PERFORMANCE OF ACHROMATIC LATTICE WITH COMBINED FUNCTION SEXTUPOLES AT DUKE STORAGE RING*

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Abstract

The 1 GeV Duke Storage Ring was very successfully commissioned with performance exceeding initial specifications [1]. In this paper we present design and performance data of its unique achromatic lattice with combined function magnets in the ring arcs.

I. INTRODUCTION

The third generation 1 GeV Duke storage ring is designed to drive UV and soft X-ray FELs as well as to produce high brightness synchrotron radiation from the bending magnets and insertion devices. The ring itself is a strong focusing race-track with two 34 meter long straight sections. The south straight section lattice is designed to optimize FEL operation with 7 to 28 m long FELs . The north straight section is used for injection and installation of the RF system and synchrotron radiation insertion devices. There are plans for installation of a variety of FELs and undulators in the straight sections. It was essential to develop a lattice which can be adjusted for variable configurations in straight section without reduction of the ring performance and its dynamic aperture.

Two typical practical examples demonstrate flexibility of the lattice:

1. Present design of the south straight section includes eight quadrupoles and is optimized for 8 m long OK-4 FEL. This system can accommodate also 26 m FEL wiggler without losing performance;
2. The lattice for location of the 4 m NIST undulator in the North straight section was designed after completion of the Duke ring design. There was no problem to incorporate this device into the ring by modifying the last 7 m of the North straight section without any loss of the ring performance.

To satisfy these and other vaguely defined, but complicated, requirement we chose to use modified second order achromatic lattice for the ring arcs. All sextupoles required for chromaticity compensation are located in the arcs. The arc lattice design eliminates second order geometrical aberrations caused by sextupole moments. In this case, the ring dynamic aperture does not depend on the straight section lattice as soon as the β-functions are matched.

The new design of the Duke storage ring lattice was initiated in February of 1991 and was completed in October in the same year [2,3].

The modified second-order achromatic lattice for the ring arcs [2] solved the fundamental dynamic aperture problems encountered with the original Stanford design [4]. The new design provides a dynamic aperture exceeding the mechanical aperture [3].

The ring design was driven to a large extent by the necessity to use most of the hardware already acquired for the ring prior to 1991. A number of unusual concepts were used to incorporate existing hardware into the new design. The most unusual idea was the use of asymmetric excitation of quadrupole coils for generation of both quadrupole and sextupole moments [3,5]. Precision magnetic measurements [6] have confirmed the excellent quality of these combined function magnets. This idea eliminates individual sextupole magnets from a tightly packed arc lattice and creates arc symmetry for all magnetic moments.

All dipoles on the Duke storage ring are fed by one 560 kW PEI power supply, while all quadrupoles have individual power supplies. This feature provides flexibility for the lattice design.

The layout of the Duke storage ring can be found elsewhere in this proceedings [1].

Table I. Parameters of Duke Storage Ring

Operating energy [GeV]	0.20 - 1.1
Ring circumference [m]	107.46
Arc and straight section length [m]	19.52; 34.21
Number of dipoles and quadrupoles	40; 64
Betatron tunes, Qx and Qy	9.111, 4.180
Orbit compaction factor, α	0.0086
Natural chromaticities, Cx and Cy	-10.0, -9.78
Acceptances [mm mrad], Ax and Ay	56.0, 16.0
Energy acceptance, $\Delta E/E$, of ring	>±5.0%
Maximum arc β-functions [m], x and y	2.5, 5
Maximum η-function [m]	0.245

II. THE ARC LATTICE

The Duke storage ring arc comprises 20 dipole magnets and 21 quadrupoles divided into eight regular FODO cells and two end-of-arc matching cells.

<u>Combined functions magnets.</u>

The Duke arcs are packed very tightly - there are only 18 cm between the dipoles and quadrupoles. The original Stanford design [4] of the ring called for the use of "dimples and noses" as dipole endpieces to create main sextupole

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moments and individual sextupoles squeezed into 18 cm gaps with 2 cm gap between poles of different magnets. It was discovered that this design suffered from severe asymmetric saturation causing intolerable orbit shifts and field non-linearity.

We replaced the dimples and noses with a smooth symmetric endcups to achieve a high quality of the magnetic field up to 20.5 kGs [6]. We also decided to remove the individual sextupoles which also caused saturation.

We now use asymmetric excitation of the arc quadrupoles by shunting part of the current from the inner (towards the center of the ring) coils. Thus, each arc quadrupole has an individual power supply which provides current I_1 (see sketch below) and individual shunt regulator which by-pass part of current $\Delta I=I_1-I_2$ from inside coils.

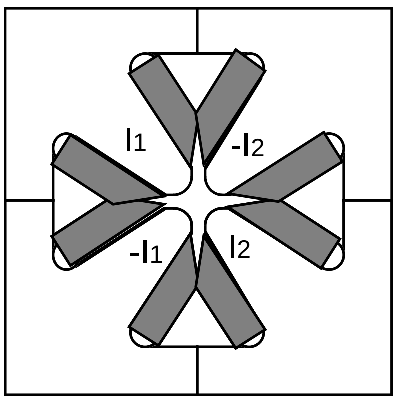

Fig.1. Asymmetric excitation of the arc quadrupole.

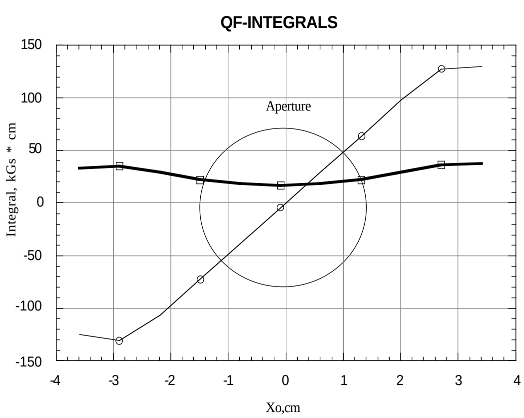

Fig.2. Symmetric and asymmetric part of the combined quadrupole function field.

The Duke ring arc quadrupoles have an inside radius of 2 cm and can operate with gradients up to 4 kGs/cm. There is no pole tip saturation even at maximum current - light saturation occurs in the neck of the yoke.

This condition provides good separation of the odd and even multipoles. Computer simulations and magnetic measurements demonstrated the excellent quality of these combined dipole-quadrupole-sextupole fields. We saw only a weak dodecapole term in the field expansion.

Typical values for the Duke ring combine function quadrupoles with 18-20% asymmetry of excitation are:

Gradient	3500 kGs/cm
Sextupole	350 Gs/cm^2
Magnetic center shift	2.25 mm.

Fig 2. show measured dependence of symmetric and asymmetric part of combined function quadrupole at 1 GeV.

It is obvious that asymmetric excitation shifts magnetic center of the quadrupole. To make shift of magnetic centers the same in both focusing and defocusing quadrupoles, we installed small shims creating defocusing sextupole moment at the center of the dipoles (see [6,7] for details). This combination provides compensation of natural chromaticity and enough flexibility to build second order achromatic lattice.

Modified Second Order Achromat.

The regular FODO cell is 1.76 m long and is comprised of two 0.33 m dipole-sextupoles (BS), one 0.20m focusing quadrupole-sextupole (QFS), and one 0.14 m defocusing quadrupole-sextupole (QDS) (all in effective length). The cell has bilateral symmetry of all magnetic multipoles with respect to the quadrupoles centers. Half-cell is sketched on Fig.3

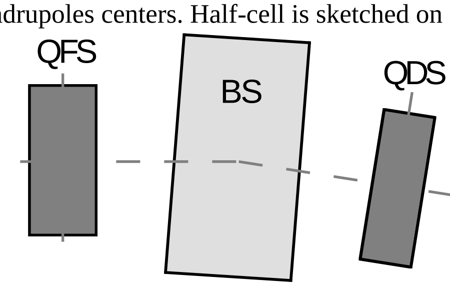

Fig.3 Half of regular arc FODO cell.

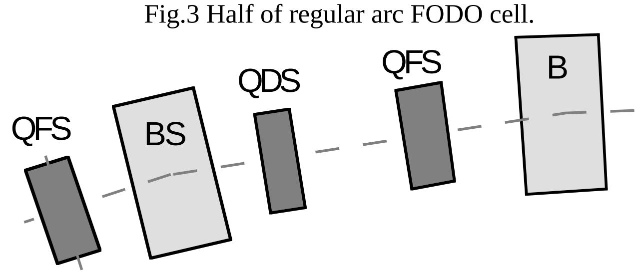

Fig.4 End-of-arc matching cell.

We chose $\Delta Q_x = 3/10;\ \Delta Q_y = 1/10$ tunes advances per cell. This lattice will provide for natural compensation of geometrical aberrations (caused by sextupole moments in the arcs) in the case of ten identical cells. Requirements for low emittance and zero dispersion (η-function) in straight sections do not allow the use of a regular 10-cell second order achromat. We modified end-of-arc cells to match η to zero at the end of the arc and to have β-functions which are easy to match from straight sections.

The 2.02 m matching cell (measured from the center of QDS) is longer than the regular FODO cell - see Fig. 4.

Because of zero dispersion in the straight sections, the natural chromaticity must be compensated in the arcs. We used combined function magnets with sextupole moments excited in both quadrupoles and dipole magnets. We do not use sextupoles in the end-of-arc dipoles where the η-function is close to zero.

We slightly modify the sextupole strength in the end-of-the-arc cells to compensate the second order geometrical aberrations in the horizontal plane [1] :

$$\int_{Arc} S(s)\beta_x^{3/2}(s)e^{i\psi_x(s)}ds = 0;$$

$$\int_{Arc} S(s)\beta_x^{3/2}(s)e^{i3\psi_x(s)}ds = 0;$$

where $S(s)$ is sextupole moment, β_x is horizontal betatron function, and ψ_x is the betatron phase. We also minimize coupling nonlinear geometrical aberrations. These conditions provide for a transverse dynamic aperture exceeding the physical aperture, and an extremely high energy acceptance (more than ±5%) on the ring [3].

III. CONCLUSIONS

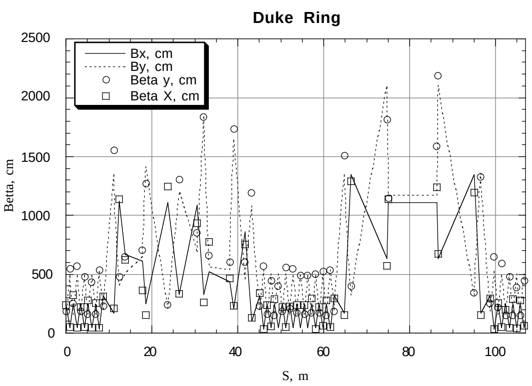

Fig.5 Measured and design values of β-functions.

Operation of the Duke storage ring lattice has not shown any indication of dynamic aperture limitation. Betatron tunes differ very little from design values : ΔQx =0.06; ΔQy =-0.04 in all 0.23 - 1.1 GeV energy range. Measurements confirm the theoretical chromaticity compensation within 3% accuracy.

The preliminary measurements of β-functions are shown on Fig.5 . There are indications, that the errors in Fig.5 are caused by a coil failure in one of the quadrupoles. We are investigating this possibility.

The orbit distortions without any correction are small : less then ±5 mm horizontal and less ±4 mm vertical. Direct measurements of the ring acceptance confirm the predicted dynamic aperture of the ring. The width of coupling resonance is small ΔQ=0.007 and is consistent with value of orbit distortions.

We measured the electron beam emittances at 1 GeV using visible optics and CCD digitizer (show below). The measured horizontal emittance is (17 ±2)*10^{-9} m*rad is in perfect agreement with 18 nm*rad theoretical value. The resolution of the vertical size measurements was limited by diffraction. Thus, we can only state that vertical emittance is less then 1*10^{-9} m*rad.

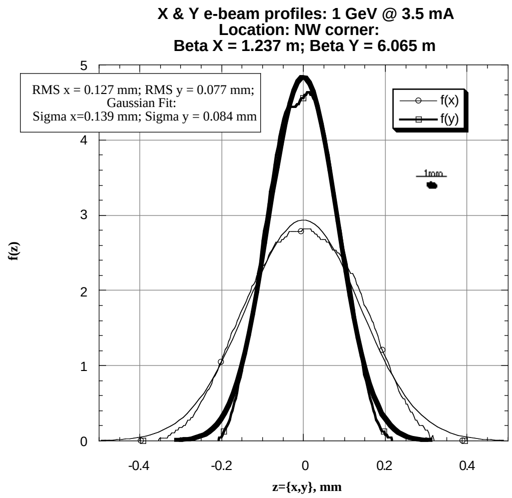

Fig.5 Measured e-beam profiles.

We did not observe any very strong resonances in the wide tune range of Q_x={9.1-9.3}, Q_y={4.05--4.3}. We used eight straight section quadrupoles for tune adjustments using the flexibility build into the lattice. Direct measurements of the transfer matrix confirm the absence of second order terms in the full arc transport map as predicted by theory [3]. It is remarkable because the half-of-the-arc map has second order terms which create a factor two asymmetry at full aperture.

We found the energy acceptance is ±6% and is limited by the vacuum chamber aperture in the focusing quadrupoles.

The overall performance of the achromatic lattice with combined function magnets is exceptionally good.

IV. REFERENCES

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