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FFADA, Final Focus Automatic Design and Analysis

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ABSTRACT

FFADA, for Final Focus Automatic Design and Analysis, is a program which allows the user to automatically design a generic final focus system corresponding to a set of a few basic beam and machine parameters for linear colliders. It also analyzes the main properties of the system in terms of momentum acceptance, collimation requirements and tolerances to field and misalignment errors.

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1 Introduction

Final focus systems must reduce the colliding beam to nanometer spot sizes at the interaction point (IP) of future linear colliders. With the transverse emittances foreseen, the corresponding β^* are in the range of 0.1–1mm. The main difficulty is then to correct the chromatic aberrations which dominate the linear optics as soon as the energy spread is larger than $\beta^*/\, l^*$, where l^* is the distance separating the IP from the last focusing quadrupole. A generic system, adapted from the SLC final focus optics [1] has been derived [2,3] which is free from 2nd and 3rd order aberrations. This solution is highly symmetric, provides several image points of the IP to monitor the beam, and contains the minimal number of four sextupoles (two non-interleaved pairs) for the chromatic correction. Its well adapted to designs where the beam energy spread is of the order of 0.1%. For energy spreads of the order of a percent, this generic solution, with additional sextupoles, can provide [4,5] a sufficient energy acceptance. It might also be used as a starting point to derive "odd dispersion" optics [6] where higher order aberrations are corrected.

The generic system is a telescopic transfer line which includes :

1. a matching telescopic transformer (MT) with π–phase advance, achieving the first demagnification of the beam with two quadrupole doublets;
2. a chromatic correction section (CCS); that is, a **+1**–transformer with 4π–phase advance including two sextupole pairs to cancel the second order chromatic aberrations generated mainly by the last focusing doublet;
3. a final telescopic transformer (FT) achieving the final demagnification of the beam to the desired spot size at the IP, with π–phase advance again and two quadrupole doublets.

In this paper we describe the computer program FFADA which allows one to design such a generic final focus system (FFS) corresponding to a given set of basic beam and machine parameters. This program generates a telescopic transfer line matched to second order, using TRANSPORT conventions. It further analyzes the following properties :

1. the energy acceptance of the system, both analytically and by tracking;
2. the beam envelopes in the last doublet down to the IP;
3. the effect of the synchrotron radiation in the last quadrupole doublet on the beam spot size [7] and on the collimation requirements;
4. the sensitivity of the luminosity to transverse position and angular offsets and dispersion of the beam at the IP;
5. the tolerances to misalignment and field errors of the magnets of the system.

The goal of this program is to automatize the lengthy and tedious operations needed to design and analyze a final focus system, in such a way that the user can rapidly optimize a system for a set of desired basic parameters, and modify or adapt it to further changes of some of the parameters.

The program can be ported on any computer working under UNIX SystemV with FORTRAN and the optics code MAD [8] available. Its structure is modular so that new functions can be easily included. The results are presented in a few output files associated with each modules, and in a series of output files for graphics presentation.

In Section 2 we describe the input parameters needed to run FFADA. Then, in Section 3, we describe each module composing the program and the corresponding outputs. For the sake of the presentation, we will consider an hypothetical design for a 'future linear collider', abbreviated to 'flc', so that, once the input parameter files are correctly created, the program can be launched by the command "`ffada flc`".

2 Description of the input parameters

The 'flc' final focus sytem derived by FFADA and its properties are essentially determined by two input data files. The final focus optics calculated by FFADA depends only on the optics and hardware parameters defined in the file 'flc.ffs', while the properties of the system, such as the bandwidth, the beam envelopes or the tolerances, are determined by the beam definitions given in the 'flc.beam'.

2.1 Beam parameters

The desired beam parameters at the IP are defined in 'flc.beam' (see Table 1). The transverse and longitudinal distributions are assumed Gaussian. The energy distribution, parametrized by

$$\rho(\delta, z) \propto \exp\left(-(\delta - \delta(z))^2/2\,\sigma_\delta^2\right) \tag{1}$$

is the superposition of an incoherent Gaussian distribution with σ_δ rms and a coherent z-dependent energy profile $\delta(z)$ where z denotes the longitudinal coordinate of the particle in the bunch. The coherent profile $\delta(z)$ describes the effect of the addition of the RF accelerating field and the longitudinal wakefield. If the incoherent energy spread σ_δ is small, the distribution amounts to a pure profile $\delta(z)$. On the contrary, if the profile is set to zero, the distribution is purely Gaussian. The energy profile $\delta(z)$ is selected by an integer option parameter `icase` such that:

1. `icase`= 0 : the profile $\delta(z)$ is set to zero and the energy distribution is purely Gaussian;
2. `icase`= 1 to 8 : eight different profiles $\delta_{\texttt{icase}}(z)$ can be defined by the user through the 10 coefficients of a 9th order polynomial fit in an auxiliary file 'wake.beams';
3. `icase`= 9 : the profile $\delta(z)$ is given point by point by the user, typically between $\pm 4\sigma_z$, in an auxiliary file 'delta.data';
4. `icase`= –1 : the profile is linear $\delta(z) = \alpha\, z/\sigma_z$ where σ_z is the bunch length. The factor α must be set by the user after the integer `icase` on the same line.

```
                        'FLC BEAM'

' Energy                             [GeV]      : '     250.

' Horizontal RMS at the IP           [nm]       : '     100.
' Vertical   RMS at the IP           [nm]       : '      10.

' Horizontal normalized emittance    [m]        : '     1.0e-6
' Vertical   normalized emittance    [m]        : '     1.0e-8

' Longitudinal RMS                   [mm]       : '     0.1
' Relative energy RMS                           : '     1.e-3
' Energy profile case [-1=linear, 0=nowake]     : '     1

' Bunch population                              : '     1.0e+10
' Repetition rate                    [Hz]       : '     1.0e+2
```

Table 1 Beam parameter definitions at the IP

2.2 Optics and hardware parameters

The optics, layout and hardware parameters of the final focus sytem which can be freely set are defined in ‘flc.ffs’ (see Table 2). Four of these parameters will, however, differ in the final focus system derived by FFADA, namely:

1. the total length of the FFS and the length of the first drift of the 2 telescopes which are the values for the thin lens solution first derived by FFADA. They are modified in the process of matching the thin lens solution to a thick lens one; and,
2. the length of the last quadrupole of the final telescope which is used as a starting value for the optimization of the final telescope [2]. This length l_Q can be initially set from the condition that the focal length of the last quadrupole is equal to the length of the last drift l^*, in such a way that $l_Q \simeq 1/K_1(Q)\, l^*$. If the starting value is too far from l_Q, a solution might not be reached for the final telescope.

The aperture diameter of the microvertex detector has of course no influence on the optics. It is used to evaluate the beam collimation requirements given the constraint that the beam-generated synchrotron radiation must not impact on the vertex detector.

```
                'Input parameters for FFS'

' Total length of the FFS                   [m]  : '  600.
' Total horizontal demagnification               : '   50.
' Total vertical   demagnification               : '  100.

                'Parameters of Final Telescope'

' Horizontal FT demagnification      XM = -R22   : '   10.
' Vertical   FT demagnification      YM = -R44   : '   20.
' Length of last drift                      [m]  : '    3.0
' Length of last but one drift              [m]  : '    0.35

' Polarity of last quadrupole                    : '   'D'
' Length of last quadrupole                 [m]  : '    1.1
' Pole-tip field of last doublet quads      [T]  : '    6.
' Aperture diameter of last doublet quads  [mm]  : '   48.

' Length of first drift                     [m]  : '    1.
' Length of first doublet quads             [m]  : '    0.3

                'Parameters of Matching Telescope'

' Polarity of last quadrupole                    : '   'D'
' Maximum pole-tip field                    [T]  : '    1.4
' Aperture diameter of last quad           [mm]  : '    4.
' Length of first drift                     [m]  : '    0.5

                'Parameters of Microvertex Detector'

' Aperture diameter                        [mm]  : '   30.
```

Table 2 Optics, layout and hardware parameters of the final focus system

3 Description of the program

As already mentionned, the command "`ffada flc`" starts the program interactively. A detailed output from each module composing FFADA is performed on the screen and the execution can be interrupted after any module. We will now describe these modules in the order in which they are executed. We will also describe the additional input required by some of them, and the output or graphics files generated by most of them. We will not mention the temporary files generated during the execution. The installation environment and running instructions are described in a "setenv" and a "README" file provided with the program.

3.1 TELE4: analytic derivation of a thin lens solution

This module generates an analytic solution for the 2 telescopes where the last quadrupole of each telescope is a *thick lens* as fixed by 'flc.ffs', while the first 3 are thin lenses. This solution is obtained by solving, for the given demagnifications, the 6 dimensional system obtained by expressing the 6 independent elements of the horizontal and vertical transfer matrices as functions of the strength of the 3 thin lenses and the length of the 3 following drifts, using the solution given in Ref.[9]. Once the total length of the telescopes is known, the CCS optics is scaled to match the total length of the FFS given in 'flc.ffs'.

The fact that an analytic solution is known for 2-doublet telescopes where the last quadrupole is already a thick lens, is crucial to the program. Indeed, in contrast with a solution with 4 thin lenses, such a solution can be automatically matched by computer to a thick lens telescope.

INPUT: In the course of the running, the user must provide a name for the FFS system. In the following we will assume that the user's answer is 'flc_ffs'.

OUTPUT: None.

GRAPHICS: None.

3.2 MAD: 2^{nd} order matching of the FFS and bandwidth calculation

This module calls the MAD program [8] in order to perform the following operations:

1. read the thin lens telescope optics generated above and the MAD input file 'ccs.mad' describing the optics of the CCS;
2. match the optics of the line (MT , CCS , FT) to first and second order, with thick elements;
3. plot layout, β–functions and dispersion;
4. plot the energy dependent β–functions at the IP;
5. store the matched FFS optics in a MAD file.

INPUT:

- a MAD file 'ccs.mad' describing the generic CCS optics is provided with the program. This file can be modified and even replaced by the user to describe another correction system. To ensure the coherence of the program, this sytem needs to have a +1–transfer matrix, and the chromatic aberrations must be corrected with two pairs of sextupoles called HS and VS. The total length of the system may still match the desired length by using the parameter 'LFOD' set by the program to 1/16 of the available length of the CCS.

OUTPUT:

- a MAD file 'flc_ffs.mad' describing the optics of the fully matched FFS,
- a MAD optics file 'flc_ffs.optics' listing the elements of the FFS.

GRAPHICS:

- a PostScript file 'flc_ffs.ps' containing a plot of the layout, the β–functions and the dispersion of the FFS, and a plot of the energy dependent horizontal and vertical β–functions $\beta^*(\delta)$ at the IP, from which the momentum bandwidth of the system can be deduced.

3.3 TRACK: tracking simulations

This module calls MAD to perform, in the background mode, tracking simulations of the FFS.

1. A fisrt simulation is made for 2 bunches of 10,000 particles distributed as defined by the file 'flc.beam'. The beam spot sizes and the luminosity are calculated from the resulting distributions.
2. A second set of simulations is made to further analyze the energy acceptance of the system. The energy distribution is assumed Gaussian for the 2 bunches. The spot sizes and luminosity are calculated for an increasing rms energy spread.

In both cases the pinch effect is neglected in the luminosity calculations.

This tracking module can also be activated with the DIMAD program [10]. However, this requires using a modified version of the DIMAD code in which beam energy distributions like in Eq.(1) can be generated and passed to the tracking routine. With the latest MAD versions (8.14 or later) as well as with DIMAD, the stochastic effect of synchrotron radiation in the magnets is taken into account.

INPUT:

- a file 'track.data' allows the user to modify the number of particles per bunch and the range of relative energy spread covered in the second set of simulations.

OUTPUT:

- a file 'flc_ffs.trackres' summarizing the results of the first simulation, with essentially the beam spot sizes at the IP and the luminosity obtained for beams as defined in 'flc.beam'.

GRAPHICS:

- a file 'track.tap' plotting the dependence of the beam spot sizes and luminosity on the Gaussian energy spread, as obtained from the second set of simulations.

3.4 DBLT: beam envelopes in the last doublet, collimation and Oide effect

This module calculates various quantities relevant to the last doublet optics and to the interaction region, namely:

1. the Twiss β and α functions and the beam envelopes from the last doublet down to the IP;
2. the beam collimation requirements arising from clearing the synchrotron radiation generated by the beam in the last doublet, through a vertex detector located at the IP, and through the opposing doublet with hyperbolic or circular aperture. The requirements which minimize the population of collimated particles, for a uniform distribution of halo, are given and used in the graphics output;

3. the Oide limit [7] for the horizontal and vertical spot sizes at the IP. The calculation is done both analytically [11] and by tracking with MAD (or DIMAD).

INPUT: None.

OUTPUT:

- a file 'flc_ffs.dbltres' summarizing the hardware and optics parameters relevant to the interaction region, the maximum extension of the beam, the collimation requirements and the Oide limits for the doublet.

GRAPHICS:

- two files 'alpha.tap' and 'beta.tap' plotting the Twiss α and β–functions in the last doublet;
- a file 'env.tap' plotting the 10-σ beam envelopes in the aperture of the last doublet;
- a file 'circ0.tap' plotting the radiated photon envelope in the circular aperture of the vertex detector;
- two files, 'circ.tap' and hyp.tap', plotting the radiated photon envelope in the circular or hyperbolic aperture of the exit face of the opposing doublet;
- two files 'oidex.tap' and 'oidey.tap' plotting the horizontal and vertical beam spot sizes at the IP with the synchrotron radiation effect in the last doublet taken into account, as a function of the linear spot size $(\epsilon\beta^*)^{1/2}$.

3.5 DIFFLUM: luminosity loss versus beam offset and dispersion at the IP

For head-on collision, the luminosity is at a maximum with respect to the beam offset, dispersion and coupling at the IP. This module calculates the second order derivatives of the luminosity with respect to the transverse position and angular offsets, the dispersion and its derivative of the two beams at the IP. The "hour-glass" effect is taken into account while the pinch effect is not. For Gaussian energy distributions the luminosity derivatives are given [12] by one dimensional integrals which are evaluated by a Gauss integration routine. For z-dependent energy distributions, like in Eq.(1), the integrals become two dimensional and a 2d Simpson method is used.

INPUT:

- a file 'accuracy.data' which allows the user to control the precision of the Simpson and Gauss integration routines used in the module.

OUTPUT:

- a file 'flc_ffs.diffres' recalling the beam parameters at the IP, the nominal luminosity expected for head-on collisions and listing the second order differentials of the luminosity.

GRAPHICS: None.

3.6 ERROR: magnet misalignment and field errors, tolerances

This module performs a detailed analysis of the effect of small 3d-displacements, 3d-rotations[1] and field errors of the quadrupole and sextupole magnets. These effects are translated to the beam centroid and beam matrix at the IP and analyzed in terms of relative beam offset at the IP, dispersion[2], spot size growth, waist shift and xy-coupling.

Then, restricting to the 2d-transverse misalignments, the loss of luminosity resulting from uncorrelated random motion of all magnets of the two FFS (except the last doublet) on the one hand, and fixed displacement of the quadrupoles of the two opposing doublets on the other hand, is calculated using the 2nd order derivatives derived in DIFFLUM. This analysis is then repeated with the assumption of a perfect steering correction of the beams at the IP. In the case of no steering, i.e. for uncorrected vibrations, the luminosity reduction arises mainly from the relative beam position offset. In the case where the offset is corrected, the reduction arises from the remaining dispersion, including that introduced by the two opposing steering kickers which are located at the first doublet of the last telescope.

INPUT: None

OUTPUT:

- a file 'flc_ffs.qsres' summarizing the number and the types of magnets included in the system, and checking the agreement between the transfer matrix as calculated from the MAD file 'flc_ffs.optics' which used to calculate the effect of errors, and the telescope matrix with the demagnifications initially set in the data file 'flc.ffs';
- 4 files, 'qs_x.res', 'qs_xp.res', 'qs_y.res' and 'qs_yp.res', giving the errors on the zeroth (beam centroid) and first (transfer matrix) order map of the FFS, resulting from transverse displacements (x & y) and rotations[1] (xp & yp) of each quadrupole and sextupole of the FFS;
- 3 files 'quad_z.res', 'quad_rot.res' and 'quad_k.res' giving the errors on the zeroth (beam centroid) and first (transfer matrix) order map of the FFS, resulting from longitudinal displacement (z), skew rotation (rot) and quadrupole gradient error (k) of each quadrupole of the FFS;
- a file 'flc_ffs.lumres' summarizing the quadratic dependence of the luminosity with respect to transverse misalignments of the quadrupoles and sextupoles with and without steering correction.

GRAPHICS: Several histograms display the effect of single magnet misalignments (quadrupoles or sextupoles) and field errors (quadrupoles) on the following quantities evaluated at the IP:

1. the luminosity:
    a. 'lum_off.tap' displays the loss of luminosity due to a magnet transverse displacement by half a beam spot size at the IP, $\sigma^*_{x,y}/2$;
    b. 'off_lum.tap' displays the magnet transverse displacement corresponding to a 1% luminosity loss;
2. the beam transverse offsets:
    a. 'off_off.tap' displays the ratio of beam to quadrupole transverse displacement;

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[1] For the rotations, the MAD definitions are used. In particular, the x and y–rotation axis are taken at the entrance of the magnet.

[2] Contrary to MAD conventions, the dispersion is defined w.r.t. x, x', y and y' and not to x, p_x/p_0, y and p_y/p_0.

3. the dispersion:
    a. ‘disp_off.tap’ displays the dispersion due to magnet transverse displacement;
    b. ‘disp_tilt.tap’ displays the dispersion due to magnet transverse rotation;
    c. ‘disp_z.tap’ displays the dispersion due to quadrupole longitudinal displacement;
    d. ‘disp_rot.tap’ displays the dispersion due to quadrupole skew rotation;
    e. ‘disp_k.tap’ displays the dispersion due to quadrupole gradient error;
4. the horizontal and vertical waist shifts:
    a. ‘waist_x.tap’ displays the waist shift due to magnet horizontal displacement;
    b. ‘waist_xp.tap’ displays the waist shift due to magnet horizontal rotation;
    c. ‘waist_z.tap’ displays the waist shift due to quadrupole longitudinal displacement;
    d. ‘waist_k.tap’ displays the waist shift due to quadrupole gradient error;
5. the horizontal and vertical spot size:
    a. ‘size_x.tap’ displays the spot size growth due to magnet horizontal displacement;
    b. ‘size_xp.tap’ displays the spot size growth due to magnet horizontal rotation;
    c. ‘size_z.tap’ displays the spot size growth due to quadrupole longitudinal displacement;
    d. ‘size_k.tap’ displays the spot size growth due to quadrupole gradient error;
6. the xy-coupling:
    a. ‘cplg_y.tap’ displays the coupling due to magnet vertical displacement;
    b. ‘cplg_yp.tap’ displays the coupling due to magnet vertical rotation;
    c. ‘cplg_rot.tap’ displays the coupling due to quadrupole skew rotation;

4 Conclusion and future developments

We have presented the first version of the program FFADA. Further developments are envisaged in the future, namely:

1. analyze the effect of misalignment and field errors of the dipole magnets;
2. include the dependence of the luminosity on the 4×4 transverse phase-space submatrix of the FFS transfer matrix (e.g. include coupling of x and y planes);
3. derive tolerances on the second and higher order field errors (sextupole and higher multipoles). This can be done by using the Lie Algrebraic method as in [13];
4. extend the application of the program to non-zero crossing angle;
5. interface the program with standard or widely distributed graphics software (GKS, Higz, TopDraw).

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