LHCb Collaboration

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Vacuum studies with a VELO module

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Abstract

LHCb VELO modules will be operated in low vacuum with voltages as high as 500 V on both hybrids of the module. This note provides the first study on the breakdown voltages of a pre-production VELO module with varying pressures and venting with air. The breakdown voltages are measured by studying the leakage currents of the sensors on the module and the measured breakdown curve is compared to the theoretical breakdown for a parallel plate capacitor. The effect of breakdown on the noise of the sensors is also studied. It is concluded that the modules should not be operated at voltages above 500 V over a pressure range of 0.1-760 Torr.

1 Introduction

The LHCb VELO modules will operate in the LHCb experiment at low pressures and with high voltages. However, there is limited information available on the voltages that may be safely applied to the modules if the modules are operated at higher than design pressures which could happen during the start-up phase of LHCb. This study presents some preliminary pressure investigations that have been performed on a pre-production VELO module to evaluate the breakdown voltages of the module when vented with air.

2 Breakdown voltage

The breakdown voltage of a parallel plate capacitor can be described by Paschen's curve [1], which is given by:

$$V_{breakdown} = \frac{B.p.d}{(C + \ln(p.d))}. \tag{1}$$

B is a constant which is 365 $\mathrm{Vcm^{-1}Torr^{-1}}$ for air. The variables p and d are the pressure in Torr and the distance between the parallel plates in centimeters. C is also a constant which is 1.18 for air and is calculated from equation 2.

$$C = \ln(\frac{A}{\ln(1 + \frac{1}{\gamma})}) \tag{2}$$

A is a constant which for air is 15 $\mathrm{cm^{-1}Torr^{-1}}$ and γ is the secondary ionization coefficient which is 10^{-2} for air. The humidity and the temperature affects the breakdown voltage of the capacitor, however, these effects are not discussed in this document.

Paschen's curve is shown in Figure 1 for three different plate separations; 0.1 mm, 1 mm and 10 mm. Breakdown occurs due to electron ionization. If an electron moves in an electron field it can generate electron-ion pairs from the atoms in the medium between the two plates. A constant supply of avalanche forming electrons are required near the cathode of the capacitor in order to have constant breakdown. The minimum voltage required to achieve breakdown is 330 V for all plate separations.

If the pressure is too low then there are too few impacts between the moving electron and the surrounding atoms to achieve an avalanche. Any electron-ion pairs that are created do not have sufficient energy to achieve any further ionization. So the breakdown voltage increases as the pressure is decreased.

If the pressure is too high then there are too many impacts between the moving electron and the surrounding medium. The energy of the electron is wasted in minor electronic excitations rather than ionization. Hence the breakdown voltage increases as the pressure is increased.

3 VELO modules

Each VELO module has a double sided hybrid, where each side of the hybrid has a single sided 300 μm thick n^+-on-n silicon sensor. There are two types of VELO silicon sensors - one is an R-sensor and one is a ϕ-sensor. Details of the design of the VELO modules are given in [2].

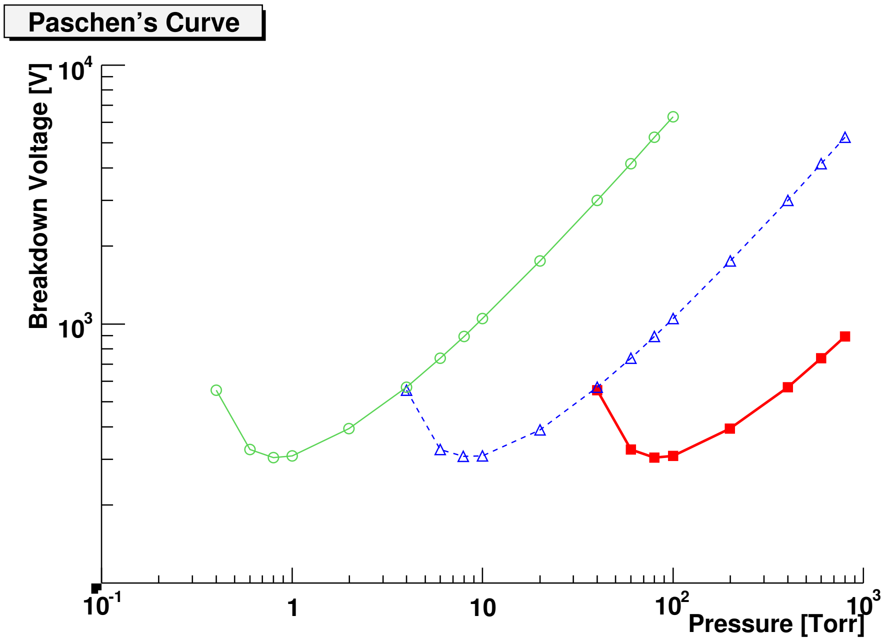

Figure 1: Paschen's curve describes the breakdown voltage of a parallel plate capacitor as a function of pressure in Torr. The green solid line with circle markers is for a plate separation of 10 mm. The blue dashed line with triangle markers is for a plate separation of 1 mm. The red solid line with square markers is for a plate separation of 0.1 mm. The minimum breakdown voltage for all plate separations is 330 V.

There are many possible places where the module could breakdown. The high voltage is routed to the sensor via the hybrid hence breakdown could happen on the sensor or on the hybrid. Possible places could be the pins on the kapton connector on the hybrid which carries the high voltage or over the edge of the sensor. Hence the typical distances over which breakdown could occur is probably between a few hundred microns up to approximately a centimeter. The maximum high voltage that will be applied to the sensors during the LHCb experiment is 500 V.

4 Experimental set-up

The experiment was performed using the VELO burn-in system which has been used to qualify the VELO modules during production [3], [4]. The system consists of a vacuum chamber which is equipped to reach pressures as low as 10^{-6} Torr. The module can be cooled using a cooling block which is pressed against the cooling face of the module. The high voltage and data readout are described in [4].

The experiment was performed on module 20 (M20) which was a high quality pre-production module. The silicon sensors were only 200 μm thick on M20 whereas the production sensors are 300 μm thick. The burn-in set-up did not have the capabilities to separate the bulk and the guard leakage currents. The vacuum chamber was placed in a well controlled class 100,000 clean room with 45 % humidity and a constant room temperature of 21^{o}C. There are three possible configurations for the use of the hybrid high voltage guard traces: floating, grounded, or shorted to the high voltage. In this experiment these traces were left floating.

5 Results

5.1 Leakage current at low pressures

The leakage currents from both the R and ϕ-sensors on M20 were characterized at low pressure to fully understand the behaviour of the module. The depletion voltage of the R and ϕ-sensors were measured using the capacitance-voltage technique in Liverpool University and it was found to be 70 V and 80 V respectively [5]. The maximum bias applied to the R-sensor was 250 V and the maximum voltage applied to the ϕ-sensor was 420 V. The R-sensor was not operated above 250 V as the sensor breakdown voltage measured from the leakage current and at low pressure (10^{-6} Torr) was approximately 300 V.The bias voltage was ramped up and down using ramp speeds between 0.4 - 1.0 Vs^{-1}. The pressure used for this characterization was 10^{-5} Torr.

The temperature of the silicon dramatically affects the leakage current. If the leakage current is dominated by the leakage of charge carriers across the band gap of the silicon, E_g, then equation 3 can be used to scale the leakage current measured, I, at a temperature T to a reference temperature T_{ref}.

$$I(T_{ref}) = I(T).(\frac{T_{ref}}{T})^2.exp((\frac{-E_g}{2k_B})[\frac{1}{T_{ref}} - \frac{1}{T}]), \qquad (3)$$

where k_B is the Boltzmann constant. The leakage current was measured at 250 V and 420 V respectively for the R and ϕ-sensors at 4 different temperatures on the hybrid. The leakage current measured at 26 ^{o}C was scaled using equation 3 to the other 3 temperatures and the measured and the temperature normalized currents were compared to verify that the sensors behaved as expected. Figure 2 shows the comparison for the R and ϕ-sensors of M20.

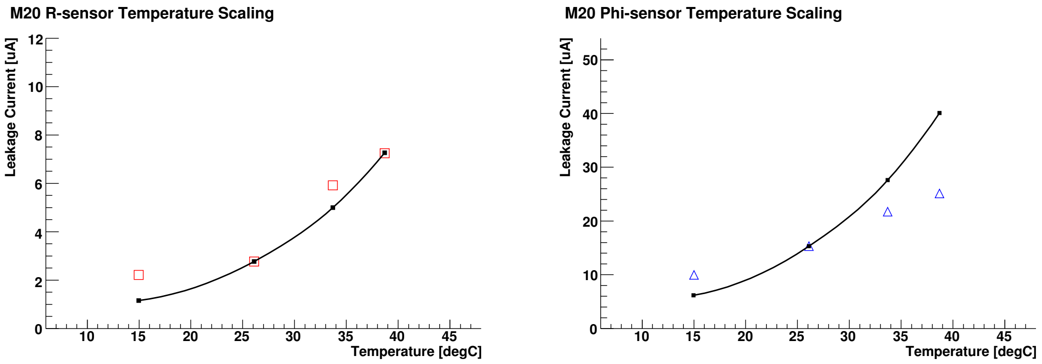

Figure 2: The leakage current measured at 250 V on the R-sensor (left plot) and 420 V on the ϕ-sensor (right plot). The pressure was 10^{-5} Torr. The leakage current measured at 26 ^{o}C was scaled using equation 3 to the other 3 temperatures. The open square (triangle) markers were the measured R (ϕ) leakage current and the solid squares were the temperature scaled leakage currents.

The temperatures used in the scaling were the temperatures of the hybrid and not the silicon temperature. However, the measured and the predicted leakage currents approximately agree to within a factor of two. This was not the case for all VELO modules [4].

5.2 Leakage current behaviour with varying pressures

The leakage current was measured at five pressures in the range of 760 Torr (atmosphere) and $6\text{x}10^{-6}$ Torr. The current-voltage plots are shown for both the ramp up and ramp down for the R and ϕ-sensors in Figure 3.

Figure 3 shows that the R-sensor leakage current does not seems to depend on the vacuum whereas the maximum leakage current of the ϕ-sensor does have a small dependence on the pressure. This is more clearly illustrated in Figure 4 which shows the maximum measured and temperature corrected leakage current for the R and ϕ-sensors at 250 V and 420 V respectively.

5.3 Measured breakdown voltages

The maximum high voltage that will be applied to the VELO modules during the LHCb experiment is 500 V. The pressures where breakdown would occur below 500 V bias can be calculated using Paschen's curves for breakdown distances between 0.1 mm and 1 cm, see Figure 1: the corresponding pressure range is 0.2 - 200 Torr.

The leakage current behaviour of the ϕ-side of M20 was measured at a pressure of 3 Torr. The bias voltage was increased to 300 V at a ramp speed of 0.8 Vs^{-1} and then it was increased at a ramp rate of 0.4 Vs^{-1} in steps of 10 V to a maximum voltage of 420 V. The behaviour of the leakage current with the bias voltage is shown in Figure 5. The sudden increase in the leakage current at 375 V in Figure 5 is indicative of breakdown occurring. The breakdown effect on the leakage current was reproducible at the same voltage within ±5 V. This breakdown voltage was measured for a total of 5 different pressures and the results are shown in Figure 6. To measure the breakdown voltage a maximum of 600 V was applied to the ϕ-side of the hybrid. The bias voltage was increased to 350 V at a ramp speed of 0.8 Vs^{-1} and then it was increased at a ramp rate of 0.4 Vs^{-1} in steps of 10 V to the voltage where breakdown was observed in the leakage current.

The minimum of the measured device breakdown is approximately 370 V. This value is very close to the minimum value of Paschen's curve which is around 330 V. The measured device breakdown has approximately the same behaviour as Paschen's curve. The breakdown voltage increases with both increasing pressure and decreasing pressure. The range of pressure at which breakdown was observed with an applied voltage of less than 500 V was 0.1-5 Torr. The measured device breakdown is shown superimposed on the Paschen's curves from Figure 1 in Figure 7. The breakdown voltage was higher than 600 V for pressures less than 0.1 Torr.

5.4 Noise

The noise of the strips on each sensor on the hybrid would be affected by breakdown if the breakdown occurred on the sensor. To investigate possible positions of the breakdown, the noise of each channel was measured as the pressure was varied. Pedestal and common mode correction were performed using the algorithms described in [4]. The mean noise

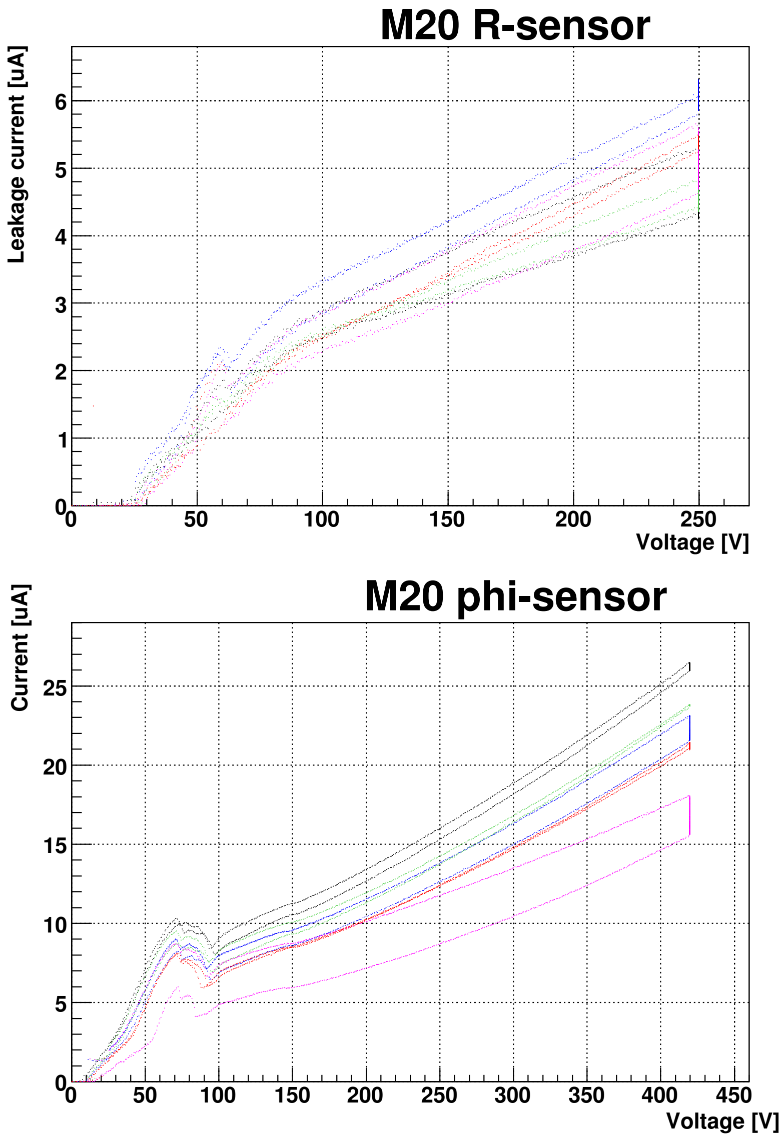

Figure 3: The leakage current-voltage behaviour for the R (top) and ϕ-sensors (bottom). The maximum voltages applied were 250 V to the R-sensor and 420 V to the ϕ-sensor. At each pressure the ramp up to the maximum and the ramp down to 0 V is shown. Each pressure is plotted in a different colour. Pink is 760 Torr, red is 6 x10^{-2} Torr, blue is 10^{-5} Torr, green is 3x10^{-4} Torr and black is 6x10^{-6} Torr. The R-sensor shows very similar curves for all pressures. The ϕ-sensor shows some dependence of the maximum leakage current on the pressure.

and the common mode corrected noise for all 2048 channels on each sensor is shown as a function of pressure in Figure 8. The noise values were measured at 250 V and 420 V for the R and ϕ-sensors except for two noise measurements on the ϕ-sensor which were taken at 350 V. These two measurements were made at 350 V and not 420 V since at these pressures the ϕ-side of M20 was breaking down below 420 V. Figure 8 shows that the mean noise and the mean common mode corrected noise do not change as the pressure is varied.

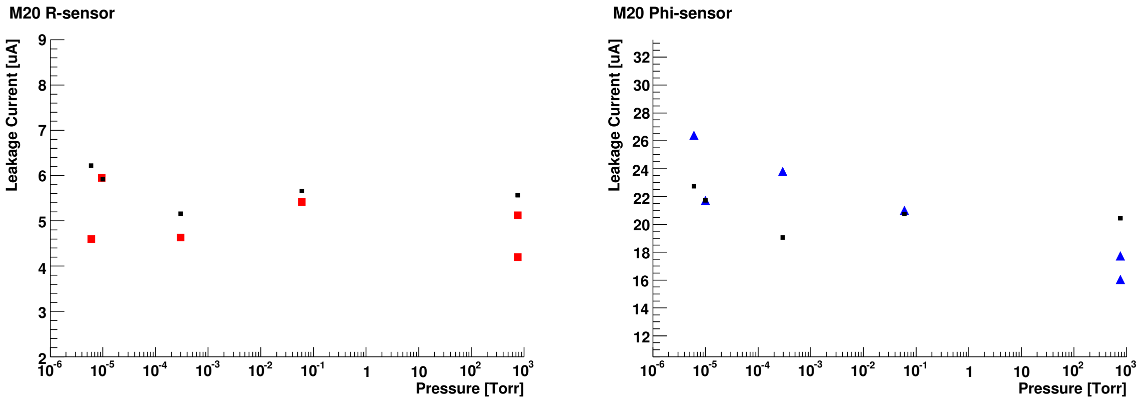

Figure 4: The left plot shows the measured (open red square markers) and the temperature corrected (closed black square markers) leakage current at 250 V for the R-sensor as a function of pressure. The right plot shows the measured (open blue triangle markers) and the temperature corrected (closed black square markers) leakage current at 420 V for the ϕ-sensor as a function of pressure.

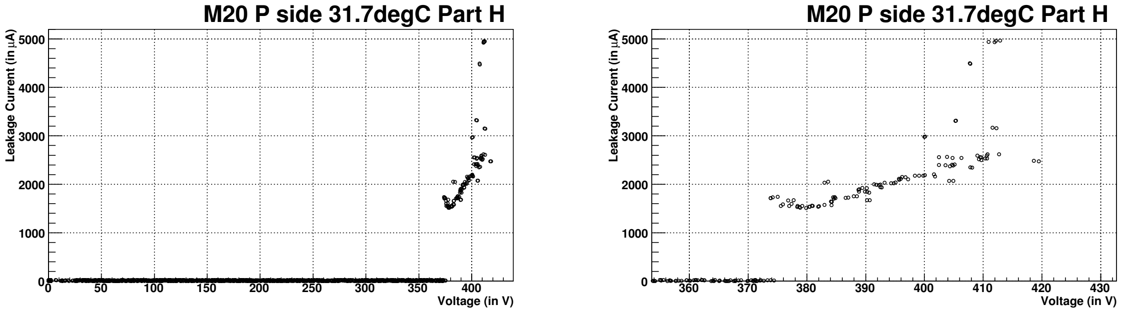

Figure 5: The left plot shows the leakage current behaviour with bias voltage on the ϕ-sensor of M20 measured at a pressure of 3 Torr. The right plot shows a zoom in section of the voltage range between 355-430 V. At 375 V the leakage current jumps from 20 μA to 1.7 mA. The leakage current behaviour up to a voltage of 375 V was standard.

Since the mean values of the noise and common mode corrected noise is calculated over a large number of strips it is useful to examine the noise of each strip. The left hand plot of Figure 9 shows the raw noise and the common mode corrected noise for each of the 2048 channels for ϕ-side of M20 at low pressure (6x10^{-6} Torr).

The left plot in Figure 9 was taken in low pressure at at 420 V and the leakage current behaviour at low pressure confirmed that there was no breakdown on the hybrid at this pressure. This should be compared to the plot on the right of Figure 9 which shows the noise values measured for the ϕ side of M20 measured at 390 V in 0.4 Torr when the leakage current measurements confirmed the hybrid had just started to breakdown.

The noise shown in both of the plots in Figure 9 are very similar, even though the leakage current measurements confirm the presence of breakdown in the latter plot. It can be concluded that it is likely that the location of the breakdown is not on the sensor.

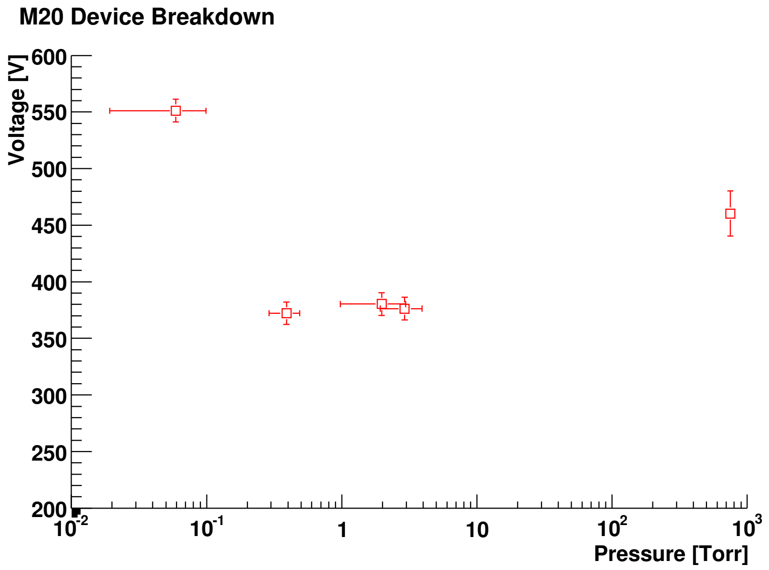

Figure 6: The measured device breakdown on the ϕ-side of module 20. The voltage at which the device broke down was defined through the sharp increase in the leakage current.

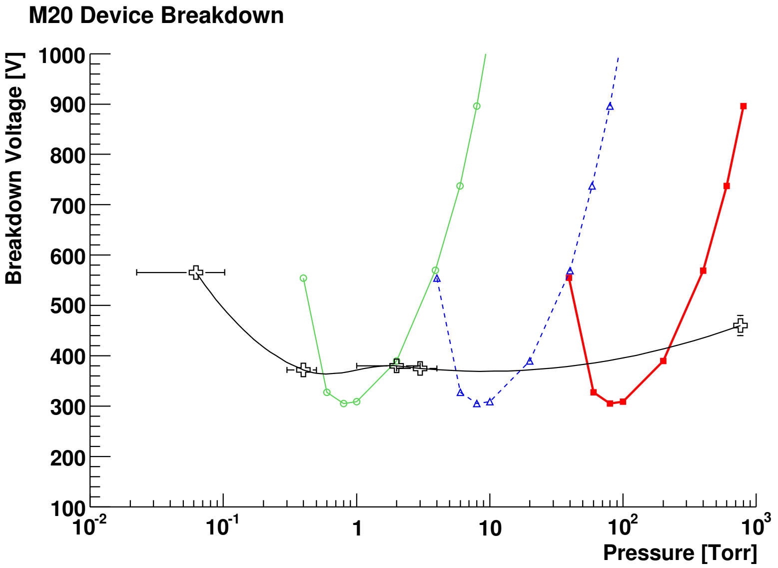

Figure 7: The measured device breakdown in module 20 (black crosses) superimposed on the three theoretical Paschen's curves for plate separations of 10, 1 and 0.1 mm (see Figure 1).

5.5 Neon

In the LHCb experiment the VELO will be vented in neon gas. The gas changes both the minimum breakdown voltage of Paschen's curve and the pressure at which the minimum occurs. The minimum breakdown voltage in air is approximately 330 V. The minimum breakdown voltage in neon is approximately 230 V [6], and drops further if the Neon

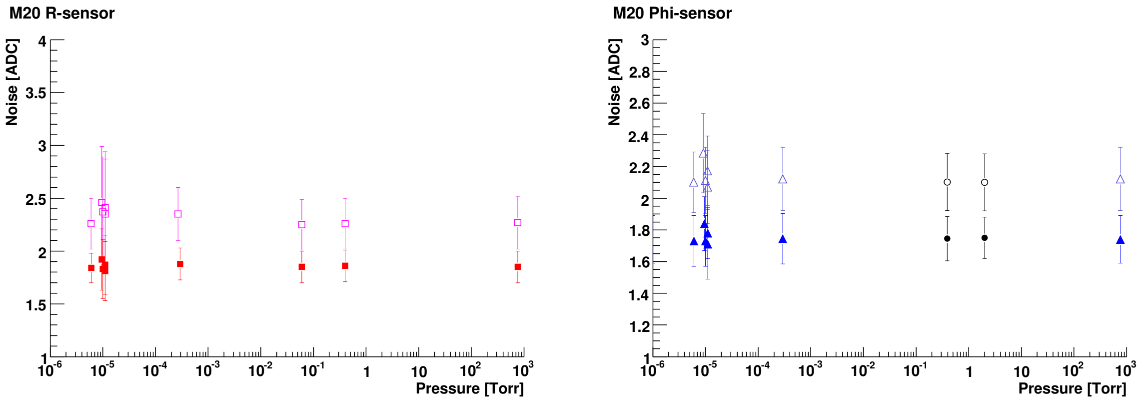

Figure 8: The left plot shows the mean noise (open pink square markers) and the common mode corrected noise (red solid square markers) for the 2048 channels on the R-sensor. The right plot shows the mean noise (open light blue triangle markers) and the common mode corrected noise (blue solid triangle markers) for the 2048 channels on the ϕ-sensor. The noise values were measured at 250 V and 420 V for the R and ϕ-sensors respectively except for two noise measurements on the ϕ-sensor which were taken at 350 V. The mean noise at 350 V on the ϕ sensor are the open black circle markers and the common mode corrected noise at 350 V are the solid black circle markers.

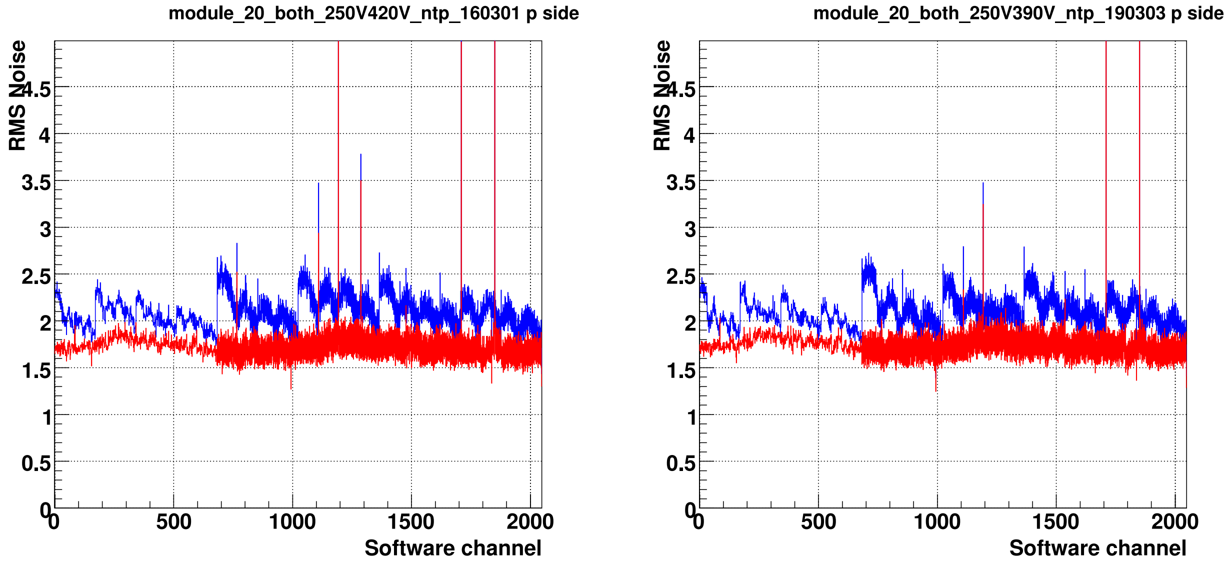

Figure 9: Left plot: The raw (blue line) noise and the common mode corrected noise (red line) for the ϕ-sensor at 420 V and 6x10^{-6} Torr. Right plot: The raw (blue line) noise and the common mode corrected noise (red line) for the ϕ-sensor at 390 V and 0.4 Torr. The hybrid had just begun to breakdown.

has small contaminants of Argon (180 V at 0.1 % contamination). Hence, for safety the LHCb VELO modules should not be operated at even the nominal start-up voltage over the critical pressure range.

The critical pressure range also differs from air to Neon, with the breakdown not occurring till higher pressures in Neon. The pressure range over which a parallel plate capacitor breaks down at 500 V in air is 0.2 - 2 Torrcm to be compared with 1 - 35 Torrcm for neon [6]; the breakdown limit very slightly increases with Neon conataining contaminants of Argon. Hence operation in Neon should be a smaller risk than in air at pressures below the minimum pressure at which breakdown is measured in air in this note. However, an experimental verification of this for the VELO would be useful.

6 Conclusions

A pre-production LHCb VELO module has been tested for breakdown with varying air pressures. No breakdown was measured for the R-hybrid which was as expected since it was only tested at 250 V bias, compared to 330 V which is the minimum voltage required for breakdown in a parallel plate capacitor. Breakdown has been measured through the leakage current of the ϕ-hybrid. The device breakdown curve has been measured as a function of pressure.

The noise of the ϕ-sensor showed no evidence of breakdown, even when the noise was measured at 0.4 Torr and 390 V bias and the leakage current was showing breakdown in the hybrid. For a parallel plate capacitor in air with plate separations of between 0.1 mm and 10 mm the pressure range over which the capacitor could breakdown with an applied voltage of 500 V is 0.5 - 400 Torr. The experimentally derived pressure range where the VELO modules could breakdown with the maximum high voltage of 500 V is between 0.1 - 760 Torr (0.13 - 1013 mbar).

The current pressure interlock for LHCb is 10^{-3} mbar so the range where the modules could be at risk from breakdown is well above the pressure interlock values. However, this experiment was limited by only testing with constant humidity, using 200 μm thick sensors and using air to vent. In the LHCb experiment the VELO modules will be vented with Neon, rather than with air. Using the burn-in set-up it was not possible to experimentally test how the gas affects the breakdown voltages. However, the pressure range over which a capacitor breaksdown in neon is higher than the pressure range over which it would breakdown in air.

From these studies we conclude that the VELO modules should not be operated at voltages above 500 V over a pressure range of 0.1 - 760 Torr.

References

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