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HIGHER MULTIPOLES IN 3RD INTEGER RESONANCE EXTRACTION*

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Abstract

The efficiency of slow extraction is becoming a limiting factor, as the demand for delivered beam power is constantly growing. New methods for improving extraction efficiency include folding the extraction separatrix using the higher multipoles. In this report we discuss a simple and effective approach to determine an optimal placement of those multipoles in the storage ring. This allows reduction of the beam losses and therefore, the level of prompt and residual radioactivity in the accelerator components and surrounding buildings by as much as 40% or more. We also explore here manipulating the higher order effects produced in the pure sextupole configurations for the same purpose and demonstrate that similar results can be achieved by only rearranging the sextupole magnets in the lattice.

INTRODUCTION

Here we focus on the concept of increasing the step size while keeping the beam size confined in the extraction acceptance channel by using higher order multipoles. This discussion starts with a 1997 conference report [1]. Attention to this technique has grown again recently, as can be seen in publications [2-8]. Most recently, the method has been successfully demonstrated in the machine studies at CERN [9]. The detailed analytical treatment of complex multipole fields is non-trivial. Because the higher order effects cannot be neglected, the complexity of the non-linear Hamiltonian formulae is growing very rapidly with the number of magnets in the lattice. Perturbative Hamiltonian harmonic analysis was also not effective because of the large number of significant harmonics [8]. In earlier publications a simplified assumption was implicitly made that all multipoles can be grouped at one location.

We are using a new and simple approach based on the single turn mapping, and we demonstrate this approach using tracking simulations. Here we present the results of case studies for the Fermilab Delivery Ring (DR).

DELIVERY RING LATTICE

The Fermilab Delivery Ring geometry has a 3-fold symmetry, as can be seen in Figure 1. There are three straight sections and three arcs. The full ring length is approximately 505m. The 114 quadrupole magnets are equally spaced around the ring, forming a regular FODO structure with nearly 60° phase advance per cell. The dispersion is suppressed in the straight sections. The detailed description of the DR lattice can be found elsewhere [10,11].

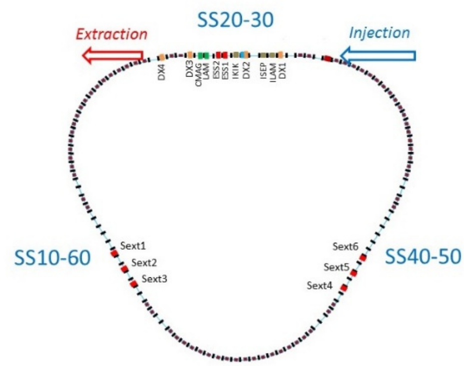

Figure 1: Delivery Ring and location of the sextupole magnets.

Injection (magnetic septa ISEP and ILAM, and kicker IKIK) and extraction (Electrostatic septa ESS1 and ESS2, magnetic septa LAM and CMAG, and orbit bump dipoles DX1-DX4) devices are all located in straight section SS20-30, making this section very crowded. Tune ramping quadrupoles are placed in the middle of each of three straight sections (not shown in the picture). Two sextupole circuits with 3 sextupoles in each are placed in straight sections SS10-60 and SS40-50. Sextupoles are placed near the focusing quadrupoles, which maximizes their driving contributions. Driving contributions of the two circuits are almost orthogonal to each other, which is convenient for tuning the resonance term phase.

TRACKING SIMULATIONS

A simple 2D tracking simulation code has been established to study the phase space formation in slow extraction. Multipole magnets (6 sextupoles plus any additional multipoles added for this study) were represented with thin lenses with the appropriate kick to the particle trajectories.

The transport between the multipoles and the reference point was performed as simple matrix transformation. This provides a clean way to see the effects of a selected configuration, separated from other nonlinear elements in the machine. Coupling and chromatic effects are neglected in this tracking.

We also benchmarked the 2D simulations with a more detailed 6D tracking. This has been done using the universal pyOrbit code developed jointly by ORNL and CERN [12]. The 6D tracking includes realistic RF tracking and momentum distribution and considers important effects of chromaticity, coupling and space charge. It also implements the complete squeeze, so we track the process through the entire spill.

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EFFECTS OF ADDITION OF A HIGHER MULTIPOLE

In classical 3rd integer resonant extraction, the regular shape of the separatrix (Figure 2, red shape) is achieved by a careful design of the sextupole circuits. Here we are looking for the deviations from this regular shape with an addition of a single octupole magnet. Depending on the location, different separatrix branches are affected differently.

We are looking for locations that affect predominantly the extraction branch. We found that the bending of the extraction branch occurs when the octupole is placed at locations with the phase advance to the septum close to a multiple of 180°. Green shape in Figure 2 shows the separatrix for this case, and blue shape shows this separatrix transformed back to the location of the octupole. Clearly, in this choice of octupole location, the extracted branch is almost horizontal and therefore, receives the biggest kick.

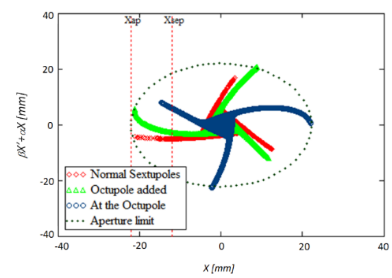

Figure 2: Phase space with an addition of an octupole magnet at the optimal location. Red shape shows the regular case (no octupole). Green and blue shapes show the phase space at the locations of the septum and the octupole.

At small amplitudes, the motion is dominated by the action of the sextupoles and separatrix arms are not significantly distorted by the octupole moments. Only as the particles reach large amplitude will the octupoles have any significant action. In fact, we have found that the octupole field can be adjusted such that most of its action comes in the last turn before extraction – this can be seen from the fact that the non-extracting branches do not show significant bending. Indeed, if we disable the octupole kick on the very last turn, as shown in Figure 3, all the bending action disappears. This justifies treatment of this action as a single turn octupole kick. By treating the action as a single turn mapping, a trivial and intuitive method can be used to calculate the separatrix folding.

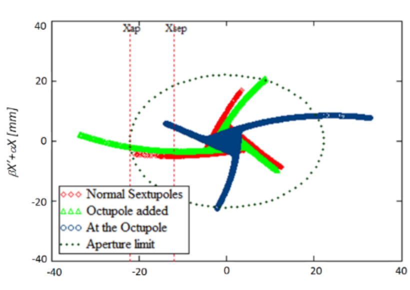

Figure 3: Same as Figure 2, with the octupole kick disabled during the last turn.

Folding the extraction branch allows us to further increase the sextupole strength. Without the octupole field such strength increase would otherwise lead to strong overlap with the aperture, as seen in Figure 3. As a result, the distribution of beam density at the septum is changing as shown in Figure 4. Reduction of beam density at x=X_{sep} (the right boundary of the plot) leads to a reduction of the fraction of scattered beam in the septum plane by 45%.

Similar modifications to the extraction separatrix shape may be achieved with higher multipoles as well, using the same technique. [8] shows similar performance demonstrated with a duo-decapole magnet.

Bending the phase space of the extracted beam results in an emittance increase. In the octupole case considered above extracted beam emittance increased by 100%, which can be an issue for some applications.

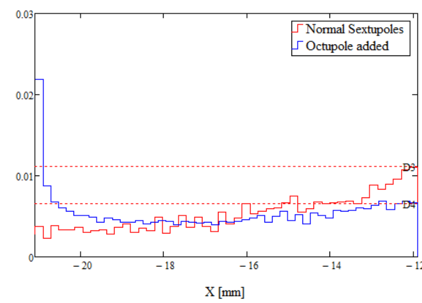

Figure 4: Extracted beam density in X. Red line shows the normal extraction, blue line shows extraction with an additional octupole. Dash lines and markers D3 and D4 are pointing to the beam density at the septum. The density D4 is reduced by 45%.

Results obtained in 2D tracking and presented above are consistent with the results of the full 6D benchmarking [8].

NATURAL HIGHER ORDER TERMS

As it was shown in [8], the higher order effects present in the sextupole configurations can be used to manipulate the shape of the phase space and the separatrix folding as well as additional multipoles. We studied the effects of changing the configuration of the sextupoles in the ring, using tracking simulations.

With a few minimal assumptions and taking into account the lattice degeneracy, all available sextupole configuration changes can be limited to just removing one of the sextupole magnets in each group of 3. From these combinations we found a configuration “1345” of 4 magnets out of 6 (“1345” means that magnets “2” and ”6”, or second in the first circuit and third in the second circuit are missing. Configuration “123456” would mean all 6 magnets are present.). With adjustment of the relative strengths between the families, the extraction phase space can be brought to that in Figure 5.

The effective reduction of the beam losses in this configuration is 30%, whereas the extracted beam emittance is also reduced by 45%, unlike in the cases considered above.

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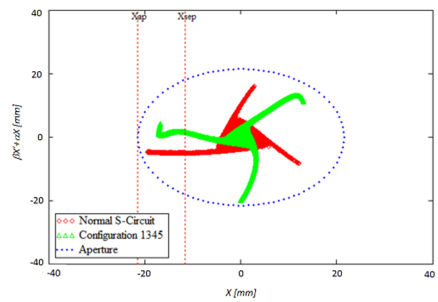

Figure 5: Extraction phase space with modified powering scheme in the standard sextupole configuration. Dash line shows the machine acceptance.

An interesting new feature of the phase space is the two kinks in the extraction branch, which suggests that there are more than one higher perturbation orders involved.

Benchmarking of the case of pure sextupole configurations presents noticeable differences, because several realistic machine operation factors and limitations had to be added in this tracking. However, it confirms similar effects in the same magnet configuration "1345". Figure 6 shows the phase space in 6D simulations and its evolution through the spill. The corresponding spatial density distribution of the extracted beam is shown in Figure 7.

The effect of separatrix folding remains through the entire spill as the tune is moved to the exact resonance, although the folding pattern is changing.

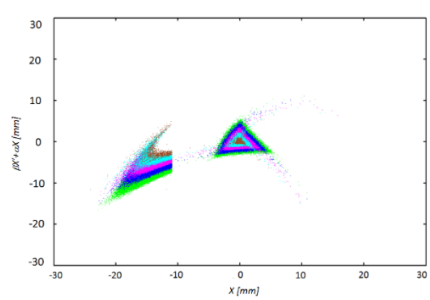

Figure 6: Separatrix shape evolution during the entire spill. Colors show the phase space at different moments of the spill.

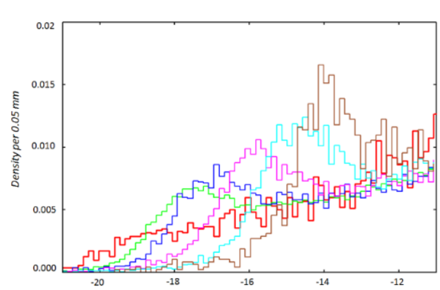

Figure 7: Evolution of the spatial density in the extracted beam during the spill. The red curve shows the distribution for the standard design configuration.

The density reduction at the septum plane is 25% and it stays approximately constant through the entire spill. The extracted beam full emittance, unlike in the 2D case, is grown by 27%, but drops down towards the end of the spill.

CONCLUSIONS

Using simple tracking simulations, we have demonstrated that an addition of a single higher multipole magnet at a proper location can be very effective to reduce the extraction beam losses originating from scattering on the septum. A simple and effective recipe is provided for the best choice of this magnet location. Reduction of beam losses up to 40% can be achieved by using an octupole magnet. The use of the higher than m=3 multipoles is also possible but may be limited because of higher field strength at the magnet pole tips. We also explored the very interesting option of using an intrinsic higher order harmonic content that is present in the sextupole configurations. We have shown that it is possible to produce a similar effect with simply changing the powering scheme in the existing lattice. In this case 2D simulations were instrumental to demonstrate the effect, but the final geometry needed to be readjusted using full 6D simulations to take into account several other realistic operational conditions.

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