EUROPEAN LABORATORY FOR PARTICLE PHYSICS

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BEAM OPTICS DATA FOR THE PS RING AND ITS TRANSFER LINES

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Abstract

The field measurements on the PS magnet, carried out during the construction of the PS machine, have been used for many years to model the optics of the ring. Since the upgrading of the poleface winding system in 1987 new data concerning operational configurations have become available. Furthermore, the presently available beam optics programs allow a much more complete description of the field and the geometry, including higher order multipole components.

Data files for use in beam optics calculations have been created containing all geometry and field parameters of the PS ring and its transfer lines. The results of magnetic measurements carried out since 1988 on presently operational working points have been converted into field and geometry parameters. This report presents the input data for the MAD program concerning the PS ring, the injections and ejections, and the transfer lines.

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1 INTRODUCTION

The field of a PS magnet prototype unit has been measured during the construction of the PS machine. Field and geometry data were presented in 1959 [1]. Since the upgrading of the poleface winding system in 1987 [2] new data concerning operational configurations have recently become available.

A campaign of magnetic measurements on presently operational working points was started in 1988. Preliminary results have been incorporated in a general description of the PS magnet system, including both the PS ring and the transfer lines, used in calculations with the MAD [3] program.

More recently the stray fields at the magnet ends and in the junction between the two half-units have been measured with care, since the field geometry is modified by the currents in the poleface windings. The results are being gradually introduced in the PS data files.

2 SPECIFIC DIFFICULTIES OF THE PS MAIN MAGNET

2.1 Curvature

The PS main magnet units are curved with the radius of the beam orbit. Consequently the magnetic measurement data sets have to be converted to the cylindric coordinate system corresponding to the orbit before they can be used in beam optics calculations. The half-units are declared as SBEND elements in MAD.

2.2 Pole profile

At medium energies the pole profile chosen for the PS magnet produces a gradient which is constant [4] in the useful aperture. At low energy the tunes are adjusted with small quadrupole lenses installed between the coils of the main magnet units. At high energy the tunes and chromaticities, modified by saturation, are corrected by means of poleface windings. The multipole components of higher order than sextupole (up to 20-pole) are declared as thin MULTIPOLE elements in MAD, inserted at entrance and exit of the half-units.

2.3 End effects

Due to the shape of the pole profile the stray field at the magnet ends does not have the same geometry as the magnet itself. An important correction to the poleface angle ($\approx 10°$) has to be applied (parameters E1 and E2 in the SBEND elements in MAD). This correction and the magnetic length of the stray field depend on the field level [5].

2.4 Half-units with opposite gradient polarity

Each magnet unit consists of two half-units which have the same central orbit field, but pole profiles which produce gradients of opposite polarity. The half-units are made of 5 blocks, aligned along the beam orbit, separated by small wedge-shaped gaps ($\approx 1\ cm$). Four different magnet types exist (the number of installed units is indicated in parentheses):

- R : D-F unit, yoke outside (35)
- S : F-D unit, yoke outside (15)
- T : F-D unit, yoke inside (35)
- U : D-F unit, yoke inside (15)

Each of the 100 straight sections (1 m or 2.4 m long) is surrounded either by two F or by two D half-units.

2.5 Central junction

The half-units are separated by a 20 mm space without iron *(junction)* where the gradient changes sign. Apart from a small dipole defect the junction has a field dependent quadrupole and sextupole component (K1J, K2J). Due to the proximity of the two half-units (with opposite gradients) the measurement of this effect requires very careful coil positioning. In MAD the junction is modeled as a combined function sector bend (SBEND) with zero deflection angle.

2.6 Effect of the Figure-of-eight loop

The F and D poleface windings are designed to produce large quadrupolar and sextupolar field components in the main magnet units, but they have little effect on the dipole component. However, the third poleface winding, the *figure-of-eight* loop, increases (decreases) the global field strength in the D (F) half-units. Due to the pole profile this lowers Q_x and raises Q_y. However, it produces equally a non-negligible distortion of the equilibrium orbit. The latter effect has to be treated in MAD as a *field error,* using the EFIELD command.

2.7 Effect of the lateral stray field on the ejected beams

The PS ring was built without long straight sections usable for injection or ejection. The initial 50 MeV injection could easily be located in a 2.4 m straight section, and even the more recent 1 GeV injection from the Booster could be installed in a 1 m straight section. However, at high energy the deflection angles of the ejection septa are so small that the ejected beam passes very close to the circulating beam in at least one PS magnet unit. Due to the mechanical dimensions of the ejected beam pipes the septum must be located in a D straight section and the ejected beams traverse first a D half-unit, where the field quality is still well controlled. However, in the subsequent F half-unit the beam passes *beyond* the radial position corresponding to maximum field, and thus the gradient seen by the beam has a reversed polarity, which results in very large horizontal beam sizes at the exit of this magnet unit. This problem exists at all ejections from the PS [6, 7].

3 AVAILABLE PS MAGNET DATA

The magnetic measurements on the main magnet were limited to a number of operational working points, defined by their dipole field level (B train value) and the poleface winding currents: two working points at 26 GeV/c (old and new *figure-of-eight* loop), two at 24 GeV/c (old and new slow ejection scheme) and one at 3.56 GeV/c with zero poleface winding currents.

3.1 1988 measurements

The first measurements on operational working points using the new *figure-of-eight* poleface winding were carried out in 1988 [8]. They concentrated on the good field region inside the magnet.

3.2 1990 measurements

A second campaign was started in 1990 [9], and aimed at measurements of the complete stray field region at the magnet ends, and of the lateral stray field which is of importance for ejected beams. These measurements have to be further converted to the cylindric coordinate system of the beam orbit, before they can be used in MAD calculations.

3.3 Conversion of measurement data to MAD input

Gradients (K1) and derivatives (K2 to K9, i.e. sextupole to 20-pole) were calculated from field measurements using least square fits. Due to the strong field non-linearities beyond radial positions of ± 60 *mm* three fits have to be made:

- fields relevant for *circulating beams* are fitted in the range -50 *mm* to $+50$ *mm* with multipoles K1 to K5. This yields a good agreement with measured tunes and chromaticities, even in the presence of ejection bumps [6].
- fields relevant for beams in the *last turn* before ejection (kicked by the ejection kicker) are fitted in the range -120 *mm* to $+120$ *mm* with multipoles K1 to K9. This fit would not be precise enough to reproduce the central orbit tunes with high precision, but it is acceptable if used during only one turn.
- the stray fields seen by *ejected beams* in the first two main magnet units downstream of the ejection septum are fitted locally around the average transverse beam position, with the values of the dipole field and multipoles K1 and K2. This is sufficiently precise as the beams traverse these elements only once, and furthermore the beam is here centered with respect to the reference system of the transfer line.

3.4 Field and alignment errors

Field and alignment errors are not measured directly, but are derived with good precision from orbit measurements. Their locations and strengths are calculated with the orbit analysis and correction program ORBCOR [10]. The errors are treated in MAD as HKICK or VKICK elements. The data is stored together with the magnetic cycle data (see below).

4 MAD INPUT FOR THE PS MAIN MAGNET

A complete magnet unit is defined in MAD calculations by the following sequence of 9 elements:

- coil space (drift, ≈ 30 *cm*)
- thin multipole (8-pole to 20-pole)
- F half-unit (dipole, quadrupole, sextupole, end effects, ≈ 2.2 *m*)
- thin multipole (8-pole to 20-pole)
- junction (quadrupole, sextupole, ≈ 2 *cm*)
- thin multipole (8-pole to 20-pole)
- D half-unit (dipole, quadrupole, sextupole, end effects, ≈ 2.2 *m*)
- thin multipole (8-pole to 20-pole)
- coil space (drift, ≈ 30 *cm*)

The lengths of these elements vary with the field level. They are defined as follows:

```
FINFF   : SBEND,L=LF+DLF,E1=EF,E2=EF,K1=KI1F,K2=KI2F,ANGLE=ANIF*REV
j       : SBEND,L=2*LJ,K1=0.5*K1J/LJ,K2=0.5*K2J/LJ ! junction F - D
c       : DRIFT,L=(CIRC*0.01-5.54-DLF-DLD-2*LJ)/2.0! coil space
mpfi    : MULTIPOLE,    K3L=KI3F*LLF, K4L=KI4F*LLF, K5L=KI5F*LLF, &
          K6L=KI6F*LLF, K7L=KI7F*LLF, K8L=KI8F*LLF, K9L=KI9F*LLF
```

In this model the dipole, quadrupole and sextupole components are distributed over the full length of the magnet, whereas the higher order multipoles are concentrated at the ends of the half-units.

Inner and *outer* yokes are differentiated by the names FINFF, DINDD (inner) and FEXFF, DEXDD (outer) respectively for the F and D half-units, and mpfi, mpdi (inner) and mpfe, mpde (outer) for the F and D thin multipoles.

5 AUXILIARY MAGNETS

All auxiliary magnet types are defined with their length and calibration constant, for example:

```
Q407  : QUADR, L=0.20; CC407:=3043.E-6/(BRHO*Q407[L]) ! quad type 407
```

In MAD runs the excitation current may then be specified in A (except for fast kickers for which the excitation is to be given in kV). The $B\rho$ value is calculated from the central orbit momentum Pc which is either specified in the input, or calculated from the B train value using the following approximation, which reflects the dependance of the magnetic length on the field level [5]:

```
PoverB   := 0.002107 - (2.7E-13) * (B-1500) * (B-1500) - 0.003 / B
Pc       := B  * PoverB   ! c.o. momentum in GeV/c
BRHO     := Pc * 3.3356
```

6 RING LAYOUT

The straight section layouts are defined by SEQUENCE commands, which allows the use of *element classes* [3]. The geometry is equal for all magnets belonging to a same class and only the position in the beam line (in this case the straight section) and the excitation have to be specified:

```
PS07     :  SEQUENCE

"UHV07" :  ULG,     AT = 0.0
"XSL07" :  X610,    AT = 0.2
"QLT07" :  Q409,    AT = 0.7, K1    = +TRIP  * CC409 / 2
"qls",              AT = 1.0
"BHZ07" :  BHZ,     AT = 1.0

ENDSEQUENCE
```

The 100 straight sections of the PS ring are defined in MAD as SEQUENCES with the above mentioned method. The names R, S, T and U denote the different types of main magnet units (see above). The complete ring is divided in 10 sectors, each defined as follows:

```
SEC1 : LINE =   (PS01,T,PS02,U,PS03,T,PS04,R,PS05,T,            &
                 PS06,R,PS07,S,PS08,R,PS09,T,PS10,R)
```

The PS datafile further contains the ejection channels from the septum to the entrance of the first transfer line quadrupole *("point R")*, including the stray field of the PS main magnet.

7 TREATMENT OF EJECTIONS

7.1 Fast Ejections

The optics of ejected beam lines is closely related to the optics of the ring. The PS ring optics is always calculated before a transfer line calculation is made. This has considerably improved the understanding of the transfer line problems [7]. Injections are treated in reversed direction, using the same method.

The calculated lattice parameters at the relevant azimuth in the ring are saved by a SAVEBETA command. These parameters are used as initial values for a subsequent transfer line calculation. A complication arises from the fact the coordinate systems of ring and transfer line are different. Therefore a position and angle offset has to be applied to the horizontal trajectory at the ejection septum. This is conveniently done after a SAVEBETA command:

```
SAVEB, LABEL = TWIS3, PLACE = #E
TWISS, DELTAP = DPP,  ....
   ...
TWISS, DELTAP = DPP, BETA0 = TWIS3, &
       X = TWIS3[X] - .072, PX = TWIS3[PX] + .0005
```

This example may be run for any momentum error value, defined by the variable DPP.

7.2 Slow Ejection

In the description of the slow ejection the TWISS calculations are not relevant in the horizontal plane. The horizontal coordinates at the exit of the first (electrostatic) septum are therefore obtained by tracking of particles along the separatrices. The vertical Twiss parameters may then be propagated through the ejection channel by using the lattice parameters of the circulating beam as initial values. The horizontal beam envelopes have to be estimated from the trajectories of 4 particles [6].

8 TRANSFER LINES

Data sets for the following transfer lines are presently available:

- TT2 (FT16, FTA, ATP)
- TT70 (FA58)
- HTE (electron injection line)
- HTP (positron injection line)
- BTP (proton injection line)

These lines start at the exit (injections) entrance (ejections) of the first quadrupole of the transfer line *(point R)*. The TT2 file contains several beam lines, which are conveniently selected by specifying a *destination* (D3, FTS, ATP or FTA, see Appendix A) as used in the PS control system.

The TT2 and TT70 tunnels are not located in the horizontal plane of the PS ring. The definition of the bending magnet positions is in this case more delicate due to the mixture of horizontal and vertical bends. In TT70 it was found necessary to apply magnet rotations around the longitudinal axis (SROTATION in MAD) in order to correctly describe the geometry of these lines. Rotations applied at both entrance and exit of each bending magnet, in addition to non-zero TILT values, make the description independent of the beam direction (TT70 is used both for positive and negative particles). To this end the angles and tilt values are multiplied by a constant 'REV' which is given the value +1 or -1 according to the beam direction.

9 DATA FILE STRUCTURE

The data concerning the layout and geometry, and sets of operational magnet settings are kept in a system of 'CALL' files in the public user PSRING on the CERN IBM (the list corresponding to file MAD-PS FILELIST is shown in Appendix B). The filenames are chosen in agreement with the names used in the PS control system. Whenever possible the cycles, working points and beam destinations have been given names used in the PLS, as shown in Appendix A.

APPENDIX

A EXAMPLE OF FAST EJECTION CALCULATION

```
TITLE, "FE16S  -  26 GeV/c"
! N.B.  CALL files have implicit default filetype 'VER01'

CALL,  PS         ! ring
CALL,  TT2        ! transfer lines

CALL,  C          ! C cycle
CALL,  HEC        ! high energy working point (K1 to K5)
CALL,  FE16S      ! fast ejection FE16S
CALL,  D3         ! destination D3

! circulating beam
USE,   PS
CALL,  BOUCLE     ! orbit distortion from boucle-en-8
SAVEB, LABEL = TWIS1, PLACE = #E
TWISS, DELTA = DPP

! ejection trajectory ss 1 to ss 100 including fast kicks 71 and 79
USE,   FE16T0
CALL,  HEC9       ! high energy working point (K1 to K9)
CALL,  BOUCLE     ! orbit distortion from boucle-en-8
SAVEB, LABEL = TWIS2, PLACE = #E
TWISS, DELTA = DPP, BETA0 = TWIS1

! ejection trajectory ss 1 to septum 16
USE,   FE16T1
CALL,  HEC9       ! high energy working point (K1 to K9)
CALL,  BOUCLE     ! orbit distortion from boucle-en-8
SAVEB, LABEL = TWIS3, PLACE = #E
TWISS, DELTA = DPP, BETA0 = TWIS2

! septum to point R
USE,   FT16
SAVEB, LABEL = TWIS4, PLACE = #E
TWISS, DELTA = DPP, BETA0 = TWIS3, &
       X = TWIS3[X] - .072, PX = TWIS3[PX] + .0005

! transfer line
USE,   TT2
TWISS, DELTA = DPP, BETA0 = TWIS4, X = 0, PX = 0

STOP
```

B LIST OF CALL FILES AVAILABLE ON PSRING

beam lines						
PS	VER01	M1 V	80	1456	29	1/08/92
BTP	VER01	M1 V	73	186	2	7/01/91
TT2	VER01	M1 V	73	549	5	7/05/91
TT70	VER01	M1 V	73	788	7	4/12/91
HTP	VER01	M1 V	68	55	1	2/22/89
HTE	VER01	M1 V	69	61	1	2/22/89
PS working points, -50 < x < +50 mm						
NONE	VER01	M1 V	45	89	1	1/27/89
HEA	VER01	M1 V	61	92	1	3/17/89
HEB	VER01	M1 V	53	83	1	2/24/89
HEC	VER01	M1 V	60	77	1	11/22/88
PS working points, extended to x = +120 mm						
NOHE9	VER01	M1 V	49	82	1	11/29/88
HEA9	VER01	M1 V	63	89	1	1/10/92
HEB9	VER01	M1 V	63	89	1	2/24/89
HEC9	VER01	M1 V	60	77	1	11/22/88
PS injections and ejections						
FI16A	VER01	M1 V	32	38	1	7/05/91
FE16A	VER01	M1 V	60	28	1	11/26/91
FE16L	VER01	M1 V	34	26	1	8/19/91
FE16S	VER01	M1 V	49	22	1	1/21/91
FI42	VER01	M1 V	47	39	1	6/13/91
FE58L	VER01	M1 V	45	21	1	6/14/91
FE58S	VER01	M1 V	54	20	1	7/03/91
SE62	VER01	M1 V	62	8	1	11/22/88
CT	VER01	M1 V	39	19	1	8/01/91
transfer destinations						
ATP	VER01	M1 V	39	3	1	2/10/89
D3	VER01	M1 V	43	3	1	12/17/88
FTA	VER01	M1 V	24	3	1	12/17/88
FTS	VER01	M1 V	44	4	1	12/17/88
PS cycles / paliers						
A	VER01	M1 V	67	16	1	6/14/89
B	VER01	M1 V	54	12	1	2/24/89
C	VER01	M1 V	57	39	1	1/15/91
C17	VER01	M1 V	56	11	1	3/17/89
C35	VER01	M1 V	56	10	1	11/29/88
D	VER01	M1 V	29	5	1	3/08/89
E	VER01	M1 V	22	5	1	3/08/89

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