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USE OF A MASSLESS SEPTUM TO INCREASE SLOW-EXTRACTION EFFICIENCY

K. Brunner*, D. Barna Wigner Research Centre for Physics, Budapest, Hungary
M. A. Fraser, B. Goddard, L. S. Stoel[1], C. Wiesner CERN, Geneva, Switzerland
[1]also at Vienna University of Technology, Vienna, Austria

Abstract

The Super Proton Synchrotron (SPS) at CERN provides slow-extracted beam for Fixed Target experiments in the North Area. For the higher extracted beam intensities requested by proposals of future experiments, beam-loss induced activation will be one of the limiting factors for the availability of such a facility. In this paper, we present and discuss a new concept of using a massless septum magnet to increase the extraction efficiency and decrease losses caused by proton scattering at the electrostatic-septa wires.

INTRODUCTION

From the CERN SPS up to $4 \cdot 10^{13}$ protons are extracted during 4.8 s using standard sextupole-driven slow-extraction at 1/3 integer tune. The main goal of using slow-extraction is to provide a semi-constant flux of particles to the Fixed Target experiments. Slow-extraction in general has much higher losses than single-turn extraction. The main source of these losses is the scattering of the particles on the wires of the electrostatic septum (ES). This greatly increases the activation of the Long Straight Section 2 (LSS2) in the SPS, and thus limits the maximum allowed proton-output of the accelerator.

To achieve the increased number of protons-on-target (POT) requested by the experiments, different loss reduction methods are being considered, and presented in [1]. Some examples of these are the dynamic bump [2], and the diffuser; either passive [3], or active using bent crystals [4]. The idea of using a massless septum for loss reduction was proposed in [5] and is presented in this paper. The novel approach is to use the massless-septum field to fold the phase space in order to increase the extraction efficiency. Studies of alternative methods for folding the phase-space, using higher order multipole magnets, are presented in [6, 7].

MASSLESS SEPTUM IN GENERAL

In the case of an electrostatic septum the goal is to have a high gradient of the field between the inner and outer regions of the septum, with the least possible amount of material, in order to reduce the scattering (and losses) of the particles. At SPS this is achieved by using a row of 60 µm and 100 µm Tungsten-Rhenium wires as the anode.

In a massless septum, high field gradient is created between regions of high and low fields without any material in between. This high gradient transition zone will be called the transverse fringe field. The transition between the regions is of course not as sharp as for a regular septum. In this work the magnetic field in the fringe field will be assumed to change linearly.

An ideal massless septum would have an infinitesimally small fringe field. This is of course not achievable. In practise the fringe field cannot be much shorter than the aperture of the magnet itself. As a consequence it is not feasible to replace an ES with a massless septum. Nevertheless, it could be used to fold the separatrix of the third order resonance in a way, that the efficiency of the slow-extraction increases.

POSSIBILITIES

There are three main concepts to use a massless septum to manipulate the slow-extracted particle distribution at the electrostatic extraction septum.

Stretching the Separatrix Arm

In the first two concepts, the separatrix arm is stretched. Particles traversing the high-field region of the septum will receive a constant kick, while the phase space of the particles traversing the transition region of the septum will be stretched along x'. The schematics of this can be seen on the left side of Fig. 1. After a certain phase advance (at the position of the ES) the stretch appears as diluted spatial density, thereby reducing the number of particles hitting the ES wires, as visualised in Fig. 1.

This can be done in two ways. Due to the limited ring acceptance, the "stretched" part cannot recirculate one additional turn. Therefore, one can either extract these particles in the same turn, but then the required extraction aperture is increased significantly, or one can introduce a second massless septum to the system (at 2π phase advance from the first), and push back the particles affected by the kick but not extracted. This idea is discussed in [8].

Phase Space Folding

The third concept is to reduce the particle density at the ES wires by using a stronger sextupole field, and to use the fringe field of the massless septum to fold back the end of the separatrix that would otherwise be outside of the extraction aperture, as illustrated in Fig. 2.

An important advantage of this approach is that only the zero field and fringe field of the massless septum are used. This relaxes the requirement of having a very narrow fringe field. The important factor is the field gradient.

* brunner.kristof@wigner.mta.hu

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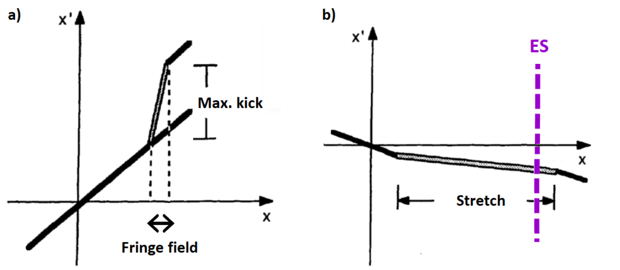

Figure 1: Effect of a massless septum kick applied to a linear particle distribution (a), and the reduced particle density hitting the ES wires (b). Figure modified from [9].

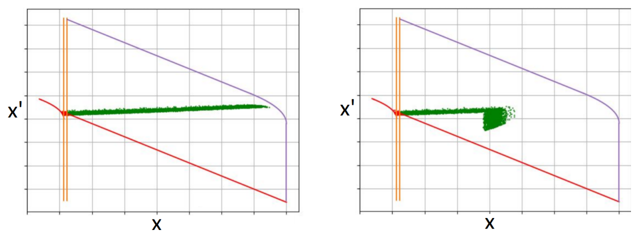

Figure 2: Original (left), and folded (right) resonance arm extracted. Phase space folding reduces the necessary extraction aperture. Red particles are lost, green particles are extracted. The double lines represent the septum wire, while the purple line is the surface of the cathode.

SIMULATIONS

Case 1

A proof-of-principle simulation tool was written in python using thin lens sextupole kicks and rotations in normalised phase space to simulate the extraction dynamics. The initial horizontal positions and momenta of the particles are generated using a 2D Gaussian distribution. The longitudinal momentum spread of the particles is assumed to be zero. Chromatic effects and coupling between horizontal and vertical plane are neglected. The particles are tracked for 5000 turns in the ring. For each turn, the following steps are repeated in the simulation.

- First a thin lens sextupole kick is applied to the particles: $\Delta p_s(x) = s \cdot x^2$, where s is the strength of the sextupole (the units are chosen so that $s = 1$ is the "original" extraction), x is the position of the particle, and $\Delta p_s(x)$ is the kick applied to it.
- The phase advance between the sextupole and the massless septum is then taken into account as a simple rotation in the normalized phase space:

$$R = \begin{bmatrix} cos(\phi_{s-m}) & sin(\phi_{s-m}) \\ -sin(\phi_{s-m}) & cos(\phi_{s-m}) \end{bmatrix},$$

  where ϕ_{s-m} is the phase difference.
- The massless septum kick is also a thin lens kick:

$$\Delta p_{ms}(x) = \begin{cases} 0, & \text{if } x < a \\ g \cdot (x - a), & \text{if } a < x < b \\ g \cdot (b - a), & \text{if } b < x \end{cases},$$

  where a and b are the two "edges" of the fringe field, and g is the integrated gradient of the fringe field.
- The phase advance between the massless septum and the electrostatic septum is a rotation with ϕ_{m-e}.
- At the electrostatic septum the particles which are extracted or lost on the wires or the cathode are taken out of the system. There was no scattering simulated. In the extraction plots the green dots represent extracted particles, while the red dots are particles which are hitting the wires.
- Finally, one last rotation is applied with ϕ_{e-s} to get the particles' phase space positions at the sextupole.

For the third order resonance the following condition applies:

$$\phi_{s-m} + \phi_{m-e} + \phi_{e-s} = i/3 \cdot 2\pi,$$

where i can be any integer. In other words the tune has to be 1/3 integer.

Results of Case 1

The simple simulations already gave considerable insight. By doubling the sextupole strength ($s = 2$) and folding back the part of the separatrix arm, which otherwise would approach the cathode, the beam density at the ES wires can be decreased by a factor of 1.9. The optimal case was achieved at $s = 4.5$ seen in Fig. 4. To achieve this one would need a massless septum with an integrated field of 0.45 Tm and a fringe field width of 9 mm. It should be stated that since only the fringe field plays a role in this concept, its width can be increased, along with the maximum field.

The limiting factor of this concept is the nonlinearity of the resonance arms. If the sextupole strength is too high the arms start to bend significantly. The direction of the bending depends on the tune. If it can be written in the form $(i + 1/3)$, where i is any integer, then the arm on the right bends upwards (as seen in Fig. 3). If the tune is $(i + 2/3)$, then the arm on the right bends downwards. Here, we consider only the case $Q = (i + 1/3)$.

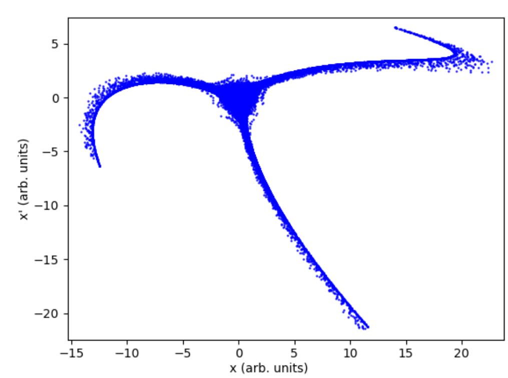

Figure 3: The nonlinearity of the resonance arms at high sextupole fields, if the tune is $(i + 1/3)$. The phase space is shown just before the sextupole kick is applied.

The nonlinearity gives an upper limit to the usable sextupole strength which is 4.5 times the nominal strength. For

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a 4.5 times higher sextupole strength than nominal, the density at the wires is reduced by a factor of 3.33. The phase space folding with these parameters can be seen in Fig. 4 and the number of lost particles as a function of sextupole strength in Fig. 5.

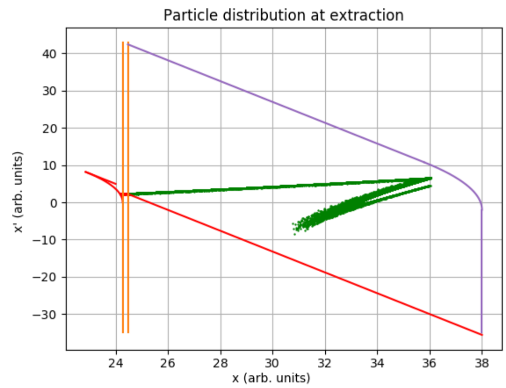

Figure 4: Extraction profile at $s = 4.5$ in Case 1.

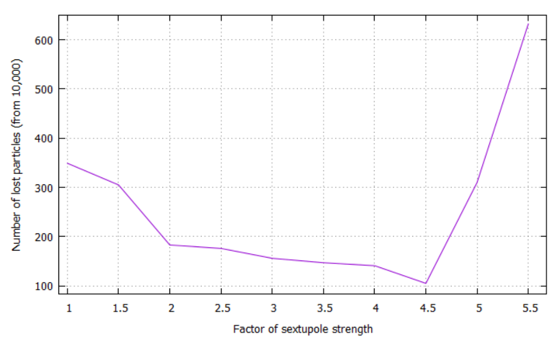

Figure 5: Number of lost particles as a function of the sextupole strength in Case 1. Units are chosen so that nominal sextupole strength corresponds to 1.

Case 2

A more advanced simulation was done to test the principle using SPS parameters. The SPS currently uses 4 extraction sextupoles for slow-extraction, with $i/3 \cdot 2\pi$ phase advance between them, which reduces the single sextupole kick required. Each of them has a length of about 740 mm, and a nominal (maximum) field gradient of 160(227) $\mathrm{T/m^2}$. The sextupole kick strength in the simulation is tuned, so that the four kicks of strength 1 is equivalent to the four sextupole magnet's effect working at 160 $\mathrm{T/m^2}$.

In the simulation optics functions are taken from a MAD-X simulation of the SPS slow-extraction. Since the tune in the SPS at extraction is 26.667 the arm of the resonance is bending downwards at high sextupole fields (as discussed above). This is a great difference from Case 1 simulation, because the particles near the end of the arm get close to the downstream end of the septum wires (as seen in Fig. 6).

Another change is that β_x is not considered to be constant inside the ES. This modifies the acceptance of the ES slightly. The change from Case 1 model was essential for the results to be comparable with the MAD-X simulation and the slow-extraction loss reduction study, discussed in [7].

Despite having four sextupoles we still used only one massless septum, that is between the "last" sextupole and the electrostatic septum. The question whether the acceptance of the ring is sufficient for the increased beam was beyond the scope of this study.

Results of Case 2

With this arrangement the maximum sextupole field strength achievable was just $s = 2.3$ times the nominal value, and the particle density at the ES wires were reduced by 52%. Although $s = 2.4$ gave a lower particle density, the separatrix approached the cathode too much, so it was not considered a feasible solution. The phase space distribution of the extracted particles at $s = 2.3$ is shown in Fig. 6 and the number of lost particles as a function of the sextupole strength in Fig. 7.

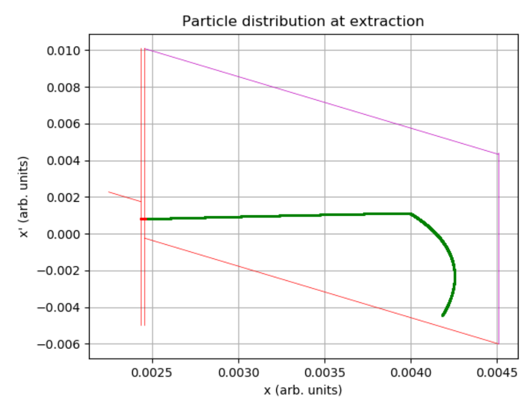

Figure 6: Extraction profile at $s = 2.3$ in Case 2 simulation.

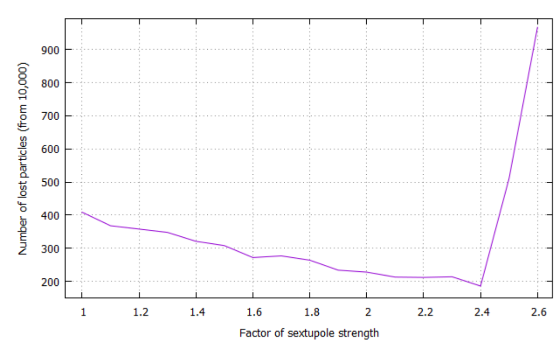

Figure 7: Number of lost particles as a function of the sextupole strength in Case 2. Units are chosen so that nominal sextupole strength corresponds to 1.

CONCLUSION

First simulations were presented showing promising results for the application of a massless septum to increase the extraction efficiency of a third order resonant slow extraction. The maximum possible increase in efficiency depends

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strongly on the system parameters. In Case 2 (simulation using SPS parameters), the density of particles at the wires of the electrostatic septum was reduced by a factor of two, while the sextupole strength used to induce the resonance was increased by a factor of two.

Further work is required to check the effect of momentum spread, and chromatic effects. But the most critical question is now whether the increased beam size (due to increased sextupole strength) fits the ring aperture. This was not studied yet, but it will most likely give a hard limit to the maximum sextupole strength.

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