

# LINAC5 - A Quasi-Alvarez Linac for BioLEIR

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**Abstract.** LINAC5 is a new linac proposed for the acceleration of light ions with  $Q/A = 1/3$  to  $1/4$  for medical applications within the BioLEIR (Low Energy Ion Ring) design study at CERN. We propose a novel quasi-Alvarez drift-tube linac (DTL) accelerating structure design for LINAC5, which can reduce the length of a more conventional DTL structure, yet allows better beam focussing control and flexibility than the inter-digital H (IH) structures typically used for modern ion acceleration. We present the main sections of the linac with total length  $\sim 12$  m, including a 202 MHz radio frequency quadrupole (RFQ) a matching medium energy beam transport (MEBT) and a 405 MHz quasi-Alvarez accelerating section with an output energy of 4.2 MeV/u. Permanent magnet quadrupoles are proposed for use in the quasi-Alvarez structure to improve the compactness of the design and increase the efficiency. Lattice design considerations, multi-particle beam dynamics simulations and RFQ and radio frequency (RF) cavity designs are presented.

## 1. Introduction

BioLEIR is a design study at CERN [1] for a multidisciplinary, biomedical research facility based on LEIR to provide light ion beams suitable for clinically oriented, fundamental research on cell cultures and for radiation instrumentation development. Within the BioLEIR framework, a new linac is required to accelerate ions with a charge to mass ratio  $Q/A$  between  $1/3$  and  $1/4$ , up to 4.2 MeV/u for injection into the existing LEIR accelerator [2]. LINAC5 has been designed to fulfil this purpose. Following acceleration in LEIR to between 50 and 440 MeV/u, ions will be extracted to several beam-lines terminating in a variety of experimental stations.

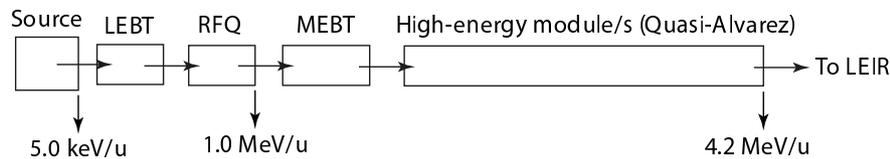
A quasi-Alvarez DTL accelerating structure [3, 4] is proposed for LINAC5, enabling the possibility for a shorter linac than those employing the more commonly used DTL, but with more focusing control than an inter-digital H structure (IH). We present a study of the complete linac with length  $\sim 12$  m, including an electron cyclotron resonance (ECR) ion source, a LEBT (Low Energy Beam Transport), a 202 MHz RFQ, a MEBT and a 405 MHz quasi-Alvarez DTL. This report focuses on the lattice design and multi-particle beam dynamics simulations of the novel quasi-Alvarez accelerating section, the MEBT and RFQ.

## 2. ECR Ion Source, RFQ and Matching Sections

A schematic overview of LINAC5 is shown in Figure 1. An ECR ion source is envisaged for the production of a 2 mA ion beam [5]. The extraction energy was selected as 5.0 keV/u to maximise the extraction efficiency over the range of ions, as shown in Table 4.4 in reference [5]. A LEBT is being studied for matching the ions from the source to the RFQ. Two concepts are being



investigated: the first comprises one or two solenoids and a spectrometer for charge selection; the second envisages charge selection carried out by the RFQ instead of a spectrometer. The latter is realisable due to relatively low beam current where the RFQ can be used to select the desired ions.

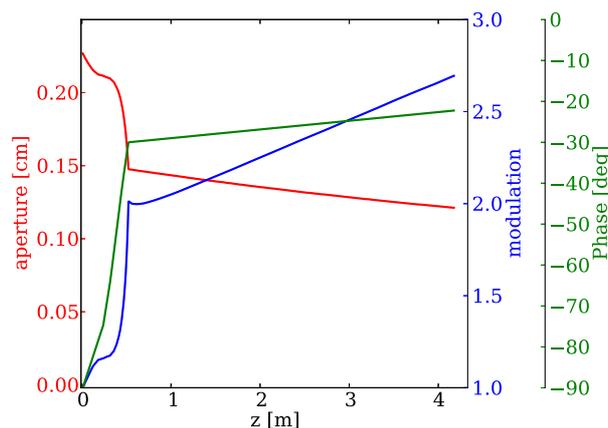


**Figure 1.** The basic schematic layout of LINAC5.

A 202 MHz RFQ was designed for the acceleration of ions with  $Q/A = 1/4$  from an energy of 5 keV/u to 1.0 MeV/u. The main parameters of the RFQ are summarised in Table 1 and the aperture, modulation and phase are shown in Figure 2.

**Table 1.** The main parameters of the RFQ.

Parameter	Value
Length	4 m
RF Frequency	202.56 MHz
In/out energy	0.005 - 1.0 MeV/u
Vane voltage	60 kV
Average aperture ( $r_0$ )	3 mm
Max. surface field $E_s$	27 MV/m
In/out. trans. $\epsilon_{rms,norm}$	0.1 - 0.1 $\pi$ .mm.mrad
Out. long. $\epsilon_{rms,norm}$	0.086 $\pi$ .MeV.deg



**Figure 2.** The aperture (red), modulation (blue) and phase (green) as a function of the distance along the RFQ.

A MEFT was studied for matching the beam from the RFQ to the quasi-Alvarez DTL. Simulations of the different ion species from the RFQ exit show that in order to control the longitudinal phase spread, two 202 MHz bunching cavities are required. Four electromagnetic

quadrupole magnets are also necessary to allow flexible matching to the down-stream focusing channel.

### 3. Acceleration from 1.0 - 4.2 MeV/u

Three different types of RF accelerating structure meeting the LEIR injection specifications were studied: a 202 MHz two-module DTL with an FFDD focusing channel, a 202 MHz three-module IH with two inter-tank triplet focusing sections and a single-module 405 MHz quasi-Alvarez DTL. A quasi-Alvarez DTL [3, 4] is similar to a conventional  $2\pi$  mode DTL structure, where a series of drift-tubes are separated longitudinally by RF gaps at a spacing of  $\beta\lambda$ . However in a quasi-Alvarez, quadrupole focusing magnets (quadrupoles) are not placed inside all drift tubes, but instead are placed inside the  $n$ th drift-tube where the periodicity  $n$  is a free parameter of the design. This allows the empty drift-tubes to be shortened and hence the frequency of the structure may be increased beyond that what is usually suitable for a conventional DTL. This allows a shorter over-all structure for the LINAC5 energy range. Table 2 shows a comparison of the length and output beam characteristics of each design.

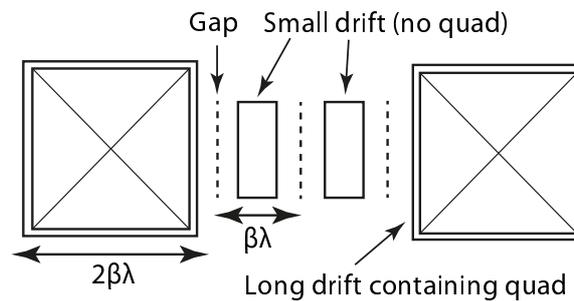
**Table 2.** Comparison of the three types of accelerating structure studied for LINAC5. The percentage change in emittance between the end and start of the structures is shown.

Structure	Length	Trans.	Long.
		$\Delta\epsilon_{rms,norm,4D}$	$\Delta\epsilon_{rms,norm}$
DTL	8.2 m	$\sim 0\%$	1.8 %
IH	3.3 m	55 %	96 %
Q-A	5.2 m	10 %	0.2 %

Whilst all the ideal (non-error) structures studied had good transmission ( $>98\%$ ), the final beam characteristics show the weakness of the IH and the superiority of the DTL for this particular case of 2 mA of current and  $Q/A=1/4$ . However, the quasi-Alvarez is around 40 % shorter than the DTL, giving it an advantage without compromising greatly on the final beam emittance; the output characteristics are still comfortably within the LEIR specifications [2].

To optimise the focusing strength required for the desired ion species with the length of the linac, the geometry was chosen such that longer drift-tubes are separated by two smaller drift-tubes ( $n=3$ ) and three respective gaps as shown in Figure 3. A FODO focusing channel was selected and the quadrupole dimensions and strengths were optimised to deliver focusing with a maximum beam size of 3.5 mm for the range of ions. A realistic normal-conducting pole-tip field of 0.56 - 0.77 T, a bore radius of 6 mm and a length of 50 mm were chosen. In order to reduce the drift-tube and stem sizes, and increase the shunt impedance, permanent magnet quadrupoles (PMQs) are proposed. PMQs have high reliability, do not require powering and reduce drift-tube cooling requirements. It has been shown that PMQs can be utilised effectively in light-ion accelerators with small drift-tube sizes, within low-beta accelerating structures and with similar field strengths to those proposed for LINAC5 [6, 7].

In the present design, one accelerating module is proposed with an RF field designed to accelerate a minimum  $Q/A=1/4$ . The voltage in the cavities will be reduced by 25 % for  $Q/A=1/3$  to preserve synchronicity and respectively for ions with  $1/3 > Q/A > 1/4$ . To reduce the length, we chose to double the frequency with respect to the RFQ, from 202 MHz to 405 MHz. The RF cavity structure design was optimised in SuperFish [8]. Table 3 shows the main parameters of the quasi-Alvarez DTL structure design.



**Figure 3.** A schematic representation of one cell (half period) of the selected quasi-Alvarez design.

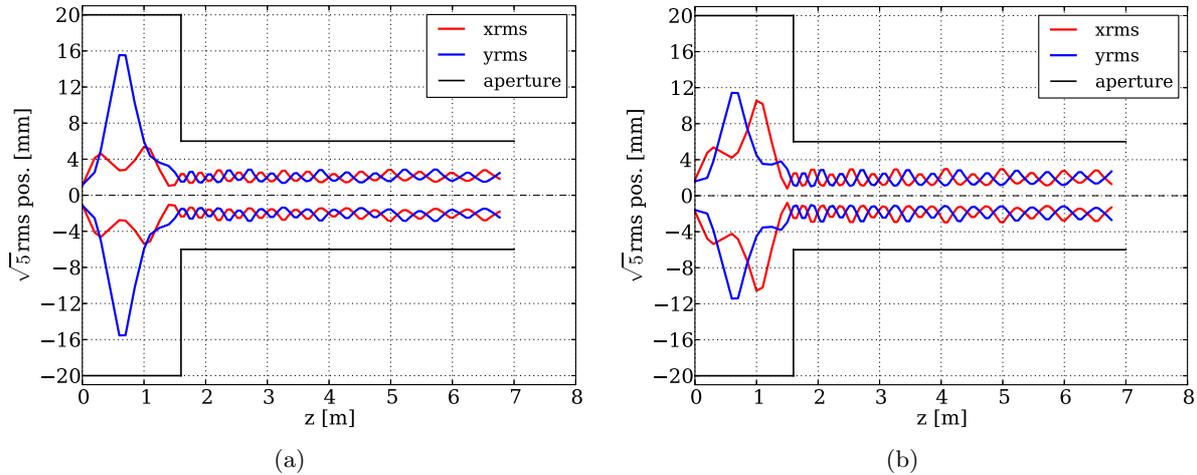
A 2 mA beam was tracked through the RFQ using the Parmteq code [9] and the output distribution was used as the input for the following tracking. The Travel code [10] was then used to track this distribution through the MEBT and quasi-Alvarez section. The transverse beam envelopes for  $Q/A = 1/4$  and  $1/3$  are shown in Figure 4 (a) and (b) respectively.

**Table 3.** The main parameters of the quasi-Alvarez accelerating module without errors. The parameter described by  $A_{trans.}/\epsilon_{rms,norm,out}$  shows the transverse acceptance divided by the output transverse emittance and  $E_0 TL/cell$  is the integrated RF field in a cell.

Parameter	Value
Length	5.2 m
In/out $E_k$	1.0 - 4.2 MeV/u
Frequency	405.12 MHz
Current	2.0 mA
Bore radius	6 mm
No. of periods	12
Quad. length	50 mm
Max/min integrated grad.	6.4 - 4.7 T
In/out. 4D $\epsilon_{rms,norm}$	0.01 - 0.011 $\pi$ .mm.mrad <sup>2</sup>
In/out. long. $\epsilon_{rms,norm}$	0.022 - 0.022 $\pi$ .deg.MeV/u
$A_{trans.}/\epsilon_{rms,norm,out}$	1.5
Transmission	100 %
Tank power	1300 kW
$L_{RFgap}/L_{cell}$ (start-end)	0.18 - 0.25
Kilpatrick (start-end)	1.5 - 1.2
$E_0 TL/cell$ (start-end)	0.09 - 0.24 MV
Sync. phase (ramped)	-30 to -20 deg.
Shunt Impedance	84 MOhm/m

#### 4. Error Studies

The sensitivity to transverse and longitudinal errors was studied independently using the Travel code. Realistic errors were chosen based on studies of LINAC4 [11]. In the transverse case, over 7000 randomly generated lattices were created with errors in: beam jitter using Gaussian



**Figure 4.** The horizontal (red) and vertical (blue) beam envelope in the MEBT and quasi-Alvarez sections for ions of  $Q/A = 1/4$  (a) and  $Q/A = 1/3$  (b). The beam-pipe aperture is shown in black.

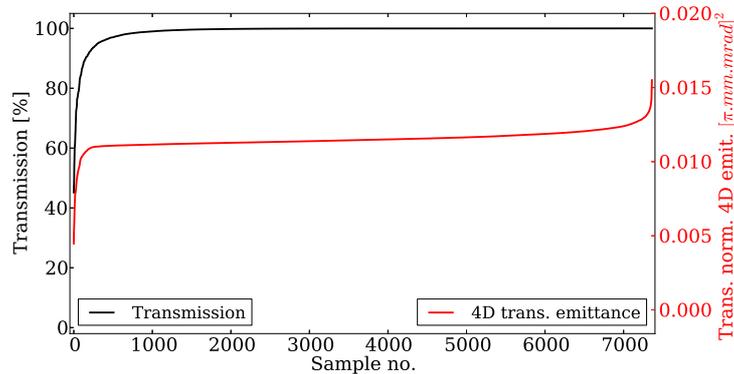
distributions in  $x$ ,  $y$  ( $\sigma_{x,y} = 0.1$  mm),  $x'$  and  $y'$  ( $\sigma_{x',y'} = 0.1$  mrad); quadrupole gradient errors with a Gaussian distribution of  $\sigma = 0.5\%$ ; horizontal and vertical quadrupole misalignments with Gaussian distributions of  $\sigma = 0.1$  mm. All had a  $3\sigma$  cut-off. Of the sample cases, 98 % had  $> 90\%$  transmission and 85 % had  $> 99\%$  transmission, see Figure 5. Figure 5 also shows that  $> 99\%$  of cases had  $< 5\%$  transverse emittance growth beyond the nominal (see Table 3 for nominal values).

Static and dynamic longitudinal errors were considered separately, with 10,000 and 1,000 samples respectively. The former are defined as individual gap errors in phase and amplitude and the latter are defined as constant amplitude errors applied to all cavities equally to simulate fluctuations in the RF power supply. The random error distributions were given by: beam jitter in energy and phase with uniform distribution and cut-off at 1 % and 1 deg. respectively; static errors in gap phase and amplitude with uniform distribution and cut-off at 1 deg. and 1 % respectively; dynamic amplitude errors applied equally to each cavity from a uniform distribution with cut-off at 1 %. Simulated particles remaining in the stable RF phase-space region were counted, where 100 % had  $> 95\%$  transmission for the static errors and 100 % had  $> 90\%$  transmission for the dynamic errors.

From the results of the transverse (see Figure 5) and longitudinal error studies, it is clear that the magnitude of the errors employed do not have a significant effect on the performance of the linac. However, it should be noted that these errors are reasonably realistic, for example max. 0.3 mm magnet misalignment error is easily achievable with current technology.

## 5. Conclusions

A design study was carried out for LINAC5 within the BioLEIR framework. A quasi-Alvarez DTL was shown to have advantages over both a conventional DTL and IH structure. More detailed designs of the RFQ, MEBT and a quasi-Alvarez DTL were successfully completed to meet the LEIR injection parameters. Beam dynamics simulations from the RFQ entrance to the end of the quasi-Alvarez DTL, including with realistic errors, show that  $> 99\%$  of cases have a maximum transverse emittance growth of 10 %, where transmission remained  $> 90\%$  in 98 % of cases.



**Figure 5.** Transmission and 4D transverse rms emittance for different random error lattices. Sample number is ordered separately for the two curves and is not correlated.

## 6. Acknowledgments

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## References

- [1] Ghithan S *et al.* 2017 Feasibility study for BioLEIR *CERN Yellow Reports* CERN-2017-001-M
- [2] Brning O S *et al.* 2004 LHC design report vol.3: The LHC injector chain *CERN Yellow Reports* CERN-2004-003-V-3
- [3] Warner D J 1988 Heavy ion acceleration using drift-tube structures with optimised focusing *Proc. Linear Acc. Conf. 1988, Williamsburg, VA, USA* pp 109-11
- [4] Lapostolle P, Tanke E, Vretenar M and Warner D J 1990 Computer design and dynamics of the quasi-alvarez linac *Proc. Linear Acc. Conf. 1990, Albuquerque, NM, USA* pp 99-101
- [5] Ghithan S *et al.* 2017 Feasibility study for BioLEIR *CERN Yellow Reports* CERN-2017-001-M Chpt. 4
- [6] Tommasini D, Buzio M, Thonet P A and Vorozhtsov A 2011 Design, manufacture and measurements of permanent quadrupole magnets for Linac4 *IEEE Trans. on App. Supercon.* **22**(3) p 4000704
- [7] Kerennoy S S *et al.* 2012 H-mode accelerating structures with permanent-magnet quadrupole beam focusing *Phys. Rev. ST Accel. Beams* **15**(9) 090101
- [8] Holsinger R F and Halbach K 1976 SuperFish - a computer program for evaluation of rf cavities with cylindrical symmetry *Part. Acc.* **7**(4) pp 213-22
- [9] Crandall K R and Wrangler T P 1988 Parmteqm - a beam-dynamics code for the RFQ linear accelerator *AIP Conf. Proc.* **177** pp 22-8
- [10] Perrin A and Amand J F 2003 *Travel v 4.06 user manual* CERN
- [11] Bellodi G *et al.* 2011 Alignment and field error tolerance in Linac4 *CERN-ATS-Note-2011-021* CERN