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ABSTRACT

A new simulation program has been made for linacs, applicable to heavy ion machines with independent long cavities (including the possibility of entering in the same bunch, ions of different charge state). This program applies also to superconducting multicell cavities for electrons and, with the inclusion of space charge, will apply to proton linacs. Apart from the introduction of a matrix formalism, it follows the same approach as proposed in 1965 by one of the authors and used in standard codes like PARMILA and MAPRO. Its range of validity, however, has been extended to long accelerating elements where, instead of second order corrections, as suggested in 1986, other simpler averaging methods are used. In addition, for the transverse motion, the introduction of reduced canonical variables simplified the expressions and increased the accuracy. The precision over one accelerating element has been shown to be appreciably better than 1% with the help of a complementary step by step integration routine of Hamiltonian form, always accessible in the code.

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Abstract

A new simulation program has been made for linacs, applicable to heavy ion machines with independent long cavities (including the possibility of entering in the same bunch, ions of different charge state). This program applies also to superconducting multicell cavities for electrons and, with the inclusion of space charge, will apply to proton linacs. Apart from the introduction of a matrix formalism, it follows the same approach as proposed in 1965 by one of the authors and used in standard codes like PARMILA and MAPRO. Its range of validity, however, has been extended to long accelerating elements where, instead of second order corrections, as suggested in 1986[1] , other simpler averaging methods are used. In addition, for the transverse motion, the introduction of reduced canonical variables simplified the expressions and increased the accuracy. The precision over one accelerating element has been shown to be appreciably better than 1 % with the help of a complementary step by step integration routine of Hamiltonian form, always accessible in the code.

Introduction

The derivation of beam dynamics equations commonly used now was presented in 1966[2][3] . It applies to symmetrical accelerating gaps and has been used for the design of Alvarez-type accelerators.

The field distribution in each gap, known usually from computation, is supposed to be expressed around its centre of symmetry in the form of a Fourier integral. Assuming straight trajectory and constant velocity and introducing a thin lens formalism, the changes in energy W, phase φ, radius r and slope r', when crossing the median plane, are given by expressions where the field distribution only appears through the so-called transit time coefficient T(k) with $k=\frac{\omega}{v}$ (angular frequency over longitudinal velocity) and its derivatives with respect to k. Energy, phase, radius and slope must however be the actual values at this median plane and they have to be computed through a second set of equations via iterations using the so-called S coefficients, which are to be treated with some care due to analytical discontinuities in the derivations [4]. Second order terms, taking into account the change in velocity across the gap, were roughly computed to obtain their order of magnitude, but were not used.

In 1986 the method was extended for the treatment of long and complicated independent structures (helix type) with no exact symmetry, to be used with various ions of quite different velocities [1]. The structures are now characterized by their axial field distribution, given in the form of a set of Fourier coefficients, which can be used to compute the usual transit time coefficients. The treatment was modified using the input plane with a thin lens formalism (avoiding the difficulty mentioned concerning the S coefficients and avoiding the use of a median plane, no longer significant in the absence of symmetry). In order to increase the accuracy for long structures, second order terms were accurately computed in the form of a double series of transit time coefficients. Such second order terms, though complicated, gave very satisfactory results for the longitudinal motion (W,φ). For the transverse motion the method lacked precision, for a reason not understood at that time, and was therefore discarded.

In 1988 an attempt was made to use such a formalism for electron machines of the superconducting type with 5 cell cavities and accelerating gradients up to 10 MeV/m . For relativistic particles (more than 2 to 5 MeV injection energy), the formalism gave correct results for the longitudinal motion. Results for the transverse motion proved to be wrong, necessitating the development of a new formalism.

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New Treatment for Transverse Motion

One drawback of the above method in the transverse motion is that the variables r and r' are not canonically conjugate. After having computed a change in transverse momentum across an accelerating gap, the corresponding change in r' has to include an additional term due to the change in longitudinal velocity. The emittance in r' is not constant: it has to be multiplied by $\beta\gamma$ to become "normalized" and invariant.

In the field of electrostatic electron optics Coue [5] makes use of a "reduced radius" R defined by the so-called Pitch transformation as :

$$R = r\sqrt{\beta\gamma} \tag{1}$$

With such a variable, the equation :

$$m_0 c d(r'\beta\gamma) = -qr\left(\frac{dE_r}{dr} + \beta c \frac{dB_\theta}{dr}\right)dt \tag{2}$$

becomes in the paraxial approximation, using Maxwell's equation :

$$\frac{d^2R}{dz^2} - \left[\frac{1}{(\gamma^2-1)^{1.5}}\frac{q}{2m_0c^3}\frac{\delta E_z}{\delta t} - \frac{\gamma^2+2}{(\gamma^2-1)^2}\frac{q^2}{4(m_0c^2)^2}E_z^2\right]R = 0 \tag{3}$$

The first of the two terms within brackets in equation (3) is in fact equal to the one generally used in the equation for r. The second term is nothing else than the electrostatic lens expression as given by Coue and is of second order in field. It is always larger than any second order correction to the first term (see previous section) and in some cases it is even larger than the first term as such (see fig 1 and 2).

The most important remark to be made however, is that the form of eq (3) implies, according to Liouville's theorem, that the emittance in RR ' is an invariant as it has no R' term.

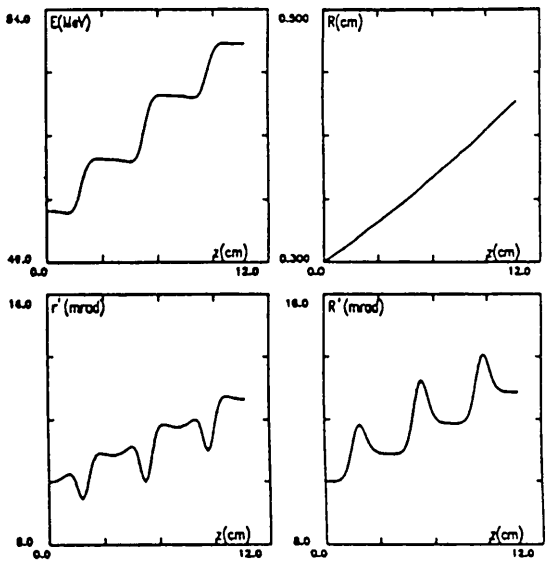

Fig.1. Evolution of energy, R, r' and R' for the acceleration of Pb^{25+} through 3 gaps of a Quasi-Alvarez period. The phase of the particle considered is at -20 deg from the crest. One observes the difference between R' and r'. While r' is of a complicated form, the R' curve clearly shows the effect of the first term of eq 3, which is the prominent one here.

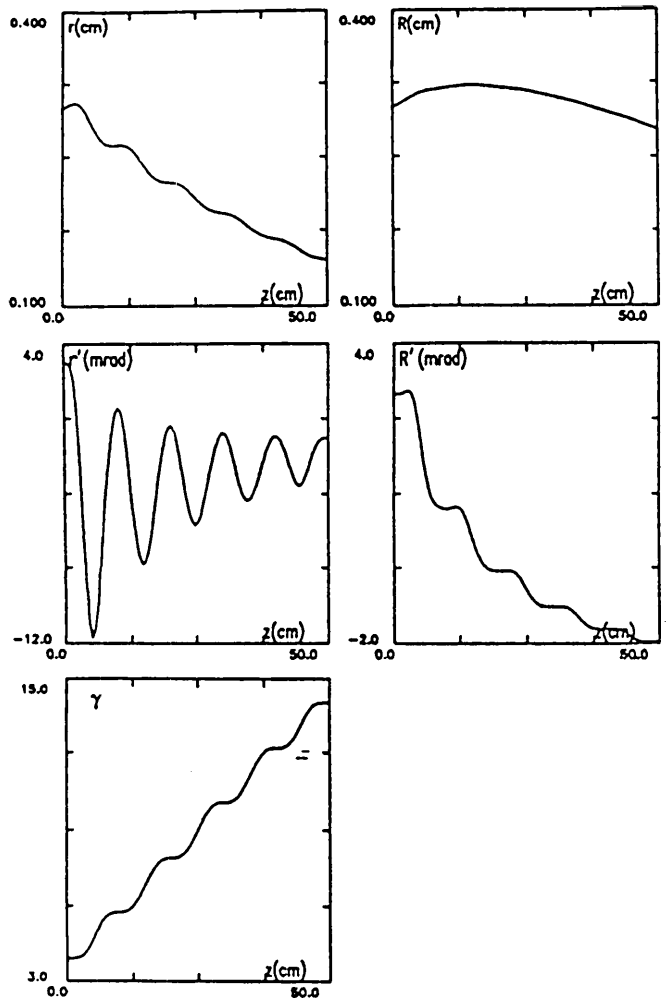

Fig.2. Same as fig 1 but for a 5 cell electron structure with an input energy of 1.5 MeV (6.5 MeV at the output). The phase is close to the crest. In eq 3 it is now the second term which is the largest; R' has a stepwise evolution, essentially converging.

New Computer Codes

With eq (3) for the transverse motion, a new 'suite' of codes to replace PARMILA and similar type codes has been developed. Such codes are now applicable to a great variety of linacs from ion machines (Quasi-Alvarez stucture or independent long cavities) to electron machines of the CEBAF type (5 superconducting cells). Integration of the equations of longitudinal and transverse motions over long structures where β may change by 5% (or more for shorter structures) and γ by a factor of up to 3 or 4 requires, in order to get accurate results with the standard formalism, either additional higher order corrections or the use of some averaging procedure. This last method has been chosen. For instance, the $k = \frac{\omega}{v}$ of the transit time factor is computed via iterations with a beta which corresponds to the velocity defined by input and output phases in the accelerating element. In eq (3) the γ terms are taken as an average over the element, assuming a linear γ variation with z. Phase and radius are also corrected. Detailed derivations will be given in another paper in preparation.

A complementary step by step integration routine of Hamiltonian form allows a check of the direct expressions as well for transverse as for longitudinal motions. Such expressions have been found to be satisfactory for several accelerating structures (see figs 3, 4, 5, 6 and 7). Nevertheless, calculations with this step by step integration routine take almost 100 times longer than the analytical procedure.

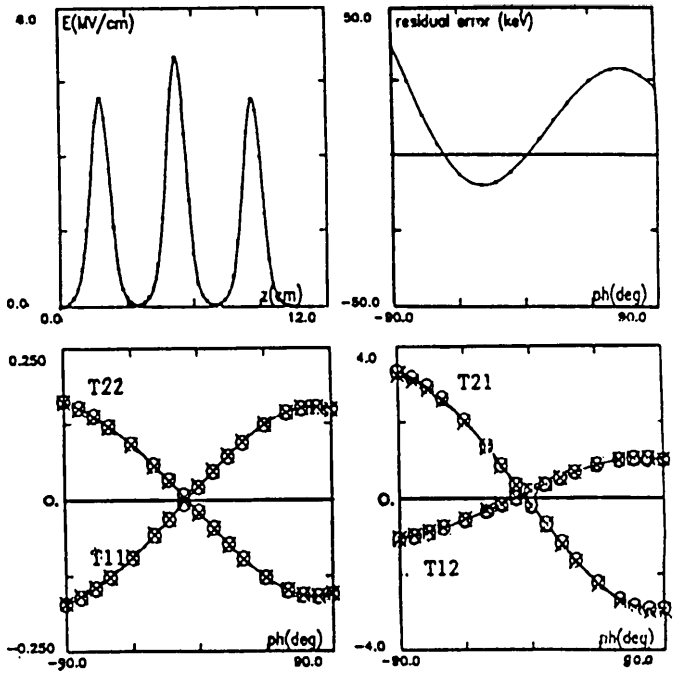

Fig.3. Comparison of the accurate step by step integration with the d... expressions used in the new codes, shown here for the acceleration of Pb^{25+} through a Quasi-Alvarez cell at around 0.24 MeV/nucleon (50 MeV kinetic energy). One can see the axial electric field distribution of the cell and the residual error in acceleration for phases in the range of -90 deg to +90 deg (at 200 MHz) around peak acceleration (here 3.4 MeV). The other two graphs show the evolution of the matrix coefficients T (T21 in mrd/mm, T12 in arbitrary units), used for the calculation of the reduced variables in the thin lens formalism (the circles correspond to the direct expressions, the crosses to the step by step integration).

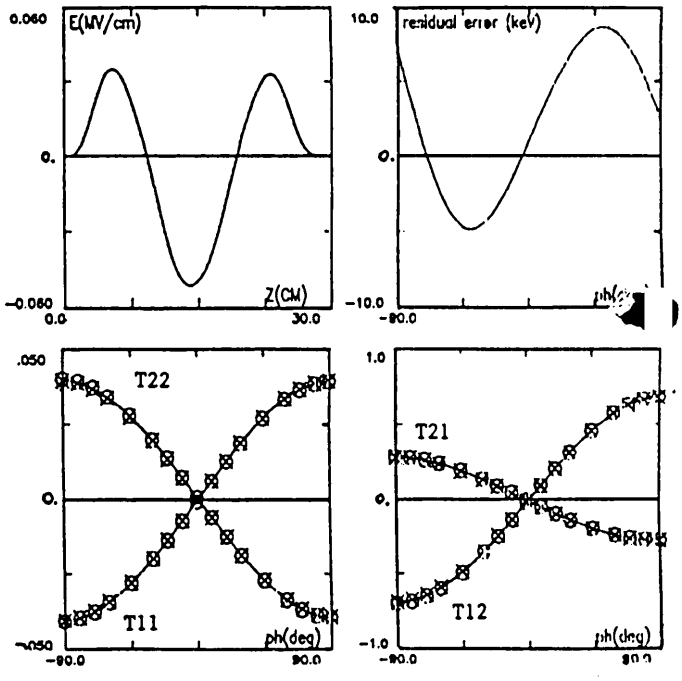

Fig.4. Same as fig 3, but for Ge^{19+} through a βλ helix for a β corresponding to optimal acceleration (close to 10 MeV, frequency 135 MHz).

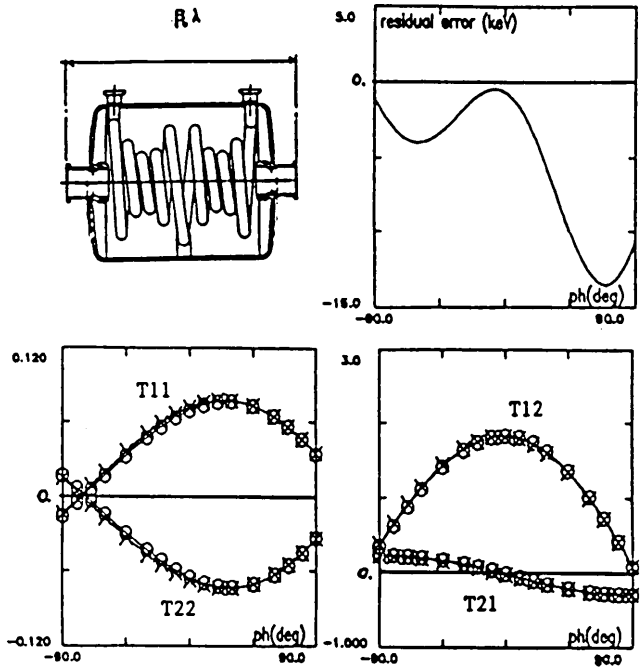

Fig.5. Same as fig 4, but at the edge of the velocity pass band (only 1.5 MeV peak acceleration). The shape of the helix is shown rather than the field distribution.

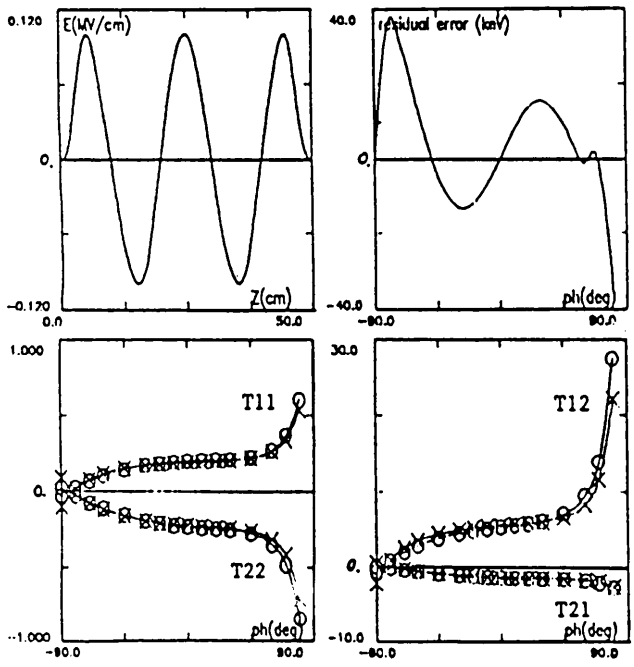

Fig.6. Same as fig 3, but for electrons injected at 1.5 MeV into a 5 cell cavity (frequency 1500 MHz, 5 MeV peak acceleration).

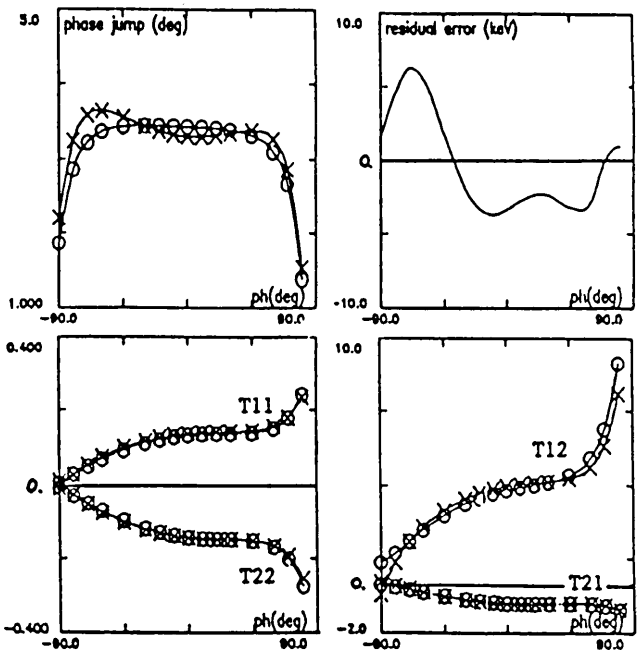

Fig.7. Same as fig 6, but for electrons injected at 2.5 MeV. Rather than the field distribution, the phase jump is shown (the phase variation across the cavity is around 1000 deg). The circles correspond to the direct expressions, the crosses to the step by step integration; the maximum difference between these two is of the order of a few tens of a degree. The errors found at higher injection energies are even smaller.

Conclusion

These codes, initially developed for the computation of a heavy ion booster at Saclay, and also installed and partially developed at CERN, now also include the possibilty of computing recirculating electron machines with the effect of synchrotron radiation in bending magnets [6]. At CERN, they form an integral part of a suite of programs for the design of a Quasi-Alvarez lead linac [7]. For present applications, space charge has not yet been included, but the logic used in the programs allows for such an addition. An extension for the simulation of an RFQ could also be foreseen.

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