SUMMARY OF DENSE HYDROGEN GAS FILLED RF CAVITY TESTS FOR MUON ACCELERATION *

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Abstract

We show the recent analysis of a dense gas-filled RF cavity test by using a 400 MeV proton beam from Fermilab Linac. A large amount of RF power loading was observed in a gas-filled RF test cell when protons pass through the test cell. It can be explained that an ionized electron-ion plasma consumes RF power and transfers its kinetic energy to neutral gas molecules via the Coulomb interaction. We used several correction factors based on certain assumptions to evaluate the RF power consumption. The validity of these corrections and assumptions is discussed in this report.

Protons lose some of their kinetic energy before entering the RF field. Table 1 shows the average energy loss of protons in the various materials in which the protons pass through. Secondary particles are produced in the apparatus and air via the interaction between protons and materials.

The stopping range of electrons in air has been reported [4]. Low energy electrons (K < 1 keV) in air are eliminated from this analysis because their stopping range is very short (<< 1 mm). On the other hand, a large number of delta rays (K > 1 keV) that are produced upstream of the collimator are eliminated by the collimator. A very small number of delta rays (< 2 × 10^4 e/p) can be produced in air and go through the beam monitor system. The yield of surface emission electrons [5,6] in the collimator hole is calculated. Although there are some uncertainties due to the details of geometric correlation between the beam angle and the material surface, the spectrum of surface emission electrons per proton is given

$$P(\varepsilon) = c \varepsilon U_0 e^{-\varepsilon K_0 a},$$

where c is a constant, $U_0$ (∼ 10 eV) is the work function of material, and $a$ is the power of stopping power ($a$ ∼ 4). $P(\varepsilon)$ is maximum at $\varepsilon \sim 2$ eV and it is $\sim 10^{-9}$ at $\varepsilon > 1$ keV. The overall effect of secondary electrons on the toroid current transformer and the scintillating screen is less than 1%, which is negligible in the rest of analysis.

Table 1: Material, thickness, energy loss and initial and final kinetic energies of a proton beam, respectively.

<table>
<thead>
<tr>
<th>Element</th>
<th>Thickness</th>
<th>dK</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>MeV</td>
<td>MeV</td>
</tr>
<tr>
<td>Initial</td>
<td></td>
<td></td>
<td>401.5</td>
</tr>
<tr>
<td>Ti-vacuum window</td>
<td>0.05</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>880</td>
<td>0.283</td>
<td></td>
</tr>
<tr>
<td>Scintillating screen</td>
<td>1.00</td>
<td>0.814</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>400</td>
<td>0.129</td>
<td></td>
</tr>
<tr>
<td>SS-beam window</td>
<td>3.18</td>
<td>5.56</td>
<td></td>
</tr>
<tr>
<td>Cu electrode</td>
<td>3.18</td>
<td>5.99</td>
<td></td>
</tr>
<tr>
<td>Final</td>
<td></td>
<td></td>
<td>388.2</td>
</tr>
</tbody>
</table>

Estimating the yield of gamma rays and its contribution in the TC is more complicated because high energy photons have long attenuation lengths in a material. We use G4beamline [7] to estimate the yield of gamma rays in our exact geometry. Table 2 shows the abundance of secondary particles in the TC. A large amount of high-energy gamma rays (> 10 keV) are produced in the

Fig. 1: Whole layout of experimental apparatus and simulated radial distribution of electron-ion gas plasma in the TC and the normalized radial electric field distribution.

*Work supported by Fermilab Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
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upstream apparatus from the TC via nuclear interactions. The cross-section of electron-production interactions of high-energy gamma rays with hydrogen is negligible \((10^{-21}\, \text{cm}^2\) or less). Photons in the middle energy range \((100\, \text{eV} \text{ to } 10\, \text{keV})\) could also be produced via the Bremsstrahlung and K-shell electron capture processes. However, the production rates of such photons are negligible (See Table 2). Overall contributions of the photo-ionization process should be less than 1%. It is reasonable to ignore all secondary particles except for secondary protons in the analysis.

Table 2: Simulated yield of secondary particles in the TC. The values are normalized by the yield of protons.

<table>
<thead>
<tr>
<th>Species</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton (With the primary)</td>
<td>1.0</td>
</tr>
<tr>
<td>Gamma (All K)</td>
<td>0.73</td>
</tr>
<tr>
<td>Gamma (K &lt; 10 keV)</td>
<td>(4.2 \times 10^{-5})</td>
</tr>
<tr>
<td>Pion (+/-)</td>
<td>(8.0 \times 10^{-4}/1.6 \times 10^{-4})</td>
</tr>
<tr>
<td>Electron-Positron</td>
<td>6.3 \times 10^{-4}</td>
</tr>
</tbody>
</table>

The electron-ion pair production rate is estimated by using a formula,

\[
\dot{N} = \dot{N}_b \times \sum_k w_k \left( \frac{\rho_m dE/dx}{W_i} \right)_{k} ,
\]

where \(h\) is the propagation distance, and \(w_k, \rho_m, dE/dx,\) and \(W_i\) are the abundance, mass density, stopping power, and effective average energy to produce single ion-pair of the \(k\)-th gas molecule \(\sum_k w_k = 1\), respectively. The mass density of hydrogen is calibrated by using the Van der Waals equation. The correction factor is 7.5% in 100 atm \(\text{H}_2\).

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In order to estimate the RF stored energy in the TC, we calculate the capacitance of the TC, \(C_{TC}\). \textit{SuperFish} provides the RF stored energy, \(\varepsilon = 2.4 \times 10^{-4}\) Joules at \(E = 1\) MV/m in 100 atm \(\text{H}_2\) gas (frequency = 801.4 MHz). The gap between the two electrodes is 17.7 mm. Thus, \(C_{TC}\) is 1.53 \(\text{pF}\) \((C_{TC} = 2\varepsilon/V^2)\). \(C_{TC}\) is a function of resonant frequency, hence it is a function of gas pressure. It is worth noting that the capacitance correction also takes into account the possible deformation of the TC due to high gas pressure because we use the measured resonant frequency to estimate \(C_{TC}\). Fig. 3 shows the measured
resonant frequency as a function of gas pressure in pure H$_2$ gas.

**POSSIBLE SYSTEMATIC ERROR IN BEAM INTENSITY DEPENDENCE ON RF POWER LOADING MEASUREMENT**

Fig. 4 shows the measured $dw$ in 20 atm H$_2$ gas at various electric fields ($E_{\text{peak}} = 5, 10, 18 \text{ MV/m}$) as a function of beam intensity. First, the fluctuation of RF peak gradient is calibrated by using a power curve fit to $dw$ as a function of $X_0$ where $X_0$ is the ratio between $E_{\text{peak}}$ and the gas pressure. The residual of fit is within a few %. Then, the $dw$ is averaged. That is the corrected $dw$.

![Fig. 4: Measured $dw$ vs Beam current. Gas pressure is 20 atm. The middle line in the set of lines is the best fit and other two correspond to a range of error with 3σ confidence level.](image)

Fig. 5 shows the deviation of measured $dw$ at the lowest and highest beam intensities for various gas pressures. The measured $dw$ tends to be low at high beam intensity in low gas pressure (negative deviation) and vice versa in high gas pressure (positive deviation). We define this deviation as a systematic error, which is $5\sim10\%$.

![Fig. 5: Plot shows the systematic error due to the beam intensity dependence.](image)

Fig. 6 is the corrected $dw$ as a function of $X_0$ for various gas pressures. Each $dw$ has an analysis error which involves the statistic and fit errors. It is typically a few %. The solid lines are the analytical $dw$ that is estimated by using Eq. (2). The analytical $dw$ is in good agreement with the measured $dw$ at low gas pressure. However, the measured $dw$ has larger discrepancy at higher gas pressure and lower $X_0$. It can be a gas pressure effect. We discuss the gas pressure effect in refs. [1,10,11].

![Fig. 6: Corrected $dw$ as a function of $X_0$. The solid lines are a prediction from gas-plasma dynamics in RF fields [1,2].](image)

**SUMMARY**

We investigated the measured $dw$ and evaluated its systematic error. The large systematic error was found in the beam intensity dependence. It is $10\%$. On the other hand, the statistic error is very small, i.e. it is typically $2\sim3\%$. The deviation of measured $dw$ from the prediction is larger than any systematic and statistic errors. It means that the pressure dependence is real.

**ACKNOWLEDGMENT**

We thank to Vladimir Shiltsev and Mark Palmer for supporting this program. We also great thank to the Fermilab Accelerator Division, the safety group, and the beam operator for helping this experiment.

**REFERENCES**