OPTIMIZATION OF THE DYNAMIC APERTURE FOR SPEAR3 LOW-EMITTANCE UPGRADE†

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Abstract

A low emittance upgrade is planned for SPEAR3. As the first phase, the emittance is reduced from 10nm to 7nm without additional magnets. A further upgrade with even lower emittance will require a damping wiggler. There is a smaller dynamic aperture for the lower emittance optics due to a stronger nonlinearity. Elegant based Multi-Objective Genetic Algorithm (MOGA) is used to maximize the dynamic aperture. Both the dynamic aperture and beam lifetime are optimized simultaneously. Various configurations of the sextupole magnets have been studied in order to find the best configuration. The betatron tune also can be optimized to minimize resonance effects. The optimized dynamic aperture increases more than 15% from the nominal case and the lifetime increases from 14 hours to 17 hours. It is important that the increase of the dynamic aperture is mainly in the beam injection direction. Therefore the injection efficiency will benefit from this improvement.

INTRODUCTION

The SPEAR3 ring has racetrack layout with a circumference of 234.1m. It consists of 14 standard cells and 4 matching cells. The emittance of the present operations lattice is 10nm with betatron tunes of (14.1, 6.18). It is important to significantly reduce the emittance for SPEAR3 to remain competitive with other new light sources. A study of the low emittance scheme in SPEAR3 started about year ago [1]. Several steps of upgrades are proposed to reduce the emittance. As a first step, we could reduce the emittance to 7.0 *nm* with the existing ring by simply increasing the horizontal betatron tune by about one integer. Additional power supplies for sextupole magnets become necessary to get enough dynamic aperture. Meanwhile, the thickness of the injection septum wall is planned to be reduced from ~6.3 to ~2.5 *mm* with new in-vacuum septum. The required DA at injection is 12mm in the horizontal towards the inside of the ring. Damping wiggler will be required to futher reduce the emittance below 5nm.

One of the challenges of the low emittance optics is the strong non-linear dynamics. We use MOGA [2] to optimize both the dynamic aperture (DA) and the momentum aperture (MA). Magnet errors are included during the optimization.

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SEXTUPOLE CONFIGURATION STUDY

In the existing SPEAR3 ring, there are only four sextupole families, two in the standard cells and another two families in the matching cells. Thus, there are only two free variables for optimizing DA and MA after the chromaticity correction. Inspired by the success at APS [2], we plan to add more sextupole families in order to optimize the DA and MA. To mimimize the cost and thus the number of sextupole families, systematic studies have been done to find the optimal configuration of the sextupoles.

The study is done for an optics with betatron tunes (15.13,6.22) and an emittance of 7nm. Figure 1 shows an example of the optmization procedure. The speed of convergence is problem dependent. Typically, it takes a few thousand runs. Table 1 shows the DA for different combinations of sextupole families. The configuration is symmetric from the east to the west. The table shows the configuration in half of the ring. Each letter represents the sextupole magnet in each cell. Letters *a* and *b* stand for two different sextupole families (each family shares one power supply), letter *x* means that the strength of this sextupole is an independent variable during the optimization. The overall difference in DA is small. There is no superior configuration found. The configuration 10 is slightly better with a larger DA and faster convergence speed.

It is also important to check the variation of the strength of sextupole magnets in various configurations. As shown in Figure 2, the overall variation is about 20% level, except for the magnets in the matching cells, where the magnets are weak. The insensitivity to the configurations leaves more room for the choice of sextupole magnet configuration.

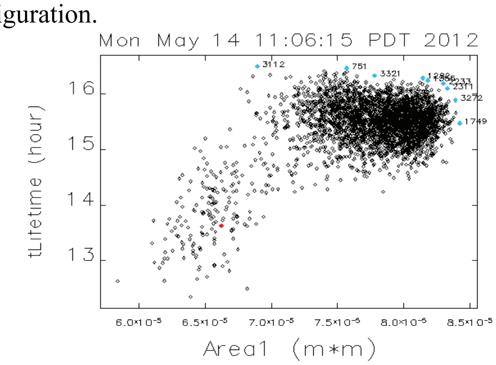

Figure 1: Example of MOGA optimization of DA and lifetime. Each dot represents one run and the cyan dots are the best solutions.

Table 1: DA for Various Sextupole Configurations

No.	Arrangement of sextupole families	DA (1e-5 m^2)
1	bxxaaaxxb	8.42
2	baxxaxxab	8.50
3	xaxaxaxax	8.76
4	baxaxaxab	8.30
5	bxaaxaaxb	8.63
6	xxaaxaaxx	8.83
7	xaxxaxxax	8.78
8	xxaxaxaxx	8.63
9	xaaxxxaax	8.72
10	xxxaaaxxx	8.85

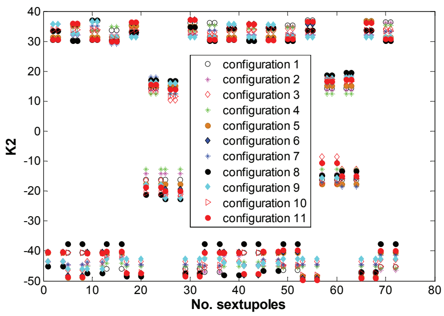

Figure 2: Distributions of the strengths of sextupole magnets along the whole SPEAR3 ring for various configurations shown in Table 1.

AUTOMATIC REDUCTION OF THE RESONANCE DRIVING TERMS

It is important to set an effective objective for optimizer. It is not straight forward to minimize the sextupole driving terms in order to get a large DA. There are many driving terms, and there is an uncertainty about how to combine them into one or two objectives. One driving term may be more important than others for one particular optics. For instance, frequency maps can tell whether a particle crosses important resonance lines. MOGA uses the area of the dynamic aperture as one of the objectives. It was found that most the driving terms can be reduced automatically during the optimization although the DA is the objective. Figure 3 shows the reduction of the driving terms in one of the best solutions. The reduction is larger for some particular terms. It is interesting that Sun's study [3] shows it is more effective to minimize diffusion rate of the lattice than the dynamic area. However, one study using AT and NSGA-II doesn't show much advantage for our optics.

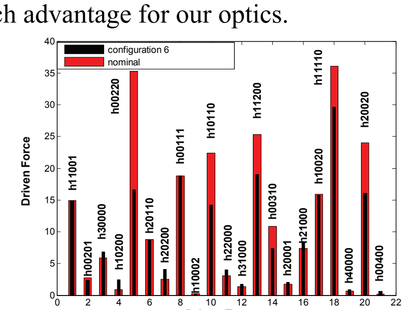

Figure 3. Automatic reduction of the driving terms after the optimization although DA is set as one of the objectives during the optimization.

RESONANCE CROSSING

When the tune shift with amplitude is large, the particles can cross the strong resonance lines. For one optics, particles with horizontal amplitude up to 20 mm can cross four 4th order resonance lines $4\nu_y$, $\nu_x+3\nu_y$, $2\nu_x+2\nu_y$ and $3\nu_x+\nu_y$. It was found that particles with certain amplitude (not necessarily the maximum) are lost in a long run. Particle tracking with various initial amplitudes shows different resonances at different amplitude as shown in Figure 4. It clearly shows the strong $3\nu_x$ near the boundary of DA and $4\nu_x$ resonance with 10~15mm amplitude. There is also $4\nu_y$ resonance in the vertical plane. It is interesting that particles with large amplitude can survive from $4\nu_x$ resonance but particles with intermediate initial amplitude can be lost in the long run as shown in Figure 5. FFT shows strong horizontal resonances, however, a slow growth occurs in the vertical plane. The particle finally is lost due to a small vertical aperture of 3mm there. This feature requires the tracking to be done with many revolutions. Basically, this kind of optics is not suitable. The DA should be first checked with long term tracking to see whether there is particle loss in a long run. For a good linear optics, 500 turns tracking would be sufficient. There would be a similar DA for 500 and 5000 turns tracking. See Figure 6.

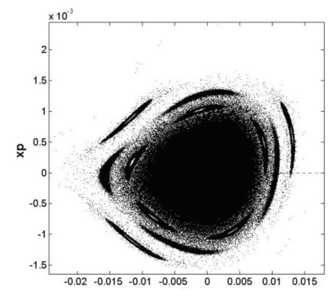

Figure 4: Horizontal phase space of particles with different initial amplitude.

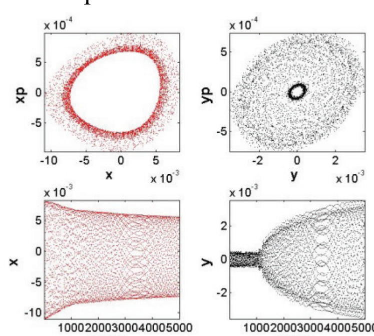

Figure 5: Horizontal (left column)/Vertical(right column) phase space of particles with intermediate initial amplitude.

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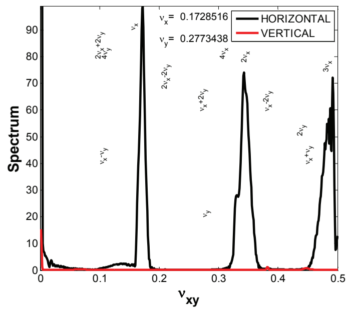

Figure 6: Spectrum of the particle motion shown in the above figure.

OPTIMIZATION WITH TUNE

Besides the sextupole magnets, the linear optics, especially the betatron tune can be optimized. In SPEAR3 ring, there are only a few independent quadrupole variables. There are three quadrupole families in the DBA cells, two focusing magnets (QF) and two defocusing quadrupole magnets (QD) and a central quadrupole (QFC). On the other hand, there are many constraints for the optics. We manually generate a tune table with the strengths of all quadrupole magnets to cope with these constraints so that all solutions in the table are good. During the optimization, an interpolation is done to get the required tune. Figure 7 shows an example of the optimization procedure. Each particle is tracked 4000 revolutions in order to avoid the resonance crossing mentioned above. It clearly shows that there are two groups of candidates. One is in favor of the dynamic aperture and another one favors the lifetime. There is a large lifetime with the small tune end (in both horizontal and vertical planes), while the best DA appears with tune near (15.11, 6.24).

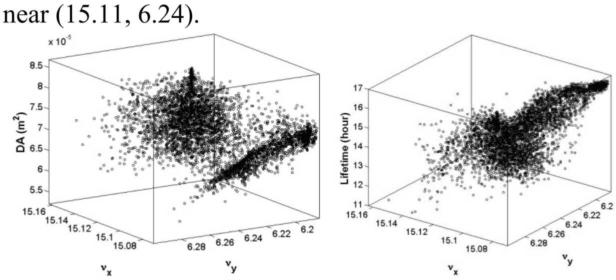

Figure 7: The effects of betatron tune on DA (left) and lifetime (right) during the optimization procedure. The sextupole magnets have the configuration No. 10 as shown in Table 1.

HIGH RF VOLTAGE WITH DAMPING WIGGLER

The radiation loss per turn increases from 1.4MeV to 1.8MeV with damping wigglers. This increment in radiation loss reduces the momentum acceptance (MA) as shown in Figure 8. The maximum RF voltage of SPEAR3 existing cavities is 3.2 MV. To achieve a similar MA, a RF voltage of 3.7MV is required. One alternative way is to reduce the momentum compaction factor by a factor 1.4/1.8. MOGA simulation clearly shows a limitation in lifetime by the RF voltage when damping wiggler is added. The lifetime is limited to 6.7 hours with 3.2MV RF voltage and it increases to 11 hours with 3.7MV voltage.

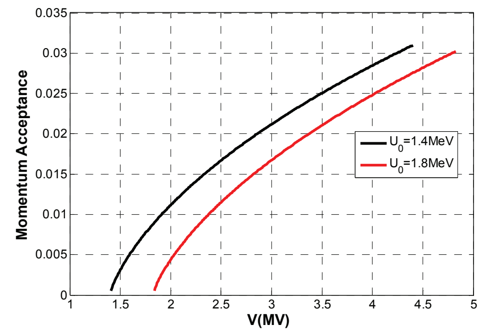

Figure 8: Effect of RF voltage on momentum acceptance.

CURRENT STATUS

The most recent design without damping wiggler has betatron tune (15.32, 6.10) and effective emittance of 6.74 nm (6.08nm with IDs). There is a leakage of dispersion of 12cm in the straight section to reduce the emittance. Figure 9 shows the DA at the injection point. It is close to the injection requirement of 12mm. The experiment shows the injection efficiency is limited by the DA with the existing sextupole magnet configuration. With damping wiggler, an emittance of about 5.0nm can be achieved. The optimization of DA is under the way.

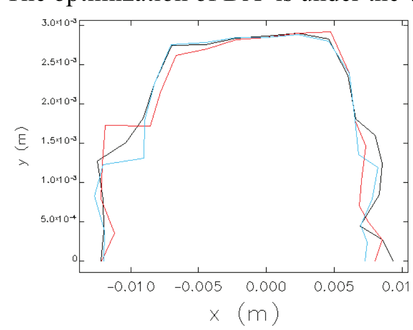

Figure 9: DA at the injection after 5000 revolutions.

SUMMARY

Systematic optimization with MOGA has been done for the SPEAR3 low emittance upgrade scheme to improve both DA and life time. The improvement in DA is more than 15%. For the most recent design, the optimized DA is just about to meet the injection requirement. A higher RF voltage with damping wiggler is required to maintain the same momentum acceptance.

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