ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO009

VACUUM MODEL OF THE C400 CYCLOTRON FOR HADRONTHERAPY

V. E. Nuttens†, J. Mandrillon, W. Kleeven, Q. Flandroy, Ph. Cailliau
Ion Beam Applications, Louvain-la-Neuve, Belgium
Ph. Velten††, Normandy Hadrontherapy, Caen, France

Abstract

Since 2020, NHa and IBA collaborate on the development of the C400 cyclotron dedicated to hadron therapy. This machine accelerates C^{6+} and He^{2+} up to 400 MeV/n and H_2^+ up to 260 MeV/n. The H_2^+ are extracted by stripping and the other particles by an electrostatic deflexion.

Vacuum management in the injection line and in the cyclotron are of prime importance to avoid large beam losses. Indeed, C^{6+} ions are subjected to charge exchange during collision with the residual gas. On the opposite, H_2^+ will suffer from molecular binding break up. According to cross section data, the constraints on the residual gas pressure is driven by C^{6+} in the injection line and by H_2^+ in the cyclotron. An electrical equivalent model of the vacuum system of the cyclotron, its injection and extraction lines has been developed in LTSpice® software to determine the pressure along the particle path. Contributions from outgassing surfaces, O-ring outgassing, and permeation are included, and vacuum pump requirement could be obtained. The expected beam transmission is then evaluated based on cross sections available from the literature.

INTRODUCTION

Detailed theoretical studies has been conducted to estimate the beam transmission expected in each sub-part of the C400 hadron therapy system. Electrical equivalent circuits are built using inputs as detailed as possible and coming from the IBA design office, including the complex geometries of the numerous components located inside the cyclotron accelerator chamber (RF parts, elements of the extraction systems, etc.). This enables to compute the pressure level expected in any point of the circuit which in turn drives the dimensioning and location of the vacuum pumps to achieve the required pressure level. Combining these outputs with the relevant cross-sections of the interaction of the ion beam with the residual gas, the transmission can be estimated with a reasonable level of confidence.

VACUUM MODEL IN LTSPICE®

Electrical Equivalent Circuit

Thanks to the similarity between the electrical equations and the molecular flow equations, it is possible to make use of modelling tools such as LTSpice® [1] to build simulated vacuum circuits providing the equivalencies shown in Table 1. Providing the vacuum system can be approximated by an ensemble of elements connected either in series or parallel and defined by their conductance and/or gas throughput, such a model can provide a relatively precise estimation of the pressure at any point in the circuit.

Table 1: Electricity/Vacuum Equivalencies

Electricity	Vacuum
Voltage / [V]	Pressure / [mbar]
Current / [A]	Gas throughput / [mbar.L/s]
Resistance / [Ω]	Conductance / $[L/s]^{-1}$

Conductance

The general conductance equation for a vacuum element is:

$$C = \frac{aAv}{4} \quad (1)$$

where a is the transmission probability ϵ [0,1];
A is the vacuum element transverse cross section in [m²];
$v = \sqrt{\frac{8RT}{\pi m}}$ is the average speed of the gas molecule of molar mass m in kg/mol at temperature T in K; $R = 8.3144621$ J/mol/K is the gas constant.

In the electrical equivalent circuit, the generic conductance is a simple resistor with resistance value equal to the inverse of the conductance.

The coefficient a is component dependent, in particular function of its geometry, see [2] for more detailed information of how the transmission probability is modelled using tabulated data for specific geometry taken from [3]. Moreover, parametric formula is directly implemented in LTSpice® to enable modelling of various geometries: tubes of different inner diameter, conduct having rectangular slit-like shapes, etc. The impact of the gas nature is modelled entirely into the gas speed through its molar mass. Therefore, to consider multiple gas effect, specific runs must be performed for each gas.

Gas Throughput

All gas throughput present in a vacuum system (outgassing surfaces, permeation, leaks) are modelled in the software by means of a source current. For example, an outgassing pipe will be represented by two resistors in series whose conductance value is computed as explained previously and with a source current connected between them. The total gas throughput is parameterized with the product of the inner pipe surface times the outgassing rate of the considered material.

† vincent.nuttens@iba-group.com
†† philippe.velten@normandy-hadrontherapy.com

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO009

Contributions to the Residual Pressure

The following contributions were identified and modelled as precisely as possible within the model:

- Inner wall outgassing: The outgassing rate formula and values for different material used in this study are taken from [3], including time dependent formula to compute pumping speed, recovery after venting, etc.
- O-rings: Vacuum flange gaskets made of rubber like material provide contribution both from their permeation and outgassing of the material itself. In the C400 system, a mix of metal (no permeation), nitrile and Viton gaskets are used. The permeation rate values of water vapor for those materials are taken from [4].
- Outgassing and O-rings permeation calculations were performed with only water vapor as source of gas since it is the major contributions in those cases. But specific calculations were also performed using the neutral support gas coming out from the ion source (C_2H_2), since it is the major contributor in the first few meters downstream the extraction point of the ion source.
- Vacuum pumps are modelled as ideal diodes with a resistance in the passing current direction equal to the inverse of the pumping speed and infinite resistance in the blocking direction.

THE C400 VACUUM MODEL

Description of the Model

In the C400 system, the ions of interest are generated with dedicated ECR ion sources. The ion beams are extracted at 26 keV/Z, selected by a 90° switching magnet and transported down to the cyclotron through a ~10 m long vertical line. In the cyclotron, the Carbon and He beams are accelerated up to 400 MeV/u whereas H_2 are stripped to protons and extracted at about 260 MeV. Therefore, two extraction lines are present that are finally regrouped before reaching the degrader [5].

In the vacuum model, the system is divided into three sub parts: injection, cyclotron, and extraction. Each of them can be connected with each other to study their potential interdependencies and standalone run can be performed to investigate their specific dynamics. For brevity, only the cyclotron part is shown in Fig. 1. Representing the injection and extraction lines as equivalent electrical circuit is rather straightforward since their geometries naturally follow a linear layout. But for the geometry of the cyclotron, the inner volume needed to be 'unfolded' by approximating it as a succession of hills and valleys connected in series, as 'seen' by the accelerated particle trajectory. The

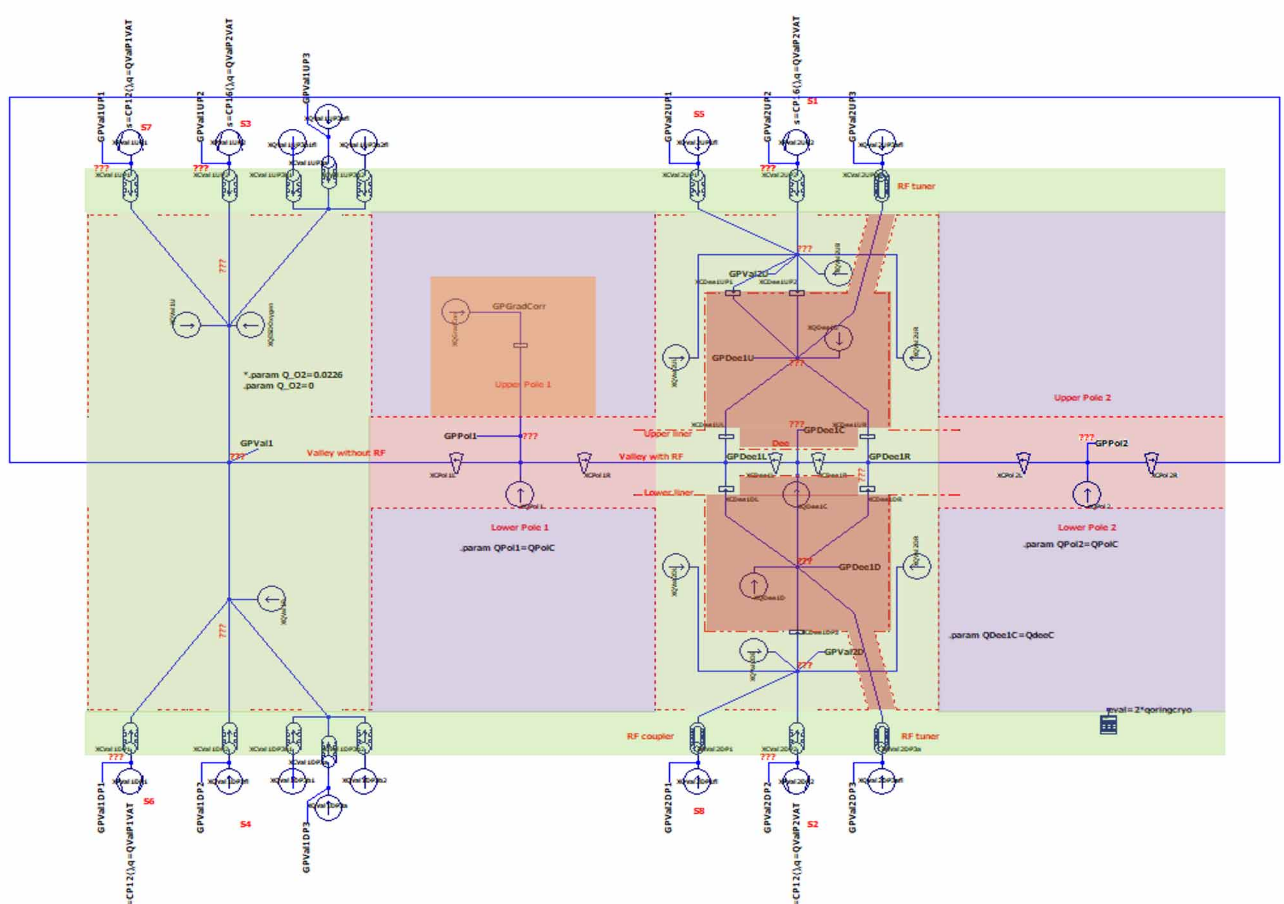

Figure 1: LTSpice® model of the C400 cyclotron.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO009

valleys themselves are considered as infinite conductance vacuum chambers but all elements present in those sectors and impacting the vacuum are included:

- the surfaces of all objects together with their materials, even from complex mechanical design like the Dees or the RF tuners and couplers,
- the pumping ports, including the flange diameter of the pumps to the estimate pumping efficiency,
- the O-rings of all sockets (pumps, valves, etc.).

The hills are represented by pie-slice shaped conducts whose conductance can be approximated by the integration of a bunch of variable thin, rectangular slit-like pipes connected in parallel [2].

Results and Discussions

Using these modelling tools, the conducted studies provided the following outputs:

- the dimension and performance of the cryopumps in the cyclotron have been increased to fulfil the required pressure level,
- the numerous O-rings in the cyclotron should not significantly compromise the pressure level, especially the two very large pairs of 3.65 m diameter O-ring between the yoke and the cryostat ensuring the vacuum of the accelerator cavity, with a separate differential pumping for the volume between the two O-rings of each pair.
- the pressure level in the extraction line whose requirement ($\sim 10^{-5}$ mbar) are lower than inside the cyclotron is not compromising the vacuum in the cyclotron either,
- the design of the injection line has been updated to stay as close as possible to the $\sim 10^{-6}$ mbar pressure level or below, especially in the first few meters downstream the ECR source extraction point. The critical point is to pump as efficiently as possible the neutral gas coming out of the source. A differential pumping system is foreseen to be located at this position (see Fig. 2).

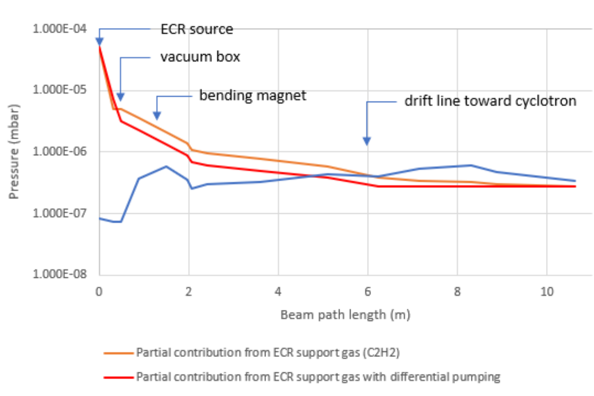

Figure 2: Pressure level coming from the contributions of the neutral ion source gas source gas and water vapor along the injection beam line.

TRANSMISSION CALCULATION

The general formula for transmission calculation with pressure and beam loss cross section is the following:

$$T = 1 - \frac{dN}{N} = 1 - \sigma(E)\frac{P}{k_B T}dl \qquad (2)$$

where N is the number of particles, σ the total gas stripping cross section, P the pressure, T the temperature and dl the elementary particle trajectory length. In the case of the transport beamlines, one must integrate only over the beam line length considering potential pressure variation, whereas the treatment is more complex inside the cyclotron. In the latter case, it is necessary to compute the closed orbit separated by the energy gain per turn and integrate over the energy range and length, also considering the variation of the cross-sections over the increasing energy.

In the injection line, beam losses are dominated by charge exchange cross-section of C^{6+} ions, whereas in the cyclotron, the pressure requirements are driven by the molecular break-up cross-section of H_2^+ ions [6].

H_2^+ Cross Sections

Literature has several references for the molecular hydrogen break-up cross section (Fig. 3). Olson has proposed a fit of the experimental data [7] that is being used here as the nominal case for the present study and for which σ goes from $\sim 2 \cdot 10^{-15}\ cm^2$ at low energy (<50 keV/u) down to $\sim 3 \cdot 10^{-18}\ cm^2$ at max energy (~200 MeV/u). Berkner-Gryzinski and Berkner-Born [8] cross section fits are used as maximum and minimum uncertainty limits.

Carbon Cross Section

The value of $\sigma \sim 6.8 \cdot 10^{-15}\ cm^2$ representing the electron capture by C^{6+} from H_2O already used in the C400 preliminary design report from 2009 [6] has been used in this study since no better input was found in the literature after cross-checks. The value $\sigma \sim 9.5 \cdot 10^{-15}\ cm^2$ is used for the electron capture by C^{6+} on the source support gas C_2H_2 at 26 keV/Z, following [9].

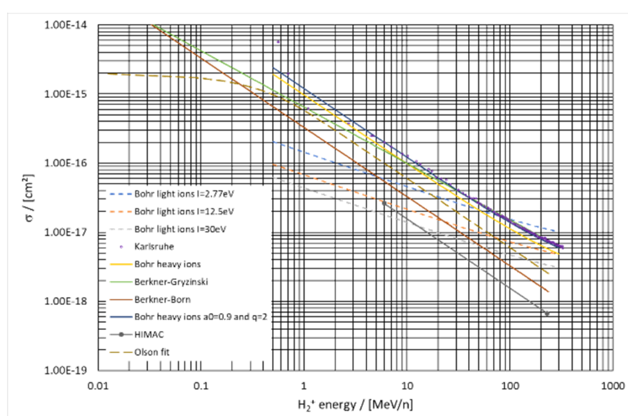

Figure 3: Molecular hydrogen break-up cross section from the literature as function of H_2^+ incident energy.

ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-THPO009

Injection Line Results

Using the pressure output level from the electrical current model and the cross-section described before, it is found that a transmission between 80% and 95% should be achieved in the injection line and mainly depends on the pressure level at the extraction point driven by the support gas coming out from the source. The ECR source to generate the C^{6+} beam is still currently under development, but preliminary studies show that with such transmission level, the required carbon beam current of several µA should be easily achieved at the cyclotron injection level.

Cyclotron Results

Depending on the actual pressure achieved in the accelerator vacuum chamber, the beam transmission considering only the beam losses due to the interactions with the residual gas have been calculated and are shown on Fig. 4.

Outgassing of materials in vacuum depends not only on the material, but also on its surface state. In the case of an iron-dominated cyclotron, the surface of the poles therefore may play an important role. This is especially true for an accelerator dedicated to medical applications since the downtime following maintenance opening is one of its critical performance parameters. It was therefore studied whether pumping time could be significantly improved with the application of nickel-plating on the inner poles of the cyclotron. According to the simulation results (the different surface state cases are pointed out on Fig. 4), only a limited gain on transmission could be saved after a given pumping time. Therefore, since this procedure would not significantly impact the clinical functioning of the system and because of the risk presented by the manufacturing process (manual application of the nickel was mandatory due to the very large yoke size), it was decided not to proceed with the nickel plating of the poles.

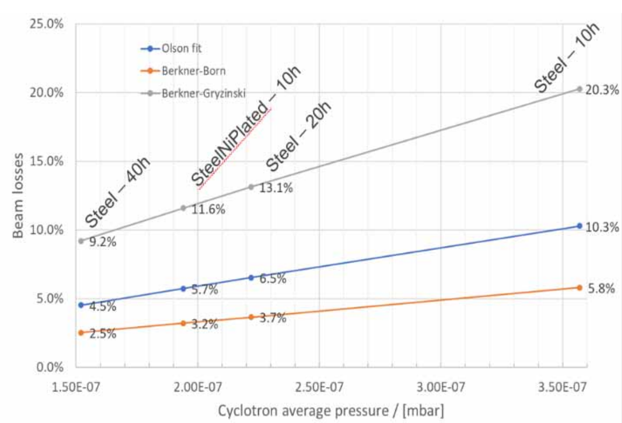

Figure 4: Beam loss versus cyclotron pressure after a given pumping time, with or without nickel plating, and according to different stripping cross section limits.

CONCLUSION

Models for the vacuum computation of the critical beam parts of the C400 system have been performed to help and orient various design steps. They confirmed that the pressure level was well under control to ensure a beam transmission matching the performance requirements. Those studies also permitted to optimize the vacuum, mechanical and manufacturing processes.

REFERENCES

[1] LTSpice®, `https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html`

[2] V. Nuttens *et al.*, "Cyclotron Vacuum Model and H- Gas Stripping Losses", in *Proc. Cyclotrons'10*, Lanzhou, China, Sep. 2010, paper MOPCP075, pp. 200-202.

[3] J. F. O'Hanlon, "A User's Guide to Vacuum Technology", Wiley, 3rd Edition.

[4] Marco Rubber & plastics, "O-Ring Permeation Coefficient Chart of Common Materials," [Online]. Available: `https://www.marcorubber.com/o-ring-permeation.htm`

[5] J. Mandrillon *et al.*, "Carbon cyclotron for particle therapy", presented at Cyclotrons'22, Beijing, China, Dec. 2022, paper THBI01, this conference.

[6] G. Karamysheva, "Beam losses due to interaction with the residual gas ", IBA internal report, 2009, unpublished.

[7] T. Tabata,H. Kubo, and M. Sataka, "Formulating analytic expressions for atomic collision cross sections", Japan Atomic Energy Research Institute, JAERI-Research 2003-015, Aug. 2003 (23 pages).

[8] K. H. Berkner *et al.*, "Collisional breakup of high-energy H2+ ions", *Phys. Rev.*, vol. 146, no. 1, p. 9, 1966. `doi:10.1103/PhysRev.146.9`

[9] J.B. Greenwood *et al.,* "Experimental investigation of the processes determining x-ray emission intensities from charge-exchange collisions", *Phys. Rev. A,* vol. 63, no. 6. p. 062707, 2001. `doi:10.1103/PhysRevA.63.062707`