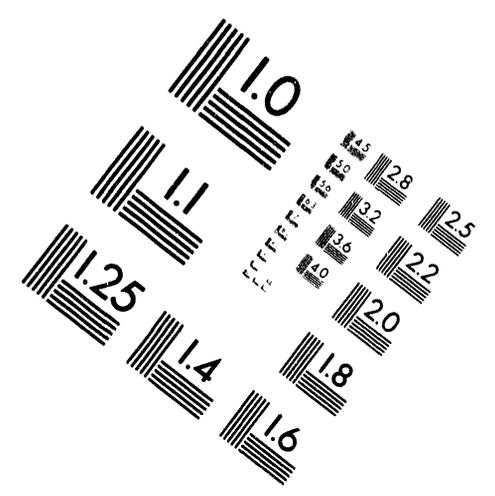
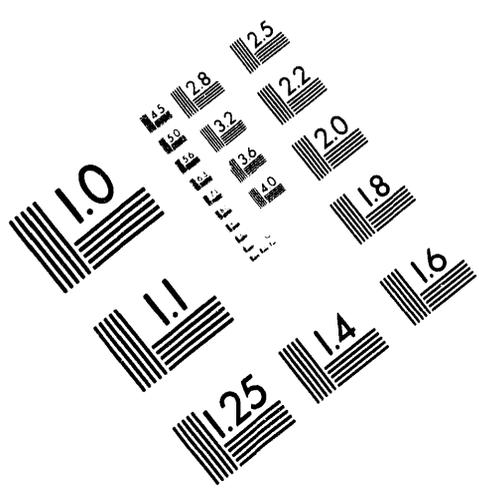




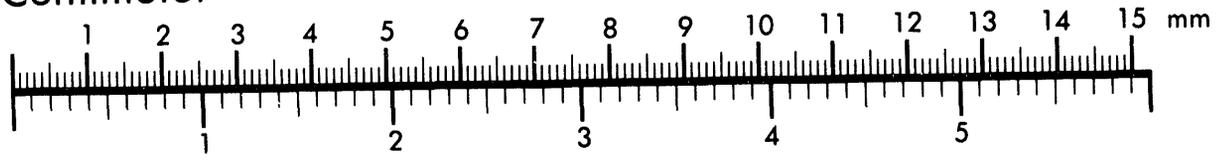
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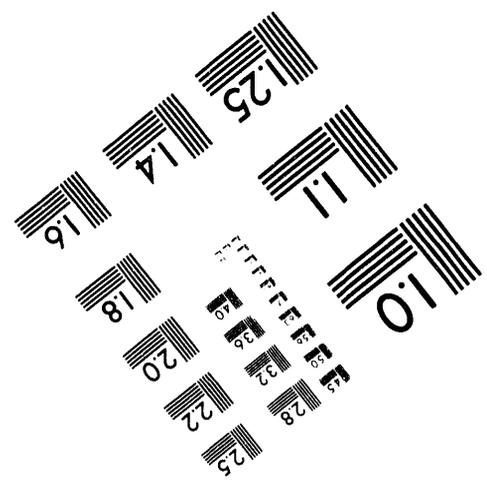
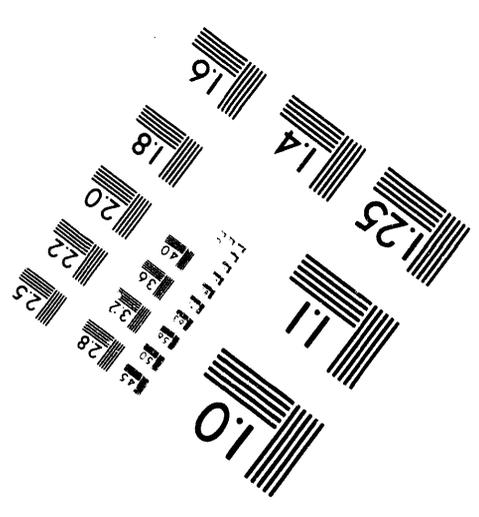
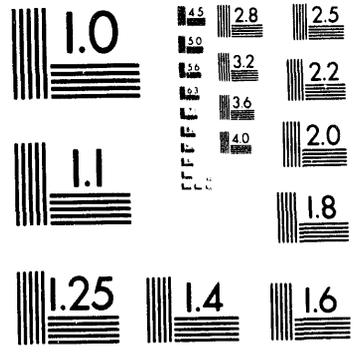
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A NEW APPROACH TO MODELING LINEAR ACCELERATOR SYSTEMS

Author(s):

G. H. Gillespie
B. W. Hill
R. A. Jameson

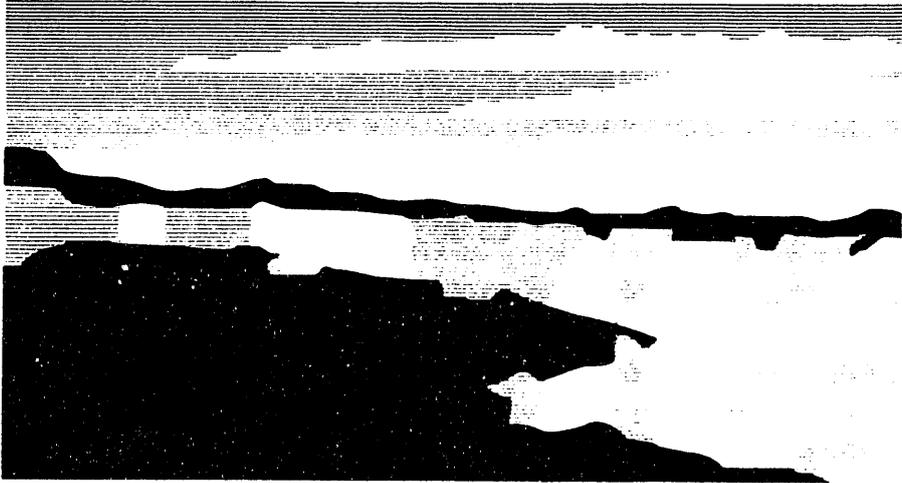
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**A NEW APPROACH TO MODELING LINEAR
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George H. Gillespie and Barrey W. Hill

**G. H. Gillespie Associates, Inc.
P. O. Box 2961
Del Mar, California 92014, U.S.A.**

and

Robert A. Jameson

**Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, New Mexico 87545, U.S.A.**

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A New Approach To Modeling Linear Accelerator Systems

George H. Gillespie*, Barrey W. Hill* and Robert A. Jameson†

**G. H. Gillespie Associates, Inc., P.O. Box 2961, Del Mar, CA 92014, U.S.A. and*
†*Los Alamos National Laboratory, P. O. Box 1663, Los Alamos, NM 87545, U.S.A.*

Abstract. A novel computer code is being developed to generate system level designs of radiofrequency ion accelerators with specific applications to machines of interest to Accelerator Driven Transmutation Technologies (ADTT). The goal of the Accelerator System Model (ASM) code is to create a modeling and analysis tool that is easy to use, automates many of the initial design calculations, supports trade studies used in assessing alternate designs and yet is flexible enough to incorporate new technology concepts as they emerge. Hardware engineering parameters and beam dynamics are to be modeled at comparable levels of fidelity. Existing scaling models of accelerator subsystems were used to produce a prototype of ASM (version 1.0) working within the Shell for Particle Accelerator Related Code (SPARC) graphical user interface. A small user group has been testing and evaluating the prototype for about a year. Several enhancements and improvements are now being developed. The current version of ASM is described and examples of the modeling and analysis capabilities are illustrated. The results of an example parameter trade study, for an accelerator concept typical of ADTT applications, is presented and sample displays from the computer interface are shown.

INTRODUCTION

The development of a variety of accelerator-driven concepts to meet differing requirements for a spectrum of transmutation related applications [1]-[3] has placed increased demands on accelerator designers to explore a rapidly expanding region of the parameter space available to accelerators. Overall system efficiency, performance optimization and cost minimization are of critical importance in establishing the feasibility of many of these applications. System level tradeoffs of the type needed for ADTT applications require computer models capable of tracking the large numbers of parameters involved and their relationships to each other. A computer model that also offers the ability to change the conceptual design of the accelerator can provide designers with a new paradigm for carrying out system studies. The Accelerator System Model (ASM) is a computer program developed specifically to model proton and deuteron radiofrequency linear accelerators and to assist accelerator designers in carrying out system-level trade studies. An object oriented approach has been used that provides flexibility to the users in changing, and comparing, the conceptual designs for accelerator systems.

Several programs have been developed to model ADTT accelerator systems and ASM has similarities to some of these other codes. The LIDOS code system [4] developed at the Moscow Radiotechnical Institute represents one of the most developed and integrated packages for ion linac beam dynamics design. LIDOS provides for different levels of accelerator modeling and utilizes an expert help system to assist scientists in developing designs. The LINACS program [5] written at Los Alamos National Laboratory also provides for different levels of modeling and incorporates engineering models. ASM focuses on one level of modeling, but includes both beam dynamics and engineering. ASM features an advanced graphical user interface with some expert system type features to facilitate ease of use. One approach to incorporate multi-level modeling is to integrate ASM with other programs working within the same graphical interface environment [6]. Another approach is to incorporate more detailed accelerator system models into user defined ASM modules. In this vein, Grumman is working with us to utilize in ASM the engineering models available from their ABSOC program [7].

ASM OVERVIEW

ASM consists of two primary parts: (1) a set of accelerator physics and engineering models and (2) a graphical user interface. The physics and engineering models are written in FORTRAN and the interface is written in C. Both parts of the program are modular, or object oriented. The modules on the FORTRAN side of ASM correspond to specific accelerator "subsystems," such as the ion source, radiofrequency quadrupole (RFQ) or drift tube linac (DTL). The interface side incorporates object-oriented structures that correspond to the same subsystems. A baseline set of modules was developed for the prototype version (1.0) of ASM for test and evaluation. In addition to the set of built-in baseline modules, the current version (1.1) of the program contains a large number of user definable modules. Table 1 summarizes the modules available in ASM version 1.1. In a joint effort with Grumman, we are developing new ASM modules to be incorporated in the future.

Table 1. Accelerator Modules Available in ASM Version 1.1

Module Types	Accelerator Subsystems	Number of Modules
Linac Baseline		
	Ion Source	3
	Low Energy Beam Transport (LEBT)	2
	Radiofrequency Quadrupole (RFQ)	2
	Drift Tube Linac (DTL)	1
	Coupled Cavity Linac (CCL)	1
	Funnel	2
User Defined Linac		
	Ion Source	4
	Low Energy Beam Transport (LEBT)	4
	Radiofrequency Quadrupole (RFQ)	4
	Drift Tube Linac (DTL)	4
	Coupled Cavity Linac (CCL)	4
	Funnel	4
	"Black Box" Transport Line	4
	"Black Box" Accelerator Component	4
Advanced Linac Baseline (in development)		
	IMS, BCDTL, ...	4
Baseline Support Systems		
	Radiofrequency (RF) Power	4
User Defined Support Systems		
	Radiofrequency (RF) Power	1
	Vacuum	1
	Thermal Management (Cooling)	1

Accelerator Physics and Engineering Models

The beam physics parameters and engineering parameters in ASM are represented by two vectors for each of the linac components listed in Table 1. These vectors are referred to as the Beam Vector (BV) and Engineering Vector (EV). A given module in ASM generates a BV and EV as the primary output.

The BV represents the state of the beam at each point in the accelerator and the vector's elements are physical properties of the beam at that point. Versions 1.0 and 1.1 of ASM use an eight-dimensional representation of the BV:

$$BV = [E, I, \langle x^2 \rangle, \epsilon_{t,rms}^2, \langle \Delta p^2 \rangle, \epsilon_{l,rms}^2, \alpha_t, \alpha_l] . \quad (1)$$

Here, E is the beam energy, I the current, $\langle x^2 \rangle$ the mean-square extent of the beam (envelope), $\epsilon_{t,rms}$ and $\epsilon_{l,rms}$ the normalized (rms) transverse and longitudinal emittances, Δp the momentum dispersion and α_t and α_l are the transverse (magnitude) and longitudinal Twiss parameters. The quadratic form for several parameters was suggested by the types of models used. Note that although because only one transverse dimension is included in the definition in BV, it is intended that the BV be used to represent the beam at points of cylindrical symmetry near the exit of each device, where $\langle y^2 \rangle = \langle x^2 \rangle$, $\epsilon_{x,rms}^2 = \epsilon_{y,rms}^2 = \epsilon_{t,rms}^2$, and either $\alpha_x = \alpha_y = \alpha_t$ or $\alpha_x = -\alpha_y$ with $\alpha_t = |\alpha_x| = |\alpha_y|$. Internally, within a given module, any expanded parameter set may be used. The parameter set defined by the BV is used only to describe the beam out of, and into, each module.

The EV is used to describe the requirements of the accelerator component that produces the beam defined by Equation (1). In the current version of ASM, the EV is also eight dimensional:

$$EV = [L, V, M, P, x, y, Conf, Cost] . \quad (2)$$

The EV elements shown in Equation (2) are: L device length, V device volume, M device mass, P device power requirement, x the maximum horizontal and y vertical dimensions of the component, as measured from the beam axis, $Conf$ a confidence factor for the device as modeled, and $Cost$ a cost estimate for the device.

The basic requirement for each module in ASM is that the input BV, in the form of Equation (1), be mapped into an output BV of the same form, and that an EV of the form given by Equation (2) be generated by the module. Other outputs can be generated, and are for all baseline modules, but the minimum requirement for a linac module to work within the ASM framework is that these two vectors be created. The two vectors are used for interfacing to other ASM linac and support system modules. It is beyond the scope of this paper to describe the ASM modules individually, but we will briefly describe the structure of the interfacing between modules.

For the baseline modules, a matrix is used to represent the effect on the beam of each device of the linac system (e.g., RFQ, DTL, etc.). This matrix maps the input BV into an output BV by matrix multiplication. In addition to this matrix, the baseline modeling uses the addition of a column vector which augments the output BV by vector addition. For a particular accelerator component, this matrix and its associated augmentation vector are labeled the device matrix (DM) and the device vector (DV). They define the component's effect on the BV. The general model equation for each device is:

$$[BV_o] = [DM] [BV_i] + [DV] \quad . \quad (3)$$

Equation (3) need not be linear. The elements of the DM and DV can, and in most ASM models do, depend upon elements of the input BV. Although ASM uses the matrix formulation for the data structure of the built-in baseline models, the ASM program does not require a matrix representation. For a particular device, any set of formulae mapping the input BV into the output BV will suffice. Formally, the flexibility of this approach to accelerator modeling is easy to visualize. One starts by specifying numerical values of the beam vector at any point $(BV)_i$ in the system. By repeated application of the matrix Equation (3), one can advance the beam to any further position along the system.

The EV is used to store the engineering and other systems data for the individual components. The individual component EVs are utilized in a set of system integration algorithms to combine this information into an overall system EV. For example, the overall length and power requirement of the linac are generated. These are not simple additions of the corresponding vector components. The geometry associated with funneling must be taken into consideration and the nature of the power required (dc or rf, pulsed or continuous, etc.) for each component must be addressed.

The types of mathematical models used for the baseline modules of ASM are frequently referred to as scaling models [5]. This means that most computations are algebraic and program execution times are fast, permitting a highly interactive mode for the use of ASM. One compromise associated with this approach is a limit on the detail and accuracy in the accelerator component modules. Our goal for the level of accuracy in the primary outputs (described below) from the baseline ASM modules is in the 10-20% range. Benchmarks against existing accelerators, and accelerator designs, are used to assess how well this goal is achieved [X6] and to develop modifications in the modeling algorithms. However, the user definable modules offer the analysts the ability to improve this accuracy by incorporating higher fidelity models. The object oriented approach requires that users adhere to certain guidelines in developing individual modules, but the guidelines are sufficiently flexible that relatively sophisticated models of accelerator components can be incorporated into the program. This is currently being demonstrated in a joint project with Grumman [7].

Graphical User Interface

The graphical user interface (GUI) for ASM is provided by the Shell for Particle Accelerator Related Codes (SPARC). SPARC [6] is a unique software environment that includes the basic elements needed to support a GUI: specialized windows, palettes, menus, icons, etc. The interface is written in C, but is easily linked with FORTRAN programs. For ASM, the configuration of a linac is set up by selecting icons representing the components from a palette and dragging them to a Document Window. Parameter values for the components are entered using Data Tables in Piece Windows for each linac component. The Data Tables are constructed so that expert system rules may be incorporated. For example, guidance limits are displayed for input parameters, that incorporate design rules of thumb, and alert users when their input data may have impractical consequences. Default input parameters may be automatically scaled using other rules of thumb. Other GUI features also support system design, including: (a) different options for units, including "smart units," (b) multiple linac Document Windows open at once and (c) copying and pasting groups of linac components between windows. SPARC has been described in detail elsewhere [6] so we now discuss a specific example of using ASM.

USING ASM

Figure 1 illustrates a typical computer screen for ASM. In this example a linac system has been constructed by selecting accelerator components, from the vertical palette bar shown on the left, and dragging them to the Model Space pane (lower part) of the Document Window, which occupies the majority of the illustration. The example linac system, or model, includes a funneled beamline. Each leg of the funnel consists of an electron-cyclotron resonance (ECR) ion source, an electromagnetic solenoid (EMS) low energy beam transport section for matching and one of the radiofrequency quadrupole models (RFQ2) available in ASM. A funnel component and drift tube linac (DTL) complete the accelerator model for this example. An alternative model for the legs of the funnel is shown on the Work Space pane of the Document Window. The Work Space pane is useful for temporarily storing components when comparing different linac concepts.

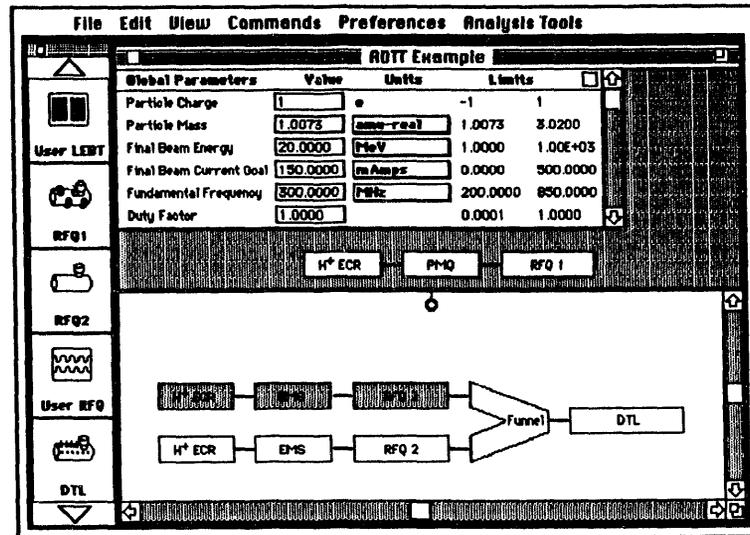


Figure 1. Example of computer screen for the Accelerator System Model (ASM) program.

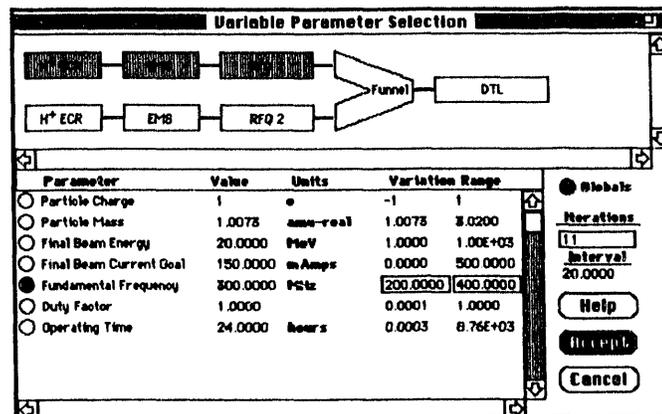
System parameters such as the particle charge and mass, the fundamental radiofrequency of the accelerator, and other Global Parameters are assigned using the Data Table shown in the top part of the Document Window. Input parameters for an individual component are set using Piece Windows accessed by double clicking the icon of the component. Scaling options for input parameters are also set using the component Piece Windows. Figure 2 illustrates the Piece Window for the RFQ of the example and shows how the user accesses the scaling options.

Element #3 RFQ2			
Element Parameters	Value	Units	Limits
Output Energy	2.5000	MeV	
Intervane Voltage	1.51E+05	V	<input checked="" type="checkbox"/> Scale Value
Final Synchronized Phase	-20.0000	Degrees	
Avg. Aperture Radius, front	0.0037	m	<input checked="" type="checkbox"/> Scale Value
Final Vane Modulation Factor	1.9000		
Design Current Limit	0.1180	Amps	<input type="checkbox"/> Scale Value
Kilpatrick Factor	1.8000		
Q-Enhancement Factor	1.0000		<input type="checkbox"/> Scale Value
Max. Power of Drive Loop	100.0000	kW	
Structural Material	Ca 9.92 gm/cm ³ cm		
Max. Coolant Temp. Rise	10.0000	°K	

Figure 2. Piece Window for the input of RFQ parameters. The use of scaling options for two inputs, the Intervane Voltage (based on the Kilpatrick Factor) and the Average Aperture Radius at the front of the RFQ (i.e. radial matching section), is illustrated.

Parameter variations, useful for carrying out system trade studies, are automated in ASM by using one of the selections available from the Analysis Tools menu shown in Figure 1. Special windows, which contain a duplicate graphic image of the current linac model, are used for running a parameter variation. Figure 3 illustrates the set up of a parameter variation analysis. The user may select any Global Parameter to be varied, or an individual component parameter may be selected by clicking on the icon of the desired component.

Figure 3. Selecting the independent variable for an ASM trade study. In the example shown, the Fundamental Frequency of the linac is to be varied between 200 and 400 MHz, in ten equal steps of 20 MHz. Outputs to be plotted as a function of the frequency are selected using a similar window.



A window similar to that shown in Figure 3 is used to select the outputs, from any BV or EV, that are to be plotted as a function of the independent parameter. Figure 4 shows the results, for the example parameter variation, when the final longitudinal and transverse emittances are selected for plotting.

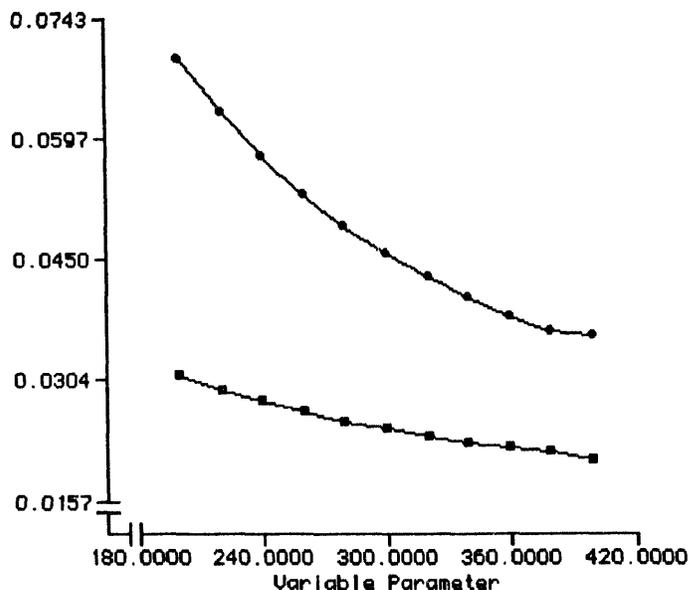


Figure 4. Final emittances in the longitudinal (circles) and transverse (squares) planes as a function of the linac frequency between 200 and 400 MHz. Units are π -cm-rmad, rms, normalized. An arbitrary number of such graphs, with up to four curves each, may be displayed in individual windows. The graphs may also be copied and pasted directly into other documents.

The results shown in Figure 4 quantify the characteristic decrease in normalized emittances, as the linac frequency is increased, for the example accelerator shown in Figure 1. This example only takes a few minutes to set up and run, and illustrates the power of the computer program we

are developing. The precise details depend upon the parameters used and the scaling options selected. Analyses of this type are currently being used to benchmark the ASM modules, but will provide the basis for carrying out future trade studies of ADTT concepts. A collaboration with Grumman [7] is integrating ASM into an overall ADTT facility systems model.

SUMMARY

A new computer code for modeling radiofrequency accelerator systems has been described. Beam dynamics and engineering parameters are incorporated on an approximately equal footing. An advanced graphical user interface makes the program easy to use and provides interactive tools for supporting trade studies and other analyses important in system design. The formalism used for describing the accelerator components is sufficiently flexible that relatively sophisticated models of linac technology can be used. Additional work is on-going to bring ASM up to the standards necessary to provide accelerator scientists with a comprehensive system design tool for ADTT applications. The progress to date is encouraging and demonstrates the usefulness of the approach being taken.

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