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EXTENSION OF MAD VERSION 8 TO INCLUDE BEAM ACCELERATION*

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In this paper, we describe modifications to MAD version 8.23 to include linear accelerator cavities and beam acceleration. An additional energy variable has been added which is modified as the beam passes through LCAV elements (linear accelerator cavities) and can be used as a constraint in matching commands. The calculation of the beta functions and phase advance is consistent with that in other codes that treat acceleration such as TRANSPORT or DIMAD. These modifications allow this version of MAD to be used for the design and modeling of linacs and we present examples from the Next Linear Collider design as well as a muon acceleration complex. The code is available from CERN or SLAC.

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In this paper, we describe modifications to MAD version 8.23 to include linear accelerator cavities and beam acceleration. An additional energy variable has been added which is modified as the beam passes through LCAV elements (linear accelerator cavities) and can be used as a constraint in matching commands. The calculation of the beta functions and phase advance is consistent with that in other codes that treat acceleration such as TRANSPORT or DIMAD. These modifications allow this version of MAD to be used for the design and modeling of linacs and we present examples from the Next Linear Collider design as well as a muon acceleration complex. The code is available from CERN or SLAC.

1 INTRODUCTION

The MAD (Methodical Accelerator Design) program was first developed at CERN in the early-1980's. Since then it has become the standard optics design tool for storage rings and transport lines. Although the program is extremely useful, it's capability has been limited to beamlines without acceleration. In this paper, we describe modifications to version 8.23 of MAD to support beam acceleration in a linac or a recirculating linac. In addition, we describe modifications to generalize the Standard Input Format (SIF) [1] to support linear accelerators. This generalized input language, referred to as XSIF, is used by the new version of MAD as well as DIMAD [2] and the linear accelerator simulation program LIAR [3]. Finally, a few examples calculated with this new version of MAD are presented.

2 MAD 8.23/ACC

The most significant modification to this new version of MAD is the addition of linear acceleration and the resulting variation of the beam energy. These additions were made to MAD version 8.23/0 which is written in standard Fortran 77. The code now allows the beam energy to be specified at the entrance to a beamline and this energy will be modified by LCAVITY elements which model traveling wave accelerator cavities; note the LCAVITY elements are treated differently from the standard MAD RFCAVITY elements which do not modify the beam energy. This allows the code to be used for both storage rings and linacs.

The LCAVITY elements are specified as below:
LCAVITY (traveling wave structure element type)

L	length (m)
E0	for consistency with DIMAD (not used in MAD8acc)
DELTAE	voltage gain in structure (GeV)
PHI0	cavity phase from the rf crest (rad/2π)
FREQ	rf frequency (MHz)
ELOSS	loss factor for the structure (V/C) – used for nominal energy calculation
VOLTERR	error on rf voltage – used for tracking only
LAGERR	rf phase error – used for tracking only
NBIN	bins to use for tracking with wakefields
BINMAX	maximum length for bins
LFILE	longitudinal wakefield file for tracking
TFILE	transverse wakefield file for tracking

All of these parameters are treated like all other MAD element parameters and can be specified in terms of expressions, varied during matching, etc.

The beam energy can be used as a matching constraint in the CONSTRAIN and WEIGHT commands and is also included in the BETA0 structures. In addition, the initial beam energy is explicitly set via the ENERGY attribute in the TWISS, OPTICS, or MATCH commands or implicitly set via the BETA0 attribute. Alternately, the initial beam energy can be set using the BEAM command.

The calculation of the lattice functions has been modified to incorporate the variation in the beam energy. There are a couple of different methods of including the energy variation in the lattice functions. We could have maintained the original definition utilized in MAD where the lattice parameters simply depend on the transfer matrix [4]:

$$\beta_2 = \frac{1}{\beta_1}((R_{11}\beta_1 - R_{12}\alpha_1)^2 + R_{12}^2) \qquad (1)$$

etc., but this leads to lattice functions that, for a given periodic cell structure, decrease with acceleration as $1/E(s)$. For this reason, we normalize the individual transfer elements by the determinant of the transfer matrix. This leads to the more common definition which is consistent with that used in TRANSPORT [5] and DIMAD.

The LCAVITY elements also include approximate representation of the focusing that arises at the entrance and exit of the accelerator structures. The focusing and defocusing arises from the fringing fields at the accelerator structure irises and, although the effect is small, it can be significant in the low energy ($\sim 100\,\mathrm{MeV}$) regions [6, 7]. In MAD, the fringing fields are represented as thin lenses with focal lengths of:

$$\frac{1}{f} = \pm\frac{1}{2}\frac{\gamma'}{\gamma} \qquad (2)$$

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where γ and γ' are the beam energy and the accelerator gradient in units of the particle mass and the positive sign corresponds to the structure entrance while the negative sign corresponds to the exit. Finally, one can also specify files containing the transverse and longitudinal wakefields for the structures which are used when tracking.

In addition, three other changes have been implemented. First, different fringing fields can be specified for the upstream and downstream ends of bending magnets using a FINTX parameter in the element definition. This provides greater flexibility when splitting components into multiple segments and can be used to prevent the error that arises when FINT$\neq 0$ in split bending magnets. Second, an approximation for the effect of coherent synchrotron radiation in the bending magnets can be used when tracking by setting a CSR parameter for bending magnets. Finally, the beamline length CIRC has also been added as a matching constraint since it is frequently desirable to minimize to overall length of the system.

A more complete description of the changes that have been implemented is available at: http://www-project.slac.stanford.edu/lc/local/AccelPhysics/Codes /Mad/MAD8acc.html and the code is available from either the above site or http://wwwslap.cern.ch/ hansg/src/accel.

3 EXTENDED STANDARD INPUT FORMAT (XSIF)

The Standard Input Format (SIF) was proposed at Snowmass 1984 to unify the beamline descriptions [1]. This input language is used by MAD and DIMAD, as well as many other programs. However, SIF as it was implemented does not have the flexibility to treat beam acceleration. Thus, a few modifications have been made to this language:

- The keywords, parameters, and syntax of the present-day MAD and DIMAD input parsers have been made consistent, generally by adopting the present MAD syntax where conflicts existed
- Apertures have been added to most elements (APERTURE parameter) for use in tracking
- The DIMAD element LCAV, which describes a linear accelerator structure, has been added to MAD; the original LCAV syntax has been extended to allow filenames for wakefield data to be included in the element description
- A number of instrument types (BLMO, SLMO, PROFILE, WIRE, IMONITOR) have been added
- All elements can take a 16 character alphanumeric engineering class (TYPE parameter) and a 24 character alphanumeric database name (LABEL parameter) as parameters
- The DIMAD parameter FINTX (exit-face fringe-field integral) has been added to MAD to improve description of bend magnets which are split into multiple elements in the deck.

The resulting beamline description language is known as the Extended Standard Input Format (XSIF) [8]. The present versions of MAD and DIMAD will read a beamline description written in XSIF. In addition, a stand-alone library version of the DIMAD XSIF parser has been created which can be linked to any new or existing application. The present version of LIAR [3] has been so linked.

In addition to the XSIF standard, a fully-instantiated sequential ASCII beamline description was desired. The MAD tape format [9] was enhanced to include new beamline features (beam energy, engineering and database names, new instrument classes, and linac RF structures), resulting in the Extended Tape File Format (XTFF) which can be generated by MAD 8.23/acc or the NLC group's version of DIMAD [10]. The SURVEY XTFF provides a compact lattice description that can be used by the engineering teams for component layout while the TWISS XTFF is used to transfer the lattice information into an Oracle database which could become the backbone of the control system and provides a straightforward method of tracking components.

4 EXAMPLES

In the following, we present three examples using MAD 8.23/acc: the Source Development Laboratory (SDL) linac which is a 200 MeV linac constructed at BNL [11]; a recirculating linac for a muon collider or storage ring that is being designed at CERN [12]; and the main linac for the Next Linear Collider that is being designed by a US/Japan collaboration [13, 14, 15].

The SDL is a low energy electron injector for that will provide beam to an undulator to test the SASE FEL action. It consists of four 3-meter S-band accelerator structures separated by a magnetic chicane for bunch compression. The optics are plotted in Fig. 1 starting at the end of the first structure at 40 MeV. Here, the beta functions have been matched through the chicane to reduce the emittance dilution due to the coherent synchrotron radiation and matched at the end of the line for the emittance diagnostic.

In Fig. 2, the optics are plotted through four turns of the second recirculating linac where the beam is accelerated from 10 GeV to 50 GeV. One can see from the dispersion (shown in grey) where the arcs and dispersion-free linacs are located. Each linac is roughly 2 km in length and, as the beam energy increases, the beta functions increase because of the reduced focusing from the quadrupole magnets.

Finally, in Fig. 3, the optics in one of the linacs of the Next Linear Collider is plotted. The linac tunnels are roughly 11 km in length. Initially, only half of the tunnel would contain accelerator sections and the linac would accelerate the beams from 8 GeV to 250 GeV. The optics has been matched to allow the beta function to increase as the beam energy increases. After reaching 250 GeV, the beams are matched into a weak focusing lattice and drift through the second half of the linac tunnel. In a later upgrade, additional accelerator structures would be added to accelerate the beams to 500 GeV for collisions at 1 TeV in

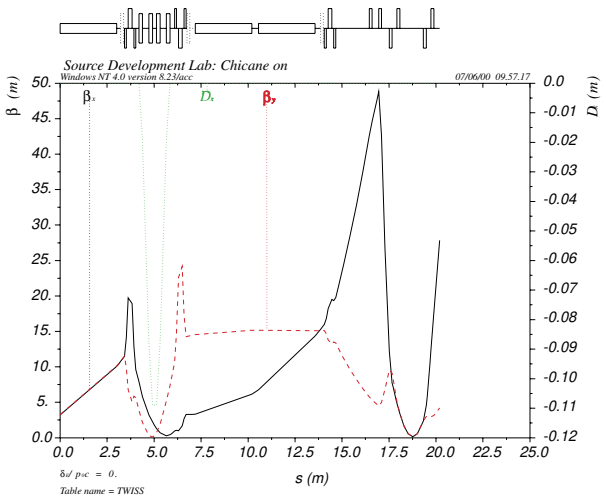

Figure 1: Linac for the SDL from 40 MeV through 200 MeV [16].

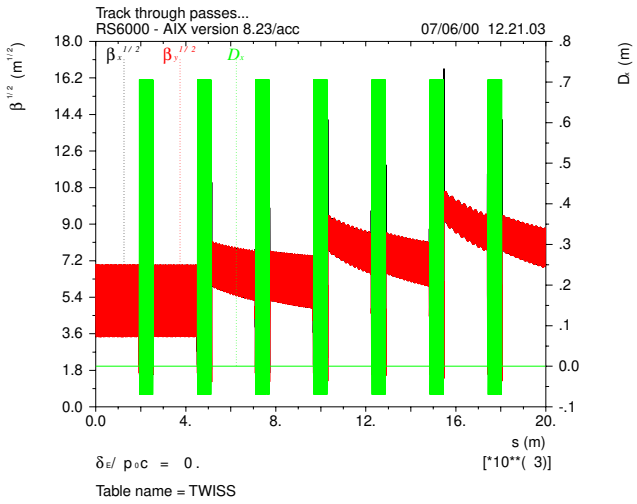

Figure 2: A recirculating linac for the muon storage ring which accelerates the beam from 10 to 50 GeV in 4 passes.

the center-of-mass. Finally, one can also see the dispersion in the energy diagnostic chicanes located at 1 and 3.5 km.

5 SUMMARY

In this paper, we describe a new version of MAD that will treat beam acceleration so that the power of the MAD program can be used when designing linear accelerators. The code is available from either CERN or SLAC.

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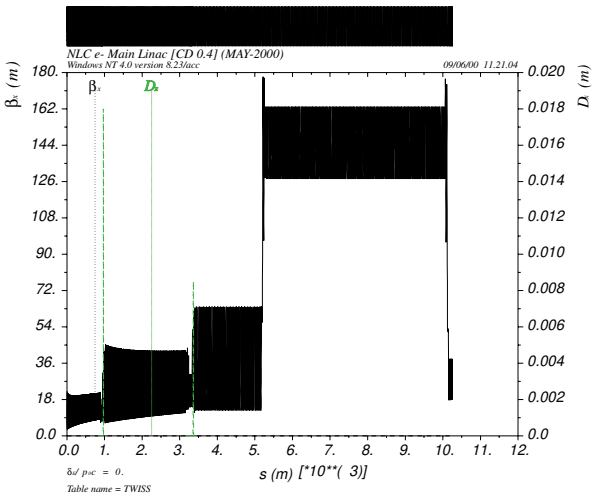

Figure 3: Optics in one of the NLC main linacs which accelerate the beams from 8 GeV to 250 GeV.

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