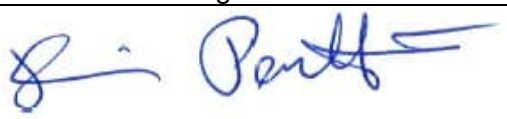
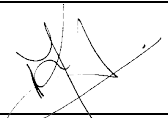
HORIZON 2020

HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

Nuclear Fission and Radiation Protection 2018 (NFRP-2018-4)

Project acronym:	**SANDA**
Project full title:	**Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities**
Grant Agreement no.:	**H2020 Grant Agreement number: 847552**

Workpackages:	***WP1***
Identification N°:	***Deliverable 1.2***
Type of document:	Deliverable ***report***
Title of deliverable:	Report on the design of the large gas cell for IGISOL
Dissemination Level:	***PU***
Reference:	
Status:	***Achieved***
Actual Dalivery date:	1/11/2023
Comments:	

	Name	Partner	Date	Signature
Prepared by:	H. Penttilä	15	1/11/2023	
WP leader:	MKerveno	5	2/11/2023	
IP Co-ordinator:	E. González	1	05-08-2020	Signed by GONZALEZ ROMERO ENRIQUE MIGUEL - DNI ***3708** at 27/11/2023 with a certificate emitted by AC Sector Público

Report on the design of a large gas cell with electric field guidance for IGISOL

Heikki Penttilä, on behalf of the collaboration

University of Jyväskylä, Department of Physics, P.O. Box 35, FI-40014 Jyväskylä, Finland

Department of Physics and Astronomy, Uppsala University, BOX 516, 75120 Uppsala, Sweden

Background and goals

The IGISOL facility at JYU-ACCLAB uses the original ion guide gas catcher technique [1-3] that is based on stopping and thermalizing the primary (positive) ions from nuclear reaction in flowing helium gas and transporting to differential pumping section of mass separator acceleration stage via helium flow.

The mean transport time of the thermalized ions is thus proportional to the evacuation time of the stopping gas. The ions stopped close to the gas cell exit aperture are transported quickly and efficiently. For those stopped further from the exit, transportation takes more time,and the efficiency drops due to the limited survival time of the ions. For the most short-livednuclear species, the radioactive lifetime starts to set limitations as well.

The technique is thus most appropriate for the light ion induced fusion evaporation reactions, where the kinetic recoil energy and consequently the range of the reaction products are small. The reaction products can be stopped in small volume close to the exit nozzle.

The major reaction utilised at IGISOL is however fission, induced mostly with $25 - 30\ MeV$ protons, in some cases with other charged particles (α, d), and occasionally with neutrons [4].

For fission the stopping efficiency is limited by the volume of the gas cell: a large fraction of ions is not stopped before colliding on the gas cell walls. Increasing the gas cell volume increases stopping efficiency, but the ions that have large energy range will not however help, since after the average buffer gas evacuation time becomes larger than the survival most time of the stopped ions, the number of the survived ions will not increase. What is said above about fission, applies also to heavy ion induced reactions, heavy ion fusion and multinucleon transfer.

This problem for energetic recoils has been solved in some other laboratories [Argonne National Laboratory (ANL), Michigan State University (MSU), Gesellschaft für SchwerIonforrschung (GSI)] using electric fields to transport ions through the buffer gas, and only the few last millimeters ate aided mostly by the gas flow.

To design a similar system at IGISOL, a sufficient large gas cell with electric field guidance, some issues that do not take place elsewhere in the same extend need to be solved. The main restrictions for the large gas stopping cell at IGISOL arise from the following. Some of those are discussed in more detail in the report on simulations, and they are just briefly recollected here.

Specific concerns

The nuclear reaction takes place in a **target located inside of the gas cell**. At GSI and at MSU, for example, a recoil separator is used to select the ions of interest and guide them to the gas cell through an entrance window. The uninteresting reaction products and in particular the primary ion beam are dumped elsewhere. At IGISOL, when charged particle fission is utilized, the primary charged particle beam must go through the ion guide (this is discussed below in connection to the design), which can cause heating and activation of the structures of the gas cell, as well as ionization of the buffer gas. In the case of neutron induced fission, the situation is even more challenging since the accelerator beam will be dumped in the proton to neutron converter. Some values used as guidelines of the design are $30\,MeV$ protons and $100 - 150\,\mu A$ intensity that was originally expected to be available from MCC30/15 cyclotron. Such intensities may become available, when the refurbishing of this Russian made accelerator is finalized, expected to happen in 2024. The heating power of such beams would be $3 - 5\,kW$, and the relatively small sized proton to neutron converter should be located as close to the gas cell as possible.

The gas stopper needs to be **in high radiation area**, which limits the access to the front end area, not only during the operation, but due to activation of materials, also a significant period after the primary beam has turned off.

The gas stopper needs to be **in high voltage**, which limits means for the remote operation, necessary due to the fact it is also a high radiation area.

The **room** in the area where the gas stopper is to be located **is limited**, largely due to the required radiation shielding.

The space at the IGISOL mass separator target area where the gas cell and ion beam forming ion optics are located, herein called the front end of the mass separator, is quite limited. The target chamber is a $1000\,mm$ long, $600\,mm$ wide and $300\,mm$ high aluminum box with $30\,mm$ thick walls. The cyclotron beam enters and exits through collimated beam windows. This target chamber is evacuated via a $300\,mm$ diameter pumping channel by a roots pump array located in the basement below with an effective volume displacement of $8000\,m^3/h$ (or $\approx 2000\,l/s$)

The **large gas cell should neither limit the divergent use of the IGISOL mass separator target area**. While the large gas cell is most useful for particle induced fission as well as for the multinucleon transfer (MNT), experiments utilizing light ion induced fusion reactions cannot use a large gas cell. The use of the light ion fusion ion guides, and the recently developed hot cavity ion source must not be prohibited due the use of the large gas cell. It has to be removable with a reasonable amount of effort, and it has to fit in to the same target chamber than the other ones, preferably in the existing one, to avoid excessive remodeling and redesigning of things.

The length of the **shutdown of the IGISOL facility** operations because of installation of a large gas cell should be **as short as possible,** and the expenses on acceptable.

Simulations

The simulations of the stopping efficiency of the fission product ions as function of gas cell size and pressure are described in detail in the preceding report "Bel 2023" [5], which also includes the manuscript of [6]. As a part of this report, also the electrode structure to produce the required electric field was simulated. The simulations of the ion drift in the buffer gas were however not finalized.

A key question of the simulations was whether it is beneficial aim for cryogenic operation of the gas cell (like GSI cryogenic gas cell) or can the gas cell realized in room temperature (or slightly below the room temperature to be able to freeze such impurities as water vapor and some molecules, as has been done at CARIBU gas cell in ANL). The first potential benefit of cryogenic cell is improved stopping efficiency: if gas cell pressure is kept constant, the number density of buffer gas is inversely proportional to the gas temperature. Reducing the temperature from vicinity of $300\ K$ to around $100\ K$, a temperature that can be reached by liquid nitrogen (boiling point $77\ K$) cooling, would thus triple the areal thickness of helium. Another benefit is improved gas purity ("freezing of the impurities") that reduces the charge exchange reactions, leading to neutralization of the ions produced in the nuclear reaction.

On the other hand, the things that tend to tip the balance in favor of room temperature operation were the sheer cost and complexity of cryogenic system.

The result of the stopping efficiency simulations was that $400\ mbar$ pressure of room temperature gas cell was sufficient to stop $\approx 10\ \%$ of the yielded fission products in the gas. Roughly the same stopping efficiency was reached for both proton and neutron induced fission despite the very different positioning of the fission target, $9\ \%$ for proton induced and about $10½\ \%$ for neutron induced fission. The same simulated stopping efficiency could be reached with $115\ mbar$ at $80\ K$, which makes sense because the areal density of helium is the same in both cases. Increasing the pressure in the $80\ K$ temperature from 115 mbar to 400 mbar, that is, making the areal density of helium more than three times larger, increased the number of ions stopped in the helium from $9\ \%$ only to $12\ \%$. This is because there were not much more ions to be stopped, $70\ \%$ of the fission products were stopped already in the target.

Based on the simulation, the room temperature option was selected as the basis of technical design, which was started during the summer 2023.

About the use of high ≈500 mbar stopping gas pressure

The helium pressure in the current proton induced fission ion guide is $\approx 300\ mbar$, measured in the gas feed line about 2 meters before the gas cell. This means that the actual pressure in the gas cell is somewhat but not significantly lower. The optimum yield of fission products can be found close to this pressure, and increasing the pressure beyond the optimum starts to decrease the fission product yield.

In tests of the neutron induced fission ion guide it was found that the optimal helium pressure for it was higher. The optimum pressure was however not reached, since at $400\ mbar$ the

background pressure in the front end target chamber became too high. The fission product yield improved up to $400\ mbar$, thus the optimum has to be higher.

The pumping capacity of IGISOL front end is yet sufficient for large ion guide operated at $400\ mbar$ or even beyond. The current fission ion guide has an exit aperture whose diameter is $1.2\ mm$. In the gas cells using electric field guidance, existing and designed, a typical exit aperture diameter is of the order of $0.5\ mm$. Gas flow is needed just to kick the ions out of the gas cell, inside the gas cell the electric fields push the ion in the vicinity of the exit orifice. The calculated helium flow through a $1.2\ mm$ diameter circular exit aperture of the fission ion guide is $142\ mbar\ l/s$. In typical fission run the measured consumption of helium gas is $\approx 500\ bar\ l/h \approx 140\ mbar\ l/s$, which increases confidence on the calculated helium flow value. The calculated helium flow through a $0.5\ mm$ diameter exit hole is $\approx 50\ mbar\ l/s$ if the gas cell pressure is $400\ mbar$, $\approx 60\ \ mbar\ l/s$ at $500\ mbar$. In either case, the current Roots station is capable of handling the gas load. An optimistic interpolation predicts gas stopping fraction of about 12 % for the fission products at $500\ mbar$. This needs to be still verified with new simulations, as well as whether it is possible to use this high stopping gas pressure.

The ion transportation speed through the buffer gas, the drift velocity v_d, depends on the electric field E and the ion mobility K:

$$v_d = K\,E$$

Ion mobility K in turn is $\propto {}^{1}/_{N}$, where N is the number density of the buffer gas, so in fixed temperature $K \propto {}^{1}/_{p}$ as well. In fixed pressure $K \propto T$ since the number density $N \propto {}^{1}/_{T}$. The normalized or reduced mobility K_0 is defined as

$$K_0 = \frac{T_0}{T}\frac{p}{p_0}K$$

where $T_0 = 273\ K$ and $p_0 = 1013\ mbar$. The reduced mobility of helium is known: $17.5\ {}^{cm^2}/_{V\ s}$. The above equation can be reversed, and mobility calculated in given temperature and pressure:

$$K = \frac{T}{T_0}\frac{p_0}{p}K_0 = \frac{280\ K}{273\ K}\frac{1013\ mbar}{500\ mbar}17.5\ {}^{cm^2}/_{V\ s} = 36\ \ {}^{cm^2}/_{V\ s}$$

$$K = \frac{T}{T_0}\frac{p_0}{p}K_0 = \frac{280\ K}{273\ K}\frac{1013\ mbar}{400\ mbar}17.5\ {}^{cm^2}/_{V\ s} = 45\ \ {}^{cm^2}/_{V\ s}$$

Using a field strength $E = 25\ V/cm$ one obtains ion drift velocities in room temperature at $400\ mbar$ and $500\ mbar$ pressure, respectively:

$$v_d(400\ mbar) = 1.36\ cm/ms$$

$$v_d(500\ mbar) = 1.09\ cm/ms$$

In a $\approx 40\ cm$ long gas cell where the fission products are stopped in average approximately either $25\ cm$ from the exit nozzle (neutron induced fission) or $15\ cm$ from the exit (proton

induced fission), the average drift time to the nozzle is 15 or 25 ms at 500 $mbar$, 11 or 18 ms at 400 $mbar$. In the currently used fission ion guide the mean evacuation time is of the order of 100 ms. What it comes to the ion transportation speed, even 500 $mbar$ pressure produces a reasonable transportation speed with a modest field strength. A field strength $E = 25\ V/cm$ over the length of the gas cell requires a voltage of the order of 1 kV between the ends of the gas cell. The voltages used in simulations in [6] were a factor of about 5 higher; drift velocity calculation however suggests that smaller voltages would be sufficient.

There is an additional benefit of higher pressure and lower field strength in the design of the gas cell, namely required distances from the live electrodes to avoid discharges inside the gas cell. The pressure must in any case so high that distances have to be matched on the right-hand side of the Paschen curve (see figure 1). Assuming a minimum distance from the DC electrodes of the order of 10 mm and pressure 500 $mbar$, the value of pd (pressure times distance) becomes larger than 500 $Pa\ m$ everywhere inside the gas cell. The breakdown voltage in any possible gap is then $\geq 1.3\ kV$; when maximum voltage is kept in the same ballpark, the design should be sufficiently safe against discharges.

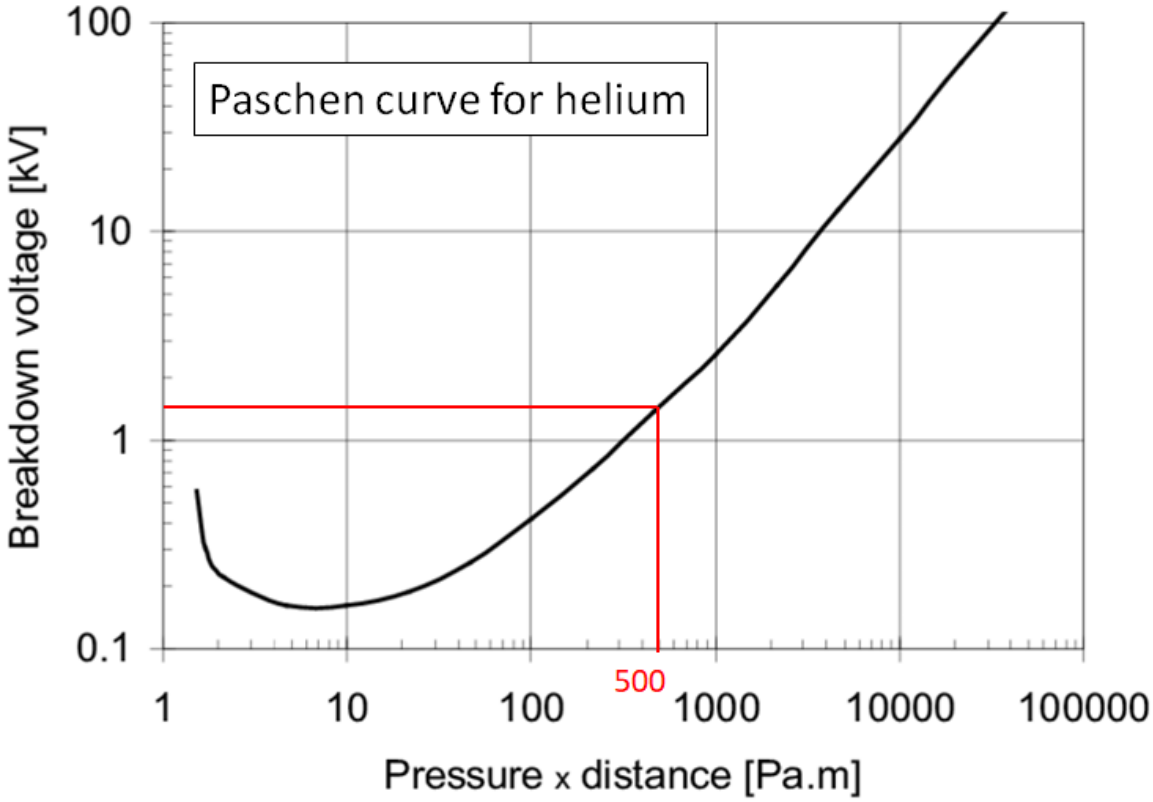


Figure 1. The helium Paschen curve, showing the breakdown voltage dependence of as function of pd, the product of pressure and the gap width. If the gaps to and between live electrodes are kept larger than 10 mm, the minimum breakdown voltage is well over 1000 V.

The design of the large gas cell

Two separate designs are currently being developed based on the above discussion, one for neutron induced and another for charged particle induced fission. The gas cells have the same base structure and major dimensions, same positioning of both DC electrodes and RF carpets, but different location of fission targets.

The neutron-induced fission target is located on the inside wall of the gas cell, as close to the proton to neutron converter outside of the gas cell as possible, since even in the forward-peaked neutron production a large fraction of the produced neutrons is emitted and scattered to large angles.

In the case of charged particle induced fission the situation becomes even more complicated. Neutrons can easily penetrate the gas cell wall. The charged particles instead need a beam window to enter and exit. In addition, the charged particles cannot be allowed to move through the same gas volume where the fission products are stopped, since the primary beam would (unnecessarily) ionize the helium buffer gas. For example, $25\ MeV$ proton beam produces twice the amount of ionization than the proton induced fission products. Therefore, a closed beam tube has designed to allow locate the proton induced fission targets in the middle of the chamber. The emitted fission products need to get in the stopping gas volume, which is, similarly to the current IGISOL fission ion guide design, made possible by thin (about $1\ mg/cm^2$) metal windows.

In the current IGISOL fission ion guide there is one 16 by 50 mm nickel window allowing the fission products to enter to the stopping volume. The larger dimensions of the new design allow use of larger windows; positioning the beam tube in the middle of the gas cell also allows windows for fission products to be placed on the back side and the sides of the tube. Although the pressure difference over the fission product windows will be kept small, the actual size of the windows and the need of possible supporting structures must be tested in practice.

These fission product windows have to be so thin that they cannot stand a large pressure difference, thus, the pressure in the beam tube needs to follow the pressure in the stopping cell. Helium gas is supplied to the beam tube from the same supply as to the stopping volume and evacuated through a separate channel. This is to minimize the backstream diffusion of fission products stopped in the target volume via helium feeding lines to the stopping volume of the chamber. The flow of the helium gas has also a cooling effect on the fission targets in which $70\ \%$ of the fission products will be stopped.

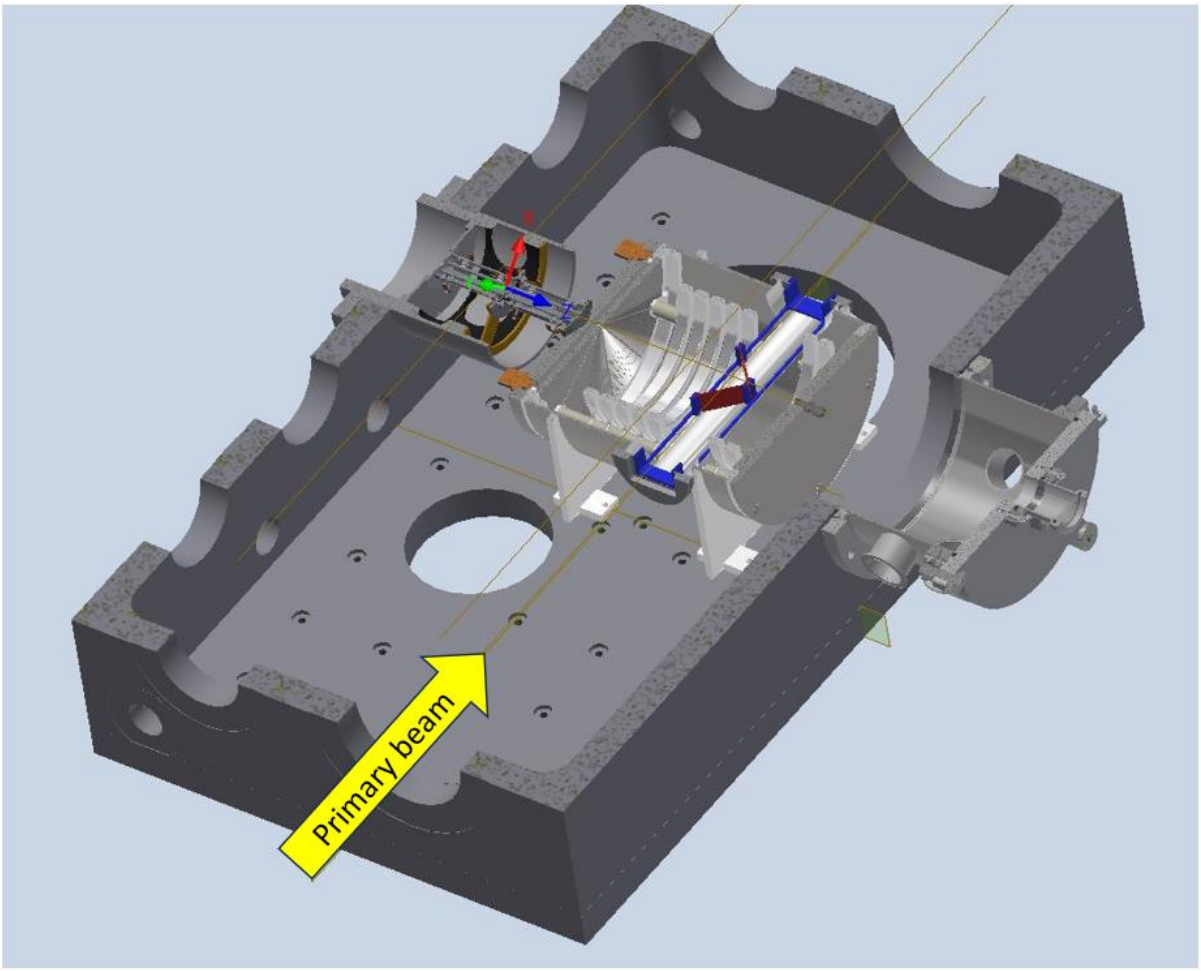


Figure 2. The large ion guide for charged particle induced fission reactions. The primary beam will enter from left. The beam tube through the large gas cell holds two tilted targets. The sequence of DC-electrodes has a gap on the position of the beam tube which is compensated by a larger voltage difference between the DC electrodes next to the beam tube. The fission ion guide for neutron induced fission has the same gap in the DC electrode structure to allow the fission products from the target located close to the ion guide wall pass the electrodes and become stopped in the middle of the gas cell; see the report [5] for the simulations.

This fraction (see result of simulations in the corresponding report [5]) can be reduced by utilizing thinner ($10\ mg/cm^2$) targets instead of current ($15\ mg/cm^2$) ones. This reduction will not change the amount of fission products thermalized in the stopping gas volume, but it minimizes the number of products that do not get out of the production target. The technology developed to produce IGISOL uranium targets [7] in principle allows this implementation, but the feasibility need still to be tested in practice, as well as the actual performance of the thinned targets.

The forthcoming action

The preparation of the technical drawings has been started. A laboratory design engineer has made the first designs of the gas cell structures, gas feeding, DC electrodes, RF voltage feedthroughs, beam tube going trough the gas cell and the associated target holders (charged particle induced fission model), coupling to the differential pumping section, etc. The possible cooling of the gas cell to lower but not cryogenic temperatures is kept as an option whose design in any detail has not started yet.

An issue that is holding back the process is lack of manpower. The design engineer worked on the drawings so far retired at the end of October 2023. The discussions of providing workforce from the JYFL technical design staff have taken place in good atmosphere. The production of technical drawings of the large gas cell has now a reasonable high prioritization.

The next step will anyway be taking the designs prepared so far back to simulations to see whether appropriate electric fields can be produced with these structures and make more proper ion drift simulations than was performed in the initial simulations. Additional ion optical calculations are needed for the modification of the coupling to the differential pumping section, that is, the SPIG electrodes and possibly the first HV extraction electrode.

This iteration process will continue as many rounds as necessary. For some parts such as target holders and beam tube coupling some prototyping to study the strength and durability may be needed. These will be done as soon as the status of design work allows.

References

[1] J. Ärje, *et al*., Nuclear Inst. Meth. **B 26** , 384 (1987)

[2] J. Äystö, *et al*., Nuclear Inst. Meth. **B 26**, 394 (1987)

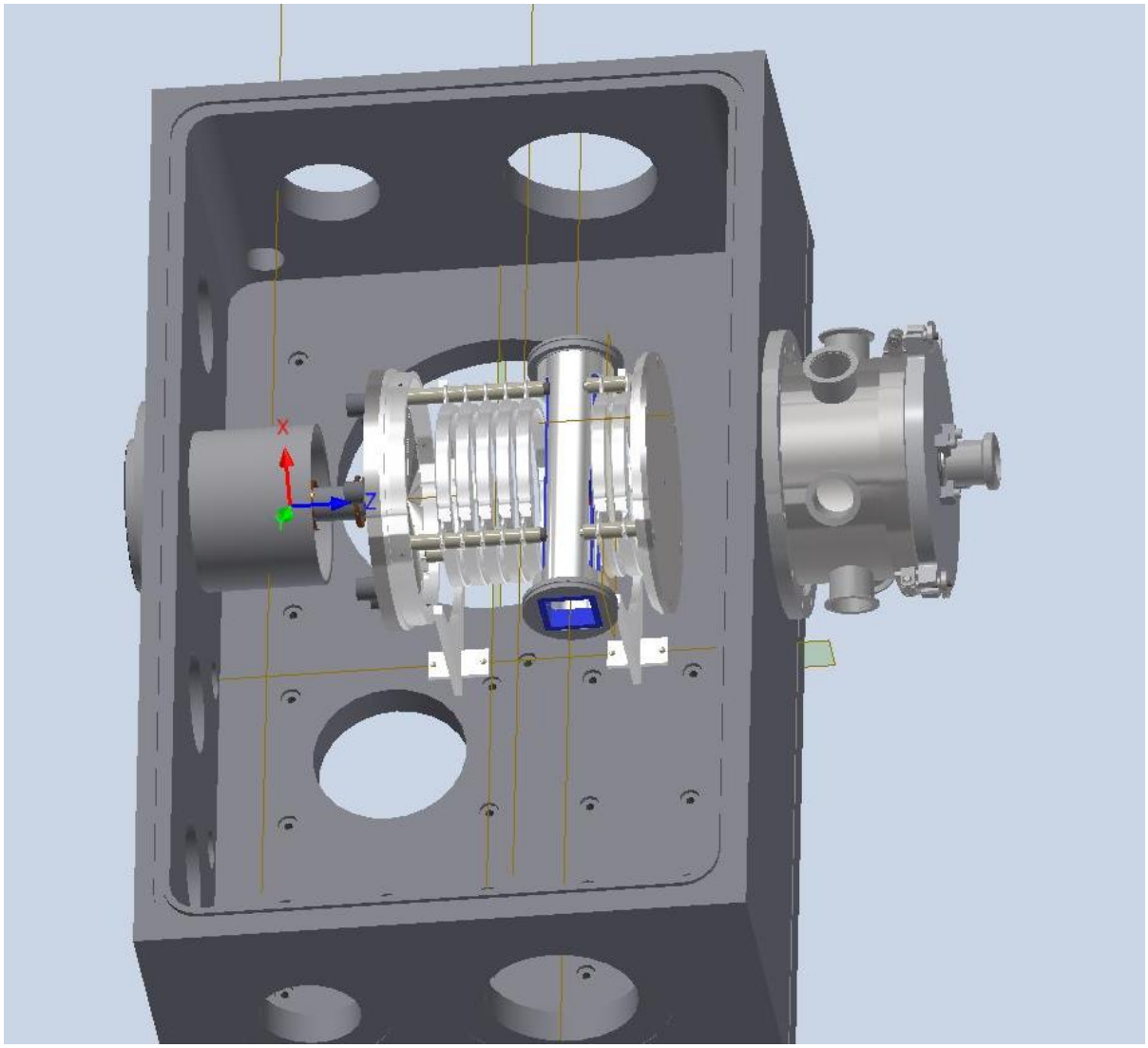
[3] P. Taskinen, *et al*., Nuclear Inst. Meth. **A 281**, 539 (1989)

[4] H. Penttilä, *et al*., Eur. Phys. J. A (2012) **48**:43

[5] H. Penttilä, O Beliuskina, Z. Gao, *et al*., Report on the simulations of a large gas cell with electric field guidance for IGISOL (2023), http://www.sanda-nd.eu/system/files/docs/MS.2_SANDA_Report%20on%20the%20simulations%20of%20a%20large%20gas%20cell%20with%20electric%20fiel...IGISOL.pdf

[6] Z. Gao, *et al*., EPJ Web of Conferences, 284, 04011 (2023).

[7] H. Penttilä, *et al*., Proceedings of The European Research Reactor Conference (RRFM) 2021, Helsinki, Finland, September 26 - 30, 2021. https://az659834.vo.msecnd.net/eventsairwesteuprod/production-ens-public/4dad2b15a85e4e879573bd79672fe380


X
Z