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LINAC DESIGN ALGORITHM WITH SYMMETRIC SEGMENTS*

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Abstract

The cell lengths in linacs of traditional design are typically graded as a function of particle velocity. By making groups of cells and individual cells symmetric in both the CCDTL [1] and CCL, the cavity design as well as mechanical design and fabrication is simplified without compromising the performance. We have implemented a design algorithm in the PARMILA code [2] in which cells and multi-cavity segments are made symmetric, significantly reducing the number of unique components. Using the symmetric algorithm, a sample linac design was generated and its performance compared with a similar one of conventional design.

Elements in a Symmetric Unit

For the purpose of the discussion we define a cell as an acceleration unit that includes a single rf accelerating gap. We define a cavity as a single rf resonant cavity which may contain one or more accelerating cells and may be resonantly coupled to other cavities.

CCDTL cavities may contain two types of cells. One type extends from the center of one drift tube to the center of the next within the cavity, much like in a drift tube linac. The other type starts from the up-stream face of a cavity and extends to the center of the first drift tube. The reverse of this type occurs for the last cell in a CCDTL cavity. In a graded-β design, each cell in a CCDTL would be unique resulting in asymmetric cavities. In a CCL, cells and cavities are synonymous and are typically symmetric.

We define a symmetric unit or segment as a series of coupled cavities all of which by themselves are symmetric and all of which have identical geometry. Symmetric units have the property that the rf fields in each cavity are the same and are locked to each other by the common resonant structure. In a CCL, the fields in every cell are identical by definition. In a CCDTL, however, the fields in each cell are fixed but are not necessarily the same within a cavity. A symmetric unit will not support a cell-to-cell or a cavity-to-cavity phase ramp or field tilt.

Symmetric units may include space between cavities for focusing elements however their placement is not constrained by symmetry arguments. Neglecting any quadrupole lenses, a symmetric unit with none or one space between cavities is non-directional, i.e. it can be flipped so that either end can be located up-stream and perform correctly. The quadrupoles may be positioned independently within the drift provided to accommodate space and lattice requirements.

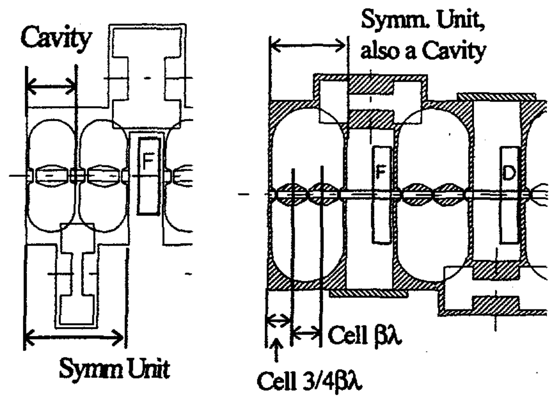

Fig. 1 Cell, Cavity and Symmetric Unit in a 1 and 2 drift tube CCDTL

Algorithm of Linac Design

In a graded-β linac design (β=relativistic particle velocity), each cell length is prescribed by a synchronous particle that arrives at the center of the accelerating gap when the rf fields just reach the "synchronous" phase. Any phase programming along the linac is folded into the increasing cell lengths which are otherwise proportional to βλ, where λ is the rf wavelength. In PARMILA the acceleration across a gap is represented by a thin-lens approximation [3]. Longitudinally, the Prome term [4] corrects the phase advance across the gap to supplement the thin-lens approximation and assure that emittance is conserved.

A gap is divided at its electrical center. In a multi-drift-tube CCDTL cavity, the fields in the end cells are asymmetric and the geometrical and electrical centers would not normally coincide. Because the PARMILA code assumes their coincidence, we design CCDTL cavities so that the geometric center of the gap coincides with the center of the field integral over the cell using the code CDTFISH [5].

CDTFISH adjusts the length of the noses in a cell for a given geometrical velocity β_g while maintaining its resonant frequency until the electrical field integrals in each half of the cell are equal [2]. For this purpose we define the cell center as the geometrical midplane of the gap. SUPERFISH then calculates the transit time factors and other relevant cavity parameters. This is the procedure that is now used by PARMILA to determine the cell lengths of

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graded-β linac also. In principle, a linac designed by a graded-β method accelerates slightly more efficiently than one designed by the symmetric method.

To maintain average phase synchronism in a symmetric unit, the cell lengths are set so that the phases at which the reference particle arrives at the gap centers, averaged over all gaps in the segment, is made equal to the design phase. In conventional designs the reference particle sees cells of increasing length. However, imposing equal cell lengths, optimized near the mid section (near the average velocity) of the symmetric unit, inevitably results in cells that are the incorrect length at both ends of the segment. A reference particle sees a longer cell length than preferred in the earlier cells, and shorter cells near the later part of the segment resulting in a phase slip through the segment (fig. 2). We determine β_g so that the reference particle phase increases at successive gaps until the mid section, then, decreases from above the design phase until the end of a symmetric unit.

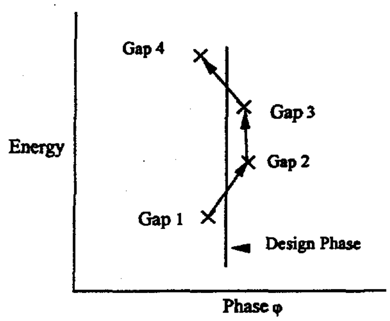

Fig. 2. The entry phase to the symmetric unit and the symmetric unit length is set such that the design phase equals the average reference particle phase.

Determining the Geometrical β_g

In designing a symmetric linac, we define a "design particle" and a "reference particle." We no longer use a "synchronous particle" that arrives at the center of cells at the synchronous phase. The design particle is loosely defined, and is used to keep track of the phase programming. The design phase may not correspond to phase at any particular gap for multi-gap symmetric unit..

The reference particle is a sample particle that obeys the particle dynamics. The length of a symmetric unit must be chosen such that all of the phases seen at the center of gaps by a reference particle are close to the design phase of the symmetric unit. We determine the geometrical velocity β_g from the requirement that the time required for the reference particle to traverse a symmetric unit is equal to a time that should lapse to maintain the synchronicity at both ends of the segment. We impose no restrictions on the phase or energy of the particle at the gaps within the segment. The total length of a symmetric unit must be $n_s\beta_g\lambda/2$ (n_s=integer) where the geometrically determined velocity β_g is constant over the symmetric unit. We have investigated alternate approaches for determining β_g such as choosing its value corresponds to half the energy gain in the segment, or to half the velocity gain in the segment. These schemes were found to be unsatisfactory especially when the number of cells in a symmetric unit is small. In our calculation of β_g we include the Prome phase correction [4] as an extra time contribution in a gap transformation. This is normally used only in the particle dynamics simulation portion of PARMILA . The effect of positive value reduces the design cell lengths. For example, for the 2 drift tube CCDTL in fig 1, β_g is determined from the following expression.

$$\frac{\frac{3}{4}\beta_g\lambda}{\beta_1 c} + P_1 + \frac{\beta_g\lambda}{\beta_2 c} + P_2 + \frac{\frac{3}{4}\beta_g\lambda}{\beta_3 c} + P_3 = \left(\frac{3}{4} + 1 + \frac{3}{4}\right)T \qquad (1)$$

where T is the rf period (λ/c). Terms P_j (j=1,2,3) are the time delay converted from the Prome phase corrections for each gap ($P_j = \lambda/(2\pi c) * (\text{phase correction})_j$). With this correction, the cell lengths and the particle dynamics through the symmetric unit become consistent. If the Prome correction is neglected during the cell generation process, an error of the order of 0.1 degrees per cell accumulates in the longitudinal dynamics. If the linac design requires the accelerating field gradient to be ramped, we step E_0, the average axial electric field, from segment to segment while maintaining E_0.constant within each segment. Because the E_0 tilt needs a known β_g, we iterate about 5 cycles through each symmetric unit until the correct β_g is used for the tilt calculation.

After the symmetric unit length is determined, we adjust its longitudinal position so that the reference particle arrives at the entrance to the symmetric unit at the correct phase. The exit phase of the reference particle traversing a symmetric unit does not necessarily equal its entrance phase. We calculate and adjust this phase difference using single particle dynamics through each symmetric unit. Once a preferred entry phase is determined, we adjust the drift space between segments. If the design requires phase ramping, the ramping is achieved by adjusting this intersegment drift space. The phase is not ramped within segments. If additional space is required for external quadrupole magnets it is added in units of $\beta\lambda/2$ while maintaining the correct reference particle phasing.

The Entry Phase into a Symmetric Unit

The average phase of reference particle must bear some relation with the design particle phase. Because the design particle is simply a programmed phase angle, there are number of ways to approach this problem. Using a reference particle that follows the correct beam dynamics, one can constrain the entry and exit phases of the reference particle through the symmetric unit to be equal. If however the number of cells in a symmetric unit is small (~ 2 or 3), we often encounter the difficulty that the extreme phases (phase at gap1, 4 and gap 2,3 in Fig. 2) do not bracket the design phase. Another approach requires that phase angles seen by the reference particle at the center of first and the last gap in a symmetric unit be equal. This approach also suffers from ~~the~~ similar problem of design phase. We therefore require that the average of phases at the gap centers in a symmetric unit equal the design phase. In this approach the design phase is normally bracketed by the extreme phases in the segment, but the entry and exit phases are not necessarily equal. We iterate to equal the entry and exit phases by propagating a single particle multiple passes through the symmetric unit. In the PARMILA code, we employ Brent's zero-crossing technique [7] in determining the entry phase angle. This method converges quickly and accurately.

When the number of gaps becomes large in a symmetric unit, β_g is appreciably different from the actual particle β near both ends of the segment. This situation requires a correction on the transit time factors for the reference particle. In CDTFISH, the cavity is designed for specified β_g and SUPERFISH is used to calculate the transit time factors (T, T', S, S' etc.) assuming that the reference particle velocity $\beta=\beta_g$. When the reference particle β is not equal to β_g, we expand the transit time factors around β_g with respect to the wave number k ($=2\pi/\beta\lambda$). This expansion is applied in PARMILA for both the single particle dynamics calculation used in the linac design as well as in the multi-particle simulation sections of the code.

When the entry phase is determined, PARMILA stores the phases at the entrance, center and exit of each cell as well as the energy at the exit of the segment. Normally, the exit phase of one segment is not equal to the entry phase of next one due partly to phase ramping, and partly to the phase slip through the multiple cells in the segment. This phase discontinuity, which is normally small (about 0.1°), is then corrected by adding extra space between segments. PARMILA code generates one additional symmetric unit beyond the end of linac which it uses to calculate the correct spacing between the last and the next symmetric units if a different accelerating structure follows.

The exit energy of one segment is used as the starting value for the design of next segment. We repeat this process until the linac is completed. All of the pertinent design information are all stored in memory for the multi-particle beam dynamics simulation.

In a more general CCDTL structure (see Fig. 1, CCDTL with 2-drift tube), the cell lengths within a cavity may differ according to their position in the cavity. Symmetric units may be comprised of multiple cavities which are completely interchangeable. If there are no external quads between the cavities within the symmetric unit, either end can be placed to the beam up-stream. If there are multiple drifts within a symmetric unit for quads, the segment is not necessariry interchangeable because the drift lengths may be increasing. Each symmetrically designed unit has a unique β_g and all of the cell lengths within the segment are proportional to $\beta_g\lambda$.

Example: Design of 2 Drift tube CCDTL

We designed a 2 drift tube CCDTL that accelerates 100 mA of protons from 8 to 20 MeV proton in two ways; using the traditional graded-β approach and using symmetric segments . Table 1 compares the two of designs. at the end of 59 cavities.

	Length (cm)	Energy (MeV)	# of cavities	#of cells
Graded-β	1639.9	20.274	59	177
Symmetric	1637.9	20.215	59	177

Table 1. CCDTL with 2 drift tubes: graded β and symmetric designs.

In this design, the cavity fields and synchronous phase are ramped: the cavity phase from -54° to -40° and the field E_0 from 1.56 MV/m to 2.26 MV/m. The energy difference is 0.06 MeV and length difference is about 2 cm.

Summary

We have implemented a PARMILA code which can design symmetric cavities and symmetric linac sections, and calculate the beam dynamics through the linac. The symmetric design process eases the design, fabrication and engineering complexity. The difference in between the graded β design and the symmetric designs of a CCDTL is small.

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