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OPTIMIZATION OF DIFFUSER (PRE-SCATTERER) CONFIGURATIONS FOR SLOW EXTRACTION LOSS REDUCTION AT ELECTROSTATIC SEPTA

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Abstract

Uncontrolled beam loss at the electrostatic septum is a performance limit for several existing or planned high power hadron accelerators delivering slow-extracted spills to fixed targets. A passive diffuser, or pre-scatterer, in a suitable configuration has been shown to reduce such beamloss significantly, with the actual gain factor depending on the parameters and details of the extraction process and hardware. In this paper, the optimization of diffuser configurations is investigated for a range of beam energies and extraction conditions, and the sensitivity to the available parameters explored via simulation results. The advantages and limitations of the diffuser are discussed and conclusions drawn concerning the specific case studies of the 8 GeV Fermilab debuncher ring and 400 GeV CERN SPS.

INTRODUCTION

The high intensity frontier is being explored for proton-driven fixed-target experiments like SHiP at CERN [1] and Mu2e at FNAL [2], which aim to exploit the performance reach of high power multi-GeV proton beams available from SPS (400 GeV) and the debuncher ring (8 GeV), respectively. For both, slow extraction via the third-integer resonance is essential to provide the required time structure for the experiments, and the beam loss at the electrostatic septum is the limiting factor for the accelerator performance in terms of integrated proton flux delivered to the experiments.

A diffuser, as postulated by Durand [3], is a promising approach to reduce the performance-limiting beam loss [4,5] at the electrostatic septum (ES) for both projects [6,7].

SLOW EXTRACTION AND ES LOSSES

In the SPS, the beam is debunched with chromaticity set to large negative value. The extraction sextupoles are excited and the tune moved towards $Q_h = 26.666$ by varying the main quadrupoles The extraction is made in combined momentum and betatron space, with largest $|\delta p|$ particles extracted first.

In the 8 GeV FNAL debuncher ring, where space charge also contributes significantly to the beam dynamics, the beam remains bunched and the tune will be ramped to the resonance. Natural diffusion is augmented by RF knock-out using a transverse damper to provide a fine control of diffusion rate and improve spill structure to the required uniformity.

The ES comprise thin foil or wire arrays, typically 50 - 100 μm in width, precisely aligned by an anode support. Mechanical tolerances, alignment precision, stability and thermal dilation effects can all significantly increase the actual septum width as presented to the beam, which is one of the key factors in the beam loss level.

Impacting particles can be lost from scattering (inelastic and elastic nuclear, or Multiple Coulomb), either locally or later in the machine. Beam loss and equipment activation depends on the proton energy and the specific septum material but is always directly proportional to the number of particles impacting the material of the ES septum.

DIFFUSER (PRE-SCATTERER)

A diffuser generates an angular spread in the particle distribution, which can reduce the transverse density at the septum wires and result in an overall beam loss reduction. This is used at CERN in the CERN PS and is also under study for SHiP [6, 8] and for the Mu2e beam from the Fermilab debuncher [7].

The distance of the diffuser from the septum entrance determines the extent to which the angular scattering is translated into a positional spread at the ES. (Small distances corresponding to a few degrees only in betatron phase have been considered to date, but much larger phase advances may be advantageous in some configurations.)

A proton traversing a thin scatterer has a (small angle) Gaussian MC RMS scattering angle per transverse plane [9]

$$\langle\theta_{MC}^2\rangle^{1/2} = \frac{13.6}{p\,[GeV/c]\beta_r c}\sqrt{\frac{L}{X_0}}(1+0.038ln(L/X_0))\ \mathrm{mrad}$$

The position spread at the ES depends linearly on this angle and the distance to the diffuser, while beam loss depends on the material length and probability of nuclear interaction.

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 [9] of

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

In addition the protons lose energy in their passage through the material. At lower energies the effect of energy loss in the diffuser and septum wires becomes more and more important. In W/Re, between 8 and 400 GeV the dE/dx slowly increases from 2.6 to 3.5 GeV/m [10], which means the relative loss for a given scatterer length is a factor of almost 40 higher at 8 GeV, where a 1 mm long W/Re scatterer gives an energy loss of 3.3×10^{-4}.

To make a quantitative comparison, some assumptions are needed on diffuser location and distance to the ES. In

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the FNAL debuncher the diffuser is planned immediately upstream of the ES, with a phase advance of about 1° and $\beta \approx$ 12 m. In the SPS the diffuser is around 10 metres from the ES, with a phase advance of 3.2° and $\beta \approx$ 94 m. This means that, according to [6], in the debuncher to achieve a factor 2 loss reduction, the RMS scattering angle is $\langle\theta_e^2\rangle^{1/2} \approx$1.1 mrad, while in SPS $\langle\theta_e^2\rangle^{1/2} \approx$30 μrad. These angles determine the length of scattering material required.

A comparison of considered materials and lengths needed to achieve these scattering angles is given in Table 1. The total loss includes all p scattered inelastically, and those scattered elastically by more than 1 mrad/50 μrad at 8/400 GeV respectively. $^{184}_{74.3}(W_{75}Re_{25})$ alloy was assumed.

In terms of beam loss denser W/Re or Ta material is preferred at both energies, although Mo also looks reasonable. The effect of the ionisation energy loss -dE/dx is quoted but not taken into account in the loss fraction: it is clear that this effect needs to be included in future studies.

Ta was evaluated because it has actually been deployed in the prototype diffuser currently under test in the SPS: the 0.2 mm diameter wire is much more malleable than similar thickness W/Re, and can mounted with reasonable straightness. From Table 1, it seems almost identical W/Re in terms of the loss produced for a given scattering angle. The mounted wire array had a 0.26 mm effective thickness.

SIMULATIONS

Simulations evaluated the diffuser performance as as function of parameters and energy. A python tracking routine was used [6], benchmarked against MADX and pyCollimate [11]. The tracking includes tune sweep, sextupole driving terms, scattering at diffuser and ES, and losses, but no chromatic effects. The diffusers were modelled as a full density blade, the ES as full blade with uniform reduced density calculated from total material, length and assumed width.

Table 1: Diffuser length and loss fraction for 8 and 400 GeV

Parameter	$^{12}_{6}$**C**	$^{28}_{14}$**Si**	$^{96}_{42}$**Mo**	$^{181}_{73}$**Ta**	**W/Re**
ρ [g/cm^3]	2.0	2.3	10.2	16.7	19.7
λ_n total [cm]	29.6	30.2	9.1	6.6	5.6
λ_i inelastic [cm]	42.9	46.5	15.3	11.5	9.8
X_0 [cm]	21.4	9.4	0.96	0.41	0.35
8 GeV (1.1 mrad RMS scattering angle)					
Length [cm]	9.5	4.2	0.43	0.18	0.16
$\langle\theta_e^2\rangle^{1/2}$ [mrad]	10.8	8.1	5.4	4.4	4.3
Inelastic loss [%]	19.9	8.6	2.8	1.6	1.6
Total loss [%]	27.3	13.0	4.6	2.7	2.8
-δp/p [10^{-3}]	4.2	2.1	0.7	0.5	0.5
400 GeV (30 μrad RMS scattering angle)					
Length [cm]	17	7.0	0.77	0.32	0.28
$\langle\theta_e^2\rangle^{1/2}$ [μrad]	215	162	108	87	87
Inelastic loss [%]	32.7	14.9	4.9	2.7	2.8
Total loss [%]	41.7	20.3	7.0	3.9	4.0
-δp/p [10^{-3}]	0.2	0.09	0.04	0.02	0.02

The extraction process was adjusted to give a rather thick separatrix angle in normalised phase space, of about 700 μrad RMS (with the real spread in angles a factor β lower). 10^5 particles were tracked per scan point. Results are normalised to the losses with no diffuser present.

Parametric scans were made to optimise diffuser length, width, transverse offset and alignment angle, for different diffuser materials. The assumed parameters for the machine and ES configurations are shown in Table 2.

8 GeV Diffuser Optimisation

The length, width and transverse offset were optimised iteratively, with one-dimensional parameter scans. Figures 1 and 2 illustrate the results obtained for a Ta diffuser at 8 GeV.

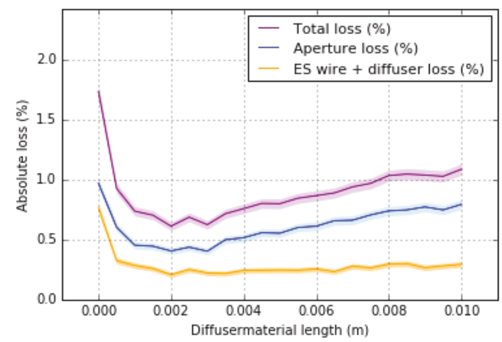

Figure 1: 8 GeV loss vs. length for 0.2 mm wide Ta diffuser 1° upstream of 0.2 mm W/Re ES.

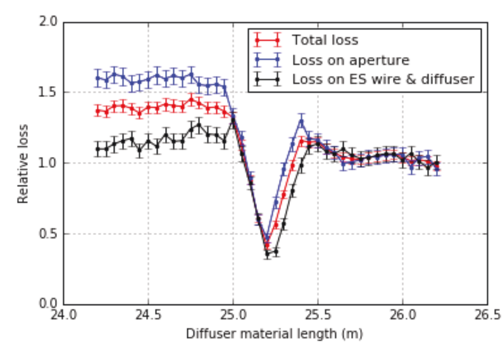

Figure 2: 8 GeV loss vs. position for 2 mm long, 0.2 mm wide Ta diffuser 1° upstream of 0.2 mm wide W/Re ES.

The optimum length for Ta is about 2 mm of scattering material, in agreement with the estimate in Table 1 with a

Table 2: Parameters assumed for 8 and 400 GeV beams

Parameter	8 GeV	400 GeV
β_x (ES and diffuser) [m]	12	94
Phase advance diffuser to ES [°]	1.0	3.2
ES effective width [mm]	0.2	0.4
ES total length [m]	3.0	17.25
ES field [MV/m]	6.0	11.0
ES blade total area (w×l) [mm^2]	42.8	50.8
Separatrix angular spread [μm]	60	8

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reduction of losses by 60%. The minimum with diffuser position is a very sharp one, since the diffuser is the same width as the ES - this is a crucial point, in that the optimum loss reduction can only be obtained if the diffuser width matches very closely the real width of the ES, at the cost of tight positioning tolerance.

A low-Z C diffuser was simulated, Figs 3, 4. As expected, the optimum diffuser length is longer at ≈50 mm, and the potential gain is slightly lower, at 45%. Scans for Mo diffuser material were also made (not shown), to similarly determine optimum parameters.

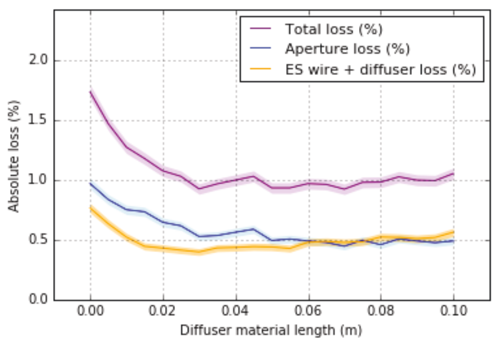

Figure 3: 8 GeV loss vs. length for 0.2 mm wide C diffuser and 0.2 mm W/Re ES.

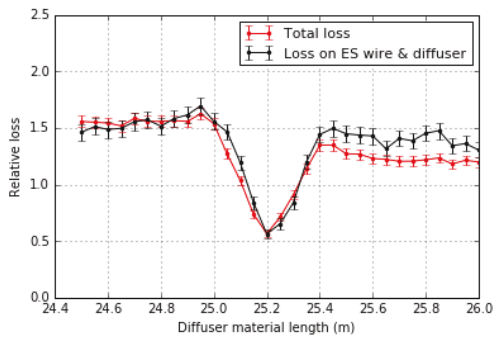

Figure 4: 8 GeV relative loss vs. position for 40 mm long, 0.2 mm wide C diffuser and 0.2 mm W/Re ES.

400 GeV Diffuser Optimisation

At 400 GeV the diffuser optimisation was already studied with W/Re and Mo wires [6]. However, the prototype device recently installed in the SPS is equipped with an array of 20× 0.2 mm Ta wires (with 0.26 mm width). It gives a measured 15% loss reduction.

The expected performance with this arrangement was also simulated, varying the ES width to match the measured results. A diffuser with 0.6 mm ES width is compared with the measured results in Fig. 5. Although the simulation reproduces very well the measured dip width and depth, the difference in the asymmetry of the side-peaks is striking: this is being investigated with (more time consuming) MADX and FLUKA simulations. One possible explanation is that the energy loss in the diffuser significantly moves the scattered distribution in angle towards the septum wires on the high-field side, due to the intervening focusing quadrupole.

Simulations are ongoing, together with beam measurements using the installed device, and will be reported in detail elsewhere.

A 0.6 mm Ta diffuser was simulated with a 0.6 mm ES width, Fig. 6. At this septum width the maximum loss reduction for SHiP beam is expected to be about 40%, depending on the separatrix angular width that can be achieved.

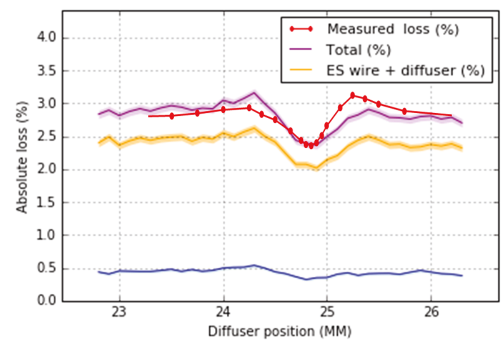

Figure 5: 400 GeV measured and simulated losses, with 0.26 mm wide Ta diffuser and 0.6 mm wide W/Re ES.

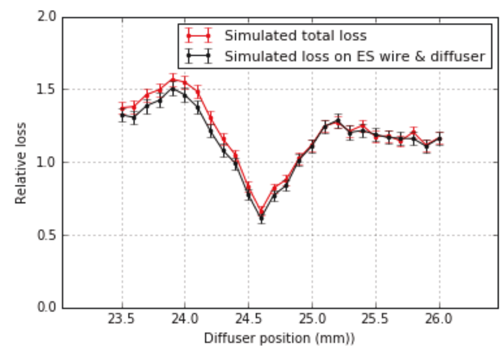

Figure 6: 400 GeV losses vs. position for 2 mm long, 0.6 mm wide Ta diffuser and 0.6 mm wide W/Re ES.

CONCLUSIONS

Simulations were performed with 8 and 400 GeV parameters, for different diffuser materials, lengths and widths. The simulations indicate that high Z materials perform the best at both energies, and that the diffuser needs to be very similar in width to the ES including tolerances. For the 400 GeV case, results could be compared with preliminary SPS measurements with a 260 μm wide Ta diffuser and seem to indicate an ES width of about 600 μm. The measurements confirm the need for ±50 μm positioning precision. The effect of the dE/dx in the diffuser must be included to better understand the experimental results.

Overall, a gain of a factor 2 looks possible for the 8 GeV debuncher ring, but will be more challenging for the 400 GeV SPS. The septum width is the dominating parameter both in the absolute loss level without diffuser and in the gain a diffuser can bring.

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