KNOWLEDGE RULE BASE FOR THE BEAM OPTICS PROGRAM TRACE 3-D

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Abstract

An expert system type of knowledge rule base has been developed for the input parameters used by the particle beam transport program TRACE 3-D. The goal has been to provide the program's user with adequate on-screen information to allow him to initially set up a problem with minimal "off-line" calculations. The focus of this work has been in developing rules for the parameters which define the beam line transport elements. Ten global parameters, the particle mass and charge, beam energy, etc., are used to provide "expert" estimates of lower and upper limits for each of the transport element parameters. For example, the limits for the field strength of the quadrupole element are based on a water-cooled, iron-core electromagnet with dimensions derived from practical engineering constraints, and the upper limit for the effective length is scaled with the particle momenta so that initially parallel trajectories do not cross the axis inside the magnet. Limits for the quadrupole doublet and triplet parameters incorporate these rules and additional rules based on stable FODO lattices and bidirectional focusing requirements. The structure of the rule base is outlined and examples for the quadrupole singlet, doublet and triplet are described. The rule base has been implemented within the Shell for Particle Accelerator Related Codes (SPARC) graphical user interface (GUI).

I. Introduction

There are several applications of expert systems to accelerator problems, notably in the area of control systems [1,2]. Accelerator analysis software is another area where expert systems offer a profitable avenue of development. The application of expert system shells such as the Knowledge Engineering Environment (KEE) is one approach to developing expert systems for analysis codes [3]. However, the requirement to work within the SPARC GUI precluded the use of such environments. For ease of integration with SPARC it was also desirable to write the rules in C rather than LISP.

II. The Shell for Particle Accelerator Related Codes (SPARC) Environment

SPARC is a unique GUI environment developed to support accelerator simulation and analysis codes. The approach is similar to that suggested by Heighway [4]. Figure 1 shows a TRACE 3-D [5] SPARC application screen [6]. The SPARC interface has a number of important features which improve the speed and ease of setting up and defining a TRACE 3-D problem. The use of expert system type rules is the focus of this paper and several are discussed below.

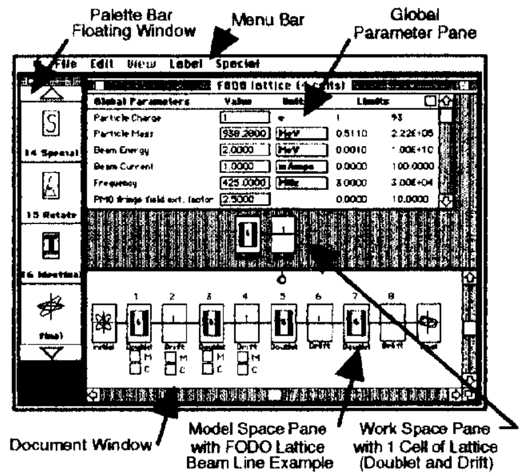

Figure 1. TRACE 3-D SPARC Application Screen.

III. Knowledge Rule Base Description

The primary objective of the expert system rules is to assist users in setting up beam line problems for TRACE 3-D. Both beginning and experienced users are intended to benefit. For novices the rules provide guidance. For advanced users the goal is to reduce the number of off-line calculations. In addition, the rules assist in the training of new users.

There are two classes of knowledge base rules in SPARC: (1) problem configuration rules and (2) input parameter rules. Problem configuration rules are concerned with the arrangement of components and are implemented in SPARC with rules defining the placement of graphical elements on the Model Space Pane of a Document Window (Figure 1). Input parameter rules are quantitative and are of two types: those specifying default values and those providing lower and upper limits for user guidance.

To facilitate development of the parameter rules, the TRACE 3-D input has been divided into four categories: (1) Global Parameters, (2) Piece Parameters, (3) Matching Parameters, and (4) User Preferences. The first two categories encompass the numerical input required to define a TRACE 3-D beam line. This work discusses rules developed for these parameters. The latter two categories are associated with the tasks that TRACE 3-D can preform once the beam line is defined. SPARC has special features to assist in their setup and are discussed elsewhere [6].

There are ten TRACE 3-D input parameters which have been assigned as SPARC Global Parameters. These include the five "top level" beam line parameters: particle charge (Q), particle

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mass (ER), initial beam energy (W), beam current (XI) and radiofrequency (FREQ). Also included are two parameters which impact calculations for magnetic elements: the fringe field extension factor for permanent magnet quadrupoles (PQEXT) and a binary parameter which determines if chromatic aberrations are to be included (ICHROM). Two other Global Parameters set the maximum step sizes used in the TRACE 3-D beam dynamics: SMAX and PQSMAX. The last Global Parameter defines the initial beam setup (IBS) in terms of either emittances and Twiss parameters, or a sigma matrix.

The Piece Parameters include the transport parameters used by TRACE 3-D (arrays NT and A), the initial beam characteristics (arrays BEAMI, EMITI and SIGI), and the final beam characteristics used for matching (BEAMF array). These parameters are accessed by "double clicking" on the piece icons appearing in the Document Window. The transport parameters start with default values that can be modified by the user. The rules are applied to the parameters of a given piece, and a set of upper and lower limits for each parameter are displayed giving the user guidance. Several choices for units are available, often including a "smart units" option [6].

The limits for each of the Global and Piece Parameters are generated by a knowledge rule base developed specifically for the TRACE 3-D program. These rules are of three origins:

- TRACE 3-D driven,
- Particle beam optics utility, and
- Practical hardware constraints.

The first type includes constraints such as requiring the input parameter for any "identical element" (type 16) to lie between the first and last element numbers of the beam line model, and others based on step sizes (SMAX and PQSMAX) used in the beam dynamics calculations. Practical hardware constraints are derived from specific accelerator technology. Section IV describes rules for three TRACE 3-D transport elements, the quadrupole singlet, doublet and triplet, and illustrates examples from the three origins given above.

Guidelines have been developed in terms of what parameters can be used for rules relating to other parameters. For the baseline rules these guidelines limit the number of logic paths and eliminate circular paths and other conflicting requirements. Such conflicts can be handled in expert systems, but this was considered to be beyond the scope of the baseline rules. The guidelines assume that a "top-down" flow of information is the most important and they may be summarized as:

- Global limits may depend on Global Parameters,
- Global limits may not depend on Piece Parameters,
- Piece limits may depend on Global Parameters,
- Piece limits may use Piece Parameters of that Piece,
- Piece limits may not use Parameters from other Pieces,
- Default values must be constants and self-consistent.

As is apparent from the examples described below, these guidelines are not overly restrictive. It should be noted also that the TRACE 3-D guidelines are not determined by SPARC limitations; other SPARC applications have different guidelines.

IV. Rules for Quadrupole Singlet, Doublet and Triplet Elements

A. Quadrupole Singlet (TRACE 3-D Element Type 3)

There are two input parameters for the TRACE 3-D quadrupole element. These are the magnetic field gradient, B', and the effective length, l. The limit rules and default values developed for these parameters are based on a water cooled, iron core, electromagnetic quadrupole, similar to the type discussed by Steffen [7]. A cross section is shown in Figure 2.

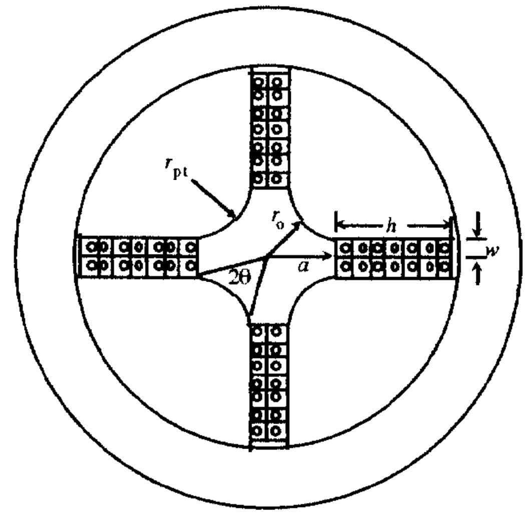

Figure 2. Electromagnetic Quadrupole Geometry.

The magnetic field gradient is

$$B' = 2\mu_o N I / r_o^2 \quad , \tag{1}$$

where I is the current in the windings, N is the number of turns per pole and r_o is the (radial) aperture. The guidance limits for the quadrupole field strength use a maximum estimate for NI consistent with a minimum estimate for r_o.

For low harmonic field content, Halbach suggests [8] that the radius of curvature of the pole tip, r_{pt}, be $1.15r_o$ and that the half angle, θ, subtended by the pole tip be $\pi/6$. From these values and the geometry it can be shown that the distance a is $1.404r_o$. Using $a = w/\tan[(\pi/4)-\theta]$ then gives $r_o = 2.658w$. Characterizations [8] of hollow, water cooled, copper wire indicate that a good choice is square Anaconda wire of 3.665 mm. This is used to estimate a minimum practical radius:

$$r_{min} = 2.658\, w. = 9.74 \text{ mm} \tag{2}$$

The maximum current density for such wire is typically 3×10^7 A/m^2, so the maximum current in the wire, I_{max}, is 201 A. The number of windings per pole, N, is set by the ratio h/w, generally about 4 [7,8]. We assume an aggressive upper design limit of 8, hence $N = 8$. The gradient limits are then:

$$B'_{max,min} = \pm\, 2\mu_o\, NI_{max} / r_{min}^2 = \pm\, 42.5 \text{ T/m} \tag{3}$$

The upper limit on the effective length, l_{max}, is determined by requiring that the focal point of the quadrupole be outside of the lens itself, i.e. that incoming parallel trajectories do not cross the axis inside the quadrupole, which would result in a lens that is defocusing in both transverse planes. If the length is less than this upper limit then the quadrupole will be focusing in one plane. This condition can be written as

$$l_{max} = (\pi/2)k^{-1} \quad , \qquad (4)$$

where $k = [|B'|/B\rho]^{1/2}$ and $B\rho$ (in Tesla-meters) = $(1/300)[p / |Q|]$ is the particle rigidity. The lower limit on the quadrupole length is taken to be the maximum step size, SMAX, used in the TRACE 3-D beam dynamics calculations.

B. Quadrupole Doublet (TRACE 3-D Element Type 6)

The doublet transport element in TRACE 3-D is an antisymmetrical doublet [9] and consequently has three input parameters: the magnetic field gradient of the two quadrupoles, B', (the sign is that of the upstream quad), the effective length, l, of the two quadrupoles and the drift distance, d, between them. In TRACE 3-D the doublet subroutine calls the subroutines for the quadrupole and length elements. The limits and defaults for the quadrupole parameters in the doublet are adopted from those of the quadrupole (Section IV A). The rule for the upper limit on the drift distance between the quadrupoles is based on the zero-current stability condition for a FODO channel composed of drifts and these doublets (Figure 1). The stability condition for the channel can be written as [9]:

$$|\cos kl \cosh kl + (\cos kl \sinh kl - \sin kl \cosh kl)(kd) - (\sin kl \sinh kl)(kd)^2/2| < 1 \quad . \qquad (5)$$

This results in an upper limit on the drift spacing between the quadrupoles which can be expressed as a multiple of the quadrupole length, $d_{max} = Dl$, where:

$$D = [(\cos kl \sinh kl - \sin kl \cosh kl) + (\sinh kl + \sin kl)] \times [(kl)(\sin kl \sinh kl)]^{-1} \quad . \qquad (6)$$

The lower limit on the drift distance d is taken to be SMAX.

C. Quadrupole Triplet (TRACE 3-D Element Type 7)

The triplet transport element in TRACE 3-D is a symmetrical triplet [9] and has five input parameters. These are (1) the magnetic field gradient of the two outer quadrupoles B'_o, (2) the effective length of each of the two outer quadrupoles l_o (3) the drift distance between the inner and outer quadrupoles, (4) the magnetic field gradient of the inner quadrupole B'_i, and (5) the effective length of the inner quadrupole l_i. Figure 3 shows a schematic of the symmetrical triplet.

The limits for the parameters of the two outer quadrupoles are based on those of the quadrupole (Section IV A). For the inner quadrupole and drift spacing, the rules are based on the conditions for achieving bidirectional focusing. The conditions for bidirectional focusing can be written in terms of the parameter $s = d + (l_o + l_i)/2$ as:

$$l_o / [(k_o l_o) \sin(k_o l_o)] - 2l_i / [(k_i l_i) \sinh(k_i l_i)] < s < l_o / [(k_o l_o) \sin(k_o l_o)] \quad , \qquad (7)$$

and

$$s > 2l_i / [(k_i l_i) \sin(k_i l_i)] - l_o / [(k_o l_o) \sinh(k_o l_o)] \quad . \qquad (8)$$

Here, the k's for the inner (i) and outer (o) quadrupoles are defined the same as for the singlet quadrupole (Section IV A). The constraints (7) and (8) are used to form the limit rules for the parameters of the inner quadrupole and drift length.

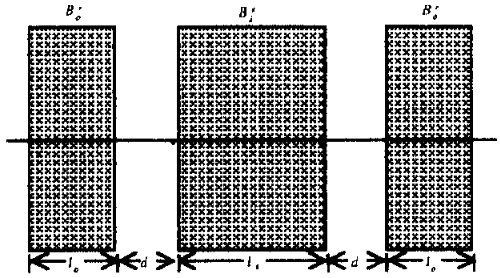

Figure 3. Schematic of Triplet Transport Element.

VI. Summary

An expert system type of knowledge rule base for the beam optics program TRACE 3-D has been developed. Limit guidelines for each input parameter incorporate constraints imposed by TRACE 3-D, beam optics utility and practical hardware experience. The rule base has been integrated into the SPARC interface for TRACE 3-D.

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