Tracking of Electrons and Positrons Through the IP1 Spectrometer

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Abstract

This note describes the programs used to track electrons and positrons through the magnets around IP1 and to create the tables with nominal momenta versus $\hat{y}$-position at the $\hat{z}$-location of ECAL and PCAL. The coordinate systems used in the calculations are explained and the processing of the permanent magnet field maps is discussed.

1 Introduction

E-144 utilizes the FFTB dump line as a spectrometer to measure the energy of electrons and positrons originating at the first electron-laser interaction point (IP1). The configuration of magnets around IP1 is shown in Fig. 1. The beam electrons first pass through a soft bend (SB) and a very soft bend (VSB) magnet before they collide with the laser pulse (or flag) at IP1. An equivalent pair of a VSB and a SB is installed downstream of the interaction point. The purpose of these low field electro-magnets is to keep synchrotron radiation in the direction of the backscattered laser photons to a minimum (CCD spectrometer).

The main transverse kick for charged particles is provided by a string of 6 permanent C-magnets downstream of the soft bends. Electrons are deflected downwards and their energy is measured in ECAL, located behind the last magnet, while positrons are bent upwards and are intercepted by PCAL above the fifth C-magnet.

An accurate calculation of these particle trajectories is needed to find the correlation between particle momentum and impact point at the calorimeters. For this purpose, the magnetic field in the permanent magnets has been measured in detail (see section 3). The output of the tracking program described in section 4 is the $\hat{y}$-position of tracks at a certain $\hat{z}$-location as a function of the track momentum. In order to have a convenient interface to the E-144 online and offline software, this output is converted to a table that lists the nominal momentum of tracks at the upstream face of Ecal and Pcal as a function of the $\hat{y}$-position. The program used for this conversion is described in section 5.

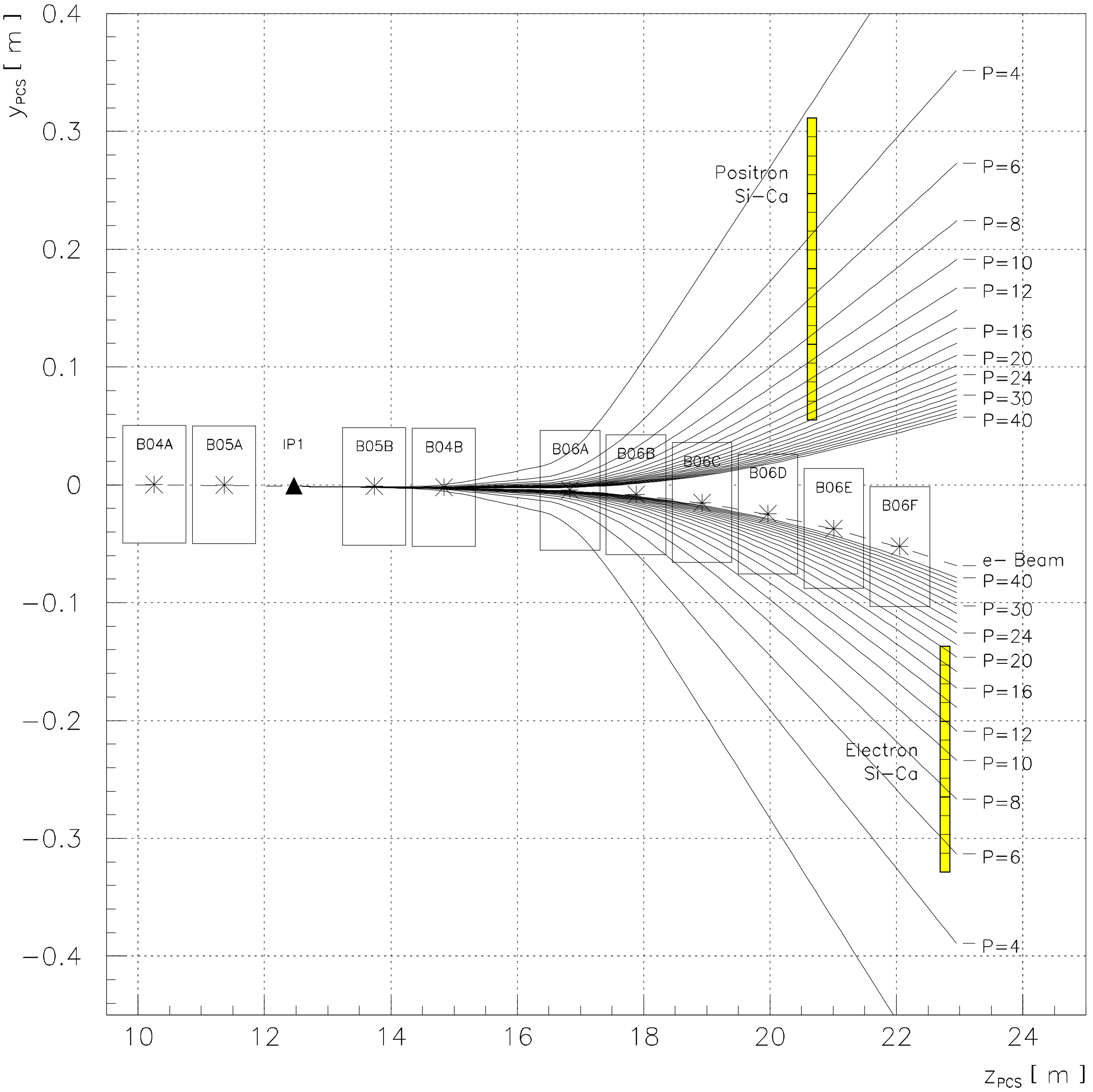

Figure 1: The IP1 spectrometer consisting of two soft bends (B04A and B04B), two very soft bends (B05A and B05B) and a string of 6 permanent C-magnets (B06A to B06F). Also shown is the electron-laser interaction point and the approximate location of the electron and positron calorimeters.

2 Coordinate Systems

The SLAC alignment team measures the position of elements along the beam line in a geodetic coordinate system (GCS), i.e. a reference frame that takes into account the curvature of the earth. Since this coordinate system (CS) is not ideal for particle tracking, all measurements provided by the alignment team are first converted to a SLAC Cartesian CS (SCS). For convenience, the actual tracking of charged particles is done in the Private CS (PCS) which has its origin closer to the elements relevant for E-144 and is tipped downwards to compensate for the downward pitch of the beam line. Finally, each magnet has its own Magnet CS (MCS) which is used to store the magnetic field values. The four types of reference frames and the coordinate transformations between them are described below:

Geodetic Coordinate System (GCS): This CS has its origin at 'station 100', a point more than 300 m upstream from the KEK Final Focus (FF) in the FFTB tunnel. The $\hat{z}$-axis is bent in such a way that every point on the axis has the same distance to the center of the earth. I will ignore the offset of the GCS origin with respect to the beam line and assume that the beam is at $x = 0$ for all coordinate systems.

SLAC Coordinate System (SCS): The SCS originates at the same point as the GCS, but defines a Cartesian reference frame. In this CS, the FF is at $y_{SCS} = 76.15526$ m and $z_{SCS} = 312.6726$ m. The electron beam propagates in the $x_{SCS} = 0$ plane and at the FF points downward at an angle of -0.2755 degrees with respect to $\hat{z}_{SCS}$. The coordinate transformation from GCS to SCS is given by

$$\begin{aligned} x_{SCS} &= x_{GCS}, \\ y_{SCS} &\cong y_{GCS} - \frac{z_{GCS}^2}{2R}, \\ z_{SCS} &\cong z_{GCS}, \end{aligned}$$

with $R = 6.37814 \times 10^6$ m the radius of the earth. A downward pitch angle α in radians transforms as

$$\alpha_{SCS} = \alpha_{GCS} - \frac{z_{GCS}}{R}.$$

Private Coordinate System (PCS): The origin of the PCS is at the FF and the $\hat{z}_{PCS}$-axis is parallel to the nominal beam trajectory at this location. The relation between PCS and SCS coordinates is the following:

$$\begin{aligned} x_{PCS} &= x_{SCS}, \\ y_{PCS} &= (y_{SCS} - \Delta y_{SCS}^{PCS})\cos(\theta_{SCS}^{PCS}) - (z_{SCS} - \Delta z_{SCS}^{PCS})\sin(\theta_{SCS}^{PCS}), \\ z_{PCS} &= (y_{SCS} - \Delta y_{SCS}^{PCS})\sin(\theta_{SCS}^{PCS}) + (z_{SCS} - \Delta z_{SCS}^{PCS})\cos(\theta_{SCS}^{PCS}), \end{aligned}$$

with $\Delta y_{SCS}^{PCS} = 76.15526$ m and $\Delta y_{SCS}^{PCS} = 312.6726$ m the origin of the PCS in the SCS and $\theta_{SCS}^{PCS} = -0.2755$ degrees the pitch angle of the PCS w.r.t. the SCS.

Magnet Coordinate Systems (MCS): Each magnet has its own MCS with the origin at the geometric center of the magnet. The axes of the MCS are by definition parallel to the sides of the magnet. A MCS is then defined by either Δy_{PCS}^{MCS}, Δy_{PCS}^{MCS} and φ_{PCS}^{MCS}, the coordinates of its origin and the pitch angle in the PCS or by the equivalent quantities in the SCS, i.e. Δy_{SCS}^{MCS}, Δy_{SCS}^{MCS} and φ_{SCS}^{MCS}. Coordinates in PCS can then be expressed as

$$\begin{aligned}
x_{MCS} &= x_{PCS} = x_{SCS}, \\
y_{MCS} &= (y_{PCS} - \Delta y_{PCS}^{MCS}) \cos(\varphi_{PCS}^{MCS}) - (z_{PCS} - \Delta z_{PCS}^{MCS}) \sin(\varphi_{PCS}^{MCS}) \\
&= (y_{SCS} - \Delta y_{SCS}^{MCS}) \cos(\varphi_{SCS}^{MCS}) - (z_{SCS} - \Delta z_{SCS}^{MCS}) \sin(\varphi_{SCS}^{MCS}), \\
z_{MCS} &= (y_{PCS} - \Delta y_{PCS}^{MCS}) \sin(\varphi_{PCS}^{MCS}) + (z_{PCS} - \Delta z_{PCS}^{MCS}) \cos(\varphi_{PCS}^{MCS}) \\
&= (y_{SCS} - \Delta y_{SCS}^{MCS}) \sin(\varphi_{SCS}^{MCS}) + (z_{SCS} - \Delta z_{SCS}^{MCS}) \cos(\varphi_{SCS}^{MCS}).
\end{aligned}$$

The position and orientation of the magnets w.r.t. the SCS as well as their dimension and nominal field strength are summarized in table 1. Table 2 shows the SCS coordinates of other objects relevant to E-144.

Magnet Name	$\mathbf{y_{SCS}}$ **[m]**	$\mathbf{z_{SCS}}$ **[m]**	$\varphi_{\mathbf{SCS}}$ **[mrad]**	$\mathbf{D_y}$ **[m]**	$\mathbf{D_z}$ **[m]**	$\mathbf{B_0}$ **[Tesla]**
B04A	76.10636	322.92850	-5.06796	...	1.0	0.0800
B05A	76.10062	324.03250	-5.35763	...	1.0	0.0100
B05B	76.08794	326.40897	-5.42234	...	1.0	0.0100
B04B	76.08190	327.51294	-5.66927	...	1.0	0.0667
B06A	76.06986	329.50711	-7.24453	0.0381	0.944	0.4480
B06B	76.06094	330.55106	-9.96544	0.0381	0.944	0.4480
B06C	76.04917	331.59500	-12.68632	0.0381	0.944	0.4480
B06D	76.03457	332.63889	-15.40721	0.0381	0.944	0.4480
B06E	76.01711	333.68274	-18.12810	0.0381	0.944	0.4480
B06F	75.99683	334.72656	-20.84899	0.0381	0.944	0.4480

Table 1: Position and pitch angle of the 10 magnets in the FFTB dump line in the SLAC Coordinate System. Also listed are the magnet dimensions D_y and D_z in $\hat{y}$ and $\hat{z}$ as well as the nominal field strength B_0.

3 Permanent Magnet Field Maps

The accuracy of the FFTB dump line as a spectrometer depends primarily on how well the B-field in the permanent C-magnets is known. Although analytic formulas give good approximations in the region between the magnet poles, they cannot account for irregularities in the magnetization and tend to be less reliable outside the central region of the poles. However, all the relevant charged particles originating from IP1 cross these fringe fields on their way to the calorimeters. Therefore, the $\hat{x}$-component of the B-field has been measured for seven permanent magnets in the symmetry plane at $x = 0$ by J. Cobb at SLAC with a

Object Name	y_{SCS} [m]	z_{SCS} [m]
FF	76.15526	312.67260
IP1	76.09474	325.13647
ECAL	75.90930	335.36600
PCAL	76.11150	333.26000
IP2	75.95702	336.54337

Table 2: Positions or various objects relevant to E-144 in SCS coordinates. The values listed for ECAL and PCAL are for the March 95 run. The $\hat{y}$-position represents the top (ECAL) or bottom (PCAL) of the active silicon while the $\hat{z}$-coordinate is the upstream side of the first tungsten plate. The ECAL values are for $V_{acc} = -50$ mm on the ECAL mover.

quoted precision of 0.5 %. The range and step-size of the measurements in both the $\hat{y}$- and $\hat{z}$-directions as well as their order of installation in the FFTB tunnel is given in table 3.

Magnet Number	**Measured Range**		**Step Size**		**Installation Order**
	y [cm]	**z [cm]**	**y [cm]**	**z [cm]**	**(looking downstream)**
FFTB_1	-25 to +10	-85 to +85	2.5	1.0	not installed
	-10 to +10	-85 to +85	1.0	1.0	
	+10 to +25	-85 to +85	2.5	1.0	
FFTB_2	-11 to +11	-50 to +49	1.0	1.0	5 (B06E)
FFTB_3	-10 to +12	-50 to +49	1.0	1.0	3 (B06C)
FFTB_4	-11 to +11	-50 to +49	1.0	1.0	2 (B06B)
FFTB_5	-11 to +11	-50 to +49	1.0	1.0	6 (B06F)
FFTB_6	-11 to +11	-50 to +49	1.0	1.0	1 (B06A)
FFTB_7	-11 to +11	-50 to +49	1.0	1.0	4 (B06D)

Table 3: Range and step-size of field measurements for the 7 permanent magnets, as well as their order of installation in the FFTB tunnel.

The results of these measurements, presented graphically in Fig. 2 and 3, show clearly that the area measured for the magnets installed in the beam line (FFTB_2 to FFTB_7) is not sufficient for accurate tracking of off-energy particles. The field strength along the boundary is still approximately 10 % of the peak value.

I first tried to fit a two-dimensional field model to the measured points and then use this model to extend the field maps. However, this attempt failed because I could not obtain satisfactory agreement between the model and the measurements in the fringe field region. An easier and more successful way to extend the field maps of magnets FFTB_2 to FFTB_7 is to use the measurements from FFTB_1, which was mapped more extensively than the other magnets. At the edge of the $\hat{y}$-range measured for FFTB_1, the field has dropped to $\sim 1\%$ of its peak value, while at $z_{MCS} = \pm 85$ cm the field is less than 0.1% of the field

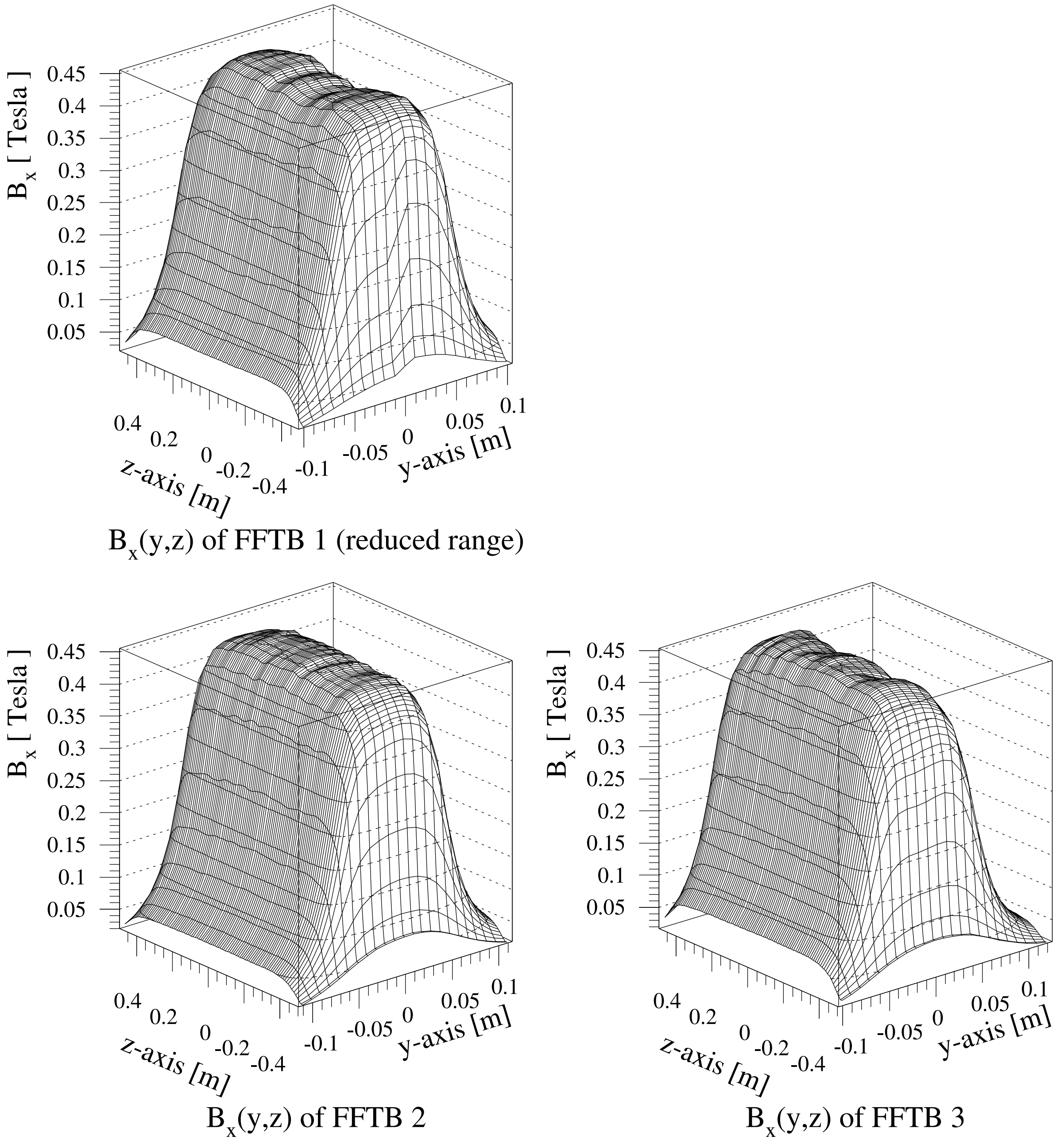

Figure 2: Field maps of $B_x(y, z)$ for FFTB_1, FFTB_2 and FFTB_3. Note the edge in the surface lines of FFTB_1, caused by a damaged magnet pole. FFTB_1 has been mapped in a more extensive area then shown here.

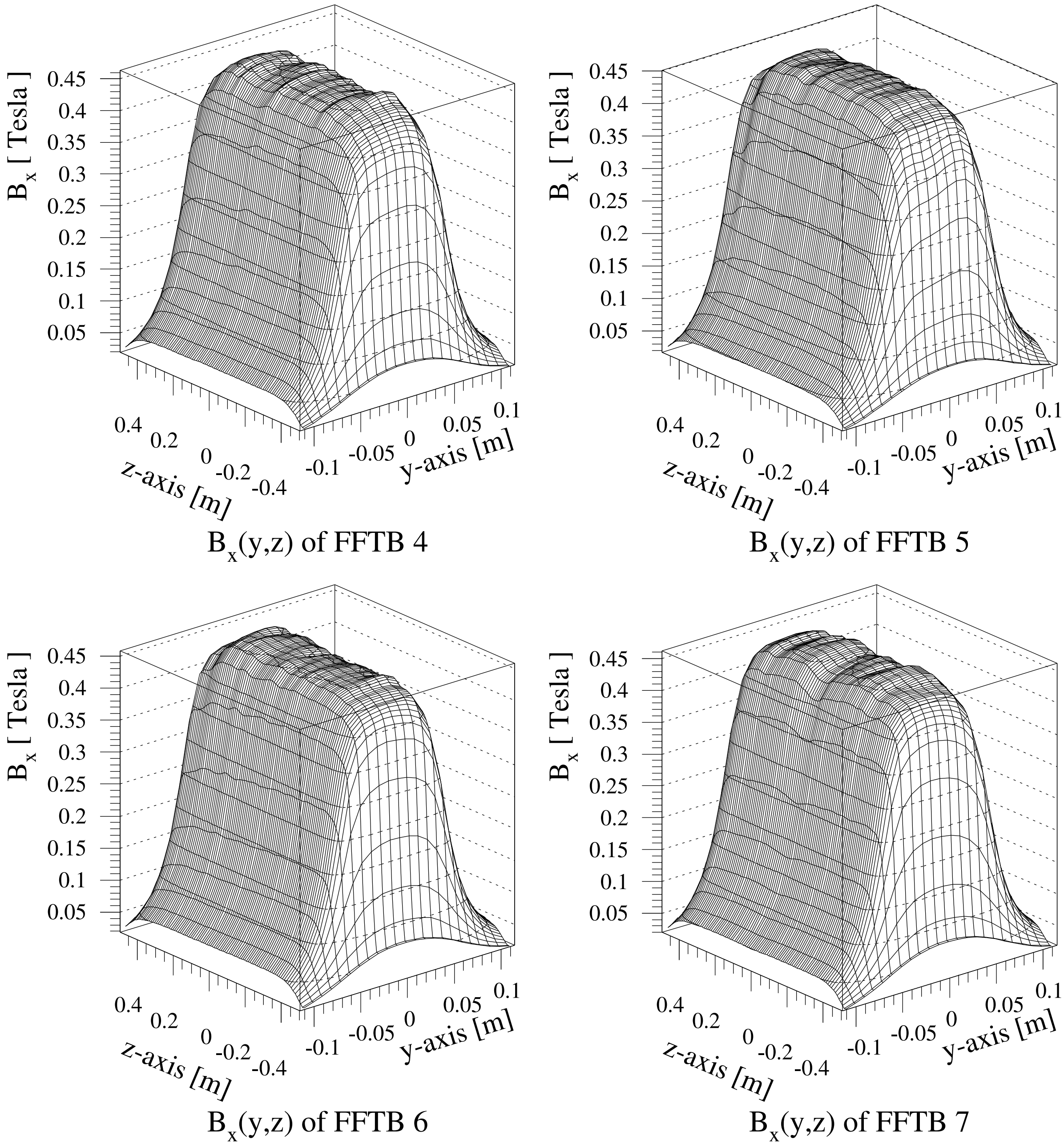

Figure 3: Field maps of $B_x(y, z)$ for FFTB_4 to FFTB_7.

at the magnet center. Unfortunately, the right hand magnet pole (looking downstream) of FFTB_1 is damaged at the downstream end. The effect on the field is clearly visible as an edge in the surface lines in Fig. 2. I used the following assignment in the region affected by the damaged pole to get a smoother field map:

$$B_x(y,z) = B_x(-y,z) \qquad \text{for } z < -0.35 \text{ m and } y \leq 0.01 \text{ m, and}$$
$$B_x(0,z) = B_x(0.01,z) \qquad \text{for } z < -0.35 \text{ m.}$$

With this convention, the field maps for magnets FFTB_2 to FFTB_7 could be extended to a range of ±25 cm in $\hat{y}$ and ±85 cm along the $\hat{z}$-axis. The maps used by the tracking program described in section 4 are stored as histograms with a bin size of 0.5 cm both in $\hat{y}$ and $\hat{z}$. They were filled according to the following algorithm:

1. Enter all measurements for magnet FFTB_x in the map.
2. Add points from FFTB_1 in the region not measured for FFTB_x.
3. Use interpolation to fill all remaining bins.

4 The Tracking Program

The program to calculate the trajectories of charged particles in the FFTB dump line is written in FORTRAN. For convenience, I moved the code from the VAX to a PC. The code is now implemented as a PAW Kumac file and a FORTRAN subroutine file. The Kumac file sets all the program options and parameters and then calls the FORTRAN subroutines to do the actual tracking. All files needed to run the program are installed in `C:\trajec` or one of its subdirectories.

4.1 Program Files

The code to calculate the particle trajectories and to plot the results is contained in the following files:

trajec.kum is the PAW Kumac file that

- sets the path and file names of input/output files,
- sets the program options and parameters,
- opens the necessary input/output files,
- calls the tracking routine `trajec.for`,
- saves histograms and closes all files.

The various program options and switches are explained in the file itself. They allow to control

- the energy of the electron beam,
- the charge and momenta of the particles to track,
- the starting point and direction of trajectories,

- the end point as well as the step size of the tracking,
- the range and frequency (along $\hat{z}$) at which to save the track positions,
- the type of B-field approximation used for the permanent magnets (field maps or one of the analytic approximations).

trajec.for is the FORTRAN file with the routines to calculate the trajectories.

trajec.inc is a FORTRAN include file used by `trajec.for`.

trplot.kum is the PAW Kumac file that draws the plot shown in figure 1.

4.2 Input Files

The input values for the tracking is read from the following files:

trajec.inp contains the positions, dimensions and field strengths of the magnets, the coordinates of some 'special' points (e.g. Final Focus, IP1, ECAL, PCAL) and the parameters for coordinate transformations.

start.dat is an optional input file which is used if the parameter `'lstart'` is set to 3 or 4 in `trajec.kum`. It gives the position and pitch angle of the tracking start.

part.dat is an optional input file which is read in case the parameter `'lpart'` is set to 2 in `trajec.kum`. It contains the momentum and charge of the particles to track.

4.3 Output Files

The tracking program writes its output to the following files:

trajec.out first lists the options and input values used in the calculation. It then gives the various parameters as well as the initial and final position and direction of each track.

trajec.evy lists the $\hat{y}$-position at several $\hat{z}$-locations along the trajectories. This file is used by the program `calkin.c` (see section 5) to calculate the nominal track momentum at a given $\hat{y}$- and $\hat{z}$-position.

trajec.his contains the histograms created by `trajec.for`. This file is read by `trplot.kum` to create the plot shown in Fig. 1.

magnet.cor and special.cor contain the coordinates of the magnets and 'special' points. The Kumac file `trplot.kum` uses these files to read the positions and dimensions of these objects.

5 Nominal Momenta and Acceptance for Ecal and Pcal Rows

In the Ecal analysis, we want to convert the energy deposited in a row to the number of scattered electrons intercepted by that row. To do this we need to know the average momentum of these electrons. In a similar way, in the Pcal analysis we want to compare the measured energy of a single hit or cluster with the nominal momentum of a positron that originates at IP1 and hits Pcal at the reconstructed cluster center. Finally, to compare the measured particle rates in an Ecal or Pcal row with a simulation, the energy range covered by that row must be known.

Of course, the output files of the tracking program described in section 4 contains all this information but not in a very convenient form. The program that converts the output file `trajec.evy` to a table that contains all the necessary information for an Ecal or Pcal row at a given position is `calkin` and runs on a PC. The files needed to run and produced by the program are described below:

calkin.c is the C program file. The program options and parameters are set up in the header of the file and allow to

- define the range and step-size of Ecal/Pcal $\hat{y}$-positions for which output should be generated,
- set the $\hat{z}$-position of Ecal/Pcal,
- define the uncertainty in Ecal/Pcal positions ($\hat{y}$ and $\hat{z}$),
- set the path and name of the tracking program output file (see `trajec.evy` in section 4),
- select the laser color (IR or green) and polarization (circular or linear), as well as the lookup-table version that will be used, and
- define an array of laser η-values for which the spectrum shape will be analyzed.

calkin.bat is a DOS batch-file to compile and link all modules necessary to run `calkin`.

calkin.log is the program log file.

calkin.err is the program error file.

ck___.dat is the output file that contains the table with nominal momenta and acceptance for Ecal/Pcal rows. The file contains a header which lists the input parameters and then a section for Ecal followed by a section for Pcal. The file name is `ck_xxyy.dat`, where ‘`xx`’ describes the laser color and polarization (e.g. ‘`gl`’ for green, linear or ‘`ic`’ for IR, circular) and ‘`yy`’ specifies the numeric integration lookup-table version (e.g. ‘`a1`’ for March 95 or ‘`c4`’ for August 96, 46.6 GeV). The information in the sections for Ecal/Pcal is given for rows starting at a certain $\hat{y}$-position and is organized in columns with the following labels:

SICA: Name of the calorimeter, either ’ECAL’ or ’PCAL’.

Y_HI: y_{PCS} of upper edge of row.

INR: 'IN Range' flag, indicating whether the row is within the momentum range covered by the tracking program output file `trajec.evy` (1=yes, 0=no).

AVERAGE_ENERGY: The following three columns give the mean and error of the rate-weighted average energy for the row:

- **Mean:** Mean energy of particles intercepted by this row. This is the rate-weighted average energy for this row, obtained by using the energy spectra from the Numeric Integration Lookup Tables (NILTs) as weights.
- **Sigma:** Estimated absolute error of mean energy, all uncertainties combined.
- **Sigma/Mean:** Relative error of mean energy, all uncertainties combined.

SIGMA YPOS: Error in mean energy due to uncertainty in δy, the Ecal/Pcal $\hat{y}$-position. This error is estimated as $(\Delta E/\Delta Y_{\mathrm{Row}}) \times \delta y$, with ΔE the energy acceptance of the row and ΔY_{Row} the size of the row (i.e. 16 mm).

SIGMA ZPOS: Error in mean energy due to uncertainty in δz, the Ecal/Pcal $\hat{z}$-position. This error is estimated as $(\Delta E/\Delta Y_{\mathrm{Row}}) \times \delta z \times \theta_c$, with ΔE and ΔY_{Row} defined as above and θ_c the nominal pitch angle of a track hitting the center of the row.

SIGMA RATE: Error in mean energy due to uncertainty in shape of spectrum. This error is estimated by analyzing all the η-values listed in the header and then taking the RMS of the calculated average energies.

ENE_HI: Nominal energy of a track at the upper edge of the row.

ENE_CE: Nominal energy of a track at the row center.

ENE_LO: Nominal energy of a track at the lower edge of the row.

ENE_AC: Nominal track energy acceptance of the row.

PIT_HI: Nominal pitch angle of a track at the upper edge of the row.

PIT_CE: Nominal pitch angle of a track at the row center.

PIT_LO: Nominal pitch angle of a track at the lower edge of the row.

PIT_AC: Nominal track pitch angle acceptance of the row.