scheme (FLNR, Dubna) [5]

1.3 Optical Time Projection Chamber detector

To study light exotic nuclei decays processes specific type of Time Projection Chamber with optical readout was invented [6]. OTPC is a box filled by adequate gas mixture to stop ion inside the active volume of detector. Both implanted ion and emitted protons ionizes gas particles along the way that they move. Inside chamber there is voltage applied to carry electrons to amplification section. Electron's signal is amplified due to application of GEM foils. GEM is an acronym of Gas Electron Multiplier [7] and has a form of very thin kapton foil (50 μm of thickness) covered on both sides by even thinner copper layer. Copper is metal so layers could be treated as two electrodes. In foil there are plenty of tiny holes and applying voltage leads to emergence of a strong electric field inside them. Electrons which are near to GEM foil and drop into holes are duplicated and in that manner signal increases. In result the avalanche of electrons reach to gating electrode which is in the form of a grid.

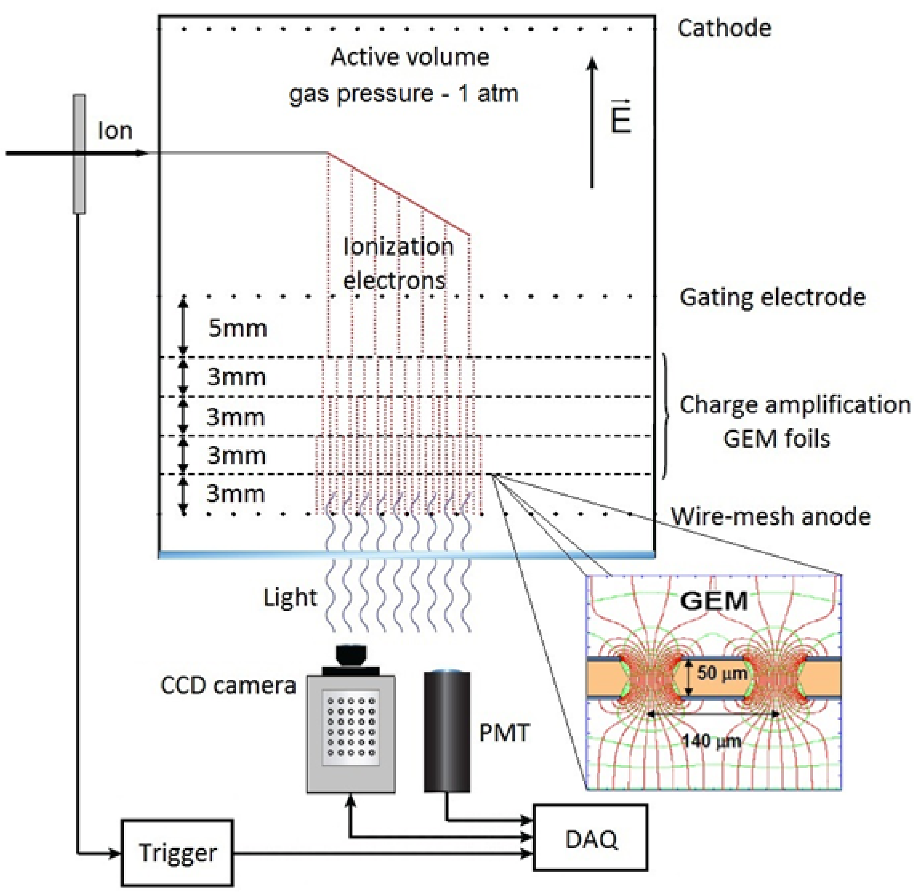


Figure 4. Scheme of Optical Time Projection Chamber [6]

Afterwards electrical signal is converted into optical by exciting gas particles, which emit light. Whole described construction is completed by optical window at the bottom. There are collected alike optical signal in the form of pictures from CCD camera and PMT signal. Pictures from CCD are perpendicular projection of charged particles trajectory. From PMT is getting information about time of particle movement, so if drift velocity is known it is easy to calculate the component along z-axis and reconstruct track completely.

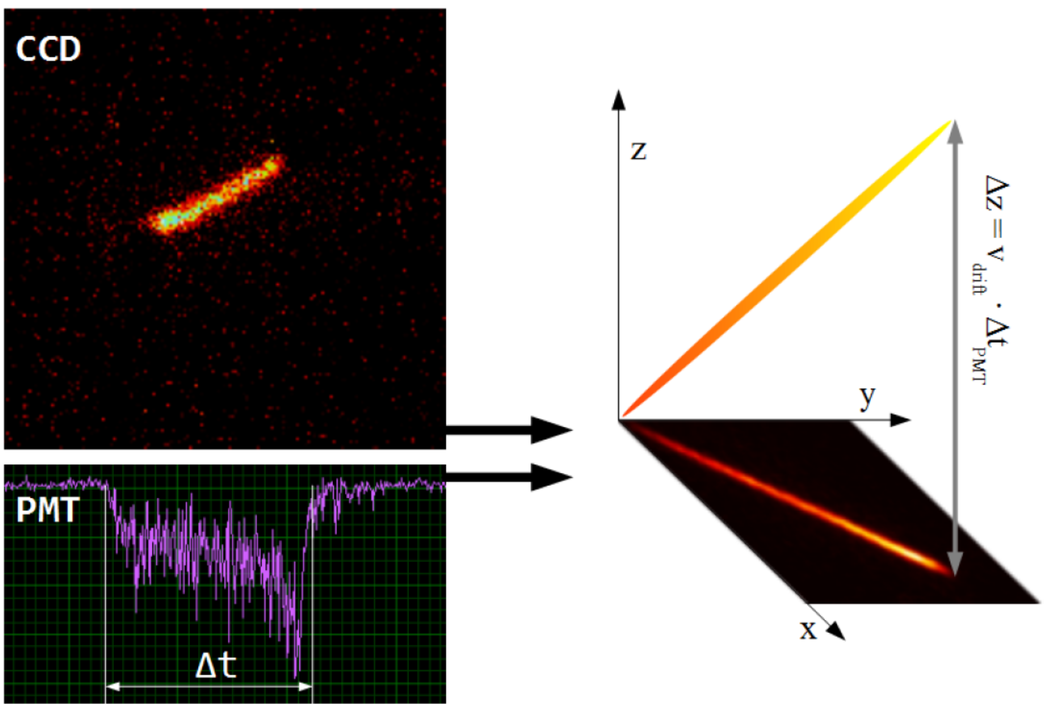


Figure 5. Three dimensional track reconstruction from both OTPC signals [3]

The advantage of the presented detector compared to common TPC is the first that it is smaller and it is characterized by greater sensitivity in the range of low energy. OTPC is extremely useful device in researches of light exotic nuclei radioactivity and was very helpful in many discoveries of new decays channels e.g. β- delayed 2 and even 3 proton emission. As every appliance, OTPC may be improved application of various new technical solutions and this is the motivation of an effort put in the work of detector construction developement.

2 Summer practice project

The Summer Student Program project was divided into two main parts:
I. manual work with equipment including mechanical and electronic test
II. design of test detector with graphical visualization

Short description of tasks from first section is presented below. Result from the second, it means demonstrative technical drawings and rendered pictures, are also include in that report on the following pages.

2.1 OTPC assembly and electronic tests

First part of project consisted of practical operations with OTPC elements. Appropriate frames were prepared for electrodes and GEM foil installing by scratching the surface in the grid pattern to form grooves for the glue. Then top electrode has been mounting. The biggest difficulty during construction of that kind of detector is flat and uniform straining of GEM foil on its frame. For this purpose foil is placed in special rack with slot which is larger than the frame size and heats it up. Foil is inserted between two heavy frames and then rack is tighten. Functionality of an exemplary rack was also tested with using solo kapton foil, which is of course significantly cheaper than GEM foil. The result of that test was rack well fulfills its function, but there could be made some improvements like e.g. pasting screw nuts into holes for easier turns two parts of the rack together.

There ware also performed electrical insulation tests of GEM foils. Each GEM consists of two copper layers - one on the top, second on the bottom - and kapton foil in between which should be insulating. Even though voltage is applied to both copper layers there should not be any current flow. During these tests was applied voltage with a value from 10 V to 550 V and no current except noise was recorded. Further voltage increasing was discontinued for fear of short circuit which leads to destroying GEM.

Tasks described here are only small piece of work with which must be tackled during preparing detector for real measurement in physics experiment.

2.2 OTPC Mini design

Next part of SSP project was to design chamber and main elements for new test detector. The main requirement was to make detector more compact and to remove all electrodes from active volume of chamber for unification electric field acting on charged particle. An additional idea was to paste foil with copper wire on walls inside detector which could help to control electric field in the active volume with gas mixture (in previous models walls were covered by only kapton foil). Wires are thin layers of copper deposited on kapton surface with width of 7 mm and at intervals of 3 mm. Walls had to be designed in that specific way to connect wires in the corners and not break the circuit by holes dedicated to gas input and output. For testing purpose alpha source with known radioactivity is placed inside detector so that is why there is no needed any entrance for implanted ion. Prepared project should take into account airtightness and ease of assembly. The proposed dimension of chamber is 160 x 160 x 151 mm, with active internal volume 110 x 110 x 121 mm. During practice were made demonstrative sketch of all OTPC elements with initial dimensioning.

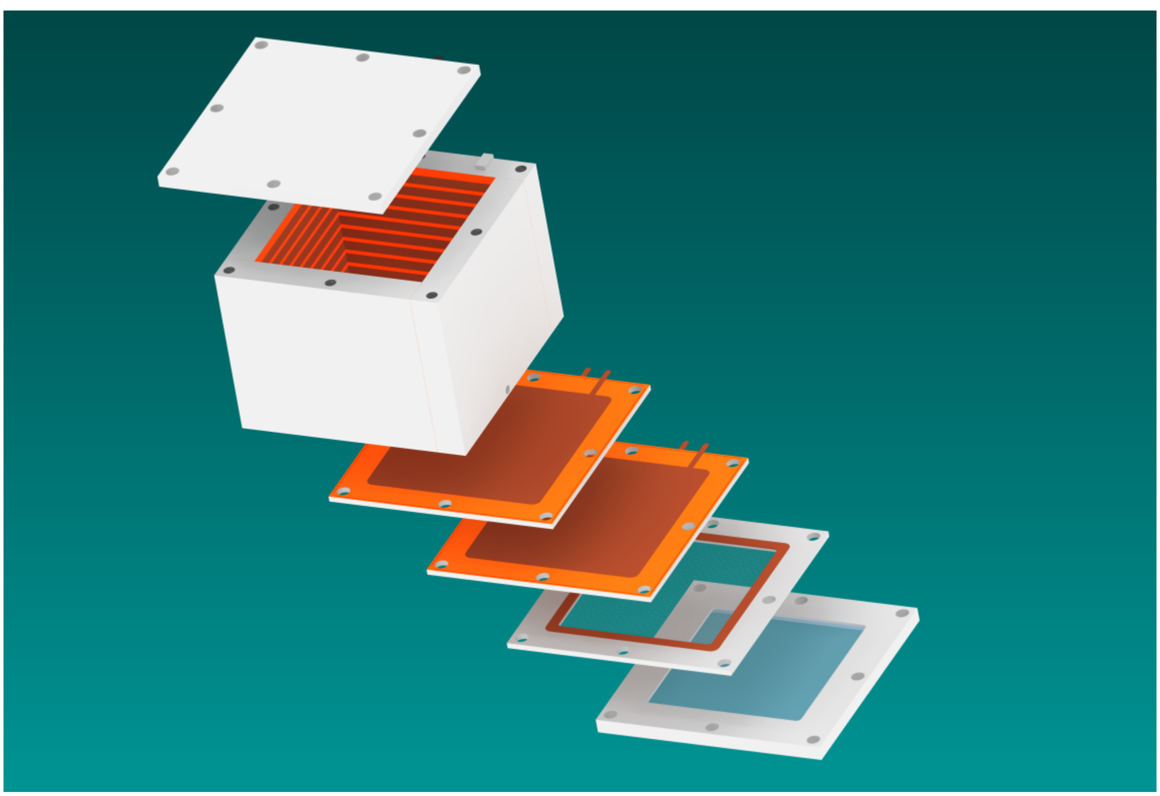
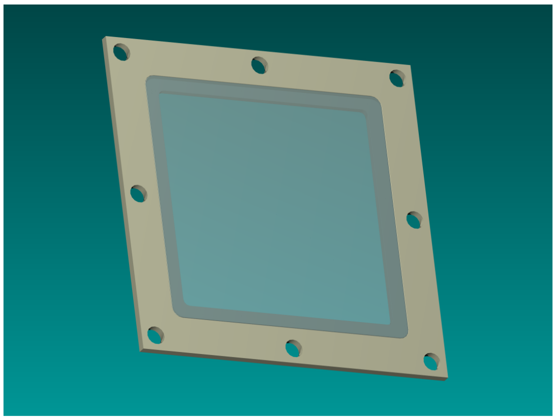
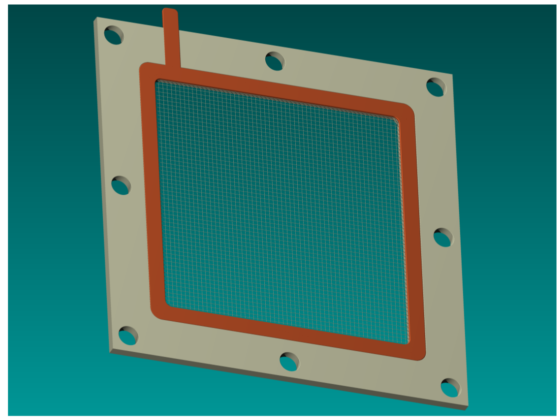


Figure 6. Visualization of OTPC Mini with manifestation of all main elements.

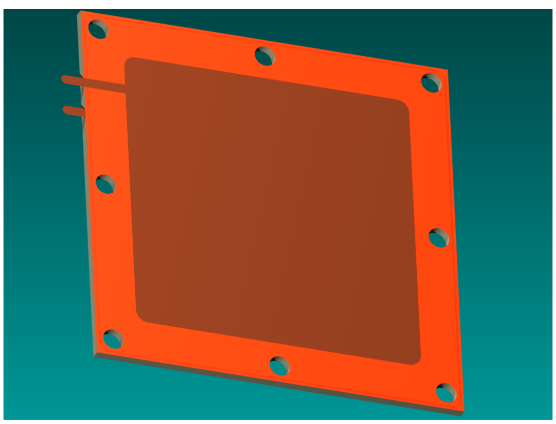
All schemes and graphics were done using the *Autodesk Inventor Professional* program. During practice there were made demonstrative sketch of all OTPC elements with initial dimensioning. On the current page are presented chosen rendered pictures of main OTPC elements (**a-f**). Further on *Pages 13-23* are included resized schemes of all designed elements.



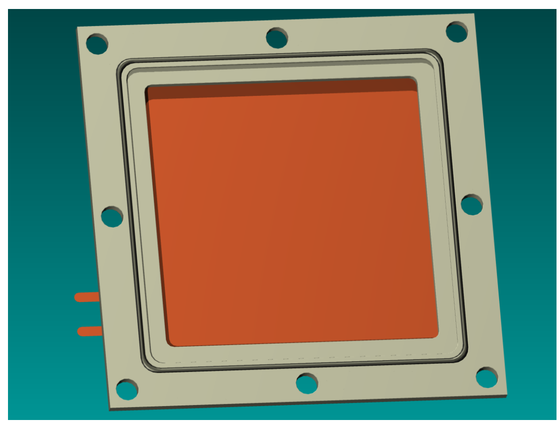
(a) frame for bottom window



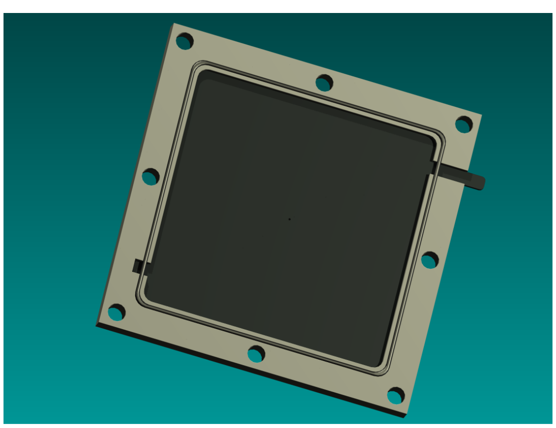
(b) frame for bottom electrode



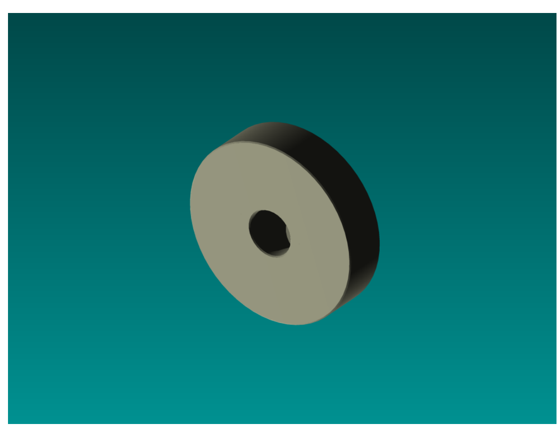
(c) top view of GEM



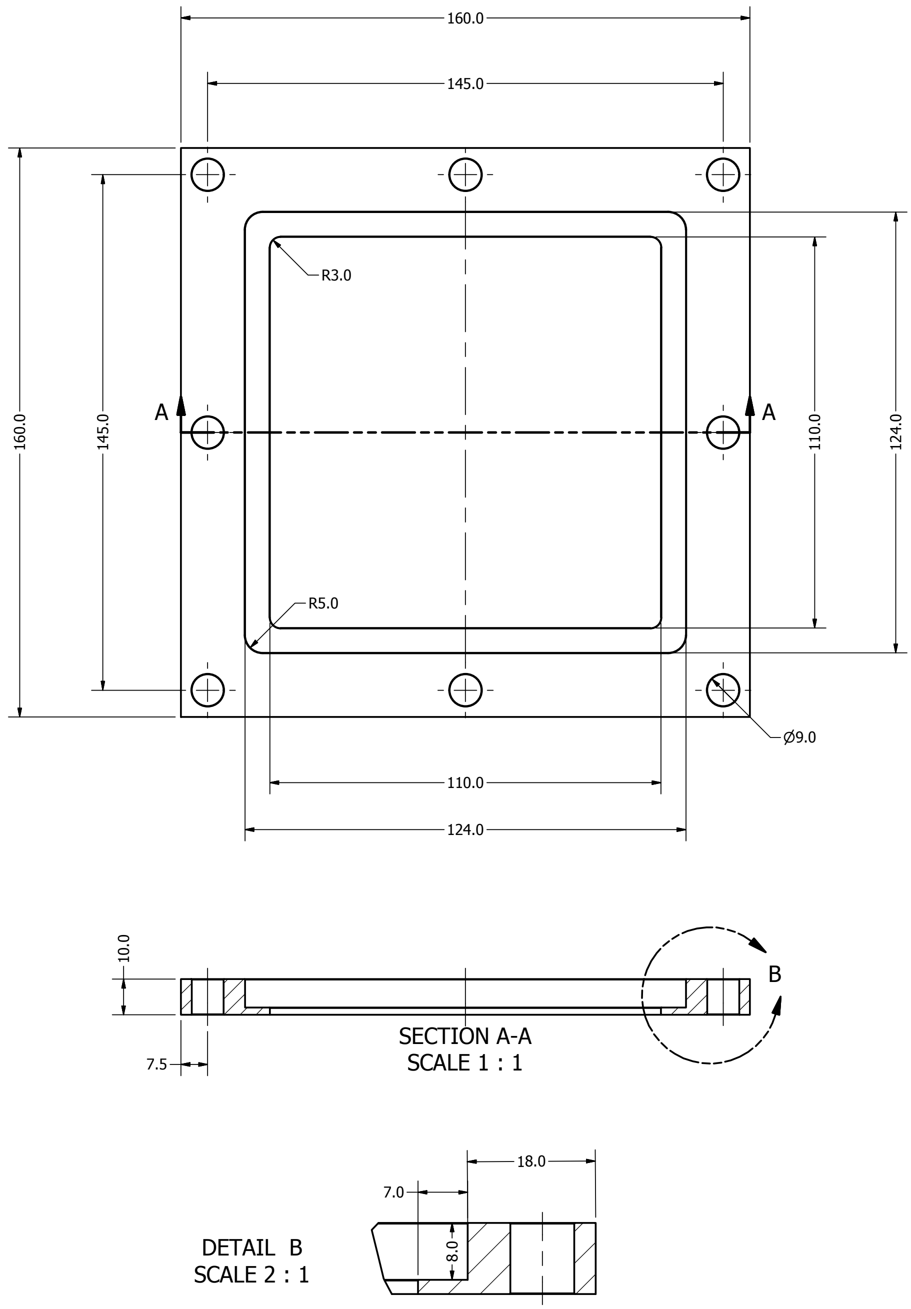
(d) bottom view of GEM



(e) frame for top electrode



(f) holder for source



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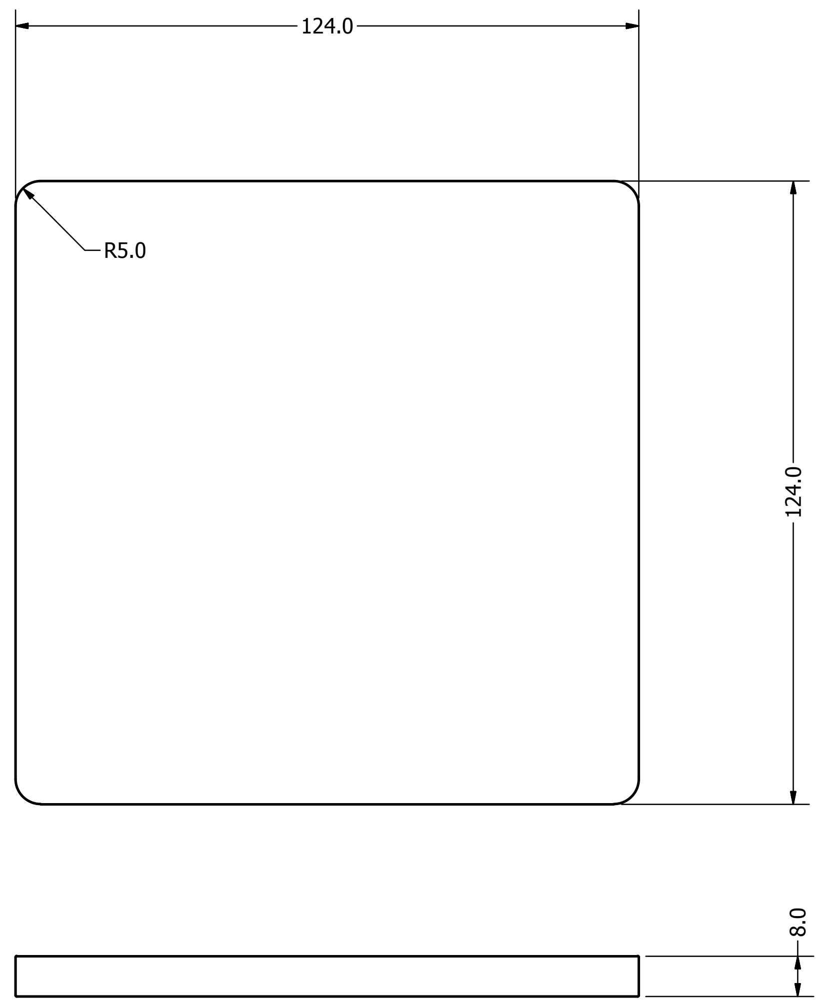

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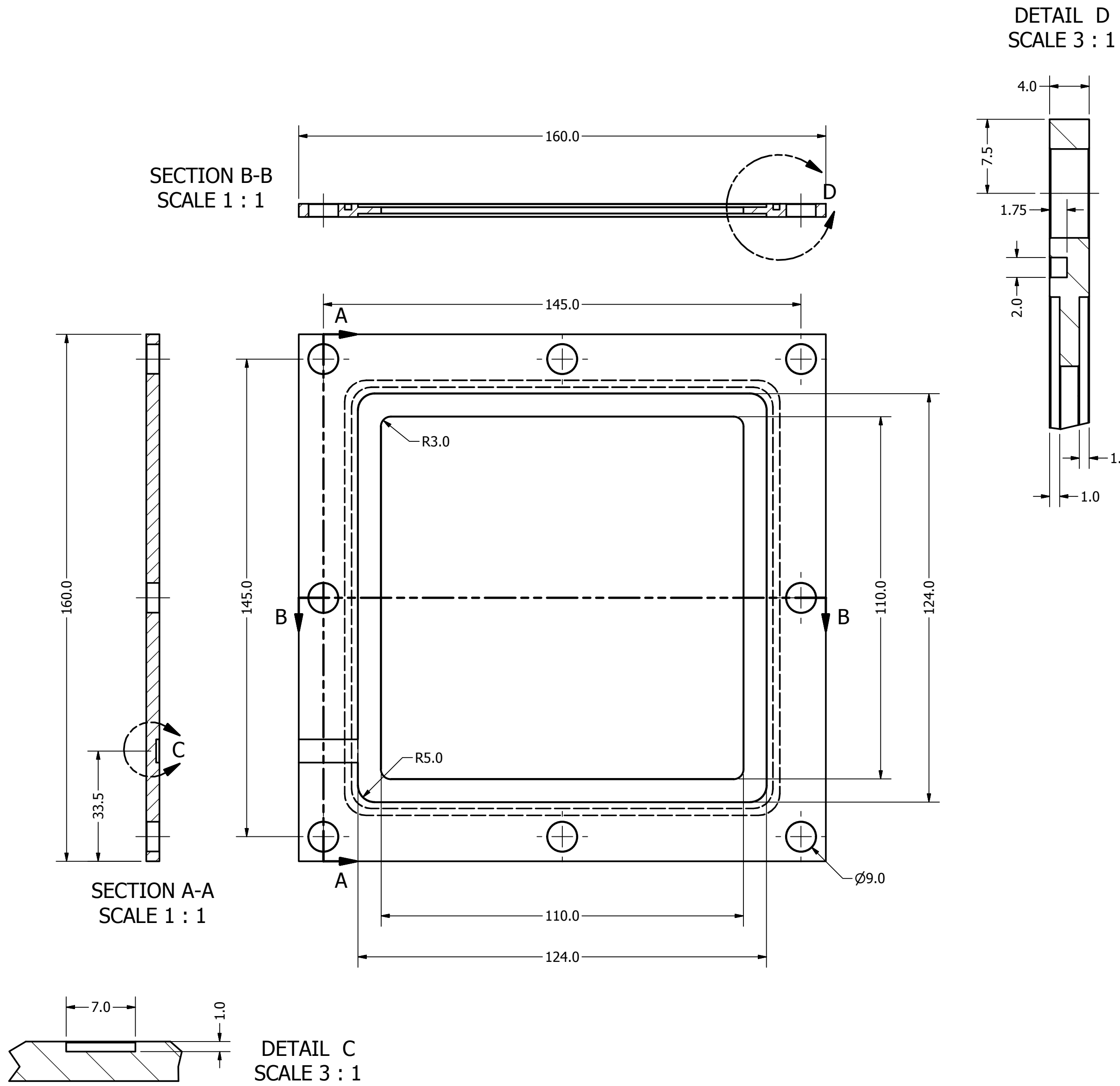

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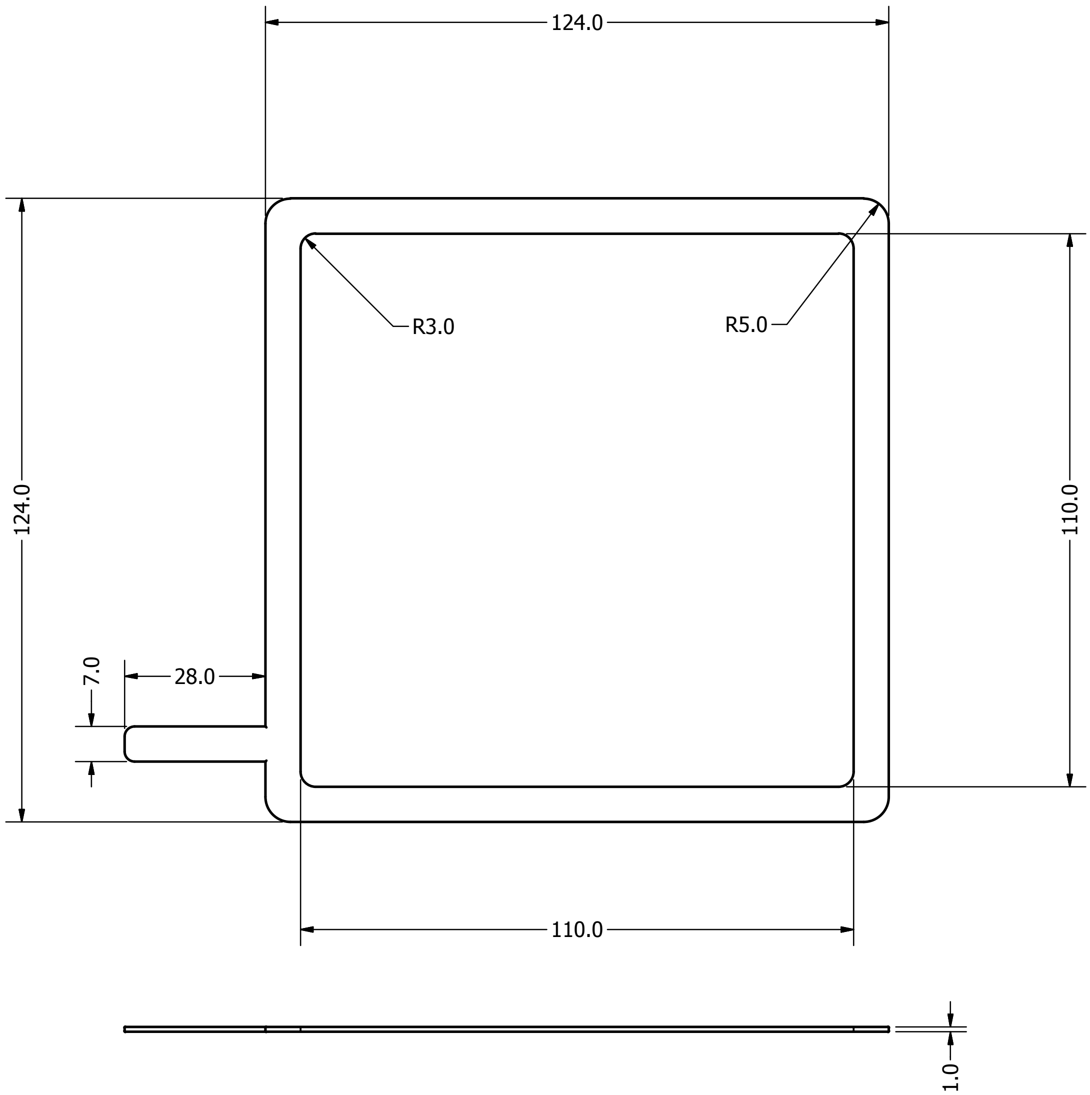

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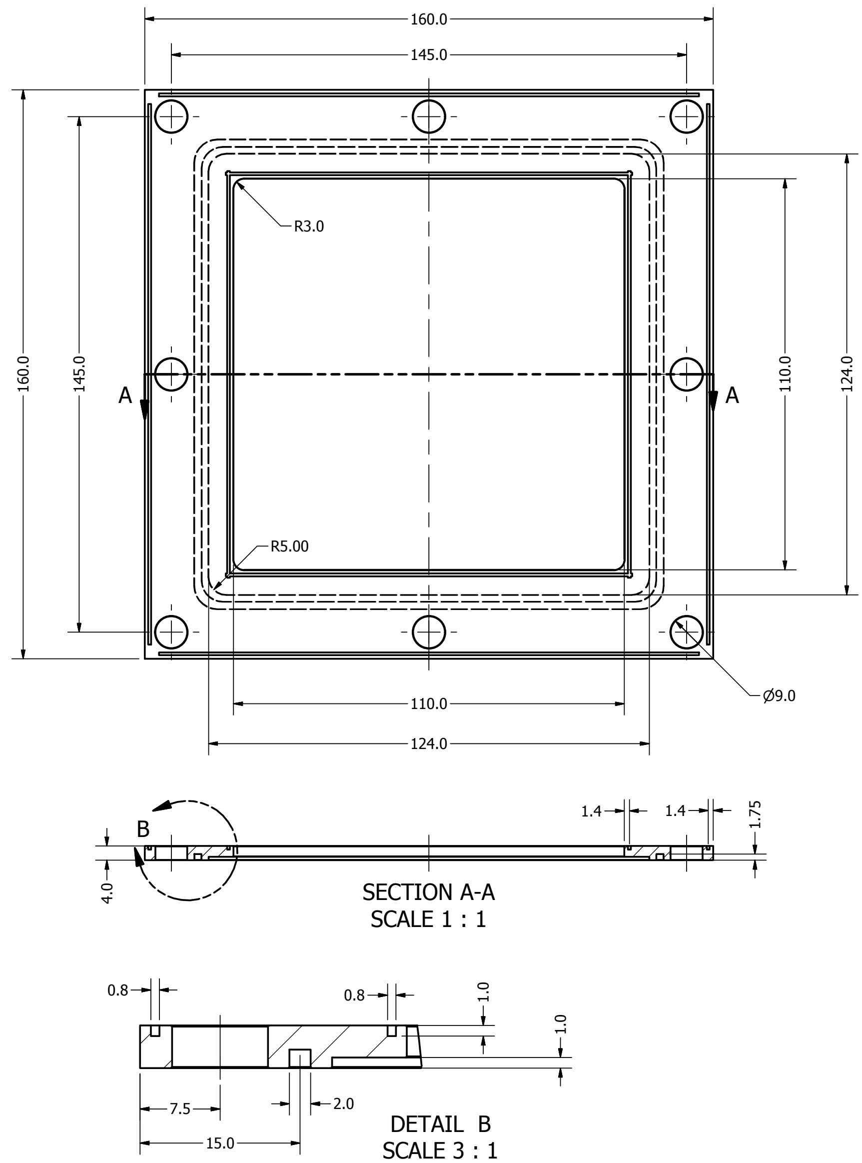

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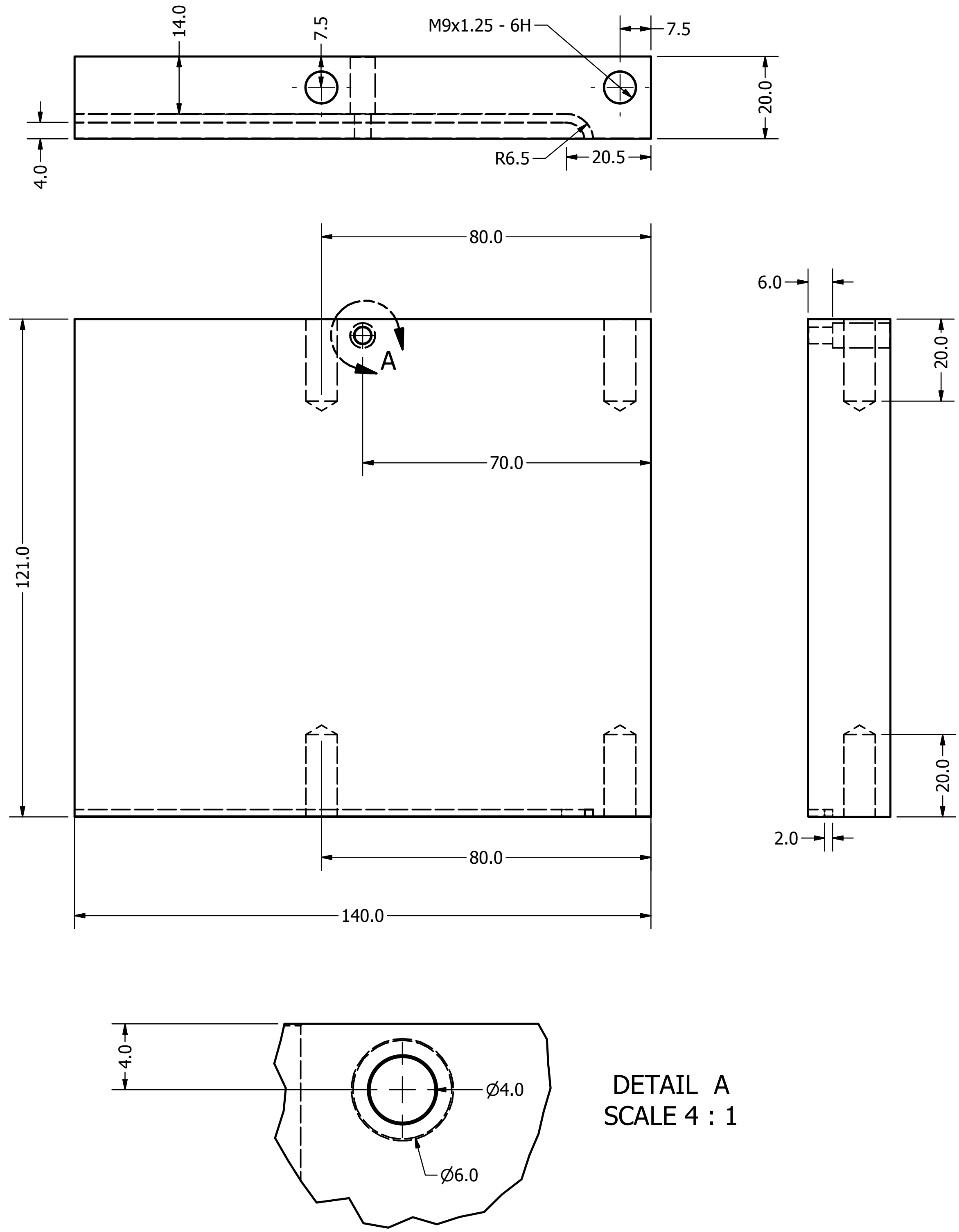

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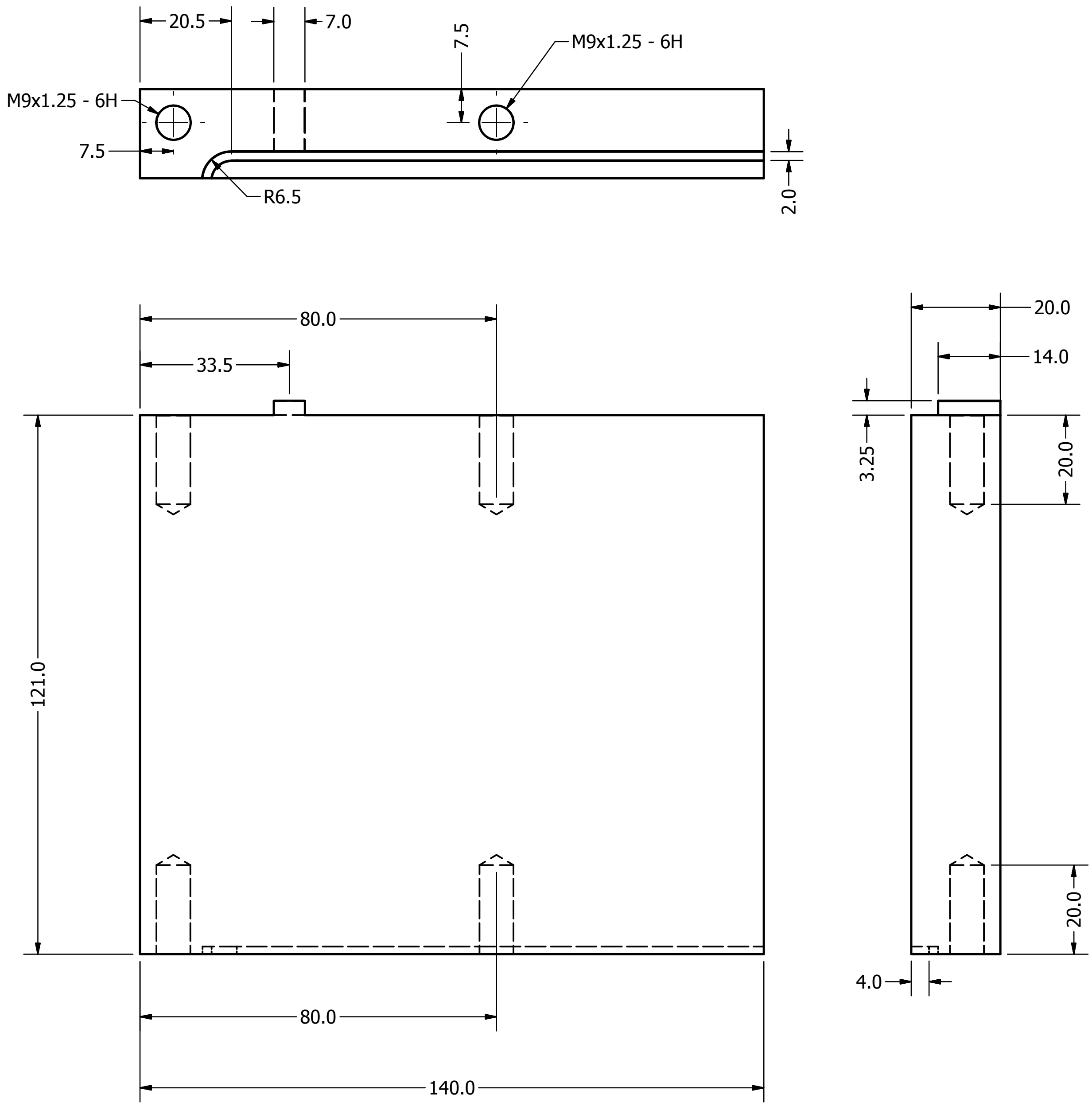

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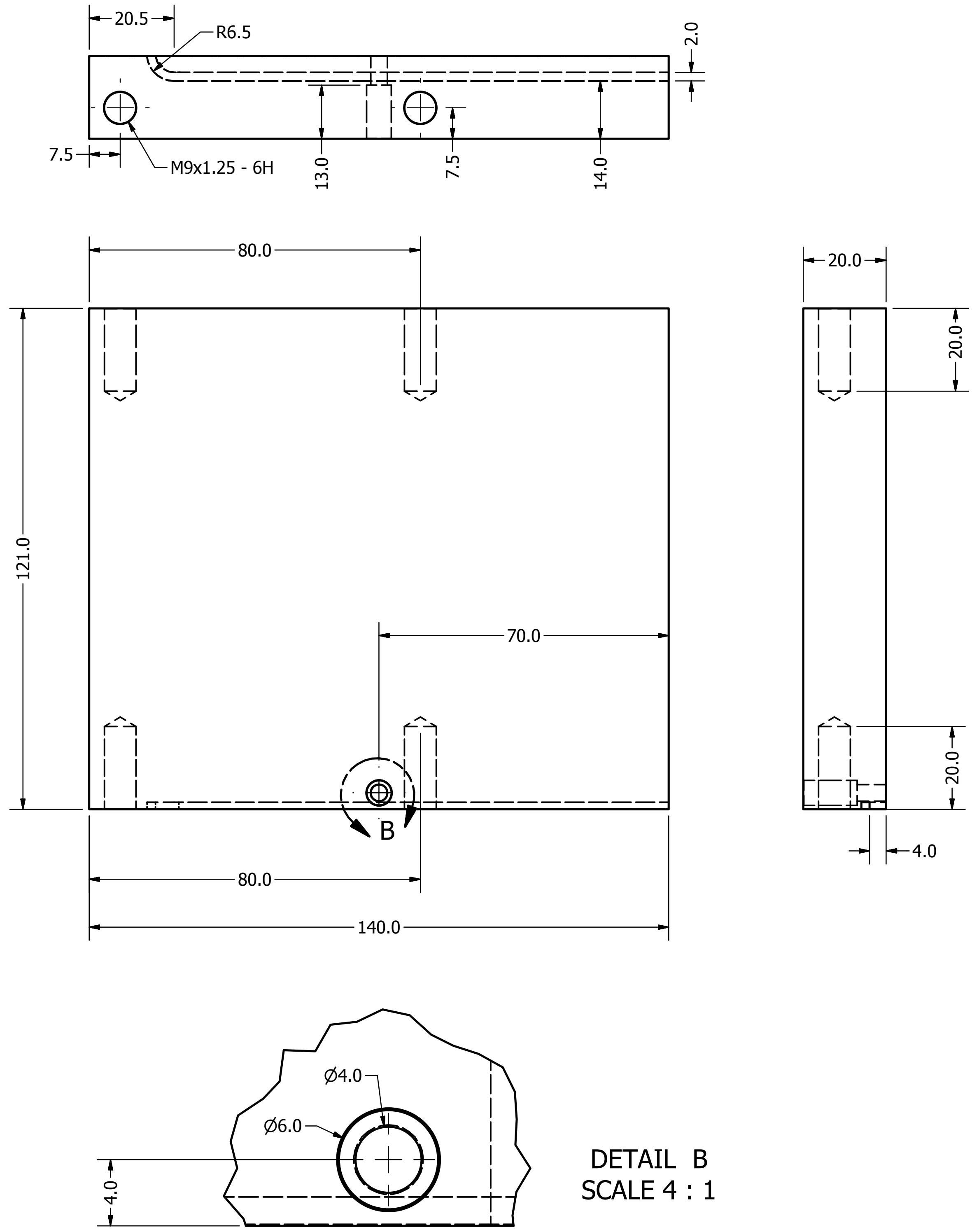

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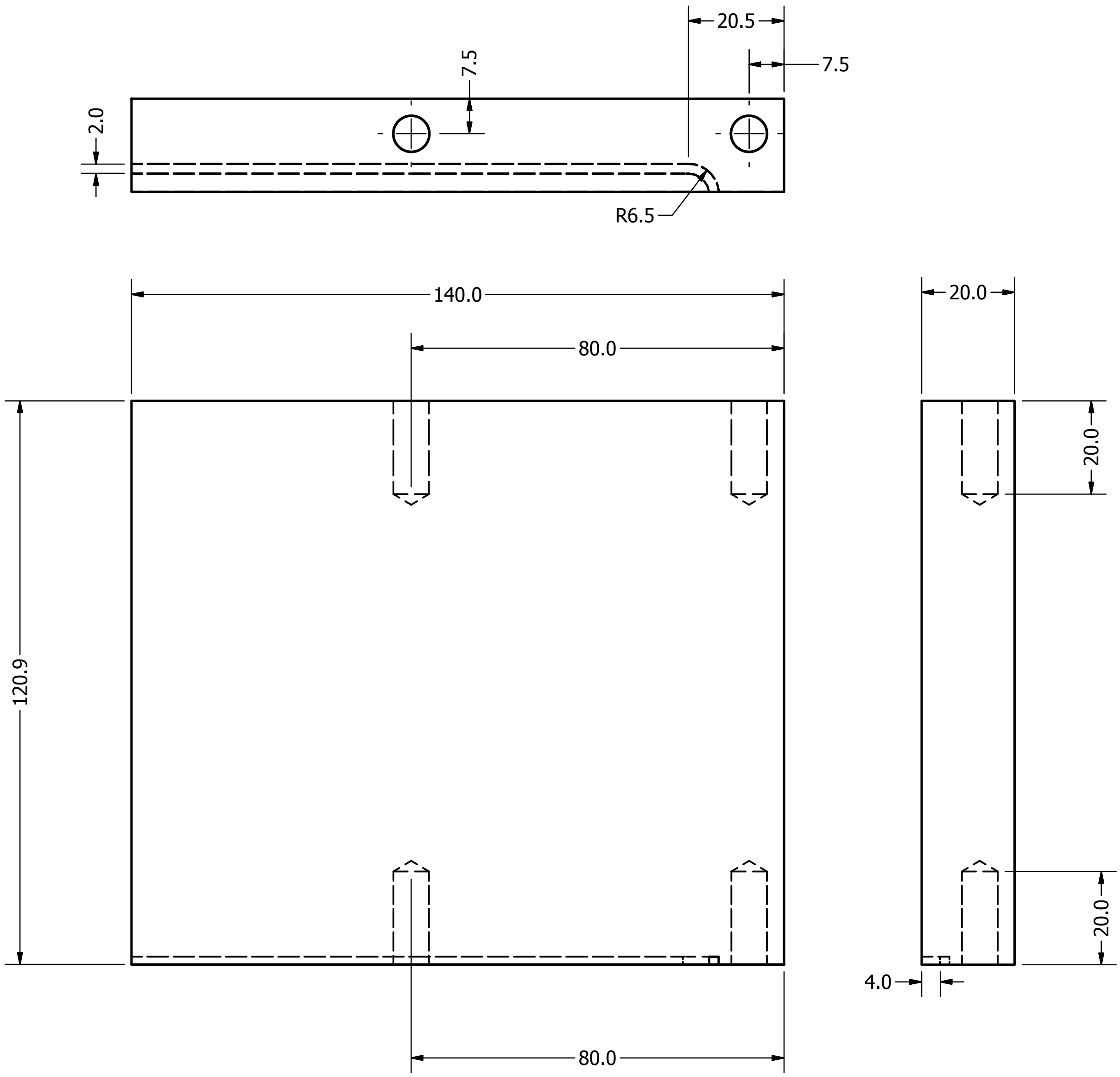

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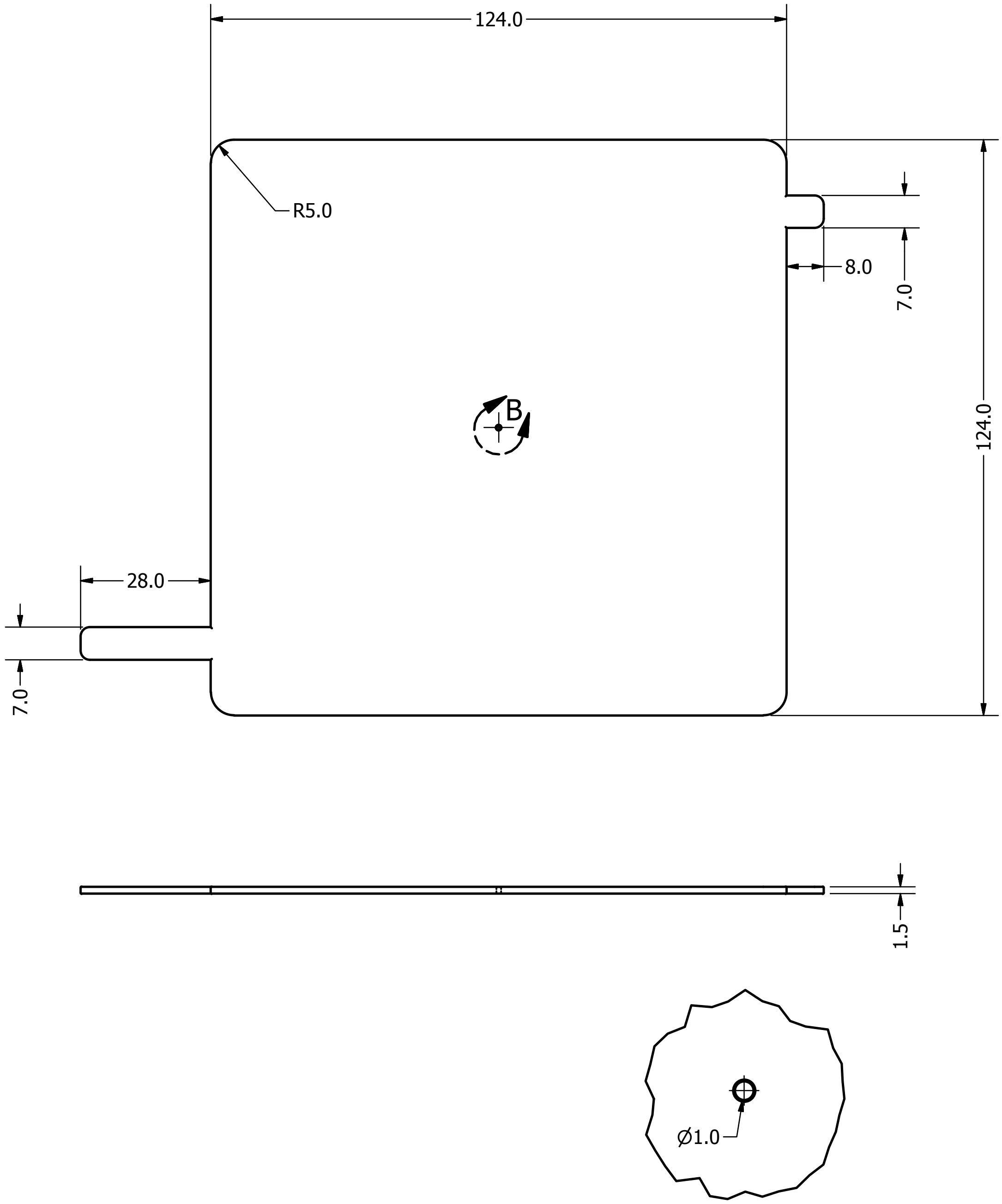

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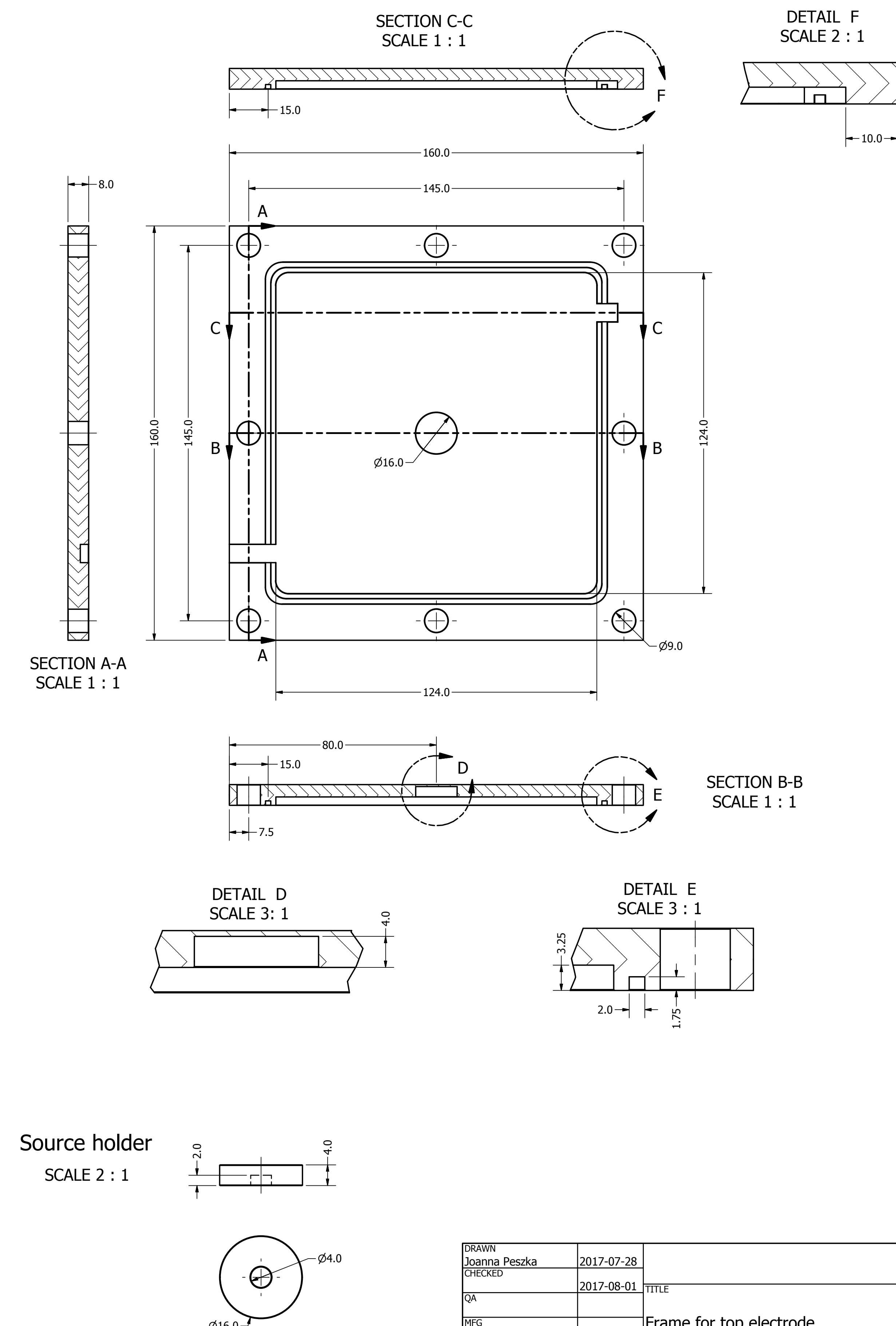

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3 Summary

Topic of the project executed within the framework of Summer Student Program at JINR concerned designing of specific gaseous detector called Optical Time Projection Chamber, which would to be use in charged particle detection.

First part of the project was dedicated to various OTPC elements tests like insulation of kapton layer in GEM foils, its mechanical behavior under the temperature and usefulness verification of special rack for foil tensioning. Next task was to design structure of the new OTPC chamber, which will be smaller, all electrodes including amplification section of GEM foils will be mounting outside the walls and it will be covered with copper wires inside to control electric field better.

Tasks carried out during the practice allowed me to familiarize with the *Autodesk Inventor Professional* program and the basic principles of technical drawing and project creating. There were made demonstrative sketches of all main OTPC elements with initial dimensioning. Presented schemes are still in preliminary design phase. It is still necessary to take into account all the design standards, resistance for external conditions like e.g. vibrations and achievable execution precision. I hope that based on my work and created sketches will emerge a new device making easier and better detection of exotic nuclei decay products.

Within the project were made many visualizations of proposed OTPC Mini detector. Created graphics may be used for introduction of OTPC construction and presentation appearance of necessary elements like electrodes and GEMs.

In conclusion OTPC detector is very useful facility used in nuclear physics field of study. OTPC significantly improves resolution in the range of low energy and offers opportunities to discover new channels of exotic decays like e.g. 3 proton emission from β-delayed processes. That is the reason why it is worth to search for new solutions of OTPC construction and test them.

Acknowledgments

In that place I want to heartily thank to my supervisor dr Grzegorz Kamiński from Flerov Laboratory of Nuclear Reactions for the introduction into the world of exotic nuclei and showing all advantages of work in the nuclear physics laboratory.

I would also sincerely thank to Joint Institute for Nuclear Research for the possibility of participating in Summer Student Program, which is not only important scientific experience, but also open minding adventure and opportunity to get to know Russian culture. I will mention very well in the beautiful Dubna surrounding.

In the end I wish to thank all of people that I met during my practice - other students and workers of JINR for interesting discussions, experience they shared with me and unforgettable time that I spend here.

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[1] www.nndc.bnl.gov/chart.

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