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A METHOD FOR OBTAINING LINAC BEAMS OF CONTINUOUSLY VARIABLE ENERGY*

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ABSTRACT

The beam energy obtained with an Alvarez linac is normally determined within narrow limits by the design energy of the synchronous particle. In the SuperHilac poststripper the tank is divided into several separately excited sections. In each section varying the electric field from zero to maximum causes the energy increment of that section to vary from zero to the maximum (synchronous value). By so adjusting each of 5 seconds, the output energy can be varied continuously from 2.6 to 8.5 MeV/N. Some aspects of the expected behavior of the partial energy beams are discussed--particularly the energy spread. A formula is suggested whereby results obtained for the heavy ion linac can be scaled to predict variable energy performance of other linacs.

Introduction

Methods which have been used to obtain beams of less than maximum energy from a linac are a) the use of a movable rf diaphragm,[1] b) decreasing the electric field strength along the cavity so that at some point accelerating buckets cease to exist, c) use of degrading foils. Method a) gives beams of full intensity and good quality, but changing energy requires going up to air, followed by a lengthy pumpdown, in order to move the diaphragm. Method c) increases energy spread and foil life imposes intensity limitations. Method b) has been used for a number of years at the HILAC to obtain partial energy beams.[2] Careful tuning of the electric field tilt, of the relative phase between prestripper and poststripper, and of the poststripper quadrupole currents is necessary in order to get good results. Continuous energy variation is not possible and full intensity is not always obtainable at a given energy.

A chain of independently driven single cell resonators has been proposed for the Unilac heavy ion accelerator.[3] By adjusting voltage and phase of the resonators so as to produce appropriate synchronous acceleration (or deceleration) a wide range of final energies can be achieved.

In planning the SuperHilac, a method was desired which easily permitted continuous variation of energy, and which did not add very much to the cost. The method adopted is to insert a number of fixed rf diaphragms into the poststripper, dividing it into separately excited resonant cavities. The length of these sections is chosen so that they can be economically driven by one power tube. (See Fig. 1)

Beam Properties

Synchronous and Nonsynchronous Behavior

In a multicell Alvarez cavity a synchronous particle gains a given amount of energy $\Delta T_{s,m}$ at cell m according to the formula

$$\Delta T_{s,m} = K\beta_{s,m}\,\lambda\,E_o \cos\varphi_s \tag{1}$$

where $\beta_{s,m}$ is the velocity achieved at gap m, where the particle has a phase angle φ_s relative to the rf. The rf wavelength λ is a constant. The average axial electric field gradient in the cavity is time-varying with a peak value E_o. K usually depends slightly upon m but here will be assumed constant. Now if we regard the structure as fixed but allow the electric gradient E to vary, then so long as E satisfies the relation

$$E \geqslant E_o \cos\varphi_s ,$$

there will be a particle which can gain the required energy and consequently possess the synchronous velocity $\beta_{s,m}$. However, for $E < E_o \cos\varphi_s$ no particle can gain the energy required by (1), hence there is no synchronous particle. In this case, the energy gain per cell is

$$\Delta T_m = K\beta_{s,m}\lambda\, E \cos\varphi_m \; . \tag{2}$$

The phase angle φ_m must be found by summing up phase increments for all cells up to m:

$$\varphi_m = \varphi_o + 2\pi\sum_{k=o}^{m-1} [(\beta_{s,k}-\beta_k)/\beta_{s,k}] \; . \tag{3}$$

The relevant parameters of the Alvarez structure are indicated schematically in Fig. 2.

Single Particle Behavior

It is convenient to introduce a parameter x, relative electric field gradient, defined as

$$x = E/(E_o \cos\varphi_s) \; .$$

Equations (2) and (3) have been used to calculate T_m for a number of values of x = const., using parameters appropriate to the SuperHilac. Results are plotted as Fig. 3. In all cases, $T_o = 2.55$ MeV/N, $\varphi_o = -20^\circ$. It is seen that initially, energy gain is more or less linear, because the particle is starting in phase with the rf. As the particle slips out of phase with the rf, the energy increments drop off sharply. Finally, when φ_m is changing rapidly, the energy gain is just as likely to be negative as positive and averages to zero. The particle energy then oscillates about some mean value, which is higher for x large. On each curve x = const. The point corresponding to $\varphi = 40^\circ$ is marked. From the appearance of these curves, it seems plausible that if we look at a particular value of m (supposing a rf diaphragm is to be installed there), the energy can be varied from T_o to a maximum T_m as a continuous function of x (the maximum is equal to $T_{s,m}$ only for $\varphi_o = o$). For large m and large x, however, it is clear that a large energy increment will result from a small change in x.

Particle Distributions

It is necessary to see how particle energy is affected by φ_o in order to predict how a beam might behave. This is best done by tracing distributions of particles in T, φ space (a beam) through the structure. In considering distributions, the important quantities for this study are T_{av}, the average energy, and $(T-T_{av})_{rms}$, the rms energy spread. Calculations have been made with the computer program PARMILA[†] using parameters and beam-initial conditions appropriate to the SuperHilac poststripper. In Fig. 4 T_{av} and $(T - T_{av})_{rms}$ are plotted, with the same acceleration conditions as used for Fig. 3, as a function of x and for the values m = 5, 10, 15. As expected, T_{av} does increase as a continuous function of x. As m grows larger, however, the maximum energy spread becomes large. The peak energy spread correlates with the maximum slope of the T_{av} vs x curves.

Energy Spread of SuperHilac. The division of the poststripper tank into sections, shown in Fig. 1, is a compromise between requirements for variable energy beams and requirements for economical operation of power tubes. The first section, from 1.2 to 2.6 MeV/N, has 22 cells and is not promising for variable energy operation. The last 5 sections, going from 2.6 to 8.5 MeV/N, have values of m ranging from 8 to 13 and should give good variable energy beams. From the results of calculations using distributions, Fig. 4, it can be estimated that in the worst case we can expect about a fourfold increase in energy spread, for certain energies, over the spread expected without energy variation. However, for those energies where the energy spread is worsened, a possible remedy is to use the succeeding section as a debuncher. An example of how this might work has been submitted to PARMILA, with results shown in Fig. 5. In this calculation Section 2 is used to produce a partial energy beam of 2.9 MeV/N, which then has a rms energy spread of 45 keV/N. Section 3, used as a debuncher, is energized at full voltage (1.8 MV/m), and its phase relative to Section 2 is tuned so as to minimize the energy spread, achieving 15 keV/N at the output of Section 3. The succeeding tanks are turned off. Figure 6 shows particle distributions in T,φ at a number of cells along the system and should make clear how Section 3 operates as a debuncher.

As Section 6 has no following section to use as a debuncher, it has been made short in order to minimize the increase in energy spread when used at partial energy.

Scaling

Results of calculations for a particular example, a heavy ion linac, have been presented. Other linear accelerators will be characterized chiefly by having different

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[†] PARMILA is used here as the generic name for computer programs which transform a collection of particles step by step, through a series of elementary transformations representing a linac in the six dimensions of phase space. The first such program, for which the name was coined, was written by the MURA group.[4] Versions in use at different accelerator centers differ in content.

values for K, λ, and $\beta_{s,o}$. We can attempt a scaling by asking what conditions will make the single particle properties exhibited in Fig. 3 behave the same way. Clearly the most important condition to be satisfied is that, for a given x, $\varphi_{\overline{m}}$ (for linac 2) behaves the same as φ_m (for linac 1).

As β_s increases nearly linearly, to a good approximation

$$\beta_{s,m} = \beta_o(1+\alpha m) \tag{4}$$

represents the synchronous particle and, at least for φ_m less than about 40deg,

$$\beta_m = \beta_o\ (1+\alpha' m) \tag{5}$$

represents a particle for $x < 1$, where α, α' are constants. Substituting (4) and (5) into (3) gives

$$\varphi_m = \varphi_o + 2\pi(\alpha-\alpha')\sum_{k=1}^{m-1} \frac{k}{1+\alpha k} \ .$$

For $\alpha m \ll 1$, this becomes to a good approximation

$$\varphi_m = \varphi_o + [(\beta_{s,1}-\beta_o)/\beta_o]\pi(m-1)m(1-\alpha'/\alpha) \ . \tag{6}$$

If the scaling is successful $(1-\alpha'/\alpha)$ will be constant;
therefore the quantity

$$\Phi = [(\beta_{s,1}-\beta_o)/\beta_o)\ (m-1)m \tag{7}$$

will also be a constant.

Equation 7 has been used to predict the number of cells for a variable energy section of a 200 MeV proton linac which will give approximately the same behavior as m = 5, 10, 15 for the heavy ion machine. The results, respectively are $\overline{m}$ = 12, 25, 38. Table I gives the relevant parameters of the two linacs. Calculations of energy gain versus x for the 200 MeV linac were made, and (after suitable normalization) are compared with the heavy ion linac in Fig. 7. The agreement is good, with the largest discrepancy appearing between the m = 15 and $\overline{m}$ = 38 curves.

Acknowledgments

The SuperHilac was conceived by R. M. Main as a variable energy machine; the present work has benefited greatly from his advice. D. T. Scalise has given valuable assistance with computer programming.

References

[*] Work done under the auspices of the U.S. Atomic Energy Commission.

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TABLE I. Parameters Used In Scaling Linac Properties.

Parameter			Heavy Ion Linac	Proton Linac
T_o	Initial energy	(MeV/nucleon)	2.55	200
β_o	Initial velocity		0.0736	0.5662
K	Energy gain coeff.	(MeV/nucleon/MV)	0.143	0.852
E_o	Av. electric gradient	(MV/m)	1.8	1.8
φ_s	Synchronous phase angle	(deg)	-20	-20
λ	RF wavelength	(m)	4.27	1.5
α			0.0145	0.00224
Comparable VE cell numbers			5 (2.9)	12 (214)
(Final maximum energy)			10 (3.3)	25 (229)
			15 (3.8)	38 (246)

Figure Captions

Fig. 1. SuperHilac poststripper showing division into sections by rf diaphragms.

Fig. 2. Parameters of a typical section.

Fig. 3. Particle energy for a given relative electric field gradient as a function of cell number.

Fig. 4. Beam properties at a given cell as a function of relative electric field gradient.

Top - RMS energy spread
Bottom - Average particle energy

Fig. 5. Illustrates the use of an independently driven section (Section 3 in this case) to reduce energy spread of beam emerging from upstream sections.

Fig. 6. Phase plots of the beam of Fig. 5 at a number of cells along the accelerator.

Fig. 7. Comparison of variable energy performance of an ion linac of $T_o = 2.55$ MeV/N with a proton linac of $T_o = 200$ MeV. The number of cells ($\overline{m}$) used for the latter were obtained by scaling the number of cells used for the former (m) with Eq. (7).

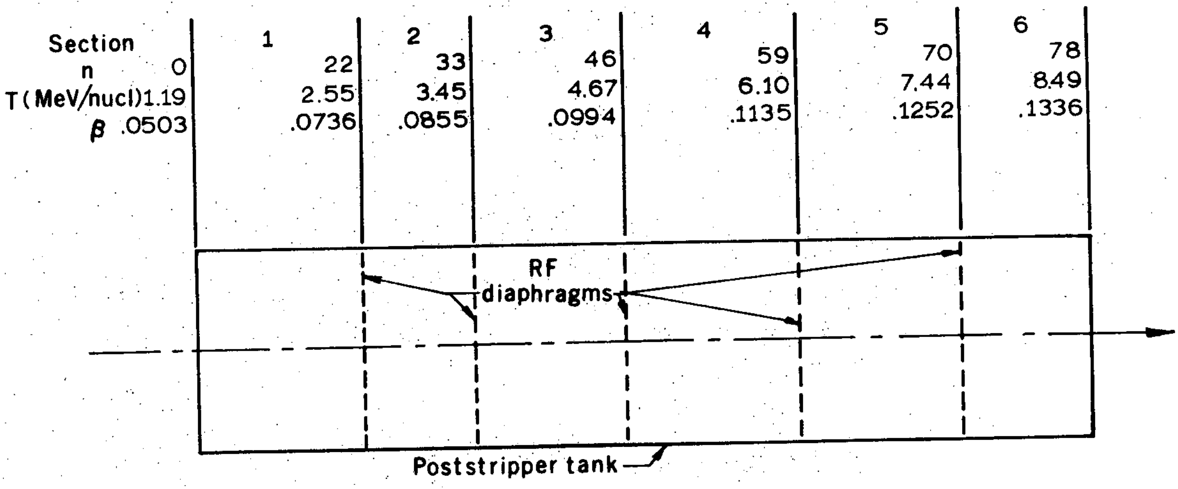

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Fig. 1

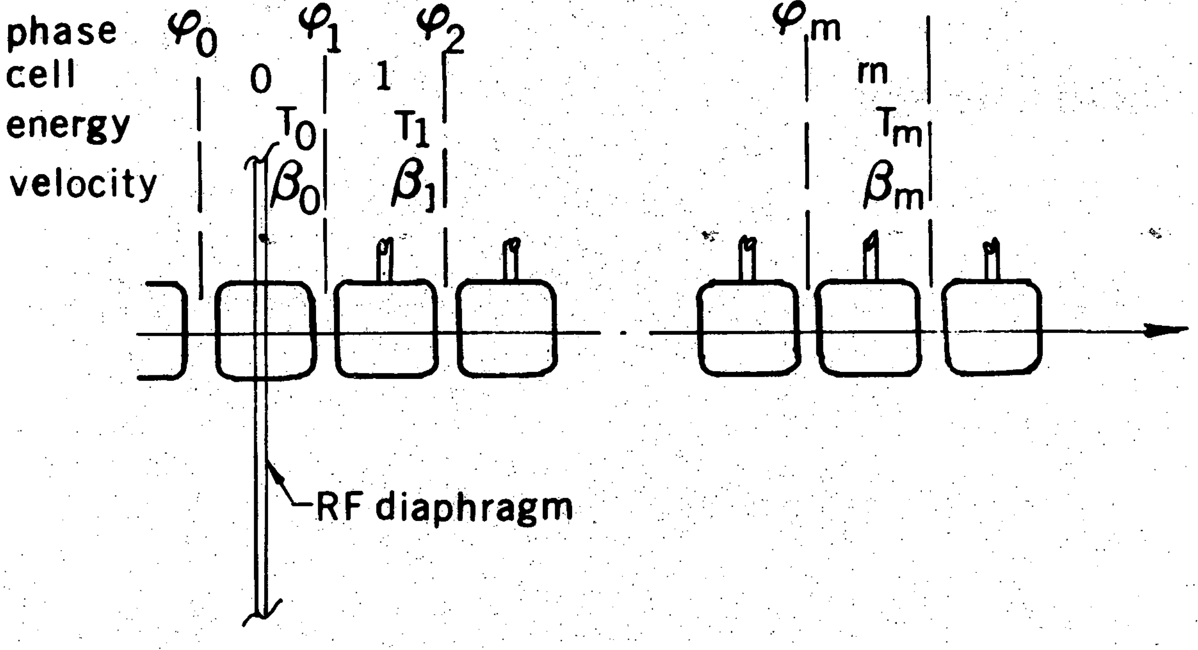

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Fig. 2

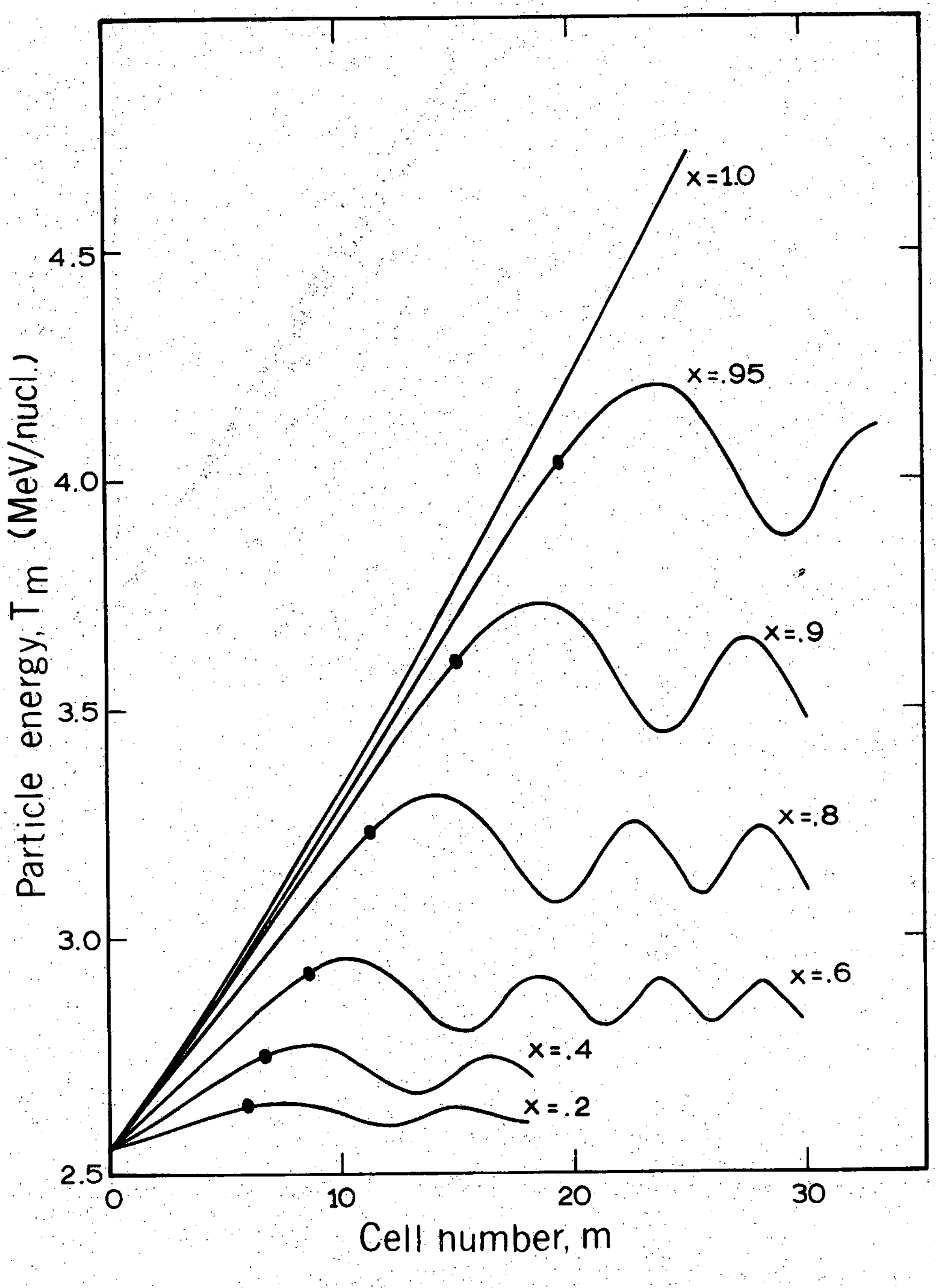

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Fig. 3

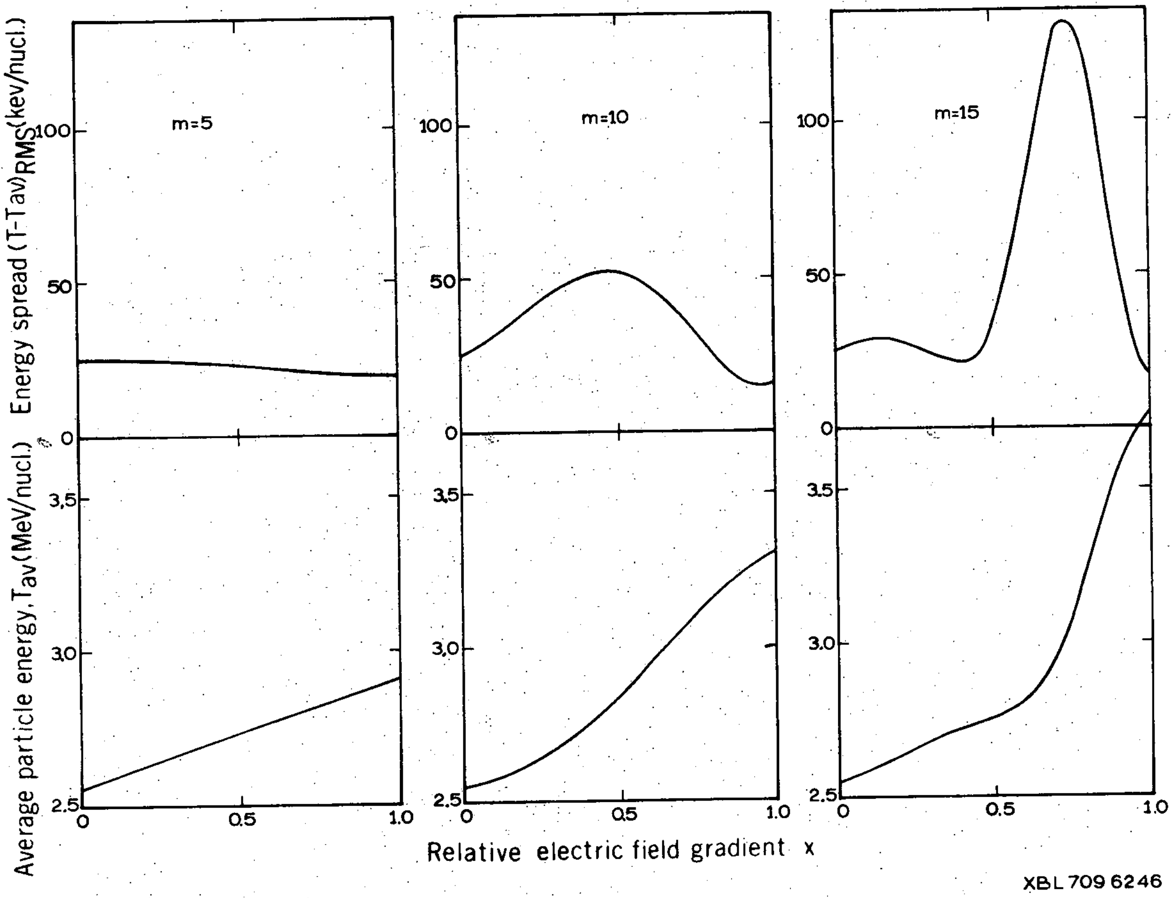

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Fig. 4

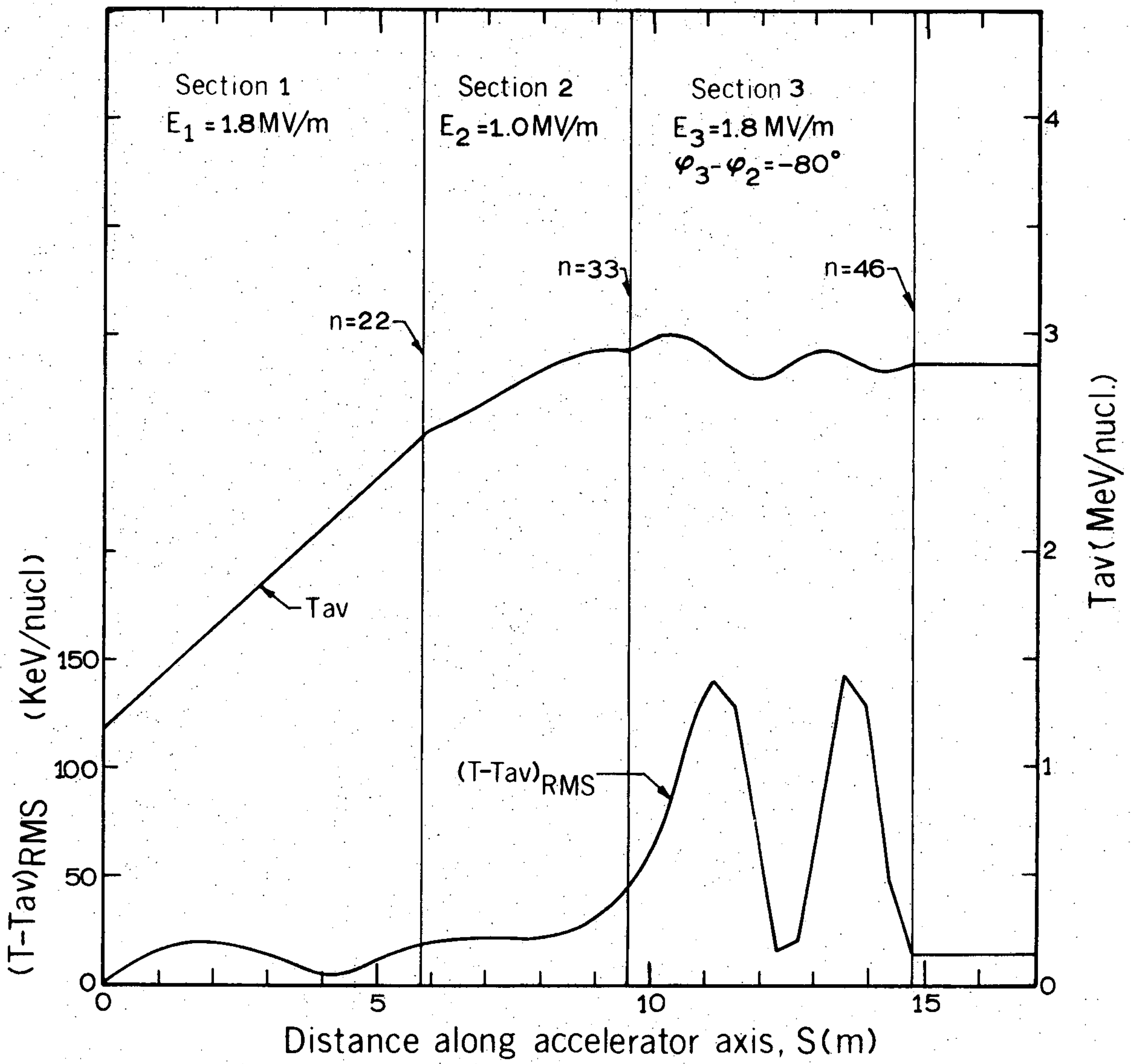

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Fig. 5

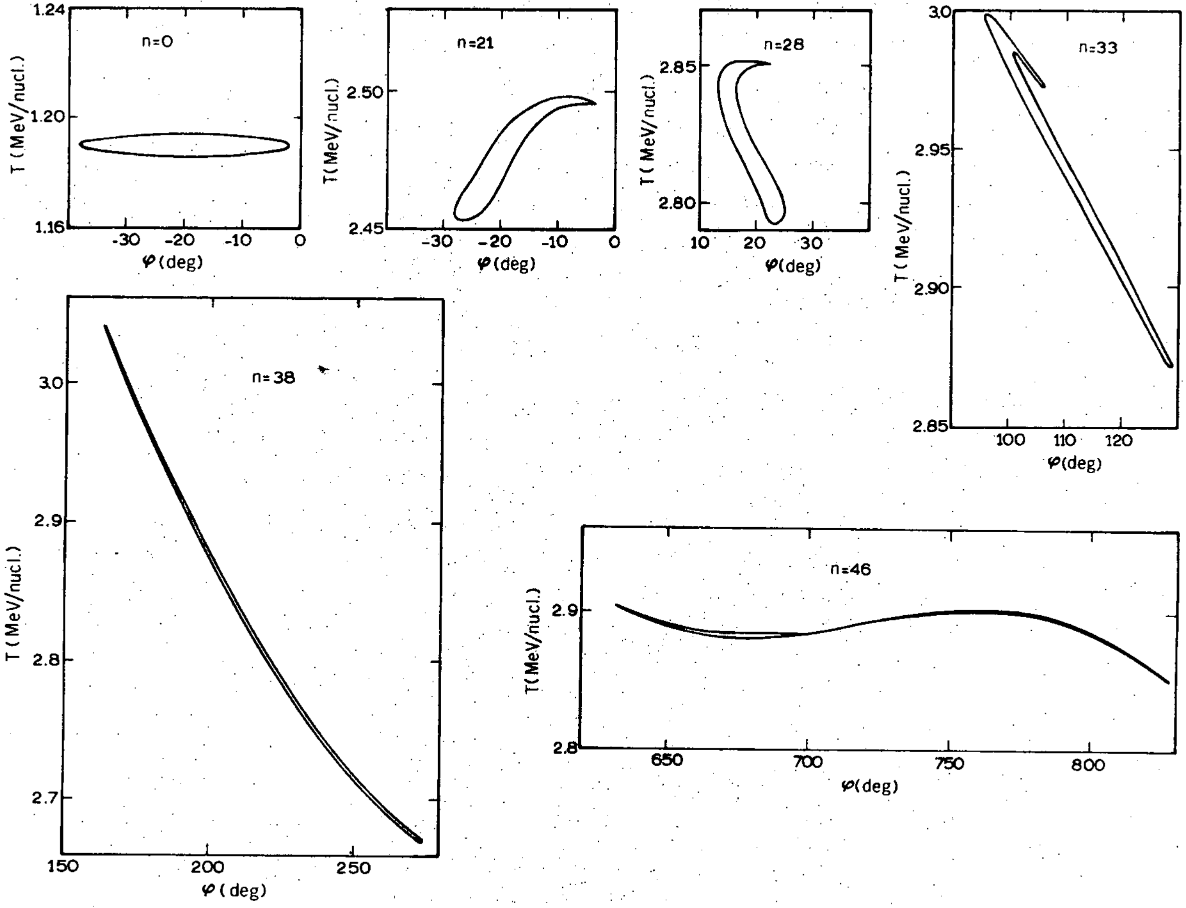

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Fig. 6

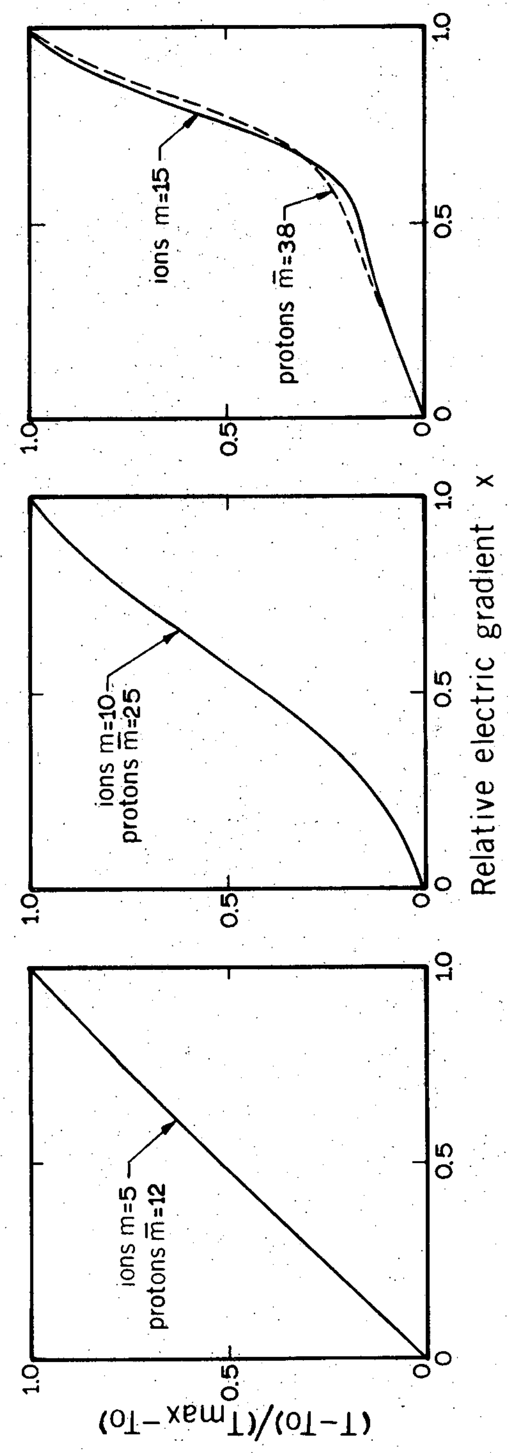

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Fig. 7

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