REDUCING THE ENERGY SPREAD OF RECIRCULATING LINAC BY NON-ISOCHRONOUS BEAM DYNAMICS*

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Abstract

The Superconducting Linear Accelerator S-DALINAC at the University of Darmstadt (Germany) is a recirculating linac with two recirculations. Currently, acceleration in the linac section is done on crest of the accelerating field. The recirculation path is operated achromatic and isochronous. In this recirculation scheme the energy spread of the resulting beam in the ideal case is determined by the electron bunch length. Taking into account the stability of the RF system the energy spread increases drastically. In this work we will present a new non-isochronous recirculation scheme which helps cancelling out these errors from the rf-control. This scheme uses longitudinal dispersion in the recirculation paths and an acceleration off-crest with a certain phase with respect to the maximum. We will present beam dynamic calculations which show the usability of this system even in a Linac with only two recirculations and first experimental results.

INTRODUCTION

The Superconducting DArmstadt LINear Accelerator (S-DALINAC) is used as a source for nuclear- and astrophysical experiments at the university of Darmstadt since 1987 [1]. It can accelerate beams of either unpolarized or polarized electrons [2] to beam energies of 1 up to 130 MeV with beam currents from several pA up to 60 μA. The layout of the S-DALINAC is shown in Fig. 1. The electrons produced in a thermionic or a laser driven electron gun are preaccelerated to an energy of 100-200 keV by a static high voltage field and prepared for acceleration in the superconducting cavities by a room temperature chopper-prebuncher section. The superconducting injector linac consists of a 2-cell and a 5-cell capture cavity and two standard 20-cell cavities fabricated from bulk niobium. These cavities are operating at a frequency of 3 GHz with a maximum accelerating gradient of 5 MV/m. After having passed the injector linac the beam has an energy of up to 10 MeV and can either be used for a low energy experimental area or be bent 180 degrees and injected into the main linac. The main linac consists of 8 standard 20-cell cavities and can achieve an energy gain of 40 MeV. By recirculating the beam two times the maximum energy of 130 MeV can be achieved. In the adjacent experimental hall the electron beam can be used for different experiments such as electron scattering in two electron spectrometers or experiments with tagged photons. For these experiments an energy spread of ± $1\cdot10^{-4}$ is required.

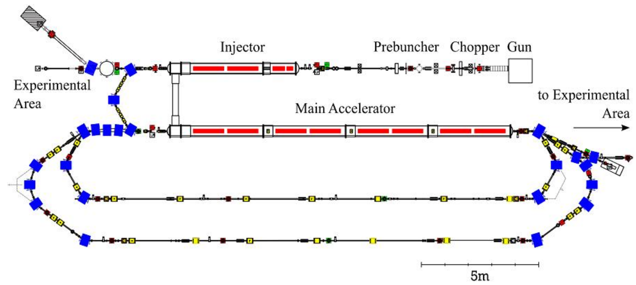

Figure 1: Floor plan of the S-DALINAC.

LONGITUDINAL BEAM DYNAMICS

The original design of the S-DALINAC uses an isochronous recirculation scheme. In this scheme the electrons are accelerated in the maximum of the accelerating field (on crest) in every turn and the bunch length is kept constantly small (± 1°) using achromatic and isochronous recirculation paths. Isochronicity is a property of beam optics and can be described as $dl/dE = 0$ meaning that the length of the flight path of all electrons is independent from their energy. The expected energy spread of the beam is determined by the bunch length of the electron bunches ideally, not taking into account that the energy spread is increased further due to amplitude and phase jitters of the accelerating field. These errors add up coherently throughout the three linac passages in a way that every electron sees the same errors in all three passes through the linac due to the large time constant of field variations in the superconducting cavities. Consequently the amplitude jitter of $\Delta E_{cav}/E_{cav} = 1\cdot10^{-3}$ leads to an energy spread of

$$\frac{\Delta E}{E} = 3\cdot\frac{\Delta E_{cav}/E_{cav}}{\sqrt{8}} = 1.03\cdot10^{-3}\,.$$

This misses the experimental requirements by one order of magnitude.

In order to meet the required energy spread in future a non-isochronous recirculation scheme has been proposed [2,3,4]. In addition a new digital rf-system for the S-DALINAC will start operation within this month [5]. In a non-isochronous recirculation scheme the recirculation paths provide a longitudinal dispersion $dl/dE = D_L \neq 0$ while the accelerating field is operated at a certain synchrotron phase $\Phi_S \neq 0$ (on edge). Formally the accelerating field seen by every electron inside an rf-cavity is given by

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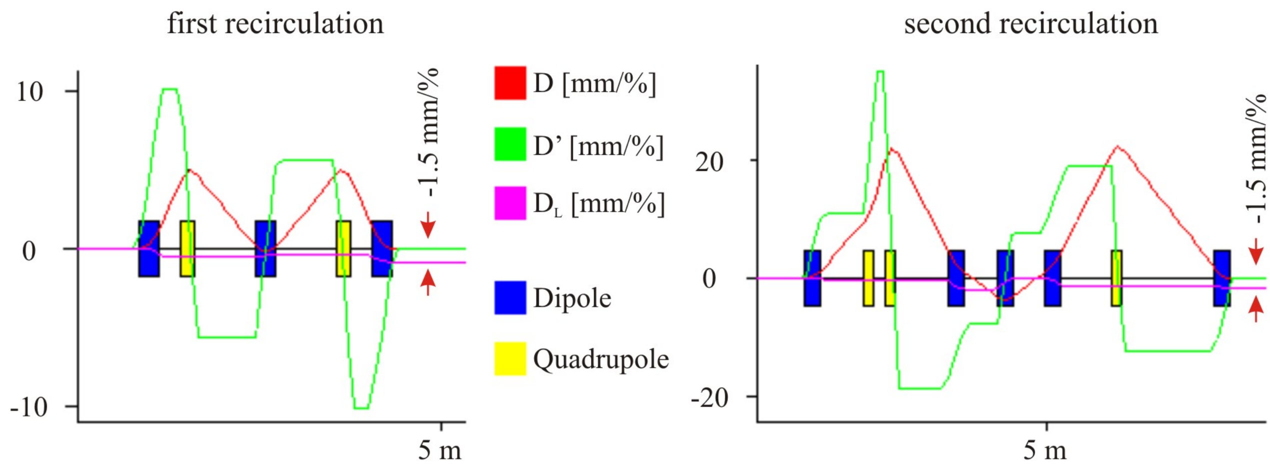

Figure 2: Optimized lattice for the bending sections of the first (left) and second. (right) recirculation. At the end of each bend *D* (red) and *D'* (green) vanish while D_L (purple) reaches the envisaged value of -1.5 mm/%.

$$E_{acc} = (E_0 + \Delta E)\cos(\omega(t+\tau) + \Delta\Phi + \Phi_S)$$

where E_0 is the amplitude setting, Φ_S the synchrotron phase, ΔE and $\Delta\Phi$ the amplitude and phase jitters, and $c\tau$ correspondents to the longitudinal distance between the electron and the reference particle. The electrons perform synchrotron oscillations in the longitudinal phase space but contrary to synchrotrons where a complete oscillation usually needs some hundred turns, in our case the longitudinal motion is used to correct the rf jitter of the accelerating cavities and the longitudinal phase advance needs to be much bigger. In fact a half or full integer number of synchrotron oscillations leads to the best energy resolution of the extracted beam. In that case the resulting energy spread at extraction is only determined by the energy spread at injection while the errors caused by the rf jitters are cancelled out. [6,7]

In numerical simulations the usability of such a non-isochronous recirculation scheme at the S-DALINAC has been verified already and a new longitudinal working point has been determined. The parameters found in these simulations (D_L = -1.5 mm/% and Φ_S = -9.5°) would lead to a reduction of the energy spread to $\Delta E/E = 6.03\cdot10^{-5}$ which satisfies the requirements mentioned above. (for more details see [2,3,4])

LATTICE OPTIMIZATION

In order to tune the S-DALINAC to the new non-isochronous working point optimizations at the recirculation paths have been carried out. In particular the lattice of the recirculation arcs has been reviewed with the objective to change the value of D_L easily while the transverse dispersion *D* and the transverse angular dispersion *D'* both equal zero at the end of every recirculation arc. The result of these optimizations is shown in Fig. 2.

For the first recirculation (Fig. 2 left) the two quadrupoles in the arc are set to the same gradient and by changing this gradient the longitudinal dispersion can be manipulated as well while *D* and *D'* always remain at zero. (dD_L/dG = 0.18 mm/% / T/m)

For the second recirculation (Fig. 2 right) one more quadrupole in the arc is needed to compensate an asymmetry of the bending angles of the dipoles. So the quadrupoles are not set to the same gradient like in the first recirculation arc but it was possible to find a solution, where changing the gradients of the quadrupoles inside the arc manipulates the longitudinal dispersion as well while *D* and *D'* remain at zero. To do so the quadrupole gradients are changed in a fixed ratio. (dD_L/dG_1 = 0.19; dD_L/dG_2 = 0.11 dD_L/dG_3 = 0.7 mm/% / T/m)

MEASUREMENT OF LONGITUDINAL DISPERSION

Even though the idea of non-isochronous recirculation was presented many years before [2], the realisation, especially tuning the machine to the new longitudinal working point, still was not done. One reason was a lack of diagnostics developed meanwhile and described in the section below.

For the measurement of the longitudinal dispersion of the first recirculation arc an rf monitor located at the beginning of the straight section behind the last dipole has been used. Usually, these intensity monitors, which are

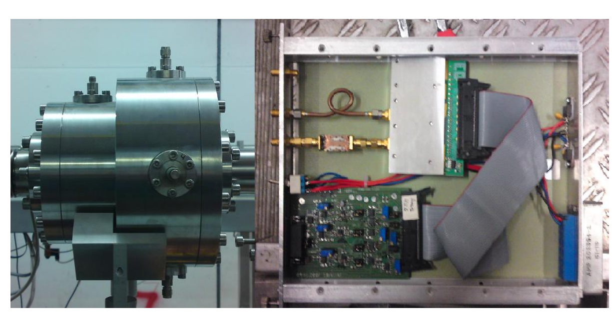

Figure 3: rf monitor (left) and rf board with level converter (right) used for the measurement.

pillbox cavities at a 3 GHz resonant frequency (see Fig. 3 left), are used for non-destructive measurement of the beam current during operation. The passing beam excites an oscillation and the rf signals can be coupled out. For the determination of the longitudinal dispersion the time of flight of the electron bunches is the matter of interest as changes of beam energy are related to changes of this time when $D_L \neq 0$. Instead of measuring the time of flight of every bunch directly it is more appropriate to determine the phase of the 3 GHz oscillation excited by the beam. This can be done by mixing the rf signal of the monitor with the local oscillator frequency of the rf control system. This down conversion to the base band [5] is done on a rf board with a level converter board (see Fig. 3 right) leading to *I/Q* values describing the relative oscillation phase of the rf monitor.

To determine D_L the magnetic field of the dipoles in the arc have been set to different values changing the energy of the reference trajectory. For every dipole setting the *I/Q*-values have been measured. Afterwards, the arc has been tuned to a different longitudinal dispersion by changing the quadrupole gradients. The pairs of *I/Q* values for every measurement are plotted in the upper part of Fig. 4. The bending system accepted a large range of quadrupole gradients. Only at very low gradients the transverse extension of the beam caused beam losses in the arc.

For the determination of D_L from the measured *I/Q*-values it is necessary to calculate the path length difference d*l* of the electrons on trajectories representing different beam energies. For this purpose the phase of the rf monitor is determined first. Afterwards the 10 cm wavelength of the 3 GHz operation frequency of the S-DALINAC is used to calculate d*l* and finally D_L:

$$\tan\varphi = \frac{I}{Q} \rightarrow \frac{d\varphi}{dl} = 3.6\frac{\text{deg}}{\text{mm}} \rightarrow D_L = \frac{dl}{dE}$$

The lower part of Fig. 3 shows the obtained values of D_L for the measurement and a linear fit of the data points. It can be seen that the measurement fits very well with the simulation results and that D_L can be changed over a large interval without the appearance of beam losses including the envisaged value of $D_L = -1.5$ mm/%.

SUMMARY AND OUTLOOK

With a new non-isochronous recirculation scheme for the S-DALINAC the energy spread of the electron beam can be reduced significantly. For this purpose a new longitudinal working point has been determined and the lattice of the recirculation arcs has been changed. Measurements on the first recirculation show a very good agreement with the beam dynamic simulations and a proof of principle for the used setup based on time of flight measurement by rf phase detection. Measurements of the longitudinal dispersion in the second recirculation will follow soon. Once, both systems will be available one can expect an easy tuning of the machine to the new longitudinal working point.

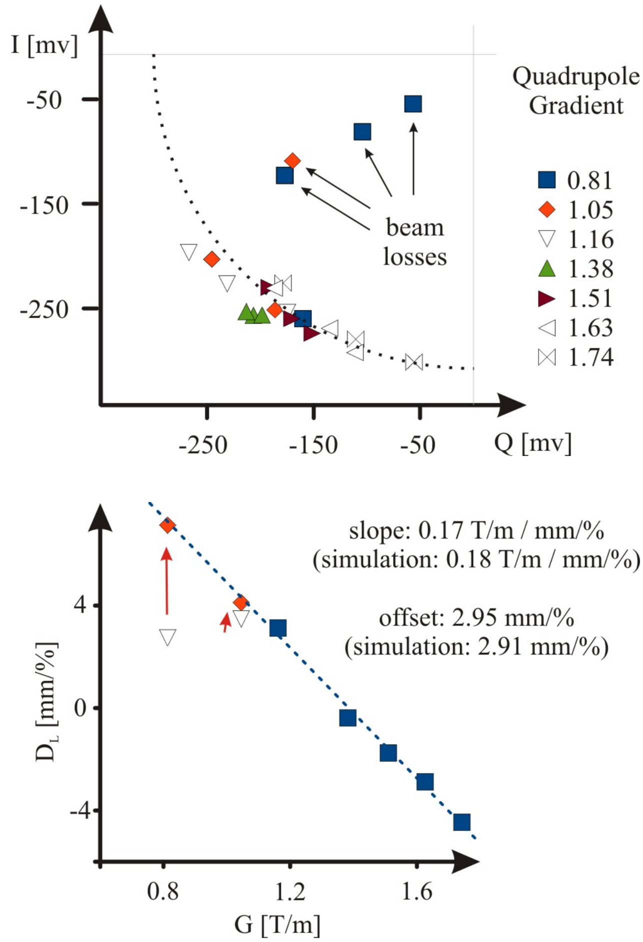

Figure 4: Measured *I/Q* values of the beam for different dipole and quadrupole settings (top) and resulting longitudinal dispersion (bottom) of the first recirculation. The red arrows mark the correction of beam losses which appeared only at very low quadrupole gradients in the arc.

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