INTERDIGITAL H-TYPE LINAC SIMULATIONS AND MEASUREMENTS IN THE FRAMEWORK OF CERN LINAC 3 RESTUDY

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Abstract

The CERN Heavy-Ion Facility (Linac 3) is being restudied for possible multicharge acceleration, which may markedly increase the heavy ion intensity available for the LHC. In the present report the optimization of the Interdigital H-type (IH) structure of the Linac 3 for multicharge acceleration is considered.

Series of simulations and measurements of the IH are performed validating the computer code used in the simulations. A parameter set for the optimal acceleration of three charge states is found and the consequences on the downstream lines are evaluated.

Keywords: Linac 3, IH, ion, multicharge, acceleration, optimization
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1. INTRODUCTION

The IH Linac consists of three tanks accelerating from 0.25 to 4.2 MeV/u, Tank 1 at 101.28 MHz and Tank 2 and Tank 3 at 202.56 MHz and has a total length of 8.129 m with an effective accelerating voltage of 32.9 MV. A complete description of the operation and beam dynamics of the IH structure is presented in [1]. Briefly, the IH Linac can be separated in three parts: acceleration, longitudinal focusing and transverse focusing (see Fig. 1a).

![Figure 1a. Overview of the IH Linac structure](image)

The parts where the synchronous particle is introduced at 0° are the accelerating parts. The beam has to be injected at higher energy relative to the 0° synchronous particle (Fig. 1b). In each 0° synchronous particle section the center particle of the bunch makes about one quarter phase oscillation around the synchronous particle. By that method it is possible to keep the position of the particle pulse mainly inside the second quadrant of the energy-phase plane providing a stable beam transport.

![Figure 1b. Principles of IH longitudinal dynamics](image)

The longitudinal focusing forces are concentrated near the end of each 0° synchronous particle section, where synchronous particle is at –30 deg. In order to complete transverse focusing, quadrupole triplets are placed after each 0° synchronous particle section.

Parameters of the IH Linac are presented in the Table 1.

Series of simulations and measurements of CERN IH Linac are performed to investigate the possibility to transport several charge states of lead ions. Single charge state simulations and measurements are performed to validate the computer code we use
and to give us a hint for parameters and procedures to be used for optimization of three charge states transport through the IH structure. The dependence of essential beam parameters on the phase and voltage in the tanks is investigated. All simulations are done using computer code DYNAC [2].

Table 1: Parameters of the IH Linac

<table>
<thead>
<tr>
<th>Design ion</th>
<th>$^{208}$Pb$^{25+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range (MeV/u)</td>
<td>0.25 – 4.2</td>
</tr>
<tr>
<td>Effective voltage gain (MV)</td>
<td>32.9</td>
</tr>
<tr>
<td>Total length (mm)</td>
<td>8129</td>
</tr>
<tr>
<td>No. of 0 deg synchr. particle sections</td>
<td>5</td>
</tr>
<tr>
<td>No. of tanks</td>
<td>3</td>
</tr>
<tr>
<td>Frequency (MHz):</td>
<td></td>
</tr>
<tr>
<td>Tank 1</td>
<td>101.28</td>
</tr>
<tr>
<td>Tank 2 and Tank 3</td>
<td>202.56</td>
</tr>
<tr>
<td>No. of quadrupole triplets</td>
<td>4</td>
</tr>
<tr>
<td>No. of accelerating gaps</td>
<td>99</td>
</tr>
</tbody>
</table>

In the simulations with one charge state it is assumed that the beam coming from the upstream RFQ is well matched to the IH input as defined by the MEBT (the line between RFQ and the IH Linac), which is not possible for several charge states. In that case the calculated beam distribution at the end of MEBT is used to obtain more realistic results. Designed for Pb$^{25+}$, the IH Linac can’t accelerate lower charge states, while acceleration for two higher charge states is rather good. As lower charge states receive an energy gain less than the design one, they stay in an unstable area, and are lost already in the first tank. With this preliminary considerations we look at the possibility of accelerating simultaneously Pb$^{25+}$, 26$^+$ and 27$^+$. The measurements are done with an equivalent In$^{21+}$ beam as they were done around the In physics run of 2003.
2. SIMULATIONS WITH ONE CHARGE STATE

As it was mentioned before, in the IH structure the beam is accelerated very close to the crest of the wave and has to be injected at higher energy relative to the 0° synchronous particle [1]. Therefore the RF settings (phase and voltage) are very important for the overall IH dynamics.

2.1. Phase dependence of the beam parameters

Here the dependence of the essential beam parameters on the RF phase of Tank 1 is investigated.

The nominal RF phase is 12 deg and is marked in the plots by a vertical line. Simulations are done for the design ion Pb25+ with input energy 52 MeV, whereas the synchronous energy is 50 MeV. Input beam parameters are summarized in Table 2. In Figures 2-4 one can see phase dependence of transmission, emittances and beam phase spread and energy spread respectively. Emittances are 4 rms un-normalized and longitudinal parameters of the beam correspond to these emittances.

From the figures one can see that transmission can be somewhat increased by injecting the beam at lower RF phase and phase spread and energy spread can be reduced by injecting the beam at higher RF phase compared to the nominal one. Phase spread and energy spread have the same behavior. Output energy varies with RF phase a little bit. Thus, varying RF phase can be a useful tool for optimization of some parameters of the input beam.

2.2. Voltage dependence of the beam parameters

IH Linac consists of three tanks, powered independently, that allows us to vary the voltage in each tank independently to investigate its effect on the beam parameters.

Simulations have shown that the transmission through the IH can be somewhat increased by increasing the voltage by a few percent. From Figure 5 one can see that transmission changes considerably with voltage in the Tank 1 while response of voltage change in the Tank 2 is rather flat. Voltage change in Tank 2 and 3 or in all three tanks simultaneously has no big effect and the same effect can be achieved by just varying the voltage in the Tank 1 only. This has been confirmed by measurements done with indium beam (see section 3.1). Consequently, the voltage can be used as another tool for optimization but it should be noticed that by varying the voltage the output energy is changed much more than in case of RF phase.

Table 2. Input beam parameters used in simulations

<table>
<thead>
<tr>
<th>Ion</th>
<th>Pb 25+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space charge</td>
<td>NO</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>52</td>
</tr>
<tr>
<td>Horizontal emittance ($\pi$ mm.mrad)</td>
<td>30 (4 rms)</td>
</tr>
<tr>
<td>Vertical emittance ($\pi$ mm.mrad)</td>
<td>30 (4 rms)</td>
</tr>
<tr>
<td>Long. emittance (deg.keV at 101.28 MHz)</td>
<td>8500 (4 rms)</td>
</tr>
</tbody>
</table>
Figure 2. Transmission through the IH vs. Tank 1 RF phase (simulations)

Figure 3. Emittances (4 rms) at the IH output vs. Tank 1 RF phase (simulations)

Figure 4. Phase spread and relative energy spread (4 rms) at the IH output vs. Tank 1 RF phase (simulations)
3. MEASUREMENTS OF TRANSMISSION VS. VOLTAGE AND RF PHASE

3.1. Measurements of transmission vs. voltage

Measurements of transmission vs. voltage in the IH Linac are performed using the following procedure. The voltage in different tanks was changed relative to its nominal value, the input current was measured in a Faraday cup placed before the IH structure, the output current was measured in a current transformer placed downstream the IH. The ratio $I_{\text{out}}/I_{\text{in}}$ is taken to be the transmission through the IH. The measurement in the Faraday cup was not taken at every change of settings. Since during the measurements the ion source was not stable the values of measured currents have an error of about 5%. All measurements are done with Indium 21+ beam.

The transmission as a function of the voltage was measured in three different ways: First, the voltage was varied in all three tanks simultaneously; second, with voltage variation in Tank 1 only; third, voltage variation in Tank 2. The voltage has been changed in steps of 1% of the nominal voltage.

In Figure 6 one can see the results of all three measurements. The transmission is much more sensitive to the voltage in Tank 1 while voltage variation in the other tanks makes relatively small difference in transmission. These measurements and the corresponding simulations (see section 2.2) are in qualitative agreement but not quantitatively. This is maybe due to source instability and errors in the measurement devices.
3.2. Measurements of transmission vs. RF phase

For these measurements, the RF phase of Tank 1 is varied with the nominal voltage in all three tanks. The nominal RF phase for Indium 21+ beam is 13 deg. Results of the measurements and corresponding simulations are presented in Figure 7.

Figure 7. Measured and calculated transmission through the IH vs. Tank 1 RF phase

Note, in Figure 7 results of the measurements are reversed with respect to the nominal RF phase, since the convention in the movement direction of RF phase using the control system is of opposite sign with respect to the phase simulated with DYNAC. The figure shows good agreement between the measurements and simulations.
4. MEASUREMENTS OF THE MEAN ENERGY AND ENERGY SPREAD VS. RF PHASE IN TANK 1

Measurement procedure

Measurements of the beam mean energy and energy spread at the output of Tank 1 as a function of RF phase have been done with Indium 21+ beam using the measurement line of the Filter part (ITF) of LINAC 3. Tanks 2 and 3 were turned off and the inter-tank quadrupole triplets were adjusted to focus the 1.855 MeV/u beam.

A schematic layout of the Filter line is presented in Figure 8. The energy spread was measured using the spectrometer magnet ITF.BHZ11 and Profile Harp ITFS.MSG10 with the transverse beam optics adjusted for the best resolution.

Figure 8. Schematic layout of the Filter

The beam half width above the threshold (6-10% of the peak signal) was measured on the Profile Harp and the beam energy spread was calculated from the following relation:

$$\frac{\Delta W}{W_0} = \frac{2\Delta x}{\alpha L},$$

where $2\Delta x$ is the full width of the beam, $\alpha$ is bending angle of the spectrometer magnet and $L$ is the distance between the spectrometer magnet and the Profile Harp.

The mean energy is measured by the same equipment but taking the central peak position. Depending on the energy of the beam, the position of the peak signal on the Profile Harp will move and the mean energy can be calculated as follows:

$$W_{\text{mean}} = W_0 - \Delta W_{\text{per wire}} N_{\text{wire}},$$

where $N_{\text{wire}}$ is number of wires on the Profile Harp counted from the peak position of the nominal energy $W_0$, and $\Delta W_{\text{per wire}} = 0.86$ MeV/wire, i.e. it has 0.22% resolution.

Results of measurements and simulations of energy spread and mean energy at the exit of Tank 1 are presented in the Figure 9 and 10, respectively.
Results of measurements are in reversed order due to the reason mentioned before. Measurements and simulations of the beam energy spread are in very good agreement.

Figure 10 shows good agreement between measurements and simulations of the mean energy out from Tank 1 except for RF phases higher than the nominal one (for which we have no explanation). The variation of the mean energy, as a function of the RF phase, is small while the energy spread can be changed considerably.

5. SIMULATIONS WITH THREE CHARGE STATES

In this series of simulations the beam consists of three charge states of lead ion Pb25+, Pb26+ and Pb27+. The particle distribution is read from a particles.dst file representing the simulated beam at the end of the MEBT, passed through all units starting from the source to the IH input. Parameters of the beam are summarized in Table 3.
Table 3. Parameters of the simulated beam at the IH input

<table>
<thead>
<tr>
<th>Beam contents:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb25+</td>
<td>26 %</td>
</tr>
<tr>
<td>Pb26+</td>
<td>56 %</td>
</tr>
<tr>
<td>Pb27+</td>
<td>18 %</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>0.231</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>52.06</td>
</tr>
<tr>
<td>Horizontal emittance ($\pi$ mm.mrad)</td>
<td>0.365 (4 rms norm)</td>
</tr>
<tr>
<td>Vertical emittance ($\pi$ mm.mrad)</td>
<td>0.443 (4 rms norm)</td>
</tr>
<tr>
<td>Long. emittance (deg.keV at 101 MHz)</td>
<td>9458.89 (4 rms)</td>
</tr>
</tbody>
</table>

To run with three charge states, quadrupoles are optimized for the highest charge state as follows. The strength of each quadrupole in the first IH triplet is varied around its nominal value (set for Pb25+) to obtain the best transmission through the IH. This value is fixed and the second quadrupole strength is varied and then the third one. Next, the same procedure is applied to the next three quadrupole triplets. The overall procedure can be repeated two or three times to achieve a better result.

Space charge of the beam is taken into account, though it has a small effect. As the beam consists of different charge states, which are focused differently and have different dynamics in the accelerating structure, emittances and longitudinal parameters are expected to be bigger than in the case of one charge state simulations.

Simulations with a beam consisting of three charge states were done to examine beam parameters as a function of the RF parameters. The beam parameters as a function of the RF phase are presented in the Figures 11-13. Transverse emittances are 4 rms normalized and longitudinal one is 4 rms. Phase spread and energy spread of the beam correspond to the 4 rms ellipses.

Figure 11. Transmission through the IH vs. RF phase in Tank 1 for three charge states beam
From the figures one can see that the longitudinal emittance as well as phase spread dPhi and energy spread dW can be reduced at the expense of decreased transmission by injecting the beam at an RF phase higher than the nominal 12 deg. The mean energy varies by 0.3 % maximum.

As it was seen before from simulations and measurements, voltage variation in Tanks 2 and 3 doesn’t contribute much to the transmission while it changes the output energy of the beam (see Fig. 14) and may change also longitudinal parameters. This was a hint to investigate effect of each tank on the beam parameters, in particular the voltage, independently.
Figure 14. IH output energy vs. RF phase and voltage (simulations)

In Figures 15-17 results of simulations of beam parameters as a function of the voltage in Tank 1 are presented. One can see that longitudinal emittance, phase spread and energy spread are decreasing with decreasing voltage and transmission drops quicker than in the case of RF phase.

Figure 15. Transmission through the IH vs. voltage in Tank 1 (simulations)
The response of all parameters except longitudinal (emittance, phase spread, energy spread) and output energy, to the voltage in Tank 2 is rather flat. For Tank 3 only longitudinal emittance, phase spread and final energy are changing slightly. Thus voltage in tanks 2 and 3 can be used for improving longitudinal parameters and tuning the output energy if necessary without much affecting the transmission and transverse emittances. But all parameters and especially transmission are sensitive to Tank 1. Simulations have shown that in order to reduce phase spread and energy spread one needs to decrease voltage in Tank 1 and increase it in Tank 2, but in that case we lose in transmission. Results of these simulations are summarized in Table 4.


In Table 4, emittances are 4 rms, normalized for the transverse plane and non-normalized for the longitudinal one. The data in the highlighted line corresponds to the nominal case with one charge state (Pb25+) and is taken from the CERN Yellow Report 93-01. Phase spread and energy spread correspond to 4 rms values. The total beam will have much bigger emittances and consequently bigger phase and energy spreads. The beam distribution in the longitudinal plane consists of a dense core containing around 95% of the beam and of a halo of poorly accelerated particles at the IH output (see Figure 18). Thus, it is worth to consider just the main part of the beam (say 95%) when speaking about longitudinal parameters.

After the IH Linac particles are stripped to several higher charge states from 52+ to 55+ (passing through the stripper, consisting of 0.5-1 µm carbon foils) and travel to the debuncher after passing through a filter consisting of bending magnets. The debuncher acts as a lens in the longitudinal phase plane to reduce the energy spread of the beam. The beam phase spread should normally be on the linear part of the RF wave around the phase of the debuncher. However, the beam has to travel more than 10 m distance from the IH output to the debuncher, so the phase spread can become large. The beam was tracked from the IH output to the debuncher: the phase spread and the energy spread of the beam at the stripper and at the entrance to the debuncher as a function of the number of particles inside the beam are presented in Figures 19-22, respectively.
Figure 18. Three charge states beam at the IH output in the longitudinal plane (simulations)

Figure 19. Phase spread vs. number of the particles at the stripper
Figure 20. Energy spread vs. number of the particles at the stripper

Figure 21. Phase spread vs. number of the particles at the entrance to the debuncher

Figure 22. Energy spread vs. number of the particles at the entrance to the debuncher
From Figures 21 and 22 one can see that, at the entrance to the debuncher, an ellipse in the longitudinal phase space with phase spread of 60 deg contains 82% of the particles of the beam and has an energy spread of 0.57%.

These results are obtained assuming that all charge states of the beam are stripped to Pb53+ and have the same distribution after the stripper. Stripper thickness, multiple scattering and energy struggling in the stripper are not taken into account.

**Beam requirements for LEIR**

The Low Energy Ion Ring (LEIR) serves as an accumulator of the ion beam injected from CERN Linac 3. There are stringent requirements to be met for the injected beam.

Both transverse emittances and energy spread of the ion beam delivered by Linac 3 have to be small [3]. Figures 23a and b show injection efficiencies as function of the momentum spread and the transverse emittance (assuming horizontal and vertical emittances are the same) while keeping all other parameter (working point, number of injected turns, septum position, bump height, momentum at the beginning and the end of the ramp…) constant.

Figure 23a shows injection efficiencies expected for injection of 70 turns with a momentum ramp of 0.4% into a lattice with a rather large normalized dispersion. The working point is (1.82, 2.72); only ions inside horizontal and vertical “acceptances” of 60 µm and 40 µm are counted as injected, all free parameters are optimized for the star in the plot. One notes that with the nominal Linac 3 parameter, $\epsilon_{rms}=2.1 \mu m$ and a relative RMS momentum spread of $0.2 \times 10^{-3}$, an injection efficiency of more than 70% is obtained.

Figure 23b shows the same, but for a lattice very close to what can be achieved with the given LEIR hardware and with a smaller normalized dispersion. In this case the momentum spread becomes less critical.

**Figure 23. Efficiency of injection into the LEIR**
For the working point, marked by the star in the plot, for RMS momentum spread of $0.2 \times 10^{-3}$, taking into account the stripping efficiency and LEIR acceptance, we obtain an intensity gain of 1.9 to 2.5 depending on the LEBT configuration [4].

6. CONCLUSIONS

Based on good agreement of simulations with measurements performed in autumn 2003 at CERN, the code DYNAC can be used for IH Linac optimization for multicharge acceleration.

A scheme for acceleration of three charge states of lead ions is found by optimizing quadrupoles for maximum possible total transmission and, depending on the final requirements for LEIR, by adjusting entrance RF phase and voltage in tanks.

Tank 1 and Tank 2 voltages are suitable for tuning the beam transmission and longitudinal parameters while the voltage in Tank 3 acts mainly on the output energy of the beam.

Due to the specific beam dynamics in the IH the output beam distribution has a long tail containing few percents of the beam that has to be cut off for proper injection into the LEIR machine.

With the IH structure and other units of Linac 3 optimized for multicharge acceleration, the gain in the current is expected to be in the range of 1.5-2.5 depending on the method of transporting the beam from the source to the RFQ. This gain is within emittances and energy spread acceptable for LEIR injection.

REFERENCES


