The STRUCT Program User's Reference Manual

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1 Introduction

The STRUCT computer program [1] performs particle tracking and interaction with material of collimators in synchrotrons and beam lines. Proton interaction with material of scattering elements (collimators) is performed using Fortran modules and procedure of MARS14 [2, 3] code. The GEANT code library is used for interactions of electrons with material of collimators and for synchrotron radiation generation in the magnetic elements of the beam line. All lattice components with their real strength and aperture restrictions are taken into account at the calculations. This Monte Carlo code, written in Fortran, allows performance analysis of already designed lattices, a simulation of the beam loss distribution along the accelerator and other tracking studies.

2 Reference system

The accelerator or beam line to be studied is described as a sequence of the beam elements placed sequentially along a reference orbit. The reference orbit is the path of a charged particle having the equilibrium momentum of the accelerator.

The reference orbit consists of a series of straight-line segments and the circular arcs. It is defined under the assumption that all elements are perfectly aligned and have a designed strength. The local s-axis (azimuth of accelerator) is the tangent to the reference orbit (Fig. 1). The two other axes are perpendicular to the reference orbit and have positive direction radially away from the accelerator center for the horizontal plane and up for the vertical plane.

Every element can be misaligned with respect to the reference system. This misalignment is described by horizontal and vertical displacement, by rotation around the reference orbit, and by rotation around local horizontal and vertical axes.

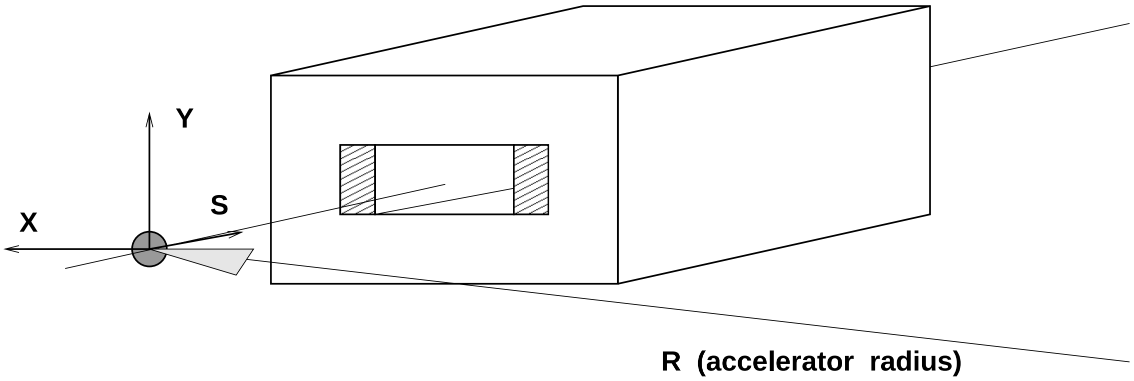

Figure 1: Local reference coordinate system.

Because of field errors, misalignments, momentum deviation, and nonlinearities, the real orbit of the particle does not coincide with the reference orbit.This orbit is described with respect to the reference orbit, using local reference system of coordinates.

3 Beam parameters

The main parameters of the beam applied to a beam definition are:

$\beta_{x,y}$ - transverse betatron amplitude function (m);

$\alpha_{x,y}$ - Twiss parameter;

$E_{x,y}$ - unnormalized transverse emittance ($mm \cdot mrad$);

The phase ellipse is defined by equation:

$$E_x = \frac{G}{\pi}\beta_x \left[X^2 + (\beta_x X' + \alpha_x X)^2\right] \quad , \qquad E_y = \frac{G}{\pi}\beta_y \left[Y^2 + (\beta_y Y' + \alpha_y Y)^2\right]. \tag{1}$$

particle betatron amplitude is a half-size of this ellipse:

$$X_{max} = (\beta_x E)^{1/2} \quad , \qquad X'_{max} = \left[E(1 + \alpha_x^2)\beta_x\right]^{1/2}. \tag{2}$$

$$Y_{max} = (\beta_y E)^{1/2} \quad , \qquad Y'_{max} = \left[E(1 + \alpha_y^2)\beta_y\right]^{1/2}. \tag{3}$$

Normalized transverse emittance ε is invariant of energy:

$$\varepsilon_{x,y} = E_{x,y}(\gamma^2 - 1)^{1/2}, \tag{4}$$

here γ is ratio of total particle energy to its rest energy.

4 Accelerator (beam line) elements aperture

The aperture definition is required for every lattice element. Code uses five types of aperture for all elements: uniform along the element with rectangular, circular, elliptical and trapezoidal (or pole rotated) cross section. The element may have different aperture along its length (so called "conical" aperture). In this case the element has a rectangular aperture at any cross section along the element length, and horizontal and vertical size of aperture is a linear function of length.

Trapezoidal (or pole rotated) aperture may be used, for example, for definition of pole shape of gradient magnets. It has parallel vertical jaws and horizontal jaws rotated with respect to the horizontal plane by angle $\pm\alpha$. Positive angle corresponds to a defocusing magnet.

A half-angles of cone for conical aperture (Fig. 2) and angle of trapezoidal aperture are defined in "subroutine apeel" and "subroutine apeel1" in the file "hdz.f".

A special conical aperture can be defined for collimators. Code of conical aperture in collimators is equal to 14. A half-angles of cone (in mrad) for conical aperture in collimators (Fig. 2) are read in the input line of the element, in the positions of element rotation in the horizontal and vertical planes. The cone aperture collimators are supposed to be positioned without transverse displacement and rotation.

The aperture is defined by a half-size of the hole in both directions (a and b) in the center of element. Aperture transverse position is defined by the position of element. Particles intercepted by the element are supposed to be lost for all elements except collimator, scraper and target, where particle can be lost or survive being outscattered after interaction with material of element. Coordinates of lost particles are tabulated in a file for possible later on use in the energy deposition calculations [2, 3].

5 Accelerator (beam line) lattice input format

Accelerator (beam line) lattice is described in STRUCT by a formatted sequence of all physical elements. Formated input was chosen because it is straightforward and very easy for changing and correction. 11 parameters of one lattice element are placed on one input line. Format of input line and procedure of lattice file construction is described below in a section "short instructions for using STRUCT code".

An example of STRUCT lattice input line is shown here. Each of lattice elements is described by parameters:

COD	FL	FK	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
22	0.0500	2.800	12.60	ES-def	18	5.280	-1.002	2.400	1.571	-1.050

Here

- COD - element code, listed below (100 signals end of lattice definition)

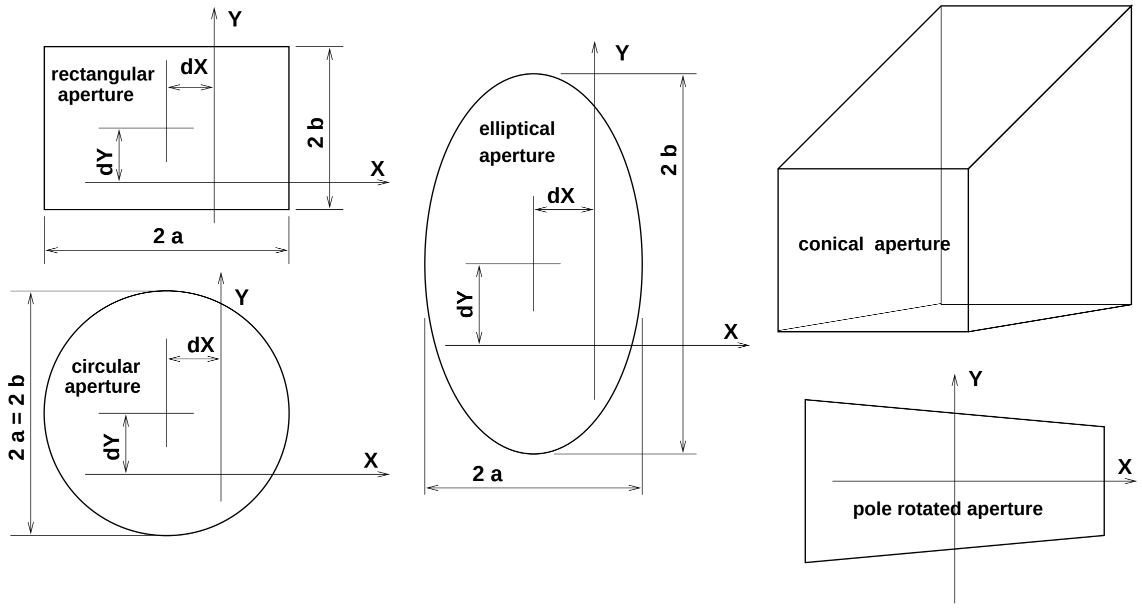

Figure 2: Geometry definitions for different types of aperture.

- FL - length of element (m)

- FKO - strength of element, $[1/m^2]$ for quads or magnetic field [KG] for bending magnets

- DFKO - deviation of strength for element. Strength $= FKO \cdot (1 + DFKO)$ for quadrupoles. For bending magnets usually DFKO=0. Bending magnets are used to put the circulating beam to the accelerator orbit. Particle coordinates are calculated with respect to this orbit. Because of that it is assumed that bending magnets do not bend equilibrium particles. If effect of element strength deviation from the designed value should be studied, the DFKO is equal to $\Delta B/B$ or $\Delta G/G$. DFKO=1 if magnet is used for particle bending from the accelerator orbit (kicker magnet, bump magnet, Lambertson and septum magnets, and some others).

- NAME - name of element

- CODAPE - aperture line number in the list of apertures, corresponding to "I" in the aperture definition. See section 8.2.1, subsection "accelerator aperture".

- DXO, DYO - center of element displacement from the reference orbit, (mm)

- FIO - rotation of element around longitudinal axis, (radians)

- PSIXO, PSIYO - angle between longitudinal axis and reference orbit in horizontal and vertical plane, (mrad)

6 Physical elements

6.1 List of STRUCT physical elements and element codes

1 - Straight section;

2 - Focusing quadrupole;

3 - Defocusing quadrupole;

4 - Horizontal bending magnet;

5 - Vertical bending magnet;

6 - Matrix (does not used now);

7 - Last matrix of the turn (does not used now);

8 - Inverted aperture;

9 - Target for protons;

10 - (does not used now);

11 - Code is used to multiply a group of elements;

12 - Scraper for protons;

13 - Collimator for protons;

14 - Octupole;

15 - Sextupole;

16 - Beamstrahlung (does not used now);

17 - Horizontal magnet with defocusing gradient;

18 - Collimator for electrons;

19 - Horizontal magnet with focusing gradient;

20 - Horizontal electrostatic deflector or septum-magnet;

21 - Vertical Lambertson magnet;

22 - Vertical electrostatic deflector or septum-magnet;

23 - Horizontal Lambertson magnet;

24 - RF acceleration;

26 - Bent crystal;

27 - Magnetized collimator for protons;

28 - Horizontal sector magnet;

29 - Vertical sector magnet.

6.2 Drift space

A drift space is a field-free region. Element code - 1. Input line example:

COD	L	FK	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
1	2.0500	0.000	0.00	DRIFT1	18	0.000	0.000	0.000	0.000	0.000

There is only one parameter: L - drift length (m). The transformation is presented by equation:

$$\begin{pmatrix} X_f \\ X'_f \\ Y_f \\ Y'_f \end{pmatrix} = \begin{pmatrix} 1 & L & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} X_i \\ X'_i \\ Y_i \\ Y'_i \end{pmatrix}, \tag{5}$$

where

X_f, X'_f - horizontal coordinate and angle $(mm, mrad)$;

Y_f, Y'_f - vertical coordinate and angle $(mm, mrad)$.

6.3 Quadrupole

For bending elements, the trajectory is bent by the magnetic field existing inside the elements. Element code - 2 for focusing (in horizontal plane) quadrupole, and - 3 for defocusing quadrupole. Input lines example are:

COD	L	k_o	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
2	2.0500	0.016	0.00	QUAD-1	18	0.000	0.000	0.000	0.000	0.000
3	2.0500	0.016	0.00	QUAD-2	18	0.000	0.000	0.000	0.000	0.000

There are two parameters to be specified:

L - quadrupole length (m);

k_o - quadrupole strength for on-momentum (equilibrium momentum) particle, (m^{-2}). $k_o = G/(B \cdot \rho)$. It can be calculated from magnet field gradient G and magnetic rigidity of the equilibrium trajectory $B \cdot \rho$, or equilibrium momentum P:

The quadrupole coefficient k depends on the particle momentum $\Delta P/P$.

$$k = \frac{G}{B \cdot \rho \cdot (1 + \frac{\Delta P}{P})}[m^{-2}] = \frac{G(kG/cm)}{0.33356405 \cdot P(GeV/c) \cdot (1 + \frac{\Delta P}{P})}. \tag{6}$$

The relationships between the coordinates from the entrance to the exit faces, are given by the transport matrix equations. For a quadrupole magnet, the equation is:

$$\begin{pmatrix} X_f \\ X'_f \\ Y_f \\ Y'_f \end{pmatrix} = M_{f,d} \times \begin{pmatrix} X_i \\ X'_i \\ Y_i \\ Y'_i \end{pmatrix}, \tag{7}$$

with matrix for quadrupole magnet focusing in the horizontal plane:

$$M_f = \begin{pmatrix} cos(L\sqrt{k}) & \frac{1}{\sqrt{k}} sin(L\sqrt{k}) & 0 & 0 \\ -\sqrt{k} sin(L\sqrt{k}) & cos(L\sqrt{k}) & 0 & 0 \\ 0 & 0 & ch(L\sqrt{k}) & \frac{1}{\sqrt{k}} sh(L\sqrt{k}) \\ 0 & 0 & \sqrt{k} sh(L\sqrt{k}) & ch(L\sqrt{k}) \end{pmatrix}, \tag{8}$$

and for quadrupole magnet defocusing in the horizontal plane:

$$M_d = \begin{pmatrix} ch(L\sqrt{k}) & \frac{1}{\sqrt{k}} sh(L\sqrt{k}) & 0 & 0 \\ \sqrt{k} sh(L\sqrt{k}) & ch(L\sqrt{k}) & 0 & 0 \\ 0 & 0 & cos(L\sqrt{k}) & \frac{1}{\sqrt{k}} sin(L\sqrt{k}) \\ 0 & 0 & -\sqrt{k} sin(L\sqrt{k}) & cos(L\sqrt{k}) \end{pmatrix}. \tag{9}$$

6.4 Bending sector (wedge) magnet

A sector bending magnet implies that the central trajectory of the beam enters and exits perpendicular to the pole-face boundaries. Element code is 4 for magnet deflecting in horizontal plane, and - 5 for magnet deflecting in vertical plane. Input lines example for horizontal and vertical magnets are:

COD	L	B	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
4	2.0500	9.016	0.00	BEND-1	18	0.000	0.000	0.560	0.173	0.210
5	2.0500	2.503	1.00	BEND-2	18	0.000	0.000	0.560	0.173	0.210

There are three first order parameters to be specified for the sector magnet:

L - length of the central trajectory (m);

B - transverse component of the magnetic induction (kG).

$DFK = 0$, if magnet is used to put the beam to the accelerator reference orbit (lattice magnet).

$DFK\#0$, if magnet is used to bend the beam from the accelerator reference orbit (like kicker magnet, bump magnet, Lambertson or septum-magnet). The field, bending trajectory from the reference orbit, is $B_e = DFK \cdot B$.

The relationships between the coordinates from the entrance to the exit faces, are given by the transport matrix equations:

$$\begin{pmatrix} X_f \\ X_f' \\ Y_f \\ Y_f' \\ \Delta P/P \end{pmatrix} = M \times \begin{pmatrix} X_i \\ X_i' \\ Y_i \\ Y_i' \\ \Delta P/P \end{pmatrix} + \begin{pmatrix} \frac{10^3 F_p L}{2(1+\frac{\Delta P}{P})} \\ \frac{10^3 F_p}{1+\frac{\Delta P}{P}} \\ 0 \\ 0 \\ 0 \end{pmatrix}, \tag{10}$$

where

$$M = \begin{pmatrix} cos(F_p) & \frac{Lsin(F_p)}{F_p} & 0 & 0 & -\frac{10^3(1-cos(F_p))L}{F_p} \\ -\frac{F_p sin(F_p)}{L} & cos(F_p) & 0 & 0 & -10^3 sin(F_p) \\ 0 & 0 & 1 & L & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \tag{11}$$

with

$$F_p = -\frac{B(kG) \cdot L(m)}{33.356405 \cdot P(GeV/c)}. \tag{12}$$

Right part of equation 10 represents effect of the special bending magnets which deflect particles from the reference (equilibrium) orbit ($DFK\#0$, magnets like bump magnet, kicker magnet, Lambertson and septum-magnet).

6.5 Bending rectangular magnet

Rectangular bending magnet in the program consists of sector bending magnet and two magnetic wedges from both sides of magnet. The type of accelerator bending magnets is defined in the third line of input file $LAT92.INP$ (see section 8.2.1). Only the main accelerator magnets (which are used to put the beam to the accelerator reference orbit) can be defined as sector or rectangular ones. All other magnets (kicker, Lambertson, septum magnets) are rectangular magnets in the STRUCT.

Focusing effect of wedges is simulated by:

$$X'_f = X'_i + \frac{B(kG) \cdot X_i \cdot \frac{F_p}{2}}{33.356405 \cdot P(GeV/c)}. \tag{13}$$

$$Y'_f = Y'_i - \frac{B(kG) \cdot Y_i \cdot \frac{F_p}{2}}{33.356405 \cdot P(GeV/c)}. \tag{14}$$

6.6 Sector bending magnet, COD=28 and COD=29

Type of bending magnet (sector or rectangular) in the accelerator or beam line is defined in the input file "LAT92.INP" (see section 8.2.1). In reality most of accelerators contain both types of magnets. Additional definition of the horizontal (COD=28) and vertical (COD=29) sector bending magnets permits to realize this combination.

6.7 Sextupole

Element code - 15 for sextupole. Input line example:

COD	L_o	$k2_o$	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
15	2.0500	0.016	0.00	SEXT-1	18	0.000	0.000	0.560	0.173	0.210

There are two parameters to be specified for the sextupole:

L_o - length (m);

$k2_o$ - sextupole strength for on-momentum particle (m^{-3}).

$$k2 = \frac{\frac{d^2B}{dx^2}\left(\frac{kG}{m^2}\right)}{33.356405 \cdot P(GeV/c) \cdot (1 + \frac{\Delta P}{P})}. \tag{15}$$

Five steps of $L = L_o/5$ are done on the sextupole length. At each step sextupole is represented by two drift spaces of $L/2$ length and angular kick between these drifts. The kick is defined by the sextupole strength and particle coordinates in this point:

$$X'_f = X'_i - k2 \cdot 10^{-3}(X_i^2 - Y_i^2)\frac{L}{2}. \tag{16}$$

$$Y'_f = Y'_i + k2 \cdot 10^{-3} X_i \cdot Y_i \cdot L \tag{17}$$

6.8 Octupole, multipoles

Element code - 14 for octupole. Input line example:

COD	L	$k3_o$	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
14	2.0500	0.016	0.00	OCTU-1	18	0.000	0.000	0.560	0.173	0.210

There are two parameters to be specified for the octupole:

L - length (m);

$k3_o$ - octupole strength for on-momentum particle (m^{-4}).

$$k3 = \frac{\frac{d^3B}{dx^3}\left(\frac{kG}{m^3}\right)}{33.356405 \cdot P(GeV/c) \cdot (1 + \frac{\Delta P}{P})}. \tag{18}$$

Octupole is represented by two drift spaces of $L/2$ length and angular kick between these drifts (See "subroutine octup" from file "hdz.f"). The kick is defined by the octupole strength and particle coordinates in this point:

$$X'_f = X'_i - k3 \cdot 10^{-6} \cdot (X_i^3 - 3Y_i^2 X_i)\frac{L}{6}; \tag{19}$$

$$Y'_f = Y'_i + k3 \cdot 10^{-6} \cdot (3X_i^2 Y_i - Y_i^3)\frac{L}{6}. \tag{20}$$

Higher order multipoles can be simulated in the octupole. Strengths of high order multipoles are defined in the file "work.f" in "subroutine npole" which is called from "subroutine octup".

6.9 Scattering elements

Particle interaction with material of scattering elements is performed using Fortran modules and procedure of MARS14 [2, 3] code.

6.9.1 Collimator, scraper, magnetized collimator

Element code - 12 for scraper, - 13 for collimator, - 27 for magnetized collimator. Input lines example are:

COD	L	FK	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
12	2.0500	0.000	0.00	SCRA-1	18	9.9500	0.000	0.560	0.173	0.210
13	0.0500	0.000	0.00	COLL-1	18	-6.004	-0.98	0.560	0.173	0.210

Horizontal and vertical collimators are used to clean the circulating beam from halo particles. Collimator is a block of absorbing material with rectangular aperture (Fig.

3, 4). Depending on the material and thickness, a certain fraction of the intercepted beam will survive, either by traversing the whole collimator length or by being scattered out of the collimator inside the accelerator aperture.

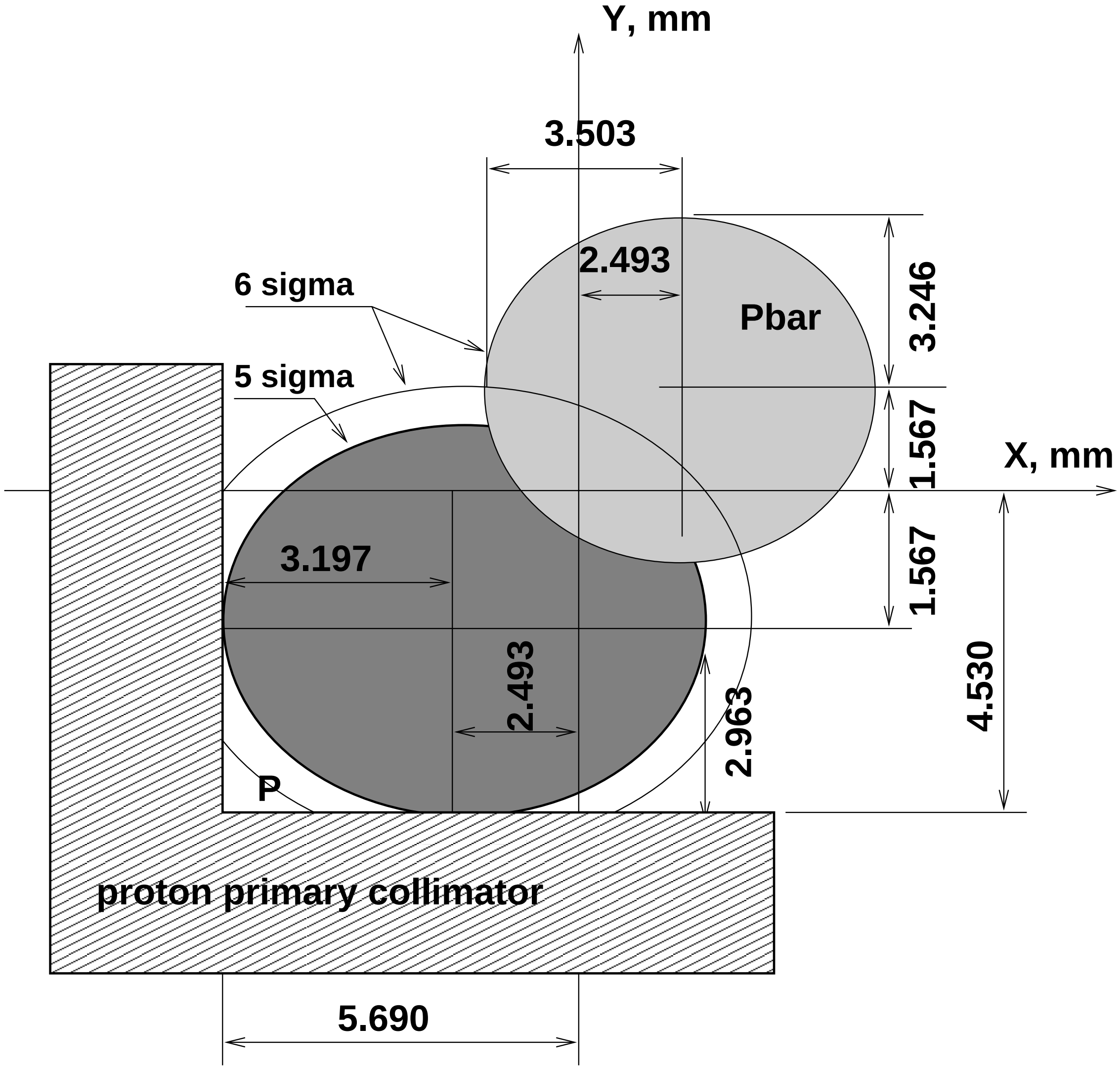

Figure 3: Primary collimator cross section.

There are two parameters to be specified for collimator:

L - length (m);

collimator material;

FK - magnetic field (kG) should be specified only for magnetized collimator.

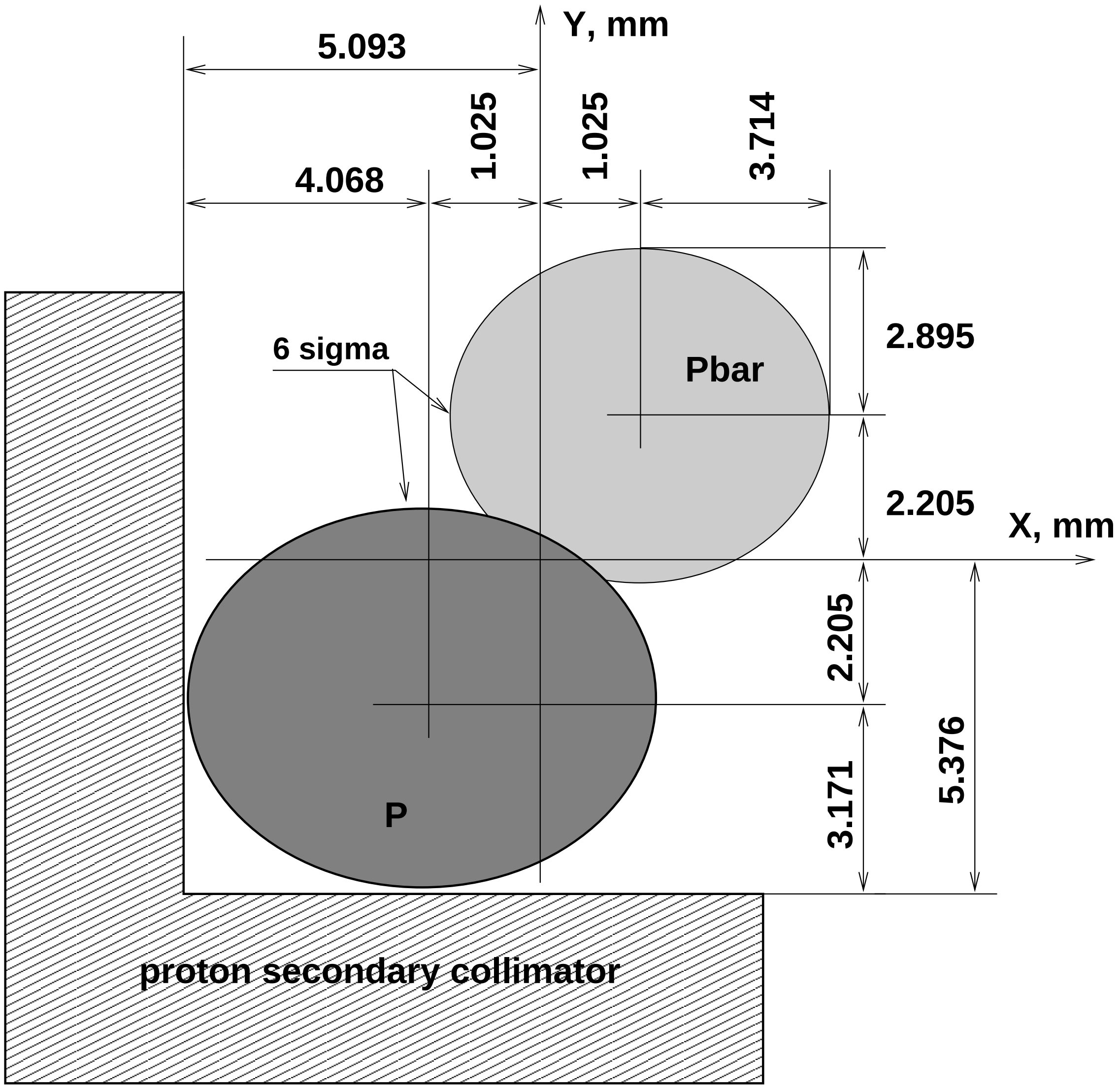

Figure 4: Secondary collimator cross section.

Scraper is a collimator with different material. Material of magnetized collimator (code=27) is the same as for the scraper (code=12). Collimator and scraper material is defined in the file "work.f" in "subroutine mater" (see below section "Material definitions for collimators, scrapers and targets").

In calculations magnetized collimator is sliced along the length to 15 pieces, and angle because of magnetization is added at the entrance of every slice.

6.9.2 Target

At most processes in accelerator the rate of betatron amplitude growth is very small, about $1\mu m$ per turn. Because of this only a thin layer of collimator intercepts the beam. This effects large number of out-scattered particles and collimator jaws heating to very high temperature.

A thin primary collimator (scattering target), introduced into the lattice, can increase particle amplitude as a result of multiple Coulomb scattering and thus effects in drastic increase of particle impact parameter on the downstream secondary collimators. This results in a significant reduction of out-scattered proton yield and total beam loss in the accelerator, decreases collimator jaws overheating and mitigates requirements to collimators alignment. The target should be placed a little bit closer to the beam compared to collimators and scrapers.

Element code - 9 for the target. Input line example is:

COD	L	k3	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
9	0.0500	3.000	0.00	TARG-1	18	9.9500	6.030	0.560	0.173	0.210

There are two parameters to be specified for target:

L - length (m);

target material.

Target material is defined in the file "work.f" in "subroutine mater" (see below section "Material definitions for collimators, scrapers and targets").

Target has a rectangular cross section. Target location in the accelerator cross section is defined by coordinates of it center and rotation with respect to the accelerator longitudinal axis (Fig. 5).

6.10 Invert aperture

"Invert aperture" is an absorbing block with rectangular, round, elliptical or pole rotated cross section. The element may have different aperture along its length ("conical" aperture). In this case the element has a rectangular aperture at any cross section along the element length, and horizontal and vertical size of aperture is a linear function of length. Angle of aperture deviation along the element is defined in the "subroutine apeel1" (see "file hdz.f").

Particles which come to this "absorbing" block are assumed being lost. The invert aperture can be used for construction of any configurations of absorbing "walls", "shadow collimators" and "septa" of electrostatic deflectors and Lambertson or septum magnets.

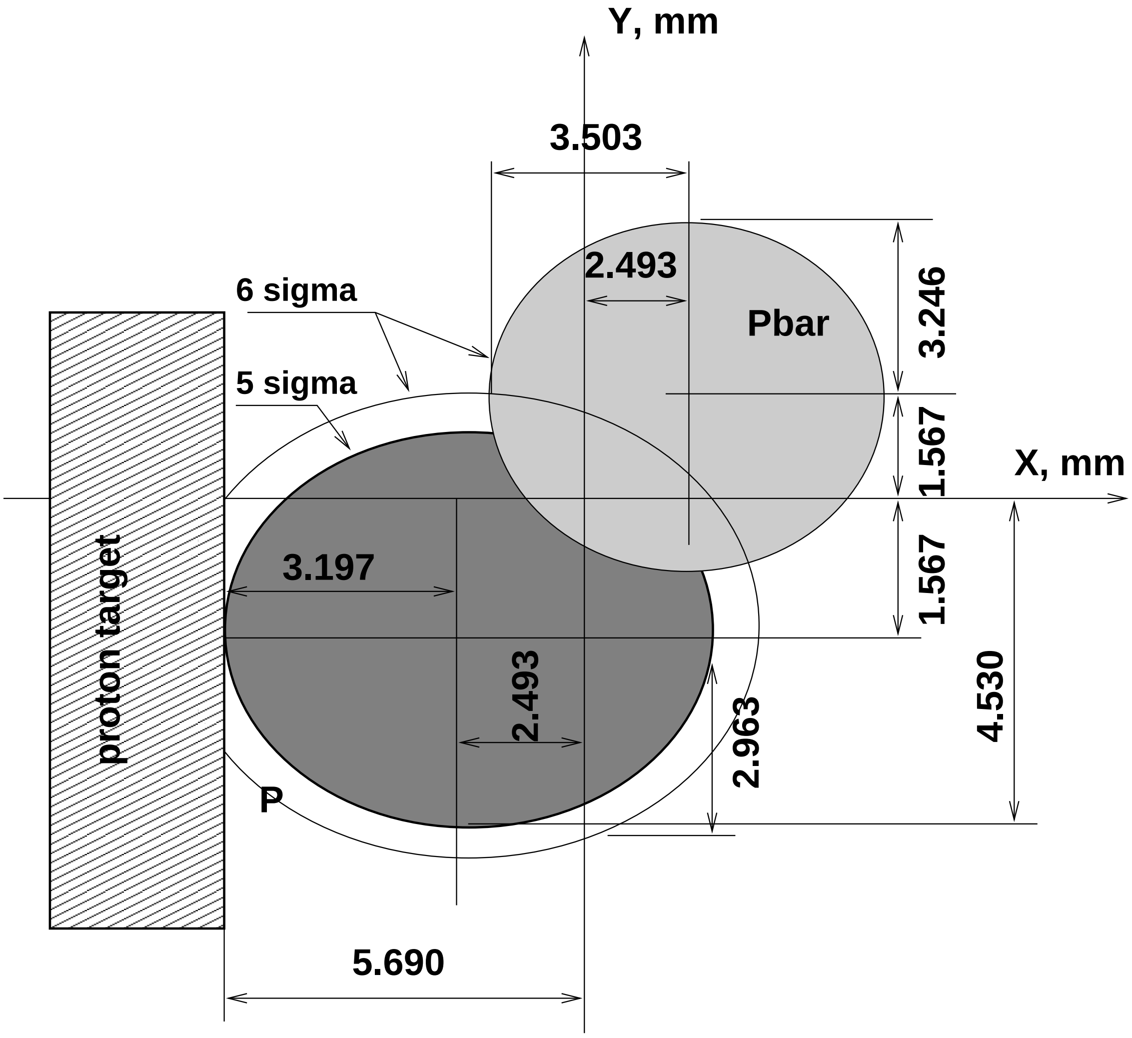

Figure 5: Target cross section.

Aperture restriction is checked only at the entrance and exit of the element. This is correct for all types of aperture, but is not correct for "invert conical aperture", where aperture restriction must be checked along the total length of the element for "conical" invert aperture. This is not done in the code.

6.11 Electrostatic deflector, septum-magnet and Lambertson magnet

Element code - 20 for horizontal electrostatic deflector or septum-magnet, - 22 for vertical electrostatic deflector or septum-magnet, - 21 for Lambertson magnet deflecting in vertical plane, 23 - for Lambertson magnet deflecting in horizontal plane.

Electrostatic deflector, septum-magnet or Lambertson magnet (Fig. 6) can be represented by a sequence of targets, which define septa, and bending magnets with magnet field defined in a certain region of aperture. In the examples below the magnetic field is defined in horizontal ES deflector in the region of $Y > 12.6mm$, in vertical ES deflector in the region of $X < -12.6mm$, in the horizontal Lambertson magnet in the region of $Y > 39.6mm$, and in the vertical Lambertson magnet in the region of $X > 39.6mm$. $0.1mm$ half-size septa (target, CODAPE=5 and 6, see below) is located at $Y = 12.5mm$ and $X = -12.5mm$ in the ES deflectors, and $1mm$ half-size septa (CODAPE=7 and 8) is located at $Y = 38.6mm$, and $X = 38.6mm$ in the Lambertson magnets. Aperture definition is described below in the section "input files". Here we only show how this definition of aperture looks like:

5	30.0	0.1	1
6	0.1	30.0	1
7	1.0	30.0	1
8	30.0	1.0	1

Septa has a rectangular cross section here, with half-thickness of $0.1mm$ or $1mm$ and large half-height of $30mm$.

Input line examples are:

Horizontal ES deflector

COD	L	B	POS	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
9	0.1200	0.000	0.00	ES-ver	5	0.000	12.50	0.000	0.000	0.000
22	0.0100	2.800	12.6	ES-ver	18	0.000	0.000	0.000	0.000	0.000
9	0.1200	0.000	0.00	ES-ver	5	0.000	12.50	0.000	0.000	0.000

Vertical ES deflector

9	0.1200	0.000	0.00	ES-hor	6	-12.50	0.000	0.000	0.000	0.000
20	0.0100	-2.800	-12.6	ES-hor	18	0.000	0.000	0.000	0.000	0.000
9	0.1200	0.000	0.00	ES-hor	6	-12.50	0.000	0.000	0.000	0.000

Horizontal Lambertson magnet

8	0.0010	0.000	0.00	Lamb-h	7	38.60	0.000	0.000	0.000	0.000
23	0.7480	-20.00	39.6	Lamb-h	18	0.000	0.000	0.000	0.000	0.000
8	0.0010	0.000	0.00	Lamb-h	7	38.60	0.000	0.000	0.000	0.000

Vertical Lambertson magnet

8	0.0010	0.000	0.00	Lamb-v	8	0.000	38.60	0.000	0.000	0.000
21	0.7480	-20.00	39.6	Lamb-v	18	0.000	0.000	0.000	0.000	0.000
8	0.0010	0.000	0.00	Lamb-v	8	0.000	38.60	0.000	0.000	0.000

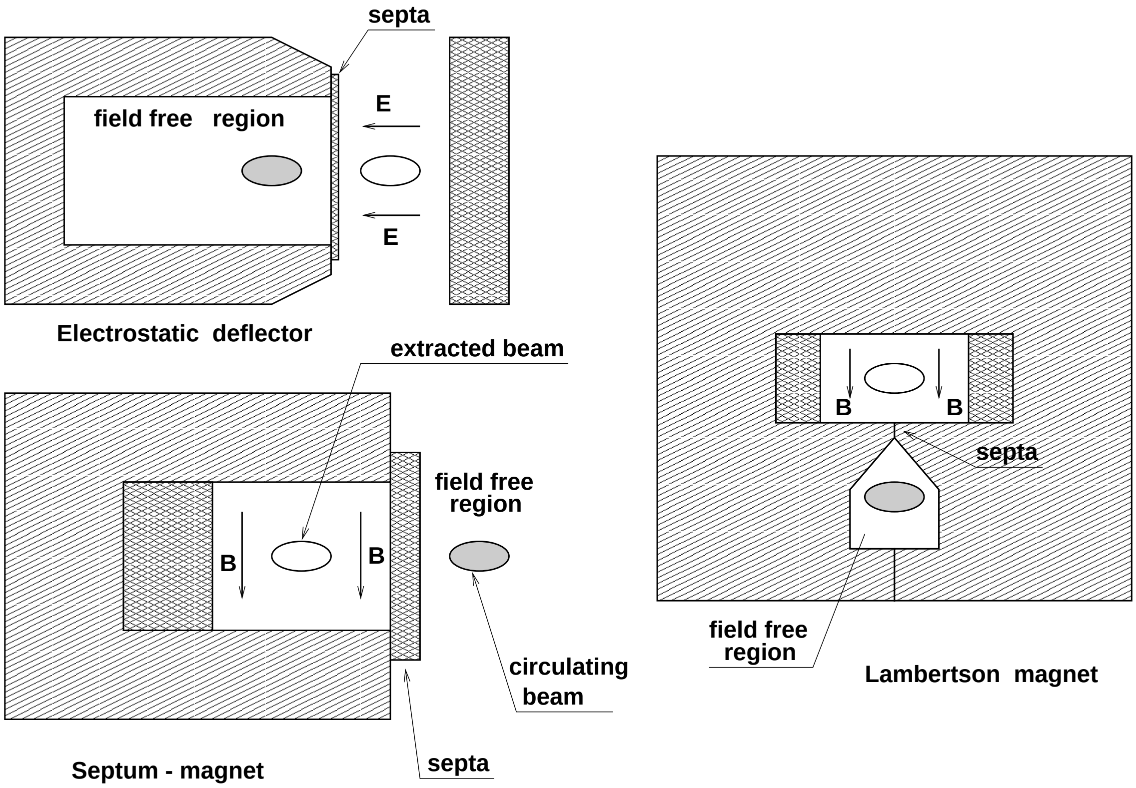

Figure 6: Electrostatic deflector, septum-magnet and Lambertson magnet cross sections.

There are four parameters to be specified for electrostatic deflector, septum-magnet and Lambertson magnet:

L - length (m);

B - magnet field (kG);

DXO, DYO - septa position.

POS - field region border. Particles with coordinates behind this border are deflected by the magnet. In the previous examples particles with $X > 12.6mm$ and with $Y < -12.6mm$ are deflected by the horizontal and vertical ES deflectors.

$0.25m$ long ES deflector consists of two septas (target) $0.12m$ long, and a short $0.01m$ long bending magnet in between them. The magnet field is increased here by a factor of 25 with respect to the real magnet to get the same kick as from $0.25m$ long deflector.

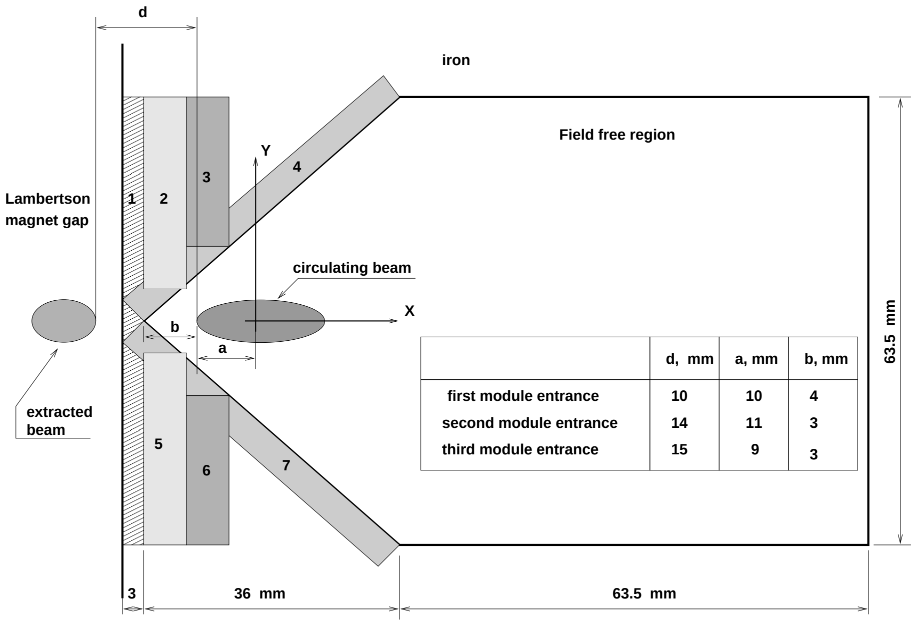

Figure 7: Lambertson magnet cross section definition in the STRUCT code. 1, 2, 3, 4, 5, 6 and 7 - fractional parts of magnet septa (invert apertures).

$0.75m$ long Lambertson magnet consists of two short septas (invert aperture) and a bending magnet of $0.748m$ long. The magnet field is slightly increased here by a factor of 0.75/0.748 with respect to the real magnet. Short septas at the entrance and exit of Lambertson magnet are absorbing elements (invert aperture) here. An example of Lambertson magnet cross section definition (Fig. 6) for calculation of particle loss at the septa is shown in Fig. 7.

6.12 Bending magnet with gradient

Horizontal bending magnets with focusing (COD=19) and defocusing (COD=17) gradient are defined by the input lines:

COD	L	k_o	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
19	2.0500	0.016	-9.016	BEND-1	18	0.000	0.000	0.00	0.173	0.210
17	2.0500	0.016	2.503	BEND-2	18	0.000	0.000	0.00	0.173	0.210

The focusing strength of magnet (k_o=0.016) is introduced here instead of magnet field, and magnetic field ($B = -9.016kG$ and $B = 2.503kG$) - instead of element DFK. It is assumed that these elements are the main lattice magnets with nominal field which is used to put the beam to the accelerator reference orbit. All other parameters are defined as for ordinary bending magnet.

6.13 RF acceleration

Element code - 24 for the RF station. RF station placed in the accelerator changes particle momentum at every turn according to equations:

$$\varphi_I = \varphi_{I-1} - 2\pi \cdot f_{RF} \cdot f_{rev}^{-1} \left[\alpha - \frac{1}{\gamma^2} \right] \frac{\Delta E}{\beta^2 \cdot E} \tag{21}$$

$$E_{exit} = E_{entrance} + \frac{e \cdot U}{1000} \left[SIN(\varphi_I) - SIN(\varphi_s) \right] \tag{22}$$

Here

- φ_I - RF phase at particle passage through the RF station [radian];
- φ_{I-1} - RF phase for this particle at the previous turn [radian];
- φ_s - synchronous phase [radian];
- E - equilibrium energy [GeV];
- f_{RF} - RF frequency [Hz];
- f_{rev} - revolution frequency [Hz];
- α - momentum compaction factor;
- $\gamma = E/(m_o \cdot c^2)$ - γ factor;
- U - RF voltage [Mv].

COD	L	FK	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
24	0.0000	0.000	0.000	RF-sta	30	9.109	0.000	0.000	0.000	0.000

RF station parameters are defined in the file “work.f” in “subroutine RFCAV”. The equilibrium energy, RF frequency and synchronous phase can be a functions of time (see “subroutine RFCAV”).

6.14 Random change of particle horizontal and vertical angle (gas)

Particle horizontal and vertical angles can be changed at every turn, at randon location along the ring by a random values A_{rnd} and B_{rnd} with amplitudes “AMPLX (mrad)” and “AMPLY (mrad)” (see file “work.f” in “subroutine GAS”) according to equations:

$$X = X + AMPLX \cdot A_{rnd} \tag{23}$$

$$Y = Y + AMPLX \cdot B_{rnd} \tag{24}$$

See subroutine “GAS” in the file “work.f” for parameters input. Random location of “beam-gas” interaction is defined in the file “hmn.f” few lines upstream of “CALL GAS”.

6.15 Bent crystal

A particle channeling in the bent crystal is simulated using the CATCH [4] code implemented to the STRUCT code. A bent channeling crystal [5] parameters are defined in the file “crystal” in “subroutine XPREP” (see lines 161 - 184). The main of them are: Particle mass and energy, bent crystal radius, crystal material (density, radiation length, absorption length, charge of nucleus, atomic weight), crystal position and angle from the reference orbit, crystal transverse thickness, amorphous layer thickness.

Element code - 26 for the bent crystal. Input line example:

COD	L	FK	DFK	NAME	CODAPE	DXO	DYO	FIO	PSIXO	PSIYO
26	0.0050	0.000	0.000	CRYSTA	30	9.109	0.000	0.000	0.000	0.000

Only three parameters from the input line are used by STRUCT - COD, L and NAME

7 Short instructions for using STRUCT code

1. Any ”OPTICS” file which content the beam line (accelerator) optical parameters (length, magnet field, gradient, sextupole and octupole strength and others) can be used to construct the input file for ”STRUCT” code. A simple program ”trnapoly.f” is an example of this transformation from MAD output ”OPTICS” file to ”STRUCT” input file ”LAT92.INP”.

2. Compile and run ”trnapoly.f” or other program which converts lattice to make the main part of file ”LAT92.INP”.

3. To complete file ”LAT92.INP” a set of other parameters must be added in the top of this file (see section 8.2.1 below). They describe the beam parameters (number of particles, energy, energy spread, beam emittance), initial conditions (number of turns, starting and final points for tracking), tracking codes (group of particles or ellipses defined by certain emittances can be tracked), codes which define output file content (beam position and size or lattice functions and linear matrixes can be calculated). A special part of ”LAT92.INP” file is elements aperture definition. Four types of aperture can be used: 1 -

rectangular, 2 - circular and 3 - elliptical in cross section and uniform along the element, and 4 - rectangular in the cross section, but conical along the element. All this parameters are read and described in file "work.f" in "subroutine INPUT(NCOLEL,NOB,NSOUEL,CODMAT,COSTAT)".

4. If a group of particles should be used for tracking it must be collected in file "PAR92.INP". A simple program "distrRF.f" can be used to produce this file for Gaussian distribution or for 1/r distribution. 1/r distribution is very useful for simulations of beam halo. Halo can be generated in a range from Ax(min) to Ax(max) and from Ay(min) to Ay(max).

5. Run f77str94 to create executable str94

6. Run str94, producing PAR92.OUT, DX.DAT, LAT92.OUT, LOSELE.DAT, and others

8 Files used by STRUCT

8.1 Fortran codes

work.f - input/output definitions and "READ" formates, can be changed;

hmn.f - the main program, should not be changed;

hdz.f - contains accelerator physics calculations, should not be changed;

hbs.f - contains physics of particles interaction with collimators, should not be changed;

rnd.f - random number generator, should not be changed;

scater.f - contains physics of particles interaction with collimators for electrons, don't need it for protons tracking;

crystal.f - contains physics of interaction with "BENT CRYSTAL", should not be changed.

8.2 Input files

8.2.1 File LAT92.INP

Input variables and accelerator (beam line) lattice (unformatted except last section, no blank lines).

FIRST LINE:

ndroz NCOLEL ECU

ndroz - any integer number to start random generator from this cycle number.

$NCOLEL$ - number of types of collimators for electron version. If $NCOLEL >$ 0, the next $NCOLEL$ lines must have NMAT(i) - number of material definition (as in "GIANT" code) and RLEN(I) - collimator length (mm)

ECU - E(min)/Eo , Eo - accelerator equilibrium energy, E(min) - minimal energy of particles taken into account at interaction with collimators. If energy is smaller than E(min) - particle is assumed is lost.

SECOND LINE: title of task (70 symbols)

THIRD LINE:

MANAGE NOB NSOUEL NPROTO ifoto CODMAT PO DP COSTAT COPROT COTASK COREAL COBEND

MANAGE ≤ 0 for particle tracking from file PAR92.INP,

MANAGE > 0 for tracking of phase plane ellipse of 100 particles (x, x', y, y')

NOB = number of full turns

NSOUEL = to begin tracking from element number NSOUEL. Ellipse tracking must be started from the first element entrance

NPROTO = number of initial particles (NPROTO = 100 for ellipse tracking)

ifoto = number of initial photons (0 for proton accelerator)

CODMAT = 0 for no matrix calculation, > 0 for matrix calculations

P0 = equilibrium momentum of accelerator in GeV/c

DP = dP/P for ellipse tracking

COSTAT = 0 (now is used only this option)

COPROT = 1 for protons, 0 - for electrons

COTASK = 0 for trajectory, 1 - for beam orbit calculations

KOREAL = 0 for real synchrotron rad, 1 - for average synchrotron radiation loss (KOREAL used only for electrons)

KOBEND = 0 - for sector bending magnets

KOBEND > 0 - for rectangular bending magnets

FOURTH AND FITH LINES:

Beta(m), alfa, betatron phase(radian), dispersion(m), angular dispersion(radian), emittance(mm.mrad), coordinate(mm) and angle(mrad) for the beam at the beginning of accelerator in horizontal and vertical plane.

BETAX ALPHAX XNUX ETAX ETAXS EEX COORX COORXS

BETAY ALPHAY YNUY ETAY ETAYS EEY COORY COORYS

- BETAX, BETAY - initial betas (at beam line entrance)
- ALPHAX, ALPHAY - initial alphas
- XNUX, YNUY - initial phase advance (set to zero for our purposes)
- ETAX, ETAY - initial dispersion D, where $\Delta X = \Delta P/P \times D$
- ETAXS, ETAYS - initial D', where $\Delta X' = \Delta P/P \times D'$
- EEX, EEY - emittances
- COORX, COORY, COORXS, COORYS - beam center coordinates x, y, x', y'

NEXT GROUP OF LINES DEFINES ACCELERATOR APERTURE:

Unformatted list of aperture types. 40 different apertures can be used. 4 types of aperture can be used: 1 - rectangular, 2 - circular and 3 - elliptical in cross section and uniform along the element, and 4 - rectangular in cross section, but conical along the element.

I APRI APZI KAPEI

I - number of aperture in the list (is used for every element aperture definition, may be from 1 to 40, 41 signals end of apertures definition)

APRI - horizontal half aperture size (mm)

APZI - vertical half aperture size (mm)

KAPEI - type of aperture (1, 2, 3 or 4)

NEXT GROUP OF LINES DEFINES ACCELERATOR LATTICE:

Formatted list of elements (see file "work.f", "subroutine input" for format definition (it can be changed)

COD FL FKO DFKO NAME CODAPE DXO DYO FIO PSIXO PSIYO

COD - element code, listed below (100 signals end of lattice definition)

FL(I) - length of element (m)

FKO - strength of element, $[1/m^2]$ for quads or magnetic field [KG] for bending magnets

DFKO - deviation of strength for element. Strength = FKO*(1+DFKO) for quadrupoles. For bending magnets usually DFKO=0. Bending magnets are used to put the circulating beam to the accelerator orbit. Particle coordinates are calculated with respect to this orbit. Because of that it is assumed that bending magnets do not bend equilibrium particles. If effect of element strength deviation from the designed value should be studied, the DFKO is equal to $\Delta B/B$ or $\Delta G/G$. DFKO=1 if magnet is used for particle bending from the accelerator orbit (kicker magnet, bump magnet, Lambertson and septum magnets, and some others).

NAME - name of element

- CODAPE - aperture line number in the list of apertures, corresponding to "I" in the aperture definition. See section 8.2.1, subsection "accelerator aperture".
- DXO, DYO - center of element displacement from the reference orbit, (mm)
- FIO - rotation of element around longitudinal axis, (radians)
- PSIXO, PSIYO - angle between longitudinal axis and reference orbit in horizontal and vertical plane, (mrad)

8.2.2 File PAR92.INP

Group of particles for tracking

File format: unformatted

BES P x x' y y' SIPH

BES - particle weight (is equal to 1.) does not used in "STRUCT", but is used in "MARS" [2, 3] code

P - particle momentum (GeV/c)

x - particle horizontal coordinate (x) at the initial point for tracking (mm)

x' - particle horizontal angle (x') (mrad)

y - particle vertical coordinate (y) (mm)

x - particle vertical angle (y') (mrad)

SIPH - synchrotron phase (is used only in RF simulations)

8.2.3 Files sept1, sept2, sept3, sept4, sept5

. The STRUCT uses different modules of program for electron and proton interaction with material of collimators. Sometimes other kind of particles need to be transported through the accelerator. This possibility is realized in the STRUCT for any kind of particles with charge equal to 1 (without taking into account synchrotron radiation). Files sept1, sept2, sept3, sept4, sept5 are used for simulations of interaction of any kind of particles with rectangular block of material. For this purpose the block of material is sliced to five layers. Usually circulating beam halo particles interact with very thin layer of collimator or electrostatic septa, and all of this particles have practically the same angle at the entrance of this element. Files sept1, sept2, sept3, sept4, sept5 can be produced as a result of these particles interaction with material using some energy deposition code. If halo particle during the tracking enters this block, the program defines to which of five layers particle interacts, and then randomly takes one of the output particle from the file corresponding to this layer. At the exit of this block halo particle parameters are changed according to the momentum and coordinates of randomly chosen particle from the file.

. We used this files generated by MARS [2, 3] for interaction of muons with thin wires of electrostatic deflector and with steel absorber (see subroutines "wiresx" and "wiresy" from file "work.f"). Each of files sept1, sept2, sept3, sept4 and sept5 contents particles emitted from one of five layers of septa. Thickness of layers are presented below for electrostatic deflector. x=+0.1 :+0.06, +0.06 :+0.02, +0.02 :-0.02, -0.02 :-0.06, -0.06 :-0.1 mm. These files must exist even with no any information in them, if ES simulations are not supposed to be done.

File format:

P dx dx' dy dy'

p - particle momentum (GeV/c) at the block exit at scattering of particle with equilibrium momentum p_o. Program calculates particle momentum at the block exit as $p_{exit} = p_{entrance} \cdot [1 - (p_o - p)/p_o]$

dx - particle horizontal coordinate change at interaction with ES deflector septa (wires) (mm)

dx' - particle horizontal angle change (mrad)

dy - particle vertical coordinate change (mm)

dy' - particle vertical angle change (mm)

8.2.4 File PARPHO.INP

Group of photons for tracking

File format: unformated

BES P x x' y y'

BES - particle weight (is equal to 1.) does not used in "STRUCT"

P - photon energy (GeV)

x - photon horizontal coordinate (x) at the initial point for tracking (mm)

x' - photon horizontal angle (x') (mrad)

y - photon vertical coordinate (y) (mm)

x - photon vertical angle (y') (mrad)

These file must exist even with no any information in it.

8.3 Output files

8.3.1 File PAR92.OUT

Lost particles file, can be used for lost particles analyses or as input for "MARS" [2, 3] code for energy deposition calculations

File format:

DL NEL TUN P x x' y y' SIPH

DL - longitudinal coordinate of the element entrance (m)

NEL - beam line element number at which particle is lost

TUN - turn number at which particle is lost

P - lost particle momentum (GeV/c)

x - lost particle horizontal coordinate (x) at the element entrance (mm)

x' - lost particle horizontal angle (x') at the element entrance (mrad)

y - lost particle vertical coordinate (y) at the element entrance (mm)

x - lost particle vertical angle (y') at the element entrance (mrad)

SIPH - synchrotron phase (is used only in RF simulations)

8.3.2 File LAT92.OUT

Beam position and size along the accelerator (beam line), self explanatory

8.3.3 File LOS92.DAT

Contents information on particle loss along the accelerator. Self explanatory. Columns number four and five represent kinetic energy lost in the accelerator aperture and kinetic energy deposited in the target, collimators or scrapers. Kinetic energy is normalized by Pc. Example: if proton Pc=1000 GeV, and if this proton is lost in the element, the normalized energy lost in the element is equal to [SQRT(1000*1000+0.93827231*0.93827231)-0.93827231]/1000=0.999062

8.3.4 File LOSELE.DAT

Is used for making histogram of losses along the accelerator

File format:

DL LOSS

DL - longitudinal coordinate (m)

LOSS - beam loss (W/m)

8.3.5 File DX.DAT

Beam position, beta functions, beam size, dispersion, phase advance, aperture along the accelerator. Beta functions, dispersion and phase advance are calculated correctly only for elliptical beam. This file is used for generation of graphs of lattice functions.

File format:

DL XC YC BETAR BETAZ XM YM DX DY PSIX PSIY APX APY

DL - longitudinal coordinate (m)

XC, YC = orbit displacement in horiz. and vert. plane (mm)

BETAR, BETAZ = horiz. and vert. beta functions (m)

XM, YM = beam half size in horiz. and vert. plane (mm)

DX, DY - horizontal and vertical dispersion (m)

PSIX, PSIY = betatron phase (radian)

APX, APY - half aperture in horiz. and vert. plane (mm)

8.3.6 File LINE.DAT

Contents information on elements type (straight section, magnet, Foc quad, ...) and aperture. Is used for generation of beam line scheme (graph).

File format:

DL TYPE APX APY

- DL - longitudinal coordinate (m)
- TYPE - size of the element in the beam line scheme (graph)
- APX, APY - half aperture in horiz. and vert. plane (mm)

8.3.7 File LAT92.NEW

Is used for beam line geometry generation for extraction, injection and other purposes, can be used for collection of information at calculations

8.3.8 Files used for collection of information at calculations

Files LOSA49.DAT, LOSPHO.DAT, LOSSEC.DAT, PARLAM.INP, PARPHO.OUT, PARSEC.OUT, ROMPOT.NEW, phase.0000 , phase.0100 , phase.0200, phase.0300 can be used for collection of information at calculations. Content and format of these files is determined in file "work.f" in "subroutines PRTARG, PRCOLL, PRDRIF, PRDIST, PRLOSS".

8.3.9 Supplementary programs

Supplementary program "distrRF.f" is used for creation of initial coordinates of particles in the file "PAR92.INP". Distribution is Gaussian with Gaussian momentum distribution. Halo can be defined with 1/r distribution and Gaussian momentum distribution.

Supplementary program "trelesec.f" is used to combine two files with loss distributions to one. For example file "los-hor.dat" and "los-ver.dat" to "los-tot.dat" with sum of two distributions. Graphics editor "gnuplot" can be used to plot file "los-tot.dat"

Supplementary program "gistogr.f" is used for histogram file preparation from file "LOSPHO.DAT" for example. Using "gnuplot" one can plot necessary histogram.

9 Material definitions for collimators, scrapers and targets

Collimators material definition for electron collimators are done in the first lines of input file "LAT92.INP" (see section 8.2.1).

Materials of target, collimator and scraper for protons are defined in the "subroutine MATER" (file "work.f"). Four types of target with different material can be used. IM=1, 6, 7, 8. ZA(IM), AT(IM), DENS(IM) - are parameters of material

```
C- - - - - - - - - (CODE = 9.1) TARGET IM=1
c graphite **********
            ZA(1)=6.
            AT(1)=12.01
            DENS(1)=1.75
            radlen9=18.8
cc          rad. length = 18.8 cm
cc          specific heat = 165 j/(Kg.K)
            write(51,781)ZA(1),AT(1),DENS(1),radlen9
            write(55,781)ZA(1),AT(1),DENS(1),radlen9
            print 781,ZA(1),AT(1),DENS(1),radlen9
781         format(3x,'TARGET (code=9.1) graphite ZA =',f5.1,' AT =',
           * f7.2,' DENS =',f6.2, ' Rad. length = ',f6.2,' cm')
```

Now GRAPHITE is used for target material. One can open any other material (titanium, steel or tungsten) here or can define the new material.

There is a possibility to have three more types of target with different materials. If codes 6.0, 7.0 or 8.0 are placed in the position for element strength, three more materials can be defined (for example scintillator, steel and silicon). Everybody can define their own type of materials if it is necessary.

Here is COLLIMATOR and SCRAPER material definition. Steel is used now. Scraper and collimator works identically, but material can be different.

```
C- - - - - - - - - (CODE = 13) COLLIMATOR IM=5
c graphite **********
            ZA(5)=6.
            AT(5)=12.01
            DENS(5)=1.75
            radlen9=18.8
            materi=graphi
c         rad. length = 18.8 cm
c         specific heat = 165 j/(Kg.K)
            write(51,783)materi,ZA(5),AT(5),DENS(5),radlen9
            write(55,783)materi,ZA(5),AT(5),DENS(5),radlen9
            print 783,materi,ZA(5),AT(5),DENS(5),radlen9
783         format(3x,'COLLIMATOR (code=13) 'A6,' ZA =',f5.1,' AT =',
           * f7.2,' DENS =',f6.2, ' Rad. length = ',f6.2,' cm')
```

```
C- - - - - - - - - (CODE = 12) SCRAPER IM=4
c steel *********
        ZA(4)=26.
        AT(4)=55.85
        DENS(4)=7.87
        radlen9=1.76
        materi=steel
        write(51,782)materi,ZA(4),AT(4),DENS(4),radlen9
        write(55,782)materi,ZA(4),AT(4),DENS(4),radlen9
        print 782,materi,ZA(4),AT(4),DENS(4),radlen9
782     format(3x,'SCRAPER (code=12) 'A6,' ZA =',f5.1,' AT =',
       * f7.2,' DENS =',f6.2, ' Rad. length = ',f6.2,' cm')
```

10 Beam loss normalization

Beam loss normalization is done in the file "work.f" in "SUBROUTINE NORPRO and NORPR". Find fragment in "SUBROUTINE NORPRO"

```
2122      FLOSS=PO*(FHPA(I)+DCOLPP(I))*20000.0/(NTOT*FL(I))
c     *** FLOSS=[PO*(FHPA(I)+DCOLPP(I))/(NTOT*FL(I))*(5.E+13-4.5E+13)
c           *1.6E-10/(0.04 sec)](W/m)
c     *** proton loss for 3 GeV JHF
c ******************************************************************
```

Find one more fragment in "SUBROUTINE NORPR"

```
3122      fx=PO*(FHPA(I)+DCOLPP(I))*20000.0/(NTOT*FL(I))
c     *** FLOSS=[PO*(FHPA(I)+DCOLPP(I))/(NTOT*FL(I))*(5.E+13-4.5E+13)
c           *1.6E-10/(0.04sec)](W/m)
c     *** proton loss for 3 GeV JHF
c ******************************************************************
```

Here 20000.0=(5.E+13-4.5E+13)*1.6E-10/(0.04sec) for 10% intensity lost during one cycle with 25 cycles per 1 second. 1.6E-10 - is transformation GeV to W*sec

11 Printing coordinates of particles passed through the certain element

If one would like to plot a phase plane pictures at the certain drift space entrance, and the current numbers of these drift space is for example 53, the particle parameters print out can be defined in the "subroutine PRDRIF" (file "work.f") using next set of lines:

```
      if(I-53)7888,7904,7888
c     53 - element (drift) number in the beam line
7904  write(54,7887)I,INOB,J,X1(J),XS1(J),Y1(J),YS1(J),PP(J),FIRF(J)
c     file 54 - FPL92.DAT
```

Using "gnuplot" graphics editor (for example) one can plot these phase diagrams.

Using the same way one can print out particles parameters in the collimators ("subroutine PRCOLL"), targets ("subroutine PRTARG") and lost particles parameters ("subroutine PRLOSS").

12 Examples of STRUCT use for beam loss calculations [6]

12.1 Construction of input file for primary collimator

At normal operation of accelerator the beam size growth and particle loss rate are small. In these conditions the step size of particle betatron amplitude raise during one turn is very small. This value was measured at HERA, TEVATRON and SPS, and was found that amplitude growth is about $1\mu m$ per turn. Because of this particles can come to the primary collimator to a very thin layer, and with angle determined by the position of collimator jaw and lattice functions in the location of collimator. It is convenient to use STRUCT code itself to generate file of this particles.

Several straightforward steps, shown below, describe this procedure:

1 - take emittance of the beam corresponding to the primary collimator position (emit=3.834 here, both for horizontal and vertical plane) and run the STRUCT with

```
1     1    1    100    0    0    .6444408    0.00    0    1    0    0
1.473    0.    0.    2.448    0.    3.834    0.    0.
6.151    0.    0.    0.       0.    3.834    0.    0.
```

But put the aperture restriction at the entrance of primary collimator to intercept all the particles in this location ("intercepting wall"). This can be done by introducing a short drift space element here and make a displacement of it to a large value (dX=200.0 mm for example).

2 - take one of particles from PAR92.OUT as initial particle for the next tracking. You can take for example particle with maximum horizontal coordinate. Write the coordinates (and momentum) of this particle to the PAR92.INP file.

3 - modify fragment of file "work.f", "subroutine PRDIST" from old version:

```
      go to 7898 ! to skip particle coordinates printing
      if(iper-56)3201,3202,3201
c     56 - is element number in the beam line (primary collimator entrance)
3202  if(x1(1)-64.394)3201,3203,3203
c     64.394 - is specific value of particle coordinate (X)
3203  print 3204,x1(1),xs1(1)
3204  format(2f10.4)
3201  continue
7898  continue
```

to the new version:

```
c     go to 7898 ! to skip particle coordinates printing
      if(iper-56)3201,3202,3201
c 56 - is element number in the beam line (primary collimator entrance)
3202  if(x1(1)-64.394)3201,3203,3203
c 64.394 - is specific value of particle coordinate (X)
3203  print 3204,x1(1),xs1(1)
3204  format(2f10.4)
3201  continue
7898  continue
```

56 - is reference number of a short drift space element at the collimator entrance.

Here 64.394 - is expected position of primary collimator. Maximum coordinate of the ellipse from the previous calculations should be a little bit larger (by about 0.01 or 0.005 mm) to get 0.01 mm impact parameter (distribution size) at the primary collimator.

4 - return the drift space element at the collimator entrance back to "dX=0" position and move primary collimators by 1 mm outside the beam to eliminate particles interactions. Start the STRUCT with

```
0    10000    1    1    0    0    .6444408    0.00    0    1    0    0
```

(This is a tracking of a single particle during many turns. Because of betatron oscillations this particles at some turns pass through the drift space with coordinate x > 64.394. This coordinates will be printed at the computer screen.)

5 - you will get print out at the screen coordinates of particles at the collimator entrance for x > 64.394

6 - collect 100 of this coordinates in the file "parXY1".

7 - using supplementary program "distrRF.f" produce 1000 particles in the PAR92.INP with 3 sigma Gaussian distribution and "0" momentum distribution.

8 - run the STRUCT with "intercepting wall" at the primary collimator entrance again. You will get 3 sigma size beam at the collimator entrance in the PAR92.OUT file.

9 - the supplementary program "trXY1.f" combines particles from "parXY1" with large amplitude (for horizontal plane) , with particles from PAR92.OUT with 3 sigma size (for vertical plane). Start this program, but define to which file you would like to print your set of particles (something like "parCOL1-X").

```
open(50,file='PAR92.OUT',status='old')
open(52,file='parCOL1-X',status='unknown')          from "trXY1.f"
open(53,file='parXY1',status='old')
```

10 - transfer file "parCOL1-X" to PAR92.INP and use it as an input file for your calculations with initial conditions:

0 150 56 10000 0 0 .6444408 0.00 0 1 0 0

150 - turns number

10000 - particle number

56 - starting point of tracking.

12.2 Simulations of beam painting at H^- injection to the accelerator

Painting injection [7] is required to realize uniform density distributions of the beam in the transverse plane. It can be performed by using two sets of horizontal and vertical bump magnets. Horizontal bump is used to move the closed orbit at the stripping foil location during beam injection to the accelerator. Vertical bump provides angle sweeping during injection time. This causes particles betatron amplitude variation and results to uniform beam after injection.

In our example painting scheme consists of 4 horizontal bumps with current numbers "ibump1,ibump2, ibump3,ibump4", and vertical angle variation at the foil. Current numbers of horizontal bump magnets are defined in the file "work.f" in "subroutine paint".

The dependence of bump-magnets strength on time is chosen to get uniform distribution of the beam after painting both in horizontal and vertical planes. An optimal waveform of bump-magnets can be simulated in the program as presented below:

- in horizontal plane

$$B = B_o \left[0.3415 + 0.6585 \left(1 - \sqrt{\frac{2\ N}{40} - \left(\frac{N}{40}\right)^2} \right) \right] \qquad N < 40 \tag{25}$$

$$B = B_o \left[0.3415 - \frac{N - 40}{44.719} \right] \qquad N > 40 \tag{26}$$

- in vertical plane

$$Y' = Y_o' \sqrt{2 \frac{40 - N}{40} - \left(\frac{40 - N}{40}\right)^2} \qquad Y_o' = 1.9444 mrad \tag{27}$$

The horizontal bump magnets strength during injection time is described in "subroutine xpaint". Fragment of the program, describing magnet strength function is shown below:

```
      if(INOB-40)8355,8356,8356
8355  DFK=FKOO*(0.3415+0.6585*(1.-sqrt(2*float(INOB)/40.-
     *(float(INOB)/40.)**2)))     !   optimal bump strength
```

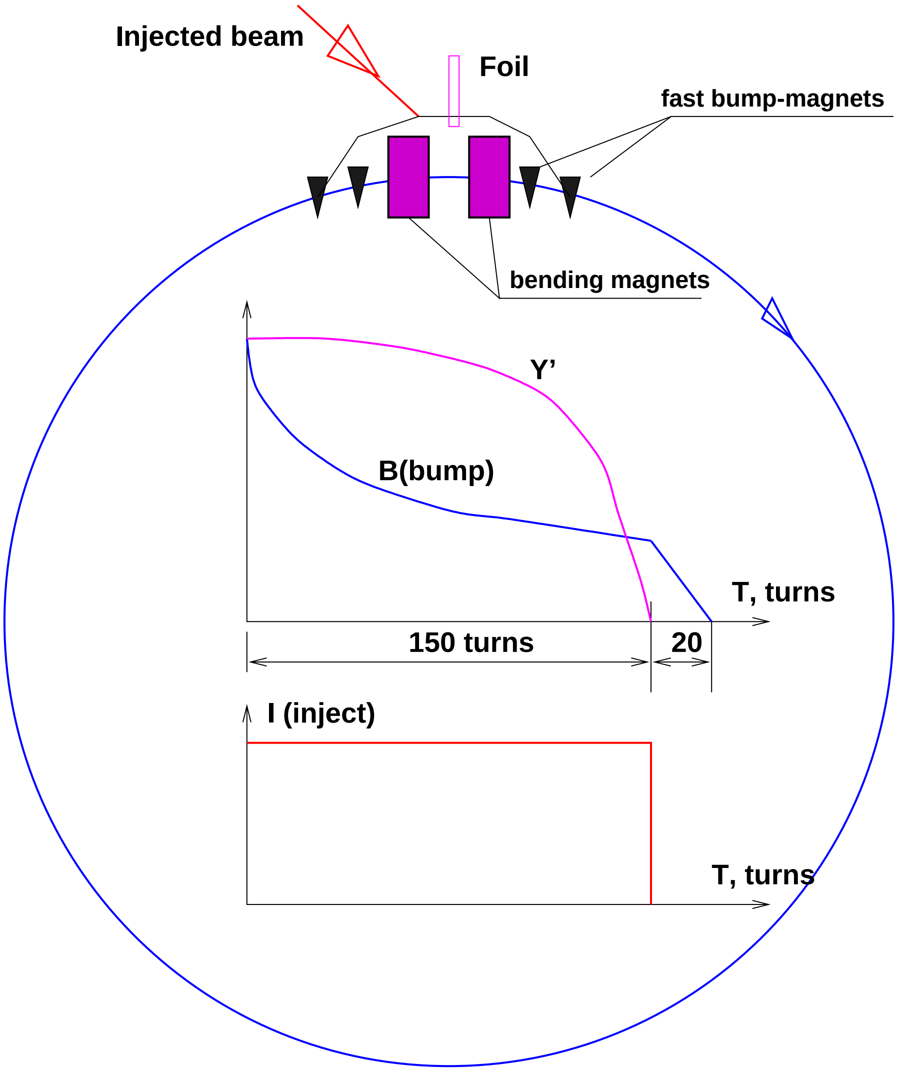

Figure 8: Beam painting scheme.

```
        go to 8357
 8356   DFK=FKOO*(0.3415-(float(INOB)-40.)/44.719)
```

Vertical angle variation at the foil is simulated in “subroutine ypaint”:

```
        DYS=1.9444*sqrt(2*(40.-float(ICYCLE))/40.-
      * ((40.-float(ICYCLE))/40.)**2)      !   optimal beam painting in vert.
direct. to +-1.9444 mrad
```

Here

INOB - current turn number;

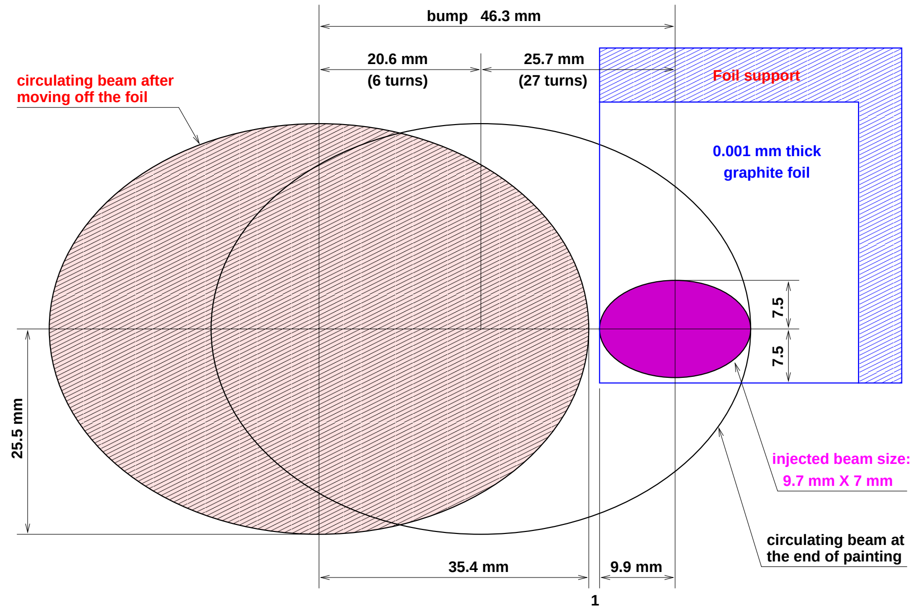

Figure 9: Cross section view at injection point.

40 turns - duration of injection;

FKOO - bump magnet strength amplitude;

DFK - current bump magnet strength;

$1.9444mrad$ - vertical angle amplitude.

The $1\mu m$ thick graphite stripping foil is located in the horizontal bump maximum, and performed as a thin target (Fig. 8 and 9).

12.3 Simulations of beam loss at abort kicker prefire [8, 9]

The accelerator abort system consists of several pulsed magnets having a short rise time (about few μs). Normally this system is triggered during the abort gap in the circulating beam. If one of the abort kicker modules accidentally prefires, this induces coherent oscillations of the circulating bunches because this prefire not necessary happens during the abort gap (Fig. 10). As a result, some fraction of the beam may be lost on the machine limiting aperture. This causes accelerator components heating, magnets quench and irradiation. The measure normally used in this case - an immediate firing of the rest of the kicker modules (unsynchronized abort) can help to eliminate or to reduce losses, but sometimes it is not sufficient to cure the problem. Any case this problem must be investigated. Kicker waveform at unsynchronized abort is shown in Fig. 11.

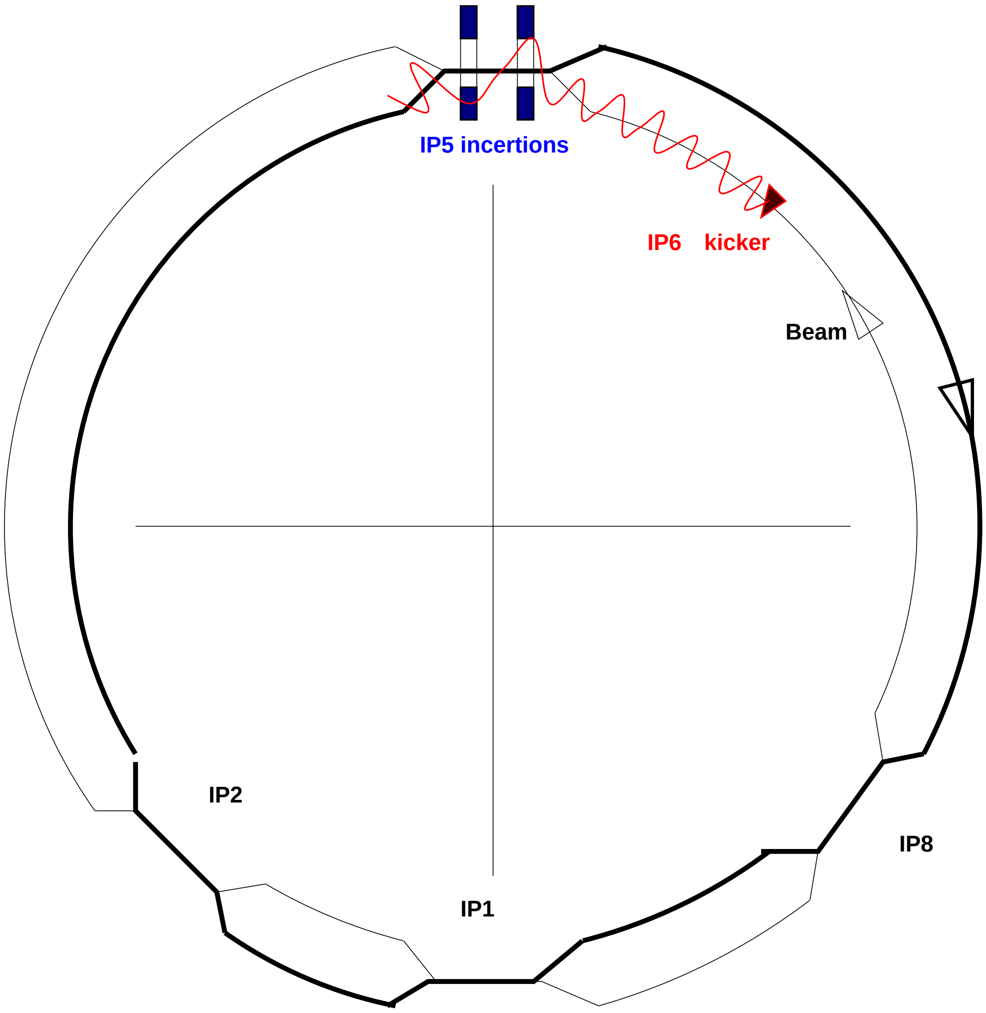

Figure 10: Schematic of the LHC abort kicker prefire.

To simulate this process certain number of bunches is taken in the beam. Each bunch is assumed consists of 1000 particles. The magnet field in the prefired kicker model is changed according to the waveform at unsynchronized abort, such a way that every next bunch is bended by increased field of the kicker compared to the previous one. Particles, lost in the accelerator, are stored in the "PAR92.OUT" file for analyses.

Kicker waveform is defined in the file "sept3", and are read in "subroutine LHCPRE" of file "work.f". The kicker magnet strength during raise time at unsynchronized abort is defined in "subroutine prefir" of file "work.f". There is an explanation of kicker parameters in the beginning of this module.

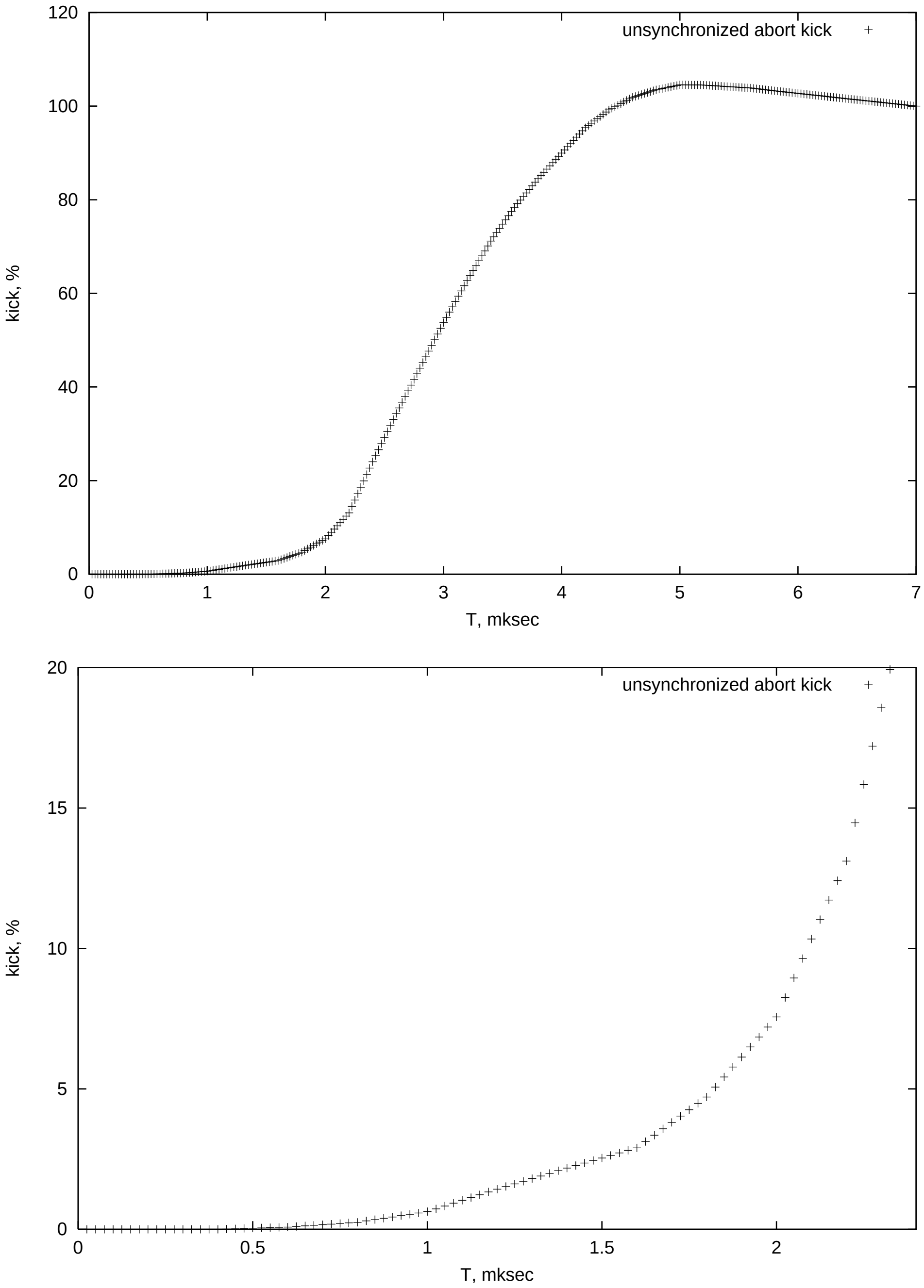

Figure 11: Kicker waveform at unsynchronized abort.

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References

[1] I. S. Baishev, A. I. Drozhdin and N. V. Mokhov, "STRUCT Program User's Reference Manual", SSCL–MAN–0034 (1994),

http://www-ap.fnal.gov/∼drozhdin/.

[2] N. V. Mokhov, "The MARS Code System User Guide, Version 13(95)", Fermilab-FN-628 (1995); N. V. Mokhov et al., Fermilab-Conf-98/379 (1998); LANL Report LA-UR-98-5716 (1998); *nucl-th/9812038 v2 16 Dec 1998*; http://www-ap.fnal.gov/MARS/.

[3] N. V. Mokhov, "MARS Code Developments, Benchmarking and Applications", *Proc. of ICRS-9 International Conference on Radiation Shielding*, Tsukuba, Ibaraki, Japan, October 17-22, 1999, *Journal of Nuclear Science and Technology*, Suppl. 1, pp. 167-171 (March 2000), also Fermilab-Conf-00/066 (2000).

[4] V. M. Biryukov, "Crystal Channeling Simulation-CATCH 1.4", User's Guide, SL/Note 93-74(AP),CERN, 1993.

[5] V. M. Biryukov, A. I. Drozhdin and N. V. Mokhov, "On Possible Use of Bent Crystal to Improve Tevatron Beam Scraping", *Proc. of the 1999 Particle Accelerator Conference*, New York, New York, March 29 - April 2, 1999, pp. 1234-1236; also Fermilab-Conf-99/072 (1999).

[6] A. I. Drozhdin and O. E. Krivosheev and N. V. Mokhov, "Beam Loss, Collimation and Shielding at the Fermilab Proton Driver", Fermilab–FN–693 (2000).

[7] A. I. Drozhdin and O. E. Krivosheev, "The Fermilab Proton Driver Beam Injection System Simulations", Fermilab–FN–694 (2000).

[8] A. Drozhdin, I. Baishev, N. Mokhov, B. Parker, R. Richardson, and J. Zhou, "Dealing with Abort Kicker Prefire in the Superconducting Super Collider", IEEE Particle Accelerator Conference (1993), SSCL-Preprint-329. May 1993.

[9] A. I. Drozhdin, M. Huhtinen, N. V. Mokhov, "Impact of the LHC beam abort kicker prefire on high luminosity insertions and CMS detector performance", Fermilab-Conf-99/060 (1999) and Proceedings of the 1999 Particle Accelerator Conference, PAC99, New York City, New York, USA, March 29 - April 2, 1999.p.1231-1233.