

# Simulations on the new VITO line for ISOLDE

Alejandro Mora

Supervisors: Ronald García and Monika Stachura

August 9, 2014

## 1 Introduction

On July of 2013 a plan for upgrading the Ultra High Vacuum (UHV) beamline at ISOLDE/CERN, in order to conduct research in nuclear and solid state physics, was proposed. The new line, which would be called VITO (*Versatile Ion-polarized Techniques On-line*), is intended to start being constructed on August of 2014. As mentioned in [4], the major enhancement will be the use of laser-based spin polarisation of the isotope beam, allowing studies on  $\beta$ -NMR and beta-asymmetry. For a more detailed list of proposed experiments for this new line, the reader is referred to [4].

A diagram of the VITO line is presented in figure 1. Since the ions interact with each other through electromagnetic forces, the beam will spread as it travels through the line. Because of this, multiple electric quadrupoles have been implemented to focus it. These quadrupoles focus the beam in one axis, but defocus it on the perpendicular one. Because of this, quadrupoles doublets were implemented instead, where the focusing is done on the two axis perpendicular to the displacement direction, one after another. The line also possesses two switchyards where the beam is deflected horizontally, and two electrodes for bending the beam horizontally. All these devices are shown in detail in figure 2.

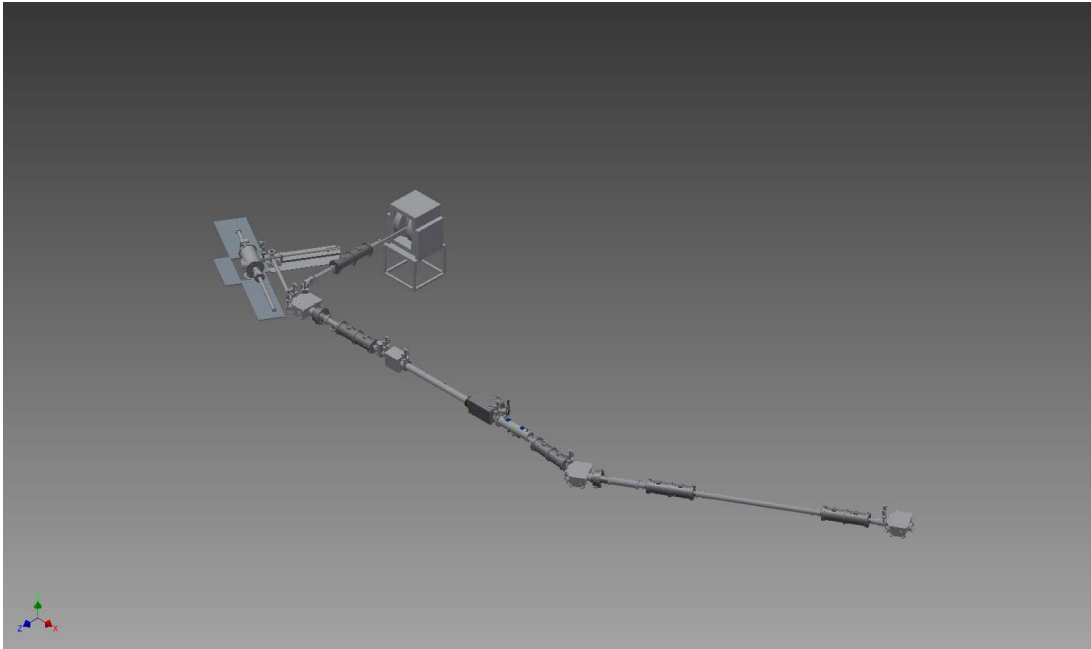


Figure 1: VITO Beamline

Because of the multiple deviations and bottlenecks the beam has to go through, it was necessary to estimate which configurations for the quadrupoles and the deflecting devices' voltages were the best suited for the functioning of the beamline. The UHV beamline had an efficiency of 17%, meaning that

from 100 ions at the beginning of the beamline, only 17 made it to the end. One of the objectives of the VITO line is to improve this fraction.

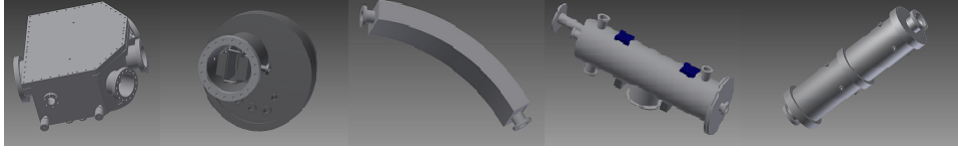


Figure 2: VITO Beamline devices. From left to right: switchyard, kicker, 55 degrees bending electrode, 5 degrees bending electrode and quadrupole doublet.

This report is intended to show, then, the results obtained from the simulation of the new beamline using the program SIMION on its 8.1 version (for the interested reader, documentation of the program can be found in [1]), and to offer a starting point for the tuning of the VITO line at ISOLDE's facilities.

## 2 Previous Work

Based on the description made by Alex Fragapane in [2], the geometry of the line was imported from an STL file to SIMION. Here we briefly list the steps followed in doing so:

1. *Simplify the Model*: delete all insulators and grounded pieces which will not affect notoriously the behaviour of the beam. This is in order to reduce the computation time consumed when importing the geometry and running the simulations.
2. *Separate Electrodes from Earth*: from the simplified geometry file construct two files: one with the electrodes, and one with all the parts which will be grounded. Save them as STL files. When exporting (preferentially from an STP file), the user will be asked to select the folder when he wants the new file to be saved. Here, before done, the user must select in the *Options* button to export the grounded parts as one file, and the electrodes as one file per part instance. This way, for each piece in the electrodes' file, an STL file will be generated, and the voltage of that piece can be manipulated independent of the others'.
3. *Rename the Pieces*: in order to have all the elements of the line together when importing them to SIMION, it is necessary to give the STL files the same name followed by a number which identifies each piece. Something as "piece(#)" —where "#" stands for the number which assigned to the piece— shall work. In order to rename the files in a fast way in Windows, the user can select all the STL files, press the *F2* key, and input the name he or she wants. The explorer will then assign each file a different number between round parenthesis.
4. *Import the STL files to SIMION*: in the principal window of SIMION, select *SL Tools* (short-cut key *T*) and then select *SL to PA* (*PA* stands for *Potential Array*, and is the file SIMION uses to solve the Laplace's Equation). Now, in the *input file* box, we write the path to any of the STL files created in the second step (they must, of course, be on the same directory). Instead of the number assigned to each file, we put the symbol "%", so SIMION runs over all the STL files with the same name. For example, if one of the user's files is named "piec-sim-(3).stl", use its path, but replace the number three with the symbol "%". So, if the path for the file is something as

C:\lines\test1\pec-sim-(3).stl

the appropriate path for SIMION is

C:\lines\test1\pec-sim-(%).stl

Now click on *Convert*. After the conversion is done, SIMION will show the complete geometry, with each electrode in a different color (if there are too many electrodes, some of the colors may be repeated).

5. *Refine the Array:* now that the geometry is in SIMION, it is time to solve de Laplace's Equation. For that, go back to the main window in SIMION and, in the PA box, load (fast key  $L$ ) the PA# file that was created in the last step. Now refine. Since this is a big geometry, the process takes around 3 hours to complete. Once this is done, the voltages of every piece of the electrodes and of the grounded elements will be modifiable.

During this process, it was necessary to rebuild the 55°bending electrode (upper right corner of figure 2) at the end of the line, since multiple pieces were needed to be at different potentials, and the original file was created as just one piece.

### 3 Simulations

The programs for the simulation were written in LUA, which is the language for which SIMION is optimized. For improving the simulations, a previous simple analysis was made. If the interaction between the ions is ignored, the focal length of a quadrupole for the focusing axis is given by the next expression (the interested reader can consult [3] for a more detailed description of the physics behind these equations):

$$f_F = \frac{1}{\sqrt{k} \sin(\sqrt{k}L)} \quad (1)$$

with

$$k = \frac{2|V|}{a^2} \frac{1}{E\rho} \quad (2)$$

where  $V$  is the voltage between the opposite plates,  $a$  is the radius of the quadrupole,  $L$  is its length, and  $E\rho$  is the electric rigidity of the beam's ions. The goal is to make the absolute value focal length as big as possible. This is achieved, according to equation (1), when argument of the sine function is an integer multiple of  $\pi$ . This is

$$\sqrt{k}L = n\pi \quad n = 1, 2, 3, 4 \dots \quad (3)$$

which in turns becomes a condition for the allowed voltages:

$$|V| = \frac{n^2\pi^2 a^2}{2L^2} E\rho \quad (4)$$

On the other side, for the defocusing axis the focal length is

$$f_D = -\frac{1}{\sqrt{k} \sinh(\sqrt{k}L)} \quad (5)$$

We want to make this focal length as big as possible as well. This is achieved when the argument of the hyperbolic sine is as small as possible. Keeping in mind the condition for the voltage stated in equation (4), the range of values for the testing may start near zero and go up to a value above that of equation (4) with  $n = 1$  (this is in order to account for the interaction between particles, which would require for a higher voltage than the ideal case). Taking Magnesium-31 as the sample, and with  $L = 0.3$  m,  $a = 0.0625$  m and with an average energy of 40 keV, the proper voltage for the quadrupole seems to be around 2558 volts. Voltages around half this value where found by Frapapane in [2], probably trying to minimize the defocusing effect of the device. For the switchyards and the bending electrode, assuming the particles travel at a speed of  $1.66 \times 10^{-3} c$  we have, using polar coordinates and Newton's second law:

$$V = \frac{w m v^2}{2Rq} = \frac{wT}{qR} \quad (6)$$

where  $w$  is the space between the electrode plates (30 mm for both),  $R$  is the radius of the arc subtended by the plates (around 600 mm for both as well),  $q$  is the charge and  $T$  is the kinetic energy of the particle (40 kev). This means that for both of them the same voltage will be needed, which is, according to equation (6),  $V = 2000$  volts.

Finally, before each switchyard we have what is known as a kicker. This is used to select the path the beam will follow. Under some approximations we obtain that the voltages on the two plates of the kicker from the next expression:

$$x = \frac{qV}{m\ell} \left( \frac{y_1}{v_0} \right)^2 + 2 \left( \frac{y_2 - y_1}{v_0} \right) \sqrt{\frac{qV}{m}} \quad (7)$$

Here  $x$  is the horizontal distance (in a upper-view plane) between the kicker and the switchyard,  $y_2$  is the vertical distance (along the beam path) between those two,  $y_1$  is the longitude of the kicker's plates,  $\ell$  the distance between the plates,  $v_0$  the original speed of the particle and  $m$  its mass. For the case given,  $y_1 \approx 110$  mm,  $y_2 \approx 425$  mm,  $x \approx 80$  mm and  $\ell \approx 40$  mm, so we get  $V \approx 1300$  V.

Given the size of the line, it is practically impossible to simulate it as a whole. Because of that, it was divided in three pieces, and the transmission rate was measured for each one, and then multiplied, obtaining then the total transmission rate for the line. Though this may obviate the effects that the voltages on one portion on the line can have in the electric field of other portion, these are reduced given the geometry and the fact that the external part of the line is grounded.

For the simulation, as stated before, magnesium-31 with an energy of 40 keV was chosen. Given the symmetry of the quadrupole doublet array, for the simulation the first quadrupole focuses in the  $x$  direction, and the second one in the  $y$  direction.

### 3.1 The Bending Devices

The bending devices correspond to the switchyards, the kickers and the two bending electrodes. For these, the simulation shows that the appropriate voltages are around those shown in table 1.

Part of the line	Device	Voltage [V]
1st	Kicker 1	1600
1st	Switchyard 1	1450
2nd	Bending Electrode 1	700
3rd	Kicker 2	1800
3rd	Switchyard 2	1385
3rd	Bending Electrode 2	1480

Table 1: Bending devices' voltages found in the simulation for magnesium-31 at 40 keV.

As it is seen, the estimation for the switchyards' voltages was close to the value obtained in the simulation, as was the estimation for the kicker's voltages. For the first bending electrode there was no prediction made, whereas for the second one we found previously a voltage similar to the switchyards. Notice, however, that for beams with another energy, the voltages will have to be readjusted (higher for more energetic beams, since the time spent inside the field decreases).

### 3.2 The Focusing Devices

Here we have five quadrupoles' doublets: three in the first part of the line, one in the second and one in the third. Whereas for the bending devices there was no need for considering the dispersion of the beam, this is not the case for the focusing devices. For simulating this phenomena in the most efficient way a cone direction distribution for velocities with a half angle of 0.12 degrees was chosen. This also takes into account the usual emittance of an ISOLDE beam. The best suited voltages and their transmission rates for each portion of the line are show in table 2. For the third part of the line, the transmission rate is the product between the transmission rate for the bending devices and the transmission rate for the final part of the line (from the last quadrupole to the  $\beta$ -NMR device). The programs used are shown in the appendix.

The final transmission rate is 34.07%, which is the double of what was found in 2012 with the UHV line. However, this value may be lower if we consider that, for the final portion of the third part of the line, we assumed that every particle that hit the final pipe—which has a hole of only 4 mm—in a point inside a circle of 2 mm radius would get through. This was done because the resolution of the simulation did not allow to take into account for this hole: The piece was completely solid, with no apertures.

Part No.	Device	Voltage [V]	Transmission rate
1st	Quad. 1	1200	78.2%
1st	Quad. 2	-1000	78.2%
1st	Quad. 3	1400	78.2%
1st	Quad. 4	-1600	78.2%
1st	Quad. 5	1800	78.2%
1st	Quad. 6	-1800	78.2%
2nd	Quad. 7	2000	69.4%
2nd	Quad. 8	-2000	69.4%
3rd	Quad. 9	1800	$70\% \times 89.7\% = 62.8\%^*$
3rd	Quad. 10	-1200	$70\% \times 89.7\% = 62.8\%^*$

Table 2: Quadrupoles' voltages found in the simulation for magnesium-31 at 40 keV. Total transmission rate: 34.07 %

## 4 What is Left to Do

1. The biggest simplification made in this simulation comes from the division of the line into three pieces, first because it ignores the interaction between the fields in different portions of the geometry, and second because it does not conserve the state of the beam at the end of one portion of the line, using as the input for one portion a beam which in most cases will be completely different to the beam that resulted from the previous simulation. Though simulating the full beamline as a whole requires a lot of computational power, it is possible to solve the second issue considering the emittance of the beams that reach the end of each portion of the line and using it as an input for the definition of the outgoing beams.
2. At the same time, since the ions in the line can have energies between 30 and 50 keV, calibration for other values must be done.
3. Finally, the effect of the vacuum tube decelerators was not taken into account (they were grounded during the simulation). Varying the voltages of these will probably spread the beam, so the voltages of the fifth quadrupole doublet would have to be readjusted.

## References

- [1] *SIMION Version 8.0/8.1 User Manual*. Scientific Instrument Services, Inc., 2006-2011.
- [2] Alex Fragapane. Simulating VITO. Technical report, ISOLDE-CERN, 2013.
- [3] Friedrich Hinterberger. Ion Optics With Electrostatic Lenses. In *CAS - CERN Accelerator School and KVI: Specialised CAS Course on Small Accelerators*.
- [4] Monika Stachura and Manfred Deicher. VITO-Versatile Ion-polarized Techniques On-line at ISOLDE (former ASPIC UHV beamline). Technical report, ISOLDE-CERN, 2013.

## Appendix A: WorkBench Programs

The WorkBench programs are actions SIMION executes every time the *Fly'm* button is pressed. They were used to do a voltage sweep on the focusing devices for each part of the full beamline.

### Fist Part of the Line

```
simion.workbench_program()
collectgarbage()    -- ensure unused files are closed
math.randomseed(os.time())

--To count particles reaching the end of the line
local n = 0

--Quadrupoles' voltages
adjustable Vq1 = 0
adjustable Vq2 = 0
adjustable Vq3 = 0
adjustable Vq4 = 0

function segment.flym()
    for i = 0,3 do
        Vq1 = 500+i*500
        for j = 0,3 do
            Vq2 = -500-j*500
            for k = 0,3 do
                Vq3 = 500+k*500
                for l = 0,3 do
                    Vq4 = -500-l*500
                    for m = 0,3 do
                        Vq5 = 500+m*500
                        for p = 0,3 do
                            Vq6 = -500-p*500
                            n=n+1
                            run()
                        end
                    end
                end
            end
        end
    end
    print("\n")
end

end

function segment.init_p_values()
adj_elect[7] = Vq3
adj_elect[8] = -Vq3
adj_elect[9] = Vq3
adj_elect[10] = -Vq3
adj_elect[11] = Vq4
adj_elect[12] = -Vq4
adj_elect[13] = Vq4
adj_elect[14] = -Vq4
adj_elect[15] = Vq1
```

```

adj_elect[16] = -Vq1
adj_elect[17] = Vq1
adj_elect[18] = -Vq1
adj_elect[19] = Vq2
adj_elect[20] = -Vq2
adj_elect[21] = Vq2
adj_elect[22] = -Vq2
adj_elect[23] = Vq5
adj_elect[24] = -Vq5
adj_elect[25] = Vq5
adj_elect[26] = -Vq5
adj_elect[27] = Vq6
adj_elect[28] = -Vq6
adj_elect[29] = Vq6
adj_elect[30] = -Vq6

end

function segment.other_actions()
if ion_px_mm < 60 and ion_pz_mm < 90 then
n=n+1
end
end

function segment.terminate_run()
print(Vq1,Vq2,Vq3,Vq4,Vq5,Vq6,n/10)
end

```

## Second Part of the Line

```

simion.workbench_program()
collectgarbage()    -- ensure unused files are closed
math.randomseed(os.time())

--To count particles reaching the end of the line
local n = 0

--Quadrupoles' voltgages
local Vq7 = 0
local Vq8 = 0

function segment.flym()
    for j = 0,10 do
        Vq7 = 1000+j*100
    for k = 0,10 do
        Vq8 = -1000-k*100
        n=0
        run()
        end
        print("\n")
    end
end

```

```

end

function segment.init_p_values()
adj_elect[8] = Vq8
adj_elect[9] = -Vq8
adj_elect[10] = Vq8
adj_elect[11] = -Vq8
adj_elect[12] = Vq7
adj_elect[13] = -Vq7
adj_elect[14] = Vq7
adj_elect[15] = -Vq7
end

function segment.other_actions()
if ion_px_mm < 40 then
n = n+1
end
end

function segment.terminate_run()
print(Vq7,Vq8,n/10)
end

```

### Third Part of the Line

```

simion.workbench_program()
collectgarbage()    -- ensure unused files are closed
math.randomseed(os.time())

--To count particles reaching the end of the line
local n = 0

--Quadrupoles' voltages
adjustable Vq9 = 0
adjustable Vq10 = 0

function segment.flym()
    for i = 0,5 do
        Vq9 = 1000+i*200
        for j = 0,5 do
            Vq10 = -1000-j*200
            n=0
            run()
            end
            print("\n")
        end
    end
end

function segment.init_p_values()
adj_elect[15] = Vq9
adj_elect[16] = -Vq9

```



```

adj_elect[17] = Vq9
adj_elect[18] = -Vq9
adj_elect[11] = Vq10
adj_elect[12] = -Vq10
adj_elect[13] = Vq10
adj_elect[14] = -Vq10
end

```

```

function segment.other_actions()
if ion_pz_mm < 874 and math.abs(ion_px_mm-135.715238) < 2 and math.abs(ion_py_mm-
n=n+1
end
end

```

```

function segment.terminate_run()
print(Vq9,Vq10,n/10)
end

```