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TIME-OF-FLIGHT MEASUREMENTS AND ANALYSIS OF THE LONGITUDINAL DISPERSION AT THE S-DALINAC*

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Abstract

The Superconducting Darmstadt Linear Accelerator S-DALINAC is capable of accelerating electrons to kinetic energies of up to 130 MeV. Due to its three recirculating beamlines the 30 MeV main linac can be used up to four times. The electron beam is recirculated non-isochronously with a distinct longitudinal dispersion to conserve the energy spread of the injector accelerator. Time-of-flight measurements at the beamline connecting injector and main linac will be presented, showing a non-linear dependency on the energy. This effect can be reproduced by simulations using *elegant* [1] and are caused by traversing accelerating cavities with a small transversal displacement and a small angular deviation. Adjusting the magnetic parameters of the beamline compensates this effect. Besides the first recirculation beamline does not provide enough degrees of freedom to set the desired longitudinal dispersion for the non-isochronous recirculation mode. This has to be compensated in succeeding recirculation beamlines or by installation of additional magnets at the first recirculation beamline. Possible beamline modifications and time-of-flight measurements representing the longitudinal dispersion will be presented.

S-DALINAC

The S-DALINAC [2], shown in Fig. 1, is a superconducting, recirculating linear electron accelerator providing kinetic energies of up to 130 MeV. Due to its three recirculation beamlines the main accelerator can be used up to four times in order to reach the design energy. By using a

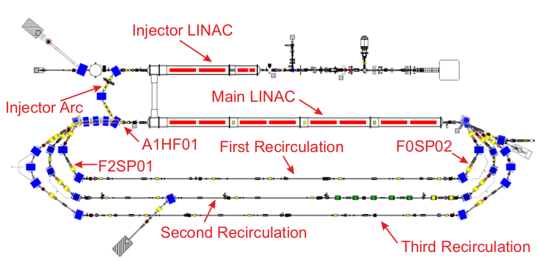

Figure 1: Floorplan of the S-DALINAC. Relevant devices are highlighted.

non-isochronous recirculation mode the energy spread of the beam provided by the superconducting injector linac can be conserved over several recirculations. To use this mode a destinct momentum deviation within the electron bunch has to be introduced and a matching longitudinal dispersion R_{56} has to be implemented by quadrupole magnets. The momentum deviation can be introduced by accelerating off-crest with a phase offset of Φ_S.

DETERMINING THE OPERATING POINT

Since the setup of the S-DALINAC has been upgraded from two to three recirculation beamlines [3] a new operating point for the non-isochronouly recirculated mode had to be found. A operating point consists of all quantities influencing longitudinal beam dynamics. Off-crest-acceleration introduces a quasi-proportional energy deviation in respect to the reference particle within a electron bunch since the longitudinal bunch length is short in comparison to one RF period [4]. The slope of this energy deviation can be characterized by the slope of the energy gain ΔE of each particle

$$\Delta E = \hat{E}_z \cos\left(2\pi \cdot f_{\mathrm{RF}} \cdot t + \Phi_{\mathrm{S}}\right)$$

with the maximum energy gain $\hat{E}_z$, the RF frequency f_{RF}, the time t and the synchrotronphase Φ_S. The longitudinal position of an electron in respect to the reference particle can be manipulated by the longitudinal dispersion R_{56} of the beamline, which is associated with the 6×6 beam transport matrix R. This matrix describes the tracking of the particle vector $\vec{x}(s)$ at position s_1 to position s_2:

$$\vec{x}(s_2) = R \cdot \vec{x}(s_1).$$

Assuming all longitudinally coupling components of R to be zero the longitudinal position Δl relative to the reference particle can be expressed by

$$\Delta l = R_{56} \cdot \frac{\Delta p}{p_0}$$

and the optimal operating point using the (I)njector, the (F)irst, (S)econd, and (T)hird recirculation can be calculated:

Φ_S	$R_{56,\mathrm{I}}$	$R_{56,\mathrm{F}}$	$R_{56,\mathrm{S}}$	$R_{56,\mathrm{T}}$
−5.8°	0.21 m	0.2 m	0 m	0.54 m

Several states of the longitudinal phase space for acceleration using all recirculations are plotted in Fig. 2.

Requirements for Optimal Beam Tuning

As mentioned above the electron beam should fulfill specific properties when entering a cavity. Especially the correct alignment of the longitudinal phase space ellipse is crucial for an optimal acceleration process. This is ensured if the longitudinal dispersion outside the cavity is only influenced

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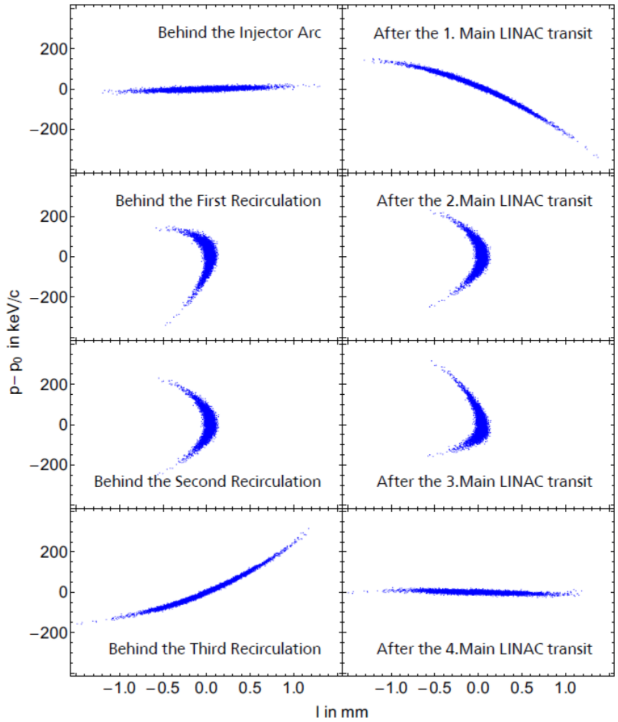

Figure 2: Simulated behavior of the longitudinal phase space at the optimal operating point using all recirculations [5].

by the R_{56} parameter. Therefore the parameters R_{51}, R_{52}, R_{53}, R_{54} as well as the parameters R_{16}, R_{26}, R_{36}, R_{46} have to be zero. It can be shown that most of those parameters vanish simultaneously for the beamline of the S-DALINAC [6] leaving only the parameters R_{16}, R_{26} and R_{56} to be set manually, by adjusting the quadrupole magnets in the injector and all recirculation arcs. The recirculation beamlines of the S-DALINAC consist of two 180° bending arcs and a straight section, that should only be used for pure transversal focussing of the beam. As mentioned before R_{16} and R_{26} should be zero individually at the end of each arc and along with the desired R_{56} five degrees of freedom per recirculation are required.

Upgrade Options for the First Recirculation

Since the first recirculation beamline only includes two quadrupole magnets per 180° arc the neccessary amount of degrees of freedom to arbitrarily choose R_{56} is not available. To achieve the desired parameter value the straight beamline has to be used to manipulate the other transport parameters as well so that the straight beamline can not be used for transversal focussing only. To improve this situation it is desireable to increase the amount of degrees of freedom in the recirculation arcs. This can be achieved by installing additional quadrupole magnets. Due to restricted spacial conditions within the arcs this can only be achieved by replacing existing elements. Until now there are two sextupole magnets named "F0SP01" and "F2SP01" (see Fig. 1) formerly used for beam-break-up experiments that are not in use any more and could be replaced by quadrupole magnets of the same longitudinal length. Alternatively some steerer dipole magnets could be replaced eliminating valuable possibilities to adjust the electron beam within the arcs. Also the installation of combined function magnets is currently taken into account.

MEASUREMENT OF LONGITUDINAL DISPERSION R_{56}

By changing the momentum of the center of the electron beam a phase shift can be introduced. For ultra relativistic particles this phase shift is approximately proportional to Δl since the speed deviation within a bunch is negligable. This leads to the relation

$$\Delta\Phi_{\text{beam}} \approx 360° \cdot \frac{f}{c} \cdot \Delta l = 360° \cdot \frac{f}{c} \cdot R_{56} \cdot \frac{\Delta p}{p_0}$$

The momentum of the beam can be manipulated by changing the amplitude of a accelerator cavity within the momentum acceptance of the respective recirulation arc. By measuring the resulting phase shift the longitudinal dispersion can be calculated.

Phase Measurement Devices

To measure the beam phase at the S-DALINAC RF monitors are used. These devices consist of a stainless-steel pillbox cavity tuned to the RF frequency of the beam. The beam traverses the monitor resonantly exciting electromagnetic fields inside that are measured using RF antennas as shown in Fig. 3. While the time resolution is not sufficient

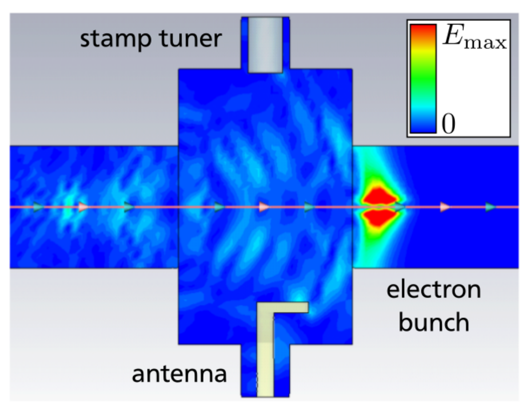

Figure 3: Schematic cross-section of a RF monitor used to measure the beam phase.

to measure the phase of each bunch individually the mean beam phase can be extracted due to the used continuous-wave mode of the S-DALINAC. With these devices phase measurements with a resolution of less than 0.2° are possible assuming the beam current to be greater than approximately 500 nA.

Measurements in the Injector Arc

Measurements at the injector arc using the RF monitor A1HF01 to aquire data (see Fig. 1) for three different val-

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ues of R_{56} are shown in Fig. 4. During this measurement

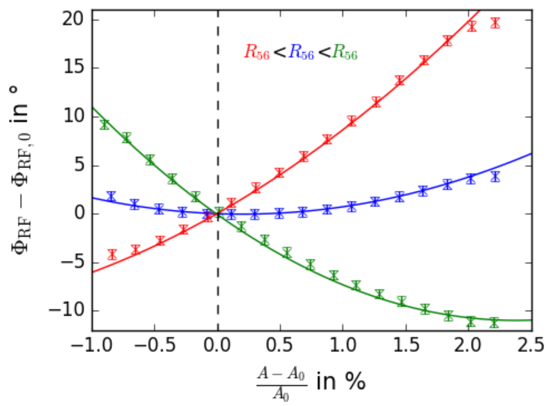

Figure 4: Measured phase shifts behind the injector arc as a function of the relative change in amplitude of the last accelerator cavity for different values of R_{56} measured by RF monitor A1HF01 [5].

the amplitude of the last injector cavity has been varied to change the beam momentum. For small variations from the desired amplitude A_0 the phase response is nearly linear while for bigger changes a parabolic dependency is visible. This shape is a result of two effects. The total path length of the center of the bunch increases, because the electron bunch with momentum mismatch is not traveling through the arc on the designed orbit. This effect already leads to a parabolic shape as can be seen in the simulation results shown in Fig. 5. But as shown, the effect on the phase

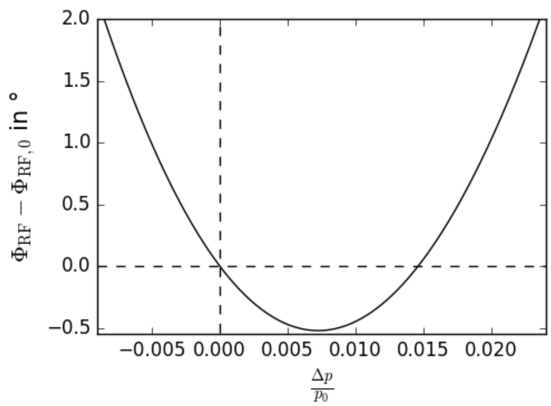

Figure 5: Simulated behavior of the bunch phase behind the injector arc depending on the initial momentum [5].

shift caused by the absolute value of the momentum only is smaller than the measured behavior. A combined change in transversal displacement and angular deviation while changing the amplitude of the accelerating cavity is the reason for the big phase shift, since a transversal displacement and an angular deviation at the entrance of the accelerating cavity lead to a modified transversal displacement and an angular deviation at the exit of this cavity, depending on the acceleration field. The influence of these quantities on the phase shift can be seen in Figs. 5 and 6. To check this dependency

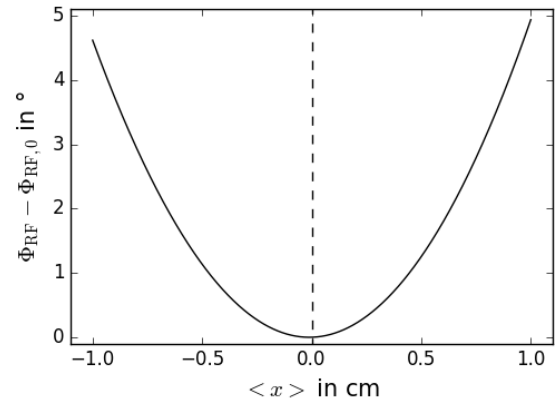

Figure 6: Simulated behavior of the bunch phase behind the injector arc depending on the initial horizontal displacement [5].

a separate measurement has been performed at which the accelerating cavity has been traversed with different entrance displacements. Figure 7 shows the comparison between the measurement and the simulated behavior. Taking into ac-

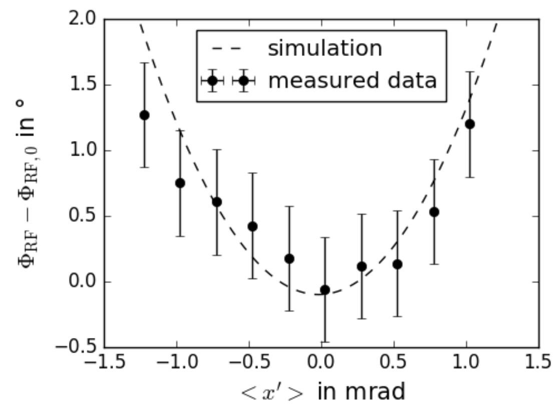

Figure 7: Comparison of the simulated horizontal angular deviation dependency and the measured dependency created by changing the beam position at the entrance of the injector arc using a dipole magnet [5].

count both these effects leads to a simulated behavior which is consistent with the measurement data of Fig. 4.

CONCLUSION

To use a non-isochronous recirculation mode at the S-DALINAC it is neccessary to accelerate off-crest and use a particular longitudinal dispersion R_{56} to conserve the energy spread of the injector accelerator. The first recirculation beamline does not provide enough degrees of freedom to arbitrarily adjust this parameter due to a lack of quadrupole magnets. Proposals for the installation of additional quadrupole magnets replacing existing sextupole or

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steerer magnets in the first recirculation arcs are currently being evaluated. Several time-of-flight measurements have been performed to determine the actual longitudinal dispersion of the 180° bending arcs showing a non-linear phase shift. These parabolic dependencies can be explained by non-linear increases of the traveled distance depending on the transversal displacement and angular deviation at the entrance of the arc and the momentum variations artificially induced to measure the longitudinal dispersion.

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