DYNAMICS AND TOLERANCES FOR THE CERN INTERDIGITAL H LINAC

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Abstract

A three tank Interdigital H structure has been chosen for the 0.25 to 4.2 MeV/u part of the CERN heavy-ion injector linac. The complete design has been developed by GSI, in particular the longitudinal dimensions have been determined and multi-particle studies have been made using the program LORAS. Some RF tolerance studies have also been made at CERN using this program.

For a more general approach to the dynamics, the program DYNAC is being used at CERN especially where statistical analyses are essential i.e for determining emittance growth, tolerances on accelerator parameters and alignment. The approaches and results of these two programs are compared for this novel type of accelerator.

Introduction

The project for a heavy ion facility at CERN [1] is now in its construction phase. In particular, the linac injector is being made in collaboration with several institutions, mostly from CERN member states. For the acceleration from 0.25 to 4.2 MeV/u two contrasting and novel linacs were proposed: the Interdigital H structure [2] and the Quasi-Alvarez structure [3].

The choice of the IH structure for the CERN heavy ion linac followed the design, construction and first commissioning of a 1.4 MeV/u IH structure at GSI, Darmstadt [4]. This accelerator comprises most of the difficult and novel features proposed for the higher energy CERN version. Important differences concern the increase in the acceleration rate and two additional accelerator tanks at 202.56 MHz to increase the output energy.

With the IH structure we rely on computed dynamics as comprehensive analytical tools are not readily available. The program LORAS, which was developed for the design of IH linacs, has been used to design the CERN linac and to make estimates of RF tolerances. The program DYNAC [5] had been developed to treat all types of linacs, so it could be applied, using its facilities for beam analysis to the IH Linac. We use the design and beam specifications of LORAS as a standard against which to compare the detailed results from DYNAC.

Qualitative Description of IH Principles and Design

A complete description of the operation and beam dynamics of the IH structure exists in several papers (e.g. [6]) and a brief recall is given here. The beam dynamics with "Combined Zero Degree Synchronous Particle Sections" is illustrated in Fig. 1 where the effective phase of the bunch centre varies from positive to negative along a section (1 to 2). The subsequent drift space (including triplet focusing) and a few longitudinally focusing drift tubes, restore the working point and the beam orientation (2 to 4) to that required at the input of the next accelerating section (4 to 5). Note that due to operation around φ_s=0 the average RF defocusing is much reduced; in addition the mean energy of the beam is somewhat above that for synchronous motion.

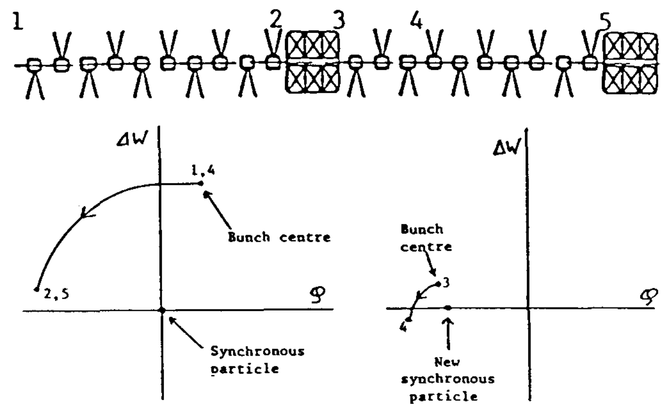

Fig. 1 Principles of IH Dynamics

The design follows from these principles. The cavity H mode, loaded by drift tubes, has a mainly accelerating field component on the axis . As RF defocusing is weak, there is no need for focusing within the thin-walled accelerating drift tubes, which leads to low capacitive loading i.e. high shunt impedance and modest RF power requirements. These drift tubes can stand exceptionally high fields, reducing the length of structure required. Longitudinal and transverse acceptances are closely matched to the beam from the RFQ but operation at 1% to 2% above threshold RF level (i.e. above the RF level for minimum beam transmission) allows good beam transmission.

Brief Description of LORAS

For the design of (low current) IH structures, the program LORAS has been developed. LORAS calculates (i) the structure, consisting of accelerating sections, transverse and longitudinal focusing sections and (ii) the beam dynamics.

i) The generation of the structure leads to a table of period lengths for the synchronous particle as function of the voltage distribution and phase. This is very fast and independent of outside field data. An estimate of the longitudinal acceptance is obtained from the output energy as a function of input particle energy and phase.

ii) The dynamics is computed in longitudinal and transverse phase-space. Electric fields are calculated, separately, by a 2D Poisson solver. For tracking, the gaps are divided into sections for which the fields are approximated by linear functions and the transit-time factors obtained by interpolation.

For the bunch centre, injection energy and phase w.r.t. the synchronous particle have to be given. Input data include the number of particles, the transverse and longitudinal emittances and their tilts. LORAS provides particle trajectory plots in the X-Z, Y-Z, dW/W-Z and dφ-Z planes and emittance plots.

Brief Description of DYNAC

DYNAC is a 6-D multi-particle program using a new concept "the equivalent accelerating field" [5] able to treat dynamics of electrons, protons and ions in complex accelerating structures. It contains many possibilities for tolerance studies and for simulations of systematic or random error effects. The input beam conditions are similar to those of LORAS. Structures and beam lines are represented by a series of elements, with the possibility to obtain emittance plots as well as detailed information about the beam at any element. Plots of the beam envelopes are also available. The electrical fields of the accelerating elements, which can be obtained using codes such as SUPERFISH or URMEL, are converted into a Fourier series.

IH Linac Parameters

The parameters in table 1 are necessary for a discussion of the dynamics. Cell lengths (gap centre to gap centre) are approximately $\beta_r\lambda/2$, with the reference ion (Pb^{25+}) energy being significantly bigger than that expected from the structure periodicity.

Table 1
Principal Parameters of the CERN IH Linac

Parameters, Units	Tank 1	Tank 2	Tank 3
Input Energy, MeV/u	0.251	1.859	3.040
Output Energy, MeV/u	1.859	3.040	4.202
Frequency, MHz	101.28	202.56	202.56
Length*, m	3.567	1.549	2.019
# of accelerating gaps	13+14+14	28	30
Cell length range, mm	35 - 93	47 - 59	60 - 72
Gap voltage range, kV	230 - 420	280 - 400	240 - 370
Triplet lengths**, mm	402, 402	412	438
Quad. gradients, T/m	6.25, 6.65	6.85	6.9

* Between flanges; total length of the structure : 8.129 m
**Two triplets are in tank 1, the others precede tanks 2 and 3

Particle Distributions and Statistical Methods

Both LORAS and DYNAC use several hundred "macro-particles" to represent the beam but the particle distributions are different.

In DYNAC, the distribution applied is uniform in the longitudinal phase plane and simultaneously uniform within a 4-D hyperellipsoid representing the transverse phase-space. Projections in any transverse coordinate phase plane are not uniform. The "macro-particles" are initially chosen randomly within boundaries which correspond to the correct r.m.s. parameters of the phase-space ellipses. The first and second moments of the distributions still have statistical errors which are removed by readjusting the distributions slightly using the subroutine CORRECT. During acceleration in the IH linac there is considerable distortion of the longitudinal distribution and particles near or outside the separatrix tend to form "tails". As the r.m.s. emittance analysis including all the particles at the output can be strongly influenced by a few particles in the "tails", the emittance is computed both for the complete beam and for a beam in which the outermost 5% of the particles have been eliminated using the subroutine CHASE.

In LORAS the particles are uniformly distributed in an ellipse in the longitudinal plane and simultaneously uniformly in a transverse plane. The other transverse plane is treated with the longitudinal plane in an independent manner so the beam projection is uniform in each of the two transverse phase planes. The LORAS version used here includes the subroutines CORRECT and CHASE.

Analysis of Results

All results (except Fig. 2) are from DYNAC and emittances quoted are $4\varepsilon_{rms}$ (normalized for the transverse planes). Figures in Table 2 are for 95% of particles retained (CHASE).

Table 2
Beam Parameters for Nominal Settings

	α_{in}	β_{in}	ε_{in}	α_{out}	β_{out}	ε_{out}
XX'	1.69	0.94	0.735	-2.29	4.26	0.806
YY'	0.47	0.55	0.744	-2.64	4.55	0.798
dWdt	-1.29	0.63	0.302	0.259	0.019	0.385

Units for transverse planes: β (mm/mrad), ε (mm.mrad)
Units for long. plane: β (ns/MeV), ε (MeV.ns), relativistic β_r at the input and output are 0.0231 and 0.0943 respectively

Some additional parameters are important when studying tolerances, especially for misalignment studies. These are the beam centroids in the transverse phase planes i.e. mean position and angle. All through the linac particles are eliminated from the subsequent part of the calculation if they are outside limits of aperture, energy and phase. A transmission efficiency, η, is defined by the ratio of the number of particles at the output to the number of particles at the input. The emittance growth is defined as the ratio of the output to the input emittance (including CHASE).

Tolerances on RF voltage ΔU of ± 0.3 % and on phase $\Delta\varphi$ of $\pm$ 0.3 deg are based on GSI experience. The tolerence on triplet position ΔXt of $\pm$ 0.1 mm is based on practical alignment techniques. Errors in quadrupole strength related to power supply stability should have a negligible effect on output beam parameters. These values are used as the basis of the tolerence investigations presented below where in addition the input beam misalignments ΔXb, ΔYb are treated. Each of the results quoted represents the worst possible combination of errors e.g. the η = 70 % (line 3, Table 3) arises from -0.6%, +0.6%, +0.6% error in the RF field levels of Tanks 1, 2 and 3 respectively. Each entry in one line could correspond to a different distribution of errors.

Table 3
Emittance Growth and Transfer Rate as Function of Tolerances

	XX'	YY'	dWdt	η (%)
nominal	1.10	1.07	1.27	94
ΔU, $\pm 0.3\%$	1.14	1.06	1.49	87
ΔU, $\pm 0.6\%$	1.18	1.14	1.84	70
$\Delta\varphi$, ± 1.5 deg	1.11	1.11	1.38	80
$\Delta\varphi$, ± 3.0 deg	1.12	1.20	1.52	67
ΔXt, ± 0.25 mm	1.14	1.08	1.42	93
ΔXt, ± 0.5 mm	1.18	1.09	1.60	83
ΔXb, 3. mm	1.07	1.11	1.70	75
ΔYb, 3. mm	1.09	0.86	1.48	67

Where output beam centroid displacements in position and angle are significant, they can be normalised to the relevant errors $\Delta Xt = 0.1$ mm and ΔXb, $\Delta Yb = 1$ mm as, in case of neglible beam loss, the displacements are proportional to the errors. Thus for $\Delta Xt = 0.1$ mm the output beam dislacements in position and angle are 1 mm, 0.8 mrad, and for ΔXb, $\Delta Yb = 1$ mm the displacements are -0.4 mm , -0.6 mrad and -1.0 mm, 0.5 mrad respectively. If these errors are random and short term they cannot be corrected by steering magnets and thus contribute to the effective transverse emittance.

A major concern has been to investigate the effects of errors in RF levels on two main output parameters, longitudinal emittance growth and transmission efficiency η . Fig. 2 compares results from LORAS and DYNAC for these two parameters with each plotted point and its error bar derived from 10 runs with different random number seeds.

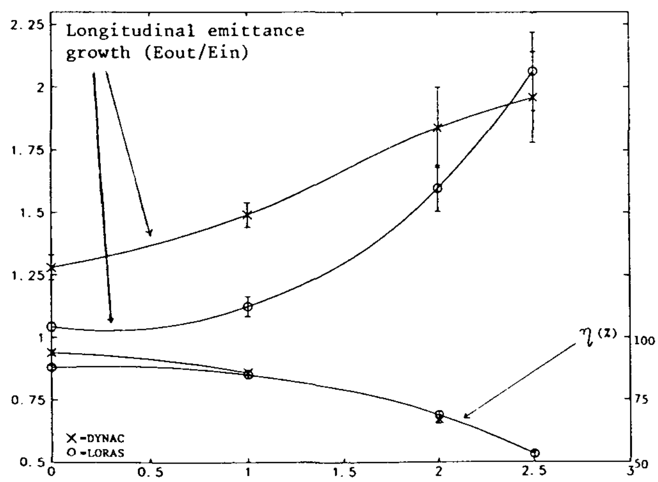

Fig. 2 Comparison DYNAC-LORAS

The problems of these analyses in the longitudinal plane are illustrated by the particle "scatter plots" (Fig. 3) in the longitudinal plane for the nominal (left) and the worst "2-tolerance" (right) cases. Computed ellipses are shown for three different percentages (100, 95 and 80 %) of particles retained (CHASE). An important parameter of the output beam, which determines the energy spread after the debuncher in the PS Booster (PSB) injection line, is the $\Delta\phi_m$ coordinate at the mean energy. The two cases shown on Fig. 3 have $\Delta\phi_m = 4.7$ deg and 12.9 deg respectively (for 95% of particles), the latter giving 2.7 times the nominal energy spread after debunching, which could cause problems for a future PSB RF system.

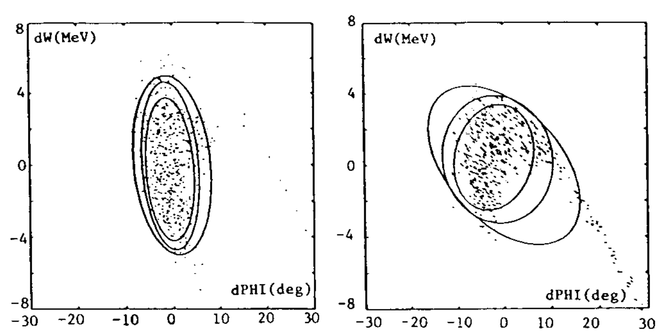

Fig. 3 Scatter plots Nominal (left), 2 tolerances (right)

In summary, the results confirm that the tolerences given for RF levels are necessary to ensure good beam transmission and acceptable longitudinal emittance increase; even for the nominal settings there is a significant effect on these two parameters. Our results indicate that the tolerance on $\Delta\phi$ could be relaxed somewhat, e.g to $\pm$ 1 deg. For the triplet position the 0.1 mm tolerance should be retained for the initial alignment and any long term misalignments partially corrected by the steering dipoles within the triplets.

Conclusion

In the comparisons of DYNAC with LORAS there was good agreement for beam transmission (η) at any tolerance. For the longitudinal emittance growth, larger values are found with DYNAC than with LORAS, both for the nominal and the 1 tolerance cases (Fig. 2). With the assumption that the RF voltage can be kept within $\pm$ 0.3 % (and without misalignment errors), we expect a particle loss of < 13 %, a beam phase spread $\Delta\phi_m < 8$ deg, an increase in longitudinal emittance < 50 % and increases in transverse emittances < 14 % .

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References

[1] CERN Heavy Ion Collaboration (G.Amendola et. al., 33 authors), "A Heavy Ion Linac for the CERN Accelerator Complex", EPAC Conference, Berlin, 1992

[2] U.Ratzinger, "The IH structure and its Capability to Accelerate High Current Beams", IEEE Particle Accelerator Conference, San Francisco, p. 567-571, 1991

[3] P.Lapostolle, E.Tanke, S.Valero, M.Vretenar and D.J.Warner, "Computer Design and Dynamics of the Quasi Alvarez Linac", Linac Conf. 1990 Albuquerque, p. 99-101, 1990

[4] GSI Darmstadt - IAP Frankfurt Collaboration (N.Angert et. al., 20 authors), "Commissioning and First Operation of the New Heavy Ion Injector of the UNILAC", EPAC Conference, Berlin, 1992

[5] P.Lapostolle, E.Tanke and S.Valero, "New General Beam Dynamics Formulation for the Program DYNAC", this conference

[6] U.Ratzinger, "Interdigital RF Structures", Linac Conf. 1990 Albuquerque, p. 525-529, 1990