

MODELLING OF GRADIENT BENDING MAGNETS FOR THE BEAM DYNAMICS STUDIES AT ALBA

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Abstract

ALBA is a 3rd generation light source under construction close to Barcelona, Spain. The lattice chosen consist in a DBA-like structure where most of the vertical focusing takes place in the bending magnets, in order to maximize the space allocated for insertion devices in the lattice and to reduce the emittance. In this case the tunes of the Storage Ring will be strongly affected by the focusing of the magnetic field of the bending magnet. In existing storage rings with gradient bending magnets it has been realized that the real vertical tune of the machine is slightly different from the theoretical one. In order to avoid this for ALBA we investigated the right modelling of the bending magnet. The corresponding procedures are described within this paper. The parameters of the model are estimated from the field map on the magnet midplane computed with 3D simulations.

INTRODUCTION

The ALBA Storage Ring (SR) has 32 rectangular bending magnets, with magnetic length 1.38 m and gradient of 5.66 T/m (SR-MA-BEND), while in the Booster there are 8 bending magnets with magnetic length of 1 m (BO-MA-BM05) and 32 magnets of 2 m (BO-MA-BM10), both are rectangular type with quadrupolar gradient of 2.29 T/m and sextupolar gradient of 22.2 T/m². Table 1 lists the parameters for the three types of the gradient magnets, more details on the ALBA dipoles can be found in [1].

The use of combined function dipoles has the advantage of the reduction of the space taken up by the magnets and of the decrease of the natural emittance by introducing additional damping due to the field gradient. On the other hand, this reduces the flexibility of the ALBA SR lattice [2], in

particular in the vertical plane, and enhances the sensitivity to the gradient value of the bending magnets, as well as to the edge focusing due to the pole face rotations. Experience in other light sources using combined function bending magnets, as the ASP, CLS or Spear-III, has shown that the effective edge angles of the real magnets can differ significantly from the design ones, changing considerably the vertical tune. Figure 1 shows as an example the change in the vertical tune with the edge angle for the ALBA lattice: between 2.5° and 4.5° there is not any stable solution. The flexibility of the ALBA lattice is however large enough in order to compensate the focusing errors given by the edge focusing.

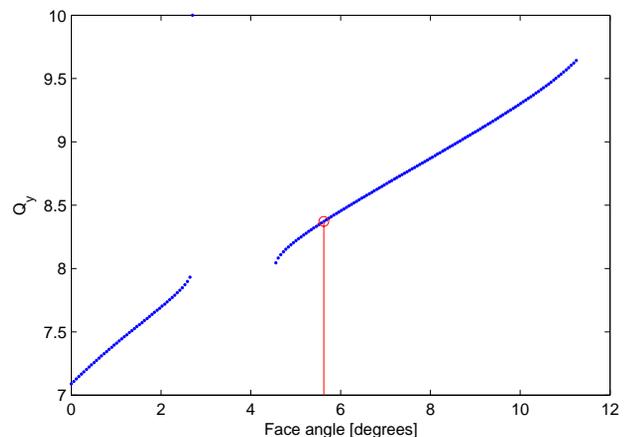


Figure 1: Change in the SR vertical tune as a function of the pole face rotation in the bending magnet varying from zero (sector magnet) up to a value twice the rectangular magnet case. The red circle marks the nominal one.

FIELD AND GRADIENT PROFILE

The magnetic field for every magnet has been calculated with 3D simulations performed with OPERA. Figure 2 shows the relative longitudinal behaviour of the magnetic field B_y , as well the gradient. Within the homogeneous part of the combined bending magnet, the magnetic field and the gradient show the same distribution, which is not the case at the end of the magnet where the gradient shows a sharp peak. This peak is given by the fringe field and the rotation angle of the pole face with respect to the beam trajectory.

Table 1: Design parameters of the ALBA SR and Booster combined function magnets.

Parameter	SR-BEND	BO-BM05	BO-BM10
Length (m)	1.3837	1.0000	2.0000
Field (T)	1.4200	0.8733	0.8733
Grad. (T/m)	5.6600	2.2916	2.2916
Sext. (T/m ²)	0.0	22.215	22.215
Energy (GeV)	3.0	3.0	3.0
Angle (°)	11.25	5.00	10.00

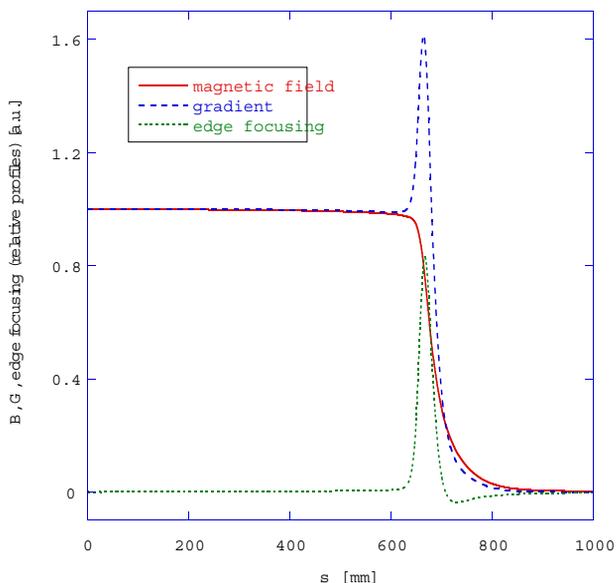


Figure 2: The magnetic field B_y profile of the magnet SR-MA-BEND along the nominal trajectory (red full line) compared with the gradient distribution (blue dashed line) and the peak contribution from the pole face rotation (green dotted line). The curves are in arbitrary units.

MODELLING APPROACH

Conventional beam optics codes, as MAD or TRACY, represent a combined function dipole as an element whose first order attributes are the radius of curvature (or the arc length), the bend angle, the quadrupole coefficient, the rotation angles for the entrance and exit pole faces, etc... Therefore in defining the transformation through a dipole the field and the gradient are assumed to be step functions with constant values within the magnet and zero outside. Such a field distribution is just an idealization, since in a real magnet the field drops off smoothly to zero in the edge region, and if we want to model the transformation characteristics for a real dipole we have basically two options: either a piecewise model or an effective hard edge model.

Piecewise model

In the piecewise approach no assumption is made on the field behaviour: the whole dipole real distribution is sliced in small segments of varying field and gradient, and the total transformation matrix is the product of the matrices for all pieces.

An automatic procedure to generate the elements has been written for the Accelerator Toolbox of Matlab. The function reads the data table with s , $B(s)$ and $G(s)$ produced by the 3D magnetic simulations. Then it creates the arrays with L , B and G for a slicing of the dipolar field where the maximum change in a slice is 0.1 of the field and 0.2 of the gradient at $s = 0$, and each slice has a maximum length of 0.3 m. This settings slice the SR dipole in around

40 pieces allowing a very good simulation of the field behaviour. The advantage of this model is the accuracy in the optics simulations, the drawback is the large CPU time consumed in tracking simulations.

Hard edge model

In this second option the dipole is represented as a single block of constant field and gradient embedded in two thin lenses that reproduce all the focusing effects in the edge region (different effective length of the field and the gradient, pole face rotation...).

For the proper linear modelling of a gradient dipole magnet two conditions require to be fulfilled. First, the deflection angle (i.e. the total field integral) and the length must be same of the actual trajectory of a nominal particle. Next, the focusing (in the body and in the edge region) represented in the model must be the same experienced by a particle traveling around the nominal trajectory.

The first order attributes of the dipole model will be the arc length L , the bend angle α , the quadrupole coefficient k , the rotation angle ψ for the entrance and exit pole faces, the fringing field integral and the magnet gap g .

The arc-line effective length of the magnet SR-MA-BEND was estimated by taking the total field integral and dividing it by the average field in the centre for $-400 \text{ mm} \leq s \leq 400 \text{ mm}$, (Fig. 2):

$$L_{eff} = \frac{\int_{-\infty}^{+\infty} B_y(s) ds}{B_y^{ave}}. \quad (1)$$

The gradient factor $\partial B_y / \partial x$ in the body was also estimated as the average value for $-400 \text{ mm} \leq s \leq 400 \text{ mm}$. Therefore the transport matrix of the magnet body for the four transverse coordinates plus the energy deviations, (x, x', y, y', δ) , is completely defined.

For the focusing effect produced by the edge angle some more considerations have to be made. The entrance and exit edge focusing effect are modeled through a thin element whose matrix is

$$F = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ \frac{1}{\rho} \tan \psi & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{1}{\rho} \tan \bar{\psi} & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \quad (2)$$

The focusing angle in the vertical plane $\bar{\psi}$ differs from the horizontal angle ψ by a small correction term given by the first integral of the fringing field [3].

The modelling problem basically consists in the determination of the effective edge focusing strength ψ that produces the actual transformation through the magnet.

Edge focusing angle from the effective length

An ideal rectangular magnet has an edge angle $\psi = \alpha/2$, then for SR-MA-BEND it should hold $\psi = \alpha/2 = 5.625^\circ$.

Nevertheless, in a real magnet, due to the finite width of the magnetic pole (60 mm to be compared with a gap of 36 mm), the effective magnetic edge angle can differ very much from the mechanical edge angle. In fact, calculating the effective length on different trajectories parallel to the nominal one, and considering L_{eff} as a function of the transverse position x , one can infer the slope that gives an estimate for the effective magnetic pole face rotation angle. For SR-MA-BEND with the end chamfer of 13° it is obtained $\psi_{mag} = 5.597^\circ$.

Edge focusing angle from the gradient profile

An other way to assess the edge focusing is from the gradient profile in Fig. 2. Taking into account the same distribution of the field as well for the gradient, the contribution of the edge focusing can be estimated subtracting this distribution to the real one (green dotted line). Then, the integral of the peak in Fig. 2 divided by $B\rho$ must equal the term $F_{21} = 1/\rho \tan \psi$ in Eq 2. For SR-MA-BEND it is then inferred $\psi_{peak} = 5.400^\circ$, which is a variation of 4% with respect to $\psi_{mag} = 5.597^\circ$: what is the most proper value to use?

Edge focusing angle from the real transfer matrix

To solve this problem we have introduced a more precise way to estimate the edge focusing from the real transport matrix calculated from the the map of the field [4].

The physical problem of calculating the transformation through the magnet is solved by numerically integrating the motion of a particle through the magnetic field map with different initial coordinates (x, x', y, y', δ) displaced with respect to the reference trajectory by $(1 \text{ mm}, 0, 0, 0, 0)$, $(0, 1 \text{ mrad}, 0, 0, 0)$ and so on, the final coordinates at the end of the the path are the columns of the transport matrix.

Special attention has been paid in order to obtain displacements little enough to remain in the linear regime. Once the complete transport matrix of the magnet is known, the face pole rotation angle ψ in the hard edge model is used as adjustable variable to fit the modelled linear transport matrix, in the least square sense, to the actual matrix. The edge angle determined with this method is $\psi_{matr} = 5.395^\circ$, very close to ψ_{peak} .

MODELLING RESULTS

The optical functions both with the piecewise model (AT) and for the hard edge (MAD) have been computed for three different end chamfer designs, 10° , 13° and 20° and the tunes are listed in Table 2. From the tune change with the chamfer angle the best value of 14° is then found for the SR bending magnets.

A completely similar treatment has been carried out also for the Booster magnets, but in this case the lattice is not so critical with the gradient dipoles and the nominal optics can be recovered even with the three quadrupole families of the matching sections.

Table 2: SR: betatron tunes for the so called “unit cell lattice” with three different end chamfers in the dipoles, with the piecewise and the hard edge model. The nominal tunes are $Q_x = 18.9143$ and $Q_y = 9.7243$.

Chamfer angle		10°	13°	20°
Piecewise	Q_x	18.9465	18.9144	18.8237
	Q_y	9.1988	9.6419	10.4674
Hard edge	Q_x	18.9636	18.9272	18.8318
	Q_y	9.2360	9.6324	10.4977

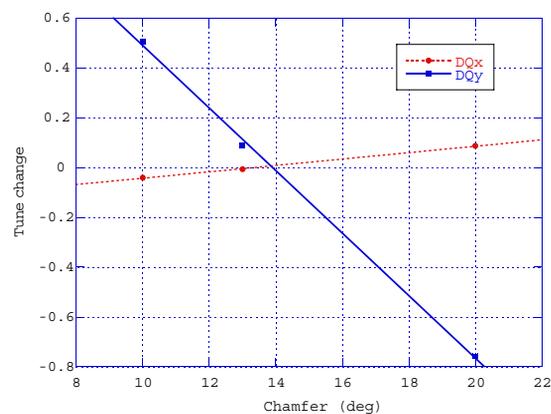


Figure 3: SR tune change as a function of the end chamfer. According to this plot the best end chamfer should be 14° .

CONCLUSIONS

The advantage of the sliced model is the accuracy of the lattice simulations, but on the other hand in the hard edge approach we have to deal with a reduced number of simple variables in order to study a lattice, and tracking calculations for many turns in a ring are much less time consuming. However it is clear that once a field contains nonlinear components, the main advantage of taking the hard edge matrix approach may be lost.

Finally the agreement between the two modelling approaches is satisfactory and the changes obtained in the lattice linear parameters varying the chamfer angles are consistent. This has allowed to find the value of the end chamfer for the prototype production. The optics calculations then will be checked with the magnetic data taken on the gradient dipole prototypes.

REFERENCES

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