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BENDS

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ACHRO: A PROGRAM TO HELP DESIGN ACHROMATIC BENDS*

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ABSTRACT

ACHRO is a very simple 2000-line FORTRAN code that provides help for the designer of the achromatic bend. Given a beam momentum, the program calculates the required drift lengths and dipole parameters which it will apply to any one of several different types of achromats. The types of achromats that the code helps to design include the Enge dual-270°, the Brown 2-dipole, the Leboutet 3-dipole, and the Enge 4-dipole, as well as the periodic systems which can be designed to any order in symmetric, nonsymmetric and stair-step varieties. Given the dimensions into which a bend must fit, ACHRO will calculate the geometrical parameters in an X-Y plane for a single or multiple achromat, and for achromatic "S-bend" configurations where possible. ACHRO makes it very easy to optimize a bend with respect to drift lengths and magnet parameters by allowing the user to change parameter values and see the resulting calculation. Used in conjunction with a beam-transport code, ACHRO makes it possible for a designer to consider various types of achromatic bends in the same beamline layout in order to compare important bend characteristics such as dispersion, isochronicity, sensitivity, geometric and chromatic aberrations, aperture requirements, space for diagnostics, etc., all of which are largely a function of the geometry and the type of achromat selected.

INTRODUCTION

The most laborious task in designing a bend, achromatic or not, is often the bend geometry, and ACHRO was written to do the "dog work" of such calculations. For some bends, especially the periodic types, the geometry can get rather complicated; and to change one value, such as a drift length or a dipole parameter, means that a whole new set of calculations of bend geometry is again required. The code helps the user optimize bend geometry by facilitating change in parameter values while maintaining desired distances or other chosen parameters. For the most part, ACHRO must be used in conjunction with a beam-transport code such as TRACE¹ to fit dipole edge angles or quadrupole fields where required. For second- or third-order achromats, codes such as TRANSPORT² or MARYLIE³ which have higher order elements must be used.

ACHROMAT DESIGN CAPABILITY

The types of achromats that ACHRO can help design are listed in Table I. With the given required dimensions, the program calculates all the geometrical parameters in an X-Y plane for a single or multiple achromat,

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and for an "S-bend" configuration where possible. Most of the first-order bends listed in Table I require no additional elements beside the dipoles to be completely achromatic to first order. The periodic systems, on the other hand, require at least quadrupoles to be achromatic to first order, but can be made achromatic to second order with the addition of sextupoles and to third order with the addition of sextupoles and octupoles.

Table I: Types of Achromats Available

First-Order Systems	Periodic Systems
Enge Dual-270°	Stair-Step
Brown 2-Dipole	Symmetric, 1-Dipole/Cell
Leboutet 3-Dipole	Symmetric, 2-Dipoles/Cell
Enge 4-Dipole	Nonsymmetric, 1-Dipole/Cell

A USER-FRIENDLY CODE

ACHRO is extremely user-friendly, prompting for information as needed, and providing a little sketch of the selected achromat. When the code is first executed, the user sees the following display:

```

*****ACHROMATIC BEND DESIGN HELP*****
Types of Achromats available are listed below.
Calculations are done for Single/Multiple Achromats,
and where possible an S-BEND Configuration.

1. ENGE DUAL 270 (1st order)
2. 2-DIPOLE      (1st order)
3. 3-DIPOLE      (1st order)
4. 4-DIPOLE      (1st order)
5. STAIR-STEP
6. PERIODIC      (Symmetric)
7. PERIODIC      (Nonsymmetric)

Enter Selection [1-7] (<CR> to Exit): 6

```

Once a choice is entered, the sketch of the achromat is printed to the terminal (the symmetric periodic system with 1-dipole/cell is used as the example):

```

<---1 cell--->
"a"  D  "a"      "a"  D  "a"      "a"  D  "a"
|-----DDD-----| + |-----DDD-----| + |-----DDD-----| + ...
  DDDDD             DDDDD             DDDDD
      #1              #2              #3

```

The user is prompted to enter either a design momentum or the particle mass and kinetic energy. A single entry signifies beam momentum while two entries indicate kinetic energy and mass.

```

Enter KE and MASS (in MeV), or MOMENTUM (in MeV/c): 94,.511

```

The desired number of cells, achromats and the total achromatic bend angle is entered, followed by a choice for one of three possible dipole entries (only one entry is required):

```
Choose one of these Entries:
Dipole Field (B)
Dipole Radius (R)
Dipole Length (L)
Enter ["B", "R" or "L"]: B
Enter Dipole Field [Kg]: 2
```

Finally, the desired achromat height dimension is entered.

```
Enter Req'd Achromat Height Dimension [m]: 4.3
```

THE OUTPUT

In this example of a periodic bend, no further information was necessary to produce a design. ACHRO displays the resulting calculation as follows:

```
***** Number of Achromats      =          1
***** Total Number of Cells     =          4
***** Total Number of Dipoles   =          4
***** Field of Dipoles [Kg]     =    2.0000000
***** Path Length of Dipoles [m]=    0.2200861
***** Chord Length of Dipoles [m]=    0.2199074
***** Radius of Dipoles RHO [m] =    1.5762508
***** Angle of Dipoles [deg]    =    8.0000000
***** Angle of Dipoles [rad]    =    0.1396263
***** Total Angle of Bend [deg] =   32.0000000
***** Beam Momentum [MeV/c]     =   94.5096186
***** Beam Rigidity, BRHO [Kg-m]=    3.1525015
***** Beam Kinetic Energy [MeV] =   94.0000000
***** Beam Particle Mass [MeV] =    0.5110000
***** BETA (v/c)                =    0.9999854
***** GAMMA                     =   184.9530333

<SINGLE ACHROMAT > X-Coordinate:  14.5958819 m
<ENDPOINT LOCATION> Y-Coordinate:  4.3000000 m
*** Cell Path Length (incl bend):  3.9572794 m
*** Total Drift/Cell (excl bend):  3.7371933 m
*** Drift "a" (half total drift):   1.8685966 m
*** Total Achromatic Path Length:  15.8291175 m

Add Quadrupoles in each Cell to complete ACHROMAT

< MULTI-ACHROMAT> X-Coordinate:  29.9917638 m
<S-Bend ENDPOINT> Y-Coordinate:   8.6000000 m
```

All the entered information is "echoed back" in addition to the achromat's dimensions (coordinates, angles, drift lengths), dipole data (path length, chord length, field, radius), and beam parameters (K.E., mass, momentum, rigidity, beta, gamma). The final endpoint coordinates of the achromat are given assuming the bend path traverses in a positive direction in the positive X-Y plane from the origin (0,0). Achromats that require completion with dipole edge-angles or quadrupole focusing are provided with an additional note such as that shown above.

If an S-Bend configuration is possible, the user may be prompted for an additional "height" dimension (the height of the "S" or the offset in the

bend plane), and as before, the endpoint coordinates are given along with any additional drift distance required between achromats.

If the selected design is periodic (as in this example), the user can request a printout of the centerline coordinates after each cell and dipole:

```
***** CENTERLINE COORDINATES *****
LOCATION      X-COORDINATE  Y-COORDINATE
(at exit)    (meters)    (meters)
Dipole  1    2.0879683    0.0153400
Cell    1    3.9383799    0.2753984
Dipole  2    6.0038934    0.5811781
Cell    2    7.8001037    1.0962331
Dipole  3    9.8029595    1.6865009
Cell    3    11.5100074    2.4465276
Dipole  4    13.4112221    3.3097946
Cell    4    14.9958819    4.3000000
```

All the above calculations are written to an output file.

MODIFYING DESIGNS

ACHRO allows the user to modify any or all entries in a very user-friendly fashion. All change menus use character data input, so "no change" translates to a simple "carriage return".

```
Enter New Values if desired
                OLD VALUE  NEW VALUE
-----
Achromat Angle: 32.00000
Dipole Field:   2.00000    )
Kinetic Energy: 94.00000
Particle Mass:  0.51100
No. of Achro:   1
No. of Cells:   4
Achro HEIGHT:   4.30000
```

If, for example, the dipole field strengths are increased, the dipole physical lengths will decrease, causing the drift lengths to increase in order to maintain the same overall height dimensions. Following the change menu, the code once again displays the calculation. This continues until no further changes are requested, after which the output file is written. The program continues, allowing the user to choose another achromat which is designed using the same beam momentum.

BEYOND DRIFTS AND BENDS

Completing the achromat is done most of the time using a beam-transport code such as TRACE or TRANSPORT as previously mentioned. Using the notation found in TRANSPORT², it is only necessary to have the R_{16} and R_{26} terms of the achromat's transfer matrix equal to zero to define a first-order achromat. In our example (the periodic achromat), focusing quadrupoles in both the X and Y planes are required in each cell, and the focusing strength depends on the phase advance per cell which is dependent on the

number of cells (for a 4-cell achromat, a phase advance of 90° is needed per cell). Thus, the geometry and dipole parameters calculated in ACHRO are entered into one of the above-mentioned codes, remembering that the quadrupole lengths must be subtracted from the drift lengths calculated by ACHRO. In this case, fitting is done on the quadrupoles, setting the R_{16} and R_{26} terms at the end of the achromat to zero. For second- and third-order achromats (which will not be discussed here), higher-order codes must be used with fitting being done using the higher-order elements.

An additional plus for periodic achromats is that they will produce a unity transfer matrix in the transverse planes. This means that the beam exiting the achromat looks identical to the beam entering the achromat in transverse phase space. This unity matrix is not possible to achieve with the non-periodic types, although there are some things that can be done to produce zeros in certain off-diagonal matrix elements. Each of the achromats is different, and this is discussed below.

COMPARING ACHROMATS

If more than one achromat is designed using ACHRO and a beam-transport code is used to obtain the R-transfer matrices, various characteristics can be compared which may be important to the overall design of the beamline. For example, if the resolving power of a system is important, the maximum values of the R_{16} terms inside the achromat should be compared, since they represent the magnitude of dispersion (referred to as the "Dispersion Index") and are directly proportional to the resolving power. If isochronicity is an important consideration, the R_{56} term can be used as a direct measure of isochronicity. If achromat sensitivity is an issue, one can observe the change (from zero) in the matrix terms R_{16} and R_{26} at the end of the achromat with, say, a 1% change in the field of any magnet element. Table II below shows a comparison of these and other characteristics for several achromats all designed to fit into the same geometry. Note that the "Max Beam Radius" data is normalized to our periodic example; the same beam was used in each bend design.

TABLE II: Characteristics of Achromats Compared

Achromat	Dispersion Index (m ²)	Isochronicity (m ²)	Sensitivity		Max Beam Radius		Hardware Req'd (dipole/quadrupole)
			R_{16} (m ²)	R_{26} (rad ²)	X_{max}	Y_{max}	
Dual 270	4.969	-28.386	0.4552	0.0492	7.31	0.72	2/-
2-D	1.497	-0.011	0.0006	0.0007	2.36	0.94	2/1
3-D	1.462	0.704	0.0070	0.0048	2.33	0.40	3/-
4-D	2.372	2.490	0.0511	0.0062	3.98	0.41	4/-
Stair Step	5.461	5.768	0.2171	0.0652	13.29	0.25	4/12
Periodic	0.679	-0.099	0.0063	0.0156	1.00	1.00	4/8

*Units are per fraction momentum spread

As can be seen, the periodic achromat has the smallest Dispersion Index while the Stair-Step has the largest. The 2-Dipole achromat is the most isochronous and the least sensitive to field changes, while the Dual-270° and the Stair-Step appear to be the most sensitive and least isochronous. For aperture requirements, the periodic achromat has the definite advantage. Comparisons such as these can be quite useful in finding both the right achromat and the one best optimized for the specific application. A more detailed discussion of achromats and the comparison of their characteristics, including beam quality considerations, is referenced below.⁴

NOTES ON SPECIFIC ACHROMATS

Edge Dual-270°: Unlike other achromats, the Dual-270° has a fixed dipole angle (270°). It is a 0°-bend, similar to an S-bend configuration, useful for a beam offset. The only parameter beside beam momentum needed for a design is the offset distance. It will produce an inverse unity R-matrix except for nonzero R_{12} and R_{34} terms. Edge-angle fitting may be required on the inside edges of the dipoles, although it should be close to 32.4°. It has a very high dispersion index, is most non-isochronous, and has the highest sensitivity factor relative to the other achromats. It requires a large aperture.

Brown 2-Dipole: The only two parameters needed for the geometry design in addition to particle momentum is the desired angle and a dipole parameter (field, length or radius). A bend-plane focusing quadrupole must be added at the symmetry point (or quadrupoles symmetrically placed) to complete the achromat to first order. If the achromatic distance "d" is observed, an inverse R-matrix in the bend plane will be achieved except for a nonzero R_{12} term. The 2-Dipole achromat has a moderate dispersion index, is the most isochronous, and has the least sensitivity.

Leboutet 3-Dipole: The 3-Dipole achromat is complete with the three dipoles. All that is needed for a design (beside the particle momentum) is the achromat angle and a dipole parameter. Additionally, the geometry results in an inverse unity matrix in the bend plane. Qualitatively, the 3-Dipole is similar to the 2-Dipole, but with a shorter achromatic distance and a smaller aperture requirement in the nonbend plane.

Enge 4-Dipole: To complete this achromat, fitting must be done on the entrance and exit edge angles of dipoles #1 and #4. The entrance edge angle should equal the exit edge angle. In addition, the entrance edge angle of dipole #2 and the exit edge angle of dipole #3 should equal the dipole angle. This achromat has great flexibility with respect to its geometry, but has high dispersion, low isochronicity (large R_{56} term), and wins no prizes with respect to aperture requirements. Beside the standard input as required for the 2- and 3-Dipole achromats, a drift length and a height dimension must be specified. An inverse R-matrix in the bend plane will be achieved except for a nonzero R_{12} term; however this term can be set to zero if fitting is also allowed on the drift spaces (note that this will change the length and height of the achromat).

Stair-Step: The Stair-Step is similar to the Dual-270° in that a single achromat is equivalent to an S-Bend (0°-bend). A height dimension is a required entry along with the standard beam momentum, achromat angle and dipole parameter. Two geometries are available: one periodic and one nonperiodic. To complete the achromat, two quadrupoles/cell (focusing in both planes) must be added in the cell geometry, while at least two quadrupoles will be needed for achromaticity in the nonperiodic geometry. The Stair-Step has the highest Dispersion Index, has very low isochronicity, is highly sensitive, and requires a very large aperture, the largest relative to the others.

Periodic: ACHRO will design periodic systems with either one- or two-dipoles per cell. Required input includes the number of cells and achromats in addition to the standard entries of beam momentum, achromat angle and a dipole parameter. A height dimension must also be entered. If one-dipole per cell is chosen, the dipole is centered in the cell if symmetric, and if nonsymmetric, the user must specify the dipole offset. If the choice is two-dipoles per cell, the user must specify an additional distance within the cell, such as the distance separating the two dipoles. Periodic systems characteristically have low dispersion indices, low sensitivities, and low aperture requirements. As previously mentioned, a unity matrix is obtained in both transverse planes.

CODE AVAILABILITY

ACHRO is available through the Los Alamos Accelerator Code Group. Write to the Los Alamos Accelerator Code Group, Mail Stop H829, Los Alamos National Laboratory, Los Alamos, New Mexico, 87545, or contact through E-Mail: LAACG@lanl.gov.

¹K. R. Crandall, D.P. Rusthoi, *TRACE-3D Documentation*, Los Alamos National Laboratory report LA-UR-90-4146 (December 1990),

²K.L. Brown, K.C. Carey, Ch. Iselin, and R. Rothaker, SLAC 91 (1973 rev), NAL91 and CERN 80-04.

³A.J. Dragt, et. al., *MARYLIE 3.0, A Program for Charged-Particle Beam Transport Based on Lie Algebraic Methods*. Univ. of Maryland Technical Report, Mar. (1991).

⁴D.P. Rusthoi, E.A. Wadlinger, "First- Second- and Third-Order Achromatic Bend Systems for Free-Electron Laser Applications", 1991 IEEE Particle Accelerator Conf., Vol 1, p.607, (1991).

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