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Ion-Electron pairs production in the ESS Cold Linac (ESS-0092071)Ion-Electron pairs production in the ESS Cold Linac

Cold Linac NPM – Calculation of ion/electron pair production

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	Name	Role/Title
Owner	Jacques Marroncle	In-Kind Principle Responsible for the NPM Cold Linac
Reviewer	Cyrille Thomas	System Lead for the NPM system
Approver		

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1. INTRODUCTION

Ionization Profile Monitor (IPM) relies on collection of residual particles, ionized by the beam, with a read-out system. The design of the IPM must incorporate a good knowledge of the number of particles to be detected by the readout system. To this aim we present in this document the calculation that evaluates the number of ions/electron produced by the interaction of the ESS proton beam and the species present in the residual gas of the vacuum chamber.

1.1 Purpose

The purpose of this document is to estimate the quantity of ions/electrons, which should be detected by the read-out device. This estimation can be done without any particular tool.

1.2 Definitions, Acronyms and Abbreviations

Abbreviation	Definition
IPM	Ionization Profile Monitor
MCP	Microchannel Plate
NPM	Non-invasive Profile Monitor
RGA	Residual Gas Analyser
SC	Semi-Conductor

2. PREREQUISITES

This section explains briefly theoretical aspects of calculus and specific considerations for ESS beam.

2.1 Bethe-Bloch Formula & ion/electron pairs created

Bethe-Bloch formula [1] is used to quantify energy loss per distance in matter of a charged particle.

$$\frac{dE}{dx} = K \cdot \rho \cdot \frac{Z}{A} \cdot \frac{z^2}{\beta^2} \left[\frac{1}{2} \cdot \ln \frac{2 \cdot m_e \cdot (\beta\gamma)^2 \cdot T_{max}}{I^2} - \beta^2 \right]$$

Terms can be split in two parts, except for K which is an independent constant. First ones are particle related:

- The number of charges z
- The Lorentz factors β and γ
- And T_{max}

$$T_{max} = \frac{2 \cdot m_e \cdot (\beta\gamma)^2}{1 + 2\gamma \cdot \frac{m_e}{m_p} + \left(\frac{m_e}{m_p}\right)^2}$$

Then matter related terms:

- The matter density ρ
- Z/A ratio, always about 0.5 except for hydrogen.
- The mean excitation energy I [2]

Afterwards the quantity of ions/electrons created per pulse is given by:

$$N_{ionization\ pairs} = N_{beam} \cdot \frac{1}{W} \cdot \frac{dE}{dx}$$

Where:

- N_{beam} is the number of protons per pulse
- W is the necessary energy to produce an ion/electron pair [3] [4]
- $\frac{dE}{dx}$ energy loss as descripted above

2.2 ESS Beam & ESS Vacuum Chamber

The most important characteristics of ESS Beam are summarized in Table 1.

Table 1: Beam characteristics.

Characteristics	Value
Proton Energy (max. cold section)	2 GeV
Proton Energy (min. cold section)	90 MeV
Current (max)	62.5 mA
Pulse length	2.86 ms
Pulse repetition rate	14 Hz

Residual gas inside ESS vacuum chamber is consider like a mixture of gases,

Table 2. Those gases are supposed to behave like perfect gas. Therefore, the density of each gas in vacuum is:

$$\rho_i = \rho_{norm} \cdot \frac{n_i(\%) \cdot P}{P_{norm}}$$

Where, P is the total pressure in vacuum (10^{-9}mbar). P_{norm} is the pressure at Normal Temperature and Pressure Conditions (NTPC: 20°C, 1.01325 bar). Finally ρ_{norm} is the density of the i gas at NTPC.

The total quantity of ions/electrons created is the sum of contributions of each gas [1].

$$N_{total\,ionization\,pairs} = N_{beam} \cdot \sum_i \frac{1}{W_i} \cdot \left[\frac{dE}{dx}\right]_i$$

Table 2: Gas inside vacuum chamber.

Gas	**I(eV) [2]**	**W(eV) [3] [4]**	**n(%)**	**Partial density (g/cm3)**
H_2	19.2	36.3	79	6.5 e-17
CO	85.9	33.5	10	1.15 e-16
CO_2	85	32.5	10	1.8 e-16
N_2	82	35.5	1	1.15 e-17

3. RESULTS

The Bethe-Bloch formula shown in the previous section is implemented in both Excel sheet and C++ program.

3.1 At P=10^{-9}mbar, $L_{readout}$=1 cm, I_{nom}=62.5 mA, T=20°C, K={90 to 2000} MeV

Calculation is done with the following nominal value, 62.5 mA, for the current and with a readout length of 1 cm.

Figure 1 shows contribution for each gas. As described in section 2.2, the total amount of ion/electrons pairs is sum of these contributions, see Table 3.

Table 3: Ions/electrons created, charge and current, depending of protons beam energy for a read-out length of 1 cm.

Energy (MeV)	**Ions/Electrons per pulse**	**Charge (fC)**	**Current (pA)**
90	105986	17	5.9
200	60159	9.6	3.4
500	36622	5.87	2
1000	29463	4.72	1.65
1500	27717	4.44	1.55
2000	27224	4.36	1.52

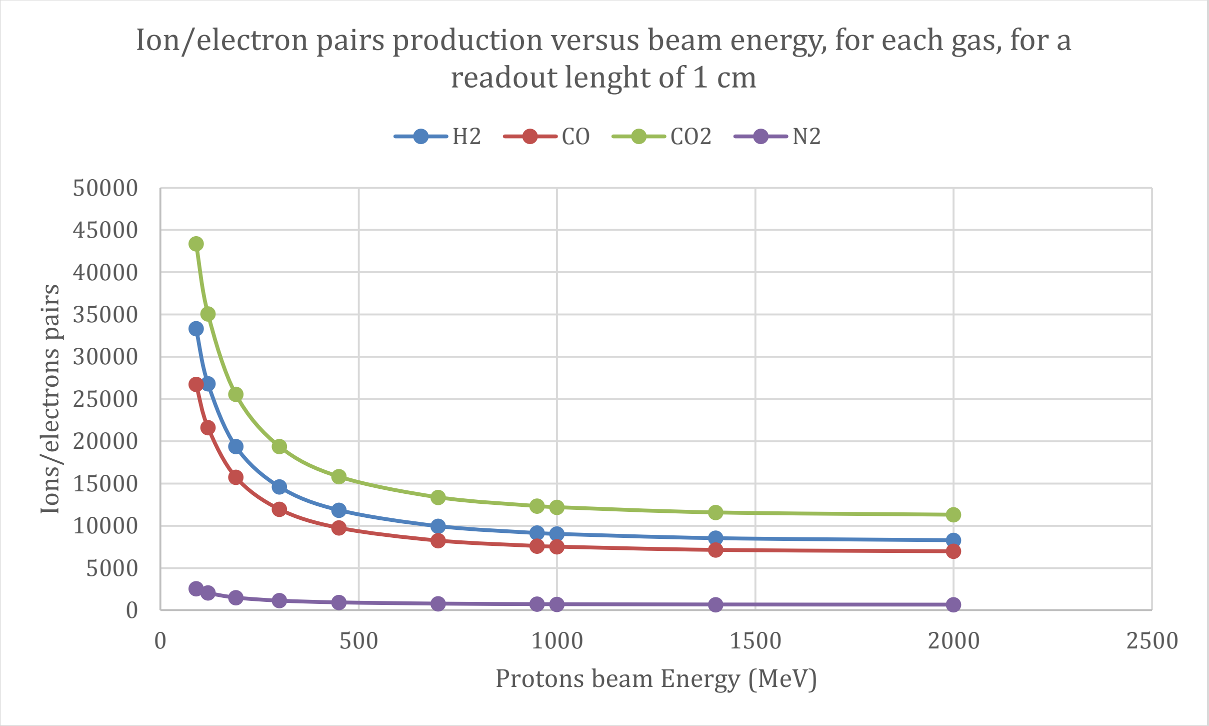

Figure 1: Ion/electron pairs production versus beam energy, for a readout length of 1 cm.

The more the energy of protons increases the less is the amount of ions/electrons. This result is in accordance with the Bethe-Bloch theory.

Also the contributions of carbon (mono/di)-oxide gas and dihydrogen are close even the huge proportional differences between them, due to their density.

3.2 CO_2 production by UV enlightening

Illumination of the vacuum chamber walls by UV light or even visible produces additional outgassing. This feature can be used to control the signal intensity for the IPMs.

In order to illustrate and partially quantify this phenomenon, we used a Residual Gas Analyser (RGA) coupled to a gas pressure gauge so that we could measure the increase of pressure together with what species are desorbed from the walls. The illumination is produced by a laser, 401nm which has approx. $\sigma = 3.8 \times 1.8\ \pi\ mm^2$, and a power of 5mW.

The main species measured by the RGA are H_2O, OH and CO_2. Figure 2 bellow shows the mass spectrum of the RGA with and without illumination with the laser. The total increase of pressure is $\Delta P = 8.0\ 10^{-11}$ mbar. The desorption efficiency depends on the wavelength, the power of the laser, but also the amount of surface illuminated. Here a small surface is illuminated since the divergence of the laser is 0.8mrad. Another experiment done earlier, but without recording the RGA data showed the main specie to increase to be CO_2. The total power of the LEDs used is much less than the laser one, but the divergence, and thus the total surface illuminated is larger. In this case the total increase of pressure is:

$\Delta P = 12.0\ 10^{-11}$ mbar. Further quantitative analysis should be done. But these observation may lead to take into account desorption phenomenon while designing the calibration system for the NPM. The level of additional pressure created by these small illumination powers and surfaces may not be enough, but pressure bump of the order of several 10^{-9} mbar could be expected for controlling and increasing the signal for the NPM.

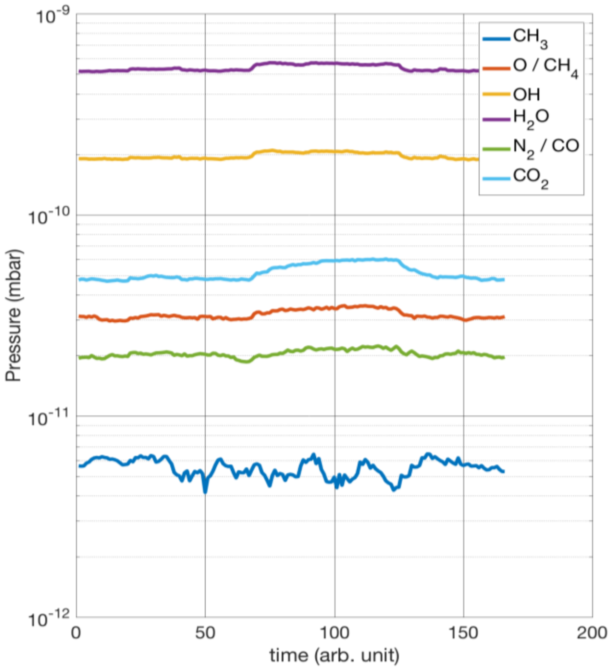

Figure 2: RGA data showing the partial pressure for the main species in presence. At the time shown as '60' the laser was switched on, illuminating a few mm^2 of wall in the chamber.

4. OVERALL CONCLUSION

4.1 Conclusion

As expected the amount of ions/electrons created is very low mainly because of the low gas pressure in vacuum chamber. Also at GeV energy, protons probability interaction is at its minimum. This is also predicted by the Bethe-Bloch formulation.

Read-out systems for the IPM must be able to detect weak signals as calculated above. Two kind of read-out systems can be considered:

- Directly acquire signal and integrating over several pulses
- Use high gain transductor like MCP or Semi-Conductor, and then acquire the single event amplified signal

These different read-out systems will be experimentally tested under beam. This topic is investigated more precisely by another document *(see "Read-Out systems for cold NPM")*.

4.2 Limitations of this study

The first kind of limitations depends of Bethe-Bloch formulation itself. Indeed, few parameters (I and W) come from experiments with some uncertainty.

Finally, Bethe-Bloch model only give just an estimation of amount of particles but nothing about the characteristics of these particles like the position, the motion and the behaviour inside the IPM.

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