

## CYCLOTRON VACUUM MODEL AND H- GAS STRIPPING LOSSES

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### Abstract

A model to compute the vacuum in the different parts of IBA H<sup>-</sup> cyclotrons has been developed. The pressure results are then used to compute the beam transmission through the cyclotron by integration of the residual gas stripping cross-section along the ion orbits. The model has been applied to the ARRONAX Cyclone<sup>®</sup>70 with the initial vacuum design and the results are compared to the experimental data. The pressure and the transmission are in good agreement with experimental data.

### INTRODUCTION

Many proton cyclotrons use the advantage of stripping extraction, by accelerating H<sup>-</sup> ions. However, before extraction, the negative ion beam can suffer losses from stripping by the residual gas. The higher is the pressure, the higher are the losses. Moreover, the stripped beam will be stopped on the inner wall of the cyclotron, inducing an additional degassing that increases the pressure and hence losses in the cyclotron. For high beam currents, degassing can be too large compared to the pumping capacity and the beam transmission can drop down to zero. The pressure inside the cyclotron has therefore a large impact on the current that can be extracted from the cyclotron. A simple model has been set up at IBA to determine the vacuum pressure in the hills and in the valleys of the Cyclone<sup>®</sup>70 and then deduce the beam transmission.

### MODELS

A first model to compute the beam transmission through the cyclotron has been set up. The succession of hills and valleys leads to pressure inhomogeneities in the machine. Therefore, we have set up a model to compute the vacuum in the pole gaps and in the valleys.

#### Beam Transmission

The number  $dN$  of H<sup>-</sup> ions that can be stripped by the residual gas is obtained from:

$$dN = -\sigma n N v dt \quad (1)$$

where  $N$  is the number of incident ions;  $dt$  is the time spent by the ions in the residual gas of atomic density  $n$ ;  $v$  is the ion velocity; and  $\sigma$  is the total stripping cross section. We use the analytical fit proposed by the Nakai et al to compute the stripping cross section [1]. The beam transmission in an isobar region for particles with a transit time  $t$  is:

$$T = 1 - \frac{\Delta N}{N} = \exp(-vt n \sigma) \quad (2)$$

The residual gas analysis (RGA) performed on ARRONAX Cyclone<sup>®</sup>70 have shown that the residual gas was composed mainly by 70% of H<sub>2</sub>O, 30% of air and 0.15% of rare gas. However, the parameters of the Nakai et al fit are not reliable for water in the Cyclone<sup>®</sup>70 energy range. Therefore, we consider the worst case scenario (i.e. largest stripping cross section) of 100% O<sub>2</sub>. The cyclotron has been subdivided into three isobar regions: the poles at pressure  $p_1$ , the pumping valleys at pressure  $p_2$  and the RF valleys at pressure  $p_3$ . The ion orbit is supposed straight segments in valleys and circular arcs in hills (figure 1). The particle track length in the hills and in the valleys is obtained from:

$$r_{magn} = (B\rho)/B_z \quad (3)$$

$$l_{hill} = \frac{\pi}{2} r_{magn} \quad (4)$$

$$l_{valley} = \frac{r_{magn} \tan(\nu)}{1 - \tan(\nu)} \quad (5)$$

The injection energy is 40keV. Acceleration is supposed to occur once a turn with an energy equal to the energy gain per turn defined by:

$$dE = q \cdot V_{RF} \cdot 2 \cdot n_{dee} \cdot \sin\left(\frac{\delta}{2} \cdot h\right) \quad (6)$$

where  $q=1$  is the particle charge,  $V_{RF}=65kV$  is the RF voltage,  $n_{dee}=2$  is the number of dees (two gaps per dee);  $\delta=36^\circ$  is the dee angle; and  $h=2$  is the harmonic mode.

The total transmission is the product of the transmission in the eight regions (4 poles and 4 valleys) for each ion energy.

#### Vacuum

As the ion travels along its trajectory, it sees a series of vacuum chambers of infinite conductance (valleys) and conducts of finite conductance (hills). However, in the RF valley, the dees limit the conductance and have to be taken into account. The two-fold rotational symmetry allows us to consider only a half-cyclotron as shown on figure 1. Without the beam, the main contribution of

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outgassing is coming from the surface of the different parts of the cyclotron. In order to simplify the model, we consider that the surface outgassing is only located at different points in the machine as shown in figure 1:

- In the middle of each pole;
- In the accelerating gaps;
- In the middle of each dee;
- In the middle of the pumping valley;
- In the middle of the extraction vacuum chamber;
- At the exit of the switching magnet;
- A contamination at the end of each beam line (due to the target, ...)

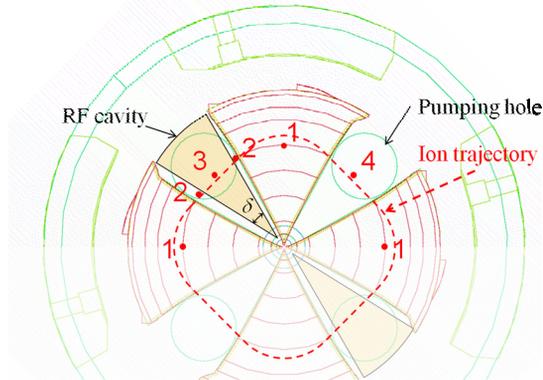


Figure 1: Outgassing points in the cyclotron.

The equivalent diagram used for the vacuum model is shown in figure 2. By symmetry, we can deduce that  $P_1=P'_1=P''_1$  and  $P_2=P'_2$ .

The outgassing rates were taken from the literature [2]. RF cavities surfaces were supposed made of fresh copper, vacuum chamber of bright rolled aluminum and magnetic part of mild steel slightly rusty. We sum up all the surfaces surrounding each outgassing point multiplied by

the corresponding outgassing rate depending on the material. Note that the ARRONAX Cyclone<sup>®</sup>70 contains correction coils surrounding the poles which are covered by epoxy which can be heated by Joule effect. These coils can therefore lead to a significant additional outgassing. However, in the throughput calculation, each interface between two pieces in contact is considered as two outgassing surfaces. Results of our calculations show that this method is sufficient to account for the outgassing contribution from correction coil epoxy. The gas throughputs considered in this calculation are listed in table 1.

We consider the stationary case where the pressure is constant in time everywhere in the cyclotron. The pressure is below  $10^{-5}$ mbar and the molecular regime can be considered to determine the conductances. In this case, the conductance of a conduct can be written in the form:

$$C = aAv/4 \tag{7}$$

where  $a$  is the transmission probability of the conduct;  $A$  is the cross-sectional area of the conduct; and  $v$  is the thermal velocity of the gas which depends on the composition of the gas and its temperature. We considered according to the RGA analysis that the gas is 100% of  $H_2O$  at 22°C, which lead to a thermal velocity  $v=586m/s$ . Many conducts (extraction vacuum chambers, pipes in the switching magnet) in the cyclotron can be considered as thin, rectangular slit-like pipes. The transmission probability for such a conduct can be fitted by an analytical function:

$$\log_{10} a = \sum_{i=0}^6 b_i (\log_{10}(l/h))^i \tag{7}$$

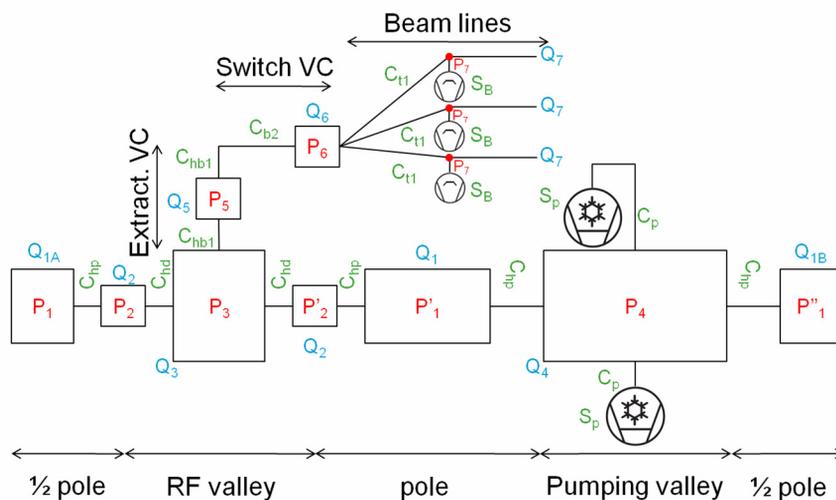


Figure 2: Equivalent diagram of the cyclotron vacuum model.  $P_i$  is the pressure at the point  $i$  in the cyclotron;  $Q_i$  are the outgassing throughput,  $C_i$  are the conductance and  $S_i$  are the pumping speed.

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where  $b_0=-0,165$ ;  $b_1=-0.288$ ;  $b_2=-0.170$ ;  $b_3=-6.84E-3$ ;  $b_4=1.46E-2$ ;  $b_5=-3.08E-3$ ;  $b_6=2.08E-4$ . The poles and dees can also be seen as slit-like corner conduct with variable length while the radius increases (figure 3). As the transmission probability is independent of the width, we can approximate the slit-like corner by a series of slit-like tubes with no lateral wall. The conductance can then be computed by the integration of the transmission probability:

$$C = \frac{vh^2}{8 \tan(\theta/2)} \int_{\lambda_1}^{\lambda_2} a(\lambda) \cdot d\lambda \quad (7)$$

where  $\lambda = l/h = 2l/h \cdot \tan(\theta/2)$ . The conductance of half a pole/dee is the double of the pole/dee conductance.

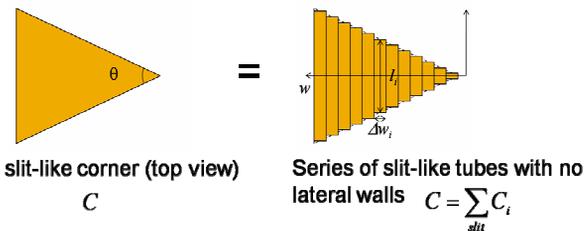


Figure 3: Model used for the conductance calculation of poles and dees.

The pumps are also considered as conduct with a zero pressure at one end. Conductances and pumping speeds used for this model are given in table 1.

Table 1: Gas throughputs and conductances

Throughput			Conductance		
Q <sub>1</sub>	mbar-L/s	$5.4 \times 10^{-4}$	C <sub>hp</sub>	L/s	2236
Q <sub>2</sub>	mbar-L/s	$1.1 \times 10^{-3}$	C <sub>hd</sub>	L/s	2624
Q <sub>3</sub>	mbar-L/s	$5.8 \times 10^{-4}$	S <sub>p</sub>	L/s	17300
Q <sub>4</sub>	mbar-L/s	$1.2 \times 10^{-3}$	C <sub>hb1</sub>	L/s	4734
Q <sub>5</sub>	mbar-L/s	$6.7 \times 10^{-5}$	C <sub>b2</sub>	L/s	473
Q <sub>6</sub>	mbar-L/s	$1.0 \times 10^{-4}$	C <sub>t1</sub>	L/s	76
Q <sub>7</sub>	mbar-L/s	$8.4 \times 10^{-5}$	S <sub>B</sub>	L/s	300

### RESULTS AND DISCUSSION

The computed pressures at the different points in the cyclotron are given in table 2. Experimentally, we have no information on the pressure in the hills and in the valleys (in the median plane). However, the pressure measured at the level of the cyclotron cryopumps can be compared to the pressure in the pumping valleys (P<sub>3</sub>). Although there is a factor ~1.5 between these two pressures, it has little impact on the transmission results because the beam losses are mainly due to residual gas stripping in the poles and in the dees where the pressure is higher by a factor ~10. The pressure at the level of the

extraction vacuum chambers agrees well. Finally, it can be seen that the total transmission through the cyclotron is in good agreement with the experimental data.

Table 2: Pressure and transmission results for the ARRONAX Cyclone®70: our model versus measurements.

Position			Model	ARRONAX
Pole	P <sub>1</sub>	mbar	$1.02 \times 10^{-6}$	-
Gap	P <sub>2</sub>	mbar	$1.65 \times 10^{-6}$	-
Dee	P <sub>3</sub>	mbar	$1.75 \times 10^{-6}$	-
Pump. Val.	P <sub>4</sub>	mbar	$1.47 \times 10^{-7}$	$2.23 \times 10^{-7}$ *
Extraction	P <sub>5</sub>	mbar	$1.74 \times 10^{-6}$	$1.85 \times 10^{-6}$ †
Switch	P <sub>6</sub>	mbar	$1.47 \times 10^{-6}$	-
BTL	P <sub>7</sub>	mbar	$5.20 \times 10^{-7}$	-
Transmission	T	%	86.7	87.7

\*Average of the pressures measured close to the valley cryopumps.

†Pressure measured on the extraction vacuum chamber.

### CONCLUSIONS

The models set up to compute the residual gas pressure and beam transmission are in good agreement with experimental data. They were used to compute the performance of the ARRONAX Cyclone®70 (with the initial vacuum design) with an agreement of 1% on the beam transmission.

### REFERENCES

- [1] Y. Nakai et al, "Cross sections for charge transfer of hydrogen atoms and ions colliding with gaseous atoms and molecules", Atomic Data and Nuclear Data Tables 37 (1987) 69-101.
- [2] J.F. O'Hanlon, "A User's Guide to Vacuum Technology", Wiley, 3<sup>rd</sup> Edition.