# EMITTANCE AND DYNAMIC APERTURE IN COMPACT STORAGE RINGS WITH SUPERCONDUCTING BENDING MAGNETS

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Abstract: Using the lattice cell of the proposed Karlsruhe deep-etch microlithography superconducting synchrotron radiation source as an example the influence of the bending angle on the emittance and the dynamic aperture is studied. Over the angular range from 0.01 to 1.7 rad the minimum emittance varies with the cube of the bending angle. Dynamic apertures were calculated by tracking with the symplectic third order code MARYLIE 3.0 for the angles $2\pi/n$ with $n = 3, 4, 5, 6, 8$. They are satisfactory for the cases $n = 4, 5, 6$, without and with chromaticity correcting sextupoles, but significantly smaller for $n = 3, 8$.

## Introduction

Compact storage rings with superconducting bending magnets are currently developed with the aim to build comparably small and cheap synchrotron light sources for use in microlithography and in deep-etch microlithography [1]. It has been shown previously that the use of superconducting bending magnets leads to a significant but tolerable reduction of the dynamic aperture in the lattice of the proposed Karlsruhe deep-etch microlithography ring, the main reason for this reduction being the influence of the fringe fields of the bending magnets [1,2]. Though designed as a synchrotron light source for x-ray deep-etch microlithography this ring will obviously be useful for a variety of other applications, too.

Under this aspect we explore the influence of the bending angle, up to now fixed at 90°, on the multipolar components of the bending field, on the emittance, and on the dynamic aperture. This information will be useful in order to select the appropriate lattice with respect to a given task. The different magnets were designed in such a way that the integral sextupolar component of the body which increases with the length is compensated by the corresponding component arising from the winding at the end of the magnet. We find that the variation of the emittance with the cube of the bending angle which is well known for small angles holds up to angles exceeding 120°. The reduction of the dynamic aperture caused mainly by the fringe fields of the superconducting dipole magnets and by the sextupoles used for chromaticity correction turns out to be tolerable over a certain range of bending angles. So, satisfactory dynamic apertures are found at 90°, 72°, and 60°, while the cases of 45° and 120° appear less satisfactory.

## Method

The bending field is computed by combining a program to optimize the position of the coils with a 3-dimensional code based on the law of Biot and Savart as described in [3]. The emittance is computed by numerical integration of the function $H(s)$ [4] along the bending magnet which is assumed to be isomagnetic. The analytic solutions of the Twiss functions and the dispersion function for a constant bending field are used. They are restricted by symmetry considerations, i.e., the betatron and the dispersion values at the entrance of the bending magnet are equal to those at the exit while their derivatives are equal, but have opposite sign. Furthermore, we enforce radial damping by setting $\langle\eta\rangle=0$ which results in $\eta_0' = -\phi/2$ (at the entrance to the magnet). The minimum emittance is found numerically using a gradient method. Dynamic apertures are calculated by tracking with MARYLIE [5] as described in [1,2]. One of the transverse deviation coordinates, x or y, is varied, the other held fixed, until the distance between values leading to stable or unstable trajectories is less than 1 %. Here, the non-isomagnetic nonlinear field of the real magnet is taken into account up to third order.

## Results and discussion

### Bending magnets

The design of our magnet is derived from the Fermilab [6] and HERA [7] magnets except for the strong curvature and the outlet slot for the synchrotron radiation. A mechanical design of this type of magnet has already been presented [3, 8]. Fig. 1 shows the cross-section of the magnet with two 1 cm-thick layers. The design field of 4 T is

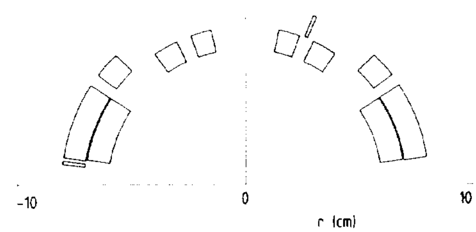


Fig. 1: Cross-section of the upper half of the bending magnet.

achieved with an acceptable value of the current density of 480 A/mm². The maximum field at the superconductor is 5.3 T. To provide the space for the synchrotron radiation outlet slot the windings start at an angle of 9°. The asymmetric sectors in the outer layer compensate the quadrupolar component arising from the curvature of the magnet. A similar two-layer configuration has already been wound by BBC [8]. A top view of the winding heads of the 60° magnet is depicted in fig. 2. The precise configuration

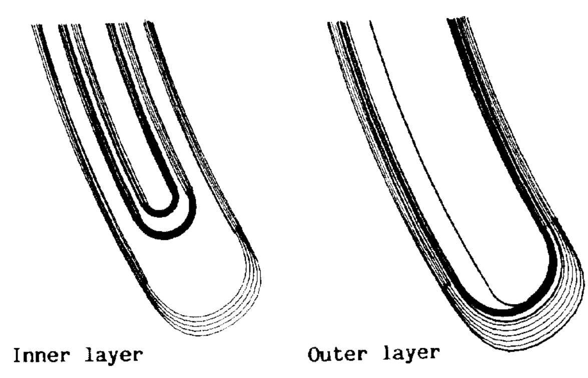


Fig. 2: Top view of the windings at the end of the 60° bending magnet.

of the end windings is used to control the integral sextupolar component. In fig. 3 the multipolar components are plotted versus the path length s along the reference orbit. No attempt was made to compensate the quadrupolar component. The main contribution to the sextupolar component comes from the end. However, there is also a smaller contribution from the body as shown in fig. 4 where the absolute values of the integral multipolar components of the body alone are plotted versus the bending angle. By trading off both contributions the integral sextupolar component is kept below 1 T/m.

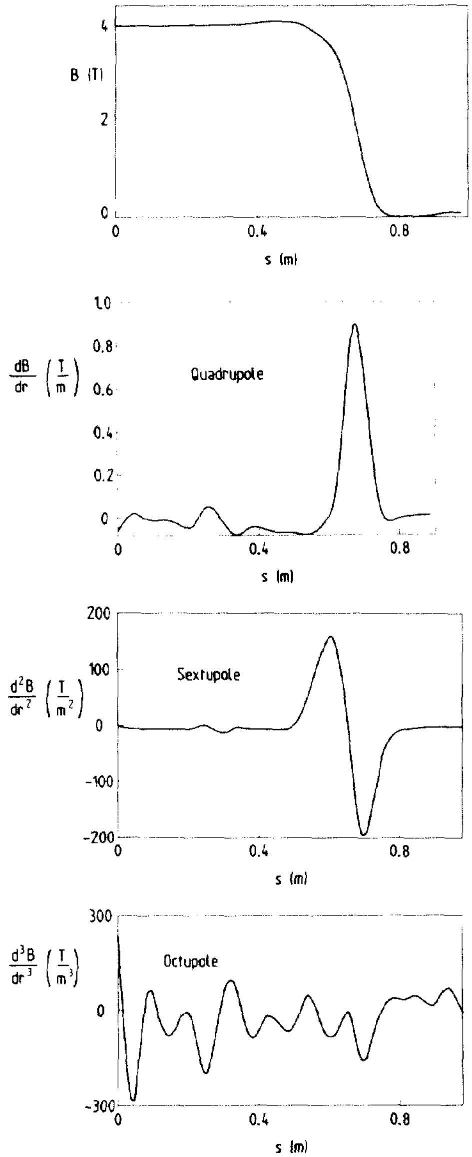


Fig. 3: Total field and multipolar components of the 60° bending magnet along the reference orbit.

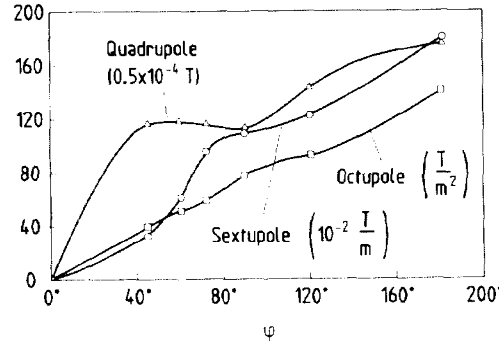


Fig. 4: Absolute value of the integral multipolar components for the bodies of the magnets without contribution from the windings at the ends as a function of the bending angle φ.

Emittance

Fig. 5 shows the minimum emittance ε and the corresponding Twiss and dispersion values $\alpha_0$, $\beta_0$, $\eta_0$, and the absolute value of $\eta_0'$ at the entrance versus the bending angle. The five ticks around φ = 1 mark the angles 45°, 60°, 72°, 90°, and 120°. It can be seen that the minimum emittance depends on the cube of the bending angle over the whole angular range. For small angles, this result has already been derived by several authors [9]. More recently, it was obtained for 90° and 180° by Walker et al. [10].

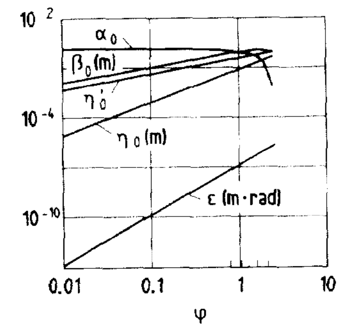


Fig. 5: Minimum emittance ε and corresponding Twiss and dispersion values $\alpha_0$, $\beta_0$, $\eta_0$, and the absolute value of $\eta_0'$ at the magnet entrance versus bending angle φ.

Dynamic aperture

Dynamic apertures are calculated for a lattice formed by n cells, n = 3, 4, 5, 6, 8. A cell is depicted in fig. 6. The bending angle is 2π/n, accordingly. Fig. 7 shows dynamic apertures from 120° down to 45° with chromaticity correcting sextupoles off. Points are calculated, lines are to guide the eye. Normally, the points are obtained by varying y at fixed x. However, some points were found varying x at y fixed, and they are labelled with a small horizontal bar. Except for the case of 120° the dynamic apertures are rather large. Assuming a circular physical aperture of 4 cm inner radius the curves span a larger range horizontally and extend more or less up to the wall vertically. As would be expected, they exhibit a tendency to shrink for decreasing bending angles because the number of cells

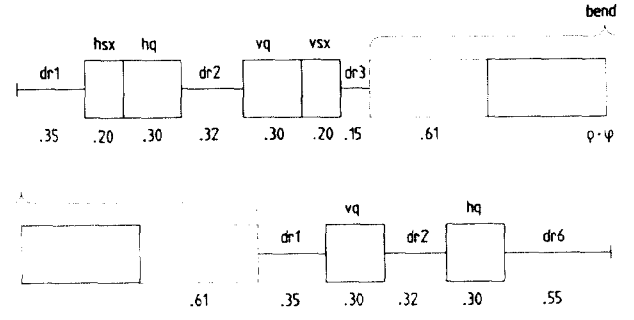


Fig. 6: Lattice cell: hq, vq horizontally and vertically focussing quadrupoles, hsx, vsx sextupoles for horizontal and vertical chromaticity correction.

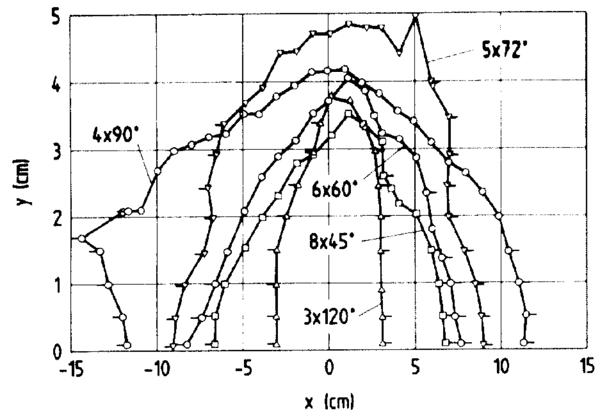


Fig. 7: Dynamic apertures for five different bending angles. Sextupoles off.

and, correspondingly, the number of sources of nonlinear fields increase. On the other hand, the coefficients describing nonlinear behaviour in the transfer map of a magnet increase with its bending angle. These two effects act oppositely on the dynamic aperture. In addition, the dynamic aperture may depend on the mutual phase advances between the individual positions of the fringe fields. In order to reduce the sextupolar influence the horizontal phase advance per cell was set more or less close to one half.

To explain the particular behaviour of the 3x120° ring we observe that those transfer map coefficients of the 120° magnet which describe nonlinear behaviour are significantly higher than those of the 90° magnet, partly by more than one order of magnitude. Since the field components are not very different between the magnets considered we infer that the larger coefficients are caused by the greater integration length. Furthermore, the horizontal tune of the 120° magnet is 0.45 while the other magnets have tunes ranging within 0.18 and 0.33. Because of this tune a stronger influence of the fringe fields is expected.

Fig. 8 shows the effect of the chromaticity correcting sextupoles. The dynamic apertures are significantly reduced except again for the case of the 120° magnet where it was already rather small. Obviously, the cases 6x60°, 5x72°, and 4x90° appear to be more favorable than the others.

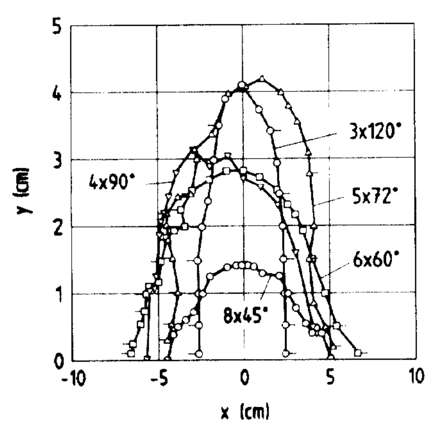


Fig. 8: Dynamic apertures for five different bending angles. Sextupoles on, hsx ranging from 4.5 to 12.5 T/m$^2$, vsx from 18 to 38 T/m$^2$.

## Conclusion

Our results show that from the dynamic aperture point of view it is possible to choose lattices with more than four strongly curved large-bore superconducting bending magnets, in particular 5 or 6. Corresponding dipole magnets with bending angles less than 90° have been designed. The emittance can so be selected over a certain range according to the accessible bending angles.

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