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. In this paper we present design and performance data of its unique achromatic lattice with combined function magnets in the lattice. The layout of the Duke storage ring can be found elsewhere in this proceedings [1].

Table I. Parameters of Duke Storage Ring

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

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.

Combined function magnets:
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.](image)

Typical values for the Duke ring combine function quadrupoles with 18-20% asymmetry of excitation are:
- Gradient 3500 kGs/cm
- Sextupole 350 Gs/cm²
- 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.](image)

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.

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

![Fig.4 End-of-arc matching cell.](image)

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 ($\eta$-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 $\eta$ to zero at the end of the arc and to have $\beta$-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 $\eta$-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]:

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

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

where $S(s)$ is sextupole moment, $\beta_x$ is horizontal betatron function, and $\psi_x$ 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 $\pm5\%$) on the ring [3].

### III. CONCLUSIONS

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 $\pm6\%$ 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