MODIFIED PARMILA CODE FOR NEW ACCELERATING STRUCTURES*

H. Takeda and J. E. Stovall, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

The PARMILA code was originally developed as a numerical tool to design and simulate the beam performance of the drift-tube linac (DTL). We have extended PARMILA to the design of both the coupled-cavity linac (CCL) and the coupled-cavity drift-tube linac (CCDTL). We describe the new design and simulation features associated with these linac structures and improvements to the code that facilitate a seamless linac design process.

PARMILA and New Accelerator Architectures

PARMILA stands for Phase And Radial Motion in Ion Linear Accelerators. This computer code originated in the 1960's to study DTL structures[1] and it has been widely used in the accelerator community. This popular code has benefited from years of use and improvements. It has been the basis of many successful linac designs and has been rigorously studied and tested. In recent years, we have seen the development of high-energy RFQ linacs and the CCDTL, a new rf structure[2] that extends the operating range of the CCL down to the output energy of the RFQ. These developments have motivated work to generalize the PARMILA code for various accelerator architectures.

A CCDTL cavity contains one or more drift tubes. Unlike the conventional DTL, the CCDTL drift tubes usually contain no focusing elements. Quadrupole lenses between cavities or between multi-cavity tanks provide the transverse focusing just like the arrangement in CCL structures. The section of PARMILA that generates the linac now also calculates the lengths of the inter-cavity drift spaces containing the quadrupole lenses. The input stream has several new options that describe the new cavity geometries and their associated focusing requirements. The cavity periodicity and the type of focusing lattice (e.g. FODO) are among the new input-stream entries. To make room for beam-line diagnostic equipment, quadrupole lenses can be either upstream, downstream, or centered in the inter-cavity drift space.

Cavity Configuration Options

PARMILA treats each accelerating gap and the adjacent drift distances as a "cell." A cavity can contain one or more cells. For example, DTL cells have length $\beta\lambda$, where β is the synchronous particle velocity and λ is the rf wavelength. The accelerating gap is in the middle of this cell. Previous versions of the code assumed that the quadrupole magnets were inside the drift tubes of the DTL. We have extended the linac-design and the beam-dynamics-simulation parts of PARMILA to accommodate new cavity structures as well as external quadrupole magnets. CCLs and CCDTLs consist of tanks containing one or more cavities with the focusing magnet between tanks. CCDTL cavities always contains two or more cells. In the CCDTL, a cell extends from the center of one drift tube to the center of the next one or to the start of a drift space between cavities. Individual cell lengths in a CCDTL cavity differ depending on whether the cell abuts a cavity outside wall or another drift tube. Figure 1 shows short sections of CCDTL and CCL structures. The length of a CCDTL internal cell is $\beta\lambda$, while the length of an end cell is $3\beta\lambda/4$. The gap is not centered in this end cell. Each CCL cell has length $\beta\lambda/2$.

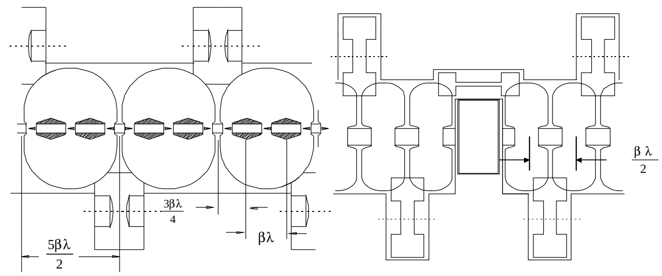

Figure 1. Short sections of CCDTL (left) and CCL (right). The coupling cells above and below the accelerating cells are nominally unexcited in the $\pi/2$ structure mode. The CCL shows a dead space between accelerating sections containing a quadrupole magnet.

The code stores a unique length for each cell in a cavity. For the CCDTL, this generality allows asymmetric cavities, though we expect most designs to use symmetric cavities. The cell geometry as well as the electric fields are treated differently in cavities containing single and multiple drift tubes. To calculate the individual cell geometry the cell generator uses multiple transit-time-factor tables for each type of cell tabulated as a function of β. The code interpolates intermediate values as required. The user supplies these tables as part of the input stream.

PARMILA designs each cell so that the beam maintains synchronism with the time-varying rf fields. The algorithm[3] used to derive the cell lengths is the same for all types of linac. The code divides each gap at its midpoint and calculates the length of each side separately using the synchronous particle velocity before and after applying an energy kick. In CCL and CCDTL structures, the electric fields in adjacent cavities are 180° out of phase. The electric field for all cells within a CCDTL cavity are in phase. Most linac designs use a transverse focusing period that changes gradually with β. If a quadrupole lens is inserted between two cavities, additional multiples of $\beta\lambda$ may be needed to maintain synchronism with the drifting beam.

In our recent linac designs, we start with two-drift-tube CCDTL structures at low β and later switch to single-drift-tube CCDTL. This procedure uses each cavity type where it has high shunt impedance. In these $\pi/2$-mode structures,

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conventional TM_{010}-mode coupling cells provide the usual phase shift of π radians between accelerating cavities. Adjacent gaps in such a structure must be $\beta\lambda/2$ apart. Longer coupling cells can add odd-integer multiples of $\beta\lambda/2$ between active structures to create additional space for focusing lenses and diagnostics while still maintaining synchronism. By reorienting the coupling cavity (see Fig. 1 for the CCL), the designer can provide a 2π phase shift between cavities. This technique allows integer multiples of $\beta\lambda$ between cavities. Long spaces between active structures may require a bridge coupler when the length of a coupling cell approaches a full wavelength. Bridge couplers contain excited and unexcited cells placed off the beam axis to allow space for longer focusing elements or diagnostic devices. Using these techniques, the drift length between tanks can be tailored to practically any value of $n\beta\lambda/2$, where n is an integer. In PARMILA, these adjustments can be specified globally or for individual tank junctions. These options are controllable from the input stream. The code divides the space charge calculation in the connecting drifts into steps corresponding to a distance of about $\beta\lambda$.

PARMILA accepts input data for either FODO or FOFODODO lattices. It assumes, as a default, a constant magnetic field gradient for all focusing lenses. The designer can specify each quadrupole gradient individually or automatically ramp the gradient linearly with accelerator length, or as $1/\beta$. If part of the accelerator is turned off (for example, to produce a beam of lower energy than the nominal design), the code can compensate for the over focusing using the automatic ramping feature.

Tables of Transit-Time Factors

An important addition to the code has been expansion of the transit-time data tables to account for different boundary conditions at the ends of cells. A section of linac might require up to three separate tables of data from a cavity design code such as SUPERFISH. Each table includes transit-time factors and other properties of representative cells tabulated by particle β. One table includes data for internal cells that are symmetric about the gap center. This type of cell includes the usual DTL cell or CCL cells, each with the appropriate boundary conditions. DTL cells have Neumann boundaries between cells and CCL cells have Dirichlet boundaries. A second table defines end cells of a cavity that have a Neumann boundary on one side and a Dirichlet boundary on the side adjacent to the next cavity. A third table corresponds to cells at the end of an accelerating structure. Neither Neumann nor Dirichlet boundaries are appropriate for one end of this type of cell. The fields penetrate into the inter-tank drift space and attenuate exponentially because the resonant frequency is below the cut-off frequency of the bore tube. Single-drift-tube CCDTL structures use only the second and third tables. A CCL would use the first and third tables. In multi-gap cavities such as in a CCDTL, the voltage gain across gaps may vary for a nominal cavity excitation. The field distribution depends upon the detailed cavity geometry. New table entries include the relative electric field strength for each type of cell.

PARMILA calculates each cell length using the transit-time factor and electric-field data interpolated from the supplied data tables. The code stores each cell geometry, the data interpolated from the tables, plus cavity power losses estimated from the shunt impedance contained in the tables. It saves this information in a separate file for each run. The present PARMILA generates only graded-β linacs, so unlike many existing CCLs, every cell has a different length. In a future version we plan to implement tanks of constant length cells.

Longitudinal Phase Space Considerations

To adjust the longitudinal acceptance, the user can manipulate both the synchronous phase ϕ_s and the spatially averaged electric field E_0. Two types of ramping schemes are provided. A static ramp varies either ϕ_s or E_0 linearly with real-estate length. A dynamic ramp varies these parameters as a function of β. Another feature allows the designer to maintain a constant synchrotron oscillation frequency or constant longitudinal phase advance per cell. Additional ramping options based on cell number and active cavity length will be added to give the designer more flexibility.

The input stream includes the distribution of E_0 for designing the linac. For DTLs, E_0 can be ramped linearly with tank length. This type of ramped field distribution is relatively easy to achieve in an actual cavity. When an accelerator design varies E_0 in a CCDTL, the ramp applies only cavity to cavity. The cells within each cavity will have the relative field strength determined by a code such as SUPERFISH. For example, the center gap of a two-drift-tube cavity may in general have a different voltage gain from the end gaps. Designers will usually avoid longitudinal ramps within a cavity, because of the way it would complicate the cavity-to-cavity coupling.

The actual phase of the field in the cavities, of course, is fixed by the resonant rf mode. But, as seen by the beam, arbitrary phase shifts between cavities are possible by adjusting drift lengths between cavities. Using this feature we can create flexible longitudinal bunching and matching sections between different linac structures, for example between a RFQ and a CCDTL.

Simulation Studies

Like previous versions of PARMILA, the new code designs the linac and simulates its performance with beam in the same run. The design process involves generating cells of the appropriate length for the synchronous particle's increasing velocity. For the particle dynamics simulation, PARMILA treats each cell as a drift-gap-drift sequence of elements. For DTLs, this sequence can also include the half quadrupole lenses in the drift tubes. To continue a simulation into a linac section with a different cavity type, the code uses quadrupole half lenses on the end to complete a lattice period.

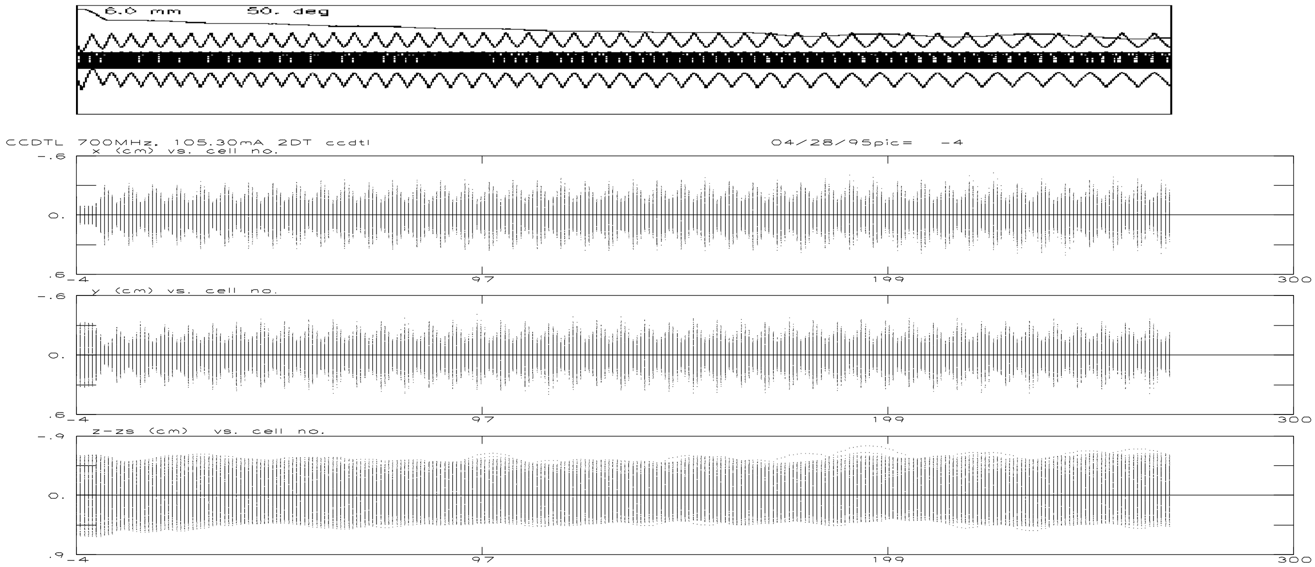

Figure 2. Sample output from a beam simulation study. The upper plot shows the beam envelope from a TRACE 3-D calculation. The other three plots are the X, Y, and Z beam profiles after each cell from a 1000-particle PARMILA run.

It writes the entire particle distribution to a data file. The next run reads the particle distribution and starts with another quadrupole half lens. PARMILA also can read the particle distribution produced by PARMTEQ at the RFQ exit and use it as the input distribution for a dynamics simulation. These features facilitate the design of a linac comprised of several different types of accelerating structures and provides a true end-to-end simulation capability.

During the simulation part of the calculation, the code reports after each cell several parameters of interest to the designer. The bunching is characterized by two bucket filling factors. These factors measure the distance of the beam from the separatrix. Also calculated is the synchrotron wavelength. These three parameters are used as the tools for manipulating the longitudinal match. A post processor program DTLPROC creates plots of the beam envelope and particle distributions. These plots are available at the end of each cell and at the centers of the external quadrupole lenses. Besides the standard geometrical quantities, PARMILA also lists other parameters associated with the new structures, including CCDTL and CCL cell lengths, cavity spacing, and the external quadrupole-magnet characteristics.

Figure 2 shows sample profiles for a proton beam in a CCDTL between 7 and 20 MeV. The beam first goes through a matching section made of three CCDTL cavities and four quadrupole lenses. The next section ramps the accelerating gradient and the synchronous phase. The ramp stops at an energy of about 12 MeV. After the ramping section, the beam is accelerated to 20 MeV at a fixed accelerating gradient and synchronous phase. For a seamless design process, PARMILA can write a TRACE 3-D[4] input file that contains all the linac beam-line elements. TRACE 3-D calculates a variety of useful matching conditions. For the example shown in Fig. 2, PARMILA used matched parameters that were determined by an earlier TRACE 3-D run.

Summary

PARMILA can now design DTL, CCL, and CCDTL linacs and simulate their beam dynamics performance. The code designs a single structure per run. Separate runs of each linac structure can be linked together to design and simulate the entire accelerator. At the time of this conference (May, 1995), documentation for the new code is still in preparation. We plan to announce the release of the code and its on-line documentation on the World Wide Web. Interested users can consult the home page of the Los Alamos Accelerator Code Group[5] (URL:http://www.atdiv.lanl.gov/doc/laacg/codehome/html) for the latest information on PARMILA.

References

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