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A1_6 Critical Pressure Inside the Large Hadron Collider

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Abstract

In the paper we examine the vacuum conditions inside the beam pipe at the Large Hadron Collider. A hypothetical degradation of the ultra-high vacuum by air particles is modelled. By considering the mean free path, we calculate the maximum pressure that would allow the accelerated protons to complete one lap of the accelerator without being scattered by gas particles. This threshold pressure is found to be 0.246 mbar.

Introduction

In September 2008, just nine days after coming online for initial tests, the Large Hadron Collider (LHC) experienced a catastrophic mechanical failure known as a quench incident [1]. An electrical fault caused liquid helium used to cool a series of the magnets to vent into the tunnel, and the explosive release also caused a degrading of the vacuum in the beam pipes [2]. In this paper we investigate the consequences of a compromise in the vacuum conditions under which the LHC operates, and estimate the minimum pressure that the beam pipe could tolerate in order to allow protons to travel around the accelerator without being scattered.

Mean free path and pressure

The mean free path, λ, is distance that a particle can travel before undergoing a collision. It can be shown that for particles moving at high velocity relative to an ensemble of other particles each with a cross section σ, the mean free path is given by

$$\lambda = \frac{1}{\sigma n}, \tag{1}$$

where n is the number of target particles per unit volume.

In the scenario of a breach in the vacuum at the LHC, the particles entering the beam pipe are assumed to be air particles. The proton-air scattering cross section is approximately 400 mbarns (4.0×10^{-29} m^2) for the standard energies used at the LHC (~ 4 TeV) [3]. In order for an accelerated proton to travel the circumference of the LHC, we require the mean free path to equal the distance of the circumference, L. Rearranging Eq. (1) we find that the threshold number of air molecules per unit volume is

$$n = \frac{1}{\sigma L}. \tag{2}$$

Using the value of the circumference of the LHC, $L = 2.67 \times 10^4$ m [4], along with $\sigma = 4.0 \times 10^{-29}$ m^2 results in a value of $n = 9.36 \times 10^{23}$ m^{-3}. To see how this value compares with vacuum conditions that would normally be present in the LHC, we can use the ideal gas law:

$$P = \frac{N}{V} k_B T = n k_B T, \tag{3}$$

giving a pressure inside the beam pipe of $P = 0.246$ mbar, where we have used $T = 1.9$K [4]. CERN states that the actual pressure inside the LHC beam pipe is an ultra-high vacuum (UHV) of the order 10^{-10} - 10^{-11}mbar [5]. For the UHV inside the beam pipe we can use equations (1) and (3) to calculate the mean free path for a proton in the LHC under normal conditions, and find $\lambda = 6.56 \times 10^{13}$ m (using $P = 10^{-10}$ mbar in this instance).

Beam lifetime

The LHC uses tightly focused bunches, each containing $\sim 1.1 \times 10^{11}$ protons [4]. Even with such a high number of protons, and a mean free path of 6.56×10^{13} m, the lifetime of the bunches is an important consideration for experimenters. Since the protons in the beam at the LHC travel at speeds just below the speed of light, we can find the lifetime τ of the bunches by the relation $\tau \simeq \frac{\lambda}{c} \simeq 60$ hrs. A beam lifetime of this magnitude allows the protons to complete a high number of orbits in any one run of an experiment. Therefore, our assumption that the critical pressure is that which prohibits just one orbit is not in line with realistic practicalities of experiments run at the LHC.

None of the analysis presented here has considered proton-proton scattering, which would also contribute to the beam lifetime. Such a calculation is beyond the scope of this report, and is suggested as a possibility for future investigation.

A brief sidenote observation is that the high relativistic speeds of the protons does not alter the analysis in the report. Although the length of the beam pipe will contract by the Lorentz factor in the particles' reference frame, the number of air particles per unit volume will increase by an equivalent factor. The two effects precisely cancel out, and so relativistic effects do not impact the results.

Conclusion

The UHV conditions at the LHC are crucial to its successful operation. We have shown that a degradation of the vacuum to 0.246 mbar would prevent any protons completing a single circuit of the accelerator. In reality the LHC would be unable to function at pressures much lower than 0.246 mbar, and actually requires UHV pressures of the order 10^{-10} mbar in order to preserve the beam for sufficient time in order to carry out controlled collisions in the detectors.

References

[1] `http://press.web.cern.ch/press-releases/2008/10/cern-releases-analysis-lhc-incident`, accessed on 23/10/2014.

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[3] Pierre Auger Collaboration, *Measurement of the proton-air cross-section at* $\sqrt{s} = 57$ *TeV with the Pierre Auger Observatory*, Phys. Rev. Lett. 109, 062002 (2012)

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