# THE PROPOSED RACETRACK LATTICE FOR THE SYNCHROTRON LIGHT SOURCE "ASTRID II"

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## 1 INTRODUCTION

The Institute for Storage Ring facilities (ISA) at the University of Aarhus is currently developing a third generation synchrotron light source, ASTRID II, capable of operating at the two energies of 600 MeV and 1.4 GeV. At the lower of these energies, ASTRID II would be optimised for the production of vacuum ultra-violet (VUV) and soft X-ray (SXR) radiation, providing high flux through the use of insertion devices and high brilliance by optimisation of the machine parameters to minimise the natural electron beam emittance. Operation at the higher energy of 1.4 GeV will provide sufficient flux of harder X-rays (~10 keV).

In considering various lattice layouts, it is desirable to provide sufficient flexibility in the optics, if possible, to take advantage of any future advances in insertion device technology, perhaps by a renewal of the straight sections without a significant disturbance. The type of facility envisaged would include either two, or four, or six straight sections, with some perhaps up to 10 m, 5 m and 3 m in length each one correspondingly.

The proposed lattice should meet the following criteria:

- horizontal emittance of the electron beam less than 2 nm at 600 MeV, or 10 nm rad at 1.4 GeV;
- dispersionless straight sections between 3 m and 10 m in length;
- flexible straight sections decoupled from the bending sections;
- convenient method to correct the chromaticity by the sextupoles;
- large dynamic aperture, more than 100 mm mrad;
- small number of families of the magnetic elements.

In this paper we describe a racetrack style lattice which is capable of achieving these design requirements at a modest cost.

## 2 LATTICE CONSIDERATIONS

In the X ray regime the source is far from diffraction-limited and the brightness is governed by the electron beam emittance, conversely in the VUV regime the source is complitely diffraction-limited, and the brightness is dominated by diffraction. Thus, in order to produce tuneable radiation from 5 eV to 100 eV and from 1 keV to 10 keV the lattice has to be optimised for two extreme regimes at 600 MeV and 1.4 GeV. The classic ring structure of a number of identical achromat cells arranged in a highly symmetric circular form has been used in the vast majority of synchrotron sources untill now. In particular, a modified Chassman-Green layout proposed in an earlier design study by V.Lebedev for ASTRID II, in which the central focusing quadrupole was replaced by a type of "inverse" combined function bending magnet, gave a horizontal emittance of ~ 90 nm.rad at 1.4 GeV. Due to the requirements mentioned above, it soon became apparent that a large circular lattice capable of achieving the desired performance should be discounted in favour of a more compact racetrack layout.

The proposed racetrack lattice geometry consists of two identical arcs separated by two similar optical channels consisting of one, two or more straight sections. Between the arc and the straight sections a matching section is required to control the parameters for the beam in the insertion devices. A significant advantage of such a design is the ability to separate the functions of the arcs and the straight sections, with the former largely determining the final equilibrium emittance and the latter, with the inclusion of small additional elements, able to tune the β functions as required.

Since the horizontal emittance depends upon the horizontal dispersion function $\eta_x$, as $\varepsilon_x \propto \langle H \rangle_{dipole}$, where $H = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2$, it is apparent that the minimum emittance is reached in the lattice, where the beta-function and the dispersion function have a minima in the middle of the bending magnet. Teng and Lee have shown [1] that the theoretical minimum emittance is reached, when these functions meet special required values. Several lattices with such a features have been worked out by Einfeld, Plesko and Schaper [2] following the theoretical minimum emittance strategy.

However, these special required values of the beta and dispersion functions pose restrictions in the choice of the arc tune, which is a very negative for the optimum placement of sextupoles to correct the chromaticity, and, as consequence, for the lattice dynamic aperture. In our proposed racetrack lattice each arc includes eight periodical cells, containing combined function bend magnets and focusing quadrupoles. Figure 1 shows a lattice of arc and straight section. A reduction in symmetry can lead to a reduction in the dynamic aperture. However, if we could tune the arcs in the horizontal and vertical planes to a value of $n_{x,y} \times 2\pi$, we form a second-order pseudo-achromat and it would be possible to maintain an acceptable dynamic aperture[3,4].

Simultaneously we should remember that the dispersion function in the periodical structure is inversely proportional to the square of the phase advance per cell. The most appropriate values of tune for our arc are the integer numbers $n_x = 3$ and $n_y = 2$, giving a phase

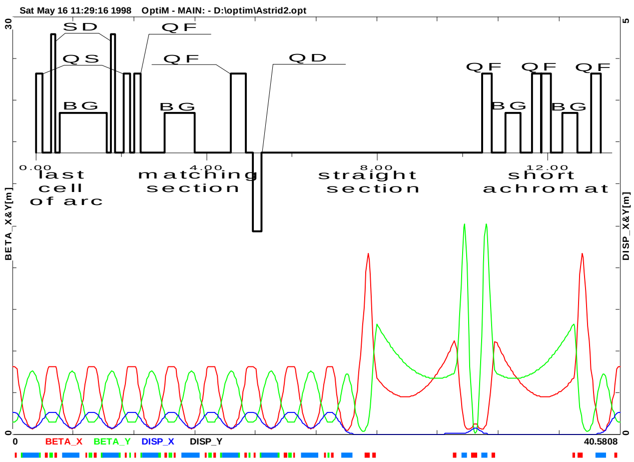


Figure 1. The lattice of arc, matching section and straight section (QF, QD –focusing and defocusing quadrupole, QS-focusing quadrupole incorporated with sextupole, SD-defocusing sextupole, BG-combined function bend magnet with negative gradient).

advance per cell equal to $135^{\circ}$ and $90^{\circ}$ correspondingly. To a first approximation in this condition, the non-linear action of each $n-th$ sextupole is compensated by $(n+4)-th$ in the horizontal and $(n+2)-th$ in the vertical planes correspondingly. Figure 1 shows the scheme for two families of sextupoles in which one incorporates with focusing quadrupole. Tracking calculations indicate very acceptable values of the dynamic aperture; 140-150 mm mrad. In another variant with independent sextupoles and quadrupoles the dynamic aperture has approximately the same value. As a comparison, the dynamic aperture of a modified circular Chasman-Green lattice with the same number of sextupole families is smaller by a factor of four.

Separated function lattices, based on second-order pseudo-achromat arcs and decoupled straight sections, have been previously developed for proton accelerators [3,4] but up to the present have not been applied to synchrotron radiation sources. With such a scheme, we are able to use the simplest cell periodicity in constructing the arcs, removing the small inter-cell straight sections with a consequent reduction in overall length. This is a very simple and compact lattice with one family of focusing quadrupoles and one combined function bending magnet. The maximum in the dispersion function is concomitantly reduced, resulting in an equilibrium emittance of 6 nm.rad at 1.4 GeV.

The classical solution to dispersion suppression is the “half-angle” magnet which causes minimum perturbation to the periodic β functions. However, since we would like straight sections much longer than the cell of arc, we have to increase the beta function just at the entrance to the straight sections. This solution is achieved through a weaker focusing quadrupole and a longer combined function bend magnet in comparison with the “half-angle” option. In figure 1, upper part, we show an arc cell, the matching section and a straight section. The matching section consists of two focusing, one defocusing and one a combined function bending magnet.

An essential feature of this racetrack geometry is the inherent flexibility of the long straight sections which, as noted previously, are decoupled from the arcs. It is possible to install several insertion devices in the “straights” joining the arcs by dividing them into smaller sections separated by short bend achromats, of perhaps $2\times 5^{\circ}$, reducing the turning angle of the arcs by the appropriate amount. The number of sections could easily be increased either to three or reduced to one in order to increase the length available for insertion devices. Such a super-long straight section could be used for a free electron laser (FEL) or a very long undulator, perhaps with helical geometry or rotated field sections. We have considered two types of deflection magnets with either separated or combined functions and the later gave more acceptable performance due to small contribution in the total chromaticity value.

In determining the optimum β functions for the straight sections, we need to consider the length of the proposed insertion device and the emittances of both the electron beam and the photon beam at the wavelength of interest, as follows. The total emittance of the photon beam when radiated by all the electrons is given by:

$$\varepsilon_{\Sigma} = \sqrt{(\varepsilon_e + \varepsilon_r)^2 + 2\cdot\varepsilon_e\cdot\varepsilon_r\left(2\pi\cdot\frac{\beta}{L} + \frac{1}{8\pi}\cdot\frac{L}{\beta} - 1\right)}\,,$$

where $L$ is the length of an insertion device, $\varepsilon_e$ is the natural electron beam emittance and $\varepsilon_r\ (=\lambda/4\pi)$ is the diffraction limited photon beam emittance. In order to minimise the total emittance, we essentially have only the ratio $\beta/L$ as a variable parameter and $\varepsilon_e$ as an invariant. Obviously, it is impossible to reduce the total emittance to a value less than the diffraction limit. Therefore, in the VUV regime, where the diffraction limit will be rather large, it is particularly important not to add any additional contributions. We can best illustrate this point by an example. At a photon energy of ~8 eV, or $\lambda = 1.6 \times 10^{-7}$ m, the diffraction limited and electron beam emittances are $\varepsilon_r$ = 12 nm and $\varepsilon_e$ = 1.1 nm at a machine energy of 0.6 GeV. Actually, since the absolute minimum in the total emittance is reached at $\beta/L = 1/4\pi$ and this is hard to achieve in practice, we should try to get it as nearby as possible. In the race track option, a reasonable value of β/L would be between 1 and 2, which together with the reduced electron beam emittance results in a total emittance, $\varepsilon_{\Sigma}$, about ~15 nm. On the other hand, if either of the two emittances, $\varepsilon_e$ or $\varepsilon_r$, is significantly greater than the other, we are less constrained in the choice of the β function without seriously degrading the total emittance. Both these factors give us an anticipated gain in the total emittance of about a factor 8 in comparison with the circular lattice. The ratio of the electron beam emittance to the diffraction limit scales as $\gamma^4$, and therefore as we increase the machine energy to 1.4 GeV, $\varepsilon_e/\varepsilon_r \sim 0.01$ and the total emittance becomes determined solely by the electron beam emittance, ~6 nm.

Table 1. Main parameters of the ASTRID II

| | | |
|---|---|---|
| Maximum energy, GeV | 1.4 | 0.6 |
| Injection energy, GeV | 0.6 | 0.6 |
| Circumference, m | 81 | |
| Momentum compaction factor | 0.0064 | |
| Vertical tune | 7.82 | |
| Horizontal tune | 9.84 | |
| Natural vertical chromaticity | -20.6 | |
| Natural horizontal chromaticity | -17.3 | |
| Energy loss due to SR, keV | 106 | |
| Horizontal emittance, nm | 5.6 | 1.1 |
| RMS energy spread | 0.0008 | 0.00015 |
| Vetical acceptance, mm mrad | 145 | |
| Horizontal acceptance, mm mrad | 145 | |
| Beam current, mA | 500 | |
| Touschek lifetime, hours | 16 | 5*2 |

In table 1, we show the main parameters of the beam for the chosen lattice at the two working energies.
To compare the emittances for different lattice structures, one can look at a normalised value which takes

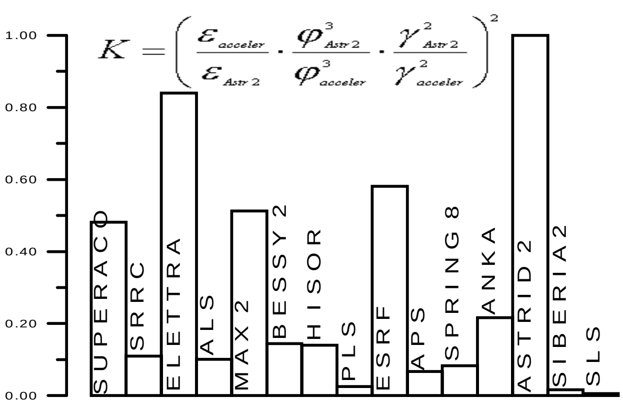


Figure 2. The normalised K value for different lattices.

into account the increase of emittance with the square of the machine energy and the third power of the bend angle of one magnet (see fig.2).

There is much interest at present in magnetic lattices, which can be operated over a range of momentum compaction factor. This would provide several advantages, the possibility to work without sextupoles, high bunch compression and the high peak current for driving of a free electron laser. This tunability is obtained due to a special modulation of the closed orbit curvature[5]. Our proposed lattice could be re-adjusted into this mode after some change to the structure. Figure 3 shows the arc with the tuneable momentum compaction factor. In this lattice one cell is formed by two adjoining cells, and each second focusing quadrupole is replaced by a short combined function bend magnet with positive

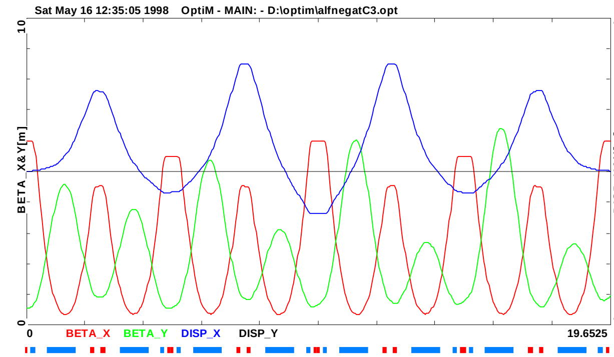


Figure 3. The arc lattice with tunable momentum compaction factor.

gradient BG(G>0). As result the arc consists of four cells and each half cell has a structure: trim QF+short BG(G>0)+long BG(G<0)+QF. The trim quadrupole is used for fine tuning. The dispersion function is equal to zero at the ends of arc automatically due to an integer tune number for the arc and the matching sections are not needed. Due to the low beta function and zero dispersion function in the middle of each long bending magnet the electron beam emittance has a rather low value of 15 nm at 1.4 GeV.

In this short report we have summarised the development of a lattice scheme for ASTRID II. The preferred choice is based on a racetrack geometry with decoupled arcs and straight sections. The principal advantages are firstly, optimal matching between the electron and photon beam emittances, and secondly, maximum dynamic aperture due to the achromatic features of the arcs.

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