Proceedings of the Linear Accelerator Conference 1990, Albuquerque, New Mexico, USA

COMPUTER DESIGN AND DYNAMICS OF THE QUASI-ALVAREZ LINAC

P.Lapostolle*, E.Tanke, M.Vretenar, D.J.Warner
PS Division, CERN, CH-1211 Geneva 23, Switzerland
S.Valero
LNS, CEN-Saclay,F-91191 Gif-sur Yvette Cedex France

Abstract

A possible structure for the Linac of the CERN heavy ion complex is the quasi-Alvarez. This has superperiods including $2\beta\lambda$ cells and $\beta\lambda$ cells with focusing quadrupoles only in the longer cells. We have applied a new fully relativistic general formalism to three stages of the design. Firstly the longitudinal dimensions are defined via prescribed synchronous phase and electric field laws, using cavity computations to derive the axial fields. Then the transverse matching and quadrupole parameters are checked. Finally, multiparticle dynamics computations are used to investigate coupling and emittance variation between 0.25 MeV/u and 4.2 MeV/u.

Introduction

For the heavy ion programme at CERN [1,2], several distinct options for the injector linac are being developed, in particular the "quasi-Alvarez" drift-tube structure to accelerate lead ions (Pb25+) between 0.25 MeV/u and 4.2 MeV/u [3].

For low energy ions with small q/A ($\approx$ 0.1) impracticably high quadrupole gradients are required in a $\beta\lambda$ accelerating structure, so the quasi-Alvarez minimises the number and strength of the quadrupoles by a) using an optimum quadrupole separation and a betatron phase advance of about 80^0/focussing period and b) making the quadrupole length about $1.5\beta\lambda$ i.e. using a $2\beta\lambda$ period locally. To maximise the acceleration rate, $\beta\lambda$ periods are used between quadrupoles with smaller "empty" drift-tubes for RF power economy and mechanical simplicity. Thus each focusing period between 0.25 MeV/u and 2 Mev/u is $8\beta\lambda$ long (N=8) and has two long cells ($2\beta\lambda$) and 4 normal cells ($\beta\lambda$). Between 2 MeV/u and 4.2 MeV/u an N=10 focusing period is used.

Design Methods for Feasibility Study

The initial design was developed using simple programs for the beam dynamics. To study the transverse motion, and quadrupole strengths and dispositions, an analytical approach and a precise matrix formalism were applied to the critical region at 0.25 Mev/u [3]. With the selected period layout (N=8), the allowable RF defocusing and limits for tolerable surface fields, the first structure designs, could be tested using the RF cavity program, SUPERFISH to compute cells between 0.25 Mev/u and 2 MeV/u. Electric field results were interpolated at intermediate energies to give a first linac design e.g. cell lengths, numbers of cells and quadrupoles, and RF power. As the increase in β/accelerating gap is only 1.5% in most of the first section, the analytical formulae give good indications of acceptance in the longitudinal phase plane for comparison with computational results.

Beyond the feasibility stage, a more systematic approach is necessary, to cover the stages between the cavity computations and multiparticle optics. This was done for CERN Linac2 [4] but the programs used cannot treat the superperiodicity and local asymmetrics of the quasi-Alvarez.

* Consultant

Design with a New Formalism

It was decided to apply the gap acceleration treatment of Lapostolle and Valero [5] to the three logical stages viz. longitudinal design (for precise cell dimensions), transverse design (to confirm the quadrupole settings) and multiparticle dynamics (to study coupling and emittance evolution). These new fully relativistic codes allow accurate trajectory computations through long rotationally symmetric accelerating elements for a wide range of particles e.g. protons and electrons as well as heavy ions. No particular symmetry is required for the longitudinal electric field.

For a bunch of particles, the speed of computation is substantially increased by developing the dynamics variables as a Taylor expansion around the bunch centre. In the longitudinal motion, the phase and energy dependant terms are such that the Jacobian is close to unity so the treatment satisfies Liouville's Theorem. Although the 4 x 4 matrix formalism applied to the transverse motion ignores third order abberations, all the chromatic terms are included as well as phase dependant effects and again the Jacobian is very close to one. This allows observation of transverse-longitudinal couplings and vice-versa, filamentation effects and emittance transfers. Comparisons with a very accurate but much slower step-by-step integration routine show no significant differences with the Taylor expansion method.

Particle Type:	Lead Ions with A=208, q=25+
Tank 1:	W_i = 0.24 MeV/u W_f = 2.0 MeV/u
Tank 2:	W_i = 2.0 MeV/u W_f = 4.2 MeV/u
Frequency	202.56 MHz
Effective Synchronous Phase ($\phi_{s,eff}$):	
Tank 1:	$\phi_{s,eff} = A\beta^{-0.27}$ = -40^0 at 0.24 MeV/u
Tank 2:	$\phi_{s,eff}$= -30^0
Mean Electric Field (MV/m):	
Tank 1:	E = 2.09 + 0.278z
Tank 2:	E const., W' continuous between tanks
Acceleration Periodicity:	
Tank 1:	3 gaps/$4\beta\lambda$
Tank 2:	4 gaps/$5\beta\lambda$

Table 1: Starting Conditions for Linac Design

Computations of Cell Dimensions

This section concerns the development of a program which will compute the sequence of cell lengths, given the starting conditions of Table 1 and interpolating between cavity field computations corresponding to a small number of different cell lengths to obtain axial field distributions.

Eleven cases corresponding to nine cell lengths between 0.25 MeV/u and 2.0 MeV/u (with two increases in aperture diameter) were computed for half RF supercells i.e. for a length of $2\beta\lambda$. Good resolution in the axial field results with an adequate representation of the drift-tube profile, could be obtained with 60 or more mesh points on the axis. The program HARMNY processes the field data by making a spline fit to 33 equally spaced points in each $\beta\lambda$ interval centred on the three gaps per superperiod. Then for other period lengths, the axial fields are derived from the two nearest cases computed by SUPERFISH. Best results were obtained by logarithmic interpolation (versus cell length) between actual fields rather than Fourier coefficients. Then a Fourier analysis over the $\beta\lambda$ interval provides up to 20 coefficients for HARMNY.

The condition $\phi_{s,eff} = A\beta^{-0.27}$ cannot be applied directly as a) the particle phase is only computed at the input and output of an accelerating interval and b) $\phi_{s,eff}$ will be some average value over three gaps (four for Tank 2). For the tank input at 0.24 Mev/u the unknowns are, the (exact) cell length and the particle input phase. These are adjusted iteratively using a simple algorithm so that $\phi_{s,eff}$= -40^0 and the ratio of input to output phase varies as β^{-x}. In subsequent cells the input phase is known so only the cell length need be adjusted to satisfy the phase relation. At each iteration the accelerating field distribution and average accelerating field must also be reset. The starting value for the cell length is an extrapolation from the two preceding cells and the linac cavity ends after the superperiod nearest to the prescribed energy. The design parameters produced by HARMNY (Table 2) correspond to the largest surface electric fields considered feasible at present.

	TANK 1	TANK 2
Energy (MeV/u)	.240→2.129	2.129→4.238
Length (m)	7.684	6.634
RF superperiods	31	12
Mean E field (MV/m)	2.090→4.152	3.960
Aperture dia. (mm)	12→16	18→20
Quad.length (mm)	51→125	145
Quad. Grad. (T/m)	170→61	46→41

Table 2: High Gradient Quasi-Alvarez Linac

First Order Transverse Dynamics

The transverse envelope matching, quadrupole strengths and batching are tested with the program TRANSPORTVA which has input data as a sequence of beam transport elements (c.f. TRANSPORT). In particular the accelerating regions use the above mentioned formalism. Cell lengths, electric fields and input conditions are as derived in HARMNY thus giving identical longitudinal dynamics. Transversely, the evolution of the beam envelope is computed using the RF defocusing term for the synchronous particle and the given quadrupole gradients. The usual matching and quadrupole optimisation features were unnecessary as the gradients derived by the matrix treatment gave sufficiently good beam envelopes . There was a slight worsening of the results when the quadrupoles were grouped into threes with identical gradients. Transverse matching features may be needed between the linac tanks, but here the difficulty may be to control the longitudinal phase increase.

TRANSPORTVA gives ideal first order dynamics results with no emittance increase or distortion and so provides a bench-mark for the multiparticle simulations.

	Tank 1	Tank 2	
Input Ellipse Semi-Axes			
x,x′ plane	5.10 x 8.6	2.17 x 6.9	mm mrad
y,y′ plane	1.99 x 22.4	5.66 x 2.64	mm mrad
W,ϕ plane	5.77x20.0	15.63 x 7.39	keV/u^0
Output Ellipse Semi-Axes			
x,x′ plane	1.94 x 7.6	5.42 x 1.95	mm mrad
y,y′ plane	4.90 x 3.12	2.22 x 4.78	mm mrad
W,ϕ plane	15.0 x 7.7	18.5 x 6.13	keV/u^0

Table 3: Nominal Input and Output Matching

Multiparticle Dynamics with SIMUL

This program uses the the Taylor expansion approach to advantage when it is applied to a bunched beam (represented here by 200 particles). With the dimensions and fields from (HARMNY), and the quadrupole and matching parameters as confirmed by TRANSPORTVA this program, SIMUL, checks the behaviour of the quasi-Alvarez linac. In particular, the way the emittance varies for changes in beam and machine parameters can be studied. The structure of the program follows the TRANSPORT model with additional subprograms concerning the accelerating regions, the filling of the input emittances with particles, and statistical analyses and graphs of the output beam .

The main optics problem at low energy concerns couplings between the phase planes. Qualitatively these are due to the variation of acceleration with radial position essentially as $I_0(2\pi r/(\beta\lambda))$ and the variation of RF defocusing with phase, essentially as $r\sin\phi$. In fact the standard input data uses an upper limit for normalised input emittance $E_n = 1\pi$ mm mrad, and the corresponding longitudinal emittance of $1.6\pi\ 10^{-6}$ eVs/u [1]. The (4 rms) emittances given in Table 3 are right ellipses with axes defined by the matrix treatment (transverse) and the linac acceptance formulae [3]. Two distinct ways of assigning particle initial co-ordinates were used.

Initially particles were chosen at 13 positions in the transverse planes so that the linear region near the axis and the limit of the emittance were represented. Then for each of these transverse positions, 13 co-ordinates in the longitudinal phase plane were assigned, (8 on the emittance boundary), giving sets of co-ordinates for 169 particles in total. The results at 2 MeV/u in fig. 1 show that particles initially at the same position in the longitudinal plane spread out depending on their initial transverse positions. However the net effect does not appear to be an increase in the longitudinal emittance because the limiting particles fall inside and outside the emittance ellipse fitted to the paraxial particles. In the transverse planes the dominant effect seems to be a spread in betatron phase for particles with differing initial longitudinal co-ordinates , but no net movement to outside the ideal emittance.

These coupling effects are rather smaller than might be expected at 0.24 MeV/u, as with a maximum radial excursion of 5mm, $I_0(2\pi r/(\beta\lambda)) = 1.23$. In fact the beam envelope in the accelerating gaps is less than 85% of the maximum, the envelope is not representative of the motion of individual particles and this coupling reduces with increase in beta.

For other beam simulations, random selections of particle co-ordinates were made so as to fill the 4-dimensional transverse phase space uniformly and simultaneously, to fill the longitudinal ellipse uniformly. These distributions were adjusted so that the first and second moments as computed by the standard statistical formulae, are exactly as prescribed despite the relatively small number of particles selected (200). Except where otherwise specified the standard input conditions of Table 3 were used. Surprisingly , for the majority of cases the emittance changes between 0.24 MeV/u and 2 MeV/u were barely significant. Thus for the normal case (Table 3) two results corresponding to distinct sets of random numbers differ by about 3% whereas the nominal emittance increases are less than 5%. A similar, comforting result was obtained when batching the quadrupoles in threes (to reduce the number of power supplies). The output projections on the three normal phase planes and the x,y plane are given in Fig. 2.

Attempts to demonstrate significant coupling between the phase planes were not conclusive. The method used was to make, in turn, one of the 3 emittances either twice the normal value or 10% of the normal value. The only significant emittance increases occurred in the longitudinal plane, by 10 to 15% when the transverse emittances were increased and then by 50% when the longitudinal input emittance was 10% of normal. Results where large increases in transverse dimensions could occur, are somewhat hypothetical as there might also be beam losses. Other tests were made using mismatched beams as would occur if the normal beam passed through a drift space until its length increased by 22%. These mismatches persisted throughout the acceleration to 2 Mev/u with a significant emittance increase, 18%, only for the longitudinal plane when it was mismatched.

One advantage of the quasi-Alvarez structure is its large longitudinal acceptance, which should allow efficient acceleration for several charge states around q=25+. Two complementary approaches were tried. Firstly the RF field level was varied by ±10% about the nominal level with the nominal input beam, which will evidently be mismatched both in input phase (by -6^0 and +8^0) and in ellipse dimensions. These fields would be ideal for fictitious particles with q=22.5+ and q=27.5+ respectively! Another test used the normal accelerating conditions but for a beam with mixed charge states viz. q=24+, 25+ and 26+ in ratios 25%, 50% and 25% respectively. When varying the RF level there was a 10% longitudinal emittance increase at the -10% setting whereas for the nominally smaller effect (dq=± 1 cf dq=± 2.5) the superposition of three beams each making coherent oscillations gives a longitudinal emittance increase of 16%.

The results obtained between 2 and 4.2 MeV/u confirmed the above findings with negligible emittance increases except for the longitudinal plane with large input mismatch (18%).

Conclusions

This package of programs has been used to design a Quasi-Alvarez linac as far as its beam dynamics is concerned. Further iterations on the design e.g. to optimise cavity lengths for RF or post-coupler reasons [6], should be straightforward. With the relatively small rate of increase in β and the absence of space charge the close agreement with the simpler matrix and analytical approaches was not unexpected, but the negligible emittance increase, even with rather drastic mismatches, was an agreeable surprise.

References

1. H.Haseroth (Ed.), "Concept for a Lead-Ion Accelerating Facility at CERN", CERN 90-01 (1990)
2. H.Haseroth (Ed.), "A Heavy Ion Injector at CERN", This Conference
3. D.J.Warner, "Heavy Ion Acceleration Using Drift-Tube Structures with Optimised Focusing", 1988 Linac Conference Proceedings, CEBAF-Report-89-001, p109 (1989)
4. D.J.Warner, "Accelerating Structure of the CERN New 50 MeV Linac", Proc. 1976 Proton Linear Acc. Conf., AECL-5677, p49 (1976)
5. P.Lapostolle, F.Meot, S.Valero and E.Tanke, "A New Dynamics Code for Electrons, Protons and Heavy Ions", This Conference
6. M.Vretenar and D.J.Warner, "Field Stabilization in the Quasi-Alvarez Structure", This Conference

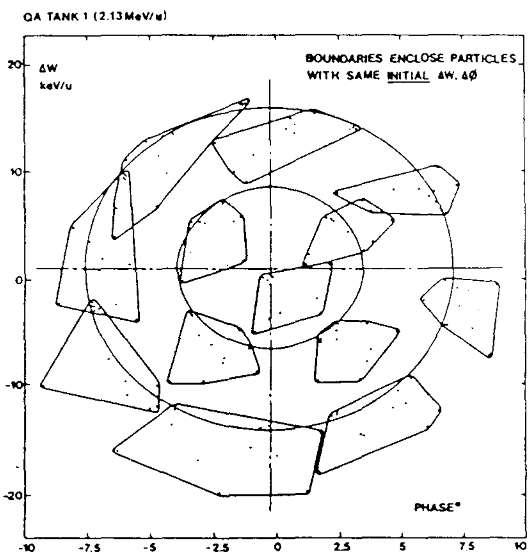

Figure 1: Coupling from Transverse to Longitudinal Phase Plane

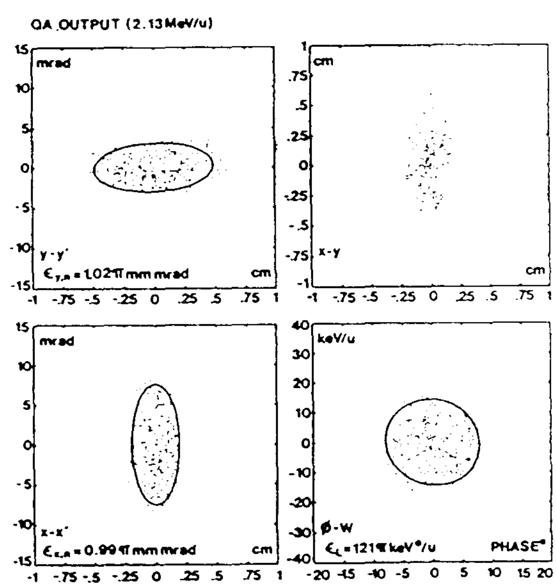

Figure 2: Phase Plane Projections at 2.13 MeV/u