Unified Accelerator Modeling Using the Bmad Software Library *

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Abstract

The Bmad software library has proved to be a useful tool for accelerator simulations owing to its modular, object-oriented design. It is now used in a number of design, simulation, and control programs at Cornell's Laboratory for Elementary-Particle Physics. Work is ongoing to expand Bmad in a number of directions. One aim is to have a complete framework in order to simulate Cornell's Energy Recovery Linac from gun cathode (including space-charge) to photon generation to photon tracking through to the x-ray experimental end stations. Other work includes synchrotron radiation tracking including reflections from the vacuum chamber walls, spin tracking, beam break-up instability, intra-beam scattering, etc. This paper will discuss the current state of the Bmad software along with the long-term goals.

INTRODUCTION

The open source Bmad subroutine library[1], developed at Cornell University's Laboratory for Elementary Particle Physics, is an object oriented framework for the simulation of charged-particle and x-ray beams.

With the advent of Cornell's Energy Recovery Linac (ERL) project[2], it has become clear that the ability of Bmad to do a "complete" front-to-end simulation beginning from electron generation at the gun cathode, through x-ray production, and tracking x-rays to the experimental end-stations would be very useful and so a major thrust of current development work is towards this end. While much development work has already been done, a full x-ray optics description is an ambitious goal that is still in development. The purpose of this paper is to outline the current status of Bmad and to present a road map for the future.

GENERAL DESCRIPTION

Bmad has proven to be an exceptionally useful tool and a variety of modules have been developed so that Bmad today has the capability to do such things as spin tracking, synchrotron radiation calculations, transfer maps to arbitrary order, symplectic integration, dark current tracking in RF cavities, Touschek lifetime and emittance growth calculations[3], etc.

The Bmad "ecosystem" has spawned a number of programs. Programs include `bmadz` which is used for lattice design[4], the `synrad` program which is used for calculating the heating of the vacuum chamber walls due to synchrotron radiation, `BBU` a program for simulating the beam break-up instability in recirculating accelerators[5], and `Tao`, a general lattice design and simulation program[6]. For the Cesr storage ring, Bmad is used as the calculational engine for the online `CesrV` program which is used for simulation and correction of such things as the orbit, coupling, and betatron phase[7].

Bmad has been used to simulate a number of machines. In particular, Bmad has been used for simulations of the International Linear Collider (ILC). In this regard Bmad has been used to design and evaluate "baseline" damping ring lattices. Also Bmad has been used to characterize emittance dilution, spin depolarization in the ILC RTML and main linac, and electron cloud effects[8]. Here the symplectic tracking that is built into Bmad via Etienne Forest's PTC code[9] has been essential to including effects of damping wigglers on dynamic aperture.

Over the years Bmad has been well tested. It is used extensively for lattice design[4], accelerator modeling, and online data analysis and lattice correction at the CESR storage ring[7]. Additionally, Bmad has been benchmarked against other simulation programs[10].

INTEGRATION WITH OTHER CODES

To supplement the software being developed at Cornell, and to take advantage of code already developed elsewhere, integration with other codes is actively being pursued. Specifically, for low-energy simulations where space charge forces have a strong impact, an interfaces are presently being developed to allow Bmad to interoperate with the OPAL[11] and Impact-T[12] codes. For x-ray simulations, integration of XRAYLIB[13] for computation of crystal structure factors is in progress and an interface to the SHADOW x-ray simulation code[14] is in development that will allow photon simulation in Bmad for such things as crystal diffraction, bent mirror reflection, Fresnel zone plate diffraction, etc. In the long term, integration with the ray tracing code McXtrace[15] and the code SRW[16] which can be used with partially coherent x-ray beams, is being investigated.

Integration with external codes can be accomplished in various ways. Coarse integration, which involves making the output of one code readable by another is one possibility. Bmad, however, has a number of features that make it a good platform for fine integration. For one, each element in Bmad is assigned a user selectable "tracking type" which specifies what algorithm is used for propagating particles or x-rays through the element. It is thus a relatively simple

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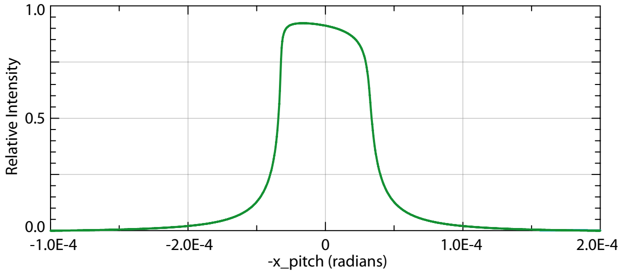

Figure 1: Rocking curves for a Si111 symmetric Bragg Crystal for 10 KeV photons. The curves were produced by varying the x_pitch attribute of the crystal. The Darwin curves are centered on x_pitch = 0 since Bmad adjusts the reference trajectory to go through the "Q" point at the center of the dispersion surface.

matter to extend Bmad to use new propagation algorithms. This means that Bmad can serve as the framework for any number of codes and will make Bmad very flexible.

Besides interfacing with other codes for x-ray simulation capability, ray tracing code is being developed in bmad for a number of elements. This will help serve as a basis for developing custom element tracking. Currently multilayer mirror, focusing capillary, mirror, and crystal elements exist. Figure 1 shows an example of tracking with Bmad native code though a crystal element setup for Bragg diffraction. Here the x-ray intensity is plotted as a function of the `x_pitch` misalignment parameter of the crystal. The resulting curve is the well known Darwin curve.

BRANCHING AND MULTIPASS

To go beyond the simple machine topologies of storage rings and linear, lattices, Bmad has two constructs available: branching elements, and multipass lines. With these, one is able to simulate such things as linacs connected to storage rings, x-ray lines connected to accelerators, and the recirculation of beams in an ERL.

Bmad divides a machine into a number of "branch" lines. A branch line is either closed like a storage ring or open like a linac or x-ray beam line. The type of particle — electron, proton, photon, etc. — can be specified for each individual branch. Connections between branches are made by "`branch`" elements or "`photon_branch`" elements which mark where a connection is made. For example, to define an accelerator with multiple x-ray beam lines, `photon_-branch` elements can be placed in the accelerator lattice. A very simplified x-ray line illustrates this: The relevant part of the input file is

```
d1: drift, l = 70
d2: drift, l = 30
m1: mirror, graze_angle = 0.05
xray: line = (d1, m1, d2)
! Now define the x-ray branch points.
br1: photon_branch, superimpose, &
```

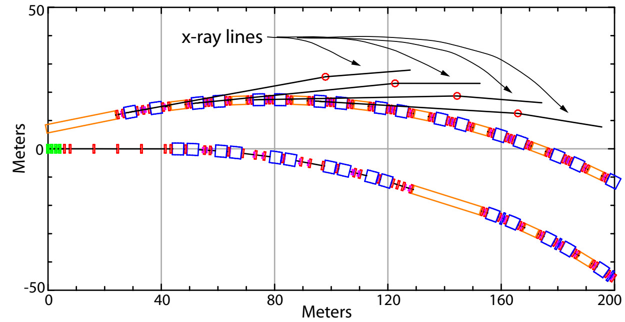

Figure 2: Simple example of the Cornell ERL with four x-ray lines. The x-ray lines are composed of two drift spaces represented by a line with a mirror element, represented by a circle, in between.

```
                          ref = sa_ben01, to = xray
br2: photon_branch, superimpose, &
                          ref = sa_ben02, to = xray
br3: photon_branch, superimpose, &
                          ref = sa_ben03, to = xray
br4: photon_branch, superimpose, &
                          ref = sa_ben04, to = xray
```

In this example an x-ray line, called "`xray`" is constructed with three elements: two field free drift spaces with a mirror in between. This defining structure is used to construct four actual x-ray beam lines. The starting point of an x-ray beam line is an element called a "photon_branch" element which has zero length and is meant simply to mark the line starting position. In this example the photon_branch elements are named "`br1`", through "`br4`" and are placed ("superimposed") with respect to reference elements that, in this case, are four bend magnets called "`sa_ben01`" through "`sa_ben04`" respectively. By default, the superposition will be at the center of the reference element. These bend magnets are defined in the accelerator line, which is a design for the Cornell ERL, and is not shown here due to its complexity. The result is shown in Fig. 2.

The Bmad lattice format allows for the creation of elements that control the attributes of other elements. A control element, for example, can thus be created to mimic the effect of a power supply that controls multiple magnets in the machine. control elements can be used to simulate various control-room "knobs" including knobs for closed orbit bumps, chromaticity knobs, betatron tune knobs, the effect of magnet movers, etc.

Control elements have proved to be an extremely useful construct since once they have been defined in the lattice file they can be used by any program that accesses the lattice file. This alleviates some of the burden on the user of having to dig up information on how things are controlled.

This concept of controller has been extended in Bmad so that simulation of the recirculating beam in an ERL may be done cleanly. The problem here is that in an ERL the beam passes through the accelerating/decelerating sections

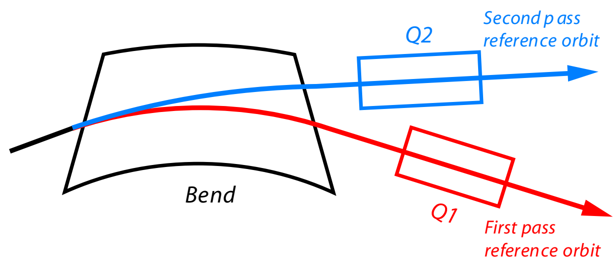

Figure 3: At the beginning or end of a multipass section the reference orbits on the different passes will diverge. The bookkeeper details of this are handled by Bmad. Shown is a bend at the end of a multipass section.

of the machine multiple times in it's journey from cathode to dump. Bmad simulates this topology by labeling element where the beam passes through multiple times as "multipass" elements. Thus if "A" is an element that the beam recirculates through, the list of elements transversed in a simulation would look like

```
... A\1, ... A\2, ...
```

Element "A\1" represents the element on the first transversal through the machine of the beam. Element "A\2" represents the element on the second transversal, etc. Concurrent with the list elements to track through, Bmad would create a multipass control element named "A" to control the "slave" "A\1" and "A\2" elements. Changes to the parameters of element "A", such as field strength changes or positional offsets, are automatically communicated to "A\1" and "A\2" relieving the user of this bookkeeping chore.

Bookkeeping details like properly keeping track of the reference orbit at the ends of a recirculation section are properly done as shown in Figure 3.

CONCLUSION

Bmad is being developed as an application library that can be used to simulate ERLs and other machines; from low energy to high, and from particle beams to x-rays. Critical to this vision is the interfacing of Bmad to existing codes. In development is interfacing to OPAL and Impact-T for low-energy space charge and SHADOW3 and XRAYLIB for x-ray simulation. In the long term, interfacing to McXtrace and SRW is being explored. Also in the planning stages are such refinements as nonlinear controllers, elements whose fields may overlap, and the implementation of support_table elements.

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