RECENT DEVELOPMENTS ON THE MUON-FACILITY DESIGN-CODE ICOOL*

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Abstract

Current ideas for designing neutrino factories and muon colliders require unique configurations of fields and materials to prepare the muon beam for acceleration [1,2]. We have continued the development of the 3-D tracking code ICOOL for examining possible system configurations [3]. Development of the ICOOL code began in 1996 in order to simulate the process of ionization cooling. This required tracking in magnetic focusing lattices, together with interactions in shaped materials that must be placed in the beam path. Eventually the early linear cooling channels evolved into cooling rings. In addition the facilities require many other novel beam manipulations besides ionization cooling, such as pion collection in a high field solenoid, rf phase rotation, and acceleration in FFAG rings. We describe some of the new features that have been incorporated in ICOOL for handling these requirements. A suite of auxiliary codes have also been developed for pre-processing, post-processing, and optimization.

PROGRAM OVERVIEW

The design of a neutrino factory or muon collider faces a number of difficulties not ordinarily encountered in more conventional accelerator design. Phase rotation makes use of induction linacs or low frequency rf cavities. Bunching is done with a series of rf cavities and drifts. The only known method that can cool the beams in a time comparable to the muon lifetime is ionization cooling. This method requires directing the particles in the beam at a large angle through a low-Z absorber material in a strong focusing magnetic channel and then restoring the longitudinal momentum with an rf cavity. Emittance exchange is the only practical method for reducing the longitudinal emittance of the muon beam. This involves passing the beam through wedge-shaped absorbers in the presence of dispersion. Thus beam interactions in matter, solenoidal focusing channels, and dispersive lattice elements all need to be included in the simulations.

A major part of the simulation effort for the Muon Collaboration has been directed toward the development of two programs to accomplish these goals. The first, ICOOL, provides the flexibility to quickly examine widely different ideas for configuring muon facilities. For example, setting up desired field configurations can be accomplished in ICOOL using predefined, analytic field models. This simplifies the adjustment of parameters for the field to obtain some desired result. The second set of programs is based on the GEANT code system [4]. It is possible to describe very complicated 3-D problem geometries using these codes and to calculate quantities to greater accuracy than with ICOOL. Geant typically gets its field distributions from maps generated by other, more accurate field computation codes. In our experience the two codes have been quite complementary. One program is frequently used to check results from the other.

Current ideas for muon facilities make extensive use of solenoidal channels. For this reason we define a region in ICOOL to encompass a cylindrical volume which has a fixed length along the reference orbit. A region can be subdivided radially in up to 4 subregions. Each subregion has a field type, material type, and material geometry associated with it. Particles are allowed to pass back and forth between radial subregions. Wedge-shaped material geometries are provided for reducing the momentum spread in dispersive regions. There is no practical limit on the number of regions in a problem.

The program tracks the particles in Frenet-Serret coordinates to the end of a given region and generates any desired diagnostics. It then continues to track the surviving particles to the end of the next region. This program structure was adopted to make it possible to eventually add space charge interactions. At present the code only has a very rudimentary space-charge model.

The region description language has looping structures to aid in describing complicated, repetitive systems. A group of regions, such as rf cavity cells, may be repeated as often as desired using a REPEAT structure. Groups of REPEAT structures and isolated regions may be combined into a CELL structure, which may also be repeated as often as desired. In addition a CELL has its own field type associated with it. This allows applying a background solenoid field, for example, over a sequence of regions, each of which has its own local field.

In addition to the physical regions described above, the user can insert “pseudoregions” into the command file at various locations to accomplish tasks, such as forcing diagnostic output, collimating the beam, transforming the beam with a TRANSPORT element, redefining the reference particle, etc.

The program can initialize the phases of long strings of rf cavities by using an on-axis reference particle. The most commonly used algorithm tracks the reference particle through absorbers and other non-cavity regions, taking into account the mean energy lost there. The energy of the reference particle is increased in rf cavity regions by assuming the particle gains a constant energy per unit length. It is then possible to calculate the time the reference particle passes the center of each cavity and to adjust the cavity electric fields to be at zero-crossing at these times. After the relative cavity phases have been

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determined, the user can control the beam's interaction with the rf fields by adjusting the mean launch time of the particles in the beam or by applying additional phase shifts to individual cavities.

For maximum compatibility across the Muon Collaboration it was decided to write the code in Fortran 77 and to restrict graphics inside the program to simple character based "printer plots". The program has been run successfully on UNIX, PC, and Macintosh platforms. A simulation of transverse cooling for the U.S. Feasibility Study 2 neutrino factory [2] took 122 min on a 500 MHz Pentium PC. This simulation involved tracking 2400 muons through 108 m. There were 1169 regions consisting of liquid hydrogen absorbers with aluminum windows and pillbox rf cavities with beryllium windows, all immersed in a tapered, alternating-direction, periodic solenoidal field lattice.

RECENT DEVELOPMENTS

As our understanding of neutrino factories and muon colliders have evolved, so have the requirements imposed on the simulation codes.

End-Field Modeling

Early simulations generally only considered isolated systems and usually used hard-edge field models. However, present facility designs make use of many short magnetic elements with large apertures. In this case end effects of the magnets, and overlap of the field of a given magnet with the fields from its neighbors are important issues. ICOOL provides a number of methods for handling this problem:

- soft-edge internal model
- table of current sheets
- external field map
- specification of on-axis fields
- specification of Fourier components of on-axis multipoles.

The soft-edge model for common magnetic elements, e.g. solenoids or quadrupoles, uses a delta-hyperbolic tangent function to describe the smooth fall-off of the on-axis field at the end of the magnet. The off-axis fields are determined from the strength of the on-axis multipole using third to fifth order expansions derived from the Maxwell equations [5]. The capability also exists to use the overlap of the field of a soft-edge element with its nearest neighbors to determine the field values used while tracking. This model has some limited usefulness when first studying the effects of end fields on beam dynamics and matching between elements.

Focusing is generally done in these facilities using solenoids. The field from straight channels of solenoids can be obtained by specifying the location of a set of current sheets. The field anywhere outside the sheets themselves can be expressed analytically in terms of elliptic integrals. The end field problem is handled automatically in this case, since the field at any location can be found from a superposition of the fields from the individual sheets. Similar capabilities exist in ICOOL to obtain the fields from specified coils or current blocks.

Realistic simulations containing bends require some other method of handling of the end field problem. This could be done using a dedicated auxiliary program that generates a suitable field map of a given region of the facility. However, this is not very convenient for designs that contain many different sub-elements and that are 100's of meters long. For that reason ICOOL provides two additional methods based on specifying the on-axis field components in a curvilinear coordinate system.

The first method, denoted BSOL(3) in the program, allows the user to specify the on-axis values of the solenoid, dipole, gradient, and geometric curvature on a grid of points along the reference trajectory (s direction). The values of nearby field components on the grid are fit to polynomials for interpolation off the grid points, and for determining derivatives of the field component with respect to s. These derivatives are used in the high-order expansions of Maxwell's equations to determine the off-axis fields.

The second method for handling bent channels, denoted BSOL(4) in the program, generalizes the capabilities discussed above. Here one can specify the on-axis solenoid, and normal and skew transverse multipoles up to b_5. The user prepares a file containing the Fourier coefficients for each multipole as a function of s for one cell of the lattice. The value of a multipole at a given s location is found by summing the Fourier series. Required derivatives for the off-axis fields are found analytically from the Fourier coefficients.

Helical Fields

One of the major problems facing the muon collider in particular is providing a method for cooling the longitudinal emittance of the beam. The only practical method for longitudinal cooling is through the process of emittance exchange. One method recently considered for doing this involves using high-pressure gas inside a helical magnet channel. ICOOL has added a command DENS for adjusting the gas pressure. As is customary, the code provides a series of different models for how the helical field is specified. The first model is a simple, constant strength rotating dipole field. The second model is the field due to an infinitely long helical current winding. The solution to this problem can be written analytically as a series containing Bessel functions. The third model is for specified helical multipoles made up from pairs of helical windings and their return windings. The fourth model allows the user to specify a file containing arbitrary sets of normal and skew helical mutipoles. All these models also allow a superposed solenoid field.

Second Reference Particle

As mentioned above, ICOOL uses a reference particle to set the phases of rf cavities. A recent neutrino factory innovation has been to do bunching and phase rotation using a series of rf cavities with continuously decreasing frequency and increasing gradient. This was accomplished in the code by defining a second reference particle using a new command REF2. The two reference particles are given different momenta. After a drift space a new acceleration algorithm requires that the difference in arrival times of the two reference particles at a given cavity correspond to a user-specified number of rf wavelengths. This information can be used to compute the required cavity frequency at that location. In addition the user can specify polynomial coefficients to determine a gradual increase in the cavity gradient.

Simulating Rings

There has been a lot of recent interest in ionization cooling rings. Besides the obvious cost savings in reusing the focusing solenoids and rf cavities, rings provide a natural method for providing emittance exchange. In addition, we also use recirculating linear accelerators and FFAGs for accelerating muons to high energy. Tracking in rings required several improvements in ICOOL. Since the accumulated distance for many turns can become quite large, all the internal variables in the code had to be specified as double precision. A new GRID command was defined to store field maps for parts of the ring lattice. Up to four maps can be stored in memory simultaneously. A new command BEGS was also provided to define the starting point for the definition of elements in the ring. This allowed other elements to be previously defined that could correspond to an injection line into the ring.

Name Substitution

As the muon facilities under consideration become larger and more detailed, the input files for the description of the facility become longer and more complicated as well. Eventually it becomes difficult for a user to find a specific location in the input file. Two auxiliary scripting programs, NIME [6] and XICOOL [7], have been developed to make it easier for the user to specify a complicated channel design. Each of these programs uses macro definition commands to define and reuse repeated phrases. These codes are used as a preprocessor before actually running ICOOL.

Several similar improvements have been made to the ICOOL code itself. Comments and blank lines can be entered almost anywhere in the input file. This improves readability by allowing the user to separate groups of related commands, and allows the user to leave notes on the particular choice of parameters. Blank lines and comments are stripped out before the program executes. In addition a name substitution command &SUB can be used in the ICOOL input file. This allows the user to define a name and give it an associated value. Any subsequent line in the file can refer to a parameter by that name.

Random Fields

The sensitivity of the beam dynamics to random errors in the magnetic field strengths is an important issue in any machine design. This capability has been added to ICOOL using the RKICK command. These commands can be inserted at any location in the problem. The user specifies the type of field error, and the mean and standard deviation of the error strength. A momentum kick is applied to all particles based on the strength and direction of the error field. A provision is provided for correlating the error strength in a given RKICK with those determined in previous commands. For ring simulations the code uses the same error at a given location for subsequent turns.

There is also the possibility for randomizing variables in a simulation using a variant of the name substitution capability. One can use the &RAN construct to randomly give a value to a subsequent quantity in the input file. The value can be determined from either a uniform or a Gaussian distribution.

AUXILIARY CODES

A number of auxiliary codes have been developed that use ICOOL input and output files. Most of these auxiliary programs use tracking information from the ICOOL output file for009 as input. Several utilities exist to extract data on tracks that meet certain criteria, e.g. all data on all particles that reach the end of the simulation (ENDOF9). The program ECALC9 [8] gives standardized calculations of the beam emittances. The utility OPTICOOL [9] builds an optimizer around ICOOL.

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