TRI-DN-99-16
April, 1999

Design of Betatronic and Momentum Collimation Systems with Code DJ ("Distribution of Jaws")
DJ User's Guide

Dobrin Kaltchev

Abstract

This note is the User's Guide to the code DJ applied by the author in the design of the LHC collimation systems. It also provides a simple theory which demonstrates the need of tune split along the beam line for collimation of the combined (x-y) betatron amplitudes. We have derived the 2D analogue of the well known phase criterion for collimation in a plane.

1 Introduction

This note is the user's guide to the code DJ which algorithm and application to the design of betatron and momentum collimation systems of LHC were reported in [1],[2].

The DJ source (Fortran 77) and demo files can be downloaded from `http://decu10.triumf.ca:8080/dk/dj.html` and freely used, modified and distributed.

For a fixed optics of the collimation insertion, DJ optimizes the locations and orientations of flat collimator jaws so as to restrict the secondary halo produced by scattering of circulating protons at the primary collimators. The primary jaws are positioned upstream with respect to the optimized secondary jaws and 1-2 sigma closer to the beam axis. DJ models the initial conditions describing the secondary halo by a set of point-like sources x_0, y_0 along the edges of the primary jaws. At each source point, the initial non-normalized angles (x', y') are assumed to be within $(-\frac{\pi}{2}, \frac{\pi}{2})$. For a given relative momentum offset δ, DJ minimizes the maximum betatronic invariants (amplitudes) of particles escaping all secondary jaws – combined: A_{max}=max$(\sqrt{X^2 + X'^2 + Y^2 + Y'^2})$ and in-plane: $A_{x,max}$, $A_{y,max}$.

For a fixed set of halo sources, the secondary jaw phases $\mu_x^{(k)}$, $\mu_y^{(k)}$ (k=1,2...) define the maximum escaping amplitudes in the following way: all jaws (pairs of parallel lines in normalized X-Y space) are transformed (rotated by angles $\mu_x^{(k)}$, $\mu_y^{(k)}$) to the location of the source and the "escape window" in initial-angle space is found – its vertices giving A_{max}, $A_{x,max}$and $A_{y,max}$. This procedure is equivalent to linear tracking with the maximum escape angles being recorded, but is much faster.

The paper also provides a simple theory of betatronic collimation (Chapter 3) based on an unpublished TRIUMF note [4]. This theory was initiated by T. Risselada from CERN [5] as an attempt to demonstrate the need of tune split to achieve adequate collimation.

A lattice setup that favours collimation of the combined (x and y) amplitude A_{max}can be defined as follows. Consider a beamline with a nonzero split of the tune advances: $\mu_x(s) \neq \mu_y(s)$, s is the longitudinal coordinate. For each source x_0, y_0, the optimum collimator phases lay in the vicinity of a curve in the (μ_x, μ_y)-plane, defined by the relation;

$$(x_0/R)^2/\cos^2\mu_x + (y_0/R)^2/\cos^2\mu_y = 1, \quad (1)$$

where for a circular primary: $x_0^2 + y_0^2 = R_0^2$. This relation is the 2D analogue of the well known phase criterion for collimation in a plane: $\cos\mu = R_0/R$, where μ is the optimum phase of the collimator; R_0 and R are normalized radii at which the source and the collimator are set.

2 DJ User's Guide

The present guide corresponds to the program version dated April 15 1998.

To run DJ with input data from file `fname`, type:

`dj fname`

If no `fname` is specified, then DJ reads input from file `djin` which must be present.

2.1 *DJ Input Files*

The file `fname` contains input parameters, flags specifying the kind of calculation and printout, and one or two input tables containing locations and angles of rotation of pairs of opposing jaws (everywhere in the text by "jaw parameters" we understand the parameters of the pair).

An optics file contains the lattice functions of the collimation beam line – parameter `optfilename` in `djin`). Both MAD OPTICS format [3], or a DIMAD-output format are accepted. DJ reads from `optfilename` the lattice section extending from marker BEGCOL to marker ENDCOL, which markers must be present, and performs a cubic-spline interpolation with the horizontal tune advance μ_x as independent variable. Creation of the MAD optics file is normally preceded by the SPLIT command, so the DJ results can be tested by taking different values of the SPLIT parameter "`fraction`". Our experience shows that splitting all elements including drifts into 3 to 5 parts is sufficient to find the first three digits of the maximum surviving amplitudes and that the computation time is roughly independent of the value of `fraction`. An example MAD script is given in the Appendix.

2.2 *How to use DJ*

To calculate the surviving amplitudes for a **fixed set of jaws** the user sets flag `iopt` to 0 and specifies the locations and angles of the primary jaws in file `djin` and these of the secondary jaws in either `djin`, or `input-sec-jaw-tab`.

The range of values of the relative momentum deviation δ, for which the maximum amplitudes are calculated, is controlled by the variables `deltamin`, `deltastep` and `deltmax`.

The set of halo sources on the borders of the primary jaws is specified by the parameters `n1, np` and `jawlength`.

The following actions take place in the case `iopt`=0.

1) primary and secondary jaws are installed in the lattice with locations and rotation angles α_i, μ_{xi} read from `prim-jaw-table` and `input-sec-jaw-table`;

2) a set of point-like halo sources is generated along the borders of the primary jaws;

3) the maximum surviving halo amplitudes $A_{max}(\delta)$, $A_{x,max}(\delta)$ and $A_{y,max}(\delta)$ are calculated.

The maximum time needed for this calculation is 1-2 seconds.

Optimization of the secondary jaws is done for `iopt`> 0. The following actions take place in this case:

1) the primary jaws are installed in the beam line with α_i and μ_{xi} taken from the `prim-jaw-table`;

2) a set of sources is generated;

3) The minimizer routine SIMANN is called `iopt` times (the minimization method is Simulated Annealing (SA)) with minimized object $F = w_1 * A_{max} + w_2 * A_{x,max} + w_3 * A_{y,max}$.

Each SA call uses as a starting point a new randomly generated `input-sec-jaw-table` , thus it produces a different `output-sec-jaw-table`. All output tables however correspond to roughly the same F – with an accuracy of the order of `eps`. Some proof to this basic property is suggested in Chapter 3, where it is shown that for a given lattice and a fixed set of sources the minimization task has many solutions, but they all correspond to the same A_{max}. Since all secondary jaw distributions found in this way are equivalent from the point of view of A_{max}, the user can choose the one which does not cause conflicts with the rest of hardware. Finding all solutions corresponding to a given A_{max}(or F) is only possible of the total tune interval available for secondary jaws $\mu_{x,\mathtt{endcol}} - \mu_{x,\mathtt{begsec}}$ is sufficiently large.

The cpu time needed depends on the number of secondary jaws and on the total number of sources.

2.3 *DJ Input Format*

The file `djin` has the following structure:

```
optfilename
iopt   delta   n1  n2  emitt DXN
iprint deltastep deltmax
w1 w2 w3
nprjaws  np  jawlength
prim-jaw-table
nsjaws begsec iseed eps
input-sec-jaw-table
```

Parameter definitions

`optfilename` — the name of the MAD OPTICS file. This name must begin with "opt", or "OPT". Two markers must be present in the lattice to denote the starting point (marker "BEGCOL") and the end point (marker "ENDCOL") of the collimation section. Use of the SPLIT command is recommended.

`iopt` — optimization flag

- 0 — no minimization is done. $A_{max}(\delta)$, $A_{x,max}(\delta)$ and $A_{y,max}(\delta)$ are calculated using the `input-sec-jaw-table`.
- > 0 — the minimizer routine SA is called `iopt` times. The independent variables are:
  $0 < \alpha_i < 180^o$ and $\mu_{x,\texttt{begsec}} < \mu_{xi} < \mu_{x,\texttt{endcol}}$.
  The minimized object function is
  $F = w_1 * A_{max} + w_2 * A_{x,max} + w_3 * A_{y,max}$
  calculated for δ=`delta`.
  Before each SA run the `input-sec-jaw-table` is randomized, so the run produces different `output-sec-jaw-table` with, however, roughly the same F.
  The resultant `iopt` output tables are stored in file `out-sec-jaw-tab`. By simply renaming this file to `input-sec-jaw-tab` the user can use it as input to DJ (see below `nsjaws` < 0) The resultant `iopt` F values are stored in file `out-F`

`delta` — δ – relative momentum deviation with respect to the reference particle `n1(n2)` — (in σ units) aperture at which the primary(secondary) jaws are set (also half-distance between the two jaws in a pair)

`emitt` — emittance in $m.rad$. Using some dummy value will not affect any results except tracking. `In demo1.in` we use the LHC emittance.

`DXN` — The maximum normalized dispersion value around the ring $D_x/\sqrt{\beta_x}$ in $\sqrt{m}$. Using some dummy value will not affect the result. This quantity is only used when printing the halo extents in order to compare the horizontal arc aperture and $A_{x,max}$.

`iprint` — print flag

- 0 — basic printout; printed are $A_{max}(\delta)$, $A_{x,max}(\delta)$ and $A_{y,max}(\delta)$ for the following δ:
  $0 < \delta <$`deltmax` if `deltstep`$\neq 0$
  δ=`delta` if `deltstep`$= 0$

- -1 — the source points for all δ are stored in output file `sources.out`. The twiss functions after spline are written in file `twspl.dat`

- 1 — the code prints also input to and output from the SA routine. .

- 2,3,4 — the print flag of the minimization routine SIMANN is set to `iprint` $- 1$. By increasing `iprint` the user can follow in more details the optimization process (see for details the comments in SIMANN). The printout might be rather lengthy.

`deltstep`
`deltmax` — see `iprint`

`w1 w2 w3` — weights used in optimization; see `iopt`

`nprjaws` — number of rows in the `prim-jaw-table`

`np` — number of source points $P = (x_0, y_0)$ per each of the two primary jaws in a pair.
In the case `iopt`=0 and `iprint`=2 the source points for all `delta` are stored in output file `sources.out`

`jawlength` — (in σ units) length of the primary jaw over which sources are distributed
If `jawlength` =0 then it is assigned a value $n_1 tg(\pi/4)$, i.e. the primary jaw is the side of an octagon

`prim-jaw-table` — angles α_i in degrees and tune advances μ_{xi} with respect to marker BEGCOL of `nprjaws` primary jaws. The format is:
jaw_i, α_i, μ_{xi}, $i = 1, ...,$`nprjaws` .

jaw_i is some arbitrary jaw number. Jaws with negative jaw numbers are skipped (use this to easily remove jaws from a table).

`nsjaws` — number of rows in the `input-sec-jaw-table`.
If `nsjaws` < 0 then DJ reads |`nsjaws`| rows of this table from file `input-sec-jaw-tab`.

`begsec` — $\mu_{x,\texttt{begsec}}$; see `iopt`

`input-sec-jaw-table` — (used only if `iopt>0` and `nsjaws` > 0) angles α_i in degrees and tune advances μ_{xi} with respect to marker BEGCOL of `nsjaws` secondary jaws. It has the same column format as the `prim-jaw-table`

`seed` — seed for SA

`eps` — error tolerance for termination of SA (a safe choice is `eps` $=10^{-5}$)

3 Simple collimation scheme theory. The role of the lattice tune split.

The content in this section follows an unpublished 1997 note [4]. We also assume the coordinate system to be normalized at all points along the beam line and all collimators to be circular (the case of jaws will be briefly considered at the end of the section). The primary collimator has a radius R_0 and the secondary collimators have radius $R > R_0$. As before, to analyze the effect of the collimation system on the halo, particles are generated from each point x_0, y_0 on the edge of the primary collimator with all possible forward angles. The secondary collimators are assumed to stop the particles without scattering.

3.1 *The halo of the primary collimator*

The halo consists of particles with coordinates x_0, x_0', y_0, y_0', on the circle $x_0^2 + y_0^2 = R_0^2$ and with $-\infty < x_0' < \infty$,$-\infty < y_0' < \infty$ as illustrated in the following figure:

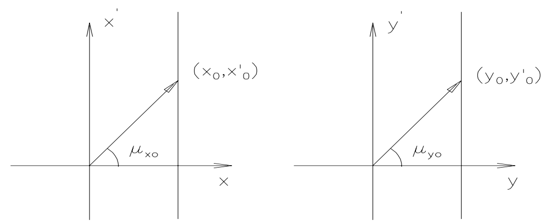


Figure 1:

Since the motion following the primary collimator in the normalized phase plane is circular, the trajectories are described by:

$$x = A_{x0} \cos{(\mu_{x0} - \mu_x)}, \quad \text{where} \quad A_{x0} = \sqrt{x_0^2 + x_0'^2} \tag{2}$$

and similar expressions for the y-phase plane. The phase advances μ_x, μ_y are assumed to have value zero at the primary collimator.

The four dimensional emittance of the particles in the halo produced by the primary collimator is $A = \sqrt{A_{x0}^2 + A_{y0}^2}$ and we shall use the symbol $\mathcal{A}$ to denote the function $(A/R)^2$:

$$\mathcal{A}(\mu_{x0}, \mu_{y0}) = \frac{(x_0/R)^2}{\cos^2 \mu_{x0}} + \frac{(y_0/R)^2}{\cos^2 \mu_{y0}} \tag{3}$$

3.2 *The Halo Emittance Function*

The source coordinates x_0,y_0 are assumed constant and both nonzero and we analyze the shape of the surface $\mathcal{A}$ as a function of the variables μ_{x0}, μ_{y0}. The function is always strictly positive and reaches a minimum when the cosine functions are equal to one, i.e. for $\mu_{x0} = 0, \mu_{y0} = 0$, with value R_0^2/R^2 which is smaller than 1 by the definition of the collimator radii. The cosine functions are squared, so $\mathcal{A}$ has periodicities π in both coordinates. We therefore limit our study to the square defined by $-\frac{\pi}{2} < \mu_{x0}, \mu_{y0} < \frac{\pi}{2}$. The surface $\mathcal{A}$ looks like a bowl that is asymptotic to a square chimney, Fig 2 (right) .

3.3 *The secondary collimator*

A secondary collimator is situated at phase advances μ_x, μ_y. The particles that originate from point x_0, y_0 on the edge of the primary collimator have the following coordinates at the secondary collimator:

$$x = A_{x0} \cos(\mu_{x0} - \mu_x); \quad y = A_{y0} \cos(\mu_{y0} - \mu_y) \tag{4}$$

All particles for which $(x^2 + y^2)/R^2$ is greater than one will be stopped by the collimator. So we define the following function associated with the secondary collimator:

$$\mathcal{C}(\mu_{x0}, \mu_{y0}, \mu_x, \mu_y) = \frac{(x_0/R)^2}{\cos^2 \mu_{x0}} \cos^2(\mu_{x0} - \mu_x) + \frac{(y_0/R)^2}{\cos^2 \mu_{y0}} \cos^2(\mu_{y0} - \mu_y) \tag{5}$$

Particles with $\mathcal{C} > 1$ are stopped by the secondary collimator.

The $\mathcal{C}$ function has the same periodicity and same asymptotes as $\mathcal{A}$. It is always positive and has only one zero at $\mu_{x0} = \pm\frac{\pi}{2} + \mu_x$, $\mu_{y0} = \pm\frac{\pi}{2} + \mu_y$ where it is tangent to the reference plane ($\mathcal{C}$=0). The plus sign is used when the μ value is negative.

The function $\mathcal{C}$ looks like a bowl distorted is a non-symmetrical fashion, Fig 2 (right). It is asymptotic to the same square chimney to which $\mathcal{A}$ is asymptotic. The amount of distortion depends on the location of the point μ_x, μ_y. The $\mathcal{C}$-function is everywhere below the function $\mathcal{A}$ except at the point $\mu_{x0} = \mu_x$,$\mu_{y0} = \mu_y$, where they are tangent.

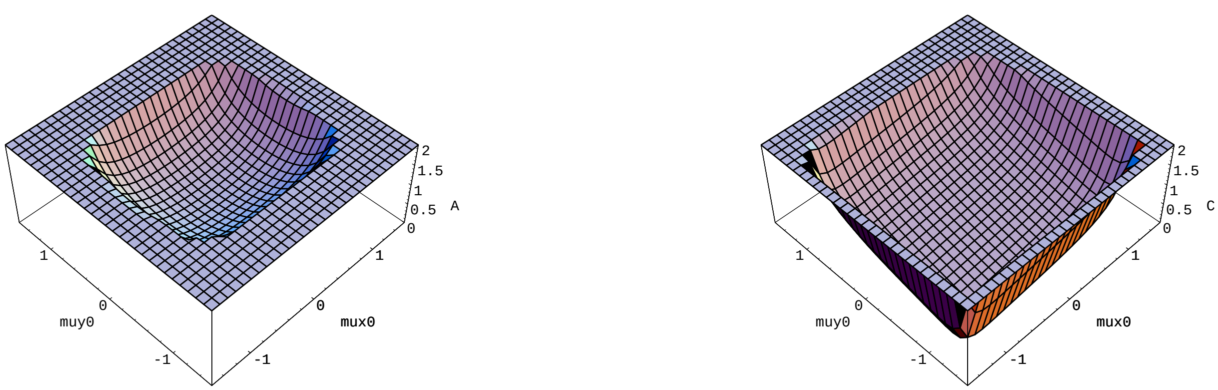
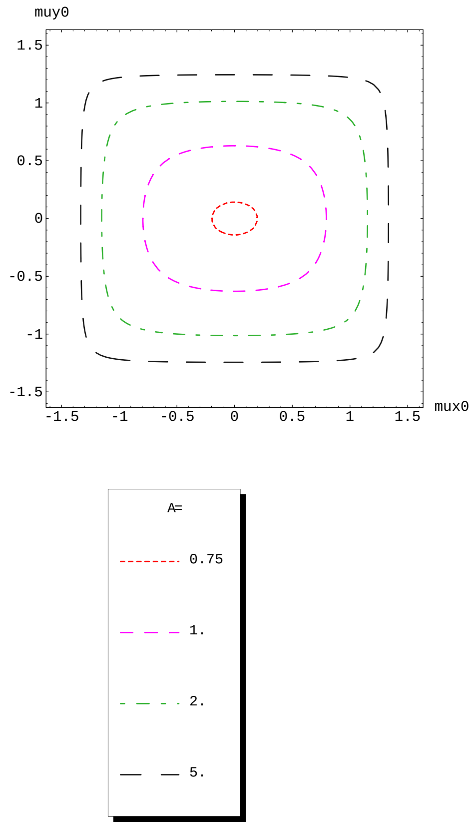


Figure 2 (a): Functions $\mathcal{A}(\mu_{x0}, \mu_{y0})$ (left) and $\mathcal{C}(\mu_{x0}, \mu_{y0}, \mu_{x1}, \mu_{y1},)$ (right) on the square $-\frac{\pi}{2} < \mu_{x0}, \mu_{y0} < \frac{\pi}{2}$ and in the range 0, 2. An optimum circular collimator location $\mu_x = \mu_y = 0.535$ is the point on the diagonal at which C is tangent to A, i.e. one of the two intersection points of the diagonal and the contour A=1.



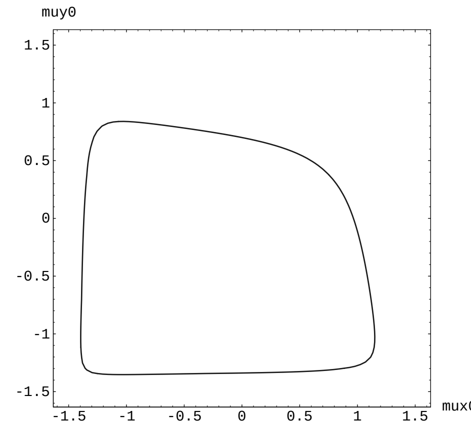


Figure 2 (b): Contours A=0.75, 1, 2, 5 (left) and contour C=1 (right).

3.4 *Collimation analysis*

The functions $\mathcal{C}$ and $\mathcal{A}$ represent two different physical entities: $\mathcal{C}$ is an area in the x-y plane and $\mathcal{A}$, an emittance in the $x - x', y - y'$ phase space. Since they are defined in the same domain, have the same periodicity and both are dimensionless, we may compare them directly. We recall that $\mathcal{A} > \mathcal{C}$ and construct a cylinder based on the contour $\mathcal{C}$=1 that extends to the $\mathcal{A}$ surface. The maximum value of the intercepted $\mathcal{A}$ function gives the maximum emittance of particles not intercepted by the collimator. To visualize the situation more easily, we will draw contours of the $\mathcal{A}$ function together with the contour $\mathcal{C}$=1, Fig 4. The plot determines the maximum escaping particle emittance – this is the maximum $\mathcal{A}$-contour value which can be found within the contour $\mathcal{C}$=1. The contour $\mathcal{C}$=1 (Fig. 3, right) is non-symmetrical and tends to be displaced towards the coordinates of the zero of the function $\mathcal{C}$.

Figures 2 and 3 represent the effect on the halo of a single collimator situated at $\mu_{x1} = \mu_{y1}$. The source coordinates x_0, y_0 are set by the relations $\frac{x_0}{R} = 0.5$, $\frac{y_0}{R} = 0.7$, which correspond to the value $\frac{R}{R_0} = 0.86$. The collimator is set at the point for which C is tangent to A – this is the solution of $A(\mu, \mu) = 1$, i.e. $\mu = 0.535$.

On Figure 4, along with the collimator positioned at (μ_{x1}, μ_{y1}), three more collimators

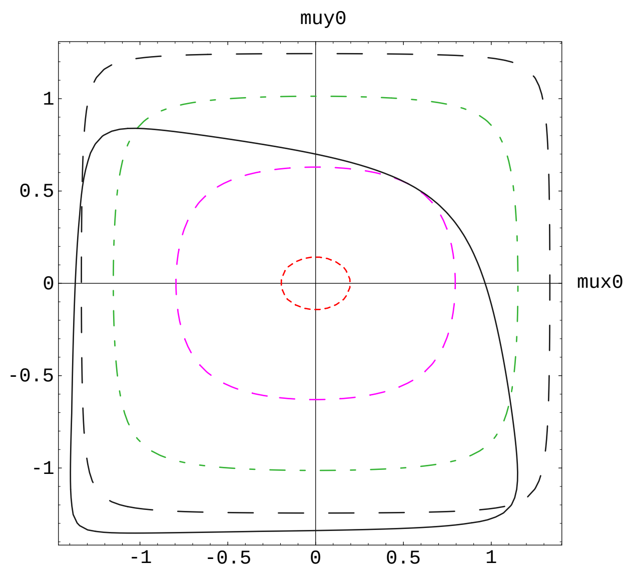


Figure 3: C-contour representing a single circular collimator.

are set at $(-\mu_{x1}, -\mu_{y1})$,$(\mu_{x1}, -\mu_{y1})$ and $(-\mu_{x1}, \mu_{y1})$. The intersection of the inside portion of all four contours $\mathcal{C}$=1 gives the set of particles escaping the system. The corresponding maximum $\mathcal{A}$ is $\mathcal{A}_{max} = 1.3$, so the maximum amplitude of escaping particle is $A_{max} = \sqrt{1.3}\ R$.

3.5 Tune split and optimum phase conditions. "Pipe".

Of the four collimators above, two have no phase shift between the x and y plane. The other two have phase split of $\pi/2$ radians. It is clear from the plot that *there is definitely a need for creating phase split* at certain points of the collimation section. If one of the secondary collimators is omitted the maximum value becomes $\mathcal{A}_{max} > 2$.

The equation $\mathcal{A} = 1$, or:

$$\frac{(x_0/R)^2}{\cos^2\mu_x} + \frac{(y_0/R)^2}{\cos^2\mu_y} = 1. \tag{6}$$

determines the optimum phase advance program for locating collimators in the following sense: as the number of collimators is increased, their phases approach the curve (6). In the asymptotic case $N = \infty$ all collimator phases satisfy $\mathcal{A} = 1$ and the maximum surviving combined amplitude is $A = R$ (case of a "pipe"). Eqn.(6) is the 2D analogue of the well known phase criterion for collimation in a plane: $\cos\mu = R_0/R$.

Determination of the actual maximum emittance, escaping the secondary collimators must be done by using graphs for each set of coordinates x_0, y_0. Also in real life jaw-collimators are used instead of circular ones, so we have to replace the $\mathcal{C}$=1 contour by

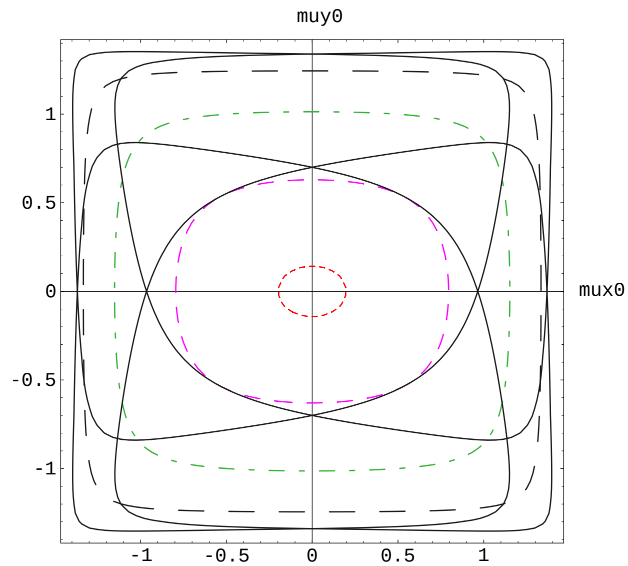


Figure 4: C-contours representing four circular collimators. A_{max} is defined by the maximum A-contour found inside the overlap area.

jaw-collimator contours $\mathcal{J} = \pm 1$. The jaw-collimator function (for a pair of jaws) is:

$$\mathcal{J}(\mu_{x0}, \mu_{y0}, \mu_x, \mu_y) = \frac{(x_0/R)}{\cos \mu_{x0}} \cos(\mu_{x0} - \mu_x) \cos\alpha + \frac{(y_0/R)}{\cos \mu_{y0}} \cos(\mu_{y0} - \mu_y) \sin\alpha \qquad (7)$$

Particles with $-1 > \mathcal{J} > 1$ are stopped by the collimator; α is the angle of rotation of the jaw around the beam axis.

The case of jaws can only be solved by computer simulation, as in DJ. On plots similar to Fig. 4, the curves $\mathcal{J} = \pm 1$ look more distorted than the circular collimator ones, but the basic property remains the same – for a large number of optimized jaws the curves $\mathcal{J} = \pm 1$ enclose tightly the contour of optimum phases $\mathcal{A} = \pm 1$.

Apparently, there are many combinations of contours $\mathcal{J} = \pm 1$ (jaw distributions) which result in the same $\mathcal{A}_{max}$, i.e. the same maximum amplitude of surviving particles A_{max}.

References

[1] D.I. Kaltchev et al., Proc PAC97, (Vancouver, 1997) (in print) and CERN LHC Proj.Rep 134,1997.

[2] D.I. Kaltchev et al., Proc EPAC98, (Stockholm, 1998)

[3] H. Grote, F.C. Iselin, The MAD Program. User's Reference Manual, CERN/SL/90-13(AP)

[4] Dobrin Kaltchev and Roger Servranckx, Simple Collimation Scheme Theory, TRI-UMF, UBC, unpublished note.

[5] T. Risselada, Optical Requirements for an LHC Cleaning insertion with Elliptical Collimators, SL Note 95-67, 1995.

4 Appendix

The flowing MAD script splits all elements in the beam line and then creates an OPTICS file `optfilename` with the column structure required for DJ:

```
select,flag=optics,range=#s/#e
split,name=some-name,fraction=0.2,range=#s/e
split,name=somename,fraction=0.4,range=#s/e
split,name=somename,fraction=0.6,range=#s/e
split,name=somename,fraction=0.8,range=#s/e
optics,beta0=...,column=name,mux,muy,s,betx,bety,alfx,alfy,dx,dpx
file="optfilename"
return
```

Demo 1

In this example we use the optics from file `optics` to calculate the maximum escaping halo amplitudes for an on-momentum beam. We have chosen an arbitrary set of 5 secondary pairs of jaws.

The set of sources are located on the tips of an octagon with four pairs of opposing sides at mux = 0.0, 0.001, 0.002 and 0.003. During calculation, the coordinates of the sources are stored in `sources.out` and the splined twiss function are stored in file `twspl.dat`.

Let's first list the input file `demo1.in`:

```
optics
0 0.0   6 7 7.82e-9 0.16
-1 0.00  0.005
1. 0. 0.
4 1 0.
        1       90.0      0.0          4 primary pairs jaws;
        2       0.0       0.01         the sources are tips
        3       135.000   0.02         of an octagon
        4       45.000    0.03
5  0.001  999  1.e-5
        1       12.34     .12         6 secondary pairs
        2      123.45     .23         jaws with some arbitrary
        3       34.56     .34         locations and angles
        4      145.67     .45
        5       56.78     .56
```

then we run DJ:

```
./dj demo1.in
 ++++++ Input file is demo1.in
 ****
 ++++++  Reading lattice functions from file: optics
  Marker BEGCOL is at s=   38.9124 m,  mux=     .07885
  Marker ENDCOL is at s=  359.1120 m,  mux=     .67305
  mux_endcol - mux_begcol =  .59420

 BEGIN SPLINE using   412 lattice locations
 END   SPLINE


  jaw alfa[deg]     mux        muy        s[m]      s_begcol[m]  betx       bety        eta      eta'     ( + )^1/2

 primary jaw table:
   1   90.000    .000        .000        38.912       .000     43.780    319.819       .152     -.013      .1527
   2     .000   .1000E-01  .1260E-02    41.547      2.634     40.276    345.527       .151     -.022      .1527
   3  135.000   .2000E-01  .2339E-02    43.979      5.067     37.355    371.342       .149     -.032      .1527
   4   45.000   .3000E-01  .3292E-02    46.263      7.351     35.512    390.891       .147     -.041      .1527
```

```
 input secondary jaw table:
   1   12.340   .1200      .1254E-01    68.915    30.002    59.261   327.863      .102     -.113      .1527
   2  123.450   .2300      .2743       184.919   146.007   100.707   111.602      .006     -.153      .1527
   3   34.560   .3400      .3052       216.606   177.694    24.756   239.908     -.092     -.122      .1527
   4  145.670   .4500      .3170       234.388   195.476    35.344   214.708     -.149     -.035      .1527
   5   56.780   .5600      .5721       332.081   293.169   224.049    96.185     -.137      .068      .1527

   delta    A_max      Ax_max      Ay_max      F
    .00000  12.520      10.968      11.468      12.520
```

and list the sources (notice that only half of the vertices of the octagon are actually used):

```
#>cat sources.out
 delta=     .00000
             x0              y0
    1   -.2485281E+01    .6000000E+01
    2    .6000000E+01    .2485281E+01
    3   -.6000000E+01    .2485281E+01
    4    .2485281E+01    .6000000E+01
```

Demo 2.

Here A_{max} is minimized for $\delta = 0$ using 5 secondary jaws.

Four independent runs are made. Each run begins with the message "CALL SA with new random input-sec-jaw-table".

The four `out-sec-jaw-table`s are stored in file `out-sec-jaw-tab`.

```
#> cat demo2.in
4 0.0   6 7 7.82e-9 0.16
0 0.00  0.005
1. 0. 0.
4 1 0.
        1       90.0      0.0
        2       0.0       0.01
        3       135.000   0.02
        4       45.000    0.03
5  0.05  999  1.e-5
        1       12.34     .12
        2      123.45     .23
        3       34.56     .34
        4      145.67     .45
        5       56.78     .56
```

```
#./dj demo2.in

++++++ Input file is demo2.in
 ****
 ++++++  Reading lattice functions from file: optics
  Marker BEGCOL is at s=   38.9124 m,  mux=     .07885
  Marker ENDCOL is at s=  359.1120 m,  mux=     .67305
  mux_endcol - mux_begcol =  .59420

 BEGIN SPLINE using   412 lattice locations
 END   SPLINE


  jaw alfa[deg]    mux       muy       s[m]     s_begcol[m]  betx      bety       eta      eta'     ( + )^1/2
```

```
 primary jaw table:
   1   90.000    .000       .000        38.912      .000    43.780   319.819      .152     -.013      .1527
   2     .000   .1000E-01  .1260E-02    41.547     2.634    40.276   345.527      .151     -.022      .1527
   3  135.000   .2000E-01  .2339E-02    43.979     5.067    37.355   371.342      .149     -.032      .1527
   4   45.000   .3000E-01  .3292E-02    46.263     7.351    35.512   390.891      .147     -.041      .1527

 ---------------------------------------------
BEGIN SA minimization of F for delta=  .00000
 sec. jaws are generated in mux interval:    .05000 < mux <    .59420
 ---------------------------------------------
 CALL SA with new random input-sec-jaw-table.
 before SA F =    .4018535E+02
 output secondary jaw table:
   1  164.040   .2344      .2779       187.536   148.623    90.727   120.022      .002     -.153      .1527
   2   94.834   .1952      .1661       145.134   106.221   334.187    35.886      .039     -.148      .1527
   3   91.666   .3583      .3070       219.361   180.449    23.370   247.483     -.106     -.110      .1527
   4  180.000   .3784      .3089       222.279   183.367    23.092   250.750     -.119     -.096      .1527
   5   27.559   .2296      .2740       184.659   145.746   101.734   110.789      .007     -.153      .1527
 after SA F=   .1027737E+02

   delta    A_max       Ax_max      Ay_max       F
    .00000  10.277      8.8889      8.1442      10.277
 ---------------------------------------------
 CALL SA with new random input-sec-jaw-table.
 before SA F =    .1857058E+02
 output secondary jaw table:
   1  132.974   .2730      .2947       202.966   164.054    45.382   178.300     -.035     -.149      .1527
   2   23.246   .3171      .3026       212.800   173.888    28.523   223.169     -.074     -.134      .1527
   3  127.881   .1986      .1931       151.639   112.727   285.512    41.557      .036     -.148      .1527
   4   77.210   .2089      .2399       166.668   127.755   188.758    64.689      .027     -.150      .1527
   5   16.837   .2317      .2758       185.989   147.076    96.547   114.993      .005     -.153      .1527
 after SA F=   .1031126E+02

   delta    A_max       Ax_max      Ay_max       F
    .00000  10.311      9.4881      9.9983      10.311
 ---------------------------------------------
 CALL SA with new random input-sec-jaw-table.
 before SA F =    .2713478E+02
 output secondary jaw table:
   1  144.510   .3040      .3008       210.327   171.414    31.886   211.293     -.063     -.139      .1527
   2  137.645   .1937      .1510       141.801   102.889   355.464    34.517      .041     -.147      .1527
   3   33.531   .3094      .3016       211.380   172.467    30.381   216.305     -.067     -.137      .1527
   4   89.625   .2199      .2627       177.580   138.668   132.232    90.256      .016     -.152      .1527
   5   40.216   .1929      .1434       140.157   101.245   363.008    34.395      .041     -.147      .1527
 after SA F=   .1012693E+02

   delta    A_max       Ax_max      Ay_max       F
    .00000  10.127      9.5646      9.6076      10.127
 ---------------------------------------------
 CALL SA with new random input-sec-jaw-table.
 before SA F =    .1499972E+02
 output secondary jaw table:
   1   13.127   .3424      .3055       216.972   178.059    24.514   241.095     -.094     -.120      .1527
   2  128.745   .2682      .2935       201.542   162.630    48.601   172.300     -.030     -.150      .1527
   3    9.810   .2207      .2638       178.247   139.334   129.153    92.057      .015     -.152      .1527
   4   76.880   .2189      .2612       176.733   137.820   136.208    88.006      .017     -.152      .1527
   5   95.212   .1918      .1317       137.622    98.710   369.730    34.993      .042     -.147      .1527
 after SA F=   .1018514E+02

   delta    A_max       Ax_max      Ay_max       F
    .00000  10.185      8.8251      9.3803      10.185

#cat out-object
F =   .10277365E+02 Nsjaws=   5 Np =   1
F =   .10311263E+02 Nsjaws=   5 Np =   1
F =   .10126934E+02 Nsjaws=   5 Np =   1
F =   .10185141E+02 Nsjaws=   5 Np =   1
```

```
#cat out-sec-jaw-tab
     1          164.03981          .23435786          .27792855
     2          94.833532          .19520874          .16613151
     3          91.665683          .35828755          .30700599
     4          180.00000          .37836497          .30886814
     5          27.559342          .22959110          .27395700
     1          132.97439          .27301126          .29474866
     2          23.246113          .31706893          .30259887
     3          127.88055          .19856045          .19306965
     4          77.209527          .20887148          .23987552
     5          16.836752          .23172702          .27583224
     1          144.51050          .30399832          .30078420
     2          137.64465          .19367284          .15099844
     3          33.530788          .30938635          .30156891
     4          89.625403          .21987217          .26268187
     5          40.216281          .19294479          .14339935
     1          13.126821          .34235720          .30545071
     2          128.74525          .26818137          .29345466
     3          9.8098208          .22068384          .26384579
     4          76.880022          .21886744          .26116832
     5          95.211526          .19184440          .13174413
```

Demo 3. Here we compute the off-momentum maximum amplitudes for the first of the 5 distribution tables generated in Demo 2. The off-momentum halo is only defined for $\delta < \delta_c \equiv x_0/\eta_0$ (or δ_{max}; see[1]); η_0 is the normalized dispersion at primary. In DJ, if $\delta > \delta_c$ for some x_0, then the corresponding source is simply skipped from the loop. If all sources are skipped, then the maximum amplitudes found are zero.

```
#cp out-sec-jaw-tab input-sec-jaw-tab
#cat demo3.in
optics
0 0.0   6 7 7.82e-9 0.16
0 0.001  0.005
1. 0. 0.
4 1 0.
        1       90.0      0.0
        2       0.0       0.01
        3       135.000   0.02
        4       45.000    0.03
-5  0.05  999  1.e-5                    !read 5 jaws from file

#./dj demo3.in
 ++++++ Input file is demo3.in
 ****
 ++++++  Reading lattice functions from file: optics
  Marker BEGCOL is at s=   38.9124 m,  mux=     .07885
  Marker ENDCOL is at s=  359.1120 m,  mux=     .67305
  mux_endcol - mux_begcol =  .59420

 BEGIN SPLINE using   412 lattice locations
 END   SPLINE


  jaw alfa[deg]    mux       muy       s[m]     s_begcol[m]  betx      bety       eta      eta'     ( + )^1/2

 primary jaw table:
   1   90.000    .000       .000       38.912      .000    43.780   319.819      .152     -.013      .1527
   2     .000   .1000E-01  .1260E-02    41.547     2.634    40.276   345.527      .151     -.022      .1527
   3  135.000   .2000E-01  .2339E-02    43.979     5.067    37.355   371.342      .149     -.032      .1527
   4   45.000   .3000E-01  .3292E-02    46.263     7.351    35.512   390.891      .147     -.041      .1527

 input secondary jaw table:
   1  164.040   .2344      .2779      187.536   148.623    90.727   120.022      .002     -.153      .1527
```

```
  2   94.834   .1952      .1661       145.134   106.221   334.187    35.886      .039     -.148      .1527
  3   91.666   .3583      .3070       219.361   180.449    23.370   247.483     -.106     -.110      .1527
  4  180.000   .3784      .3089       222.279   183.367    23.092   250.750     -.119     -.096      .1527
  5   27.559   .2296      .2740       184.659   145.746   101.734   110.789      .007     -.153      .1527

  delta    A_max       Ax_max      Ay_max       F
   .00000  10.277      8.8889      8.1442      10.277
   .00100  9.7834      8.0495      8.1442      9.7834
   .00200  8.9346      7.5195      7.6373      8.9346
   .00300  8.7442      7.3660      7.6373      8.7442
   .00400   .0000       .0000       .0000       .0000
   .00500   .0000       .0000       .0000       .0000
```

Demo 4. In the previous example `demo3.in`, the betatronic parts of particle amplitudes are A_{max}= 8.74 $A_{x,max}$= 7.37 at $\delta = 0.003$ (this is close to the edge of the LHC bucket). Here we decrease both these values by carrying minimization at $\delta = 0.003$ with mixed weights.

```
#cat demo4.in
optics
1 0.003   6 7 7.82e-9 0.16
0.0 0.001  0.005
1. 0. 1.
4 1 0.
        1       90.0      0.0
        2       0.0       0.01
        3       135.000   0.02
        4       45.000    0.03
-5  0.05  999  1.e-5

#./dj demo4.in
 ++++++ Input file is demo4.in
 ****
 ++++++  Reading lattice functions from file: optics
  Marker BEGCOL is at s=   38.9124 m,  mux=     .07885
  Marker ENDCOL is at s=  359.1120 m,  mux=     .67305
  mux_endcol - mux_begcol =  .59420

 BEGIN SPLINE using   412 lattice locations
 END   SPLINE


  jaw alfa[deg]    mux       muy       s[m]     s_begcol[m]  betx      bety       eta     eta'     ( + )^1/2

 primary jaw table:
   1   90.000    .000       .000        38.912      .000     43.780   319.819      .152     -.013      .1527
   2     .000   .1000E-01  .1260E-02    41.547     2.634     40.276   345.527      .151     -.022      .1527
   3  135.000   .2000E-01  .2339E-02    43.979     5.067     37.355   371.342      .149     -.032      .1527
   4   45.000   .3000E-01  .3292E-02    46.263     7.351     35.512   390.891      .147     -.041      .1527

 ---------------------------------------------
BEGIN SA minimization of F for delta= .300000E-02
 sec. jaws are generated in mux interval:    .05000 < mux <    .59420
 ---------------------------------------------
 CALL SA with new random input-sec-jaw-table.
 before SA F =    .5249091E+02
 output secondary jaw table:
   1  177.023   .3511      .3063       218.303   179.391    23.775   245.040     -.101     -.115      .1527
   2  150.117   .4669      .3202       238.578   199.666    44.194   194.373     -.152     -.019      .1527
   3   23.553   .5449      .4664       301.009   262.096   392.026    32.185     -.143      .055      .1527
   4   48.773   .4667      .3202       238.536   199.624    44.097   194.571     -.152     -.019      .1527
   5   41.774   .5681      .5853       341.638   302.725   159.213   138.207     -.133      .075      .1527
 after SA F=   .7941347E+01

   delta    A_max       Ax_max      Ay_max       F
```

.00000	17.409	13.149	14.100	22.402
.00100	13.645	9.3771	10.478	17.204
.00200	6.2075	5.0242	5.5766	8.3446
.00300	5.6539	4.6445	5.5766	7.9413
.00400	.0000	.0000	.0000	.0000
.00500	.0000	.0000	.0000	.0000