THE USE OF A PASSIVE SCATTERER FOR SPS SLOW EXTRACTION BEAM LOSS REDUCTION

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Abstract

A significant reduction in the fraction of protons lost on the SPS electrostatic septum ES during resonant slow extraction is highly desirable for present Fixed-Target beam operation, and will become mandatory for the proposed SHiP experiment, which is now being studied in the framework of CERN's Physics Beyond Colliders program. In this paper the possible use of a passive scattering device (diffuser) is investigated. The physics processes underlying the use of a diffuser are described, and the dependence on the diffuser geometry, material and location of the potential loss reduction on the electrostatic septum (ES) wires is investigated with a semi-analytical approach. Numerical simulations to quantify the expected performance gain for the optimum configuration are presented, and the results discussed in view of the feasibility of a potential realisation in the SPS.

INTRODUCTION

The SHiP experiment [1] aims to provide experimental proof for the νMSM theory [2], using slow-extracted 400 GeV p. The intensity of 4.0×10^{13}p/cycle has already been delivered routinely; however, slow-extraction of this would be an SPS record. The annual total of 4.0×10^{19} Protons on Target (PoT) is approximately four times higher than ever achieved for third-integer slow extraction, where losses of the order of a % are unavoidable on the wires of the ES. A factor of 4 loss reduction is sought.

A diffuser generates an angular distribution in a short element upstream of the ES, which can reduce the transverse density at the septum wires and result in an overall loss reduction, despite the extra material introduced.

SPS SLOW EXTRACTION LOSSES

In the SPS, extraction sextupoles are excited and the tune moved towards $Q_h = 26.666$. The beam is debunched with chromaticity set to a large negative value. The extraction is made in combined momentum and betatron space, with largest δp particles coming into resonance and being extracted first. There is a momentum change of the extracted beam through the spill, which via the dispersion at the ES couple into separatrix position and angle changes in time.

The ES comprised 2080 ⌀60 µm WRe wires, aligned by an anode support to ±70 µm straightness. Five such 3.15 m long units are needed to extract the beam at 400 GeV, individually aligned with the beam to minimise overall losses.

The ES shape in phase space is determined by wire (or foil) thickness, alignment, gap field and physical length. Impacting particles can be lost from scattering (inelastic and elastic nuclear, or Multiple Coulomb MC), either locally or later in the machine. Equipment activation depends on the specific material but is always directly proportional to the number of particles impacting the ES.

In the SPS the normalised [3] phase-space coverage of the actual ES is shown in Fig. 1, assuming 60 µm wire diameter, 220 kV/cm field, 400 GeV/c, ±60 µm overall septum straightness and an ES length of 17.35 m, together with a modelled extraction separatrix, for one momentum. The separatrix will be displaced in angle for different momenta due to the dispersion derivative at the ES, which increases the number of particles intercepting the ES.

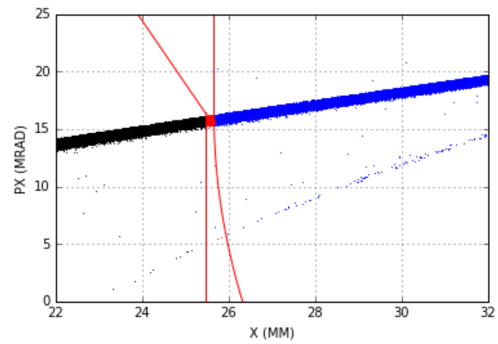

Figure 1: Separatrix and ES in normalised phase space, with extracted (blue) and lost particles (red). The normalisation is such that MM = mm [3].

PASSIVE AND ACTIVE SCATTERERS

A local reduction in transverse beam density at the ES would reduce the beam loss. Two ways of accomplishing this are being studied, with a passive incoherent diffuser (wire of foil array) [4] or active coherent scatterer (bent crystal) [5].

The diffuser works because the main loss source is particles traversing the ES with small impact angle. A small scattering angle upstream of the ES produces a spread in the particle positions at the ES, Fig. 2, which if large enough gives an overall reduction in beam loss, provided that the additional losses induced by the diffuser itself remain small.

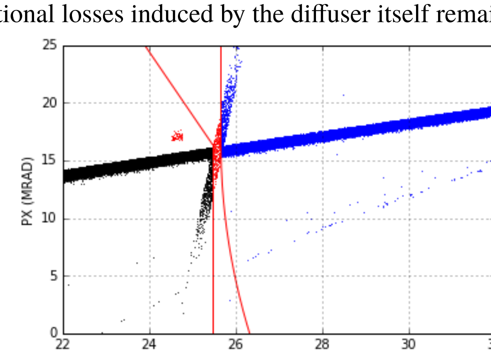

Figure 2: Separatrix, scattered particles and ES with diffuser. The coordinates of particles lost at the diffuser are also plotted.

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Passive diffusers are in use at CERN [6] and one is planned for the Mu2e beam from the Fermilab Main Injector [7]: a factor 2 loss reduction is simulated for a 0.5 m long Mo wire array upstream of the 1.25 m long foil septum.

The required scattering angle can be estimated as a function of the phase advance μ_x between diffuser and ES, under the simplifying assumption that the scatter has negligible length and that the ES losses are dominated by head-on impacts with small transverse angle, which is the case for a well-aligned ES and narrow separatrix. With diffuser width of w_s and an average beta function at ES and diffuser of β_x, an RMS scattering angle θ_{MC} at the diffuser is transformed into a position spread at the ES of

$$X_{ES} \approx \beta_x \sqrt{(\mu_x^2 \theta_{MC}^2 + w_s^2/12)}$$

With the 3.2° phase advance available for a realistic diffuser location in the SPS, a factor 2 loss reduction could be possible for a scattering angle of $\approx 30\ \mu$rad. Clearly, the incoherent diffuser suffers because the peak density of the scattered particle distribution is always at zero scattering angle, aligned with the ES, so that a large scattering angle is needed to produce a significant loss reduction factor. The material length needed to produce the given scattering angle is crucial for the overall loss reduction factor, which depends on the number of nuclear interaction lengths of material.

A proton traversing a thin scatterer has a (small angle) Gaussian MC RMS scattering angle per transverse plane [8]

$$\langle\theta_{MC}^2\rangle^{1/2} = \frac{0.0136}{p\,[GeV/c]\beta_r c}\sqrt{\frac{L}{X_0}}(1+0.038 ln(L/X_0))\ \text{mrad}$$

Some particles undergo elastic scattering with probability $1 - e^{-L/\lambda_e}$ and are deflected through an angle in each transverse plane with an RMS [8] of

$$\langle\theta_e^2\rangle^{1/2} = 197/(A^{1/3} p[GeV/c])\ \text{mrad}$$

Particles undergoing nuclear inealstic scattering are considered as lost. For the diffuser, the ratio of radiation length X_0 to the nuclear interaction length λ_I should be small, since large λ_I minimises loss through nuclear scattering, while short X_0 maximises the MC scattering angle. A comparison of considered materials and lengths needed to achieve 30 µm RMS scattering angle with 400 GeV/c p is instructive, Table 1. The total loss includes all p scattered elastically by more than 50 µrad. ${}^{184}_{74.3}(W_{75}Re_{25})$ alloy was assumed.

Table 1: Diffuser Length and Loss Fraction for 30 µm θ_{MC}

Parameter	${}^{9}_{4}$**Be**	${}^{12}_{6}$**C**	${}^{28}_{14}$**Si**	${}^{96}_{42}$**Mo**	WRe
ρ [g/cm^3]	1.8	2.0	2.3	10.2	19.7
λ_n total [cm]	29.9	29.6	30.2	9.1	5.6
λ_i inelastic [cm]	42.1	42.9	46.5	15.3	9.8
X_0 [cm]	35.3	21.4	9.4	0.96	0.35
Length [cm]	26	16	7.0	0.70	0.26
θ_e [μrad]	237	215	162	108	87
Inelastic loss [%]	46	31	14	4.5	2.6
Total loss [%]	56	40	19	6.4	3.7

Somewhat counter-intuitively, denser materials are actually significantly better. The use of a dense diffuser like $W_{75}Re_{25}$ (widely used for ES wires) can provide over a factor 10 gain in the losses per impacting proton generated at the diffuser itself, when compared to a low Z material like Carbon. Molybdenum is also interesting.

SIMULATIONS

Simulations were made to evaluate the loss reduction. A tracking routine was implemented in python including multiple turns and scattering, benchmarked against MADX and pyCollimate [9]. Included were tune sweep, sextupole driving terms, scattering at diffuser and ES, and losses.

The diffuser was modelled as a full density blade, and to model the wire array the ES had uniform reduced density, calculated from the total material cross-section, length and assumed width. The extraction process was adjusted to be similar to the real SPS extraction, but a monochromatic beam was used. The extraction of the beam was accomplished in ≈400 turns. The ES angle was aligned to minimise losses without diffuser. $\geq 10^5$ particles were tracked per case, to give good statistics on the ≈1% losses being compared. Coordinates and location of lost particles were recorded.

Parametric scans were made to optimise diffuser length, width, phase advance, transverse offset, alignment angle and material. A scan of a WRe diffuser length is shown in Fig. 3, for a diffuser width of 0.24 mm and an ES width of 0.2 mm. A loss reduction of a factor 2.5 is achievable for a diffuser length of 30 mm, while 3 mm already gives ×2 reduction.

The diffuser performance is very sensitive to its position relative to the ES. This is evident from Fig. 4, which shows the effect of scanning a 3 mm long, 0.24 mm wide WRe diffuser position. In this plot the losses are normalised to the case with no diffuser. From this plot the alignment tolerance of the diffuser can immediately be specified as ±50µm.

The diffuser width is also important and needs to match the actual septum width including misalignment, Fig. 5. This may pose a problem in reality, as the alignment tolerance of the ES is not known to such a high accuracy. Improvements in this respect are required, and being studied [10]. Again, the tolerance on the diffuser width relative to the ES width (including tolerances) is around ±50µm. It can be seen from Fig. 6 that a better loss reduction factor is obtained for a thin septum, for a constant diffuser-septum thickness difference.

A carbon diffuser was also simulated, Fig. 7. As expected the diffuser needs to be much longer, and the loss reduction is lower than WRe (a 10 cm long C diffuser reduces losses by ≈20%). The obtained (total) loss reduction factors for the optimum configurations is shown in Table 2 for different diffuser and septum materials and configurations. The diffuser material length is quoted. For all cases the ES was 0.2 mm wide and the diffuser 0.24 mm wide.

The scattered p which do not impact the ES wires increase the transverse tails of the extracted separatrix, at or below the 10^{-3} level. These may cause local losses in the transfer line for which collimation will be studied.

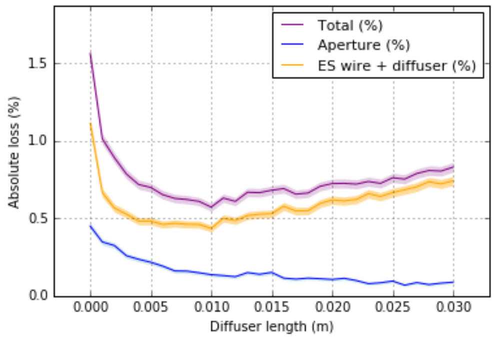

Figure 3: Losses vs. length for 0.24 mm wide WRe diffuser 3.2° upstream of 0.2 mm wide WRe ES.

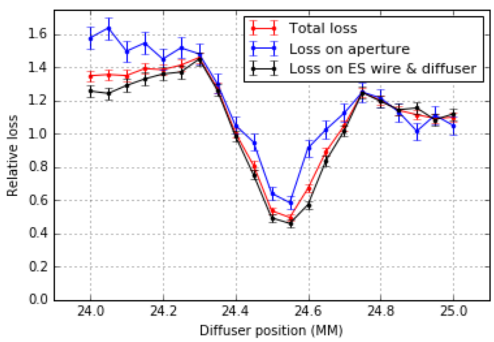

Figure 4: Relative loss vs. position for 3 mm long, 0.24 mm wide WRe diffuser.

Table 2: Absolute Total Losses and Relative Factors

ES	Diffuser	Length	Loss	Factor
WRe	none	-	1.6%	-
WRe	WRe	3 mm	0.8%	2.0
WRe	WRe	30 mm	0.6%	2.5
WRe	Mo	20 mm	0.7%	2.3
WRe	C	100 mm	1.2%	1.3
C	none	-	1.2%	1.3
C	WRe	6 mm	0.5%	3.0
C	C	50 mm	1.0%	1.7

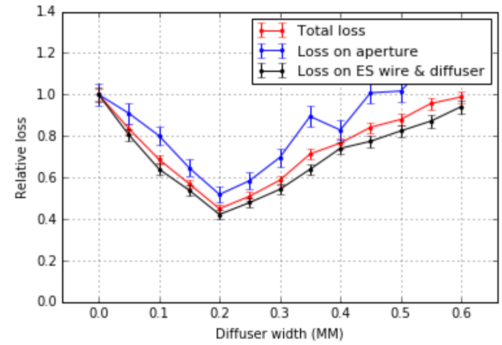

Figure 5: Relative loss vs. width for 3 mm long WRe diffuser.

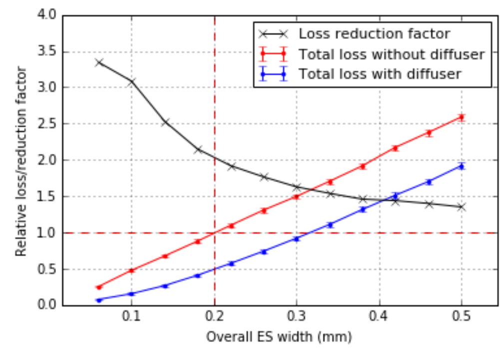

Figure 6: Relative loss (normalised to 0.2 mm wide ES without diffuser) vs. septum width with and without 3 mm long WRe diffuser 0.04 mm wider than ES.

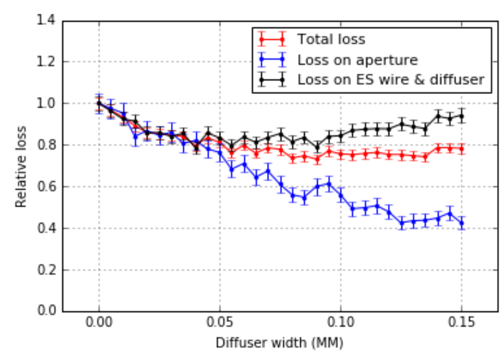

Figure 7: Relative loss vs. length for 0.24 mm wide C diffuser upstream of 0.2 mm wide WRe ES.

DISCUSSION AND OUTLOOK

The effects of a diffuser have been estimated analytically and simulated numerically. The results confirm that high Z materials perform the best. The optimum lengths agree with the estimates. A short 3 mm WRe diffuser gives a factor 2 loss reduction, for a narrow separatrix. The diffuser should be very similar in width to the ES width including tolerances, and needs to be positioned with a precision of ±50 μm. Precise knowledge of the ES width is clearly an issue in the diffuser design, and a thinner (better aligned) septum allows a larger loss reduction factor. Overlapping of extraction separatrices in angle is important, e.g. with a dynamic bump [11]. The scattered particles increase the angular spread of the separatrix but are very low density.

The results also show that carbon ES anode wires would already give a loss reduction of a factor 1.3, which combined with a short 6 mm WRe diffuser could reach a factor 3 reduction.

The simulations will now be validated using MADX and PyCollimate, to evaluate the overall loss reduction with the full extraction dynamics and also to quantify the destination of scattered p. A prototype diffuser is also being designed for testing in the SPS, with 20 WRe 240 μm wires. Given the simplicity of the device and (importantly) of its operation, a passive diffuser is a promising approach to achieve at least half of the required loss reduction factor for SHiP.

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