P3 Beamline Vacuum

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ABSTRACT

The P3 beamline vacuum system is over 30 years old, and is showing signs of failure in ion pumps, power supplies, and cabling. As part of an upgrade plan, this paper estimates the beam loss and scattering if the system upgrade involved switching to roughing pumps at milliTorr pressures. This increase in pressure would make P3 match the rest of downstream Switchyard, and will dramatically reduce both the cost of upgrading the vacuum system and the pump-down time in the.

Introduction

The P3 beamline extends from F17 in the Tevatron F-Sector to the beginning of Transfer Hall at F47. This beamline is actually the remnant of the old Main Ring synchrotron, and consists of about one kilometer of original Main Ring components. All 167 ion pumps in the Main Ring Remnant are original, and have been operating steadily since the Main Ring. Recent ion pump and power supply failures highlight that the vacuum system is far past its end-of-life.[1,2] A sustainable upgrade plan is vital to the continued operation of the Switchyard fixed target program.[3,4]

Since P3 is now used solely as a single-pass beamline, it is no longer necessary to operate at high vacuum requiring ion pumps. A much less expensive solution is to run P3 at rough vacuum of milliTorr pressure using mechanical roughing pumps, which is identical to the vacuum system downtream of P3 all the way to the experiments. As long as the beam power loss and increase in beam size due to scattering are not high, upgrading the P3 vacuum system to match the rest of the Switchyard lines is an ideal solution to the problem of aging Main Ring vacuum components.

This upgrade plan will not involve adding additional Titanium vacuum windows, as one already exists at the downstream end of P3. The future Muon campus will use the P2 beamline for their high-intensity 8 GeV beam, so we will move the aforementioned vacuum window upstream to isolate P2 from the new P3 system at higher pressure.

Beam loss due to nuclear interaction

To estimate the beam power lost due to nuclear interaction with residual air, we first estimate the maximum operational beam power. At a maximum intensity of 1E13 protons per spill, 120 GeV total energy per proton, and one spill per minute, the maximum operational beam power is:

$$P = \frac{E}{t} = \frac{(1E13)(1.602E-19)(120E9)}{60} = 3.204\,kW. \tag{1}$$

The nuclear interaction length for air at atmospheric pressure is 747.7 m, which is the distance over which all but 1/e of beam is lost; in other words, 63.212% of beam is lost after passing through 747.7 m of air at 760 Torr.[5]

For rough vacuum at $1E-3$ Torr, the nuclear interaction length scales as $\frac{760}{1E-3}$, so the interaction length for rough vacuum is 568,252,000 m. The beamline is approximately 1 km long, so the fractional interaction length of the beamline is $\frac{1000}{568252000} = 1.75978E-6$.

Thus the beam power loss per unit length in rough vacuum is

$$\frac{P_{loss}}{m} = \frac{(3204)(1.75978E-6)(0.63121)}{1000} = 3.564\,\frac{\mu W}{m}. \tag{2}$$

Beam scattering

Using the diffusion equation and angle distribution due to multiple Coulomb scattering off air, the increase rate of the normalized emittance in one plane is[6]

$$\frac{d\varepsilon_N}{dt} = \pi < \beta > (1.6E-7/sec)\frac{P[\mu Torr]}{\gamma}, \tag{3}$$

where $<\beta>\approx 25\,m$ is the average value of the betatron envelope function over the length of the beamline, $P[\mu Torr] = 1E3$ is the vacuum pressure, and the relativistic factor $\gamma = \frac{E_{total}}{E_{rest}} = \frac{120E9\,eV}{938.26E6\,eV} = 128.962$.

Integrating Equation 3 over time, and estimating that the transit time for the P3 line is $t = \frac{d}{\beta c} = \frac{1E3}{0.99997*299792458} = 3.33574\,\mu sec$, we find that the increase in normalized emittance at 10^{-3} Torr is

$$\Delta\varepsilon_N = 1.035E-10\,\pi*m*r. \tag{4}$$

Converting to physical emittance, we see that $\Delta\varepsilon = \frac{\Delta\varepsilon_N}{\beta\gamma} = 8.026E-13\,\pi*m*r$. We can now estimate the maximum increase in transverse beam size by assuming the maximum beta function value is $\beta_{max}\approx 50\,m$:

$$\Delta\sigma = \sqrt{\Delta\varepsilon\beta_{max}} = 6.334E-6\,m. \tag{5}$$

Three standard deviations correspond to 99.7% of the beam width, i.e. $3\Delta\sigma_x = 0.997*\Delta x_{max}$, so $\Delta x_{max} = \frac{3\Delta\sigma_x}{0.997} = 19.06E-6\,m$. The beam size increase is symmetric for the horizontal and vertical planes, so to estimate the beam radius increase we add in quadrature the increase in each plane:

$$\Delta r = \sqrt{\Delta x_{max}^2 + \Delta y_{max}^2} = 26.95E-6\,m. \tag{6}$$

Conclusion

We have shown that the P3 beamline can run at rough (milliTorr pressure) vacuum with an estimated beam power loss per unit length of 3.564 $\frac{\mu W}{m}$ and maximum beam radius increase of 26.95 μm. Upgrading the aging system with mechanical roughing pumps would save an enormous amount of money compared to replacing the ion pumps, without noticeably affecting the beam size or loss. It is likely that ion pumps have been used unnecessarily in the P3 beamline just to maintain the system as it had run in the Main Ring. However, with its use as a single-pass beamline, it is no longer necessary to run at high vacuum.

References

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