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# *A P E R T U R E - A COMPUTER PROGRAM TO REPRESENT BEAM DIMENSIONS AND MACHINE APERTURES IN CIRCULAR ACCELERATORS*

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Abstract

Written with the AA machine in mind, the program shows the beam dimensions for stack and injection orbits and the inner machine profile in both the horizontal and vertical planes. As output it also gives the parameters needed for beam potential calculations.

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## 1. *INTRODUCTION*

APERTURE was written to replace an earlier program, called BEPO, which ran on the now obsolete CDC. This was also written for the AA machine, and its main aim was beam potential calculations along the machine.

In its beam potential calculations BEPO used unidimensional Fourier series, assuming a beam charge distribution with a uniform density over the beam height in vertical direction and also with a uniform density but followed by cosine squared shapped tails on horizontal direction[1]. This is not a good approximation, because it seems that the balance between natural and forced cooling effects and coherent diffusive heating effects produces in negatively charged beams (such as AA) a charge density which is approximately bi-gaussian distributed over the plane perpendicular to the beam direction.

Since, for this charge density, potential calculations are complex and use a great amount of computer time, this new program will only give the parameters needed for these calculations, and other programs must be provided in order to do the calculations. However, like BEPO, APERTURE will give a representation of the beam dimensions and of the machine apertures, using the central orbit as azimuthal reference. To do this it requires lattice functions values which are provided by another program, ORBIT[2].

The program code was written in FORTRAN to run at CERN with the operating system VM/CMS on the IBM computers. The graphical system used is the standard Minimal-GKS (Graphical Kernel System), available at CERN, and it uses the GENLIB and GRAFLIB CERN libraries. Some auxiliary files are provided in order to make it easier to run.

## 2. *THE REPRESENTATION OF THE BEAM*

The AA machine has two equal super-periods, having each one a mirror symmetry. This means that it only needs ORBIT data for one quarter of the machine, the others being calculated from the first. For the second quarter of the machine, which corresponds to the other half of the first super-period, the lattice functions are calculated using the mirror symmetry:

$$s_i = 2s_{n+1} - s_{2(n+1)-i}$$

$$f_i = f_{2(n+1)-i}$$

where

$n+2 \leq i \leq 2n+1$

n is the total number of elements into which the first quarter was divided at ORBIT input.

$s_i$ is the azimuthal location of the i-th element beginning.

$f_i$ represents all the lattice functions at azimuthal location $s_i$.

The second super-period is equal to the first and:

$$s_i = s_{2n+1} + s_{i-2n}$$

$$f_i = f_{i-2n}$$

where

$$2n+2 \leq i \leq 4n+1.$$

The number of elements into which the total machine is divided is actually 4n, and we have 4n+1 azimuthal points where functions are calculated. The first point is physically equal to the last one, and at these points the functions are equal ($f_1 = f_{4n+1}$), even though the azimuthal locations as defined above are different ($s_1$ is 0 and $s_{4n+1}$ is equal to the machine length).

In the vertical plane, the beam dimension is determined only by the betatron oscillations. Since there is a symmetry about the central orbit, only half of the beam is represented (the lower half). Its maximum deviation from the central orbit is given by:

$$d_v(s) = - (\beta_v(s)\varepsilon_v)^{1/2}$$

where $\beta_v(s)$ is the vertical beta function at location s, for a given momentum, and $\varepsilon_v$ is the vertical beam emittance (in units of $\pi$ m.rad).

Since $\beta_v$ has a very small dependence on momentum, we do not need to do the representation for all momenta, and only the beam at central orbit momentum is represented.

In the horizontal planes two beams are represented, corresponding to the stack and to the injected beam. The central orbits are represented, using values of $x_p(s) = \alpha_p(s)\ dp/p$, where $x_p s)$ is the deviated orbit at location s for a given momentum, $\alpha_p(s)$ the dispersion function at location s for the same momentum, and dp/p is the momentum spread, relative to central orbit momentum. The momenta used in the representations are the stack core centre and the injection centre momenta ($\Delta p/p = -0.0246$, $\Delta p/p = +0.0215$).

The lower and upper limits of each beam are given by:

$$d_H^-(s) = x_p^-(s) - (\beta_H^-(s)\varepsilon_H)^{1/2}$$

$$d_H^+(s) = x_p^+(s) + (\beta_H^+(s)\varepsilon_H)^{1/2}$$

where $x_p$'s are the same as above, $\beta_H$'s are the horizontal beta functions and $\varepsilon_H$ is the horizontal beam emittance. The - and + signs mean that lattice functions must be calculated for the lower and upper momentum values, respectively.

For the stacked beam, the $x_p(s)$ functions are also represented in order to give an idea of betatron oscillations (represented by $d_H - x_p$) The $x_p$ and $\beta$ functions are read in as output from ORBIT.

## 3. *INJECTION ORBIT*

For the injected beam, one further aspect is added: the parameters of the orbit coordinates of the beam at entrance, before being deviated by the injection septum followed by the injection kickers. These coordinates can be calculated backwards from the exit of the last kicker, supposing beam motion in the opposite direction.

For a beam passing over a set of n kickers, we can calculate the deviation from the unaltered orbit by the formula[3]:

$$\Delta x(s) = (1 + dp/p) \sum_{i=1}^{n} (\beta(s)\beta(s_i))^{1/2} [\sin\Delta\mu(s) - \frac{\ell(s_i)}{2\beta(s_i)} (\cos\Delta\mu(s) + \alpha(s_i)\ \sin\Delta\mu(s))]\Delta\psi(s_i) \quad ,$$

where

$\Delta\mu = \mu(s) - \mu(s_i)$,

$\beta(s)$, $\alpha(s)$, $\mu(s)$ are the horizontal beta function, its derivative ($\beta' = -2\alpha$) and the phase advance function, at location s, for a given momentum,

$s_i$ is the location of the entrance of the kicker module i,

$\ell_i$, $\Delta\psi_i$ are the length and the deflection angle of the kicker module i,

$\Delta\psi(s_i) = \Delta\psi_i \, \ell(s_i)/\ell_i$, and

$$\ell(s_i) = \begin{cases} 0 & s \leq s_i \quad \text{(before kicker entrance)} \\ s - s_i & s_i < s < s_i + \ell_i \quad \text{(inside the kicker)} \\ \ell_i & s \geq s_i + \ell_i \quad \text{(after kicker exit)} \end{cases}$$

The values of $\beta(s)$, $\alpha(s)$ and $\mu(s)$ are also provided by ORBIT, but probably not at points $s_i$. Thus, interpolation is used for those functions in order to get the correct values.

Inside the septum, we have:

$$d(s) = d(s_0) + \varrho(\cos\theta(s) - \cos\theta(s_0))$$

where

$d(s)$ is the deviation from the central orbit,

$s_0$ is the location of the septum entrance,

$\varrho = p/cB$ is the septum curvature radius for a magnetic field B and momentum p,

$\theta(s) = \arcsin[\operatorname{sen}\theta(s_0) + (s-s_0)/\varrho]$ is the angle between the trajectory and the central orbit, at location s.

After the septum, a linear trajectory is represented:

$$d(s) = d(s_e) + (s - s_e)\, \operatorname{tg}\theta(s_e)$$

where $s_e$ is the septum exit location.

## 4. THE COMPLETE PLOT OUTPUT

The beam is shown in both horizontal and vertical planes. The vertical representation is scaled by a factor of 2, because it is much smaller than the horizontal one (Fig. 1).

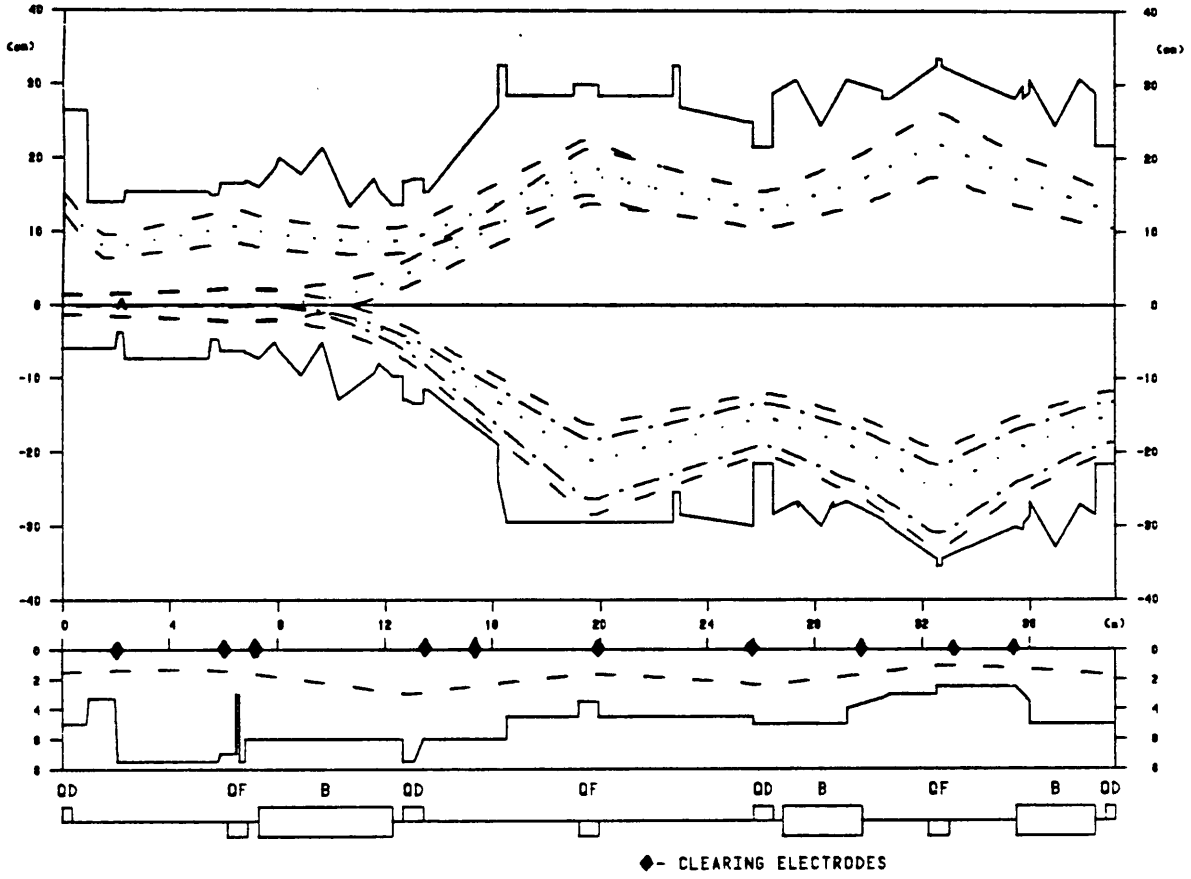


*Fig. 1 - An example of the plot output representing the first quarter of the AA.*

The machine inner dimensions are also represented in both planes. At the plot bottom, there is a diagram of the machines along a straight line. The straight sections are simply represented by the line, and the quadrupoles by small rectangles lying in one of the sides of the line (focusing ones are below the line and defocusing ones are above). The dipoles are represented by rectangles with the double height and centered on that straight line, which is deleted inside it. Clearing electrode positions are represented by small lozenges, along the central orbit, in the vertical plane. A legend explains what the lozenges mean. The transverse scale is in centimetres and the azimuthal distance given in metres.

## 5. PARAMETER OUTPUT FOR BEAM POTENTIAL CALCULATIONS

The program will also write an output file (BEPO DATA) with all the parameters for beam potential calculations, to be used by other programs.

The first value given is the particle density (the number of particles by unit length), which is simply the ratio between the total number of particles (given as input) and the total machine length (which is $s_{4n+1}$, as seen above).

The r.m.s. beam sizes in vertical and horizontal planes are calculated from:

$$\sigma_{Hp}^2(s) = \sigma_H^2(s) + \sigma_p^2(s) = \frac{\beta_H(s)\varepsilon_H}{\ell n\ 400} + (\alpha_p(s)\ dp_1/p)^2$$

$$\sigma_V^2(s) = \frac{\beta_V(s)\varepsilon_V}{\ell n\ 400}$$

where

$\sigma_H(s)$, $\sigma_V(s)$ are the horizontal and vertical r.m.s. beam sizes at location s for a given momentum,

$\sigma_p(s)$ is the longitudinal r.m.s. size,

$dp_1$ is the total momentum spread of the cooled beam.

All those values are calculated at stack core centre momentum. Since the program needs to read $x_p(s)$ rather than $\alpha_p(s)$ for all the dp/p values, the following expression is used to calculate $\sigma_p(s)$.

$$\alpha_p \frac{dp_1}{p} = \alpha_p \frac{dp_2}{p} \cdot \frac{dp_1}{dp_2} = x_p \frac{dp_1}{dp_2}$$

where $dp_2$ is the momentum difference between the stack core centre and the central orbit.

The distance between the central orbit and the vacuum chamber inner wall, is denoted in the horizontal plane by a(s) towards the machine centre, and the same thing in the opposite direction by b(s). We use c(s) for the distance between the central orbit and the vacuum chamber inner wall in the vertical plane. We then have for the beam centre position, relative to the vacuum chamber centre:

$$x_0(s) = x_p(s) + [a(s) - b(s)]/2$$

$$y_0(s) = 0.$$

where $x_p(s)$ is the same as above (and also at the same momentum).

The vacuum chamber half-dimensions are given by (Fig. 2):

$$a_H(s) = [a(s) + b(s)]/2$$

$$a_V(s) = c(s)$$

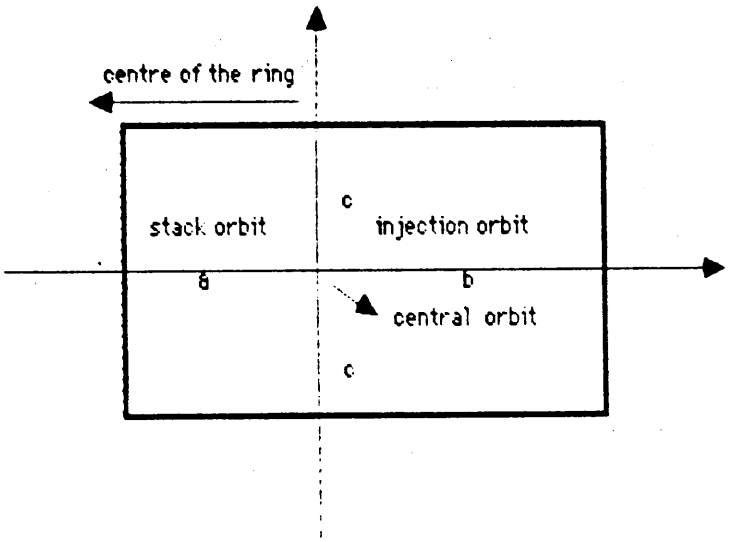


*Fig. 2 - Vacuum chamber dimensions (plane perpendicular to beam motion).*

## 6. FILES USED BY THE PROGRAM

The program runs in VM/CMS and uses the exec and data files listed below.

Data files

| | |
|---|---|
| APERTURE INPUT1 | |
| APERTURE INPUT2 | (as input) |
| BEPO DATA | (as output) |
| ORBIT DATA | |
| ORBOUT DATA | (auxiliary files) |

Exec files

APPDAT EXEC

APERTURE EXEC

Panels

APERTURE PANEL1

APERTURE PANEL2

Program

APERTURE FORTRAN or

APERTURE TEXT

GKS metafiles

APERTn METAFILE (where n is an integer)

The files:

ORBIT EXEC

ORBIT FORTRAN or

ORBIT TEXT

must also be included as they will enable us to change lattice functions as we want, using ORBIT.

The exec files (APERTURE and ORBIT) will recognise if there exists a TEXT version for each program, created from the FORTRAN version, and execute it. If not, the FORTRAN compiler will be automatically called to provide them.

Also the ORBOUT DATA and APERTURE INPUT1 need not necessarily exist, because they can be created from ORBIT DATA by ORBIT.

ORBIT DATA must always exist when using the APERTURE EXEC, because it is the source for the central orbit momentum and relative momentum spread (dp/p) values. At least the 10 first lines must be provided, in which case they cannot be altered during the execution (see below).

BEPO DATA and the GKS Metafiles are output.

## 7. TO RUN THE PROGRAM

Issuing the command "APERTURE" will start all the action, and we only need to check if the data which will appear are correct and to answer the questions.

The first action taken by APERTURE is a call to APPDAT EXEC, which is an exec file used to check some of the input data. This exec will show a panel with the central orbit momentum (in GeV/c) and the six relative momentum spreads (dp/p) needed. Three of these correspond to the stacked beam (referring to its bottom, core centre and tail top momenta), and three to the injected beam (referring to the inner, central and outer momenta).

These values can be changed by the operator, in which case the changes will be recorded, and the ORBIT EXEC will be called to create new ORBOUT DATA. (This happens automatically if neither ORBOUT DATA nor APERTURE INPUT1 exist).

The existence of ORBOUT DATA is checked and whether it was created after APERTURE INPUT1. If it is the case, all the new data will be transferred from ORBOUT to update APERTURE INPUT1. (The exec will also recognise if an ORBOUT file has been created after the last APERTURE INPUT1 update or during the execution, in which case it will be deleted at the end, to free some computer space, assuming that it was created only for APERTURE purposes).

After this a second panel appears, containing information about the workstation to which the graphical output will be sent (which can be from a graphic terminal to GKS metafiles), about the number of sections in which the machine is divided (24 in the AA), about the sections to be viewed, the total number of particles inside the machine, and the beam emittances (horizontal and vertical). Also these values can be changed, and changes will be recorded. They correspond to the first lines on APERTURE INPUT1.

It is useful to note that by only issuing the command "APPDAT", the panels will appear and data can also be changed without program execution. ORBIT will be called if necessary.

Normally after the change of the data, the program will be

executed. If the chosen workstation is a graphic terminal, the output will appear on the screen at execution time. If it is a GKS metafile, that will be created.

In order to avoid the deletion of older metafiles, every time one is created, it will have a different name: APERT1, APERT2, ... APERTn. The exec will always search for the first free value of n. The limit of metafiles is n = 999, because file names cannot be longer than 8 characters.

You will be asked whether you want to see the metafile. If the answer is YES and you have a graphic terminal it will appear. If it is NO, three options are presented in order to send the output to the VERSATEC plotter ("GKSVT" command), to the Xerox 8700 printer ("GKSX87") or to see it on a graphic terminal ("GKSTV").

This terminates the action.

## *8. AN ALTERNATIVE WAY*

It is possible to change some but not all of the values using the execs. The only way to change others is to change directly the ORBIT DATA and/or the APERTURE INPUT2 files.

To change ORBIT DATA, we only need to check ORBIT specifications (see ORBIT write-up), respecting same additional rules:

- the third line, which refers to the number of different momenta to be tracked must be set to 7, for our purpose;
- the seventh momentum (apart the six referred above) is the central orbit momentum and it corresponds to the value set on the fourth line, which must be zero (dp/p = 0);
- the six following lines correspond to the other six momenta, and its dp/p values must be given in the same order as in the first panel.

After changes to ORBIT DATA, the ORBIT command must be issued in order to ORBOUT DATA be created. When issuing the APERTURE command, this will be recognised as been created and APERTURE INPUT1 will be automatically changed.

The other input file which can be changed is APERTURE INPUT2. All values must be changed directly, and the file is self explanatory.

The first group of data on that file is about the injection septum. Lines 3 to 5 have information on field strength, effective length and central azimuthal location of the septum.

The second group of data is about the injection kickers. Line 8 gives its number, and there is one line for each kicker, beginning at line 14, giving its azimuthal location, magnetic length and kick.

The third group is about vacuum chamber dimensions, relative to the central orbit position and its shape. One line gives the total number of azimuthal positions to be read, and there is one line for each azimuthal position where exists a vertex on one of the dimensions (Fig. 1). Each of the lines will give the azimuthal location, the a(s), b(s) and c(s) values and the vacuum chamber shape ("R" for rectangular and "C" for circular).

The last group of data is about clearing electrodes. One line gives its total number and there are as many lines as electrodes, giving its azimuthal position.

## 9. *KNOWN PROBLEMS*

Care must be taken when ORBIT has previously been used for other purposes. This can lead to the wrong data and format in the ORBOUT DATA file. Also, when changing data from ORBIT DATA (which is done from the first panel), any existing ORBOUT DATA may be overwritten and lost.

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2. B. Autin, M. Bell and S. van der Meer, "ORBIT - A Computer Program for Circular Accelerators".

3. B. Autin, "Introduction to Beam Optics", CERN/PS/84-18 (AA), 1984.