REDUCING ENERGY SPREAD OF THE BEAM BY NON-ISOCHRONOUS RECIRCULATION AT THE S-DALINAC*

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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 is done on crest of the acceleration field using the maximum of the field in every turn. The recirculation of the beam is done isochronous without any longitudinal dispersion. In this recirculation scheme the energy spread of the resulting beam is determined by the stability of the used RF system. In this work we will present a new non-isochronous recirculation scheme, which uses longitudinal dispersion in the recirculations and an acceleration on edge of the accelerating field as it is done in microtrons. We will present beam dynamic calculations which show the usability of this system even in a linac with only two recirculations and first measurements of longitudinal dispersion using rf monitors.

INTRODUCTION

Since its first put into operation in 1987 the Superconducting DArmstadt LINear Accelerator (S-DALINAC) is used as a source for nuclear- and astrophysical experiments at the university of Darmstadt [1]. It delivers electron beams of 1 up to 130 MeV with beam currents up to 60 μA. The layout of the S-DALINAC is shown in Fig. 1. The electrons are produced in a thermionic electron gun and preaccelerated to an energy of 250 keV by a static high voltage field. In addition a new source for spin-polarized electrons is under construction currently [2]. After preacceleration the 250 keV beam is prepared for acceleration in the superconducting cavities by a room temperature chopper-prebuncher section. The superconducting injector linac allows a maximum energy gain of 10 MeV. It consists of a 2-cell and a 5-cell capture cavity and two standard 20-cell cavities fabricated from bulk niobium. The 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 can either be delivered to 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 up to two times the maximum energy of 130 MeV can be achieved. The beam is then extracted to the adjacent experimental hall and can be used for different experiments such as electron scattering experiments in two electron spectrometers or experiments with tagged photons. For these experiments an energy spread of $\pm 1\cdot 10^{-4}$ is recommended.

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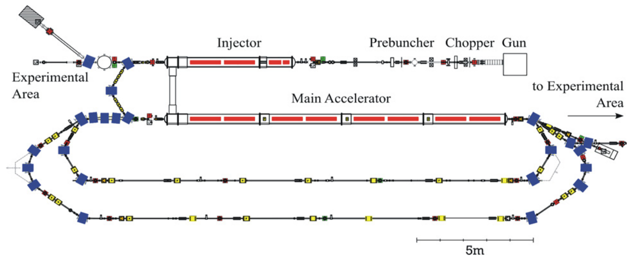

Figure 1: Floor plan of the S-DALINAC.

LONGITUDINAL BEAM DYNAMICS

Isochronous Recirculation Scheme

The original design of the S-DALINAC provides a isochronous recirculation scheme. In this scheme the electrons are accelerated always at the maximum of the accelerating field (on crest). The acceleration on crest is the norm for acceleration in linear accelerators and the expected energy spread of the beam is determined by the bunch length of the electron bunches due to the oscillating electric field. In order to keep this bunch length constantly small all electrons have to be recirculated isochronous which implies that every electron has an equal flight time from exiting the linac to being reinjected again no matter of its energy. As electrons of energies above 10 MeV can be assumed to have a constant velocity of $v \approx c$ an equal flight time means an equal flight length respectively and isochonicity is a property of beam optics and can be described as $dl/dE = 0$.

At the S-DALINAC the bunchlength of $\pm$ 1° of the rf-period leads to an energy spread of $\pm 1\cdot 10^{-4}$ which would satisfy the experimental recommendations mentioned above. But the recirculation scheme does not take into account that the energy spread is increased further due to amplitude and phase jitters of the accelerating cavities. For example a phase jitter in either direction would lead to a smaller energy gain in the cavity as the electrons would leave the maximum of the accelerating field. Furthermore all errors add up coherently throughout the three linac passages due to the recirculation of the beam. At the S-DALINAC the electron path has a length of approx. 83 m which corresponds to a total flight time of approx. 0.3 μs. The time constant for field variations in the superconducting cavities with a loaded quality factor of some 10^7 is in the order of some hundred microseconds. This implies that every electron sees the same errors in all three passes through the linac. The amplitude jitter at the S-DALINAC of $\Delta E_{cav}/E_{cav} = 1\cdot 10^{-3}$ leads to an energy spread of

$$\left.\frac{\Delta E}{E}\right|_{LINAC,oncrest} = 3\cdot\frac{\Delta E_{cav}/E_{cav}}{\sqrt{8}} = 1.06\cdot 10^{-3},$$

which misses the experimental recommendations by one order of magnitude.

To reach these recommendations in future two strategies are pursued currently at the S-DALINAC. On the one hand the implementation of a new digital rf-system with better amplitude and phase stability is in progress [3], on the other hand the use of a non-isochronous recirculation scheme will be introduced in the following sections.

Non-isochronous Recirculation Scheme

The fact, that the rf field stays nearly constant during the travel time of an electron bunch through the S-DALINAC allows the application of an advanced recirculation scheme which was first published in [4,5] and will be referred to only shortly within this text.

The accelerating field inside an rf cavity is given by

$$E_{acc} = (E_0 + \Delta E)\cos(\omega(t+\tau) + \Delta\Phi + \Phi_S), \quad (1)$$

where E_0 is the amplitude setting, Φ_S the synchrotron phase, ΔE and $\Delta\Phi$ the amplitude and phase jitter, and $c\tau$ correspondents to the longitudinal distance between electron and the reference particle (see Fig. 2).

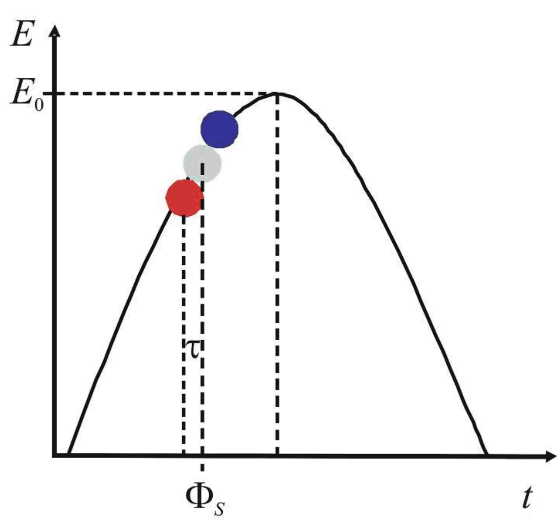

Figure 2: Parameters used in eq. 1.

By choosing a non-zero synchrotron phase Φ_S a phase jitter does not always lead to a decrease in energy. Furthermore the now introduced "overvoltage" (E_0 - $E_0 \cdot \cos(\Phi_S)$) allows to correct too low particle energies using non-isochronous recirculation paths: If one electron for example is accelerated too much within the first linac passage, the now introduced longitudinal dispersion ($D_L = dl/dE$) leads to a shorter path length and thus to a shorter travel time. The electron reenters the linac earlier than the reference particle ($\tau \leq 0$) and is therefore accelerated with a lower field. To extend this concept for an electron with too low energy one is obliged to leave the maximum of the accelerating field and to inject the particles with a certain synchrotron phase Φ_S.

This described motion in longitudinal phase space is well known as synchrotron oscillation. In synchrotrons particles always perform this oscillation. It is used to compensate the spontaneous energy loss of electrons due to radiation and 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.

Numerical Simulations of Longitudinal Beam Dynamics

To find the best combination of the parameters for the synchrotron phase Φ_S and the longitudinal dispersion D_L for the S-DALINAC, numerical simulations with a self written code have been performed. The simulation was done using 5000 particles (simulation parameters see Table 1), which leads to a sufficient statistical significance. According to the problem given above the two parameters (Φ_S, D_L) were varied independently and the resulting rms energy spread of the beam was calculated. The result of this simulation, a hill plot of the resulting energies, is shown in Fig. 3, showing areas of smaller energy spread beside the isochronous longitudinal working point. The best result for the energy spread was $\Delta E/E = 6.03\cdot 10^{-5}$ and is achieved at D_L = -1.5 mm/% and Φ_S = -9.5°, while the isochronous case leads to $\Delta E/E = 2.25\cdot 10^{-4}$. A detailed analysis of the simulation shows that the electrons perform half of a synchrotron oscillation in the non-isochronous recirculation sheme, thus the resulting energy spread at extraction is only determined by the energy spread at injection.

Table 1: Parameters for the Beam Dynamic Simulations

Energy of the injected beam	10 MeV
Energy spread of the injected beam	100 keV
Bunch length of the injected beam	$\pm$ 1°
Energy gain in the linac	40 MeV
Amplitude jitter	$\pm 1\cdot 10^{-3}$
Phase jitter	$\pm$ 1°

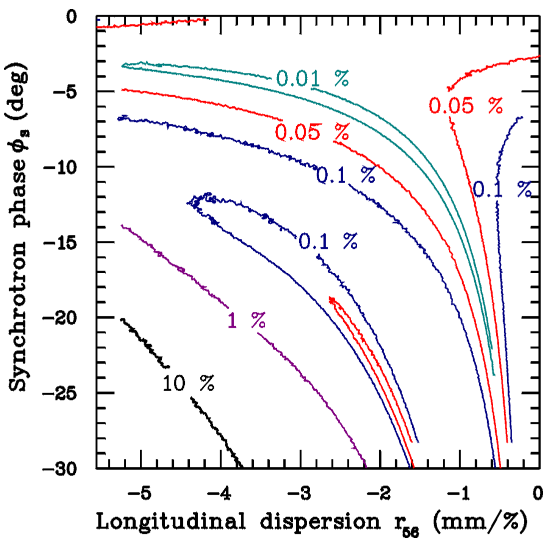

Figure 3: Hill plot of the expected energy spread ($\Delta E_{RMS}/E$) as a function of the longitudinal dispersion D_L and the synchrotron phase Φ_S.

MEASUREMENT OF LONGITUDINAL DISPERSION

The results presented in the section above implied to move the longitudinal working point to a non-isochronous one. To reach this new working point the synchrotron phase Φ_S and the longitudinal dispersion D_L have to be changed to new setpoints. As the synchrotron phase is a free parameter for the S-DALINAC rf control system already its new setpoint is quite easy to set. For the longitudinal dispersion the situation is more complicated. First the lattice of the recirculation bends had to be optimized in order to change the longitudinal dispersion easily, second a possibility to measure the longitudinal dispersion is needed. For the bends in the first recirculation the optimized lattice is shown in Fig. 4. The longitudinal dispersion can be manipulated, changing the gradients of the two quadrupoles in the bend simultaneously, while transverse dispersion will stay constantly at zero.

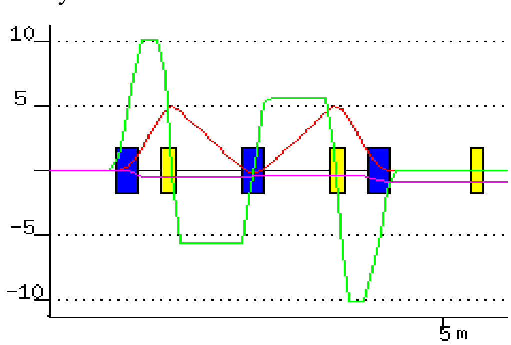

Figure 4: Lattice of the first recirculation bend, the longitudinal dispersion D_L is plotted in purple (unit mm/%), dipoles blue and quadrupoles yellow.

To measure the dispersion rf intensity monitors have been used. These monitors are pillbox cavities with a 3 GHz resonance (see Fig. 5). The passing beam excites an oscillation and the signals can be coupled out. To measure the longitudinal dispersion the passing time of the electron bunches is the matter of interest as changes of beam energy should change this time when $D_L \neq 0$. The time signal can be measured well, determining a phase of the 3 GHz oscillation. To do so, the rf signal is mixed with the reference of the rf control system on a rf board (see Fig.5) used in this system as well. The result are I/Q-vectors which can be converted to a phase. To measure D_L the beam energy is changed and the phase is determined for different quadrupole settings.

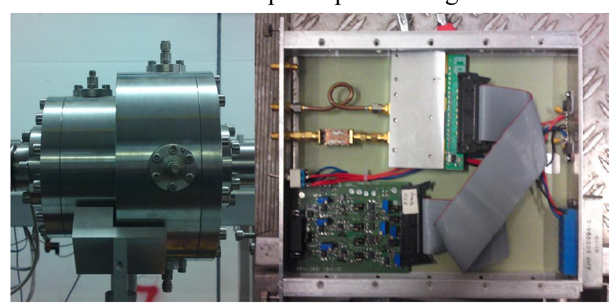

Figure 5: rf monitor (left) and rf board (right) used for the measurement.

The results of the measurement are given in Table 2. It can be seen that the simulation results are confirmed quite well.

Table 2: Measurement and Simulation Results

	Simulation	**Measurement**
Offset (D_L =0)	2.91 T/m	2.95 T/m
Slope (dD_L/dG)	0.18 T/m / mm/%	0.17 T/m / mm/%

SUMMARY AND OUTLOOK

A new non-isochronous recirculation scheme for the S-DALINAC has been presented within this article. It can reduce the energy spread of the electron beam at the S-DALINAC significantly. First measurements in the first recirculation show good conformance with the beam dynamic simulations. In the current shutdown period the bends of second recirculation will be optimized as well.

REFERENCES

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