WEAK RESONANCES INDUCED BY NONLINEAR MULTIPOLES IN A QUADRUPOLE DOUBLET LATTICE *

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Abstract

In this paper we report the effects on beam dynamics from two intrinsic multipole components of a quadrupole magnet – dodecapole and psedu-octupole, in a quadrupole doublet lattice. Weak resonances at transverse phase advances 60° and 90° per cell, which may contribute to halo formation and beam loss in a linac, are shown from multi-particle tracking simulations. Although the net effect of the psedu-octupole component alone is very small due to substantial cancellations within the same magnet, its existence may significantly enhance the weak resonances which are induced by the dodecapole component of quadrupole magnets. The combined contributions of these two magnetic field components may not be simply linear-scaled because of the extreme nonlinear nature.

INTRODUCTION

Effects of nonlinear components of quadrupole magnets are often ignored in a single-pass linac. However, nonlinear multipoles could cause beam quality deterioration and even particle losses. A weak beam resonance at a 90° phase advance in the positron return line at SLAC – a 75-cell FODO lattice, has been reported, which is induced by the dodecapole component of quadrupole magnets [1]. An even weaker resonance at a 60° phase advance in a 32-cell doublet lattice of the Spallation Neutron Source (SNS) superconducting linac (SCL) has been identified, which is also induced by the dodecapole component, and causes unexpected beam loss and residual activation [2]. More studies on this topic are necessary to understand the contributions of nonlinear components in a linac lattice, particularly, the combined effects when there are several other nonlinear fields.

A quadrupole magnet always contains two intrinsic, dominant nonlinear components: dodecapole and pseudo-octupole, in addition to desired linear quadrupole field. In our previous simulations of the SNS SCL lattice, the dodecapole was included, but the pseudo-octupole term was ignored. To investigate the combined effects of dodecapole and pseudo-octupole, we have developed a tracking code, which includes linear transfer matrices and multipole impulses. The code is applied to a model of a 100-cell quadrupole doublet lattice. We have found that the psedu-octupole component alone has very little impact, but its existence may enhance the effects of dodecapole resonances. These results are reported in this paper. In addition, beam losses in a linac generated by these nonlinear components will also be briefly discussed.

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DOMINANT MULTIPOLE COMPONENTS

The parameters of the SNS SCL quadrupole magnets are used in the model of a 100-cell doublet lattice. The quads have an effective length of 38 cm and an aperture radius of 4 cm. Magnet simulations with OPERA-3D [3] and 3D field multipole expansion [4] yield the linear quadrupole term and two dominant nonlinear components: pseudo-octupole (m=2, r^3) and dodecapole (m=6, r^5), as shown in Fig. 1. The integrated dodecapole is about 30 units at a reference radius of 3 cm, which accounts for 0.3% of the integrated quadrupole term. The integrated pseudo-octupole is zero due to the cancellation in two fringe regions. However, the effect of the pseudo-octupole on beam dynamics does not vanish; it usually causes the third-order aberration.

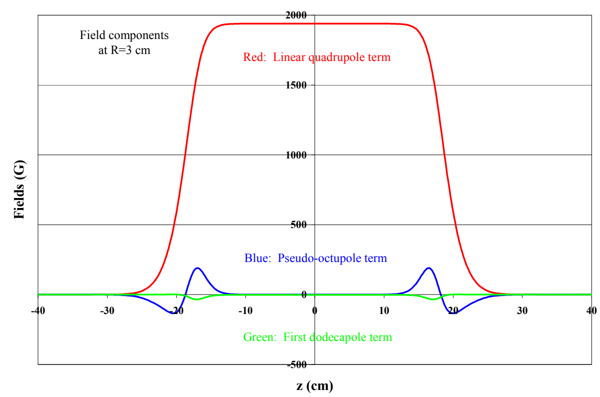

Figure 1: Quadrupole, pseudo-octupole, and dodecapole components in the SNS SCL quadrupole magnets.

Figure 2 shows a measurement result of the SCL quads by a search coil. The dodecapole term (m=6) is about 30 units, which are very close to the 3D modelling result. The pseudo-octupole component does not show up in the measurements. Though other un-allowed higher-order terms (m=3, 4, 5 etc.) exist in real quads, we do not include them in the current studies.

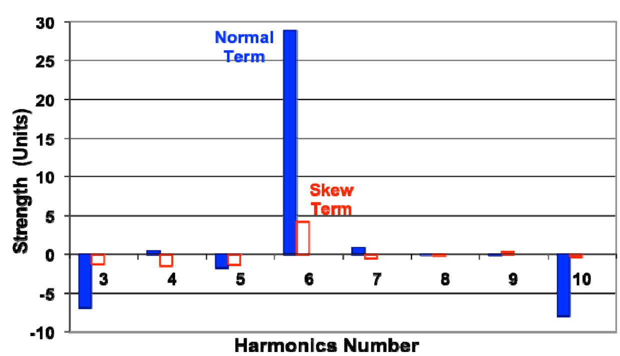

Figure 2. Measured multipole components of the SCL quads.

EACH MULTIPOLE TERM ALONE

The model of a 100-cell doublet lattice has a unit length of 5 m and quadrupole central distance of 0.8 m. We add each nonlinear component for different phase advances. To look at halo formation and beam filamentation, we use uniformly distributed injection particles. Though the pseudo-octupole term is the largest, it has no significant effect on beams because of the field cancelations.

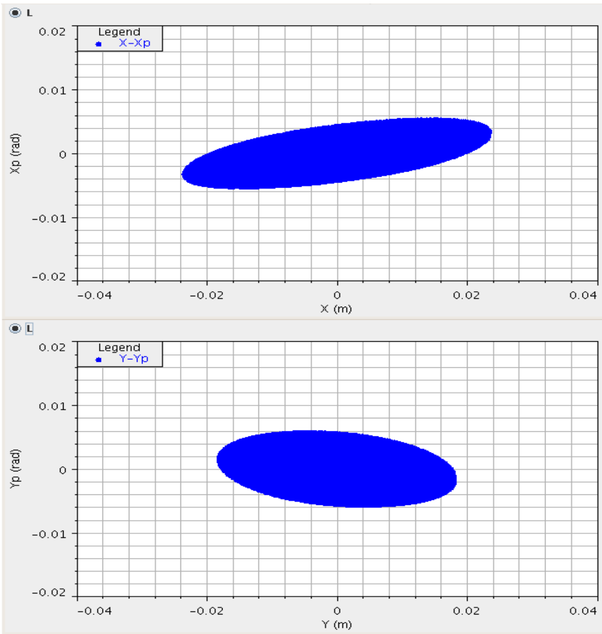

Figure 3: Particle distributions after transport through the doublet lattice of 60° advance; pseudo-octupole term alone.

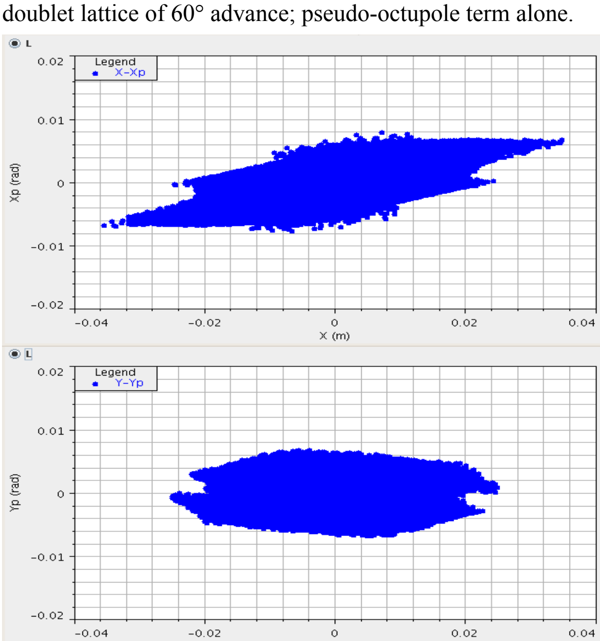

Figure 4: Particle distributions after transport through the doublet lattice of 60° advance; dodecapole term alone.

Figure 3 shows particle distributions in transverse phase space (upper: x-x'; lower: y-y') at end of the lattice of a phase advance 60° with pseudo-octupole only. Comparing with the case of dodecapole only (Fig. 4), the contribution of pseudo-octupole could be ignored. However, at a larger transverse phase advance, the effects of psedu-octupole components may begin to show up in the beam, as shown in Fig.5 for a 90° phase advance. But it is still much less than that with dodecapole term alone, shown in Fig.6.

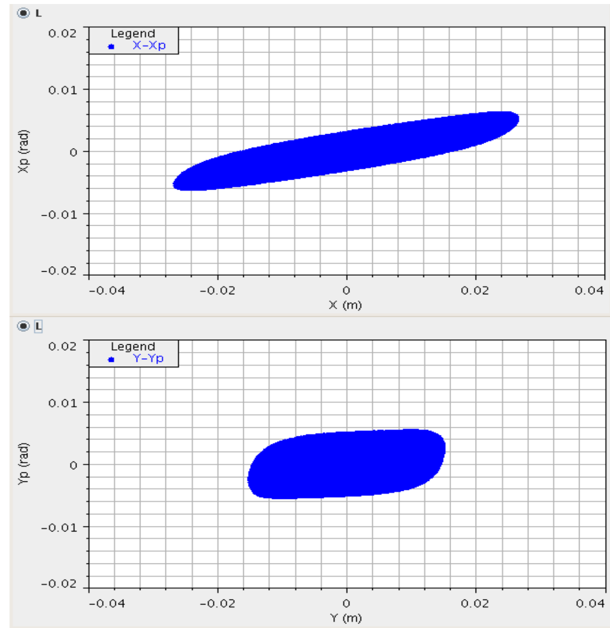

Figure 5: Particle distributions at the end of the doublet lattice of a 90° phase advance with pseudo-octupole term only.

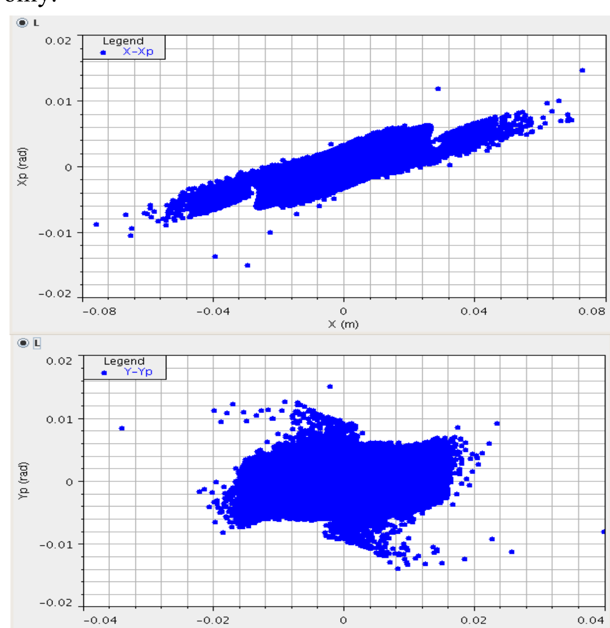

Figure 6: Particle distributions at the end of the doublet lattice of a 90° phase advance with dodecapole term only.

COMBINED MULTIPOLES

From the above simulation studies, it is known to us that dodecapole component plays a most important role in halo formation in a quadrupole magnet. Although the amplitude of pseudo-octupole component is much larger, its effect on beams could almost be ignored because of substantial field cancelations in the same magnet. We also noticed that the cancelation is reduced with an increasing phase advance. In the real world, however, we cannot isolate the effects of these two components; beams always experience both of them simultaneously in a quadrupole.

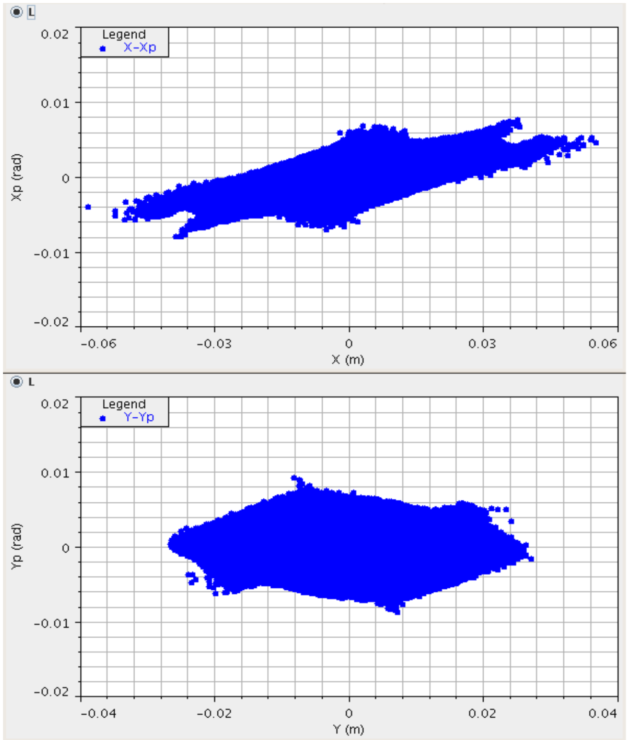

Figure 7: Particle distributions after transport through the lattice of 60° advance; dodecapole and pseudo-octupole.

Figure 7 shows a simulation of the doublet lattice of a 60° phase advance with both pseudo-octupole and dodecapole. Comparing with Figs 3 and 4, the sixth-order transverse resonance is more obvious from a 6-fold filamentation in both horizontal and vertical planes.

Effects of pseudo-octupole term alone can be ignored in a linac. But if there are other nonlinear fields, it cannot. In a high power linac, there are many other nonlinear terms.

SIMULATION OF LINAC BEAM LOSS

In simulations of beam loss due to nonlinear multipole components, accuracy is a big concern. This is not only because there are other important issues such as space charge, RF, misalignment, mismatch, and element errors of the linac, but also because the loss level is small and beam halo/tail inherited from the upstream beam delivery system matters. For example, when dodecapole strength is reduced to less than 10 units in simulations with the SNS baseline linac lattice, no beam loss is found in the SCL. Beam loss is discovered after increasing dodecapole strength to 30 units – the measured value. However, beam loss also depends on where the simulation actually starts, or initial halo particles in the injection beams.

If simulations start from the SCL, no particle loss is found; starting from the medium-energy-beam-transport (MEBT), no beam loss occurs in the warm linac, but 2×10^{-5} loss is found in downstream SCL. If simulations start from the RFQ, there is beam loss in the warm linac, and about 3×10^{-4} fractional loss in the SCL.

Phase advances of the linac lattice can be changed to avoid the resonances. And we have reduced the SCL loss by a factor of 2 to 3 with a phase advance 40° to 50°, instead of the baseline design of 60° and more [5, 6].

This reduction of beam loss could also be attributed to intra-beam stripping of H^- particles [7]. However, the simulated intra-beam stripping loss is less than 20% of the measured one. For several years of operation, SNS linac beam loss is linearly proportional to beam current from 20 to 40 mA. Intra-beam stripping would have observed a quadratic curve. For synchronous phase from -30° to -15°, linac loss is almost a constant. And by collimating a few percent beams at MEBT, beam loss may reduce up to several ten percents over the entire linac. All these cannot be explained by intra-beam stripping loss only.

Simulations of linac beam loss to a 10^{-5} or 10^{-4} level with a multi-particle tracking are still very difficult to achieve high accuracy. Among the major difficulties are the physics involved, measurement and modeling of the injection beams precisely up to 10^{-5} or 10^{-4} level.

PARMILA [8] code is in principal not capable at this small level of beam loss. Instead, a parallel tracking code such as IMPACT [9] should be considered. After adding all mutlipole components of the quadrupoles in addition to RF and space-charge effect, it could be very interesting to know, what would happen to those weak resonances, and how many particles are lost in a linac.

CONCLUSIONS

Beam halo formation caused by multipole components of quadrupole magnets is shown in the simulation studies of a 100-cell doublet lattice. Weak resonances at 90º and 60º phase advances are mainly induced by a dodecapole component that is larger than a conventional limit of 10 units. They may contribute to beam halo and beam loss in a high power linac. However, accurately computing a linac beam loss down to 10^{-5} or 10^{-4} level with multi-particle tracking simulation remains to be a very challenging task. While more beam loss measurements and numerical simulations are still necessary to shed more light on this subject, in the design of a future high power linac the issue should be avoided easily with a better magnet design practice.

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