EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN - LHC DIVISION

LHC-VAC/AGM

Vacuum Technical Note 96-01
January 1996

Beam-Gas Ionisation Cross Sections at 7.0 TeV

A.G. Mathewson and S. Zhang

1. Introduction

The quantity of interest in the ion induced pressure instability in proton storage ring vacuum systems [1] is the so-called critical current, ηI_C, which is defined as the product of the ion induced gas desorption yield η (molecules /ion) and the beam current I(A). At beam currents greater than the critical current the vacuum is unstable and large pressure increases are produced. In the calculation of the vacuum stability the equation to be solved is

$$\omega = \tan(\omega L) = \frac{S}{C} \tag{1}$$

where 2L is the distance between pumps (m)
2S is the pumping speed (ls^{-1})
C is the specific conductance of the vacuum chamber ($ls^{-1}m$)
σ is the ionisation cross section for the gas molecule (m^2)
e is the electronic charge = $1.602\ 10^{-19}$ (C)

and

$$\omega^2 = \frac{10^3 \eta\, I_c\, \sigma}{e\, C}$$

The factor 10^3 comes from the units used.

In practice L, S and C are design parameters for a given vacuum system and equation (1) is solved for ω and hence the critical current ηI_C. It can be seen that, for a given value of ω, the critical current is inversley proportional to the cross section σ thus its value is of prime importance when making estimations of the vacuum stability.

In the LHC the nominal energy of the circulating protons is 7.0 TeV, at which energy the ionisation cross sections for the gases commonly found in vacuum systems, H_2, CH_4, CO and CO_2, have not been measured.

The purpose of this note is to present, for the record, the expressions used to calculate the ionisation cross sections which were used in the analyses of the vacuum stability of the LHC experimental vacuum chambers and warm straight sections [2,3,4].

It has been proposed to measure the presssure in the cold parts of the LHC by using the 7 TeV proton beam to ionise the residual gas and collecting the resulting electrons [5]. Thus a knowledge of the ionisation cross sections at 7 TeV for the above gases and He (in case of leaks) would be an advantage in that absolute pressures in the cold parts could be measured.

2. Theory

In reference [6] and in a recent publication [7] the expressions for the ionisation cross section σ based on the Bethe theory were presented. In these same publications the relevant references were given and so will not be repeated here. However, in reference [7] only the relative ionisation cross sections were measured due to uncertainties in the calibration of the gas pressure and the sensitivity of the ionisation detector.

At energies greater than 100 keV the ionisation cross section σ for a gas by a particle of charge Ze is given by:

$$\sigma = 4\pi Z^2\left(\frac{\hbar}{mc}\right)^2 \frac{1}{\beta^2}\left(M^2 x + C\right) \qquad m^2 \tag{2}$$

where σ is the ionisation cross section for the gas molecule (m^2)
c is the speed of light=2.998 10^8 ($m\ s^{-1}$)
v is the speed of the ionising particle ($m\ s^{-1}$)
$\beta=v/c=0.99999998203$ for 7.0 TeV protons
m is the mass of the electron=9.109 10^{-31} (kg)
M^2 and C are constants depending on the molecule

and the function x is given by:

$$x = \ln\left(\frac{\beta^2}{1-\beta^2}\right) - \beta^2 \tag{3}$$

since β is ~1 this expression is more useful in the following form:

$$x = 2\ln(\gamma) - \beta^2 \tag{4}$$

where

$$\gamma = \frac{\beta}{\sqrt{1-\beta^2}}$$

and γ is the ratio of the energy of the proton relative to its rest mass
the rest mass of the proton =0.9383 GeV

and the rest mass of the electron =5.11 MeV

It is interesting that expression (2) depends only on the charge on the ionising particle and is independent of the mass i.e. in the high energy limit > 100keV, protons and electrons of the same velocity, β (or γ), have the same ionising cross section. For example 7.0 TeV protons have the same ionising effect as 3.81 GeV electrons. At CERN, 3.81 GeV electrons may be found in the SPS when it is acting as part of the injection chain for LEP. The electrons are injected from the PS at 3.5 GeV into the SPS where they are accelerated to 20 GeV before being injected into LEP.

In Table 1 are given the values of β, γ and the function x for protons at 26 GeV and 7.0 TeV.

Table 1

E	β	γ	$x=2\ln(\gamma)-\beta^2$
26 GeV	0.9986993	27.71	5.644
7 TeV	0.99999998203	7460	16.835

Putting in values for the fundamental constants the expression (2) for σ can be written:

$$\sigma = 1.874\,10^{-24}\,\frac{Z^2}{\beta^2}\left(M^2 x + C\right) \qquad m^2$$

It must be noted that the cross sections measured in reference [6] are so-called counting cross sections where the number of ionising events, irrespective of charge state, are counted. The ionisation cross section which takes into account the charge state of the ion is the gross ionisation cross section. The gross ionisation cross section is what would be measured in an ionisation cell in a proton or electron ring where all the charge from the ions produced by the beam traversing the cell is measured. The difference between the two cross sections is insignificant for molecules with few electrons such as H_2 but can be appreciable for Ar [8].

Ideally, for the stability calculations the number of ions in each charge state should be known since multiply charged ions have higher energies than singly charged ions and are more efficient at desorbing gas i.e. their ion induced desorption yield η is larger.

Table 2

Gas	M^2	C
H_2	0.695	8.115
He	0.752	7.571
CH_4	4.23	41.85
CO	3.70	35.14
CO_2	5.75	55.92

The constants M^2 and C have been calculated by Rieke and Prepejchal [5] from measurements of counting ionisation cross sections for various gases and these are given in Table 2 for H_2, He, CH_4, CO and CO_2.

The gross ionisation cross sections for H_2 and N_2 have been measured in the ISR at a proton energy of 26 GeV [9] and were found to be higher than the values calculated using the above expressions by a factors of 1.17 and 1.43 respectively (Table 3).

Table 3

Gas	**Calculated $\sigma \times 10^{-18}$ cm^2 (26 GeV)**	**Measured $\sigma \times 10^{-18}$ cm^2 (26 GeV)**	**Measured/Calculated**
H_2	0.226	0.264	1.17
N_2	1.05	1.5	1.43

To be prudent in our estimations of the vacuum stability we have therefore taken the calculated values of the ionisation cross sections from equation (2) and increased them by a factor of 1.2 for H_2 and He and by 1.5 for the heavier molecules CH_4, CO and CO_2 to bring them in line with the values measured at 26 GeV for H_2 and N_2. In Table 4 are shown the ionisation cross sections for H_2, He, CH_4, CO and CO_2 calculated for 26 GeV and 7.0 TeV protons. Also shown are the correction factors applied to the 7.0 TeV values. The corrected ionisation cross sections are those that are used in the calculations of vacuum stability in the LHC at 7.0 TeV.

Table 4

Gas	**Calculated $\sigma \times 10^{-18}$ cm^2 (26 GeV)**	**Calculated $\sigma \times 10^{-18}$ cm^2 (7 TeV)**	**Correction Factor**	**Corrected $\sigma \times 10^{-18}$ cm^2 (7 TeV)**
H_2	0.226	0.371	1.2	0.445
He	0.225	0.382	1.2	0.458
CH_4	1.23	2.12	1.5	3.18
CO	1.05	1.83	1.5	2.75
CO_2	1.66	2.86	1.5	4.29

3. Conclusions

The expressions used to calculate the ionisation cross sections of H_2, CH_4, CO and CO_2 for 7.0 TeV protons have been presented.

At energies greater than 100 keV the ionisation cross section depends only on the speed and charge on the ionising particle and is independent of the mass thus protons and electrons of the same speed have the same ionising effect.

The ionisation cross sections for 7 TeV protons may be measured by using 3.81 GeV electrons in the SPS.

The calculated cross sections for H_2 and N_2 were smaller than those measured at 26 GeV at the ISR by factors of 1.17 and 1.43 respectively. Thus the calculated values for H_2 were increased by 1.2 and all those for the heavier molecules by a factor of 1.5 and it is these corrected cross sections which are used in the calculations of the vacuum stability in the LHC.

4. Acknowledgements

The authors are indebted to Dr. K. Eggert for useful discussion and to Drs. R. Calder and O. Gröbner for a critical reading of the manuscript.

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