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## The KONUS IH-DTL proposal for the GSI UNILAC poststripper linac replacement

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# The KONUS IH-DTL proposal for the GSI UNILAC poststripper linac replacement

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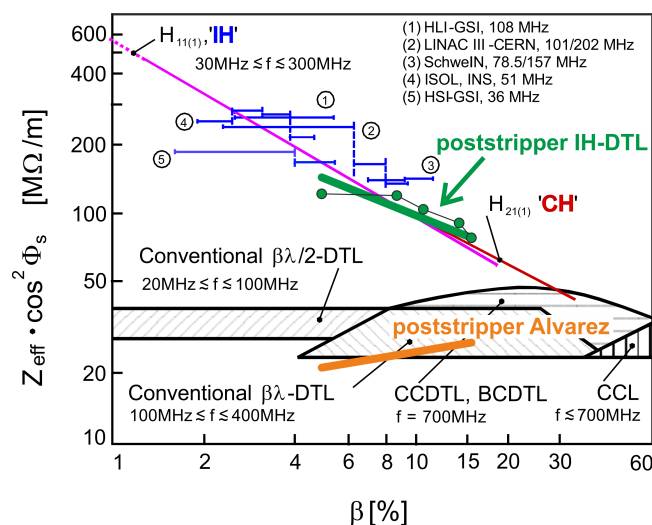
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**Abstract.** Motivated by the necessary replacement of the GSI UNILAC poststripper linac, a compact and efficient linac design based on IH-type cavities has been developed. Using KONUS beam dynamics, it was possible to design a linac consisting of only five cavities that can be operated by the existing UNILAC RF amplifier structure. The transversal focusing scheme is based on magnetic quadrupole triplet lenses. The optimized design provides full transmission and low emittance growth for the design current of 15 emA  $U^{28+}$ , accelerating the beam from 1.4 MeV/u to 11.4 MeV/u. Extensive error studies were performed to define tolerances and verify the stability of the design with respect to misalignment and injection parameters. The design provides a compact and cost effective alternative to a new Alvarez linac. With a total length of just 22.8 meters it will leave room for future energy upgrades in the UNILAC tunnel.

## 1. Technology and Layout

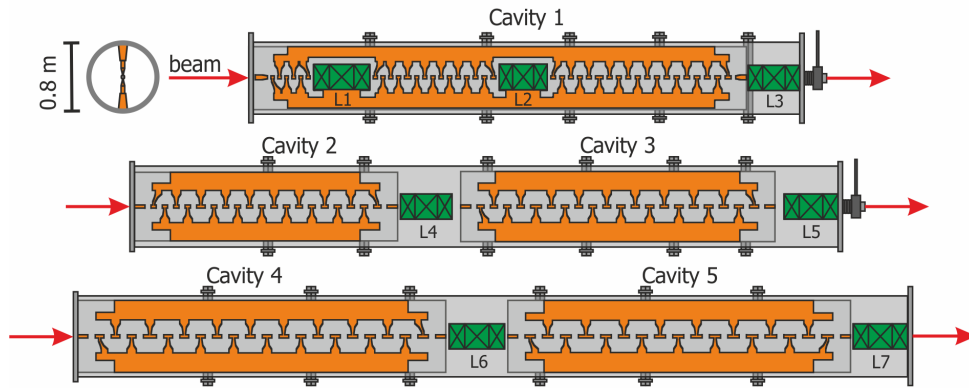
The poststripper linac of the UNILAC accelerates ions from 5.5 % to 15.5 % the speed of light. In this velocity range, the use of IH-type cavities provides high shunt impedance in combination with a period length of  $L_p = \beta\lambda/2$  (see figure 1) [1, 2, 3]. The operating frequency for the UNILAC poststripper IH-DTL is 108.408 MHz. The proposed poststripper linac design consists



**Figure 1.** Effective shunt impedance for different normal conducting structures for  $\beta = 1\% - 60\%$  (adapted from [4, 5])



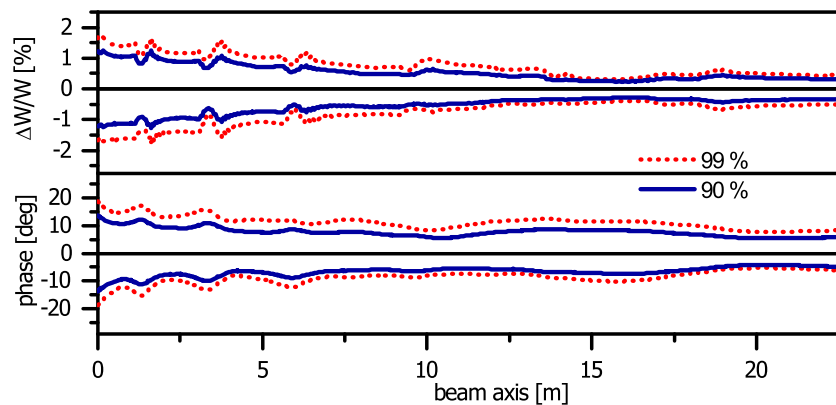
of five IH-DTL cavities and seven quadrupole triplet lenses [6, 7], as shown in figure 2. It can be operated by the existing UNILAC RF amplifier structure well within power limits [8, 9]. To achieve this, the first cavity is designed with two internal lenses, a technology that has proven reliable in several linacs built in the last decades (e.g. HSI [10] and HLI [11] at GSI UNILAC, the HIT Heidelberg [12], NICA at JINR Dubna [13]).



**Figure 2.** Layout of the proposed poststripper IH-DTL.

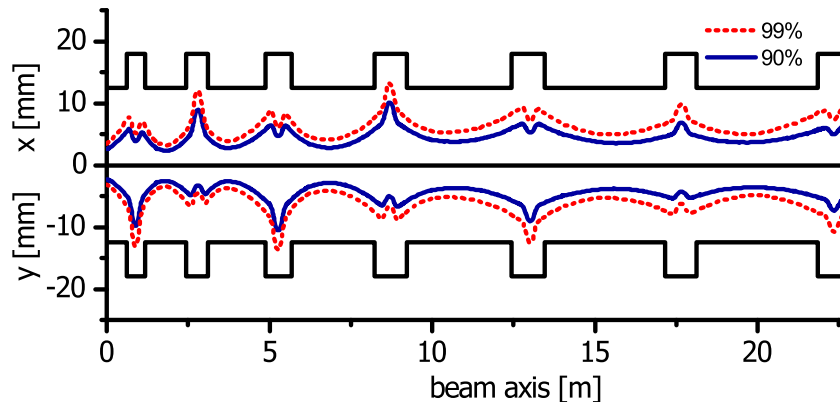
## 2. Beam Dynamics

For the design and optimization of the beam dynamics, the 3D PIC code LORASR [14, 5] was used. A waterbag particle distribution with  $5 \cdot 10^5$  macroparticles was used for the final simulations. Crosscheck calculations were performed using TraceWin, confirming the beam dynamics layout performance. To achieve low longitudinal emittance growth, the KONUS lattice was optimized for an average beam current of 15 mA  $U^{28+}$ . Finally, a longitudinal emittance growth of just 11.1% was achieved. In figure 3, the longitudinal beam envelopes show the confinement of the beam over the whole linac.



**Figure 3.** Longitudinal beam envelopes.

Investigations on the optimizations of KONUS lattices can be found in [7] and [15]. Transverse focusing of the beam is realized using quadrupole triplet lenses in a FDF-DFD lattice. By optimizing the phase advance along the linac, an RMS emittance growth of 27.5% and 25.8% in the horizontal and vertical plane, respectively, was achieved. The resulting transverse beam envelopes are shown in figure 4.



**Figure 4.** Transverse beam envelopes.

### 3. Error Studies

Error studies play an important role in the design of particle accelerators. Accounting for possible errors during fabrication, alignment and operation of the linac helps to provide a more realistic view of the linac performance. In case of the presented IH-DTL, error studies were performed using the TraceWin code. The number of simulated particles was chosen to be  $10^4$  to  $10^5$  for the sensitivity studies and combined error studies, respectively. With a total of 1000 random linacs generated using gaussian error distributions, the total number of simulated particles for each simulation run is  $10^7$  to  $10^8$ . These values were chosen to achieve reproducible results.

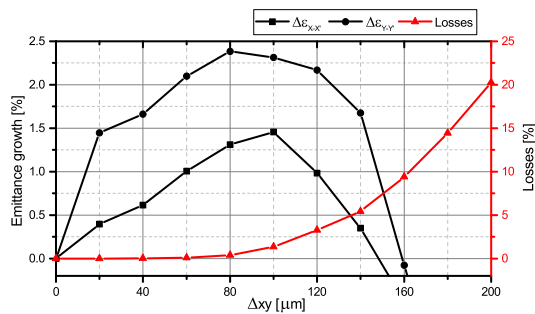
As a first step, sensitivity studies for the individual component errors were performed to find the most critical points. Following that, error studies with combined sets of errors were performed using limits deduced from the sensitivity studies. In the final step, error compensation using corrective steering elements within the linac was investigated, showing significant improvement of the linac performance.

#### 3.1. Error Sensitivity

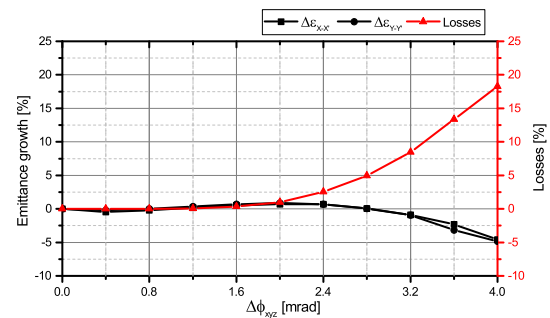
A large number of individual error types was investigated to find the components that are most vulnerable to errors. The investigated errors include the displacement of the quadrupole magnets and cavities, a rotation of the magnets, field errors of the RF cavities and errors of the injected beam parameters.

For the magnetic quadrupole triplet lenses, the displacement and rotation of the individual singlets and also the triplets as a whole were investigated, as well as gradient errors. The most remarkable result is, that the displacement of the singlets within a triplet and the rotation of the triplet as a whole are the most critical effects. As shown in figure 5, significant losses already occur for singlet displacements larger than  $\Delta xy = 100 \mu\text{m}$ . In contrast, quadrupole triplet displacements of up to  $\Delta xy = 360 \mu\text{m}$  are tolerated without significant emittance growth or losses. For a rotation of the elements, the situation is reversed. The rotation of singlets by up to 7 mrad leads to no significant losses and only introduces additional emittance growth. However, a triplet rotation of more than 2 mrad already leads to significant losses (see figure 6). Therefore, the rotation and displacement of quadrupole triplet lenses and their individual singlets should be treated separately in error studies.

Magnetic field gradient errors of the individual quadrupoles were investigated up to  $\Delta B'/B'_0 = 2\%$ . As a result, gradient errors of up to 0.7% lead to no significant losses or emittance growth. A transverse displacement of the IH-type cavities of as much as  $\Delta xy = 1 \text{ mm}$  only leads to  $< 0.01\%$  losses. Therefore, cavity displacement on its own is no problem,



**Figure 5.** Losses and additional emittance growth for quadrupole singlet displacement errors.



**Figure 6.** Losses and additional emittance growth for quadrupole triplet rotation errors.

since much better alignment accuracy can be achieved. For the electromagnetic field stability, the cavity field level, cavity RF phase and gap voltage accuracy were investigated in the range  $\Delta E/E_0 = 0 - 1\%$ ,  $\Delta\phi = 0 - 2^\circ$  and  $\Delta V_{\text{gap}}/V_{\text{gap},0} = 0 - 5\%$ . All three error types show an almost linear increase of the linac end energy variation with increasing error magnitude. While the cavity field level and phase only lead to longitudinal emittance growth of  $< 6\%$  in the investigated range, individual gap voltage errors of  $\Delta V_{\text{gap}}/V_{\text{gap},0} > 2\%$  lead to significant longitudinal emittance growth. Investigations of beam injection errors show, that beam displacements up to  $\pm 1$  mm have almost no effect. For a mismatch of the beam Twiss parameters at injection of up to 40%, no losses are observed. However, for a Twiss mismatch of  $> 20\%$ , additional emittance growth arises.

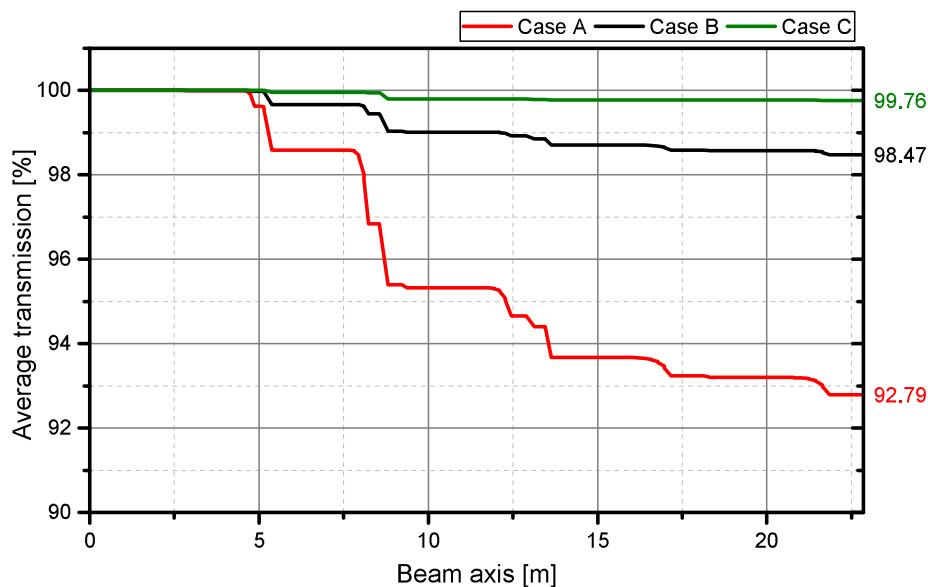
### 3.2. Combined Errors

Following the sensitivity studies, error simulations were performed with combinations of all individual component errors. To investigate the performance of the linac, three sets of combined errors were defined. The first case resembles the error limits beyond which significant losses

**Table 1.** Parameters for combined error runs.

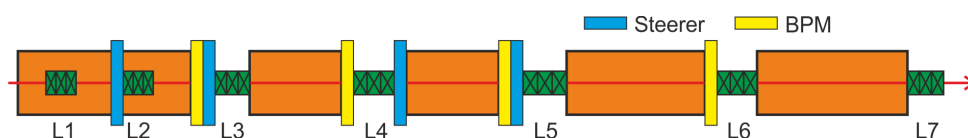
Error Type	Case A	Case B	Case C
<b>Quadrupole Lenses</b>			
Singlet $\Delta xy$	80 $\mu\text{m}$	80 $\mu\text{m}$	<b>50 <math>\mu\text{m}</math></b>
Singlet $\Delta\phi_{x,y,z}$	1 mrad	1 mrad	1 mrad
$\Delta B'/B'_0$	0.7 %	0.7 %	<b>0.1 %</b>
Triplet $\Delta xy$	360 $\mu\text{m}$	<b>100 <math>\mu\text{m}</math></b>	100 $\mu\text{m}$
Triplet $\Delta\phi_{x,y,z}$	1.6 mrad	<b>1 mrad</b>	1 mrad
<b>Cavities</b>			
Field $\Delta E/E_0$	0.7 %	0.7 %	<b>0.1 %</b>
Phase $\Delta\phi$	1.4°	1.4°	<b>0.1°</b>
$\Delta V_{\text{gap}}/V_{\text{gap},0}$	2 %	2 %	<b>1 %</b>
Cavity $\Delta xy$	600 $\mu\text{m}$	600 $\mu\text{m}$	<b>100 <math>\mu\text{m}</math></b>

and/or emittance growth were observed in the sensitivity studies. This first error set is called “Case A” (see table 1). Since it was anticipated, that the relatively loose limits for quadrupole triplet displacement and rotation would lead to significant losses, when combined with the quadrupole singlet errors, a second set of errors, called “Case B”, was defined. Here the magnetic triplet errors are reduced to  $\Delta xy = 100 \mu\text{m}$  and  $\Delta\phi_{x,y,z} = 1 \text{ mrad}$ . For “Case C”, all errors were reduced to optimistic values that could be technically achieved, (see table 1). The resulting average transmissions for these three error sets are shown in figure 7. As expected, the “Case A” error set shows significant average losses. The strong interaction between quadrupole singlet and triplet errors is evident when comparing the average transmission of “Case A” and “Case B”, where the only difference is a reduction of triplet displacement and rotation. The average transmission of “Case B” is significantly improved. Even though these combined error simulations were performed without any corrective steering in the linac, a satisfying average transmission of 99.76 % is achieved for the “Case C” scenario. The reduction of cavity RF errors in “Case C” has a big impact on the longitudinal emittance growth, which is reduced to 2.13 % (see table 2).



**Figure 7.** Average transmissions for the three cases.

### 3.3. Corrective Steering



**Figure 8.** Layout for the final steering strategy.

To find the correct steering strategy for the proposed IH-DTL, several layouts with different numbers of steerers and different steerer positions were investigated. As a result, it was found that a total of four steerers, set up as two steerer pairs, is sufficient (see figure 8). The average losses of the linac without steerers can be reduced to 0.24 %, due to tight error tolerances in

“Case C”. By using the steering strategy mentioned above, the average losses can be significantly lowered from 7.21 % to 0.03 % for “Case A” (see table 2). In combination with strict error tolerances as in “Case C”, the losses can be reduced even further to  $6 \cdot 10^{-8}$ .

**Table 2.** Resulting additional emittance growth and losses of error simulations with and without steerers.

	$\Delta\epsilon_x$ [%]	$\Delta\epsilon_y$ [%]	$\Delta\epsilon_z$ [%]	Losses [%]
Case A	1.04 %	0.23 %	13.49 %	7.21 %
Case B	2.14 %	2.11 %	11.04 %	1.53 %
Case C	0.64 %	1.27 %	<b>2.13 %</b>	<b>0.24 %</b>
<b>with steerers:</b>				
Case A	1.43 %	2.50 %	9.98 %	<b>0.03 %</b>
Case C	0.67 %	0.82 %	<b>0.38 %</b>	<b><math>6 \cdot 10^{-8}</math></b>

#### 4. Conclusion

Comprehensive error studies of the proposed poststripper IH-DTL show a high error tolerance in combination with the final steering strategy. Average losses can be reduced to below  $3 \cdot 10^{-4}$  even for large errors. Additional emittance growth due to errors is in the order of a few percent. The presented design has matured and could be used as a cost effective alternative to an Alvarez DTL.

#### Acknowledgments

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