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AA LONG TERM NOTE No. 26

Summary of the Antiproton Collector Study

December 13-14, 1982

A two day meeting was held to discuss progress towards a consistent design of an Antiproton Collector. The concept emerged of 25 m radius collector ring to be interposed between production target and the present AA. The acceptance of this new ring would be 6% in $\Delta p/p$ and 200π mm.mrad in both transverse phase planes. It would contain r.f. systems for bunch rotation and high frequency cooling for fast cooling in both longitudinal and transverse planes.

The collector would pass on its antiprotons every few seconds to the AA ring so that it could be maintained or repaired without losing the antiproton stack. To take advantage of this nearly all the systems with moving parts in the AA would be replaced by equivalent systems in the collector, thus helping to ensure a reliable source of antiprotons.

With the focusing devices and target assembly now being developed, the expected improvement in antiproton collection rate could be a factor 10 higher than the present bare AA. This seems matched to forecasts of SPS capability in the next few years. It might even be possible to reach this improved rate while only taking every alternate pulse from the PS supercycle.

Much remains to be done to establish the feasibility of the collector, and particularly its cooling systems but the conclusions of this study were sufficiently encouraging for one to be hopeful that a design will now emerge.

The unedited contributions to this study are to be found in order of presentation. Each contribution is headed by a deviding page with its title printed along the thumb margin.

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LATTICE STRUCTURE WITH FIXED AND VARIABLE η

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1. GENERAL DESCRIPTION

The AC ring, which resembles a racetrack, has a circumference of 157.08 m. It consists of two arcs and two long straight insertions, each 17 m, for installing the injection, ejection and cooling systems. The lattice structure of one half of the ring is shown in Fig. 1. It is composed of six regular cells, two dispersion suppressors and one long insertion. The main characteristics of this lattice focusing structure are as follows.

It must provide two regimes of operation, i.e. the "bunch rotation" regime and the "cooling regime". In the former regime the η value is -0.002. Once the beam is debunched, nine groups of quadrupole currents are varied in the left half of the ring to change to the "cooling regime". Under these conditions, the right half-ring is still left in its initial state. In contrast, in the left half-ring the dispersion function is raised, to correspond to an η value of -0.1.

Besides, it must also have a large acceptance in both horizontal and vertical plane, i.e. :

$\Delta p/p = \pm 3\%$, $\varepsilon_H = \varepsilon_V = 200\pi$ mm.mrad for the bunch rotation regime,

$\Delta p/p = \pm 0.75\%$, $\varepsilon_H = \varepsilon_V = 200\pi$ mm.mrad for the cooling regime.

2. NUMBER OF SUPER PERIODS

A ring with two or three super-periods can be envisaged. We prefer the solution with two super-periods for the following reasons. First, since the circumference of the ring is fixed and equal to one quarter of the PS, increasing the number of super-periods means decreasing the total space which can be used for long insertion. Much space must be consumed by dispersion suppressors. Then, due to the increased number of dispersion suppressors, a larger dispersion function in the regular cell must be provided in order to achieve a given η value. This means that larger horizontal apertures are required. We have therefore chosen to have a minimum number of super-periods. In this lattice they are two.

3. PHASE ADVANCE IN A REGULAR CELL

The typical FODO separated function lattice has been adopted to meet the requirement mentioned above. Each standard cell is composed of two bending magnets and two quadrupoles QD and QF. The phase advance per cell is $\mu_H = 62.2°$ and $\mu_V = 63.54°$.

With a 60° phase shift per cell, the orbit dispersion can be suppressed with missing magnets and only one type of dipole. It not only favours chromaticity correction, but also this phase makes it easy to constrain any perturbation within a limited region. For example, if we introduce a "kick", ΔK, in a quadrupole of the lattice, then the disturbed machine functions $\Delta\beta_{H,V}$ and ΔD will propagate along the lattice with a phase advance per cell $2\,\mu_{H,V}$ and $\mu_{H,V}$, respectively. If μ is exactly equal to 60°, then we can constrain this perturbation in four cells by introducing two other kicks with the same strength at the end quadrupole of the second and last cells (see Fig. 2). A similar method has been proposed by W. Hardt [1]. By means of this technique one can change the dispersion function in some part of the lattice without disturbing the zero dispersion region.

Unfortunately, it seems difficult to have exactly 60° phase advance, because during the bunch rotation regime we ask for $\eta = -0.002$ in the horizontal plane. According to the definition of η and γ_T, the total dispersion of the ring is determined by :

$$\int_C \frac{D}{\rho}\, ds = \left(\eta + \frac{1}{\gamma^2}\right) \frac{C}{2\pi} \quad , \tag{1}$$

where ρ is the radius of curvature in bending magnets,

C is the circumference of the ring,

γ is the injection energy (for 3.5 GeV/c it is 3.86).

Since the dispersion is zero in long insertions, the above integral is only made over the arc part.

The value of dispersion D depends on both the μ_H and the cell length L_c. L_c is only determined by the total cell number N* according the following formula :

$$L_c = \frac{C - 2L_{in}}{N} \quad , \tag{2}$$

where L_{in} is the length of the long insertion.

Once N is chosen, the only way we can use to have a desirable value of $\int D/\rho\, ds$ is to adjust the μ value. We should choose the cell number N such as to make μ as close as possible to 60°. In this design, N = 20 is more suitable.

4. DISPERSION SUPPRESSORS

As mentioned by E. Keil[2] and J.P. Delahaye[3], a particularly simple dispersion suppressor can be obtained for a μ = 60° structure by just leaving out the bending magnets in one of the two regular cells (Fig. 1). But for small machines missing bending magnet introduces some β_V modulation in vertical direction if straight bending magnets are used. Four variables are necessary in order to suppress dispersion and the β_V mismatch simultaneously. Furthermore, if μ is far from 60°, then not only the vertical, but also the horizontal β functions are disturbed. So, usually six variable are necessary to fit the six boundary conditions between regular cell and dispersion cell ($\beta_{H,V_B} = \beta_{H,V_A}$, $\beta'_{H,V_B} = \beta'_{H,V_A}$, $D = 0$, $D' = 0$). The six variables are two straight sections and four quadrupoles as shown in Fig. 3. It is worth pointing out that if the μ is not quite 60°, say ±5° away, one cannot suppress

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* Including the cells in dispersion suppressors.

the dispersion even using six variables. In this case we must use a bending magnet strength which is different from regular cell.

To simplify the power supplies we use the two lengths of straight section as variables and keep the strength of four quadrupoles unchanged, then the β_V maximum in the regular cell is increased from 9.68 m to 12.98 m, but the β_H maximum is almost unchanged, only rising from 9.8 m to 10.22 m. This may be due to μ_H being very near 60°.

5. LONG STRAIGHT INSERTION

The main purpose of long insertion is for injection, ejection and cooling, but another important purpose is to produce the necessary phase advance $\Delta\mu_{H,V}$ so that the betatron frequency $Q_{H,V}$ have the desired value. For example, the working point of our design is $Q_H = 4.27$, $Q_V = 4.30$. The total phase shift of normal cell and dispersion suppressors is $\mu_V/2\pi = 3.4426$, $\mu_H/2\pi = 3.4289$. So, this means that the insertion must produce a total phase advance $\Delta\mu_V/2\pi = 0.8574$, $\Delta\mu_H/2\pi = 0.8411$.

Injection and ejection are favourable if the insertion is composed of two doublets (Fig. 1) and has β_H maximum and β_V minimum in its centre where the magnetic kicker can be placed. Using the length between two doublets, two quadrupoles of the doublet and the final quadrupole of dispersion suppressors adjacent to the insertion as four variables, we find a solution which can satisfy all the requirements mentioned above and also leaves the Twiss parameters in the arc almost undisturbed.

The detailed Twiss parameters of the whole ring are given in Table 1.

6. TRANSFORMATION TO THE COOLING REGIME

In order to keep the machine functions of the right arc unchanged during the transformation process, the Twiss parameters at the ends of the right arc must remain unchanged. This means that one must seek a matched solution in the left side (including two insertions) with the six boundary conditions $\beta_{\underset{B}{H},V} = \beta_{\underset{A}{H},V}$, $\beta'_{\underset{B}{H},V} = \beta'_{\underset{A}{H},V}$, $D_A = D_B = 0$, $D'_A = D'_B = 0$, at the point B (Fig. 4) if we start from point A during matching.

In addition, there are three other conditions to be met : the dispersion integral $\int D/\rho \, ds$ in left arc must equal $1/2(\eta + 1/\gamma^2)\,C/2\pi$, ($\eta = -0.1$ for cooling regime) ; the maximum beat values of β_H and β_V in the left side must be as small as possible, especially in the vertical direction ; altogether nine conditions must be fulfilled. In principle nine variables are enough to find the above solution, but how should we select nine quadrupoles from among fourteen quadrupoles at the left side in order to have the best solution is still an open question.

As a first step and in order to get experience, all the fourteen quadrupoles were used as variables to find a good solution with AGS for the cooling regime. Then, based on this solution we can select nine groups of quadrupoles for the cooling regime. Finally, we use these nine groups of quadrupoles to reach any intermediate regime.

Tables 2 and 3 compare the results obtained from fourteen and nine variables for the cooling regime. We can see that β_H is increased from 14.97 m to 20.47 m and, fortunately, β_V is almost unchanged.

Comparing the cooling regime with the bunch rotation regime, one can see that the horizontal aperture is determined by bunch rotation regime because of the large momentum spread, but the vertical aperture is determined by the cooling regime because of the modulation in β_V function.

We had intended to limit the perturbation only in the left arc part, without extending it to insertion region, but the results were disappointing; even if D_{max} is increased in some regular cell to 12.26 m, the $\int D/\rho \, ds$ only increases to 2.45. The η in left half-ring is only -0.06. This means that the quadrupoles in insertion must play an important role during the matching procedure, mainly to produce necessary phase advance without changing the D function in the arc.

Figs. 5 and 6 show that the strength K of nine groups of quadrupoles should be changed in order to maintain the working point in a rather small range, say ±0.05, during the transformation process from bunch rotation regime to cooling regime. Four of them change linearly, another five follow linear segments. The tolerance on $\Delta K/K$ is about $5\ 10^{-3}$ for $\Delta Q \leqq 5\ 10^{-3}$.

7. LATTICE STRUCTURE FOR FIXED η = -0.013

In balancing versatility of operation against simplicity a compromise regime has been suggested. For example, η could be kept at a small fixed value, say $\sim$-0.015.

Fortunately, the above lattice structure has sufficient flexibility to allow us to find the solution for η = -0.013 with rather small lattice functions, i.e. D_{max} = 3.33 m, $\beta_{V_{max}}$ = 10 m, $\beta_{H_{max}}$ = 13.5 m in the regular cell. The details of lattice functions and beam size are shown in Table 4 and Figs. 9-12. At this stage of the design, the working point was moved to Q_H = 4.30 and Q_V = 4.32 in order to avoid the non-linear resonances up to the 7th order.

As the phase advance per cell is not exactly 60°, two quadrupole strengths in the dispersion suppressor are modified to cancel the orbit dispersion in the long straight section. Besides, for satisfying the requirements of injection and ejection some bending field is introduced in the last quadrupole of the dispersion suppressor. Here, we suppose that the beam center is at 52 mm from the quadrupole center.

8. REFERENCES

1) W. HARDT, AA Long Term Note 20 (1982).

2) E. KEIL, CERN 77-13 (1977).

3) J.P. DELAHAYE, this study.

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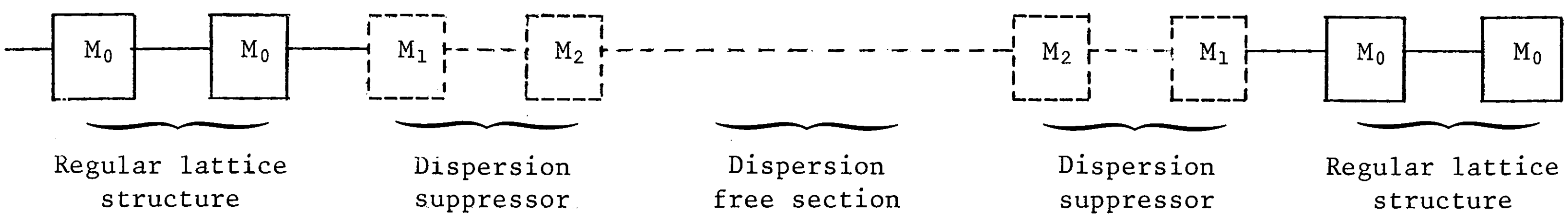
A GENERAL FORMULATION FOR DISPERSION SUPPRESSOR IN REGULAR LATTICE STRUCTURES

B. Autin and J.-P. Delahaye

1. INTRODUCTION

It has become a general practice in most of the modern storage or accelerator rings to provide dispersion-free straight sections where the orbit position is independent of the particle momentum. A well-known technique to cancel at once the orbit dispersion function D_x and its derivative D'_x consists in inserting in a regular lattice structure at least two special lattice cells called "dispersion suppressor".



Assigning to each of these two special lattice cells the same transversal focusing device that for the regular one, but different bending magnets, provides the two parameters necessary to cancel the dispersion function and its slope without perturbing the β function.

E. Keil[1)] proved that in the particular case of a FODO lattice and with the assumption of thin lenses, this result could be obtained by adopting in the two special lattice cells bending magnets of angle ϕ_1, ϕ_2 related to the angle ϕ_0 of the regular lattice cell bending magnet by :

$$\frac{\phi_1}{\phi_2} = \frac{1 - 2\cos\mu}{2(1 - \cos\mu)} , \quad \frac{\phi_2}{\phi_0} = \frac{1}{2(1 - \cos\mu)} ,$$

where μ is the horizontal betatron phase advance per cell.

This result is in fact quite general as it is demonstrated here and completely independent of the lattice structure and the elements widths, provided the dispersion function at the extremity of the lattice cell remains proportional to the deflection bending angle.

2. EQUIVALENT TRANSFER MATRIX OF THE DISPERSION SUPPRESSOR

The general horizontal transfer matrix M_0 of a periodic lattice cell can be fully described by :

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1) E. Keil, Single Particle Dynamics - Linear Machine Lattices, CERN 77-13 (1977).

$$M_0 = \begin{vmatrix} \cos\mu_0 + \alpha_0 \sin\mu_0 & \beta_0 \sin\mu_0 & (1 - \cos\mu_0 - \alpha_0 \sin\mu_0)D_0 - \beta_0 \sin\mu_0 D_0' \\ -\left(\frac{1 + \alpha_0^2}{\beta_0}\right) \sin\mu_0 & \cos\mu_0 - \alpha_0 \sin\mu_0 & \left(\frac{1 + \alpha_0^2}{\beta_0}\right) \sin\mu_0 D_0 + (1 - \cos\mu_0 + \alpha_0 \sin\mu_0)D_0' \\ 0 & 0 & 1 \end{vmatrix}$$

where μ_0 is the relative horizontal phase advance,

α_0 and β_0 the usual Twiss parameters,

D_0 and D_0' the absolute value and slope of the dispersion function, all parameters related to the extremity of the lattice cell.

As the β function and the phase advance will not be perturbed by the insertion of the dispersion suppressor, the equivalent transfer matrix of each of this two special cells are identical to the one equivalent to the periodic lattice cell M_0 except for the dispersion function D and its slope D'.

Nevertheless, a similar expression can be used subsituting to the regular dispersion value D_0 and its slope D_0' the corresponding values that the dispersion function would take at the extremities of the cell if the ring were regularly constituted by the considered lattice cell :

$$M_1 = \begin{vmatrix} \cos\mu_0 + \alpha_0 \sin\mu_0 & \beta_0 \sin\mu_0 & (1 - \cos\mu_0 - \alpha_0 \sin\mu_0)D_1 - \beta_0 \sin\mu_0 D_1' \\ -\left(\frac{1 + \alpha_0^2}{\beta_0}\right) \sin\mu_0 & \cos\mu_0 - \alpha_0 \sin\mu_0 & \left(\frac{1 + \alpha_0^2}{\beta_0}\right) \sin\mu_0 D_1 + (1 - \cos\mu_0 + \alpha_0 \sin\mu_0)D_1' \\ 0 & 0 & 1 \end{vmatrix}$$

$$M_2 = \begin{vmatrix} \cos\mu_0 + \alpha_0 \sin\mu_0 & \beta_0 \sin\mu_0 & (1 - \cos\mu_0 - \alpha_0 \sin\mu_0)D_2 - \beta_0 \sin\mu_0 D_2' \\ -\left(\frac{1 + \alpha_0^2}{\beta_0}\right) \sin\mu_0 & \cos\mu_0 - \alpha_0 \sin\mu_0 & \left(\frac{1 + \alpha_0^2}{\beta_0}\right) \sin\mu_0 D_2 + (1 - \cos\mu_0 + \alpha_0 \sin\mu_0)D_2' \\ 0 & 0 & 1 \end{vmatrix}$$

The equivalent transfer matrix [S] of the dispersion suppressor can then be calculated :

$$[S] = \begin{vmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ 0 & 0 & 1 \end{vmatrix} = [M_2] \times [M_1]$$

$S_{11} = \cos2\mu_0 + \alpha_0 \sin2\mu_0$,

$S_{12} = \beta_0 \sin2\mu_0$,

$S_{13} = [(\cos\mu_0 + \alpha_0 \sin\mu_0) - (\cos2\mu_0 + \alpha_0 \sin2\mu_0)]D_1 + [\beta_0 \sin\mu_0(1 - 2 \cos\mu_0)]D_1' +$
$[1 - (\cos\mu_0 + \alpha_0 \sin\mu_0)]D_2 - [\beta_0 \sin\mu_0]D_2'$,

$$S_{21} = -\left(\frac{1+\alpha_0^2}{\beta_0}\right)\sin 2\mu_0 ,$$

$$S_{22} = \cos 2\mu_0 - \alpha_0 \sin 2\mu_0 ,$$

$$S_{23} = \left[\left(\frac{1+\alpha_0^2}{\beta_0}\right)(\sin 2\mu_0 - \sin\mu_0)\right]D_1 + [(\cos\mu_0 - \alpha_0 \sin\mu_0) - (\cos 2\mu_0 - \alpha_0 \sin 2\mu_0)]D_1'$$
$$+ \left[\left(\frac{1+\alpha_0^2}{\beta_0}\right)\sin\mu_0\right]D_2 + [1 - (\cos\mu_0 - \alpha_0 \sin\mu_0)]D_2' .$$

3. CONDITIONS FOR DISPERSION SUPPRESSION

The dispersion function D is generally transformed in a channel by the equivalent transfer matrix [M] :

$$\begin{vmatrix} D \\ D' \\ 1 \end{vmatrix}_{(out)} = [M] \begin{vmatrix} D \\ D' \\ 1 \end{vmatrix}_{(in)} .$$

The dispersion value and its slope will therefore cancel at the end of the dispersion suppressor if the two equations are verified.

(1) $$D_{out} = S_{11}D_0 + S_{12}D_0' + S_{13} = 0$$

(2) $$D'_{out} = S_{21}D_0 + S_{22}D_0' + S_{23} = 0$$

Each of these equations can be decomposed in two equations dealing with either the dispersion values or the slopes only, where the transfer matrix elements have been replaced by their values above :

$$(1) = (3) + (4) \begin{cases} (3) \quad 0 = (\cos 2\mu_0 + \alpha_0 \sin 2\mu_0)D_0 + [(\cos\mu_0 + \alpha_0 \sin\mu_0) - (\cos 2\mu_0 + \alpha_0 \sin 2\mu_0)]D_1 \\ \qquad\quad + [1 - (\cos\mu_0 + \alpha_0 \sin\mu_0)]D_2 \\ (4) \quad 0 = \beta_0 \sin 2\mu_0 \, D_0' + \beta_0 \sin\mu_0 \, (1 - 2\cos\mu_0)D_1' - \beta_0 \sin\mu_0 \, D_2' \end{cases}$$

$$(2) = (5) + (6) \begin{cases} (5) \quad 0 = -\left(\frac{1+\alpha_0^2}{\beta_0}\right)\sin 2\mu_0 \, D_0 + \left(\frac{1+\alpha_0^2}{\beta_0}\right)(\sin 2\mu_0 - \sin\mu_0)D_1 + \left(\frac{1+\alpha_0^2}{\beta_0}\right)\sin\mu_0 D_2 \\ (6) \quad 0 = (\cos 2\mu_0 - \alpha_0 \sin 2\mu_0)D_0' + [(\cos\mu_0 - \alpha_0 \sin\mu_0) - (\cos 2\mu_0 - \alpha_0 \sin 2\mu_0)]D_1' \\ \qquad\quad + [1 - (\cos\mu_0 - \alpha_0 \sin\mu_0)]D_2' \end{cases}$$

Simplifying the equation (4) by $\beta_0 \sin\mu_0$ and the equation (5) by $[(1+\alpha_0^2)\beta_0]$, it is easy to show that the set of the 4 equations above is equivalent to :

(7) $$\frac{D_1}{D_0} = \frac{D_1'}{D_0'} = \frac{1 - 2\cos\mu_0}{2(1 - \cos\mu_0)}$$

(8) $$\frac{D_2}{D_0} = \frac{D_2'}{D_0'} = \frac{1}{2(1 - \cos\mu_0)}$$

(9) $$D_1 + D_2 = D_0 \qquad D_1' + D_2' = D_0'$$

As for a large majority of lattice cells, the dispersion function and its slope at the extremity of the cell are proportional to the bending magnet angle ϕ as it is the only dispersive element.

(10) $$\frac{D_1}{D_0} = \frac{D_1'}{D_0'} = \frac{\phi_1}{\phi_0}$$

(11) $$\frac{D_2}{D_0} = \frac{D_2'}{D_0'} = \frac{\phi_2}{\phi_0}$$

Thus, an easy dispersion suppressor can be constituted by two special lattice cells identical to the regular lattice cell except for their magnet bending angles which must be related to the one of the regular lattice cell by (Fig. 1) :

(12) $$\frac{\phi_1}{\phi_0} = \frac{1 - 2\cos\mu_0}{2(1 - \cos\mu_0)}$$

(13) $$\frac{\phi_2}{\phi_0} = \frac{1}{2(1 - \cos\mu_0)}$$

(14) $$\phi_1 + \phi_2 = \phi_0$$

In any case, the total bending deflection in the dispersion suppressor is equal to the deflection of the regular lattice cell independently of the horizontal phase advance per cell.

4. CASES OF SPECIAL INTEREST

Therefore, adopting special horizontal phase advance per lattice cell leads to some very interesting relations between the three different bending angles (Table below).

μ_0 (° mod 2μ)	ϕ_1/ϕ_2	ϕ_2/ϕ_0
60 or 300	0	1
67.98 or 292.02	0.2	0.8
70.53 or 289.47	0.25	0.75
75.52 or 284.48	1/3	2/3
90 or 270	0.5	0.5
120 or 240	2/3	1/3
180	0.75	0.25

In particular, a $\pi/3$ horizontal phase advance μ_0 enables an easy dispersion suppressor built-up by just putting off one regular bending magnet. It is the well-known missing magnet method.

On the other hand, a $\pi/2$ horizontal phase advance μ_0 leads to a dispersion suppressor with, in each special lattice cell, equivalent bending magnets whose deflection is half of the regular lattice cell's one.

Nevertheless, it is clear that the more interesting cases quoted above cannot generally be strictly adopted as the corresponding horizontal working point would suffer from low order betatron resonances. The operational procedure for a ring design therefore consists in finding first a regular lattice cell especially adapted to the envisaged machine with an horizontal phase advance very near the one which could provide an easy dispersion suppressor. A slight change of the position and/or the strength of the main lattice elements allows then to find back an ideal dispersion suppressor. Powerful minimization subroutines such "Minuit" in the AGS linear optic program[2)] are then very useful for this kind of optimisation.

5. CONCLUSION

Easy dispersion suppressor can thus be inserted without perturbing the β function in rings built up with any regular lattice cell. It imposes only to adapt to the horizontal phase advance per cell the bending angles of two special lattice cells constituting the dispersion suppressor. The ratio of the different bending strength is independent of the kind of lattice cell adopted and of the width of its elements.

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2) E. Keil, AGS - The ISR Computer Program for Synchrotron Design, CERN 75-13 (1975).