Electrical Network Analysis for Vacuum Profile of MedAustron

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Summary

MedAustron is a synchrotron based hadron therapy facility for cancer treatment currently under construction in Wiener Neustadt, Austria, 40 km south-west of Vienna. Ion beams of H$_3^+$ and C$_4^+$ are generated in gaseous plasma (H$_2$ or CO$_2$) in an Electron Cyclotron Resonance (ECR) ion source and extracted at a kinetic energy of 8 keV/u and transformed by the Low-Energy Beam Transfer line (LEBT). The beam of ions is then accelerated up to 400 keV/u in the Linear accelerator (LINAC) and transferred via the Medium Energy Beam Transfer line (MEBT) to the synchrotron. After extraction, the beam is transferred to the treatment rooms for cancer therapy use. The quality of the dose delivered to the patient for cancer treatment is ultimately determined by the performance of the beam delivery chain. The performance of beam delivery chain are accordingly influenced by many factors in the entire accelerator chain and the vacuum performance is one of key factors steering the beam quality, especially in the synchrotron. In this report, a summary of the simulations done for the entire MedAustron accelerator complex is presented by using so-called Electrical Network Analysis (ENA).

1 Introduction

1.1 Overview of MedAustron

MedAustron is a synchrotron based hadron therapy facility currently under construction in Wiener Neustadt, Austria, 40 km south-west of Vienna. The decision or construction was taken in 2004 by the County of Lower Austria in partnership with the Austrian federal government. With a capacity of 24,000 fractions per year, between 1200 and 1500 patients per year (depending on fractionation scheme) can be treated with protons and carbon ions [1].

Figure 1 shows the layout of the MedAustron accelerator complex with the transport lines to the irradiation rooms. At the beginning of the injection chain, ions (H$_3^+$ or C$_4^+$) are
generated in gaseous plasma (H\textsubscript{2} or CO\textsubscript{2}) in an Electron Cyclotron Resonance (ECR) ion source and extracted at a kinetic energy of 8 keV/u and transformed by the Low-Energy Beam Transfer line (LEBT). The beam of ions is then accelerated up to 400 keV/u in the Linear accelerator (LINAC), as shown in Fig. 2 and transferred via the Medium Energy Beam Transfer line (MEBT) to the synchrotron.

After extraction, the beam is transferred to the treatment rooms. Irradiation of the patient will be performed in three different treatment rooms as indicated in Fig. 1: (1) IR2: Fixed horizontal + fixed vertical beam line (protons and carbon ions). (2) IR3: Fixed horizontal beam line (protons and carbon ions). (3) IR4: Gantry (protons only). In addition, one irradiation room (IR1) is dedicated to non-clinical research.

![Figure 1: Layout of MedAustron accelerator chain, including source, LEBT, LINAC, MEBT, synchrotron, extraction line, and transport lines to the treatment rooms [1].](image1)

![Figure 2: Injector with Linac, LEBT line and ECR sources [1].](image2)
1.2 The aim of this project

The quality of the dose delivered to the patient for cancer treatment is ultimately determined by the performance of the beam delivery chain. The performance of beam delivery chain is accordingly influenced by many factors in the entire accelerator chain and the vacuum performance is one of key factors steering the beam quality, especially in the synchrotron. The total length of the vacuum chambers in the MedAustron accelerator complex is 363.3 m. The aim of this project is to simulate the entire MedAustron accelerator vacuum profile by using so-called Electrical Network Analysis (ENA) in order to be able to:

- monitor pressure at any specific part of accelerator with or without beam.
- monitor pressure with different leakages and different extract gas sources at any specific part of accelerator.
- monitor pressure after modification in design, e.g. adding more pumps, moving elements, etc.
- obtain pump-down curves (pressure variation as a function of time) at any specific part of accelerator in case of intervention and maintenance.

2 Methods

2.1 Calculations of vacuum systems

A schematic diagram of an elementary idealized vacuum system is considered, as shown in Fig. 3, in order to derive basic design equations of vacuum calculations [2]. A chamber of volume $V$ at a uniform pressure $p$ is connected to a pump set through a component (e.g. stainless steel tube) of conductance $C$. A gas flow $\dot{Q}_{\text{in}}$ into the system can be caused by a purposely fitted gas inlet, by leaks or permeation through seals or chamber walls. It can also be caused by gas sources physically within the system like outgassing from materials.

If we apply the ideal gas law with the assumption of constant gas temperature, a flux balance yields the basic differential equation:

$$V \frac{dp}{dt} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}$$

where $\dot{Q}_{\text{out}}$ is the flow the pump system removes from the chamber and this can be calculated as:

$$\dot{Q}_{\text{out}} = p \cdot S_{\text{eff}}$$

where $S_{\text{eff}}$ is the effective pumping speed and is determined by:

$$S_{\text{eff}} = \frac{1}{S_0} + \frac{1}{C}$$

The simplest assumptions, although not necessarily realistic, are pressure- and time-independent pumping speed and injection flow. This yields a simple expression for the pressure as a function of time in the vacuum system:

$$p(t) = (p_0 - \frac{\dot{Q}_{\text{in}}}{S_{\text{eff}}}) \cdot \exp\left(-\frac{S_{\text{eff}}}{V}t\right) + \frac{\dot{Q}_{\text{in}}}{S_{\text{eff}}}$$
Figure 3: Schematic diagram of a basic vacuum system. $V$: volume of vacuum chamber; $p$: pressure in the vacuum chamber; $\dot{Q}_{in}$: gas flow into the system; $\dot{Q}_{out}$: flow the pump system removes from the chamber; $S_0$: pumping speed of the pump system; $p_0$: pressure at the pumps inlet; $S_{eff}$: effective pumping speed and $C$: conductance.

Solving Eq. 4 for $t$ yields the pump-down time from $p_0$ to $p$:

$$t = \frac{V}{S_{eff}} \cdot Ln\left(\frac{p_0 - \frac{\dot{Q}_{in}}{S_{eff}}}{p - \frac{\dot{Q}_{in}}{S_{eff}}}\right)$$ (5)

Conditions such as constant pumping speed or time-independent injection flow are hardly ever met in real systems where transitions from viscous to molecular regime are regularly experienced. Therefore these solutions can provide approximations for real systems; but for sufficiently accurate predictions of the vacuum performance, calculations have to be based on realistic data of pumps, conductances, and gas flows.

In principle there are two ways to include real data in the design calculations:

1. Model all relevant data such as pumping speeds and flows in an analytical form and solve the basic equations analytically or

2. Use the data and solve the equations by numerical methods.

Analytical methods yield closed-form solutions which provide insight into the dependencies of different parameters. However, analytical solutions are only available for simple approximations of, for example, pumping down curves. Numerical methods on the other hand are very powerful in including the most complex dependencies and system structures.

Since the entire MedAustron vacuum system is very complex, the analytical method is unfortunately not possible. In this work, we use the open source for electrical network calculation software (LTSpice) to calculate the vacuum profile of the entire MedAustron accelerator chain. In the following section, the numerical method used for the MedAustron vacuum system is discussed.
2.2 Electrical network analysis for vacuum calculations

It has long been known that an analogy exists between vacuum systems and electrical networks. For Electrical Network Analysis (ENA), useful software tools are available. This suggests that we could apply these tools to vacuum system calculations. The relation between vacuum metrics and electrical metrics can be found by comparing terms in similar equations, as shown in Table 1.

<table>
<thead>
<tr>
<th>Electrical metrics</th>
<th>Vacuum metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohm’s law</td>
<td>The gas flow</td>
</tr>
<tr>
<td>( I = G \cdot V )</td>
<td>( \dot{Q} = C \cdot p )</td>
</tr>
<tr>
<td>Charging/discharging</td>
<td>The change of gas content in</td>
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<tr>
<td>an electrical capacitor</td>
<td>a volume ( V )</td>
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<tr>
<td>of capacitance ( C )</td>
<td></td>
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<tr>
<td>( I = C \cdot \frac{dV}{dt} )</td>
<td>( \dot{Q} = V \cdot \frac{dp}{dt} )</td>
</tr>
</tbody>
</table>

| I: electrical current [A] | \( Q: \) flow [Torr l/s] |
| V: voltage drop [V] | p: pressure [Torr] |
| C: capacitance [F] | V: volume [l] |

Table 1: Relation between electrical metrics and vacuum metrics.

Figure 4 shows a simple example on how to translate a gas flow in a tube into an electrical network by using commercial simulation software, e.g. LTSpice.

2.3 Procedure to calculate the MedAustron vacuum system

In this section, a general procedure on how to simulate a complex vacuum system, such as the entire MedAustron accelerator chain, by using ENA is presented. The following steps are performed:
• Step 1: Divide the complete MedAustron vacuum system into many small parts and identify each element.

Since the MedAustron accelerator is a very complex system and contains many different elements, as shown in Fig. 5, a simplification should be made to easier the simulation. As seen in Fig. 5, normal chambers, bending chambers in dipole, chambers containing ceramic, vacuum diagnostics tanks with different geometries, as well as vacuum chamber with NEG pump and many other types of vacuum chambers are located in different places in the accelerator chain. The first step of this work is to divide the whole accelerator chain into several small parts and then identify all the elements in each part.

Figure 5: Layout of vacuum chambers in the MedAustron accelerator complex including different elements, such as chamber with ceramic, bending chamber in dipole, vacuum chamber with NEG pump and different types of vacuum diagnostics tank.

• Step 2: Calculate vacuum parameters for each element.

Once all the elements are identified, we need to calculate vacuum parameters for each element, such as conductance, volume and outgassing rate, as already explained in Section 2.1. To be more pedagogical in explaining how to model a vacuum system by using ENA, a not so simple example, such as a vacuum diagnostics tank is considered here. As seen in Fig. 6, the vacuum diagnostics tank used as example contains one main tank, one DN160 tube for a turbo molecular pump (TMP) of HiPace 700 l/s, one DN160 tube for beam diagnostics instrument, 6 rectangular chambers for beam diagnostics instruments and 3 DN40 flanges for installation of gauges. For each of the above mentioned elements, the vacuum parameters, as conductance, volume and outgassing from the surface, are needed to be calculated.

Expression for conductance ($C_m$) is usefully formulated in term of transmission probability ($\tau$), as shown in Eq. 6. The conductance of a duct is given by the entrance
aperture conductance multiplied by the transmission probability. For a simple geometry, $\tau$ can easily be found from the general transmission probability tables. However, for complex geometries, Molflow+ [3] by using Monte Carlo simulation can be applied for the calculations of $\tau$.

$$C_m = \tau C_a$$  \hspace{1cm} (6)

where $C_a$ is the molecular flow conductance of a thin aperture, which is directly related to the rate of impingement of molecules over the aperture area $A$.

$$C_a = A \sqrt{\frac{R_0 T}{2\pi M_m}}$$  \hspace{1cm} (7)

where $R_0$ is the universal gas constant, $T$ is the thermodynamic temperature, and $M_m$ is the molar mass (e.g. 0.002 kg/mole for hydrogen).

Outgassing from the surface can be calculated by using measured values:

$$Q \left[ \frac{\text{Torr} \cdot \text{s}^{-1}}{\text{cm}^2} \right] \times \text{surface area [cm}^2\text{]}$$  \hspace{1cm} (8)

Figure 6: Example of how to model a vacuum diagnostics tank in LTSpice. Left: The corresponding electrical network for the different elements in the vacuum diagnostics tank in LTSpice. Right: The layout of vacuum diagnostics tank, containing one main tank, one DN160 tube for a turbo molecular pump (TMP) of HiPace 700 l/s, one DN160 tube for beam diagnostics instrument, 6 rectangular chambers for beam diagnostics instruments and 3 DN40 flanges for installation of gauges.

- Step 3: Model element in LTSpice program.
Once all the elements in a considered vacuum system receive vacuum parameters, we can then apply the relation between electrical metrics and vacuum metrics and then use the LTSpice to simulate the pressure profile. Figure 6 shows an example of the corresponding electrical network for the different elements in a vacuum diagnostics tank used for MedAustron.

- Step 4: Assembly all elements into one single network.

In Fig. 7, the complete electrical network for the MedAustron accelerator complex from the source to the entrance of the synchrotron is shown.

![Diagram](image)

Figure 7: Assembly all elements of MedAustron accelerator chain into one single network.

3 Results and discussion

In this section, the main results of pressure profile simulated by ENA are presented. Before starting the simulation, the operation pressures from the ion sources have to be defined. For MedAustron, the ion sources for the production of hydrogen and carbon ions are of the ECR type and the detailed description of the gas injection system of the MedAustron ion sources can be found in [4]. Since the ion source used for MedAustron is a well-established and tested system, the operation pressures applied in our pressure profile calculations are taken directly from the technical report provided by MedAustron [5]. At the present stage, only gas flows and pressures for hydrogen operation have been measured. Therefore the pressure profile simulation is only considered during hydrogen ion operation. At a later stage, the pressure profile will also be simulated for the carbon ion case. In Table 3 of [5], the pressure measured at the extraction of the ion source is listed. For our calculations, we took $1.7 \times 10^{-6}$ mbar as operation pressure for the hydrogen ion beam and then assume an upper limit for H$_2$O has a pressure of 4-5 times higher than
the measured H$_2$ pressure. For this reason, the H$_2$O pressure at the extraction of the ion source is assumed to be 7.5\times10^{-6}$ mbar in all the simulations shown in this work.

### 3.1 Static pressure profile of H$_2$O after 100 hours pumping

In Fig. 8, pressure profile of H$_2$O after 100 hours pumping at different positions of the MedAustron accelerator complex is shown. The pressure simulation is based on an operational beam with hydrogen ions of 7.5\times10^{-6}$ mbar at the extraction of the ion source. Two cases have been considered: (1) no outgassing from beam diagnostics instruments is taken into account. (2) outgassing from the Harp Profile Monitor grid (PGX) installed on different vacuum diagnostics tanks in several places of the MEBT, indicated in the ring as seen in Fig. 8 is taken into account. Since only the outgassing from the PGX installed in the MEBT is taken into account in our simulations currently due to the lack of the measurement data of the other diagnostics instruments used in the accelerator complex, the pressure is expected to be slightly higher in reality. Figure 9 shows the pressure variation of H$_2$O after 100 hours pumping at different section positions in the Main Ring (MR). As seen in Fig. 9, the crossings between the MR and MEBT contribute highest pressure while the average of the pressure in the rest of the MR stays in 10^{-10}$ mbar range. As already mentioned earlier, all the simulations are only considered without taking any outgassing from the other beam diagnostics instruments apart from the PGX installed in the MEBT. It is important to note that the results from the simulations shown in this work only provide a insight of the lowest possibility in pressure at present stage.

![Diagram of pressure profile](image)

Figure 8: Pressure profile of H$_2$O after 100 hours pumping with/without considering outgassing from the Harp Profile Monitor grid (PGX) installed in the MEBT. The outgassing rate of the PGX is measured to be 2.25\times10^{-5}$ mbar-l/s after 100 hours pumping, taken from the measurements reported in [6].
3.2 Pump down curve (MEBT)

In Section 3.1, the pressure profile of H\textsubscript{2}O after 100 hours pumping is simulated by assuming constant pumping speed and constant gas flow in molecular regime. In real systems these conditions are certainly not fulfilled for the entire pressure range. Especially, after each intervention, it is important to know how the pressure varies with time and how long it takes to pump down a vented system, i.e. to obtain pressure versus time curve - pump down curve.

To demonstrate how to calculate a pump down curve after one intervention by using ENA, we chose a sector in the MEBT with two gate valves located at both ends of the sector, as shown in Fig. 10. In Fig. 11, a detailed layout and a list of the different types of vacuum diagnostics tanks located in the investigated section are shown as well as the pumping groups with respective working pressure ranges are listed.

The water vapor outgassing rate of stainless steel surface as a function of time, is given by:

\[ Q = 2 \cdot 10^{-9} \cdot \text{surface area} \quad (9) \]

where \( t \) is the pumping time in hour [h].

As listed in the table of Fig. 11, the different pumps work at different pressure ranges. That means an ion pump or a NEG pump will not be able to be operational until the pressure reaches \( 10^{-5} \) mbar. Figure 13 shows the pump-down curve for the investigated sector with pumping down starting from atmosphere level. As seen in Fig. 13, the gauges located at VDT-H and VDT-E show a high pressure at a level of \( 10^{-4} \) mbar still after about 24 hours of pumping. This high pressure is caused by the fact that ion pumps located at the same tanks cannot be operational due to the interlock. Two suggestions would be helpful to reach a reasonable low pressure in this part after one intervention:

1. add an extra turbo-molecular pump (TMP) in-between the VDT-H and the VDT-E
to offer more pumping speed in the range of $1 \times 10^{-4} - 1 \times 10^{-5}$ mbar. A mobile turbo molecular pump could be an alternative.

2. improve the material of the PGXs installed at the VDT-H and the VDT-E and make them more vacuum compatible so that the outgassing in that range decreases, a factor 10 would help significantly.

Figure 10: Layout of the chosen sector for the pump down curve calculation by using ENA.

### 3.3 NEG pump activation

The sorption characteristics of a NEG pump are generally represented by the sorption speed (pumping speed of the NEG) as a function of the sorbed quantity [2]. This quantity corresponds to the amount of gas adsorbed onto the surface if there is practically no bulk diffusion, which occurs when NEGs work at room temperature (except for $\text{H}_2$). The speed of a NEG can decrease during time, depending on working temperature and pressure conditions. It decreases more rapidly if sorption occurs at room temperature since bulk diffusion is not promoted and the capacity is basically surface-limited. Therefore it is interesting to investigate how long a NEG pump works under certain condition until the capacity of the NEG pump reaches its saturation. When a NEG pump reaches its capacity saturation, a heating at a temperature of higher than 250°C for more than 24 hours is needed to re-activate adsorption of the material.

For MedAustron, Capacitorr D 2000 MK 5 pump provided by SAESgetters is used and this NEG pump is the highest performing pump of the Capacitorr series. With the use of a special highly porous sintered material, St 172, a Zr-V-Fe getter material, the pump is able to reach 2000 l/s pumping speed for hydrogen in UHV conditions and 1000 l/s for water. The details about the pump can be found in [7]. As explained earlier, for all the getter pumps, the pumping speed decreases with increasing of absorbed quantity on the material surface.
PGX: Harp Profile Monitor grid (High outgassing rate) are installed at pumping group VDT-H and VDT-E. Pressure gauges are installed at each pumping group.

Figure 11: Details of the chosen sector for the pump down curve calculation by using ENA.

Figure 12: Details of the chosen sector for the pump down curve calculation by using ENA.
In order to calculate the ‘time-to-saturation’ of a NEG pump, we first need to calculate the pumping speed of the NEG as a function of time. In the manual provided by SAES getter [7], only the experimental data of the pumping speed as a function of sorbed quantity is given. By fitting the experimental data, we can easily get an analytical expression of $S = S(Q)$. The sorbed quantity on the NEG pump can be caused by the outgassing from the surrounding materials and the outgassing from the beam diagnostics instruments close by, such as PGX and we can simply get $S = S(Q(t))$ with $Q(t) = \int_0^t q_{H_2O} \cdot dt$, where $q_{H_2O}$ is assumed to be the outgassing rate measured on the PGX and the outgassing from the stainless steel walls. The detailed calculation is not provided here. In this report, we only present how the pressure changes at the first crossing between the MEBT and the MR (sector 6 - 7) influenced by sorbed quantity on CapacitTorr NEG pump, see Fig. 14.

As a result, the pressure increases from $1.9 \times 10^{-9}$ mbar to $3.4 \times 10^{-9}$ mbar after 55 hours operation with beam and then stays at $3.47 \times 10^{-9}$ mbar level. As conclusion, the pressure at the crossing of the MEBT and the MR does not seem to be so critical and the activation of the NEG pump will only be used to recover from venting to atmosphere.

4 Conclusions and future plans

The simulation of the pressure profile for the MedAustron accelerator complex shows that the Electrical Network Analysis (ENA) is indeed a very powerful tool to simulate vacuum profile in a very complex system when the analytical method is no longer applicable. Since the electrical network of the MedAustron accelerator complex is now completed, all the further modifications and improvements are easy to add. In order to complete the entire simulation of the MedAustron vacuum profile and to be able to calculate the pressure as precisely as possible, all the experimental outgassing rate of all beam diagnostics instruments and other items with expected high outgassing rate is needed to be carried out at
Figure 14: Calculation of the capacity of the NEG pump used at the crossing of the MEBT and the MR (sector 6 - 7). (a): Pumping speed of Capacitorr D2000 MK5 [l/s] as a function absorbed quantity on surface by fitting the experimental data provided in [7] with two equations. (b): Pressure [mbar] measured at the crossing of the MEBT and the MR (sector 6 - 7) as a function of time [s].

the lab. Furthermore, it is very important to simulate the detailed pump-down curves for the suspected critical parts in the accelerator in order to know how many mobile pumping groups with specified pumping speed are needed during interventions.

References


