

DESIGN OF THE CERN MEDICIS COLLECTION AND SAMPLE EXTRACTION SYSTEM

A DISSERTATION SUBMITTED TO THE UNIVERSITY OF
MANCHESTER FOR THE DEGREE OF MASTER OF SCIENCE IN THE
FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

2015

CERN-THESIS-2015-251
12/12/2015



Alexander Brown

School of Physics and Astronomy

Contents

	1
Abstract	5
Declaration	6
Statement	7
Acknowledgements	8
1 Introduction	9
1.1 MEDICIS Facility	9
1.2 Scope of the dissertation	11
1.3 Purpose of MEDICIS	13
1.4 Methodology	13
2 Initial Investigation	15
2.1 CERN Visit	15
2.2 Regulation	16
2.3 Isotopes for Collection	18
3 FLUKA Simulation Results	21
3.1 Development of a model	21
3.2 Dose levels during collection	22
3.3 Transport Vessel and Transfer system	38
4 Recommended design and Costing	49
4.1 Recommendations for future work	51
Appendix	52
References	61

Word count: 10108

List of Tables

1	Table of the Isotope expected to be collected at Medicis from [1]. * limit for a type B area has been breached. Activities are the expected end of beam line activities	18
2	Parts required for the model with the model numbers and prices from Kurt J. Lesker	49

List of Figures

1	Target storage area	10
2	MEDICIS collection area	10
3	2D building plans	12
4	Artists impression of Collection Chambers	15
5	A equivalent Dose map of $2.9 \text{ e}+9 \text{ Bq } ^{44}\text{Sc}$ sample. The chamber is a 6-way chamber with walls 1cm thick and surrounded by a 5cm thick lead wall. See example code 1 in appendix	22
6	Comparison between the simple chamber in Figure 5 made from either steel or Tungsten	23
7	The geometry of the model used for dose calculations of the room . .	23
8	Comparison of dose at the Hot Cell when collection takes place in the middle and right chambers	24
9	Dose levels from ^{11}CO collection from a NaF-LiF-VD5 target. see example code 2 in appendix	25
10	Dose levels from ^{11}CO collection at the Hot Cell	26
11	Dose levels from $^{44,47}\text{Sc}$ collection from a Ti target	26
12	Dose levels from $^{44,47}\text{Sc}$ collection at the Hot Cell	27
13	Dose levels from $^{61,64}\text{Cu}$ collection from a Y_2O_3 -VD5 target	27
14	Dose levels from $^{61,64}\text{Cu}$ collection at the Hot Cell	28
15	Dose levels from $^{71,72,74}\text{As}$ collection from a Y_2O_3 -VD5 target	28
16	Dose levels from $^{71,72,74}\text{As}$ collection at the Hot Cell	29
17	Dose levels from $^{89,82}\text{Sr}$ and ^{67}Cu collection from a UC_x -Re target . .	29
18	Dose levels from $^{89,82}\text{Sr}$ and ^{67}Cu collection at the Hot Cell	30
19	Dose levels from ^{77}As collection from a UC_x -VD5 target	30
20	Dose levels from $^{152}\text{Dy/Tb}$, ^{149}Tb and ^{140}Nd collection from a Ta-Re target	32
21	Dose levels from $^{152}\text{Dy/Tb}$, ^{149}Tb and ^{140}Nd collection at the Hot Cell	32
22	FLUKA results with both $^{152}\text{Dy/Tb}$ weighted to $2.2 \text{ e}+10 \text{ Bq}$	33
23	Dose levels from $^{166}\text{Ho/Yb}$, ^{156}Tb and $^{155}\text{Dy/Tb}$ collection from a Ta-Re target	33

24	Dose levels from $^{152}\text{Ho}/\text{Yb}$, ^{156}Tb and $^{155}\text{Dy}/\text{Tb}$ collection at the Hot Cell	34
25	Dose levels from ^{161}Tb and ^{153}Sm collection from a $\text{UC}_x\text{-Re}$ target . .	35
26	Dose levels from ^{177}Lu collection from a Re-VD5 target	35
27	Dose levels from $^{212,213}\text{Bi}$ collection from a $\text{UC}_x\text{-Re}$ target	36
28	Dose levels from $^{212,213}\text{Bi}$ collection at the Hot Cell	36
29	Change in amount of $^{152}\text{Dy}/\text{Tb}$ with time during collection	37
30	Change in activity of $^{152}\text{Dy}/\text{Tb}$ with time during collection	37
31	Initial concept for a sample transfer and transport system	39
32	Dose map from ^{149}Tb at different height within a lead shielded tube .	40
33	A graph showing the affect to equivalent dose when a Tb-149 sample is a different heights within the collection vessel. The dose is highest for 2cm. The dose is an average dose received in a 1cm deep by 1m wide and by 2m high bin	40
34	A graph showing the effect to equivalent dose when a Tb-149 source within the collection vessels of varying thickness. The dose is an average dose received in a 1cm deep by 1m wide and by 2m high bin .	41
35	CF100 chamber with the transport vessel in-situ	42
36	KF50 6-way Cross design	43
37	Dose from ^{44}Sc when in the transport vessel with and without a steel insert	44
38	Dose map from ^{44}Sc within the transport vessel	44
39	A graph showing how dose varies with amount of Lead shielding for the transport vessel	45
40	A transport vessel with ^{44}Sc within it sitting in the corridor space . .	46
41	An alternative solution for the positioning of the transport vessel . .	46
42	a zoomed in image of figure 41	47
43	A 3D model of the alternative system	47
44	A dose map during collection in the alternative system. see example code 3 in appendix	48
45	Final Design CAD drawing using part DXF files from Kurt J. Lesker	50

Abstract

MEDICIS is a new facility at CERN ISOLDE that aims to produce radio-isotopes for medical research. Possible designs for the collection and transport system for the collection of radio-isotopes was investigated. A system using readily available equipment was devised with the the aim of keeping costs to a minimum whilst maintaining the highest safety standards.

FLUKA, a Monte Carlo radiation transport code, was used to simulate the radiation from the isotopes to be collected. Of the isotopes to be collected ^{44}Sc was found to give the largest dose by simulating the collection of all isotopes of interest to CERN's MEDICIS facility, for medical research . The simulations helped guide the amount of shielding used in the final design.

Swiss Regulations stipulating allowed activity level of individual isotopes was also considered within the body of the work.

Declaration

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Statement

i. The author of this dissertation (including any appendices and/or schedules to this dissertation) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this dissertation, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has entered into. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trade marks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the dissertation, for example graphs Page 6 of 14 Guidance for the Presentation of Taught Masters’ Dissertations August 2010 and tables “Reproductions”), which may be described in this dissertation, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this dissertation, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see <http://documents.manchester.ac.uk/display.aspx?DocID=487>), in any relevant Dissertation restriction declarations deposited in the University Library, The University Library’s regulations (see <http://www.manchester.ac.uk/library/aboutus/regulations>) and in The University’s Guidance for the Presentation of Dissertations.

Acknowledgements

I would like to thank Dr. Thomas Elias Cocolios, Dr Karl Johnston, Joachim Vollaire and the whole ISOLDE team for helping me along the way with my work.

1 Introduction

CERN's MEDICIS (MEDical Isotopes Collected from ISolde) is a new project with the aim of producing radioactive isotopes that will be used for medical research. This project is concerned with the designing a collection and transfer system for the radioactive isotopes once they have been produced.

1.1 MEDICIS Facility

The MEDICIS building is an addition to the ISOLDE facility which has been located at the external beam of the Proton Synchrotron Booster (PSB) since 1991 [1]. MEDICIS will be building on 50 years of research that has been undertaken at ISOLDE in radioactive ion beams. In a typical year ISOLDE will receive 50% of CERN's PSB 1.4GeV protons. This proton beam is used for a wide range of physics experiments at ISOLDE. In 2004 ISOLDE's post-accelerating High intensity and Energy Linac (HIE-ISOLDE) became operational. The creation of increasingly exotic isotopes was now possible. This is done by bombarding a target with the proton beam. More than 600 isotopes with half-lives down to milliseconds of almost 70 elements have been produced at ISOLDE [2].

It was decided that whilst CERN underwent a shutdown between January 2013 and July 2014 the ISOLDE facility would undergo major upgrades to HIE-ISOLDE and a new target storage facility was required for the targets. After the targets have been bombarded with protons they become highly radioactive with activities of up to several Gy so storage of the targets is a complicated process that requires a lot of shielding and robots to move the targets. The previous storage facility was complicated for the operation of robots for the handling of the targets. The work also included the plans to build the MEDICIS extension to the facility.

The MEDICIS project was proposed as an addition to ISOLDE because up to 85% of the proton beam used by ISOLDE to bombard targets traverse the target without interacting [1]. MEDICIS plans to use some of these wasted protons that would otherwise hit the beam dump by placing a second target behind the ISOLDE target. Once the the MEDICIS targets have been irradiated they will be transferred to the new target storage area by a rail system as shown in figure 1. The targets will take around 10 mins to travel on the rail system passing through several concrete chicanes to until it arrives at the end of the rail in the right of figure 1. A robotic arm which is able to move along a rail on the ceiling will then pick up the target and places it in one of the storage shelves - the blue object in Figure 1. The targets are then left for a period of time in the storage area. The time spent here is determined by the target type and the isotopes that are wanted to be studied. When a target is required the robot will transfer the target to either the hot cell in the right of Figure 2 or to the mass separator. The mass separator is pictured in the center of

Figure 2. Due to the high activity of the targets the mass separator is surrounded by heavy concrete used for shielding. The mass separator is separated from the target storage area by a steel shielded door which has a small window that the robot will open to pass the target through. The mass separator system works to remove the isotopes from the targets. The systems includes a electrostatic acceleration stage [1] that ionises the isotopes by stripping them of their electrons. Techniques that have been developed by ISOLDE give a high degree of accuracy to ionisation and mass separation leading to high precision in isobars.

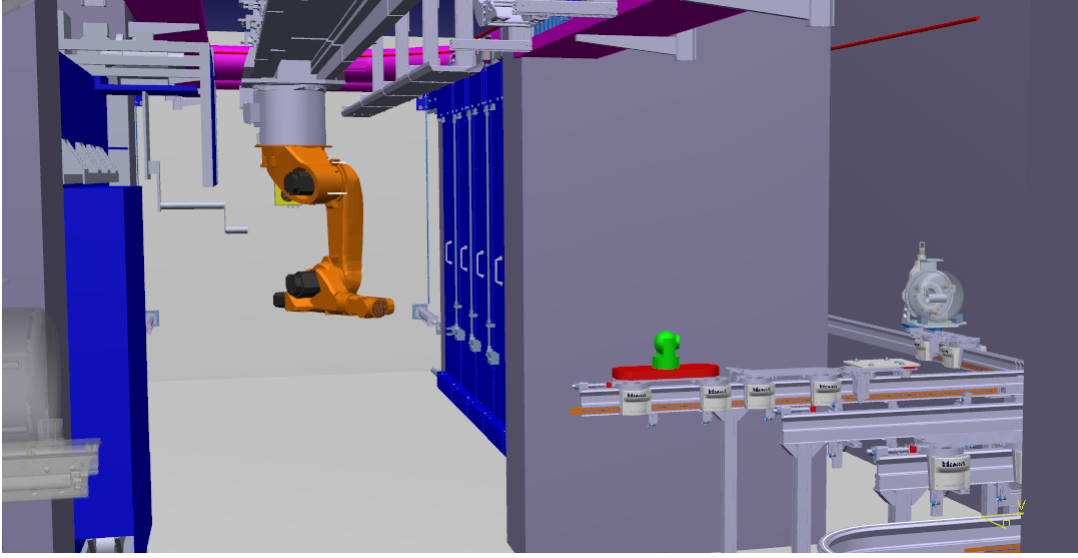


Figure 1: Target storage area

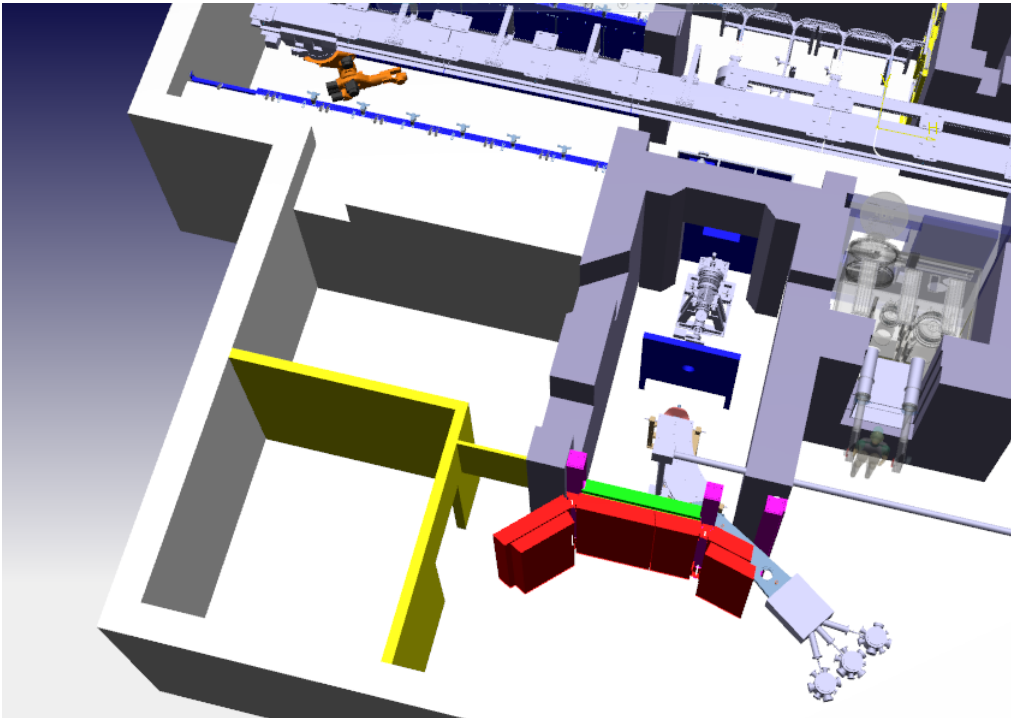


Figure 2: MEDICIS collection area

The techniques result in most nuclei only being ionised to +1 state. After the ions have been accelerated they will pass through a dipole magnet. This magnet will then separate the ions out based on their mass to charge ratio. The higher the mass the smaller the change in direction a nuclei will achieve. It is then proposed that the ion beam will pass through a switchyard and then to a collection chamber. Within collection chamber will be samples that the beam will be focused on; the ions will then implant on the sample. Collection is expected to take between 2 and 10 hours depending on the ions being collected. The original plan was to use a switchyard that would be donated by the Centre de Ressources du Cyclotron Louvain La Neuve/KU Leuven. The switchyard would direct the beam into three parallel beams to three collection chamber using slits and electrostatic deflectors [1]. Currently the thinking is that this may not be used. The building of the new extension was constrained by a road and there is only a gap of 3.3m between the bunker and the outside wall. With shielding, the collection system and space needed for access there may not be enough room for such a large switchyard and an alternative may need to be found.

The MEDICIS facility as of September 2015 is progressing well. All the infrastructure is in place and equipment is now being installed. The shielded steel doors are in place and the rail system has recently been fitted. The two robots in the target area have also been installed and work to commission them is currently under way.

1.2 Scope of the dissertation

As stated earlier this dissertation is concerned with isotopic collection and extraction from the off-line mass spectrometer. Figure 3 shows the plans for the collection of the isotopes at the beginning of the project. Collection was the last part to be considered in the planning of MEDICIS and much of the system was left to be decided at a later date. This has influenced the space that has been allocated to the collection system.

The main considerations for the design of the collection system are:

- Radiation shielding: the isotopes collected will have activities of up to 32 GBq therefore shielding will be required to protect users
- Regulations: Swiss regulations will need to be followed as well as possibly French and British on health and safety for the nuclear sites
- Transport of the samples: once a sample has been collected in a collection chamber, most samples will need to be transferred to a shielded glovebox for further chemical purification

- Physical constraints: fitting three collection chambers in the small space will shape what system is feasible
- Cost: safety is the first priority and decisions may have to be made to compromise the medical research in favour of safety due to a limited budget
- Engineering: the feasibility of a system being able to work in practice. For example, Lead is heavy therefore it may need a lot of support
- CERN standards: to allow for in-situ maintenance and operation of the equipment
- Adaptability: the MEDICIS project has many collaborators and additional collaborators are coming on-board all the time, therefore the system should be as flexible as possible to suit many different needs

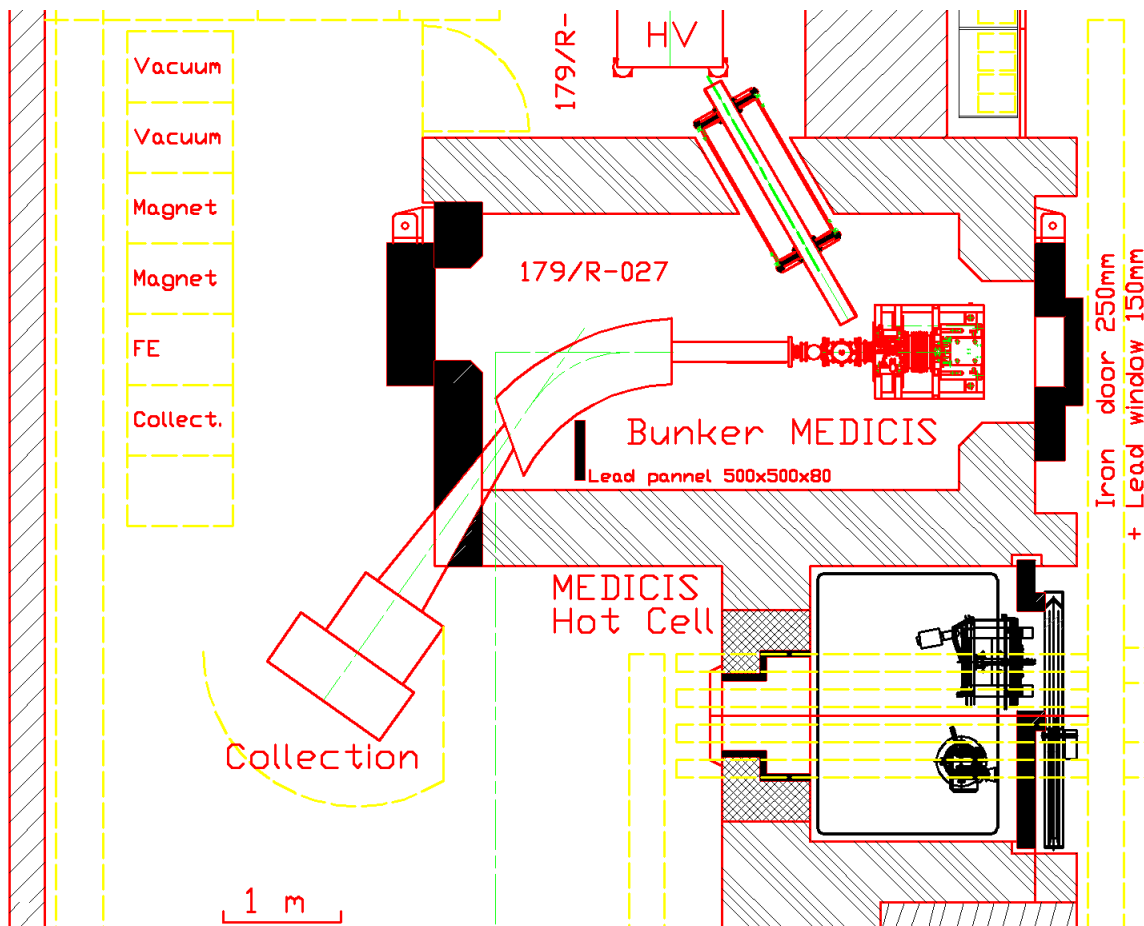


Figure 3: 2D building plans

1.3 Purpose of MEDICIS

MEDICIS has been commissioned to advance research in to Nuclear Medicine. In 1961 one of the first useful pieces of research in nuclear medicine was undertaken. Neils Lassen and David Ingvar used ^{133}Xe to pin point parts of the brain that were involved in controlling motor and sensory functions [3]. Advancement in medical science since then has been vast. PET scans are used to image the body and particularly for imaging the brain. They work by measuring emissions from positron annihilation in the body from a $\beta+$ decaying isotope. The location of the annihilation can then be calculated by measuring the time the photons produced in the annihilation are detected at different locations; if the radio-active isotope is attached to a molecule that binds with a cancer cell for example the location of the cancer cell can be ascertained. New $\beta+$ decaying isotopes are needed so that different chemicals can be produced that will bind and accumulate in different areas of interest.

Progress however, in some aspects of nuclear medicine has been slow. In many respects it is a self perpetuating cycle. To advance nuclear medicine research into new and more exotic radio-isotopes is required. Carry out such research a supply of radio-isotopes is needed. However these isotopes are not being produced or more accurately not being harnessed from waste streams of nuclear fission. Doing this is currently not economically viable as demand is low. MEDICIS aims to produce rare isotopes so that medical research can take place in to their suitability for use in applications such as dose therapy and PET imaging [1]. If an isotope proves to have good use in the treatment of patients then commercially extracting it from radio-active waste may become economically viable.

1.4 Methodology

To investigate the radiation and calculate doses that may be received, a transport code will need to be used. It would be possible to estimate the dose a person may receive using a database like Nucleonica to look up doses for the isotopes with different amounts of shielding. Although it is a good place to get an estimate for the amount of shielding required, the accuracy of an estimate from using a radiation transport code will never be met using Nucleonica. This is because transport codes can simulate any complex geometry and can incorporate effects such as reflection from walls and identify hotspots of radiation.

There are many transport code out there that could be used to shape the design of the collection system. There are two main types of transport codes - deterministic and Monte Carlo. Deterministic codes look to solve the Boltzmann transport equation. This is an incredibly hard task to achieve. The Boltzmann equation describes 7 dimensional phase space and solving it requires approximations to be made and the discretisation of space parameters. Monte Carlo transport codes give a local

solution of the transport equation by simulating vast amounts of particle histories. A particle is simulated as it travels across a geometry from a source point. As the particle travels through materials databases are used to give a probability of the particle interacting with the material in several different ways including elastic scattering and capture. Once a particle has either terminated in the material or left the geometry of the model the programme moves on to the next history. Bin or Tallies, depending on the code, keep a running total of the amount interactions and absorptions that took place in their volume of the geometry. A dose is then calculated by using weighting factors to turn interactions into energy deposited or dose.

FLUKA was chosen for simulating the dose. FLUKA is a Monte Carlo particle transport code. The choice of codes came down to MCNP another Monte Carlo code and FLUKA. FLUKA was chosen because it is a ubiquitous code for CERN so integrating work down in this dissertation to the overall work into dose at MEDICIS from the target storage room as an example would be easier in subsequent work.

FLUKA is a general purpose programme that is used for many applications at CERN. Proton and electron accelerator shielding, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics and radiotherapy are some of FLUKA's main uses [4]. CERN has a long history with particle beams and accelerators. FLUKA has been shaped by the work carried out at CERN and was initially developed to study the transport of particles in accelerators for particle physics research. FLUKA defaults are therefore to simulate beams but it is now a very versatile flexible code and can be used to simulate radiation given off from decaying particles and can simulate photons positrons and electrons from 1 keV to thousands of TeV [4].

The simulations will help guide the design of a safe collection and transport system that will meet Swiss regulations on radiation protection. Once an initial investigation into the amount of shielding options will be explored to make a design that incorporates this level of shielding in a feasible system.

2 Initial Investigation

2.1 CERN Visit

In June 2015 a fact finding mission to CERN was undertaken to find out as much information as possible about the parameters of the work required. Figure 4 shows the artists impression of the kind of system that might be in place for collection. The chambers were designs from previous work done at ISOLDE and are in the plan purely for illustrative purposes. They do however show one of the main problems facing the collection at MEDICIS: space. Previous work done at CERN has used mainly one chamber in isolation; so large chambers with plenty of space for additional equipment such as detectors and vacuum pumps are the most common used.

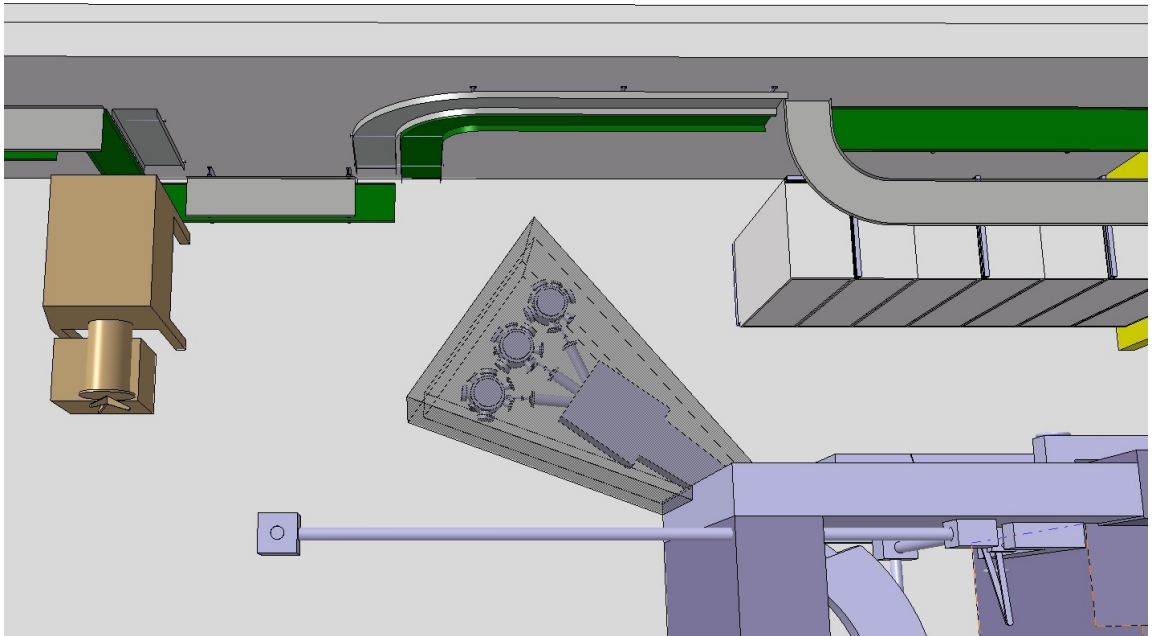


Figure 4: Artists impression of Collection Chambers

As part of the visit a tour of the storage facility of previous equipment was given to look at past chambers used at ISOLDE for collection of medical radioisotopes. Previous experience at ISOLDE on medical isotopes has had samples up to 1GBq produced in rare cases. One of the old collection chambers was used that could expose several samples in one run with a sample holder that had several samples. It also had a detachable 'suit case' that was a small shielded container with a handle to transfer the irradiated sample safely. This collection chamber had several problems with it though that led to it not being used. The collections chamber was easy to accidentally vent when removing the 'suit case' if you did not fully know how to work it. It had some interesting features such a mirror above a viewing window so that it was possible to see into the chamber without getting close; reducing a dose to a worker. However, to adjust a sample you had to manipulate controls on

the collection chamber meaning a worker would have to be next to the collection chamber for a period of time. Tungsten has been used for collection chambers in the past at CERN. Tungsten, due to its high atomic mass of 183.84 is a good absorber of radiation compared to steel which is more traditionally used for chambers.

From the meetings that took place at CERN, after discussions, the preferred option by the majority of the ISOLDE team is to build a collection chamber that can expose several samples on a slider and then have a shielded container to transfer the sample to a glovebox. The movement of the sample from the collection chamber to the shielded container should be done automatically and ideally without breaking the vacuum in order to reduce the chance of contamination. One other option is to create a simple collection chamber with little to no diagnostics for samples where time is of the essence due to their short half-lives. This could be a system where part of the collection chamber is detachable that can then be used as the transport box for the sample. Whatever option is chosen available space will be a big limiting factor. Vacuum pumps and equipment such as a Faraday Cup will take up space. As seen in figure 4, 5cm of Lead shielding was also suggested as a solution to shielding when the isotopes are being collected, though no calculations or simulations had been done to see if this was enough.

2.2 Regulation

Although the ISOLDE facility is located just on the French side of the border, Swiss laws are followed on the Meyrin CERN site predominantly [5]. Most Swiss legislation on radiation protection is based on international standards so in complying with Swiss regulation you are often also complying with French legislation.

The main piece of Swiss legislation with respect to radiation protection is Radiological Protection Ordinance 814.501. Swiss law sets out a system of classification of facilities handling radioactive substances; a facility can either be class A, B or C. For a worker working in a class A laboratory the yearly dose allowed at CERN is 20 mSv per year. In a class B laboratory it is 6 mSv per year [5]. CERN also has an additional objective of no worker should receive more than 3 mSv per year when possible [5]. The legislation also states that for the skin, hands, and feet 500 mSv per year is the legal limit for dose [6]. This means that when considering moving a source by hand a higher doses can be received for the hands than the rest of the body. CERN's radiation protection team stated that their limits for dose per hour are $10\mu\text{Sv/h}$ for the ambient dose and 2mSv/h is the upper limit for short term exposure (mins).

Swiss law makes a distinction between sealed and unsealed sources of radiation. A sealed source is a source contained within a package or container that prevents the dispersion of radioactive material. This could be a radioactive sample that has been

vitrified in glass. The samples at MEDICIS will be classified as unsealed sources. Although every effort will be made to prevent the dispersion of radioactive material when the samples are being transferred to and from the transport vessel and into the shielded glovebox they are unlikely to meet this definition. This means they will have to comply with Swiss legislation for unsealed sources.

Swiss Legislation on Unsealed sources [6]:

”Section 5: Working Areas for the Handling of Unsealed Radioactive Sources

Art. 69 Working areas

- 1 Work with unsealed radioactive sources whose activity exceeds the licensing limit specified in Annex 3 Column 10 must be carried out in working areas.
- 2 Working areas are to be established in separate rooms reserved for these purposes.
- 3 The working areas shall be classified into the following types, according to the activities handled per operation or per day:
 - a.
Type C: An activity from 1 to 100 times the licensing limit specified in Annex 3 Column 10;
 - b.
Type B: An activity from 1 to 10 000 times the licensing limit specified in Annex 3 Column 10;
 - c.
Type A: An activity from one times the licensing limit to an upper limit that shall be defined in the licensing procedure.
- 4 For activities not involving a risk of inhalation, the supervisory authority may define the type of working area on a case-by-case basis, taking into account the risk of intake.
- 5 The FDHA and DETEC shall issue the necessary regulations concerning protective measures for the handling of unsealed radioactive sources.¹

- 1 Amended by No I of the Ordinance of 24 Oct. 2007, in force since 1 Jan. 2008 (AS 20075651)”

Table 1 in section 2.3 shows the legal limits from the annex referred to in the legislation. Annex 3 column 10 known as the LA limit is the activity of a specific isotope that on a single occasion yields a committed effective dose of 5 mSv: this limit is of particular importance for α sources where this is the only likely way to receive a dose. The legislation is therefore saying that because there is a risk of inhalation of material with an unsealed source, a limit must be place on the amount allowable. For a type B area the upper limit is 10000 times the LA limit. This

means if a person inhaled 1/10000 of the source, they would receive an equivalent dose of 5 mSv.

2.3 Isotopes for Collection

Isotope	half-life	Extracted Activity (Bq)		LA limit (Bq) (an. 3 col. 10)	Limit for B area (Bq)
		1.4GeV 2 μ A	2.0GeV 6 μ A		
¹¹ C	20.3m	1.4e9	4.2e9	7e7	7e11
⁴⁴ Sc	4.0h	2.9e9	1.6e11	2e7	2e11
⁴⁷ Sc	3.4d	2.1e9	5.9e10	7e6	7e10
⁶¹ Cu	3.3h	2.6e8	2.1e10	4e7	4e11
⁶⁴ Cu	12.7h	3.6e8	2.1e10	3e7	3e11
⁶⁷ Cu	61.9h	1.1E8	2.7e9	9e6	9e10
⁷¹ As	65.3h	3.0e8	8.0e9	1e7	1e11
⁷² As	26.0d	4.6e8	1.5e10	4e6	4e10
⁷⁴ As	17.8d	1.9e7	4.5e8	3e6	3e10
⁷⁷ As	38.8h	2.9e8	9.4e9	1e7	1e11
⁸² Sr	25.5d	8.5e7	2.0e9	6e5	6e9
⁸⁹ Sr	50.5d	1.0e8	2.7e9	9e5	9e9
¹⁴⁰ Nd	3.4d	6.0e8	4.0e9	3e6	3e10
¹⁴⁹ Tb	4.1h	3.8e8	2.4e10*	2e6	2e10
¹⁵² Tb/Dy	17.5h	3.7e8	2.2e10*	-	-
¹⁵³ Sm	46.8h	1.4e8	1.0e9	7e6	7e10
¹⁵⁵ Tb/Dy	5.33d	5.3e7	6.8e8	2e7	2e11
¹⁵⁶ Tb	5.35d	5.5e5	1.3e7	4e6	4e10
¹⁶¹ Tb	6.9d	9.5e5	5.4e6	4e6	4e10
¹⁶⁶ Ho	25.8h	4.8e5	6.0e6	6e6	6e10
¹⁶⁶ Yb	56.7h	2.1e9	1.1e10	5e6	5e10
¹⁷⁷ Lu	6.7d	6.4e6	1.7e8	5e6	5e10
²¹² Bi	60.6m	1.7e8	2.5e9*	1e5	1e9
²¹³ Bi	45.6m	2.8e7	4.2e8	1e5	1e9

Table 1: Table of the Isotope expected to be collected at Medicis from [1]. * limit for a type B area has been breached. Activities are the expected end of beam line activities

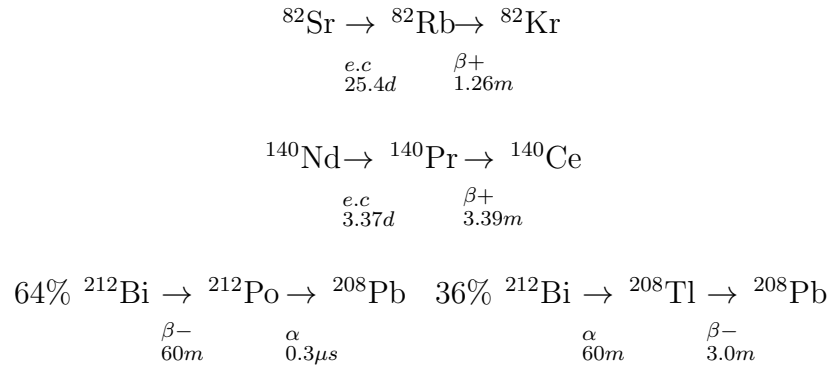
Table 1 shows the isotopes expected to be collected at MEDICIS. They have a variety of medical applications including β therapy, PET imaging, dosimetry therapy, Auger therapy α therapy, CT imaging, and SPECT.

The MEDICIS targets will be irradiated with proton beam of 1.4GeV and 2GeV if a planned upgrade takes place. The yields of isotopes for the 2GeV is higher than for the 1.4GeV. This does however present a problem. Two isotopes are over the limit for a type B laboratory. Although the MEDICIS facility will be classed as a type A area, this limit may be imposed on the collection area. ²¹²Bi is an α emitter and so has a relatively low limit. The expected activity is 2.5 times over the limit

for a type B area. ^{149}Tb is just over its limit and could be easily brought under the limit by allowing it to decay for a short time before people are allowed in close proximity. It must also be noted that the activities from [1] are end of beam line expected activities. This would therefore be the activity that reaches the chamber, but may not be the activity of isotope that is implanted on the sample. Some of the ions may bounce off the collection sample's foil and head back up the beam line, or settle in the chamber itself. This means that activities of the isotopes may not be as high when transferred to the transport vessel as some may be left in the collection chamber. For the work carried out here, a worst case scenario in terms of radiation protection will be presumed that all of the activity is transferred with the sample.

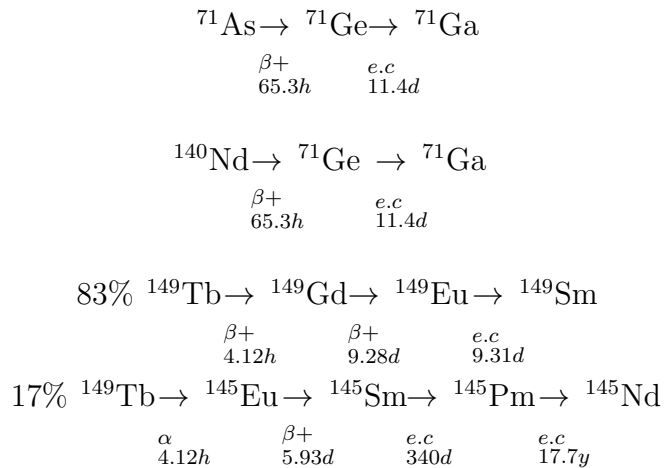
Most of the isotopes decay straight to a stable daughter. This is no coincidence as for most medical applications such as imaging the radioactive substances used need short life times so that the patient will not keep receiving a dose for long after the imaging is over.

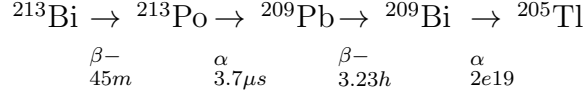
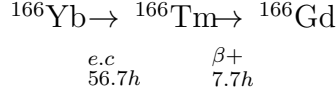
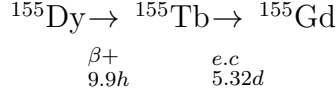
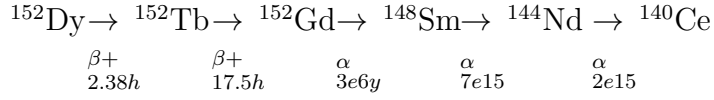
For:



the initial decay is followed rapidly by a second decay to a stable isotope. This means they can be considered to decay straight to a stable isotope with the radiation from the first and second decay given off.

The decay chains of the 7 isotopes below however are more complicated and may be hard to model. A judgement will have to be made on the relative abundance of each stage of decay chains and the simulations may have to take this into account.





When using FLUKA for the decay of radioactive particles you adapt the beam source by using a command called HI-PROPErt. This command tells FLUKA that the source of particles to be transported is the decay of the isotope given in the HI-PROPErt command. When using this command FLUKA will include decay secondaries and they will be sampled over the whole decay time from zero to infinity. All scoring will refer to the time integral of isotope activity [7]. In practice this means FLUKA will model particles that could be from any period of time along the decay chain.

For decay chains such as ^{152}Dy this would reduce the dose tallied in the bins because the decay radiation from ^{152}Gd onwards is negligible compared to $^{152}\text{Dy}/\text{Tb}$ because of the much longer half-lives. This may not be a big problem however because ^{44}Sc is also a $\beta+$ emitter and has an activity of $3.2e10$ Bq which is higher than that of $^{152}\text{Dy}/\text{Tb}$ $2.2e10$ Bq, from a 2GeV target irradiation. ^{44}Sc also has a Q-value of decay of 3652.68 KeV which close to ^{152}Tb of 3990.0 KeV and significantly higher than 598.346 KeV for ^{152}Dy [8]. This means that the radiation and daughter particles for both $^{152}\text{Dy}/\text{Tb}$ and ^{44}Sc will have similar energies. So if shielding is safe for ^{44}Sc it is also likely to be safe for $^{152}\text{Dy}/\text{Tb}$.

3 FLUKA Simulation Results

3.1 Development of a model

In the early operational stages of MEDICIS only targets such as Y_2O_3 and Ti will be used [1]. These targets can only give rise to light isotopes such as ^{44}Sc , ^{47}Sc , ^{61}Cu and ^{64}Cu . Of these isotopes ^{44}Sc is likely to give the highest dose. ^{64}Cu has two decay paths a 61.5% chance of β^+ decay and a 38.5% of β^- decay [9]. ^{47}Sc decays by β^- . The β^- is unlikely to give a significant dose through shielding that would be designed for attenuating γ radiation. The β^+ decay of ^{64}Cu however will lead to a significant dose. Annihilation of the positrons, with electrons, gives rise to high energy γ radiation. Therefore these isotopes ^{44}Sc will give the largest dose since it is a β^+ emitter and will be collected with almost ten times the activity of ^{61}Cu . ^{44}Sc will be the main isotope used in the simulations.

For the initial development of a model it was important to start with a simple case to become familiar with the use of FLUKA and understand roughly the scale of shielding that would be required. FLUKA is a Linux based programme. To use it on a Windows based system, a version of FLUKA has been produced called FLUPIX which is designed work using a virtual Linux 2.6 machine. One of the tools that comes with this is a programme called FLAIR which allows plotting of the geometries from the FLUKA input files. It also has tools to analyse the data after a simulation and produce data files which can then be plotted using GNUplot. This is the source of all the geometry plots and dose graphs within this report.

Figure 5 shows a plot of one of the first simple models used to guide the development of a model close to the actual facility. The data has been normalised to give an equivalent dose in $\mu\text{Sv/h}$ for a 2.9×10^9 Bq ^{44}Sc source. This is the end of beam line activity of ^{44}Sc expected for collection at MEDICIS from a Ti target irradiated by the 1.4GeV proton beam. 5cm thickness of lead was chosen because this was the thickness of lead expected to be installed at MEDICIS to shield people from the switchyard and collection chamber. FLUKA has some pre-set materials such as Lead and air to help simplify coding. These pre-sets were used where possible. Steel however, due to the vast amount of different types available has no pre-set. For the initial simple models a definition of 'regular steel' was used with a density of 7.82g/cm^3 [10].

MATERIAL			7.82			STEEL
COMPOUND	0.977169	IRON	0.022831	CARBON		STEEL

Tungsten was a material of interest since in the past ISOLDE had used collection chambers that required shielding made out of tungsten. Figure 5 shows a plot of the equivalent dose to distance from the lead shield. It shows the difference changing the collection chamber from steel to tungsten makes to dose. At 10cm away from the Lead shield Steel leads to $83.54 \pm 0.73 \mu\text{Sv/h}$ and Tungsten leads to a dose of

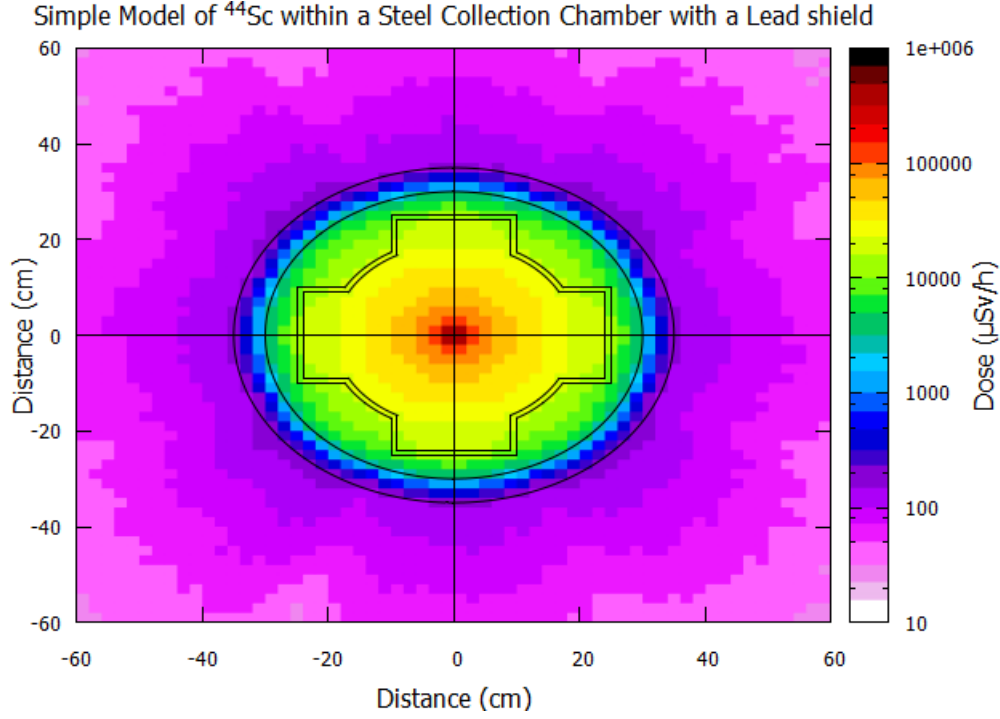


Figure 5: A equivalent Dose map of $2.9 \text{ e}+9 \text{ Bq } ^{44}\text{Sc}$ sample. The chamber is a 6-way chamber with walls 1cm thick and surrounded by a 5cm thick lead wall. See example code 1 in appendix

$39.29 \pm 0.49 \text{ } \mu\text{Sv/h}$. In comparison to the reduction in dose due to the Lead shielding from 10s of mSv/h to 10s of $\mu\text{Sv/h}$ the drop in of $44.25 \text{ } \mu\text{Sv/h}$, is of little significance. Tungsten is a very hard substance with a hardness of 7.5 on the Mohs scale compared to 4.5 Mohs for Steel [11] making it harder to engineer. If there was a situation were there would be no additional shielding other than the chamber, tungsten may be a good option but since MEDICIS will have Lead shielding, it would make more sense to use standard steel components for the chamber and increase the Lead shielding if necessary.

3.2 Dose levels during collection

Once an understanding of FLUKA as a tool had been gained, modelling of dose levels during collection was the next step. Using the technical plans of the building, a model was produced for the geometry of the MEDICIS facility. The MEDICIS bunker and the wall between the target area and the MEDICIS facility was made of special concrete. The concrete was Magnetite concrete shown in yellow in Figure 7. During the first generations of the model this was not known so a definition for normal concrete was used [10]. It was decided to re-run the simulations again once the type of concrete had been confirmed by the radiation protection team at CERN. Originally, one simulation was re-run to compare the difference using the heavy concrete made. The addition of heavy concrete to the model had the affect of increasing the dose by up to 7% in some areas of the room. Around the Hot

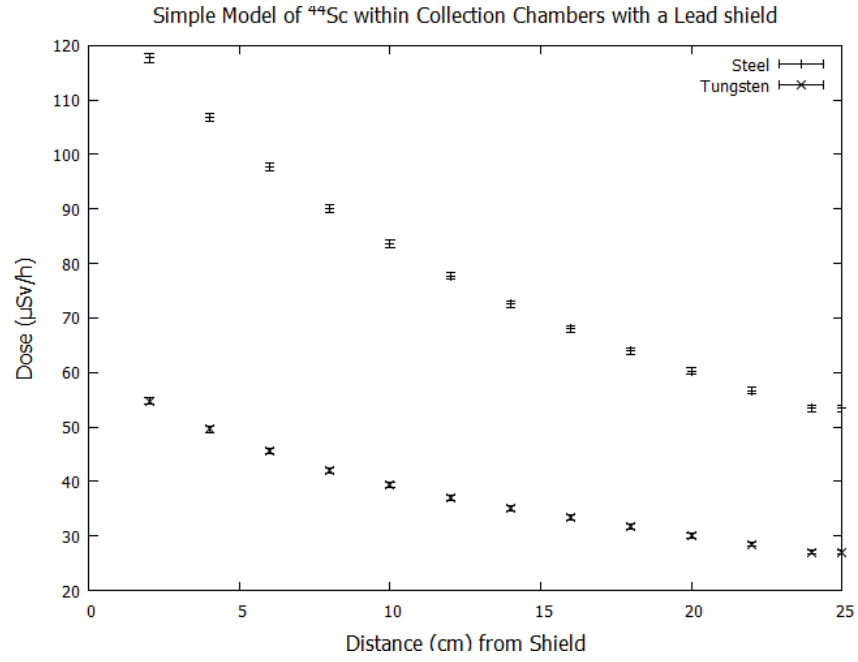


Figure 6: Comparison between the simple chamber in Figure 5 made from either steel or Tungsten

Cell, hcell in the geometry, the dose was most different. This is an area of interest because it is the closest place where a person might be for extended period of time. The heavy concrete increases the amount of reflection from the walls, and because using heavy concrete increased the dose, the simulations for all the isotopes were re-run.

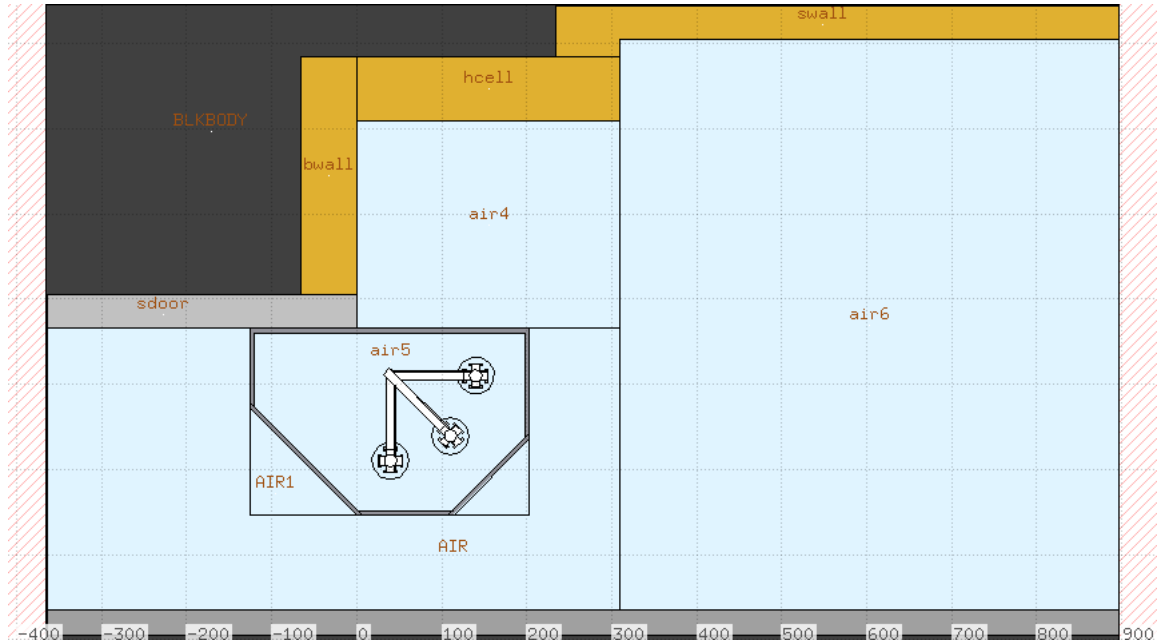


Figure 7: The geometry of the model used for dose calculations of the room

Information on the switchyard was not available at the time of these models so it was omitted from the geometry. The collection chambers in initial models were such

as the one in Figure 5 were based on Kurt J. Lesker's spherical chambers. However the spherical chambers was large and due to the space restraints a 6-way cross was deemed a better solution. The cross in the whole room dose results was that of a CF100 made from 304L steel [12] [10]. Other equipment was omitted from the model because it is not known what monitoring equipment will be chosen for the collection process. The equipment would have only reduced the amount of radiation escaping the collection area and so if the levels are safe without it in the model they will be with it in-situ. The three chambers are surrounded by 5cm thick Lead walls with a 5cm thick Lead roof 1.5m high. The center of the chambers are at a height of 1.1m. This was chosen because it is the standard beam height at Isolde. The MEDICIS beam however is an off-line system so it's height is not dictated by the ISOLDE beam height. This will only have a noticeable affect to dose levels close to the chambers.

Three chambers are planned for parallel collection of isotopes. The magnet will separate out the isotopes based on their mass. The lightest isotopes will arc with the smallest radius and the heaviest with the largest. This would mean in Figure 7 that the lighter elements were collected in the right (top) chamber and the heaviest in the left (bottom) chamber.

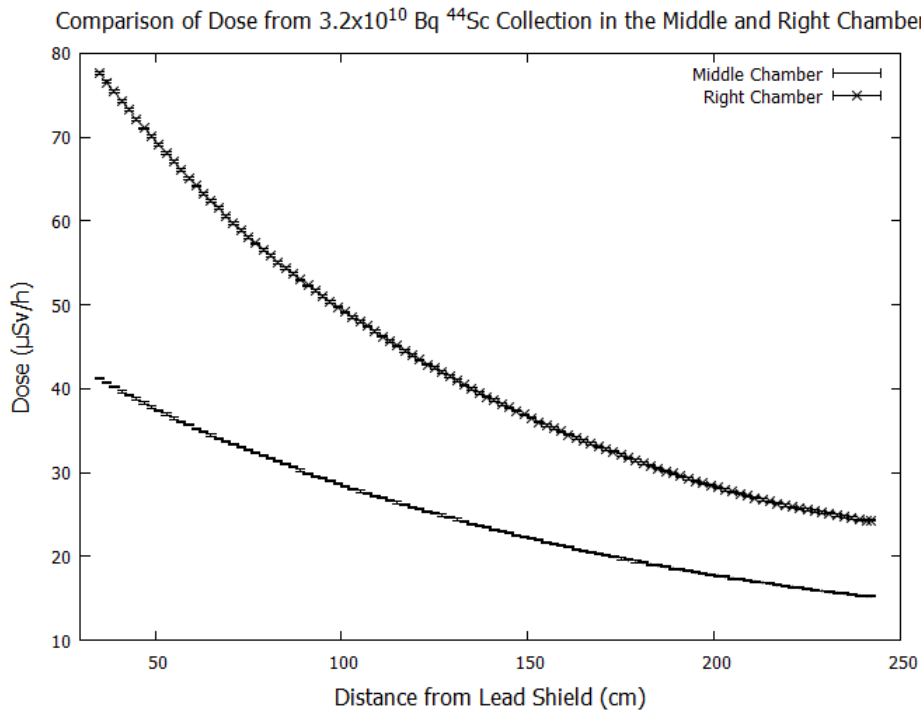


Figure 8: Comparison of dose at the Hot Cell when collection takes place in the middle and right chambers

^{44}Sc and ^{47}Sc are the only isotopes of interest produced by a Ti target. This means one of the chambers will not be collecting anything. Since ^{44}Sc and ^{47}Sc are similar in weight, it is likely that they will have to be collected in adjacent chambers. This

will depend on the magnets resolving power. This means collection will take place in either the left and middle chambers or the middle and right chambers. Since the Hot Cell may have a person operating it it makes sense to avoid using the right chamber if possible to reduce the radiation levels at the Hot cell. The space to the bottom of the collection chambers will be used as a corridor and so extended periods of time spent here are less likely. Figure 8 shows the difference in doses when collection ^{44}Sc in either the middle or right chamber. The Dose levels in Figure 8 are the average dose levels from $x=0\text{cm}$ to 309cm which is the width of the hcell wall; from $z=0$ to 170cm which is the average height in the UK [13] and 2cm deep in the y axis which is the axis plotted. Therefore all collection simulations will avoid using the right chamber if two isotopes are being collected and if one isotope is being collected then the simulation will be for the middle chamber to reduce dose in both the corridor and the Hot Cell area. All activities used to normalise the results were from the expected activities from the 2GeV targets.

Figure 9 and Figure 10 show ^{11}C collection. ^{11}C is the only isotope of interest that is bonded to another element when in the ion beam. Doses from the ^{11}C are $10\times$ below the limit of $10\mu\text{Sv/h}$.

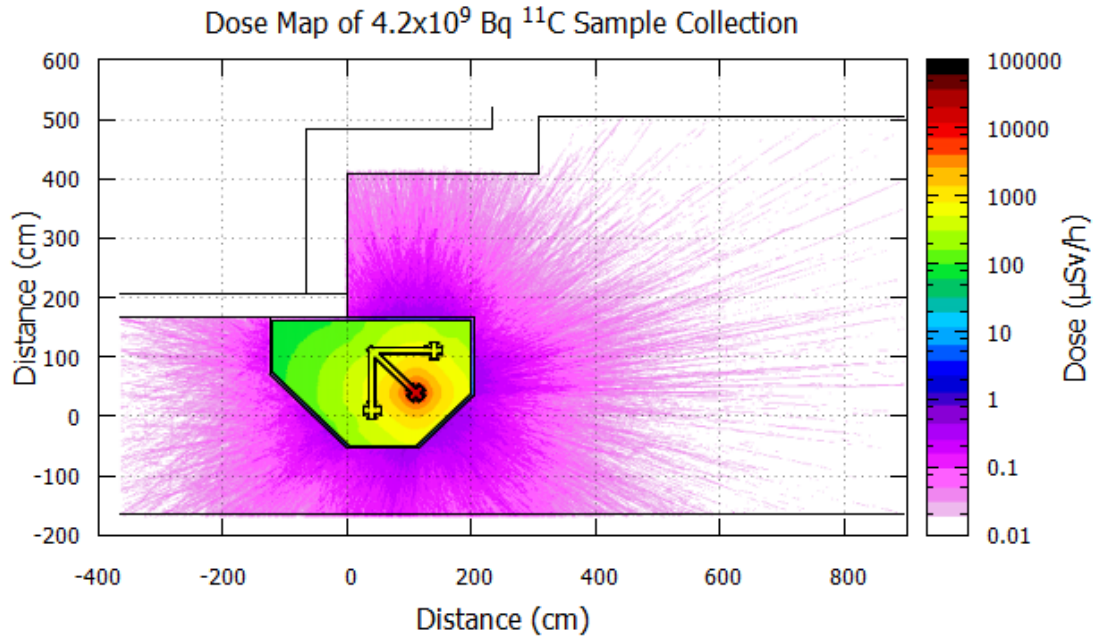


Figure 9: Dose levels from ^{11}CO collection from a NaF-LiF-VD5 target. see example code 2 in appendix

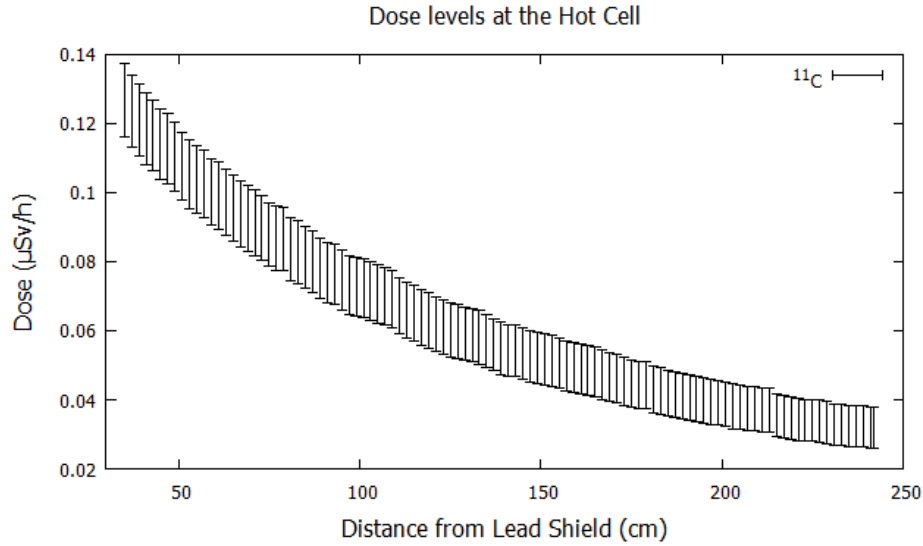


Figure 10: Dose levels from ^{11}CO collection at the Hot Cell

Figure 11 and Figure 12 are from ^{44}Sc and ^{44}Sc collection. The dose map is dominated by the radiation from ^{44}Sc in the middle chamber. Figure 12 shows that levels for ^{44}Sc are above the level allowed for anything other than short exposure. During ^{44}Sc collection, work should not be carried out close to the collection zone.

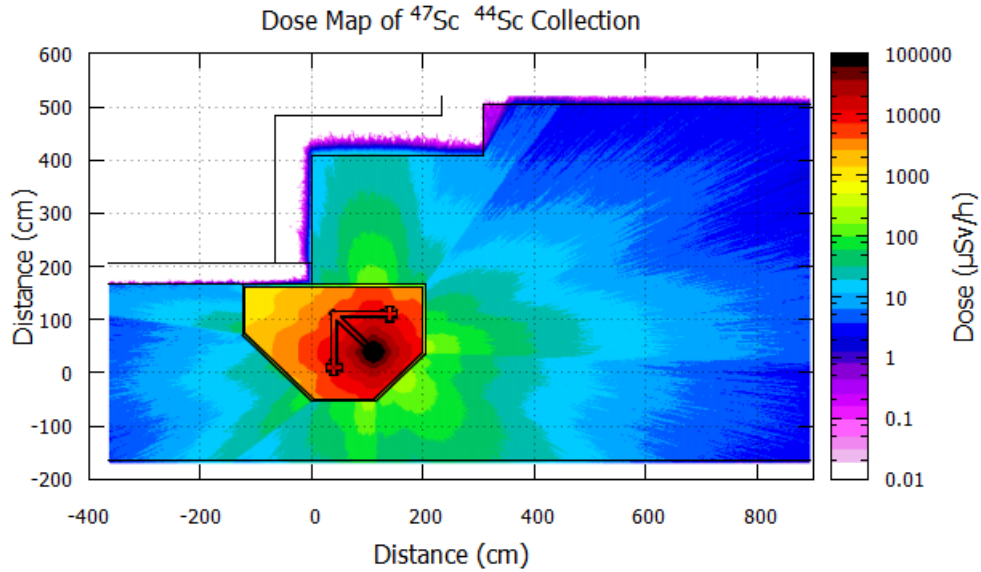


Figure 11: Dose levels from $^{44,47}\text{Sc}$ collection from a Ti target

^{47}Sc on the other hand has almost negligible doses less than $0.1 \mu\text{Sv/h}$. If you worked there 8h a day 5 days a week for a whole year your dose from ^{47}Sc would be less than 0.2 mSv per year.

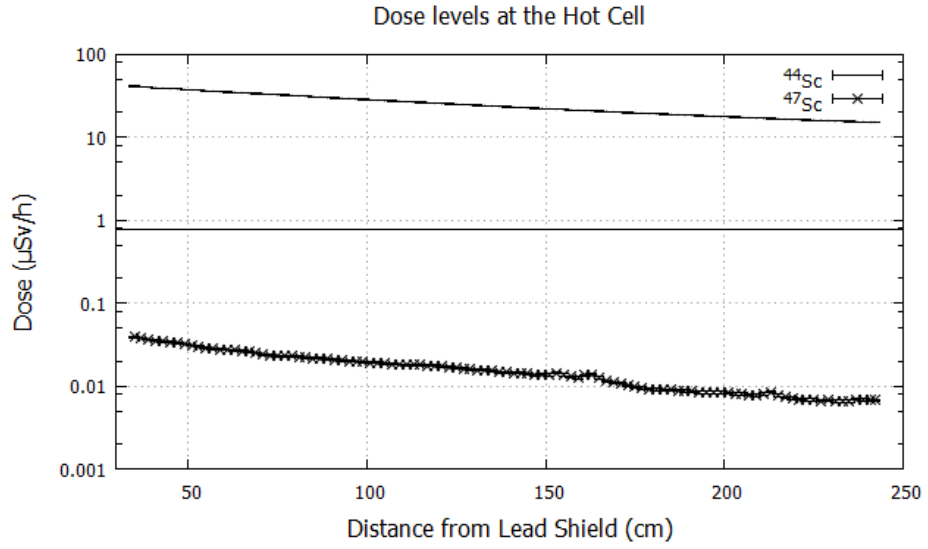


Figure 12: Dose levels from $^{44,47}\text{Sc}$ collection at the Hot Cell

Figure 13 and Figure 14 are from ^{61}Cu and ^{64}Cu . The dose from ^{61}Cu is higher due to 100% of its decay being the most dangerous, $\beta+$, compared to 61.5% of ^{64}Cu decaying by $\beta+$. Both have dose at safe levels though, with 5cm thick Lead shielding.

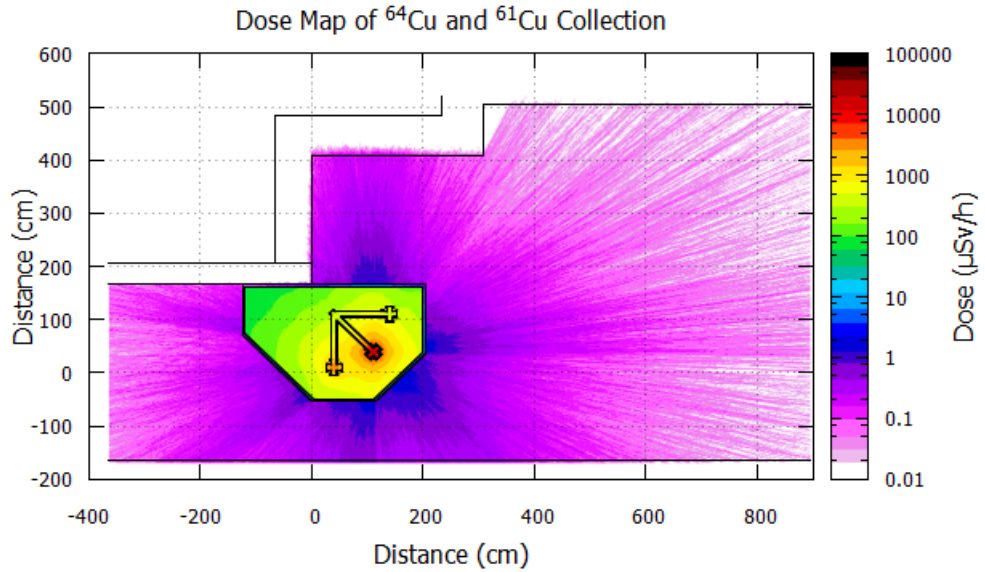


Figure 13: Dose levels from $^{61,64}\text{Cu}$ collection from a $\text{Y}_2\text{O}_3\text{-VD5}$ target

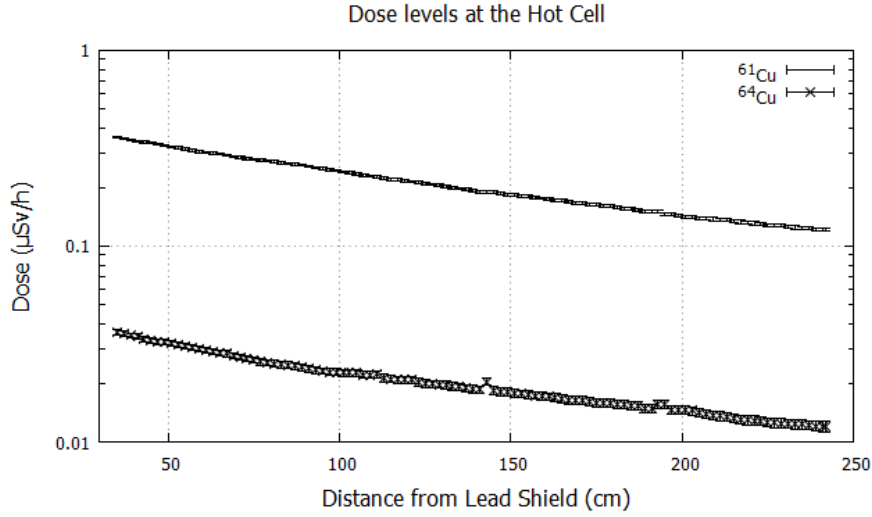


Figure 14: Dose levels from $^{61,64}\text{Cu}$ collection at the Hot Cell

Figure 15 and Figure 16 are for $^{71,72,74}\text{As}$ collection. This is the first collection with an isotope with a slightly complex decay chain for modeling. ^{71}As decays to ^{71}Ge by β^+ and then to ^{71}Ga by electron capture. Figure 16 shows the dose FLUKA simulated for ^{71}As . It should be noted that, this is lower than the dose you would get in reality. Since one decay of ^{71}As leads to one decay of ^{71}Ge , FLUKA will give the radiation from both decays a 50:50 weighting because over an infinite amount of time this would be the weighting. However the decay of ^{71}Ge is 4.19 times slower than that of ^{71}As , so in the time scale likely for collection it will not be a 50:50 weighting. Since the dose from the decay would lead to more dose the result is lower than that in reality. If however all the activity was from ^{71}As , the maximum extra dose would be double which would still be well under safe levels. Therefore the doses from ^{72}As and ^{74}As are good approximations of reality and are under safe limits.

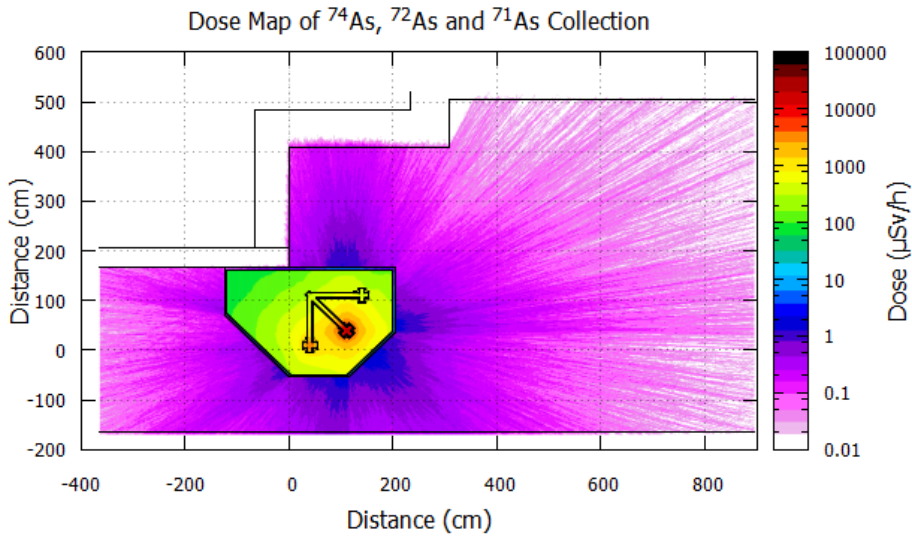


Figure 15: Dose levels from $^{71,72,74}\text{As}$ collection from a $\text{Y}_2\text{O}_3\text{-VD5}$ target

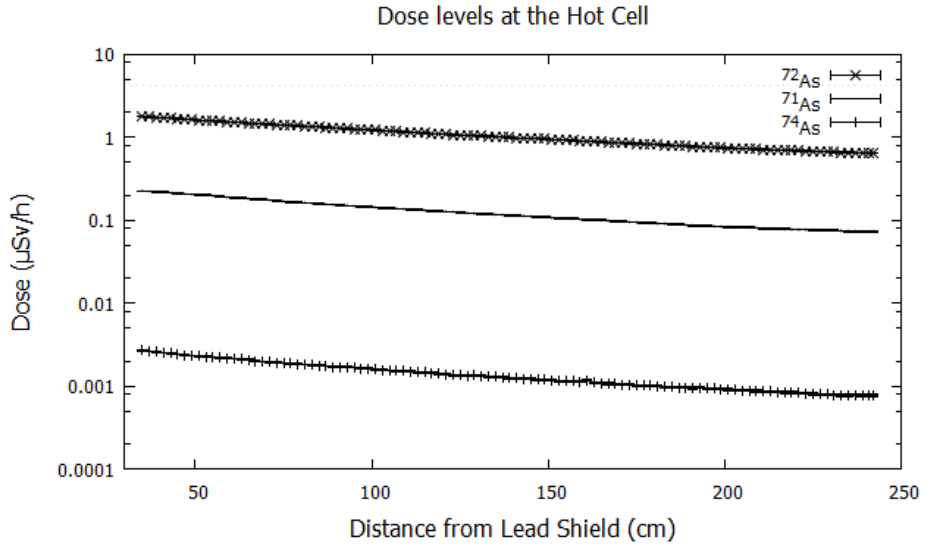


Figure 16: Dose levels from $^{71,72,74}\text{As}$ collection at the Hot Cell

Figure 17 and Figure 18 show the dose from radiation given off during the collection of $^{89,82}\text{Sr}$ and ^{67}Cu . ^{82}Sr decays to ^{82}Rb by electron capture and then to ^{82}Kr via β^+ decay. The half-life of ^{82}Kr is short at only 1.26 mins, meaning almost all the ^{82}Kr will decay shortly after being produced. This means FLUKA should give accurate results of dose for this decay. As you would expect ^{82}Sr has a relatively high dose rate. It only has a low activity of 4×10^8 Bq and therefore has a low equivalent dose after the shielding, of $0.1 \mu\text{Sv/h}$. If it had the same activity as ^{44}Sc , it would give a dose of around $10 \mu\text{Sv/h}$ which is of the same order as ^{44}Sc 's dose. These result affirm the way FLUKA models isotopes with decay chains with multiple steps.

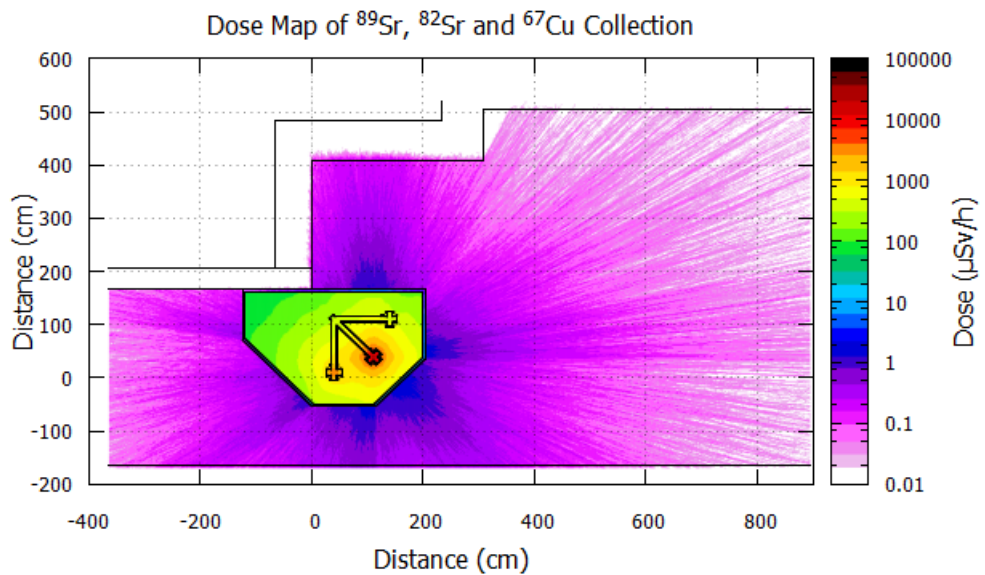


Figure 17: Dose levels from $^{89,82}\text{Sr}$ and ^{67}Cu collection from a $\text{UC}_x\text{-Re}$ target

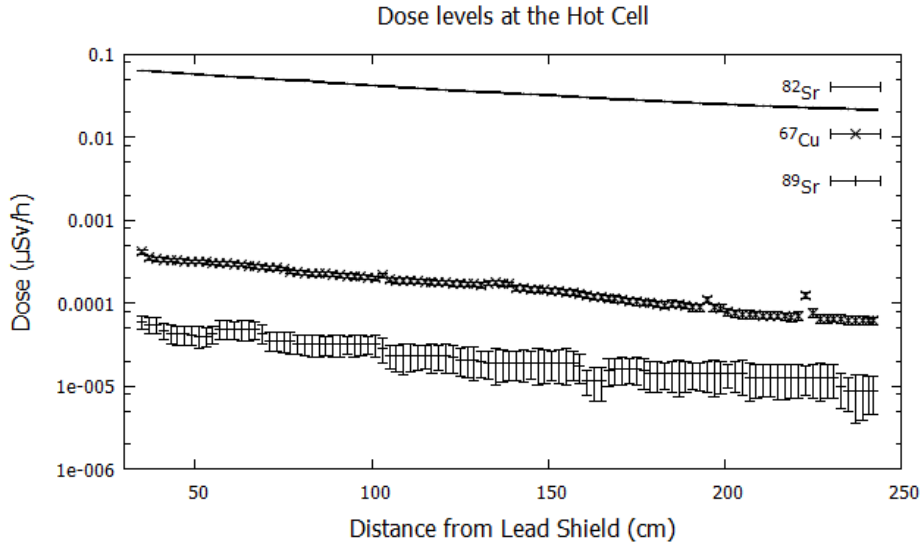


Figure 18: Dose levels from $^{89,82}\text{Sr}$ and ^{67}Cu collection at the Hot Cell

Figure 19 shows the dose from ^{77}As collection. It is so low that no radiation is shown on the plot outside of the shielding. Some radiation will escape leading to an insignificant dose outside the shielding, but it is below the $0.01 \mu\text{Sv/h}$ threshold of the key.

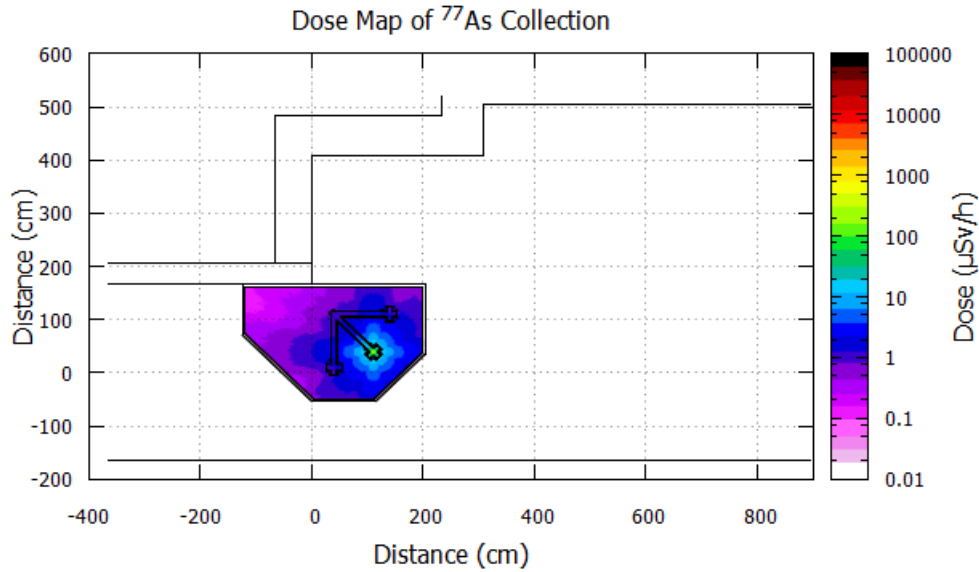


Figure 19: Dose levels from ^{77}As collection from a $\text{UC}_x\text{-VD5}$ target

Figure 20 and Figure 21 show dose levels from $^{152}\text{Dy/Tb}$, ^{149}Tb and ^{140}Nd collection. As shown in the dose map the $^{152}\text{Dy/Tb}$ duality and ^{149}Tb dominate the dose during this collection. The result in Figure 21 shows that both $^{152}\text{Dy/Tb}$ and ^{149}Tb are above the safe limits for long stay. The $^{152}\text{Dy/Tb}$ result is calculated by combining the FLUKA results from both ^{152}Tb and ^{152}Dy simulations. The results have then been normalised taking into account the particle production rates from previous

work at ISOLDE [1] and the relative half-lives of the isotopes to work out each ones share of the activity at $t=0$. This however would only be a solution if the collection was instantaneous, which it is not.

^{152}Dy and ^{152}Tb is a dynamic system. Both isotopes decay by $\beta+$ emission, but have different half-lives. ^{152}Dy has a half-life of 2.38h and ^{152}Tb has a half-life of 17.5h [9]. Since they both decay by $\beta+$ emission it can be expected that for the same activity ^{152}Dy and ^{152}Tb will give similar levels of dose from radiation. Figure 22 is a plot of a FLUKA simulation of ^{152}Dy and ^{152}Tb both weighted to $2.2 \text{ e}+10$ Bq to compare the equivalent doses after 5cm of Lead shielding. The doses received are almost identical for the same amount of activity. The dose from ^{152}Tb is 1.7% higher than that of ^{152}Dy . This could be due to the small α decay path of 0.1%. The 0.1% of activity that corresponds to α decay will not give an detectable dose after 5cm of Lead. The rest of the difference is due to the difference in Q values of the two isotopes $\beta+$ decays. ^{152}Dy 598.346 KeV ^{152}Tb 3990.0 KeV [9] which would explain the increased dose for ^{152}Tb . The difference in dose is however this is small enough when compared to the accuracy [14] of transport codes that the doses from ^{152}Dy and ^{152}Tb can be considered equal for the same activity. This means that the only bearing the ratio of ^{152}Dy and ^{152}Tb has is on the activity of the sample due to the different half-lives and not the dose per decay for the way FLUKA treats decay chains. The radiation given by ^{152}Tb should led to a larger dose because there is more energy in the decay. With the ^{152}Dy dose ^{152}Tb makes up 1/5 of the histories. The other three histories led to little to no dose as they are α decays, so the difference in the dose from ^{152}Tb to ^{152}Dy is half the difference in reality and the dose from both would be higher as the 60% weighting to α decay for ^{152}Dy and 75% for ^{152}Tb is not realistic because the α decays have much longer half lives.

Figure 23 and Figure 24 show the most complicated possible collection. $^{166}\text{Ho}/\text{Yb}$, ^{156}Tb and $^{155}\text{Dy}/\text{Tb}$ could all be collected at the same time from a Ta-Re target. Figure 24 shows that the dose from decays is dominated by ^{166}Yb . The dose for ^{166}Yb is around the threshold for limited stay. With the radiation from the other isotopes and ambient radiation from other sources such as the target area and the MEDICIS bunker it is likely to be over $10 \mu\text{Sv/h}$. ^{166}Yb however is one of the isotopes that has a complicated decay chain. It decays via electron capture to ^{166}Tm with a half-life of 56.7h [9] it then decays via β to ^{166}Gd with a half-life of 7.7h. This half-life is sufficiently long that it cannot be presumed that all of the ^{166}Tm produced by decay will have decayed so, the weighting cannot be said to be 50:50 it will be in FLUKA. Since the ^{166}Tm decay will be responsible to most of the dose, the result in reality will be lower.

For ^{155}Dy and ^{155}Tb the difference in doses is much larger than it was for $^{155}\text{Dy}/\text{Tb}$. This is because ^{155}Dy , is responsible for more of the dose this time has a much

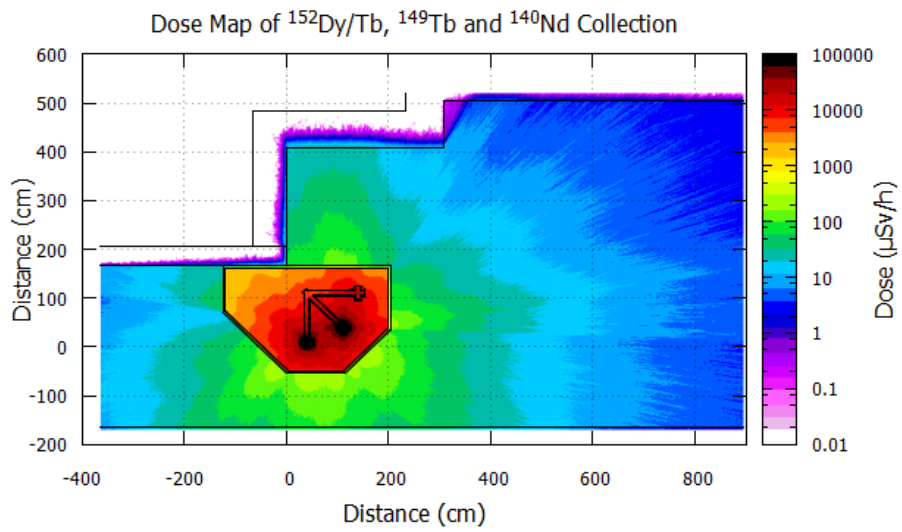


Figure 20: Dose levels from $^{152}\text{Dy/Tb}$, ^{149}Tb and ^{140}Nd collection from a Ta-Re target

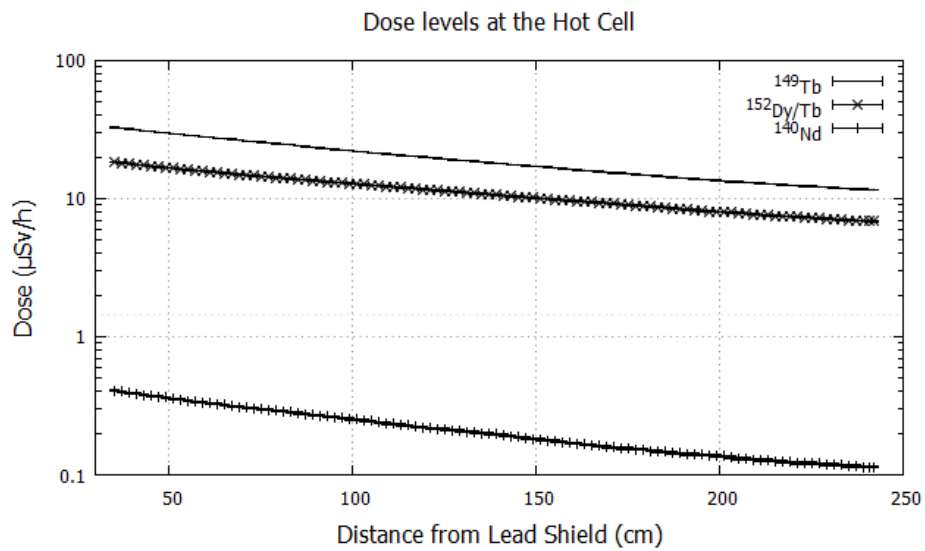


Figure 21: Dose levels from $^{152}\text{Dy/Tb}$, ^{149}Tb and ^{140}Nd collection at the Hot Cell

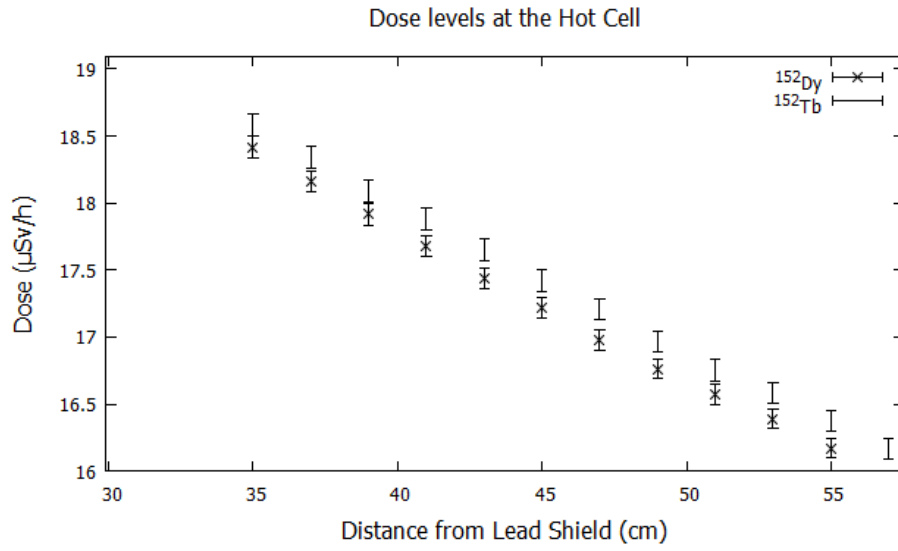


Figure 22: FLUKA results with both $^{152}\text{Dy}/\text{Tb}$ weighted to 2.2×10^{10} Bq

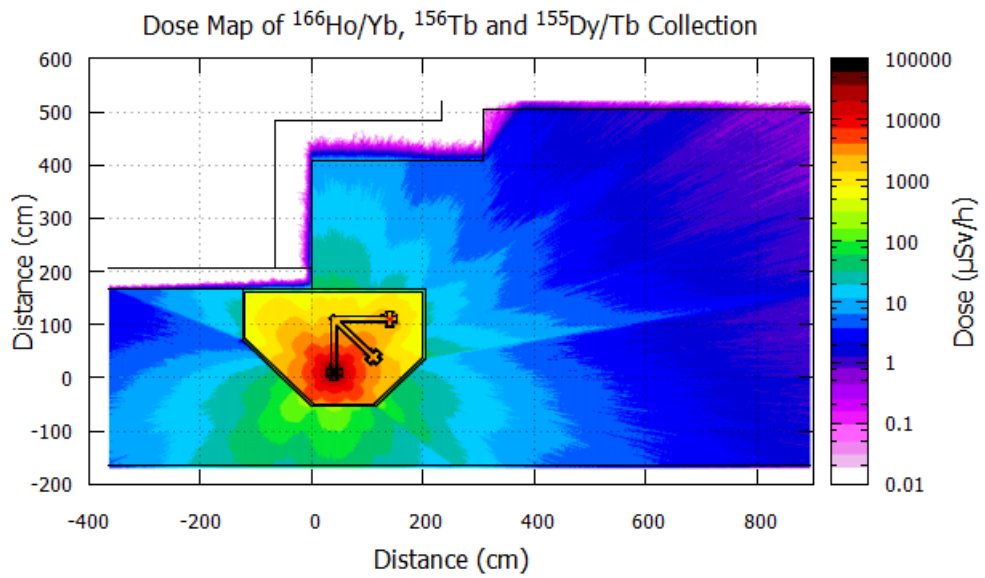


Figure 23: Dose levels from $^{166}\text{Ho}/\text{Yb}$, ^{156}Tb and $^{155}\text{Dy}/\text{Tb}$ collection from a Ta-Re target

larger Q value of 2094.5KeV compared to ^{155}Tb 's 819.74KeV. Figure 24 shows both isotopes with a weighting of $6.8 \text{ e}+8 \text{ Bq}$. Due to the activity collected, the doses are low so it is not important to consider for shielding compared to other isotopes.

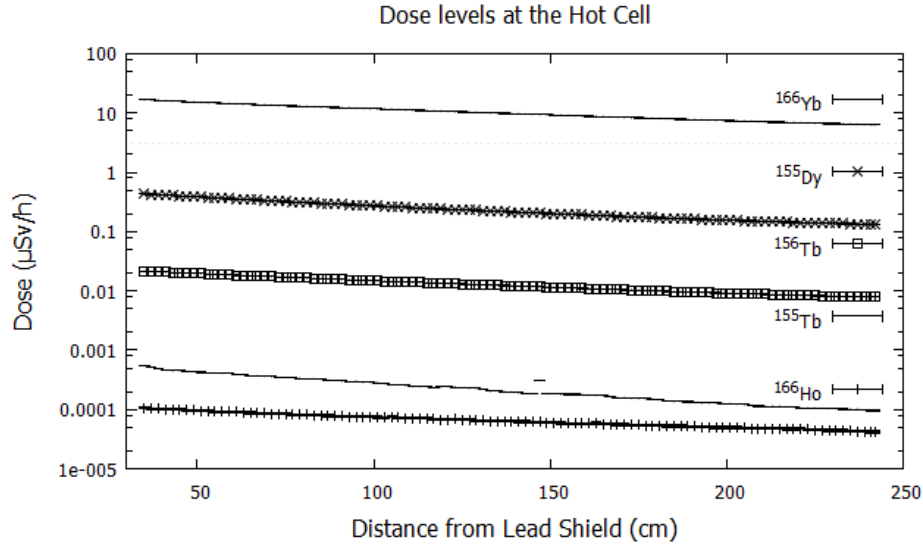


Figure 24: Dose levels from $^{152}\text{Ho}/\text{Yb}$, ^{156}Tb and $^{155}\text{Dy}/\text{Tb}$ collection at the Hot Cell

Figure 25 shows the dose from the collection of ^{161}Tb and ^{153}Sm . ^{153}Sm produces a much higher dose than ^{161}Tb due to its higher activity but neither produce a dose higher than the $0.01\ \mu\text{Sv/h}$ threshold outside the shielding.

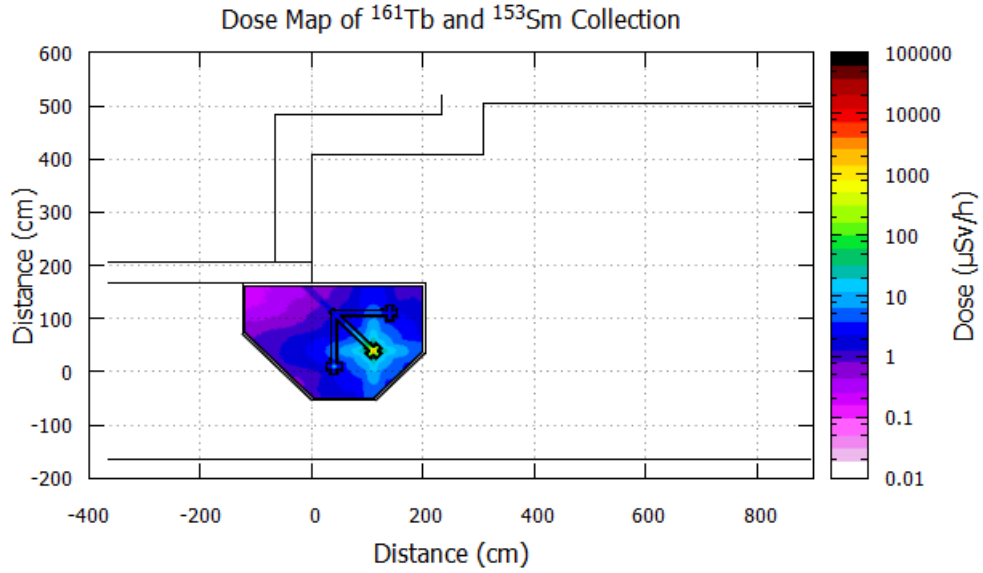


Figure 25: Dose levels from ^{161}Tb and ^{153}Sm collection from a $\text{UC}_x\text{-Re}$ target

Figure 26 shows the dose map from ^{177}Lu collection. It is another isotope that produces a negligible equivalent dose outside shielding.

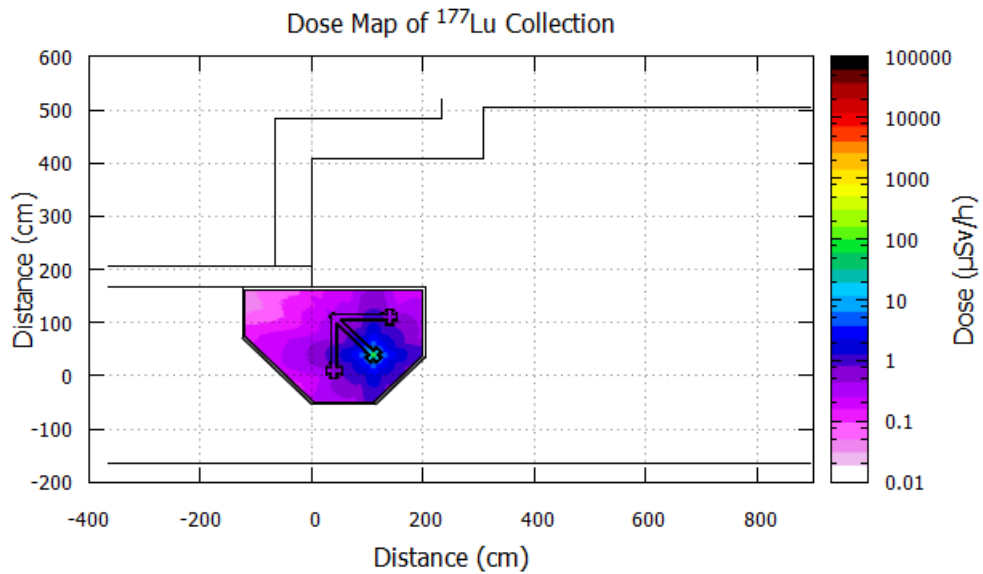


Figure 26: Dose levels from ^{177}Lu collection from a Re-VD5 target

Figure 27 and Figure 28 shows the collection of ^{212}Bi and ^{213}Bi . Both have complicated decay chains but the dose in the simulation for ^{212}Bi is so low that it need not be considered in the shielding estimates. However, ^{213}Bi does have a sizeable dose in the FLUKA simulation. It decays via β^- to ^{213}Po and then almost instantaneously α decays to ^{209}Pb . It then decays with a half-life of 3.23h to ^{209}Bi via β^- decay and then finally decays very slowly to ^{205}Tl via α decay. On the time scale of collection the activity is dominated by the first two steps meaning about 50:50 β^- to α decay. This means that the FLUKA simulation of radiation is likely to be quite accurate; taking this into account it, is unlikely the dose would increase much and highly unlikely to eclipse that of ^{44}Sc .

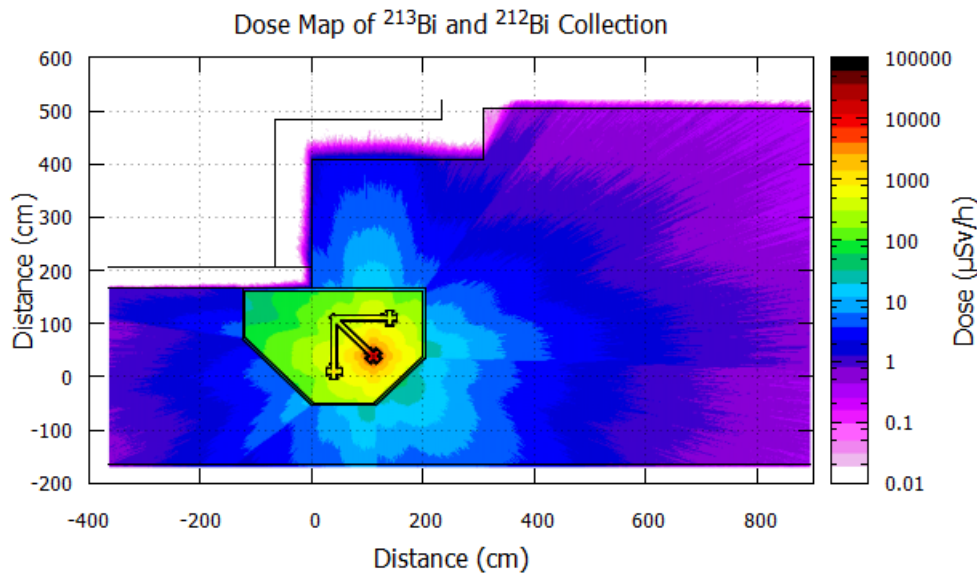


Figure 27: Dose levels from $^{212,213}\text{Bi}$ collection from a $\text{UC}_x\text{-Re}$ target

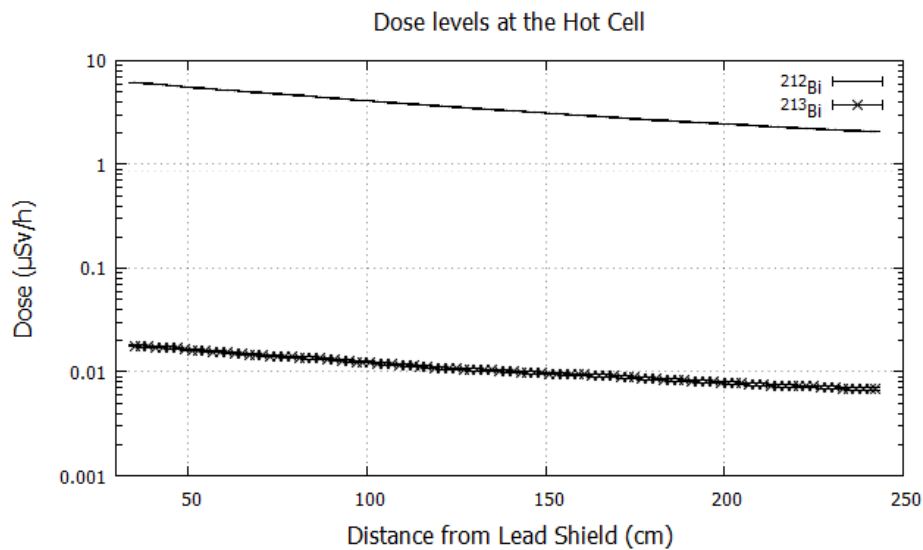


Figure 28: Dose levels from $^{212,213}\text{Bi}$ collection at the Hot Cell

^{44}Sc , ^{149}Tb and $^{152}\text{Dy/Tb}$ are the isotopes that give the highest dose. All have high activity rates and are positron emitters. Both ^{149}Tb and $^{152}\text{Dy/Tb}$ have complicated decay chains making them difficult to model accurately in FLUKA.

Figure 29 shows how the ratio of ^{152}Dy to ^{152}Tb changes with time. The longer the collection process goes on for, the more dominate ^{152}Tb becomes. Figure 30 shows that the activity of $^{152}\text{Dy/Tb}$ reaches the $2.2 \text{ e}+10 \text{ Bq}$ after 140 mins of collection. At this point the amount of ^{152}Dy is only 5.14%, so for the next stage after collection it can be considered to be all ^{152}Tb for simplicity.

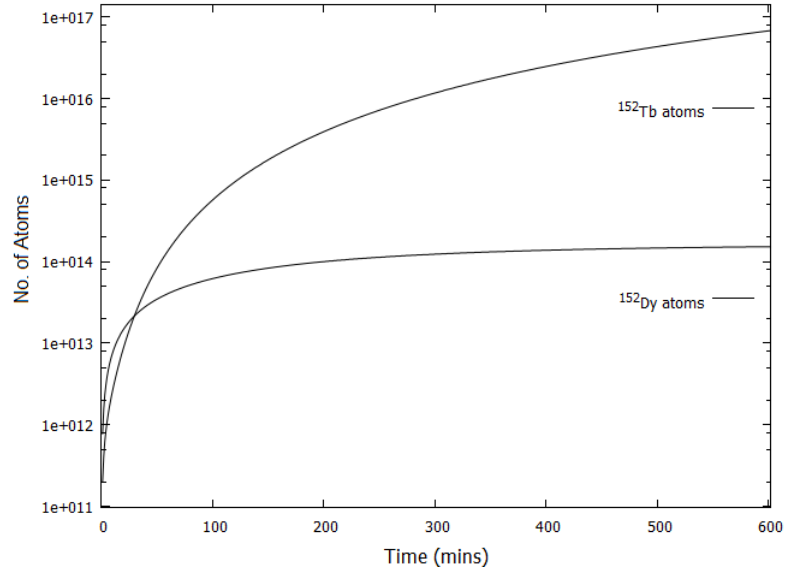


Figure 29: Change in amount of $^{152}\text{Dy/Tb}$ with time during collection

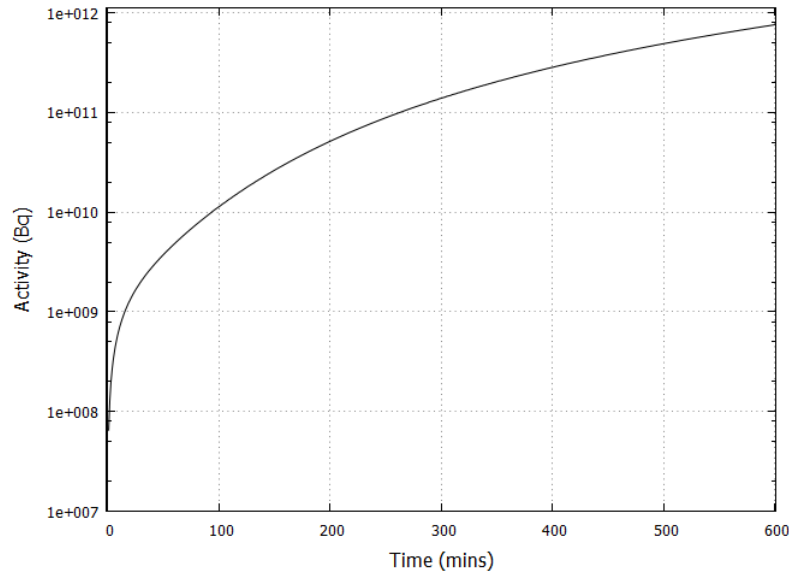


Figure 30: Change in activity of $^{152}\text{Dy/Tb}$ with time during collection

3.3 Transport Vessel and Transfer system

Once the isotopes have been collected, they will then be transported to shielded glove-boxes. This will require a shielded vessel to transport the samples in. Through discussions at CERN it was decided that the vessel would ideally be under the same vacuum conditions as the collection chamber to reduce the chances of contamination. This would mean that when moving the collected samples from the collection chamber to the transport vessel, the chamber would not have to be pressurised and de-pressurised every time a sample was to be transported. The doses calculated in section 3.2 show that it would not be possible for a person to carry out any work on the collection side of the lead shielding for any length of time whilst the isotopes are at the expected activity levels. This would result in a dose of 10s of mSv/h for some isotopes. Even the lowest isotopes still have doses of 10s of $\mu\text{Sv/h}$ within the shielding and there is likely to be an even higher dose from the switchyard where many isotopes not being collected will be dumped in the slits. Therefore the system to transfer the sample from the collection chamber to the transport vessel should be able to be remotely operated.

Figure 31 shows initial plans for a remote system. The samples are transferred from the collection chamber to a shielded transport vessel below. The transport vessel is likely to be heavy due to the lead shielding so fitting it below would be the easiest solution to support it. There is also limited space to the sides due to neighbouring collection chambers and the back of the collection chamber directly in-line with the beam is the best place to fit a detector to monitor the radiation. Monitoring the radiation is important from a safety perspective, but is also an excellent way to help track the collection and interrogate the substances collected.

This collection system would all be done behind a lead wall. Access via a door would be needed to remove the transport vessel once the sample has been moved. A linear manipulator with remote control capabilities would be used to move the sample. This plan however relies on having an engineering solution to sever the link between the sample holder and the linear manipulator. Kurt J. Lesker are the supplier that has been used in past for similar work. They do not sell a remotely operated linear manipulator with the ability to grab and let go of a sample. All ones that they sell with this capability are manually operated. Finding a solution from another supplier may also not be possible so a more feasible solution was needed. As well as this problem the linear manipulator would have to be very long to traverse the collection chamber all the way through to the transport vessel as well as passing through two gate valves - one for the chamber and one for the transport vessel. FLUKA simulations run to shape the design for this system are still relevant however for the designing of a new system.

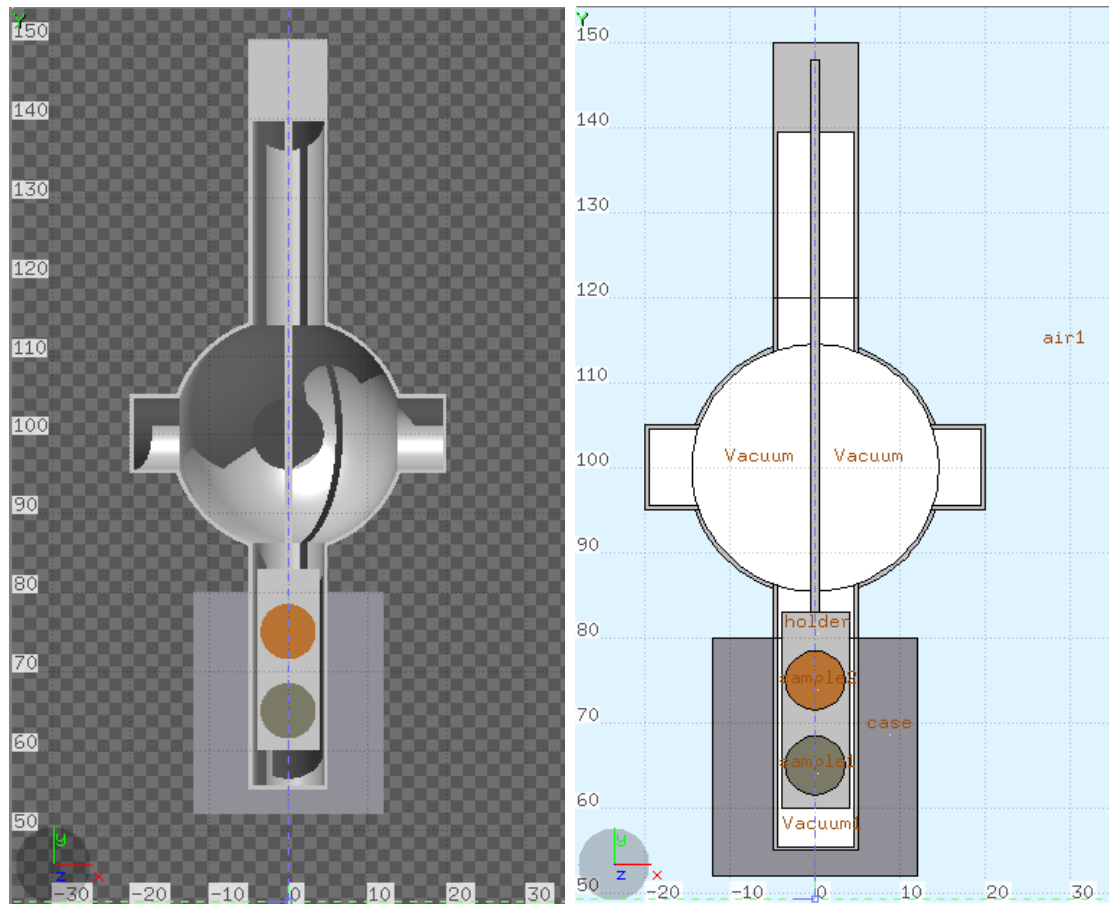


Figure 31: Initial concept for a sample transfer and transport system

When designing this system, the idea of a long tube for a transport vessel was devised. The thinking behind was that because the top of the transport vessel would have to have a gate valve for it be a vacuum inside, which would reduce the chances of contamination and make sample transfers easier; there would be little shielding at the top of the vessel. By having a long tube in the same way a light at the end of the tunnel is very dim little radiation would escape out of the top of the vessel.

Figure 32 shows the doses maps that affirm this theory. When the source is at the bottom of the vessel, it acts as a collimator with little radiation escaping from the side and some escaping from the top in a tight beam. So long as a person doesn't look directly down the tube the dose could be kept low.

Figure 33 shows how the dose changes with the depth with the vessel the source is. Initially there is a large difference between the different depths, but as you get down to around 18cm, the dose levels do not increase much. This was for a tube with an inner radius of 5cm. In the final design the tube was thinner meaning that the affect is achieved at a lower depth.

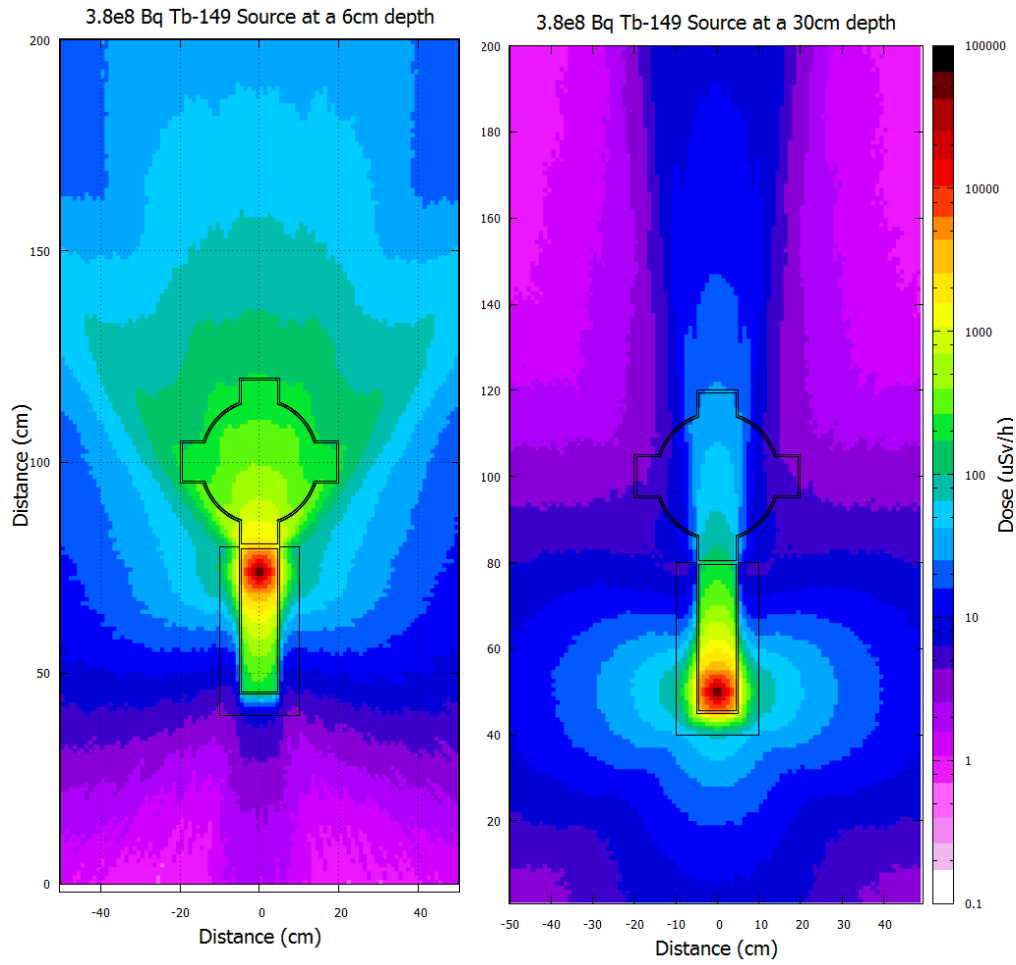


Figure 32: Dose map from ^{149}Tb at different height within a lead shielded tube

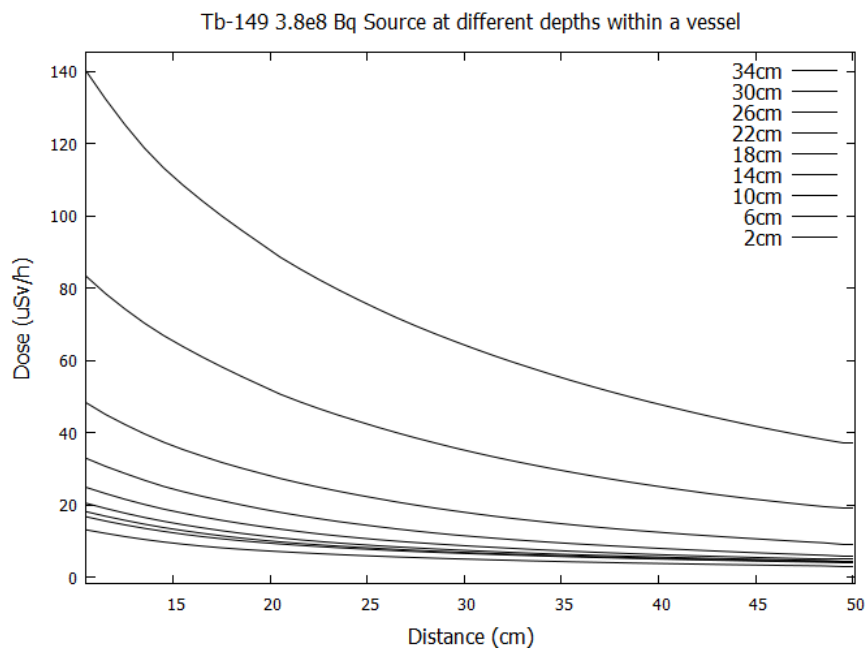


Figure 33: A graph showing the affect to equivalent dose when a Tb-149 sample is a different heights within the collection vessel. The dose is highest for 2cm. The dose is an average dose received in a 1cm deep by 1m wide and by 2m high bin

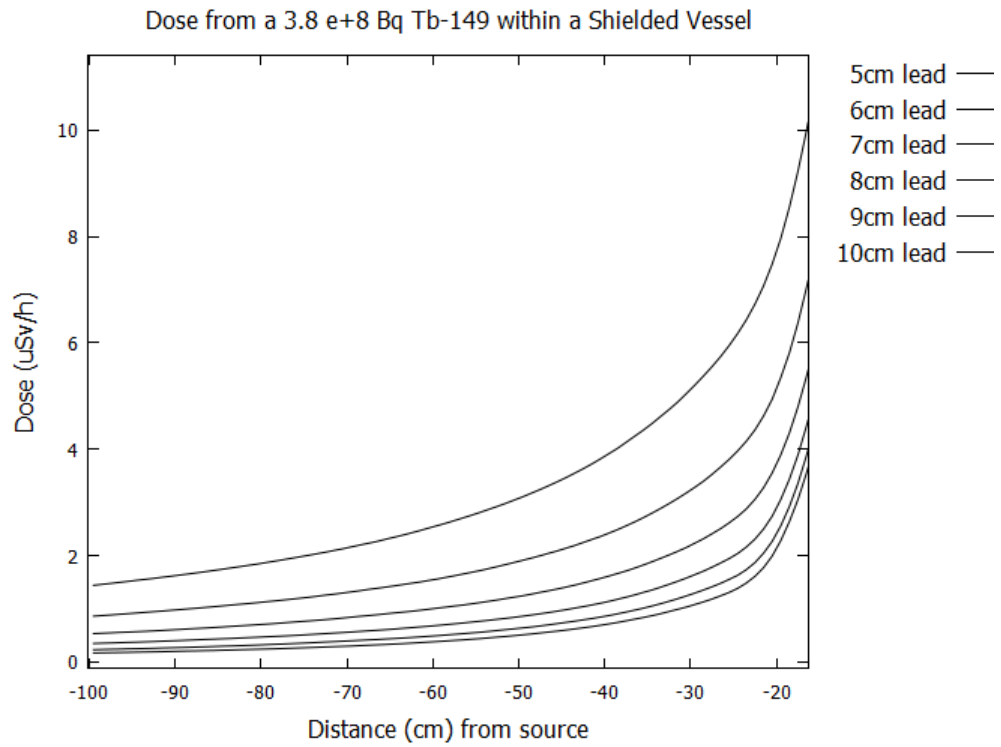


Figure 34: A graph showing the effect to equivalent dose when a Tb-149 source within the collection vessels of varying thickness. The dose is an average dose received in a 1cm deep by 1m wide and by 2m high bin

Figure 34 shows that for ^{149}Tb only 5cm of lead is enough to get the dose down to around $10 \mu\text{Sv/h}$. This is well below the limit for limited stay environments and short term exposure which has a limit of 2 mSv/h .

Lessons learnt from this failed designs are that a tube with a large length to diameter ratio is good to reduce dose from the top and that 5cm of lead is more than enough to shield ^{149}Tb . One thing to note is that the lead results is for the expected activity from the 1.4 GeV proton irradiated target and would be about 100 times higher for collection from the 2.0 GeV proton beam target. This would mean that the dose 20cm from the sample with 5cm of Lead shielding would be closer to 1 mSv/h , which is still below the limit for short time work which this would be. It should only take a maximum of 5-10 mins to wheel a transport vessel to the glovebox. Very little of that time would also spent as close as 20cm to the target. An arms length is likely to be the minimum distance a person would ever be to the transport vessel and including the radius of the vessel a person is not likely to be closer than a meter to the sample for very long. The lessons learnt will help shape the final design of the collection and transport system.

The transport vessel and collection chamber will need to be able to separate easily without human intervention. Creating a reliable system is therefore important. If a system was to fail, valuable time could be lost whilst waiting for radiation levels to drop low enough to safely fix a problem. Therefore a simple system would be

the best option as it would have less to go wrong. After studying equipment that is readily available, a basic design was put together. The chamber used in section 3.2 was a CF100 cross. A CF port is one of the best in terms of maintaining a vacuum. It has a copper gasket that is squished in between the connecting components. They are tightened by bolts until a metal bond is formed between the copper and the components. This is excellent for maintaining a vacuum but it is harder to separate components. This therefore is not ideal for the connection between the collection chamber and the transport vessel as the transport vessel will need to be connect and disconnected many times. This leaves two common options. Either a ISO or KF connection. Both of these systems use clamps and o-rings to maintain a seal. They cannot be used for ultra high vacuum environments but are much easier to disconnect and could be done remotely by a robotic arm.

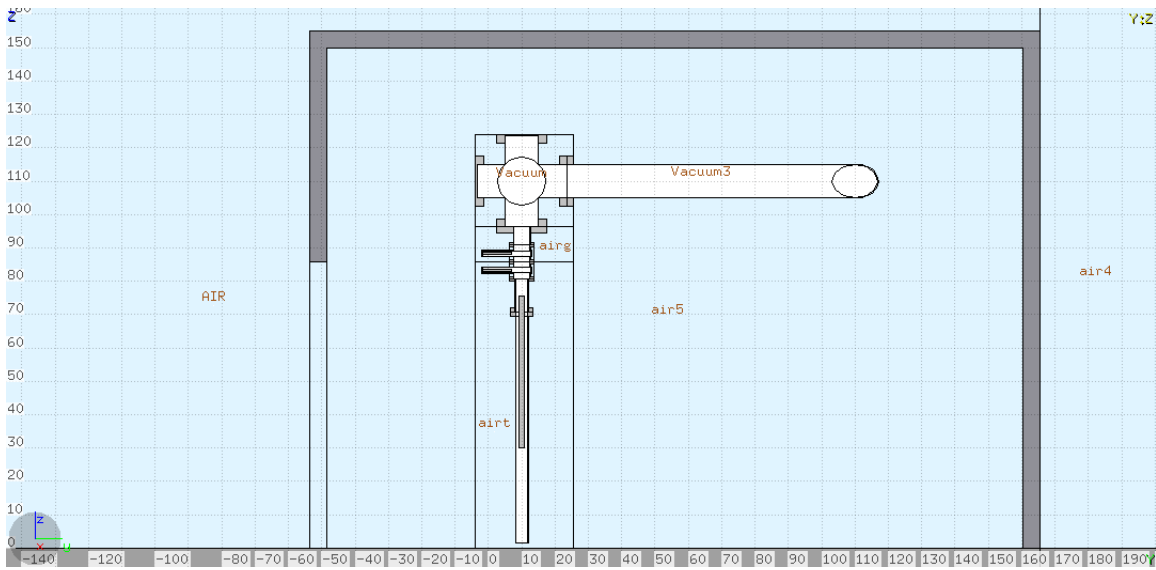


Figure 35: CF100 chamber with the transport vessel in-situ

Figure 35 shows one solution. The Chamber is a CF100 6-way cross and it has an adaptor to a KF50 port. There is a KF50 gate valve on the chamber adaptor and a KF50 gate valve on the transport vessel. The transport vessel itself is a fully nipple with a linear manipulator underneath. The linear manipulator will move the sample from the transport vessel to the collection chamber. It would then retract the sample into the collection chamber. The gate valves of both the chamber and the transport vessel would then have to be closed remotely. For the gate valve on the chamber a pneumatic gate valve can be used using air compressed air to close it. Closing the gate valve on the chamber will however be more problematic. Using a pneumatic one would require this connection to be severed when the transport vessel is moved. The environment that the gate valve is operating in is has a lot of radiation so DC motors are unlikely to last very long. VAT do produce all-metal gate valves that is solenoid actuated that can with stand radiation upto 10^6 Gy so this is one option. Another option is to have a simple robotic arm on the trolley

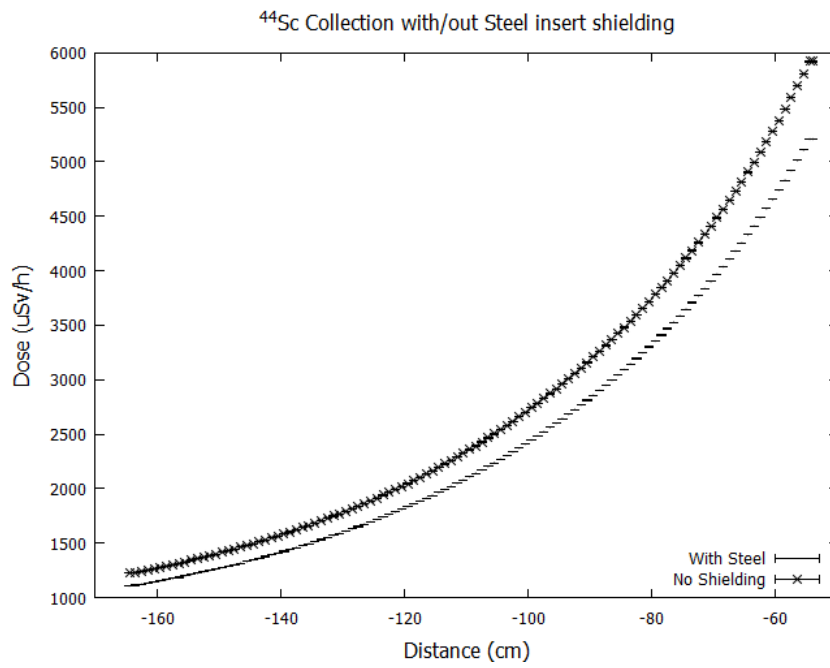


Figure 37: Dose from ^{44}Sc when in the transport vessel with and without a steel insert

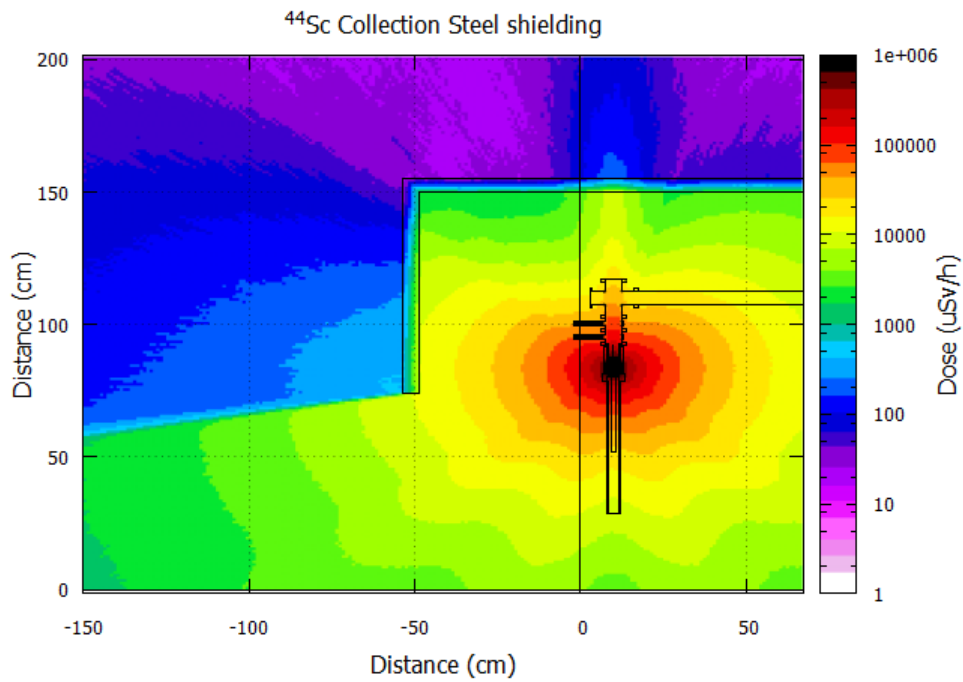


Figure 38: Dose map from ^{44}Sc within the transport vessel

Figure 38 shows the dose from the model in Figure 36 with a 1cm lead jacket around the transport vessel. Doses are too high to be safe and more shielding is required.

Figure 39 shows how doses rates decrease as the lead jacket thickness around the transport vessel is increased. With just 2cm of Lead dose levels are below the limits for short term exposure.

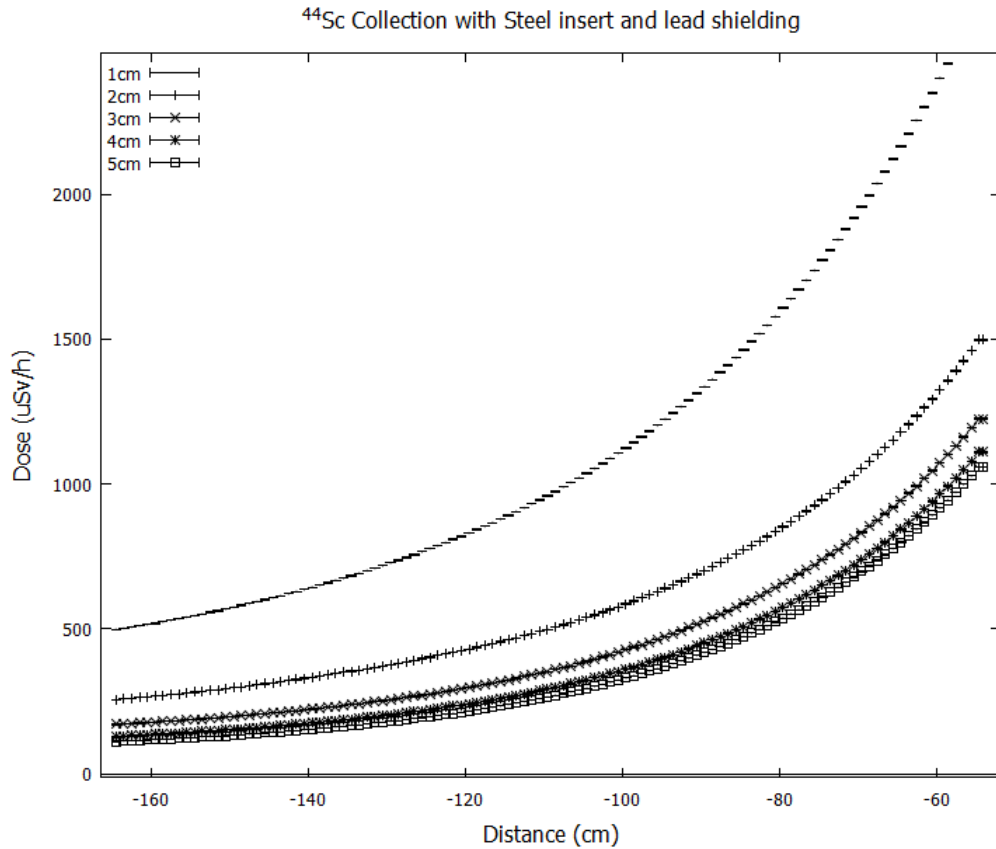


Figure 39: A graph showing how dose varies with amount of Lead shielding for the transport vessel

Figure 40 is a dose map from the radiation given off by ^{44}Sc whilst being moved. The valve on the top of the vessel is closed. There is one difference between this design and that shown in Figure 36, this model has a zero-length reducer in between the transport vessel and the manipulator. It is an adaptor to go from one size CF port to another though it is not being used for that in this situation. It is essentially being used as a 2cm thick piece of steel shielding for the bottom of the transport vessel and is also there to support the 5cm thick lead jacket which would weigh 17.43 kg. The CF100 to CF40 zero-reducer can be seen more clearly on the left of Figure 42. The dose 50cm away from the lead jacket are around the 1mSv/h level. The plot in Figure 40 is the average dose over 20cm into the page and 20cm out of the page. This dose is acceptable but not ideal and if in reality the activity of ^{44}Sc is less than that used in the simulation, as is likely due to inefficiencies in collection, then the dose levels will be even lower. 17.43 kg is a manageable weight and a trolley could be easily used to move the transport vessel.

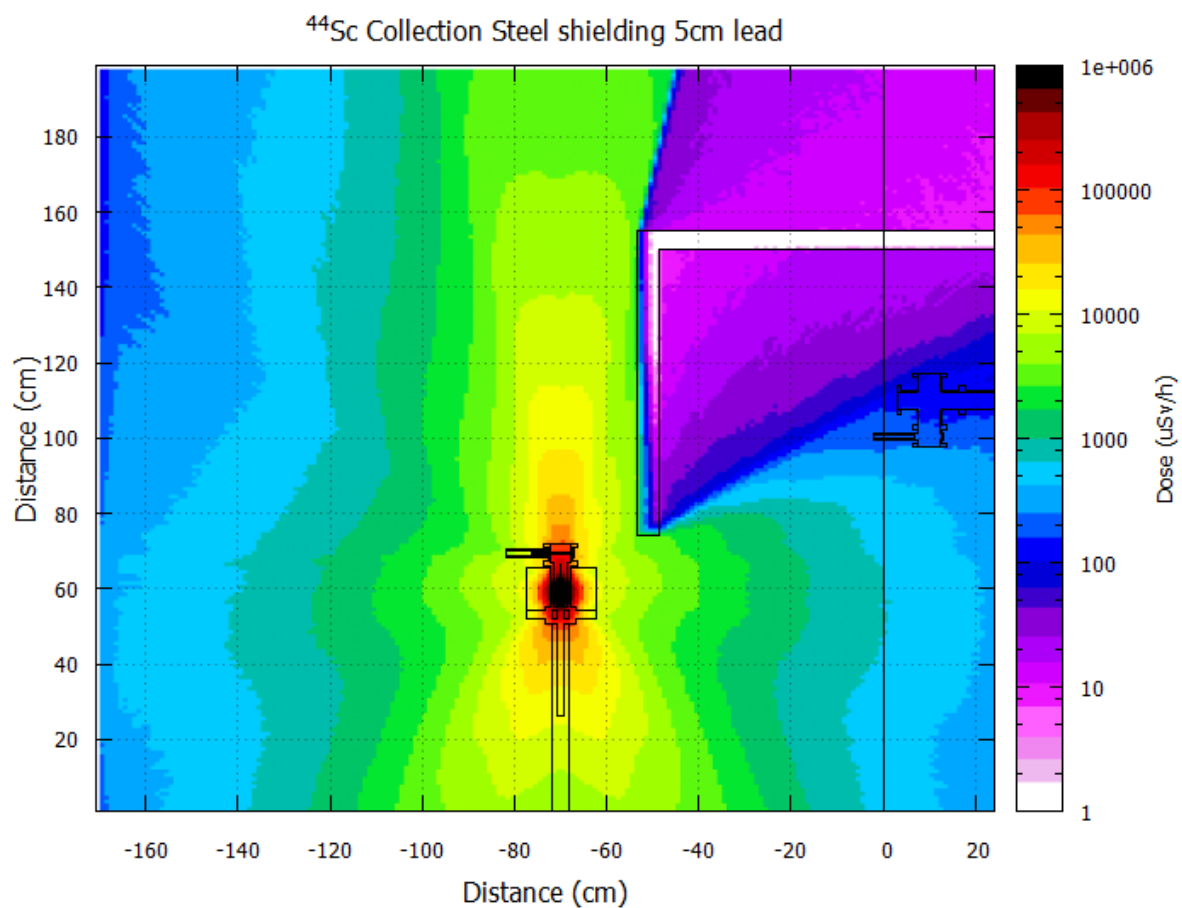


Figure 40: A transport vessel with ^{44}Sc within it sitting in the corridor space

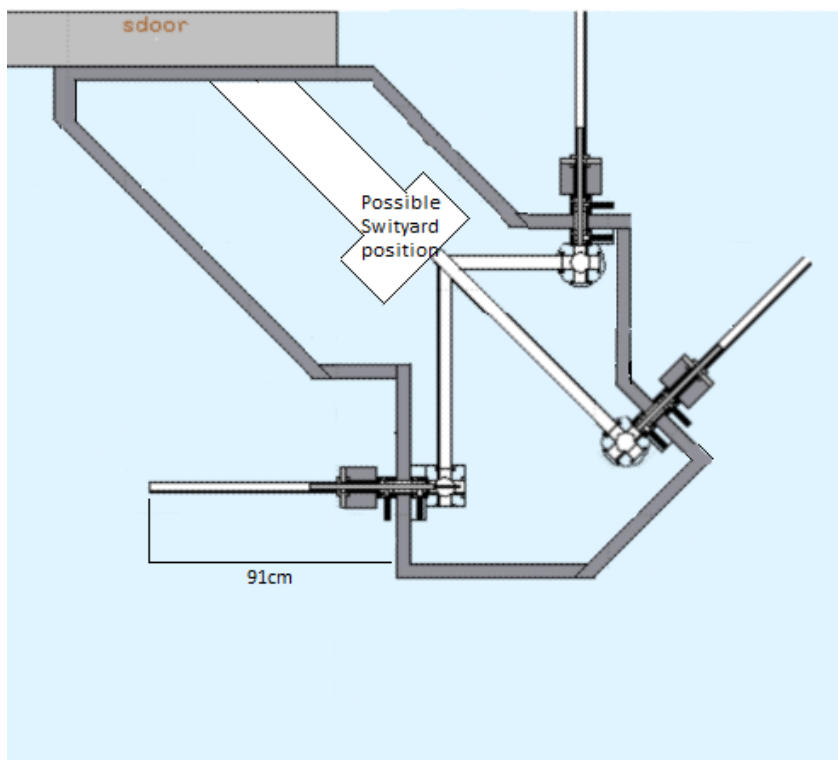


Figure 41: An alternative solution for the positioning of the transport vessel

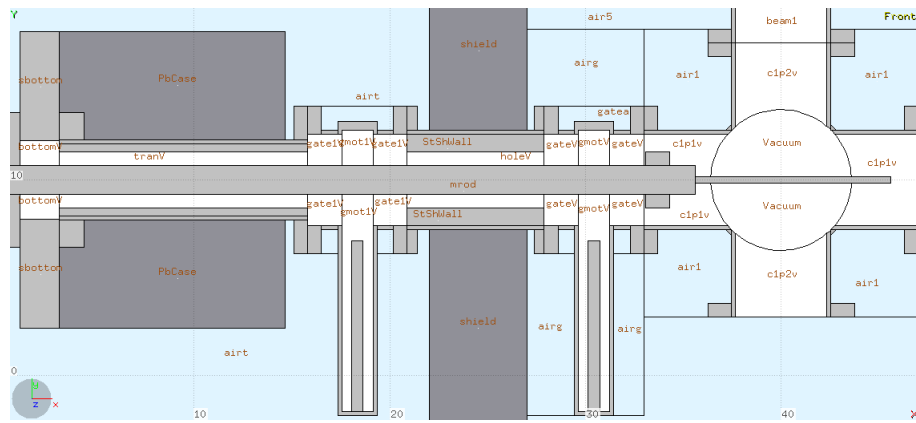


Figure 41 shows an alternative to the bottom loading transport vessel. With the new, smaller choice of collection chambers there may be space to have a side loading assemble similar to that pictured. This could cause increased leakage of radiation down the port which the transport vessel is attached to. As shown in figure 42, an additional KF50 to KF50 nipple will be needed to span the extra distance of the lead shielding. One advantage of this approach is a DC motor can be used to open and close the gate valve on the transport vessel as it would now be shielded from the worst of the radiation.

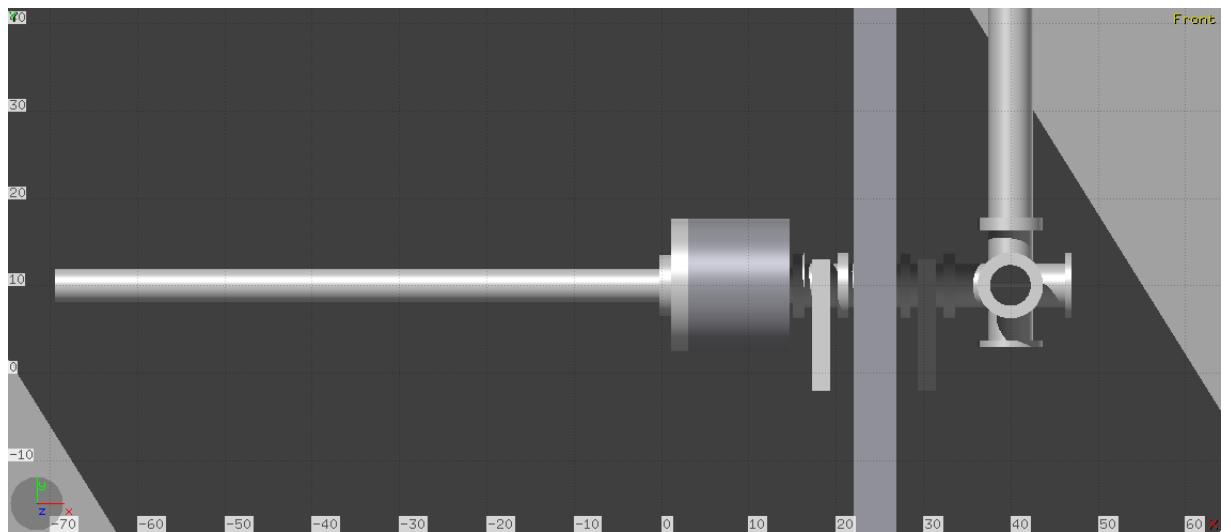


Figure 43: A 3D model of the alternative system

Figure 45 is a CAD drawing of the parts needed for the bottom mounted system. The side mounted system would need an additional KF50 to KF50 nipple.

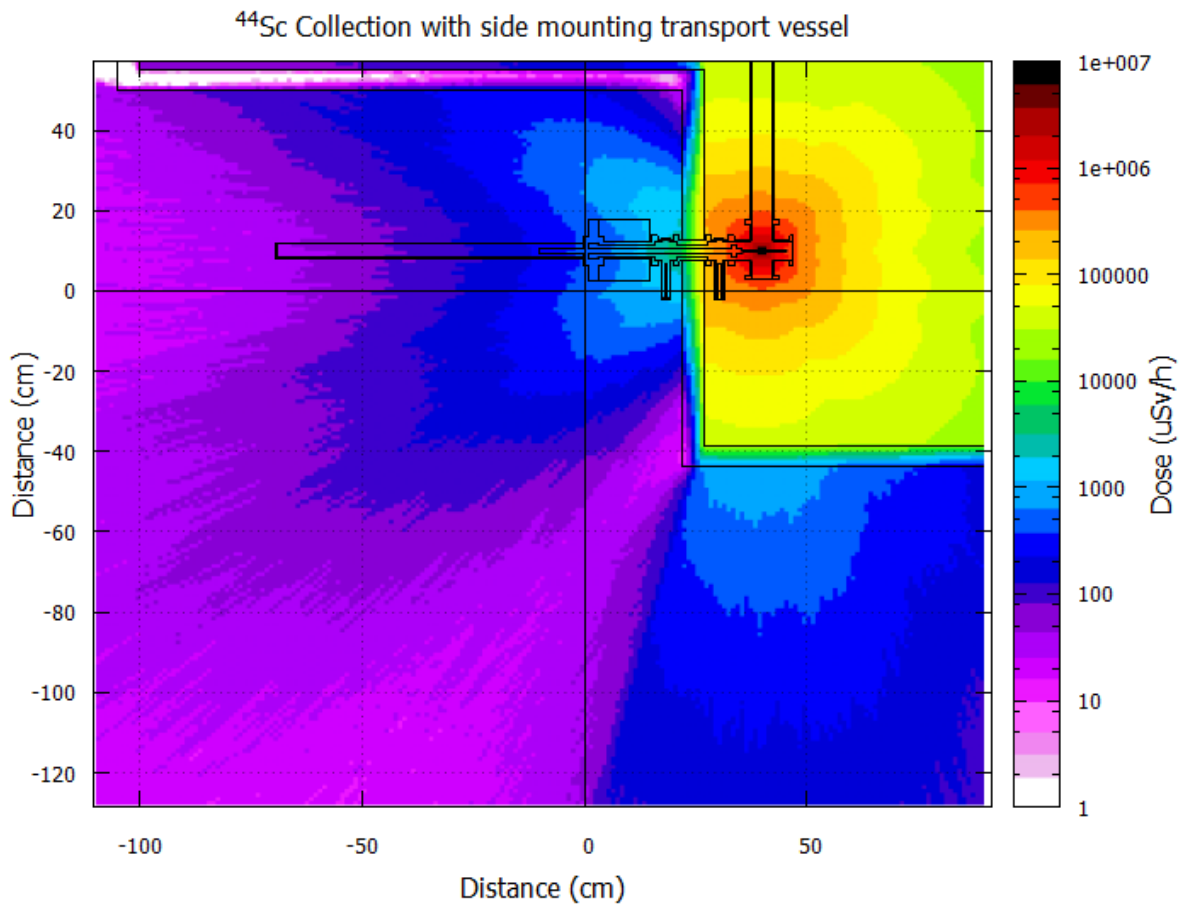


Figure 44: A dose map during collection in the alternative system. see example code 3 in appendix

4 Recommended design and Costing

Space and switchyard permitting I would recommend a side mounted system. Overall it should be a cheaper option as it allows the use of a standard gate valve for the transport vessel and a robotic arm will not be needed. It also means that a person will not be exposed to the dose from the other collection chambers and the switchyard as they would be whilst the door was opened during moving the transport vessel. 5cm is adequate for even the worst isotope ^{44}Sc and there is room to increase shielding by changing the insert to Tungsten or increasing the amount of Lead shielding - since it only weighs 17.43Kg.

6-way KF50 cross	QF50-200-6X	£345.60
Pneumatic SS Gate Valve	SG0200PVQF	£1,448.00
Manual SS Gate Valve	SG0200MVQF	£1,285.00
Custom nipple KF50 to CF40 120mm long	RN-Q4C31A-120	£120.10
Reducer Flange CF40 to CF100	RF600X275	£85.00
		£3283.70

Rotary Vane Pump (4 X 10^{-4} mbar)	KJLC-RV212SSH	£1,668.00
Standard TMP TurboVac	LH-85400	£2,958.00
Additional 70mm KF50 nipple for side mounted	FN-Q44-70	£118.30

Table 2: Parts required for the model with the model numbers and prices from Kurt J. Lesker

The turbo molecular pump is the single biggest cost of £2,958.00. A decision will have to be made as to whether the additional quality of vacuum is worth this additional cost to the 4×10^{-4} mbar backing pump.

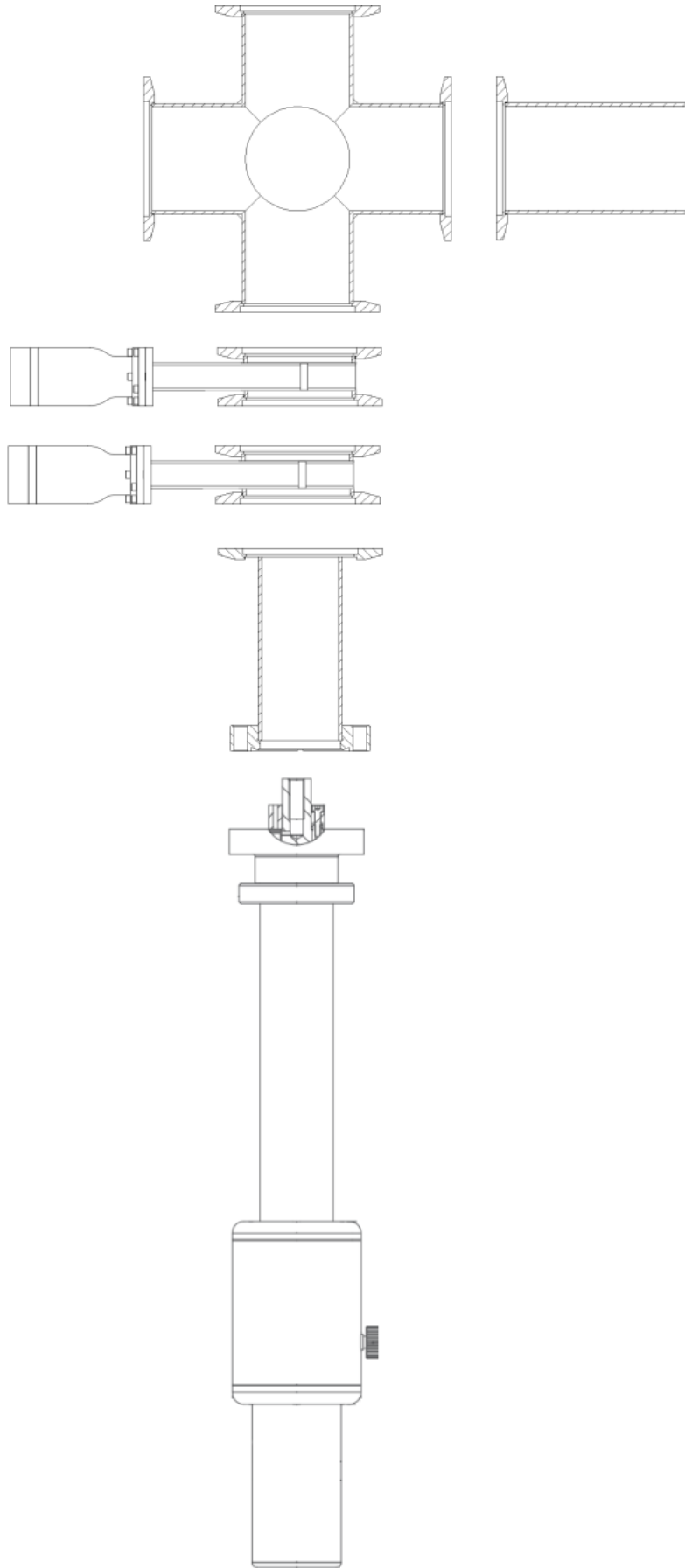


Figure 45: Final Design CAD drawing using part DXF files from Kurt J. Lesker

4.1 Recommendations for future work

- Include dose from isotopes dumped in the switchyard
- Calculate the amount of the isotopes likely to be implanted on the sample
- Liaise with MEDICIS users to ascertain their requirements for transport
- Incorporate the dose levels into RP data on doses from other sources

Appendix

Definition of Heavy Concrete courtesy of CERN's RP department

FLUKA^{[3][4]} simulations were used to find the optimal shielding configuration.

One of the basic conditions to obtain a valid result is to reproduce as exactly as possible the composition of the shielding materials:

Table 3–Mass Composition (fraction)

	Normal Concrete (2.35 g/cm ³)	Heavy (Magnetite) Concrete ^{*[5]} (3.9 g/cm ³)	Magnetite Bricks ^[6] (3.7 g/cm ³)	Cast Iron (7.2 g/cm ³)	Barite Concrete (3.5 g/cm ³)
H	0.01	0.002	0.002	-	0.0034
C	0.001	-	-	0.11	-
K	0.013	-	0.001	-	0.0454
O	0.529107	0.307	0.307	-	0.298
Na	0.016	0.001	0.001	-	-
Ca	0.044	0.004	0.004	-	0.048
Mg	0.002	0.001	0.001	-	0.0011
Fe	0.014	0.65	0.65	0.89	-
Si	0.337021	0.029	0.028	-	0.01
Ba	-	-	-	-	0.4871
Al	0.0338872	0.003	0.003	-	0.004
P	-	0.003	0.003	-	-
S	-	-	-	-	0.103

**Magnetite formula is Fe₃O₄. However, mixed with concrete it acquires different elements in its composition. The raw magnetite, in spite of having only oxygen and iron, was implemented in FLUKA with the same composition as Heavy (magnetite) Concrete, we believe this would be a slightly conservative approach. Despite that the nominal density of pure magnetite is higher than its heavy concrete form, the existence of interstices between the magnetite grains in the raw form, particularly the larger ones, decreases significantly raw magnetite's density. We measured some samples and concluded raw magnetite density was 3.0 g/cm³, this value was then used for raw magnetite in our simulations.*

Model codes FLUKA

Example Code 1

```

TITLE
test of a simple chamber
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7...
* Set the defaults for precision simulations
DEFAULTS
PRECISIO
BEAM          0.0
ISOTOPE
BEAMPOS       0.0      0.0      0.1      0.0      0.0      0.0
BEAMPOS       0.0      1.0      0.0      0.2      0.0
O.CYLI-VOL
HI-PROPE      21.0      44.0
GEOBEGIN
COMBNAME
  0      0
* Black body
SPH blkboddy  00.0 0.0 0.0 91.0
* Void sphere
SPH void      0.0 0.0 0.0 90.0
SPH spherei   0.0 0.0 0.0 19.

```

```

SPH sphereo      0.0 0.0 0.0 20.
RCC port1o      -25.0 0.0 0.0 50.0 0.0 0.0 10.
RCC port1i      -24. 0.0 0.0 48. 0.0 0.0 9.
RCC port2o      0.0 -25.0 0.0 0.0 50.0 0.0 10.
RCC port2i      0.0 -24. 0.0 0.0 48. 0.0 9.
RCC port3o      0.0 0.0 -25.0 0.0 0.0 50.0 10.
RCC port3i      0.0 0.0 -24.0 0.0 0.0 48. 9.
SPH shieldo     0.0 0.0 0.0 35.
SPH shieldi     0.0 0.0 0.0 30.
END
* Black hole
BLKBODY      5 +blkbody -void
chamber      5 +sphereo -spherei -port1o -port2o -port3o
port1        5 +port1o -port1i -spherei
port2        5 +port2o -port2i -spherei
port3        5 +port3o -port3i -spherei
AIR          5 +shieldi -port1o -port2o -port3o -sphereo
AIR1         5 +void -shieldo
port1v       5 -spherei +port1i
port2v       5 -spherei +port2i
port3v       5 -spherei +port3i
Vacuum       5 +spherei
shield       5 +shieldo -shieldi
END
GEOEND
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
ASSIGNMA      BLCKHOLE      BLKBODY
MATERIAL              7.82
COMPOUND      0.977169      IRON      0.022831      CARBON      STEEL
ASSIGNMA      TUNGSTEN      port1
ASSIGNMA      TUNGSTEN      port2
ASSIGNMA      TUNGSTEN      chamber
ASSIGNMA      TUNGSTEN      port3
ASSIGNMA      AIR          AIR
ASSIGNMA      AIR          AIR1
ASSIGNMA      VACUUM      Vacuum
ASSIGNMA      VACUUM      port1v
ASSIGNMA      VACUUM      port2v
ASSIGNMA      VACUUM      port3v
ASSIGNMA      LEAD        shield
RADDECAY      2.          0.0          0
DCYSCORE      -1.          Dose          Dose
USRBIN
USRBIN      10.      DOSE=EQ      -21.      60.      60.      60.Dose
USRBIN      -60.      -60.      -60.      60.      60.      60. &
AUXSCORE      USRBIN      ALL=PART      Dose          Dose
* Set the random number seed
RANDOMIZ      1.      10.
* Set the number of primary histories to be simulated in the run
START      1.0E6      0.0
STOP

```

Example Code 2

```

TITLE
Final design of the three chambers Lu177 collection middle chamber
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
* Set the defaults for precision simulations
DEFAULTS
PRECISIO
BEAM          0.0
ISOTOPE
BEAMPOS      110.711      39.289      110.      0.0      0.0      0.0
BEAMPOS      0.0          1.0          0.0          0.2          0.0
0.0CYLI=VOL
HI=PROPE      71.0      177.0
GEOBEGIN
COMBNAME
0      0
RPP blkbody   -365. 897. -202. 545.5 -22. 340.
RPP air       -364. 309. -165.5 165.5 0. 325.
RPP air6      309. 896. -165.5 504.5 0. 325.
RPP floor2    309. 896. -165.5 504.5 -20. 0.
RPP air4      0.0 309. 165.5 409.5 0. 325.
RPP floor1    0.0 309. 165.5 409.5 -20. 0.0
RPP ceiling1  0.0 309. 165.5 409.5 325. 339.
* Shield
RPP shieldo   -125. 203.48 -53.48 165.5 0.0 155.

```

```

RPP shiieldi      -120. 198.48 -48.48 160.5 0.0 150.
PLA diagi         -1. 1. 0.0 155.603 -5.603 0.0
PLA diago         -1. 1. 0.0 159.143 -9.143 0.0
PLA diag2o        1. 1. 0.0 0.0 -53.48 0.0
PLA diag2i        1. 1. 0.0 3.54 -49.94 0.0
* Building
RPP owall         -364. 896. -195.5 -165.5 -20. 339.
RPP floor         -364. 309. -165.5 165.5 -20. 0.
RPP ceiling       -364. 309. -165.5 165.5 325. 339.
RPP sdoor         -364. 0. 165.5 205.5 0. 339.
RPP bwall         -65. 0. 205.5 484.5 -20. 339.
RPP hcell         0. 309. 409.5 484.5 -20. 339.
RPP swall         234. 896. 484.5 544.5 -20. 339.
*
* Chamber 1
SPH air1          40.0 10.0 110.0 22.
SPH c1sphi        40.0 10.0 110.0 7.185
SPH c1spho        40.0 10.0 110.0 7.39
RCC c1p1o         26.52 10.0 110.0 26.96 0.0 0.0 5.080
RCC c1p1i         26.52 10.0 110.0 26.96 0.0 0.0 4.87
RCC c1p2o         40.0 -3.48 110.0 0.0 26.96 0.0 5.080
RCC c1p2i         40.0 -3.48 110.0 0.0 26.96 0.0 4.87
RCC c1p3o         40.0 10.0 96.52 0.0 0.0 26.96 5.080
RCC c1p3i         40.0 10.0 96.52 0.0 0.0 26.96 4.87
* CF100 ports
RCC c1p1p         26.02 10.0 110.0 2.63 0.0 0.0 7.58
RCC c1p1p1        51.35 10.0 110.0 2.63 0.0 0.0 7.58
RCC c1p2p         40.0 -3.98 110.0 0.0 2.63 0.0 7.58
RCC c1p2p1        40.0 21.35 110.0 0.0 2.13 0.0 7.58
RCC c1p3p         40.0 10.0 96.02 0.0 0.0 2.63 7.58
RCC c1p3p1        40.0 10.0 121.35 0.0 0.0 2.63 7.58
*
* Chamber 2
SPH air2          110.711 39.289 110.0 22.
SPH c2sphi        110.711 39.289 110.0 7.185
SPH c2spho        110.711 39.289 110.0 7.39
RCC c2p1o         101.179 29.757 110.0 19.064 19.064 0.0 5.080
RCC c2p1i         101.179 29.757 110.0 19.064 19.064 0.0 4.87
RCC c2p2o         120.243 29.757 110.0 -19.064 19.064 0.0 5.080
RCC c2p2i         120.243 29.757 110.0 -19.064 19.064 0.0 4.87
RCC c2p3o         110.711 39.289 96.52 0.0 0.0 26.96 5.080
RCC c2p3i         110.711 39.289 96.52 0.0 0.0 26.96 4.87
* CF100 ports
RCC c2p1p         100.829 29.407 110.0 1.86 1.86 0.0 7.58
RCC c2p2p         120.593 29.407 110.0 -1.86 1.86 0.0 7.58
RCC c2p3p         110.711 39.289 96.02 0.0 0.0 2.63 7.58
RCC c2p1p1        118.733 47.311 110.0 1.86 1.86 0.0 7.58
RCC c2p2p1        102.689 47.311 110.0 -1.51 1.51 0.0 7.58
RCC c2p3p1        110.711 39.289 121.97 0.0 0.0 2.63 7.58
*
* Chamber 3
SPH air3          140.0 110.0 110.0 22.
SPH c3sphi        140.0 110.0 110.0 7.185
SPH c3spho        140.0 110.0 110.0 7.39
RCC c3p1o         126.52 110.0 110.0 26.96 0.0 0.0 5.080
RCC c3p1i         126.52 110.0 110.0 26.96 0.0 0.0 4.87
RCC c3p2o         140.0 96.52 110.0 0.0 26.96 0.0 5.080
RCC c3p2i         140.0 96.52 110.0 0.0 26.96 0.0 4.87
RCC c3p3o         140.0 110.0 96.52 0.0 0.0 26.96 5.080
RCC c3p3i         140.0 110.0 96.52 0.0 0.0 26.96 4.87
* CF100 ports
RCC c3p1p         126.52 110.0 110.0 2.13 0.0 0.0 7.58
RCC c3p2p         140.0 96.02 110.0 0.0 2.63 0.0 7.58
RCC c3p3p         140.0 110.0 96.02 0.0 0.0 2.63 7.58
RCC c3p1p1        151.35 110.0 110.0 2.63 0.0 0.0 7.58
RCC c3p2p1        140.0 121.35 110.0 0.0 2.63 0.0 7.58
RCC c3p3p1        140.0 110.0 121.35 0.0 0.0 2.63 7.58
*
* Switchyard
RCC c1beo         40.0 23.48 110.0 0.0 86.52 0.0 5.080
RCC c1bei         40.0 23.48 110.0 0.0 86.52 0.0 4.87
RCC c2beo         101.179 48.821 110.0 -66.26 66.26 0.0 5.080
RCC c2bei         101.179 48.821 110.0 -66.26 66.26 0.0 4.87
RCC c3beo         126.52 110.0 110.0 -86.52 0.0 0.0 5.080
RCC c3bei         126.52 110.0 110.0 -86.52 0.0 0.0 4.87
* CF100 ports
RCC c1bep         40.0 23.48 110.0 0.0 2.13 0.0 7.58
RCC c2bep         101.179 48.821 110.0 -1.51 1.51 0.0 7.58
RCC c3bep         126.52 110.0 110.0 -2.13 0.0 0.0 7.58

```

```

END
* Black hole
BLKBODY      5 +blkbody -air -owall -floor -sdoor -air4
-hcell -bwall -ceiling -ceiling1 -floor1 -air6 -swall
              -floor2
owall        5 +owall
floor        5 +floor
floor1       5 +floor1
floor2       5 +floor2
ceiling      5 +ceiling
ceiling1     5 +ceiling1
sdoor        5 +sdoor
bwall        5 +bwall
hcell        5 +hcell
swall        5 +swall -air6
air4         5 +air4
c1           5 +c1spho -c1sphi -c1p1o -c1p2o -c1p3o
c1p1         5 +c1p1o -c1p1i -c1sphi
c1p2         5 +c1p2o -c1p2i -c1sphi
c1p3         5 +c1p3o -c1p3i -c1sphi
c1p1p        5 +c1p1p -c1p1o
c1p1p1       5 +c1p1p1 -c1p1o
c1p2p        5 +c1p2p -c1p2o
c1p2p1       5 +c1p2p1 -c1p2o
c1p3p        5 +c1p3p -c1p3o
c1p3p1       5 +c1p3p1 -c1p3o
c2           5 +c2spho -c2sphi -c2p1o -c2p2o -c2p3o
c2p1         5 +c2p1o -c2p1i -c2sphi
c2p2         5 +c2p2o -c2p2i -c2sphi
c2p3         5 +c2p3o -c2p3i -c2sphi
c2p1p        5 +c2p1p -c2p1o
c2p1p1       5 +c2p1p1 -c2p1o
c2p2p        5 +c2p2p -c2p2o
c2p2p1       5 +c2p2p1 -c2p2o
c2p3p        5 +c2p3p -c2p3o
c2p3p1       5 +c2p3p1 -c2p3o
c3           5 +c3spho -c3sphi -c3p1o -c3p2o -c3p3o
c3p1         5 +c3p1o -c3p1i -c3sphi
c3p2         5 +c3p2o -c3p2i -c3sphi
c3p3         5 +c3p3o -c3p3i -c3sphi
c3p1p        5 +c3p1p -c3p1o
c3p1p1       5 +c3p1p1 -c3p1o
c3p2p        5 +c3p2p -c3p2o
c3p2p1       5 +c3p2p1 -c3p2o
c3p3p        5 +c3p3p -c3p3o
c3p3p1       5 +c3p3p1 -c3p3o
AIR          5 +air -air1 -air2 -air3 -shieldo
AIR1         5 +shieldo +diag2o
AIR2         5 +shieldo +diago
air1
5 +air1 -c1spho -c1p1o -c1p2o -c1p3o -c1p1p -c1p1p1 -c1p2p -c1p2p1 -c1p3p -c1p3p1 -c1p3
air2
5 +air2 -c2spho -c2p1o -c2p2o -c2p3o -c2p1p -c2p1p1 -c2p2p -c2p2p1 -c2p3p -c2p3p1 -c2p3
air3
5 +air3 -c3spho -c3p1o -c3p2o -c3p3o -c3p1p -c3p1p1 -c3p2p -c3p2p1 -c3p3p -c3p3p1 -c3p3
c1p1v        5 -c1sphi +c1p1i
c1p2v        5 -c1sphi +c1p2i
c1p3v        5 -c1sphi +c1p3i
c2p1v        5 -c2sphi +c2p1i
c2p2v        5 -c2sphi +c2p2i
c2p3v        5 -c2sphi +c2p3i
c3p1v        5 -c3sphi +c3p1i
c3p2v        5 -c3sphi +c3p2i
c3p3v        5 -c3sphi +c3p3i
Vacuum        5 +c1sphi
Vacuum1       5 +c2sphi
Vacuum2       5 +c3sphi
Vacuum3       5 +c1bei -c2bei
Vacuum4       5 +c2bei
Vacuum5       5 +c3bei -c2bei
c1be         5 +c1beo -c1bei -c2bei
c2be         5 +c2beo -c2bei -c1beo -c3beo
c3be         5 +c3beo -c3bei -c2bei
c1bep        5 +c1bep -c1beo

```

```

c2bep      5 +c2bep -c2beo
c3bep      5 +c3bep -c3beo
shield     5 +shieldo -shieldi -diagi -diag2i
shield1    5 -diago +diagi +shieldo
shield2    5 -diag2o +diag2i +shieldo
air5
5 +shieldi -air1 -air2 -air3 -diagi -diag2i -c1beo -c2beo -c3beo
air6      5 +air6
END
GEOEND
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
ASSIGNMA   BLCKHOLE   BLKBODY
MATERIAL                                8.00                                STEEL
COMPOUND    0.977169      IRON   0.022831      CARBON                                STEEL
MATERIAL                                2.30
CONCRETE
COMPOUND    0.168038  HYDROGEN  0.563183      OXYGEN   0.021365
SODIUMCONCRETE
COMPOUND    0.021365  ALUMINUM  0.203231      SILICON  0.018595
CALCIUMCONCRETE
COMPOUND    0.004246      IRON
CONCRETE
MATERIAL                                3.9
HEAVYCON
COMPOUND    -0.002  HYDROGEN   -0.31      OXYGEN   -0.001
SODIUMHEAVYCON
COMPOUND    -0.003  ALUMINUM   -0.029     SILICON  -0.004
CALCIUMHEAVYCON
COMPOUND    -0.65      IRON   -0.001  MAGNESIU
HEAVYCON
ASSIGNMA   STEEL      c1
ASSIGNMA   STEEL      c1p1p
ASSIGNMA   STEEL      c1p1p1
ASSIGNMA   STEEL      c1p2p
ASSIGNMA   STEEL      c1p2p1
ASSIGNMA   STEEL      c1p3p
ASSIGNMA   STEEL      c1p3p1
ASSIGNMA   STEEL      c1p1
ASSIGNMA   STEEL      c1p2
ASSIGNMA   STEEL      c1p3
ASSIGNMA   STEEL      c2
ASSIGNMA   STEEL      c2p1p
ASSIGNMA   STEEL      c2p1p1
ASSIGNMA   STEEL      c2p2p
ASSIGNMA   STEEL      c2p2p1
ASSIGNMA   STEEL      c2p3p
ASSIGNMA   STEEL      c2p3p1
ASSIGNMA   STEEL      c2p1
ASSIGNMA   STEEL      c2p2
ASSIGNMA   STEEL      c2p3
ASSIGNMA   STEEL      c3
ASSIGNMA   STEEL      c3p1p
ASSIGNMA   STEEL      c3p1p1
ASSIGNMA   STEEL      c3p2p
ASSIGNMA   STEEL      c3p2p1
ASSIGNMA   STEEL      c3p3p
ASSIGNMA   STEEL      c3p3p1
ASSIGNMA   STEEL      c3p1
ASSIGNMA   STEEL      c3p2
ASSIGNMA   STEEL      c3p3
ASSIGNMA   STEEL      c1be
ASSIGNMA   STEEL      c2be
ASSIGNMA   STEEL      c3be
ASSIGNMA   STEEL      c1bep
ASSIGNMA   STEEL      c2bep
ASSIGNMA   STEEL      c3bep
ASSIGNMA   AIR        AIR
ASSIGNMA   AIR        AIR1
ASSIGNMA   AIR        AIR2
ASSIGNMA   AIR        air4
ASSIGNMA   AIR        air1
ASSIGNMA   AIR        air2
ASSIGNMA   AIR        air3
ASSIGNMA   AIR        air5
ASSIGNMA   AIR        air6
ASSIGNMA   VACUUM     Vacuum
ASSIGNMA   VACUUM     Vacuum1
ASSIGNMA   VACUUM     Vacuum2
ASSIGNMA   VACUUM     Vacuum3
ASSIGNMA   VACUUM     Vacuum4
ASSIGNMA   VACUUM     Vacuum5
ASSIGNMA   VACUUM     c1p1v

```



```

ASSIGNMA      VACUUM      c1p2v
ASSIGNMA      VACUUM      c1p3v
ASSIGNMA      VACUUM      c2p1v
ASSIGNMA      VACUUM      c2p2v
ASSIGNMA      VACUUM      c2p3v
ASSIGNMA      VACUUM      c3p1v
ASSIGNMA      VACUUM      c3p2v
ASSIGNMA      VACUUM      c3p3v
ASSIGNMA      LEAD        shield
ASSIGNMA      LEAD        shield1
ASSIGNMA      LEAD        shield2
ASSIGNMA      CONCRETE     owall
ASSIGNMA      CONCRETE     floor
ASSIGNMA      CONCRETE     floor2
ASSIGNMA      CONCRETE     ceiling
ASSIGNMA      CONCRETE     ceiling1
ASSIGNMA      CONCRETE     floor1
ASSIGNMA      HEAVYCON     hcell
ASSIGNMA      HEAVYCON     swall
ASSIGNMA      HEAVYCON     bwall
ASSIGNMA      STEEL        sdoor
RADDECAY      2.          0.0          0
DCYSCORE      -1.          Dose          Dose
USRBIN
USRBIN      10.      DOSE=EQ      -21.      895.      520.      200.Dose
USRBIN      -364.      -170.      0.      630.      345.      100. &
AUXSCORE      USRBIN      ALL=PART      Dose      Dose
* Set the random number seed
RANDOMIZ      1.      10.
* Set the number of primary histories to be simulated in the run
START      5.0E6      0.0
STOP

```

Example Code 3

```

TITLE
Final design of the transport vessel insitu 5cm of lead
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
* Set the defaults for precision simulations
DEFAULTS
PRECISIO
BEAM      0.0
ISOTOPE
BEAMPOS      40.      10.      110.      0.0      0.0      0.0
BEAMPOS      0.0      0.5      0.0      0.1      0.0
0.0CYLI=VOL
HI=PROPE      21.0      44.0
GEOBEGIN
COMBNAME
0      0
RPP blkbody      -135. 210. -202. 186.0 -22. 340.
RPP air      -134. 209. -165.5 165.5 0. 325.
RPP air4      0.0 209. 165.5 185.5 0.0 325.
RPP floor1      0.0 209. 165.5 185.5 -20. 0.0
RPP ceiling1      0.0 209. 165.5 185.5 325. 339.
* Shield
RPP shieldo      22. 203.48 -43.48 165.5 0.0 155.
RPP shieldi      27. 198.48 -38.48 160.5 0.0 150.
RPP shield2o      -105. 22. 50. 165.5 0.0 155.
RPP shield2i      -100. 27. 55. 160.5 0.0 150.
PLA diagi      -1. 1. 0.0 155.603 -5.603 0.0
PLA diago      -1. 1. 0.0 159.143 -9.143 0.0
* Building
RPP owall      -134. 209. -195.5 -165.5 -20. 339.
RPP floor      -134. 209. -165.5 165.5 -20. 0.
RPP ceiling      -134. 209. -165.5 165.5 325. 339.
RPP sdoor      -134. 0. 165.5 185.5 0. 339.
*
* Chamber 1
RPP air1      32.99 47.01 2.99 17.71 102.99 117.01
SPH c1sphi      40.0 10.0 110.0 3.595
SPH c1spho      40.0 10.0 110.0 3.8
RCC c1plo      32.99 10.0 110.0 14.02 0.0 0.0 2.54
RCC c1pii      32.99 10.0 110.0 14.02 0.0 0.0 2.33
RCC c1p2o      40.0 2.99 110.0 0.0 14.02 0.0 2.54
RCC c1p2i      40.0 2.99 110.0 0.0 14.02 0.0 2.33
RCC c1p3o      40.0 10.0 102.99 0.0 0.0 14.02 2.54
RCC c1p3i      40.0 10.0 102.99 0.0 0.0 14.02 2.33
* KF50 ports
RCC c1p1p      32.99 10.0 110.0 0.7 0.0 0.0 3.75

```

```

RCC c1p1p1      46.31 10.0 110.0 0.7 0.0 0.0 3.75
RCC c1p2p      40.0 2.99 110.0 0.0 0.7 0.0 3.75
RCC c1p2p1     40.0 16.31 110.0 0.0 0.7 0.0 3.75
RCC c1p3p      40.0 10.0 102.99 0.0 0.0 0.7 3.75
RCC c1p3p1     40.0 10.0 116.31 0.0 0.0 0.7 3.75
* Switchyard
RCC c1beo      40.0 17.01 110.0 0.0 86.52 0.0 2.54
RCC c1bei      40.0 17.01 110.0 0.0 86.52 0.0 2.33
* KF50 ports
RCC c1bep      40.0 17.01 110.0 0.0 0.7 0.0 3.75
*
* Transport vessel
RPP airg       27.00 32.99 -2.025 17.71 102.99 117.01
RPP airt       -100. 22.0 -10. 30. 0.0 130.
* gate valve
RCC gateo      32.99 10. 110. -5.1 0.0 0.0 3.75
RCC gatei      32.99 10. 110. -5.1 0.0 0.0 2.33
RCC gateai     32.29 10. 110. -3.7 0.0 0.0 2.54
RCC gateao     32.29 10. 110. -3.7 0.0 0.0 3.75
RPP gmoto      29.44 31.44 -2.025 13.00 104.77 115.23
RPP gmoti      29.64 31.24 -1.825 12.54 104.97 115.03
RPP valve      30.14 30.74 -1.825 6.89 104.97 115.03
* Shield tube
RCC adapt50    27.89 10. 110. -0.51 0.0 0.0 3.75
RCC adapto     27.89 10. 110. -7.0 0.0 0.0 2.54
RCC adapti     27.89 10. 110. -7.0 0.0 0.0 2.33
RCC adapt1     21.40 10. 110. -0.51 0.0 0.0 3.75
* gate valve 2
RCC gate1o     20.89 10. 110. -5.1 0.0 0.0 3.75
RCC gate1i     20.89 10. 110. -5.1 0.0 0.0 2.33
RCC gate1ai    20.19 10. 110. -3.7 0.0 0.0 2.54
RCC gate1ao    20.19 10. 110. -3.7 0.0 0.0 3.75
RPP gmot1o     17.34 19.34 -2.025 13.00 104.77 115.23
RPP gmot1i     17.54 19.14 -1.825 12.54 104.97 115.03
RPP valve1     18.04 18.64 -1.825 6.89 104.97 115.03
* vessel
RCC tranp1     15.79 10.0 110. -0.7 0.0 0.0 3.75
RCC tranp2     4.36 10.0 110. -1.27 0.0 0.0 3.45
RCC trano      15.79 10.0 110. -12.7 0.0 0.0 2.06
RCC trani      15.79 10.0 110. -12.7 0.0 0.0 1.85
* manipulator
RCC manpo      1.09 10.0 110. -1.27 0.0 0.0 3.45
RCC mrod       -10.09 10.0 110. 45.7 0.0 0.0 0.75
RCC mtip       34.29 10.0 110. -1.2 0.0 0.0 1.45
RCC manho      -0.18 10.0 110. -69.2 0.0 0.0 1.91
RCC manhi      -0.18 10.0 110. -69. 0.0 0.0 1.71
RPP holder     35.61 45.61 9.85 10.15 109. 111.
RCC sbottomo   3.09 10.0 110. -2.0 0.0 0.0 7.58
RCC sbottomi   3.09 10.0 110. -2.0 0.0 0.0 2.00
* steel shielding
RCC sshieldi   3.09 10.0 110. 12.7 0.0 0.0 1.45
RCC sshieldo   3.09 10.0 110. 12.7 0.0 0.0 1.85
* lead shielding
RCC PbCasei    3.09 10.0 110. 11.57 0.0 0.0 2.06
RCC PbCaseo    3.09 10.0 110. 11.57 0.0 0.0 7.58
END
* Black hole
BLKBODY
5 +blkbody -air -owall -floor -sdoor -air4 -ceiling -ceiling1 -floor1
owall          5 +owall
floor          5 +floor
floor1         5 +floor1
ceiling        5 +ceiling
ceiling1       5 +ceiling1
sdoor          5 +sdoor
air4           5 +air4
c1             5 +c1spho -c1sphi -c1p1o -c1p2o -c1p3o
c1p1           5 +c1p1o -c1p1i -c1sphi
c1p2           5 +c1p2o -c1p2i -c1sphi
c1p3           5 +c1p3o -c1p3i -c1sphi
c1p1p          5 +c1p1p -c1p1o
c1p1p1         5 +c1p1p1 -c1p1o
c1p2p          5 +c1p2p -c1p2o
c1p2p1         5 +c1p2p1 -c1p2o
c1p3p          5 +c1p3p -c1p3o
c1p3p1         5 +c1p3p1 -c1p3o

```

```

AIR          5 +air -shieldo -shield2o -airt
AIR1         5 +shield2i
AIR2         5 +shieldo +diago
air1
5 +air1 -c1sp1o -c1p1o -c1p2o -c1p3o -c1p1p -c1p1p1 -c1p2p -c1p2p1 -c1p3p -c1p3p1 -c1p3p1
c1p1v        5 -c1sp1i +c1p1i -holder -mrod -mtip
c1p2v        5 -c1sp1i +c1p2i
c1p3v        5 -c1sp1i +c1p3i
Vacuum       5 +c1sp1i -holder
Vacuum3      5 +c1bei -holder
c1be         5 +c1beo -c1bei
c1bep        5 +c1bep -c1beo
shield       5 +shieldo -shieldi -diagi -adapto -shield2i
shield1      5 -diago +diagi +shieldo
shield2      5 +shield2o -shield2i
air5         5 +shieldi -air1 -diagi -c1beo -airg
airt
5 +airt -tranp1 -tranp2 -trano -gate1o -gmot1o -manpo -manho -PbCaseo -sbottomo -adapto
airg         5 +airg -gateo -gmoto -adapt50 -adapto
tranp1       5 +tranp1 -trano
tranp2       5 +tranp2 -trano
manp         5 +manpo -mrod
trano        5 +trano -trani
tranV        5 +sshieldi -mrod -mtip -holder
gateV        5 +gatei -gmoti -mrod
gate1V       5 +gate1i -gmot1i -mrod
gateo        5 +gateo -gatei -gmoto -gateao
gate1o       5 +gate1o -gate1i -gmot1o -gate1ao
gmot         5 +gmoto -gmoti -gatei -mrod
gmotV        5 +gmoti -valve -mrod
gatea        5 +gateao -gateai -gmoto
gatec        5 +gateai -gatei -gmoto
valve        5 +valve
gmot1        5 +gmot1o -gmot1i -gate1i
gmot1V       5 +gmot1i -valve1 -mrod
gate1a       5 +gate1ao -gate1ai -gmot1o
gate1c       5 +gate1ai -gate1i -gmot1o
valve1       5 +valve1
mrod         5 +mrod
holder       5 +holder
mtip         5 +mtip -mrod
sbottom      5 +sbottomo -sbottomi
bottomV      5 +sbottomi -mrod
manV         5 +manhi -mrod
manh         5 +manho -manhi
sshield      5 +sshieldo -sshieldi
PbCase       5 +PbCaseo -PbCasei -manpo -tranp2
adapt        5 +adapto -adapti
adapt50      5 +adapt50 -adapto
adapt1       5 +adapt1 -adapto
adaptV       5 +adapti -mrod
END
GEOEND
* .+.+.+.1....+.+.2....+.+.3....+.+.4....+.+.5....+.+.6....+.+.7..
ASSIGNMA     BLCKHOLE     BLKBODY
MATERIAL
COMPOUND      0.977169      IRON      0.022831      CARBON
MATERIAL
CONCRETE
COMPOUND      0.168038      HYDROGEN  0.563183      OXYGEN  0.021365
SODIUMCONCRETE
COMPOUND      0.021365      ALUMINUM  0.203231      SILICON  0.018595
CALCIUMCONCRETE
COMPOUND      0.004246      IRON
CONCRETE
ASSIGNMA      STEEL      c1
ASSIGNMA      STEEL      c1p1p
ASSIGNMA      STEEL      c1p1p1
ASSIGNMA      STEEL      c1p2p
ASSIGNMA      STEEL      c1p2p1
ASSIGNMA      STEEL      c1p3p
ASSIGNMA      STEEL      c1p3p1
ASSIGNMA      STEEL      c1p1
ASSIGNMA      STEEL      c1p2
ASSIGNMA      STEEL      c1p3
ASSIGNMA      STEEL      c1be

```

ASSIGNMA	STEEL	c1bep				
ASSIGNMA	STEEL	manp				
ASSIGNMA	STEEL	gateo				
ASSIGNMA	STEEL	gate1o				
ASSIGNMA	STEEL	tranp1				
ASSIGNMA	STEEL	tranp2				
ASSIGNMA	STEEL	trano				
ASSIGNMA	STEEL	gmot				
ASSIGNMA	STEEL	valve				
ASSIGNMA	STEEL	gmot1				
ASSIGNMA	STEEL	gatec				
ASSIGNMA	STEEL	gate1c				
ASSIGNMA	STEEL	valve1				
ASSIGNMA	STEEL	mrod				
ASSIGNMA	STEEL	manh				
ASSIGNMA	STEEL	mtip				
ASSIGNMA	STEEL	holder				
ASSIGNMA	STEEL	sshield				
ASSIGNMA	STEEL	sbottom				
ASSIGNMA	STEEL	adapt				
ASSIGNMA	STEEL	adapt50				
ASSIGNMA	STEEL	adapt1				
ASSIGNMA	AIR	AIR				
ASSIGNMA	AIR	AIR1				
ASSIGNMA	AIR	AIR2				
ASSIGNMA	AIR	air4				
ASSIGNMA	AIR	air1				
ASSIGNMA	AIR	air5				
ASSIGNMA	AIR	airt				
ASSIGNMA	AIR	airg				
ASSIGNMA	AIR	gatea				
ASSIGNMA	AIR	gate1a				
ASSIGNMA	VACUUM	Vacuum				
ASSIGNMA	VACUUM	Vacuum3				
ASSIGNMA	VACUUM	c1p1v				
ASSIGNMA	VACUUM	c1p2v				
ASSIGNMA	VACUUM	c1p3v				
ASSIGNMA	VACUUM	gateV				
ASSIGNMA	VACUUM	gate1V				
ASSIGNMA	VACUUM	tranV				
ASSIGNMA	VACUUM	gmotV				
ASSIGNMA	VACUUM	gmot1V				
ASSIGNMA	VACUUM	manV				
ASSIGNMA	VACUUM	bottomV				
ASSIGNMA	VACUUM	adaptV				
ASSIGNMA	LEAD	shield				
ASSIGNMA	LEAD	shield1				
ASSIGNMA	LEAD	shield2				
ASSIGNMA	LEAD	PbCase				
ASSIGNMA	CONCRETE	owall				
ASSIGNMA	CONCRETE	floor				
ASSIGNMA	CONCRETE	ceiling				
ASSIGNMA	CONCRETE	ceiling1				
ASSIGNMA	CONCRETE	floor1				
ASSIGNMA	STEEL	sdoor				
RADDECAY	2.			0.0	0	
DCYSCORE	-1.			Dose	Dose	
USRBIN						
USRBIN	10.	DOSE-EQ	-21.	90.	100.	330.Dose
USRBIN	-110.	-170.	0.	200.	270.	330. &
AUXSCORE	USRBIN	ALL-PART		Dose	Dose	
* Set the random number seed						
RANDOMIZ	1.	10.				
* Set the number of primary histories to be simulated in the run						
START	5.0E6			0.0		
STOP						

Bibliography

- [1] Ricardo Manuel dos Santos Augusto, Leo Buehler, Zoe Lawson, Stefano Marzari, Monika Stachura, Thierry Stora, and CERN-MEDICIS collaboration. Cern-medicis (medical isotopes collected from isolde): A new facility. *Applied Sciences*, 4(2):265, 2014.
- [2] CERN beam Department. Isolde mandate. <https://espace.cern.ch/be-dep/OP/ISOLDE/default.aspx>.
- [3] Gabriela Bernal. History of pet scanners, 2014. Stanford University.
- [4] Alberto Fasso Alfredo Ferrari, Paola R. Sala and Johannes Ranft. *Fluka: a multi-particle transport code*. CERN, 2005.
- [5] A. Goehring-Crinon D. Perrin S. Roesler H. Vincke L. Ulrici D. Forkel-Wirth, P. Carbonez. Radiation protection aspects. Technical report, CERN, 2014.
- [6] The Swiss Federal Council. Radiological protection ordinance (rpo) of 22 march 1991. *Swiss Legislation*, 2014.
- [7] Vasilis Vlachoudis. Flair for fluka, 2005. in-built manual.
- [8] IAEA. Live chart of nuclides. 2012+ Atomic Mass Evaluation.
- [9] IAEA. Live chart of nuclides. ENSDF June 2015.
- [10] RT Pagh-RA Rucker RG Williams III RJ McConn Jr, CJ Gesh. Compendium of material composition data for radiation transport modeling. Technical report, Pacific Northwest National Laboratory, 2011.
- [11] NIST. <http://srdata.nist.gov/gateway/gateway?property=hardness>.
- [12] Kurt J. Lesker Company. Vacuum mart deviation, 2015. <http://www.lesker.com/newweb/vacumart.cfm>.
- [13] Office for National Statistics, 2010. <http://www.bbc.co.uk/news/uk-11534042>.
- [14] Florian Sommerer, Katia Parodi, Alfredo Ferrari, Karin Poljanc, Wolfgang Enghardt, and Hannes Aiginger. Investigating the accuracy of the fluka code for transport of therapeutic ion beams in matter. *Physics in medicine and biology*, 51(17):4385, 2006.
- [15] K. U. Snowden. Fatigue crack formation in bicrystals of lead. *Philosophical Magazine*, 1966.