COMPUTER PROGRAMS IN ACCELERATOR PHYSICS

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Abstract

Two areas of accelerator physics are discussed in which computer programs have been used with much success: i) single-particle beam dynamics in circular machines, i.e. the design and matching of machine lattices, and tracking of particles through these lattices; much emphasis is put on the standardization of the machine description and the modular structure of the beam dynamics programs; (ii) computation of electromagnetic fields in RF cavities and similar objects, useful for the design of RF cavities and for the calculation of wakefields needed for stability calculations of intense beams.

Lectures at the 5-th US Summer School on
High-Energy Particle Accelerators
SLAC, July 15-26, 1985

Geneva, Switzerland
October 1986

Part 1

PROGRAMS FOR BEAM OPTICS

In this part, I shall discuss programs for *single-particle beam optics*, i.e. programs for studying the behaviour of particles in the external fields due to magnets, RF fields, etc., as described in contributions of B. Autin, R. Ruth, R. Servranckx, and E.J.N. Wilson to these proceedings. I have already treated this subject in the Second U.S. Summer School on High Energy Particle Accelerators [1]. This time, I do not discuss the wide field of simulation in accelerator physics. Other survey articles on the subject can be found in Reference [2]. This discussion will be divided into the following chapters:

- Lattice programs
- Standardization
- Keyword dictionary
- Standard messages
- Conclusions

1. LATTICE PROGRAMS

1.1 General-purpose lattice programs

In order to qualify as a general-purpose lattice program in my opinion, a program has to perform at least the following tasks (Most programs will do more):

- Read *properties* of elements, i.e. their type (drift space, dipole, quadrupole, etc.), length, strength (bending field or angle, gradient, etc.).
- Read *sequences* of elements, i.e. the order in which they appear in an accelerator or a beam line.
- *Calculate* the orbit functions α , β , D , D' , μ in the two transverse planes.
- *Vary* element parameters such that the orbit functions take prescribed values at specified positions, i.e. match lattices.
- *Track* particles through the accelerator for many turns and display the motion.

1.2 Examples of lattice programs

The more popular general-purpose lattice programs are:

- COMFORT [3] was developed at SLAC mainly for use in control systems.
- DIMAT/DIMAD [4] was developed at SLAC. It uses the first and second order formalism of TRANSPORT, and includes alignment and excitation errors on the elements, and the study of their effects.
- MAD [5] is being developed at CERN. It uses the TRANSPORT first and second order formalism. It includes the processing of alignment and excitation errors, and their correction.
- SYNCH [6] was started at IBL, but has contributions from elsewhere.
- TEAPOT [7] is a thin-element code developed at the SSC Central Design Group.
- TRANSPORT [8] was started at SLAC. It has been rewritten several times. It is mainly used for designing beam lines, but contains some commands in circular machine language. It now contains terms up to third order.

Listings of the lattice functions for the example in table 4 from DIMAD, MAD and SYNCH are shown in figure 1, figure 2, and figure 3.

OPERATION LIST		STANDARD PERIOD OF 100 M LENGTH											
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ELEMENT	#	BETAX	ALPHAX	BETAY	ALPHAY	ETAX	ETAPX	ETAY	ETAPY	NUX	NUY	LENGTH	ACC.LEN
QFH	1	168.699	0.0000	29.620	0.0000	1.2145	0.0001	0.0000	0.0000	0.0024	0.0131	2.475	2.475
DS	2	162.698	2.3955	30.915	-0.5296	1.1928	-0.0176	0.0000	0.0000	0.0034	0.0182	1.000	3.475
SF	3	157.948	2.3540	32.016	-0.5711	1.1752	-0.0176	0.0000	0.0000	0.0044	0.0231	1.000	4.475
DS	4	153.282	2.3126	33.199	-0.6125	1.1577	-0.0176	0.0000	0.0000	0.0054	0.0278	1.000	5.475
B	5	148.698	2.2712	34.466	-0.6539	1.1401	-0.0176	0.0000	0.0000	0.0064	0.0325	1.000	6.475
B	6	97.747	1.7859	57.716	-1.1792	0.9362	-0.0146	0.0000	0.0000	0.0074	0.0372	1.000	7.475
B	7	94.297	1.7045	60.115	-1.2206	0.9216	-0.0146	0.0000	0.0000	0.0084	0.0419	1.000	8.475
B	8	57.721	1.1792	97.741	-1.7459	0.7557	-0.0116	0.0000	0.0000	0.0094	0.0466	1.000	9.475
B	9	55.404	1.1378	101.273	-1.7873	0.7441	-0.0116	0.0000	0.0000	0.0104	0.0514	1.000	10.475
DT	10	33.204	0.6125	153.273	-2.3125	0.6163	-0.0086	0.0000	0.0000	0.0114	0.0562	1.000	11.475
QDH	11	30.920	0.5297	162.689	-2.3953	0.5992	-0.0086	0.0000	0.0000	0.0124	0.0610	1.000	12.475
QDH	12	29.625	0.0000	168.690	0.0000	0.5887	0.0001	0.0000	0.0000	0.0134	0.0658	1.000	13.475
DS	13	32.021	-0.5711	157.939	2.3539	0.5996	0.0088	0.0000	0.0000	0.0144	0.0706	1.000	14.475
SD	14	35.204	-0.6125	153.273	2.3125	0.6171	0.0088	0.0000	0.0000	0.0154	0.0754	1.000	15.475
DS	15	38.471	-0.6539	148.689	2.2711	0.6259	0.0088	0.0000	0.0000	0.0164	0.0802	1.000	16.475
B	16	57.721	-1.1792	97.741	1.7459	0.7560	0.0118	0.0000	0.0000	0.0174	0.0850	1.000	17.475
B	17	60.121	-1.2206	94.290	1.7045	0.7677	0.0118	0.0000	0.0000	0.0184	0.0898	1.000	18.475
B	18	97.747	-1.7859	57.716	1.1792	0.9359	0.0148	0.0000	0.0000	0.0194	0.0946	1.000	19.475
B	19	101.280	-1.7873	55.399	1.1378	0.9506	0.0148	0.0000	0.0000	0.0204	0.0994	1.000	20.475
B	20	153.282	-2.3126	33.199	0.6125	1.1568	0.0178	0.0000	0.0000	0.0214	0.1042	1.000	21.475
DT	21	162.698	-2.3955	30.915	0.5296	1.1924	0.0178	0.0000	0.0000	0.0224	0.1090	1.000	22.475
QFH	22	168.699	0.0000	29.620	0.0000	1.2145	0.0001	0.0000	0.0000	0.0234	0.1138	2.475	100.000

Figure 1: Output from the DIMAD program

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																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													

*** LISTING OF ORBIT FUNCTIONS FOR CELL SD									
POS	C	CYC	1	//	CELL	SD	SF		
POS	SIM	NUX	NUY	BETAX(M)	BETAY(M)	XEQ(M)	YEQ(M)	ZEQ (M)	ALPHAX ALPHAY DXEQ DYEQ
0	0.0000	0.00000	0.00000	168.68952	29.62454	1.21426	0.00000	0.00000	0.00000 0.00000 0.00009 0.00000
1 QFH	2.4750	0.00236	0.01311	162.68844	30.91992	1.19256	0.00000	0.00000	-0.39533 -0.1757 0.00000 0.00000
2 DS	3.9750	0.00386	0.02063	155.59565	32.60217	1.16620	0.00000	0.00000	-0.59181 -0.1757 0.00000 0.00000
3 SF	3.9750	0.00386	0.02063	155.59565	32.60217	1.16620	0.00000	0.00000	-0.59181 -0.1757 0.00000 0.00000
4 DS	5.4750	0.00543	0.02775	148.68922	34.47079	1.13984	0.00000	0.00000	-0.65394 -0.1757 0.00000 0.00000
5 B	18.1583	0.02221	0.07364	97.74054	57.72140	0.93596	0.00000	0.00310	1.74588 -1.17923 -0.01457 0.00000
6 DB	19.1583	0.02387	0.07634	94.29019	60.12127	0.92139	0.00000	0.00310	-1.22064 -0.01457 0.00000 0.00000
7 B	31.8417	0.05137	0.10280	57.71556	97.74729	0.75555	0.00000	0.00561	1.17920 -1.74593 -0.01158 0.00000
8 DB	32.8417	0.05418	0.10440	55.39857	101.28057	0.74397	0.00000	0.00561	1.13778 -1.78735 -0.01158 0.00000
9 B	45.5250	0.10197	0.12063	33.19941	153.28201	0.61618	0.00000	0.00764	-2.31264 -0.00858 0.00000 0.00000
10 DT	47.5250	0.11191	0.12264	30.91519	162.69822	0.59903	0.00000	0.00764	-2.39547 -0.00858 0.00000 0.00000
11 QFH	50.0000	0.12502	0.12501	29.61995	168.69964	0.58856	0.00000	0.00764	0.00000 0.00009 0.00000 0.00000
12 QFH	52.4750	0.13813	0.12737	30.91519	162.69822	0.59947	0.00000	0.00764	-0.52963 2.39547 0.00876 0.00000
13 DS	53.9750	0.14565	0.12887	32.59728	155.60500	0.61260	0.00000	0.00764	-0.59176 2.33334 0.00876 0.00000
14 SD	53.9750	0.14565	0.12887	32.59728	155.60500	0.61260	0.00000	0.00764	-0.59176 2.33334 0.00876 0.00000
15 DS	55.4750	0.15278	0.13044	34.46577	148.69816	0.62574	0.00000	0.00764	-0.65389 2.27122 0.00876 0.00000
16 B	68.1583	0.19867	0.14721	57.71556	97.74729	0.75581	0.00000	0.00970	-1.17920 1.74593 0.01176 0.00000
17 DB	69.1583	0.20137	0.14887	60.11538	94.29485	0.76757	0.00000	0.00970	-1.22062 1.70452 0.01176 0.00000
18 B	81.8417	0.22783	0.17637	97.74057	57.72140	0.93569	0.00000	0.01225	-1.74588 1.17923 0.01475 0.00000
19 DB	82.8417	0.22943	0.17918	101.27374	55.40436	0.95044	0.00000	0.01225	-1.78730 1.13781 0.01475 0.00000
20 B	95.5250	0.24566	0.22696	153.27286	33.20834	1.15660	0.00000	0.01540	-2.31249 0.61252 0.01775 0.00000
21 DT	97.5250	0.24767	0.23690	162.68848	30.91992	1.19211	0.00000	0.01540	-2.39532 0.52969 0.01775 0.00000
22 QFH	100.0000	0.25004	0.25001	168.68952	29.62454	1.21426	0.00000	0.01540	0.00000 0.00009 0.00000 0.00000
CIRCUMFERENCE = 100.0000 M									
RADIUS = 15.9155 M									
{DS/S}/(DP/P) = 0.0001540									
THETA = 0.01800000 RAD NUX = 0.25004 DNUX/(DP/P) = 0.00000									
TGAMMA = 80.58216, 0.000000									
MAXIMA	BETX(22) =	168.68952	BETY(11) =	168.69964	XEQ(11) =	1.21426	YEQ(22) =	0.00000	
MINIMA	BETX(11) =	29.61995	BETY(22) =	29.62454	XEQ(11) =	0.58856	YEQ(22) =	0.00000	
SEXTUPOLE CORRECTIONS ----- DKSF = -0.17910621E-18 DKSD = 0.63155356E-18 KSF = -0.53063590E-01 KSD = 0.27873820E-01									
AMPLITUDE DEPENDENCE OF TUNES DUE TO SEXTUPOLES									
NU-X = 0.250038 - 0.248E+00EX - 0.119E+02EY									
NU-Y = 0.250011 - 0.119E+02EX + 0.343E+01EY									

Figure 3: Output from the SYNCH program

In addition to the general-purpose lattice programs, there is a series of popular programs which perform more specific calculations:

- ALIGN [9] simulates alignment procedures, computes alignment errors, and corrects the closed orbit.
- HARMON [10] computes effects due to sextupoles, and adjusts sextupole strengths.
- MARYLIE [11] uses Lie-algebraic techniques, mainly for tracking.
- PATRICIA [12] calculates optics and beam parameters in electron storage rings, chromatic effects, and tracks without and with synchrotron oscillations.
- PETROS [13] simulates alignment errors, computes and corrects the closed orbit, and computes beam parameters.
- TURTLE [14] tracks many particles through a beam line and prints histograms of particle distributions. It belongs to the TRANSPORT family.

1.4 Consequences

The large number of programs for doing beam optics has good and (mostly) bad consequences:

- Considerable overlap between the calculations done by the different programs.
- No single program for all calculations.
- Study of a single machine needs several programs.
- Machine descriptions needed in the dialects of all programs used.
- Transfer of results between programs has to be done "by hand" or by translation programs.

Most people have a collection of favourite programs which they use for their daily work. Not all features of all programs are used by everybody.

Many programs make approximations, usually in order to gain speed, and valid for the machine the author was working on when he developed the program. This may limit the range of machines which can be studied by a given program. Since computers become faster more rapidly than people, programs with fewer approximations should be used more often which are applicable to a wider range of accelerators.

2. STANDARDIZATION

Many of the difficulties described can be overcome by adopting a *standard language for describing accelerators*. The transfer of results between programs can be solved by a *standard message system* and a *standard data structure*.

All programs which conform to the standards become modules, i.e. subroutine packages, of one common framework for beam-optics calculations, and can easily exchange messages in both directions.

Physics modules can use a standard command language whose syntax is defined in the data, and analyzed in a *keyword dictionary*. They are easy to write because command analysis, data input and data storage have been solved once and for all by professional programmers.

It should be stressed that the intention is not to standardize the *physics* contained in a module, but rather the *form* in which the module interacts with the user and other modules. Several modules doing (almost) the same physics could co-exist in the same environment.

2.1 Standard input language

A workshop for the standardization of the input language for beam optics programs, held at SLAC in May 1984, agreed upon a language [15] which describes:

- the "*elements*" i.e. drift spaces, dipoles, quadrupoles, RF cavities, beam position monitors, etc.
- the "*beam lines*", i.e. the order in which the elements occur in the accelerator

COMFORT, DIMAD, MAD and TEAPOT already use this input language. Other programs will hopefully use it in future. My description includes *extensions* a little beyond the agreed standard.

2.2 Elements

Table 1: Examples of Element Definitions

D1	: DRIFT, L=3
B	: RBEND, L=2, ANGLE=0.02
QT	: QUADRUPO, L=LMQT, K1=0, TILT, TYPE=MQT

In the standard input language elements are defined by statements as shown in table 1. All commands are constructed according to a standard syntax, consisting of a label, a keyword, and attributes:

label: keyword [,f₁] ... [,f_m] [,p₁=v₁] ... [,p_n=v_n]

The label identifies the element, and must be unique. In MAD, an element is redefined when a given label appears more than once. The keyword defines the physical nature of the element. The f_i and p_k=v_k clauses are called attributes. They may appear in any order. Any one of them may be absent, in which case the default value is taken. The names p_k of the attributes are defined in the command language as will be discussed in Chapter 3 on page 10. The values v_k can be constants, parameters defined beforehand, and expressions. The attributes may appear in any order. The TILT attribute in table 1 turns the quadrupole by exactly $\pi/4$ radians. The input format is free. Statements may be continued on the next line, if a line ends with the & symbol. The layout of the examples is intended to improve the readability. The available element types are shown in table 2.

2.3 Beam lines

Examples of beam line definitions are shown in table 3. A machine is described by a nested set of beam lines, starting with cells which are assembled into arcs and insertions. An achromat consists of two identical halves with 180° phase advance each. In general, the definition of a beam line may include the following items:

- Names of elements
- Names of beam lines
- Repetition factors
- Reflection, indicated by - sign
- Formal arguments

Table 2: Available Elements

DRIFT	Drift space
RBEND	Rectangular dipole magnet
SBEND	Sector dipole magnet
QUADRUPO	Quadrupole
SEXTUPOL	Sextupole
OCTUPOLE	Octupole
MULTIPOL	Zero length multipole
SOLENOID	Solenoid
RFCAVITY	RF accelerating cavity
ELSEPARA	Electrostatic separator
SROT	Rotation around beam axis
YROT	Rotation around vert. axis
HKICK	Horizontal orbit kicker
VKICK	Vertical orbit kicker
HMONITOR	Horizontal position monitor
VMONITOR	Vertical position monitor
MONITOR	Beam position monitor
MARKER	Position identifier
ECOLLIMA	Elliptical collimator
RCOLLIMA	Rectangular collimator

Table 3: Examples of Beam Lines

Simple beam lines:

```

PERIOD      :   LINE=(QF, D, SF, D, B, D, QD, D, SD, D, B, D)
ARC         :   LINE=(30*PERIOD)
HSUP        :   LINE=(INS1, ARC, INS2)
SUP         :   LINE=(HSUP, -HSUP)

```

Achromat consisting of 6 periods with 60° phase advance:

```

PERIOD      :   LINE(SF,SD)=(QF,D,SF,D,B,D,QD,D,SD,D,B,D)
ACHROMAT    :   LINE=(2*(PERIOD(SF1,SD1), &
                  PERIOD(SF2,SD2), &
                  PERIOD(SF3,SD3)))

```

2.4 Complete example

A complete example is shown in table 4. It is set up in such a manner that the length of the bending magnets LB is calculated such that the total period length LP remains constant, when LQ is varied during matching. A parameter is defined by the following statement:

label := expression

Table 4: Complete Example

```

TITLE!
Standard period of 100 m length
LQ      :=      4.95
PHI     :=      0.003
LP      :=      100
SF      :      SEXT, L=1
SD      :      SEXT, L=1
DS      :      DRIF, L=1
DT      :      DRIF, L=2
DB      :      DRIF, L=1
LB      :=      (LP/2 - LQ - 2*DS[L] - 2*DB[L] - SF[L] - DT[L])/3
B       :      RBEN, L=LB, ANGLE=PHI, FINT
TESLA   :=      10
BRHO    :=      TESLA*LB/PHI
GRAD    :=      250
KQ      :=      GRAD/BRHO
QFH     :      QUAD, L=LQ/2, K1=KQ
QDH     :      QUAD, L=LQ/2, K1=-KQ
PERIOD  :      LINE=(QFH, DS, SF, DS, B, DB, B, DB, B, DT, QDH, &
                QDH, DS, SD, DS, B, DB, B, DB, B, DT, QFH)

```

2.5 Standard command language

The concept of a standard language has been extended [16] to the *commands* which operate on a beam line, and perform a beam-optical calculation. The standard command syntax is the same as the standard element syntax, i.e.

label: keyword [,f₁] ... [,f_m] [,p₁=v₁] ... [,p_n=v_n]

This results in the following benefits:

- One standard language is easier to remember than several different languages for the commands.
- The names of commands and all their attributes are defined as data, and not imbedded in code. They are analyzed by the standard KEYWORD processor, and become part of the general command repertoire.
- The routine for a new calculation (a new "physics module") need not contain code for understanding and organizing its input data, and hence becomes smaller, less error-prone, and easier to debug.

3. KEYWORD DICTIONARY

The syntax of a command is presented to the program in the data. The command which declares how a quadrupole is to be defined is shown in table 5:

Table 5: Definition of Quadrupole Keyword

QUADRUPO:	KEYWORD, MT=2, PR=1, SP=5, & L = (R*1, =0, >0, <100, /0), & K1 = (R*1, =0, >-10, <10, /0), & TILT = (D*1, =0, >-PI/2, <PI/2, /PI/4)
-----------	--

- The general appearance of the command follows the standard syntax: label, colon(:), command keyword, attributes. The label contains the name of the command. The command keyword is KEYWORD.
- The MT, PR, and SP attributes define the unique position of the QUADRUPO command in the command tree. They are called module type, process code, subprocess code.
- The last 3 lines define the attributes proper. The first attribute has the name L. It consists of one real number with assigned value (=) and default value (/) 0. The bounds for L are 0 and 100. The second and third attributes are called K1 and TILT, respectively. They also have assigned and default values, and upper and lower bounds. For the TILT attribute, the default value is $\pi/4$. This value is taken when the clause "TILT" appears without a value.

A second example is the command SURVEY which calculates the position of the elements in a beam line in a Cartesian coordinate system as shown in figure 5. At the entrance of the first element, it needs 3 coordinates x_0 , y_0 , z_0 , and 3 angles θ_0 , ϕ_0 , ψ_0 . The keyword definition of the SURVEY command is shown in table 6.

Table 6: Definition of the Survey Keyword

SURVEY:	KEYWORD, MT=6, PR=2, SP=1, DK=2, & X0 = (R*1, =0, >-10, <10, /0), & Y0 = (R*1, =0, >-10, <10, /0), & Z0 = (R*1, =0, >-10, <10, /0), & PHI0 = (R*1, =0, >-PI, <PI, /0), & THETA0 = (R*1, =0, >-PI, <PI, /0), & PSIO = (R*1, =0, >-PI, <PI, /0), & TAPE = (L*1, =.F., /.T.)
---------	--

Figure 5: Global coordinate system

4. STANDARD MESSAGES

Messages are deposited into and read from a large memory pool [16]. All messages are uniquely identified by their name. The command

QF: QUAD, L=2, K1 = 0.01

deposits a message with the name QF, the command type QUADRUPO, and all the attributes (including those defined by default) in the standard format for quadrupoles. Standard messages are the only means by which physics modules exchange information.

A service routine expands a beam line into a linear list of pointers. A physics module operating on that beam line obtains access to the messages corresponding to the elements in it by running through this list of pointers. In order to speed up the search of the memory pool, the messages are arranged in several linked lists. The pointers from one message to the next in the list are stored in a message header.

In general, messages may consist of any of the following:

- Keyword definitions
- Element definitions
- Beam line definitions
- Beam line expansions
- Command definitions
- Vectors of intermediate results
- Working space for modules

The memory pool is managed by *service routines*. They can also be called by the physics modules in order to create, find, modify and delete messages. Prototypes of the memory pool and of the service routines have been implemented in MAD Version 5.

5. CONCLUSIONS

- The general-purpose and specialized beam-optics programs compute more or less all the things needed in the design of accelerator lattices.
- A standard language has been defined and is being implemented in a few of these programs. It makes calculations much easier.
- Much double work could be avoided, and progress in the field of beam-optical computations could be much faster if all new physics modules were written in the standard language.
- Beam-optics programs are needed both for the design and the operation of accelerators from their control system. The standards discussed could also be used to make programs transportable between control systems.

Part 2

PROGRAMS FOR ELECTROMAGNETIC FIELDS

In this part, I shall discuss programs for the *computation of electromagnetic fields* occurring in accelerators, i.e. fields in RF cavities, wakefields due to moving charges, as described in contributions of G. Dôme and B. Zotter to these proceedings. This discussion will be divided into the following chapters:

- Electromagnetic programs
- FIT programs
- Conclusions

6. ELECTROMAGNETIC PROGRAMS

Electromagnetic field computations are needed to solve several problems occurring in accelerator engineering and accelerator physics. The most conspicuous applications are:

6.1 Applications of EM field calculations

- **Static magnetic fields B** in the magnetic elements of the beam-optical lattice must depend on the coordinates x, y, z in a prescribed manner, i.e. pure dipole, quadrupole, etc. fields. The magnets must be designed accordingly. When the magnets are not very long compared to their aperture, field computations may have to be done in three dimensions. A survey of these programs is given in [17]. I shall not discuss them here.
- **Oscillating EM fields** in the RF cavities used for acceleration must resonate at a prescribed frequency, and the cavity dimensions must be chosen accordingly. For a given RF power, the accelerating field should reach a maximum.
- **Wakefields** are excited by the passage of intense bunched beams through RF cavities and similar objects. Their knowledge is an essential ingredient for stability calculations.

6.2 Classes of computer programs

The shape of the objects for which electromagnetic fields are computed by cavity and wakefield programs determines the mathematical approach. The most common techniques are:

- For cavities with all boundaries coincident with planes parallel to the coordinate axes, i.e. rectangular and pillbox cavities as shown in figure 5, the fields are given by *closed expressions* which may be evaluated by programs. These programs are simple enough that they are written as needed, but not documented, distributed, etc.
- Cavities with boundaries consisting of pieces of planes parallel to the coordinate axes, as shown in figure 6, can often be split into regions for which general field expansions are known in closed form. The free constants are then determined by *field matching*. Two well-known field matching programs compute travelling wave modes in infinite periodic structures of cylindrical geometry: KN7C [18] computes accelerating modes with no dependence on the azimuth θ . TRANSVRS [19] computes deflecting modes with fields varying like $\sin\theta$ or $\cos\theta$. An example of KN7C output is shown in figure 7. It gives the resonant frequency f_0 of the accelerating mode in the SLAC two-mile linac, the loss factor k_{rf} , and the expansion coefficients of the electric field.

- For cavities with oblique boundaries with respect to the coordinate axes, as shown in figure 8, purely numerical finite integration techniques (FIT) are needed.

Figure 5: Simple pillbox cavity (from [20])

Figure 6: Disk-loaded waveguide

09/10/86 16.52.04

DIFFRACTION RADIATION OF CHARGED PARTICLES MOVING IN A CORRUGATED CYLINDRICAL PIPE

A (TUBE RADIUS) = 0.01152 M FMIN (STARTING FREQUENCY) = 2.500000000E+09 1/SEC
 B (CAVITY RADIUS) = 0.04167 M FMAX (END FREQUENCY) = 3.000000000E+09 1/SEC
 D (PERIOD) = 0.03500 M IFR (NUMBER OF STEPS) = 3
 G (CAVITY GAP) = 0.02911 M GAMMA = 1.0000E+04
 H (PITCH) = 0.00000 M ISMAX = 20
 IC (NO. OF CELLS) = 1 IMAX = 20

KPR = T
 SOLVPR = T
 PLOT = F
 ISOLV = T

F = 2.500000000E+09 DET = -9.459E+08
 F = 2.7613402543E+09 DET = -2.554E+08
 F = 3.000000000E+09 DET = 2.797E+09

SURCH NEX = 12 DET = -1.477E-06 FZERO = 0.2811073660*10 WAVELENGTH = 1.697E-02 M KM = 6.787466E-01 V/PC

SOLVE	BACKWARD XSI	FORWARD XSI	BACKWARD TW	FORWARD TW	AXIAL INTEGRAL	SLOT INTEGRAL	EVEN S.W.	ODD S.W.	GAMMA	GAMMA'
1	-1.0523E+02	-0.5892E+02	6.1472E-01	0.1000E+01	0.4947E-25	0.2571E-24	0.1392E+01	-2.5567E-02	0.5892E+02	-9.0421E+01
2	-2.9428E+02	-4.1378E+02	-2.8205E-01	-1.6294E-01	6.5937E-26	2.5781E-25	-1.5780E-01	3.2285E-02	-2.0765E+02	-3.1836E+02
3	-4.7601E+02	-5.9456E+02	1.6167E-01	2.6721E-02	6.7812E-26	2.5801E-25	1.4407E-01	-4.2765E-02	-4.2765E+02	-5.3638E+02
4	-6.5652E+02	-7.7476E+02	-6.9431E-02	-9.0743E-02	6.8247E-26	2.5811E-25	-1.2380E-01	2.5052E-02	-6.4484E+02	-7.5312E+02
5	-8.3661E+02	-9.5470E+02	5.2102E-03	1.0414E-01	6.8340E-26	2.5819E-25	1.6890E-01	-2.0004E-02	-8.6136E+02	-9.6950E+02
6	-1.0165E+03	-1.1345E+03	5.8429E-02	-9.2609E-02	6.8473E-26	2.5821E-25	-9.8008E-02	-1.6832E-02	-1.0776E+03	-1.1857E+03
7	-1.1963E+03	-1.3142E+03	-8.6441E-02	6.2710E-02	6.8508E-26	2.5821E-25	8.9821E-02	-1.2456E-02	-1.2937E+03	-1.4017E+03
8	-1.3760E+03	-1.4933E+03	8.8988E-02	-2.3332E-02	6.8630E-26	2.5824E-25	-8.3520E-02	1.1123E-02	-1.5098E+03	-1.6177E+03
9	-1.5556E+03	-1.6736E+03	-7.0055E-02	-1.5836E-02	6.8705E-26	2.5825E-25	7.8598E-02	-1.0014E-02	-1.7257E+03	-1.8337E+03
10	-1.7353E+03	-1.8533E+03	3.7149E-02	4.6203E-02	6.8720E-26	2.5826E-25	-7.1743E-02	9.0781E-03	-2.1576E+03	-2.2656E+03
11	-1.9149E+03	-2.0328E+03	3.4507E-04	-6.1925E-02	6.8735E-26	2.5827E-25	6.9498E-02	-8.2519E-03	-2.5894E+03	-2.6975E+03
12	-2.0945E+03	-2.2124E+03	-5.4253E-02	6.0930E-02	6.8750E-26	2.5827E-25	-6.7960E-02	7.4768E-03	-3.0212E+03	-3.1292E+03
13	-2.2741E+03	-2.3919E+03	5.8253E-02	-1.9390E-02	6.8765E-26	2.5828E-25	6.7268E-02	-6.6841E-03	-3.4530E+03	-3.5609E+03
14	-2.4537E+03	-2.5715E+03	-5.8604E-02	9.2109E-03	6.8780E-26	2.5829E-25	-6.8723E-02	4.4532E-03	-3.8817E+03	-4.0065E+03
15	-2.6332E+03	-2.7511E+03	5.0110E-02	-9.2109E-03	6.8795E-26	2.5829E-25	7.3125E-02	-7.1476E-03	-4.3142E+03	-4.4386E+03
16	-2.8128E+03	-2.9306E+03	-2.9000E-02	3.733E-02	6.8810E-26	2.5830E-25	-1.0632E-01	3.1426E-02	-4.8689E+03	-5.0065E+03
17	-2.9923E+03	-3.1102E+03	2.6945E-03	4.8674E-02	6.8825E-26	2.5831E-25	9.8900E-02	-2.0362E-02	-5.4386E+03	-5.5689E+03
18	-3.1719E+03	-3.2897E+03	-5.1211E-02	-5.1211E-02	6.8840E-26	2.5831E-25	-8.7362E-02	1.6362E-02	-6.0065E+03	-6.1386E+03
19	-3.3514E+03	-3.4693E+03	3.8610E-02	4.1671E-02	6.8855E-26	2.5832E-25	7.9447E-02	-1.6362E-02	-6.6894E+03	-6.8215E+03
20	-3.5310E+03	-3.6488E+03	4.3934E-02	-2.3234E-02	6.8870E-26	2.5833E-25	7.9447E-02	1.6362E-02	-7.3185E+03	-7.4506E+03

SOLVE SUM OF AXIAL AND SLOT INTEGRALS= 3.2715E-25 NORMALISATION FACTOR= 5.8797E+17

Figure 7: Output of the KN7C program

Figure 8: Cavity with oblique boundaries and triangular mesh (from [21])

7. FIT PROGRAMS

7.1 Classes of FIT programs

FIT programs may be grouped according to the following criteria:

- They compute *cavity modes*, i.e. solutions of the Maxwell equations in the absence of a driving beam, or *wakefields* in the presence of a driving beam. SUPERFISH[22], and URMEL[23] are typical examples of cavity programs, while BCI[24] and TBCI[25] are wakefield programs.
- The geometry of the beam/cavity system is cylindrically symmetric (*2D*), as in SUPERFISH, URMEL, BCI and TBCI, or three-dimensional (*3D*).
- The mesh is *triangular*, as shown in figure 8, or *rectangular*, as shown in figure 9.

The integral form of the Maxwell equations is more convenient for FIT techniques than the differential form. They relate the field components at one mesh point to the field components at all its neighbours. For a grid with N nodes, the field components can be assembled into column vectors and the Maxwell equations in FIT form can be written as equations involving large sparse matrices. The time

Figure 9: Cavity with rectangular mesh (from [23])

derivatives in the Maxwell equations are removed by introducing discrete time steps, and using the central difference operator. This scheme allows the calculation of all fields from previous values and the driving current by simple multiplications of sparse matrices with vectors. No matrix inversion or eigenvalue-finding is needed. This scheme also conserves energy.

7.2 Bellows

The electric field lines due to the passage of a bunch with $\sigma = 10$ mm through a bellows with 10 convolutions and inner/outer radius of 60 and 70 mm are shown in figure 10. Bellows dominate the impedance in large p-p colliders such as the SSC.

7.3 LEP RF cavity

The electric field lines due to the passage of a bunch with $\sigma = 45$ mm through an RF cavity for the LEP e^+e^- storage ring under construction at CERN are shown in figure 11.

Figure 10: Electric field lines due to a bunch passing a bellows (from [26])

Figure 11: Electric field lines due to a bunch passing a LEP RF cavity (from [24])

8. CONCLUSIONS

The field of electromagnetic field computations is advancing. References [26], [27] give recent surveys of the state of these programs. Truly three-dimensional programs for specific geometries have been written and used. Similar programs for arbitrary geometries should be available soon.

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