Response to Recommendation from September 1992 DOE Review
Main Injector Ring Vacuum — WBS 1.1.2.1

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Paraphrased Recommendations

1. Demonstrate dependence of performance limitations on average pressure.
2. Estimate dependence of average pressure on beam intensity.

Background

The Title I Design Report states that the average pressure P in the Main Injector ring should be $< 10^{-8}$ T based on the specified materials, preparation, and installation for the beam tube and other system components. This figure is a bottom-up estimate justified by experience with machines like the Fermilab Debuncher, which operates at $< 10^{-8}$ T average pressure without ultra-high vacuum materials or procedures. The earliest results from tests of beam tube samples with a Main Ring type 30 l/s ion pump indicate that the actual performance may not be quite that good. The magnitude is surely correct, but the prediction is safer if one replaces $< 10^{-8}$ with $\sim 10^{-8}$.

The justification for the vacuum specification was questioned at the September 1992 DOE review. The number in the design report is the assessment from the mechanical engineers of what can be accomplished using standard practice and reasonable diligence. The review recommendations suggest a top-down assessment of the relation between vacuum and performance criteria. In such assessment the incremental cost in tightening or relaxing the criterion should be gauged against effects in two general performance areas, *viz.*,

1. beam intensity and quality in the design mode and likely alternative modes
2. down time, recovery time, and cost of ion pump maintenance

This note is responsive to both aspects, but the treatment of the second merely notes some relevant considerations without assessing relative importance, and no cost information is included.

The Effects of Residual Gas on 8 GeV Beam

In this section the standard treatment of diffusive growth of the beam emittance caused by multiple coulomb scattering of 8 GeV beam particles by residual gas is used to evaluate beam lifetime, emittance growth, and halo generation as function of P. The quantities appearing in the formulae are given in the table following.

	Numerical Value	Units
P, average pressure		T
P_D, design value for P	$< 10^{-8}$	T
$\bar{\beta}$, average of Courant-Snyder beam width function	28	m
γ, Loentz factor $E/m_\circ c^2$ at 8 GeV kinetic energy	9.53	
ε, normalized transverse emittance		m
ϵ, physical transverse emittance ε/γ		m
A, normalized acceptance		m
$\bar{a}$, effective aperture radius	0.02	m
$\vartheta^2_{\mathrm{rms}}$, root mean square divergence of beam		radian
D, emittance diffusion constant		m s^{-1}
L_{rad}, radiation length		m
c, velocity of light	$3 \cdot 10^8$	m/s
$m_\circ c^2$, rest energy of the proton	0.938	GeV
τ_D, beam intensity lifetime		s
λ_1, first zero of $J_\circ$ Bessel function	2.405	

The value taken for the effective aperture radius is just slightly less than the vertical aperture in the dipoles; combined with $\bar{\beta}$ it gives

$$A = \pi\gamma\bar{a}^2/\bar{\beta} = 1.35 \cdot 10^{-4}\pi \ .$$

Although this is more than three times the $4 \cdot 10^{-5}\pi$ minimum requirement specified in the Title I design, it is consistent with tracking studies at 8 GeV.[1]

The residual gas at a pressure of 10^{-8} T should consist almost entirely of hydrogen and water vapor. To be slightly conservative, the fractional composition of the Main Ring residual gas at about 10^{-7} T will be used;[2] this will somewhat over-state the presence of high-Z gasses. This composition gives[3]

$$L^{-1}_{\mathrm{rad}} = 2 \cdot 10^{-6} P \ \ [\mathrm{m}^{-1}] \ .$$

The standard MCS ("Rossi formula") results in the expression

$$D = \left\langle \frac{\mathrm{d}\epsilon}{\mathrm{d}t} \right\rangle = \bar{\beta}\dot{\vartheta}^2_{\mathrm{rms}} = \left(\frac{0.015\ \mathrm{GeV}}{m_\circ c^2}\right) \frac{c}{\gamma^2} L^{-1}_{\mathrm{rad}} \ .$$

Substituting numerical values for everything but the pressure results in

$$D = 4.73 \cdot 10^{-2} P \ \ [\mathrm{m/s}] \ .$$

The time for 1 % growth for beam with $\varepsilon = 20\ \pi$ mm mrad is then 44 s for P_D of 10^{-8} T. This result is inversely proportional to P and would easily permit a factor ten higher pressure even if some time were to be needed at 8 GeV for some special process like stacking of p↑ or bunching of p̄. The rate of beam intensity loss depends on time and the initial distribution. However, eventually an asymptotic rate determined by the lowest eigenvalue of the diffusion equation is established for any distribution:

$$\tau_D = \frac{4}{\lambda_1^2}\frac{A/\gamma}{D} = 2.08 \cdot 10^{-4}/P \ .$$

This expression implies that intensity loss is not a consideration at any reasonable pressure.

However, a look at the actual solutions of the diffusion equation shows that there is an important consideration for high intensity operation, namely the development of beam halo that may not be extracted cleanly. The scattering that produces say a 1 % emittance growth will not simply broaden the initial distribution by a scale factor of 1.01;[1] the distribution picks up rather quickly tails of low population but considerable extent. At high intensity these tenuous tails may contribute significantly to the activation of the extraction channel and switchyard. The diffusion equation is usually written with a dimensionless time variable τ scaled so that

$$t/\tau = \frac{A}{\pi\gamma D} = \frac{\bar{a}^2}{\bar{\beta} D} = 3 \cdot 10^{-4}/P\ [s]\ ,$$

where the final numerical equality uses the 8 GeV energy and the gas composition which has been assumed throughout. If one looks at solutions starting from sharp, *i.e.* well-collimated, initial distributions, one finds that even for $\tau = 0.01$ the .1 % intensity contour has migrated considerably whereas the 1 % intensity contour has scarcely budged. This observation can be turned into a criterion for P_D by specifying the appropriate initial distribution, the acceptance of the extraction channel, and the acceptable scraping. Although this calculation has not been made, the qualitative conclusion is that the control of tenuous beam halo places much the strongest constraints on P_D.

Dependance of P on Beam Intensity

In high intensity storage rings regenerative vacuum degradation depending on beam intensity has been observed; that is, the beam loss has caused gas desorption which has led to increased beam loss. Such effects have never been observed in the Main Ring, even in the days of $\pi \cdot 10^{13}$ protons/pulse, except perhaps at $P \to 10^{-5}$. One says "perhaps" because at such pressure machine performance is seriously affected in various ways, and it may not be easy to tell what is happening. The closest to a dynamic effect that has been reported is an approximate factor of two degradation when the magnets are first turned on; they warm the vacuum chamber and increase desorption.

[1]unless, of course the initial distribution is an eigenfunction of the diffusion equation

Operational and Technical Considerations

There are important aspects to the question of the appropriate vacuum for the Main Injector that have little to do with beam dynamics. The remarks bellow are relevant to operations and maintenance but do not constitute a thorough analysis.

Pump life

Ion pump lifetime depends on the pressure in the neighborhood of the pumping port. From a manufacturer's catalog one can find specs like $5 \cdot 10^4$ hours service at $P = 10^{-6}$ T, but not a pressure scaling or a distribution of service life. However, with several hundred pumps in service, it seems prudent to aim for $P < 10^{-7}$ T. If there is some repair history on Main Ring pumps, the information might be useable in making a stronger conclusion on this point. The experience from the Debuncher is that at 10^{-8} T pumps last a "long" time. Replacement costs downtime as well as the reconditioning cost for the removed pump. If one uses the rough measure of operating budget divided by program hours to approximate the cost of downtime, one will pay considerable to avoid having to change pumps.

Initial pump-down

The same precautions leading to low ultimate pressure also result in a fast pump-down to acceptable levels for commissioning or after the vacuum chamber has been opened for repairs. If these hours are valued at $\sim \$10^4$ each, the effect of some ultimately attainable residual pressure on beam dynamics may not be a relevant guide to the vacuum system design. Perhaps a better criterion would be the acceptable time for pumping down from atmospheric pressure to the maximum acceptable for operation.

Surface preparation

At the time that CEA was being built about 30 years ago there was considerable interest in using electro-polishing technique to reduce the surface area of stainless steel for vacuum systems. Because the surface area reduction is not spectacular (about 30 %), the practice has not been widely used in accelerator vacuum systems since then. Neither the Main Ring nor the Debuncher have electro-polished beam tube, and the Debuncher, at least, has demonstrated vacuum system performance at the level desired for the Main Injector. One might infer, then, that the proposal to electro-polish the Main Injector beam tube is an anachronism. However, the resulting reduction in surface is a desirable side effect but not the principal motivation for the procedure. Rather it has been specified as an effective method of surface cleaning which has the additional virtue of leaving the surface with an enhanced nickel content. The additional nickel facilitates welding the system together. Therefore, one needs to consider more than the vacuum properties of the final surface in judging the cost effectiveness of the elecro-polishing step.

Acknowledgements

Vacuum technique is not my area of expertise. Unreferenced comments about standard practice and operating experience are generally derived from conversations with more experienced people, particularly Jim Klen and Larry Sauer. Neither they nor the others have checked anything I have said in this note, however, and are certainly not responsible of what I have construed from their remarks.

References

[1] S. Mishra and F. Harfoush, Fermilab Main Injector note MI0070

[2] D. Trbojevic, Fermilab TM-1565 (14 Feb. 1989)

[3] Y-C Chao, D. Edwards, H. Edwards, R. Gerig, S. Holmes, G. Jackson, S. Mane, M. Syphers, and V. Visnjic, Fermilab accelerator experiment note EXP-164 (16 May 1989)