Laser Induced Extraction from the LHC or SSC *

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Abstract

Recently it was proposed to extract 10^8 protons per second from the SSC for use in fixed target B experiments and/or as a test beam. In this paper a promising extraction scheme based upon Compton backscattering of a laser beam is described. The laser beam intercepts the proton beam at a point where the dispersion is large compared to the achromatic beam size. A struck proton experiences a momentum loss of up to $\Delta P/P_0 \approx 10^{-4}$. As a result, its trajectory now lies "far" from the closed orbit corresponding to its new momentum and it will now undergo "large" betatron oscillations. At a subsequent point of large β_X the oscillations will be large enough to put the proton outside a septum and in an extraction channel. While placing stringent demands on the laser system, the scheme promises a) to give large transverse kicks to the protons being extracted and b) to cause minimal disruption of the stored beam.

1 INTRODUCTION

With the construction of accelerators such as the Superconducting Super Collider (SSC) and the Large Hadron Collider (LHC) proton beams of unprecedented energies will become available. The principal foci of the research at these machines will be the study of high-P_T reactions using colliding beams. However, beams of such high energies also are extremely attractive for use with fixed external targets. For example, interest has been expressed by B. Cox *et al.*[1] in developing a Super Fixed Target (SFT) facility at the SSC, the primary purpose of which will be the study of B meson dynamics. In this application the extremely high energy of the incident proton beam results in the reaction center-of-mass moving at 0.99995c. At this velocity the laboratory decay length of B mesons is about 4.4 cm so separating the decay vertices of the B and $\overline{B}$ mesons will be possible. This separation will make possible detailed studies of, for example, CP violating asymmetries.

In extracting the beam for the SFT (or for a similar facility at the LHC) three considerations play major roles. First, the extraction rate must be between 1×10^8 per second and 2×10^8 per second in order to get a realistic interaction rate. Second, the extraction procedure must not significantly affect the luminosity at the high-p_T detector IR's (beyond reducing it at a rate consistent with the flux of extracted protons). Finally, a proton being extracted must experience a single-revolution horizontal displacement that is large compared to the thickness of the extraction septum.

A promising technique for extracting a beam while meeting these criteria involves the use of Compton scattering of visible or near ultraviolet light from the proton beam. First, the proton beam is focussed at a point (s_I) at which β_x and β_y are small and η_x is greater than zero such that $\sigma_x < \sigma_\delta \eta_x$. A laser beam is directed almost anti-parallel to the beam and is focused onto the low-β point. When struck, a proton loses momentum (ΔP) but does not measurably change its direction. Originally near its closed orbit, the proton is now away from it a distance $\eta_x\ \Delta P/P_0$. It now experiences large betatron oscillations about its new closed orbit. At a later point (s_E) where β_x is large and η_x is small or zero, this proton will be far from the beam centroid and can be extracted with high efficiency using either an electrostatic septum or, preferably, a bent crystal septum.

2 COMPTON SCATTERING

Compton scattering of low energy light at 180° from high energy particle beams has been used to generate high energy photon beams at laboratories such as CEA,[2] the Lebedev Institute,[3] SLAC,[4] and now BNL.[5] It has been used to measure electron beam polarization at many laboratories including SLAC,[6] CERN,[7] and DESY.[8] Compton backscattering from a high energy beam is, therefore, a well understood technique.

The energies E'_γ of the photons resulting from the backscattering of an incident photon of energy E_γ from a proton beam of energy E_p range from zero to a maximum of

$$E'_\gamma(max) \ = \ 4\ \gamma^2\ E_\gamma \tag{1}$$

where $\gamma = E_p/M_p$ and M_p is the rest mass of the proton. Accordingly, a 20 TeV proton will experience a change in momentum of up to

$$\frac{\Delta P}{P_0}(max) \ \equiv \Delta_\gamma(max) \approx \ E_\gamma[eV] \ \times \ 10^{-4} \tag{2}$$

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in such a collision. The maximum deflection a 20 TeV proton will experience is a negligible

$$\Delta\theta_p \approx 2\ E_\gamma[eV]\ nr \qquad (3)$$

which occurs when its momentum loss is 1/2 its maximum value.

The cross section for this process is

$$\frac{d\sigma}{d\rho} = \sigma_0 \left[4\left(\frac{\rho}{1-\Delta P/P_p}\right)^2 - 4\left(\frac{\rho}{1-\Delta P/P_p}\right) + 1 - \Delta P/P_p + \frac{1}{1-\Delta P/P_p}\right] \qquad (4)$$

where $\sigma_0 = (\pi r_0^2/2\gamma^2)(E'_\gamma(max))/E_\gamma$ and $\rho = \Delta P/\Delta P(\max)$. For a 20 TeV proton and a 1.2 eV photon the cross section peaks at 300 nb for $\rho = 0$ and 1 and has a minimum of 150 nb at $\rho = 0.5$. The total cross section is about 200 nb.

3 BEAM OPTICS

In computing the horizontal distribution of the struck protons at the high-β_x point at which the septum would be placed it was assumed that this septum defines the horizontal acceptance of the ring and that the optics of the ring are linear. Thus, it is enough to calculate the maximum possible horizontal excursion (x'_{max}) of a struck proton at the septum position (s_E). It is related to the initial coordinates of the proton (z_0, x_0, θ_0, δ_0) by

$$\frac{[x'_{max} - \eta_x(s_E)(\delta_0 - \Delta_\gamma)]^2}{\beta_x(s_E)} = \frac{[x_0 - z_0\theta_0 - \eta_x(s_I)(\delta_0 - \Delta_\gamma)]^2}{\beta_x(s_I)} + \beta_x(s_I)\theta_0^2 \qquad (5)$$

where it is assumed that $\alpha_x(s_I) = \alpha_x(s_E) = 0$. The probability (per proton per photon) of a photon being scattered such that the maximum possible horizontal displacement of the proton at s_E is less than x_s is

$$P(x'_{max} < x_s) = E'_\gamma(max) \times \int_\sim^\sim \cdots \int_\sim^\sim d(ct)\ dx\ dy\ dz\ d\theta\ d\phi\ d\delta\ \rho_p\ \rho_\gamma \int_\sim^\sim \frac{d\sigma}{d\rho} d\Delta_\gamma \qquad (6)$$

where the limits of the integrations ($\sim$) are determined by eq. 5 and ρ_p (ρ_γ) is the initial distribution of the proton (photon) bunch which was assumed to be Gaussian initially. The results of a calculation based upon parameters representative of the SSC (Proton beam: $E_p = 20$ TeV, $\beta_x(s_I) = \beta_y(s_I) = 2.0$m, $\eta_x(s_I) = 0.5$m, $\eta_x(s_E) = 0.0$m, $\epsilon_x = \epsilon_y = 5.0 \times 10^{-11}$mr, $\sigma_z =$ cm, $\sigma_\delta = 5 \times 10^{-5}$. Photon beam: $E_\gamma = 1.2$ eV, $\beta_x(s_I) = 4$cm, $\beta_y(s_I) = 6$mm, $\epsilon_x = \epsilon_y = 1.6 \times 10^{-7}$mr, $\sigma_z = 1.5$cm) is shown in Figure 1. It is to be noted that most of the struck particles are separated by distances of the order of hundreds of microns from the bulk of the beam.

The extraction efficiency, or the fraction of the struck protons that are extracted, depends upon the placement of the septum. This dependance, for the parameters used in Figure 1, is shown in Figure 2. For example, if the septum

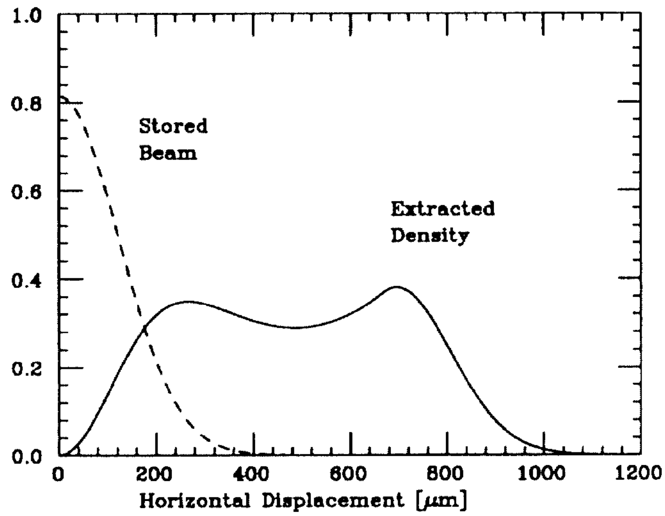

Figure 1: Distribution of maximum horizontal displacements at s_E for conditions representative of the SSC. See text for parameters.

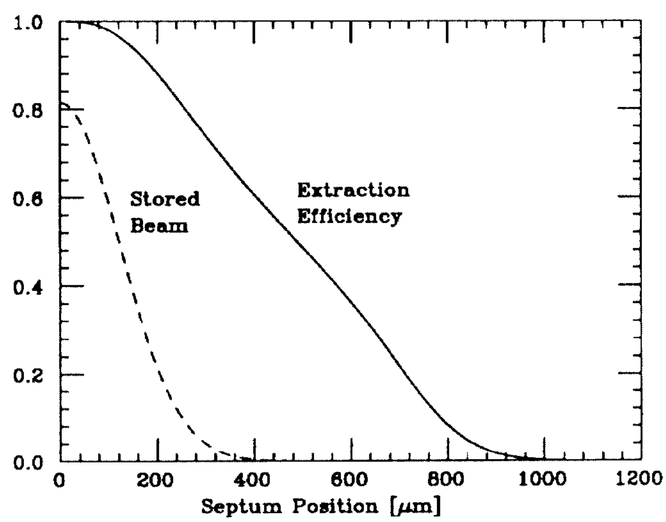

Figure 2: The fraction of struck protons extracted assuming same parameters as used in Figure 1.

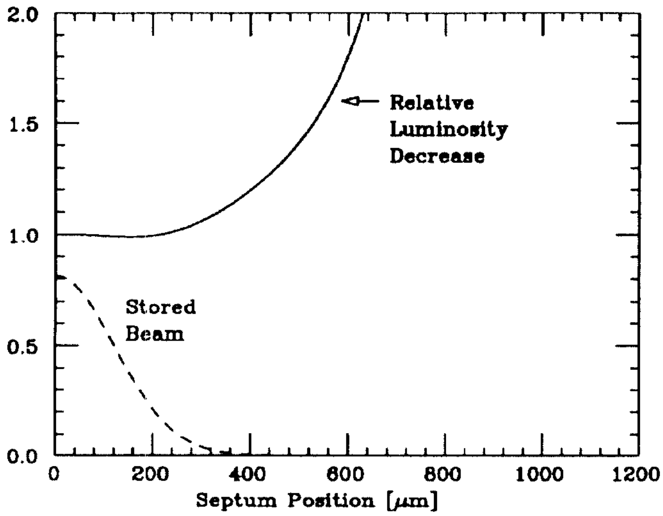

Figure 3: The decrease in the luminosity at the IR's is calculated by multiplying the direct luminosity loss due to the reduction in number of protons in one bunch by the factor shown.

is placed 500 μm from the beam centroid then about half of the struck protons will be extracted.

The protons which are struck but not extracted are no longer distributed in the same way as the rest of the stored beam. Thus, they will not contribute to the luminosity at the high-p_T detector IR's in the same way. The resultant decrease in luminosity can be computed from the overlap of the distributions of struck but not extracted protons and undisturbed protons. The result is shown in Figure 3 where the Relative Luminosity Decrease is the factor by which the luminosity loss because protons are being extracted must be multiplied to get the total luminosity loss. Again, for the parameters used in Figure 1 a septum placed at 500 μm from the centroid of the beam would cause a loss in luminosity 1.5 times what one would calculate based on the rate at which protons are extracted. In the case of the SSC, an extraction rate of $1\times10^8/s$ would entail extracting 10% of the stored beam in 24 hours. Thus, for the parameters outlined above the extraction of a parasitic beam would cause a decrease in the luminosity of about 15% over 24 hours.

4 LASER REQUIREMENTS

The rate (R) at which protons are extracted is be given approximately by

$$R = \sigma \times f_\gamma \times t_p \times E_{ext} \times E_{geom} \tag{7}$$

where $\sigma = 200$ nb is the total cross section for Compton scattering f_γ is the photon flux, t_p is the number of protons per bunch, E_{ext} is the extraction efficiency (see Fig. 3), and E_{geom} is computed from the overlap integral of the proton and photon bunches.

If we assume the parameters of Figure 1, that each proton bunch contains 0.75×10^{10} protons, and that the septum is placed 500 μm from the beam centroid then we find that we need a photon flux of about $2 \times 10^{25}/s$. If we use an NdYAg laser then E_γ is 1.2 eV and this flux represents a power of almost 4 MW. Such power levels, while high, appear within the range of possibility. To achieve it one must feed a resonant cavity with a mode locked laser delivering 100 ps pulses at 60 MHz and pass the proton beam through the cavity. The cavity would be built with $\geq$0.99999 reflecting mirrors so the power in the stored beam would be about 10^5 times that of the laser feeding it. This still implies an average laser power of the order of 40 W. However, more than one such laser-cavity assembly could be centred on a point in the ring and the demands on each correspondingly reduced.

5 CONCLUSIONS

Our calculations indicate that an extraction scheme based on Compton scattering could deliver a parasitic beam from the SSC or LHC suitable for use in fixed target experiments without unduly disturbing the stored beam. The demands placed upon the optics of the proton ring are not severe, but the laser system will require significant development effort.

6 REFERENCES

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