MEASUREMENTS OF A REDUCED ENERGY SPREAD OF A 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 providing beams for measurements in nuclear physics at small momentum transfers. For these experiments an energy spread of better than 10^{-4} (rms) is needed. 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 to more than 10^{-3} (rms).

We will present a new non-isochronous recirculation scheme which helps cancelling out these errors coming from the RF-jitters. This scheme uses longitudinal dispersion in the recirculation paths and an acceleration off-crest on a certain phase with respect to the maximum. We will present results of the commissioning of the new system including measurements of the longitudinal dispersion in the recirculation arcs as well as measurements of the resulting energy spread using an electron spectrometer.

INTRODUCTION

Operating since 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 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.

Acceleration in the injector and main linac is done by superconducting elliptical cavities with a quality factor of $Q_0 \approx 10^9$. These cavities are operating at a frequency of 3 GHz with a maximum accelerating gradient of 5 MV/m.

The main linac consists of 8 standard 20-cell cavities and can provide 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 this 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 $\pm 1 \cdot 10^{-4}$ is required.

* Work supported by DFG through SFB 634
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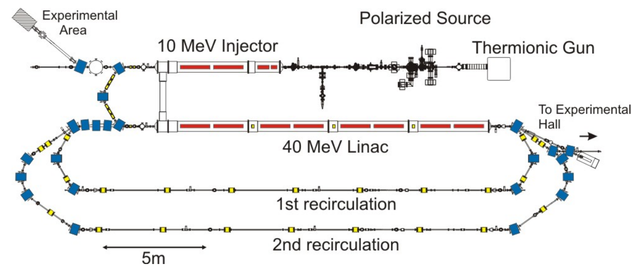

Figure 1: Floor plan of the S-DALINAC.

LONGITUDINAL BEAM DYNAMICS

The S-DALINAC is designed to use an isochronous recirculation scheme originally. On a isochronous working point the electrons are accelerated in the maximum of the accelerating field (on crest) in every turn and the bunch length is kept constantly small ($\pm$ 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. Acceleration on crest of the RF-field is the common mode for linear accelerators. Usually amplitude and phase jitters of the cavities are not correlated and the resulting energy spread is mainly determined by the short bunch length. In a recirculating linac the errors can add up coherently throughout the linac passages in a way that every electron sees the same errors in all passes through the linac due to the large time constant of field variations in the superconducting cavities compared to the short time of flight of the ultra relativistic electrons through the linac.

A way to overcome these correlated errors is changing the longitudinal working point to a non-isochronous one. This is the common operation mode for synchrotrons or microtrons 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). The electrons then perform synchrotron oscillations in the longitudinal phase space. Compared to synchrotrons a quite large phase advance per turn is needed to cancel out the RF jitters. In fact a half or full integer number of synchrotron oscillations leads to the best energy resolution of the extracted beam in a way that the resulting energy spread at extraction is only determined by the energy spread at injection while the errors caused by the RF jitters of the main linac are cancelled out. [3,4]

The usability of such a non-isochronous recirculation scheme at the S-DALINAC has been verified already by numerical simulations (see Fig. 2). The new longitudinal

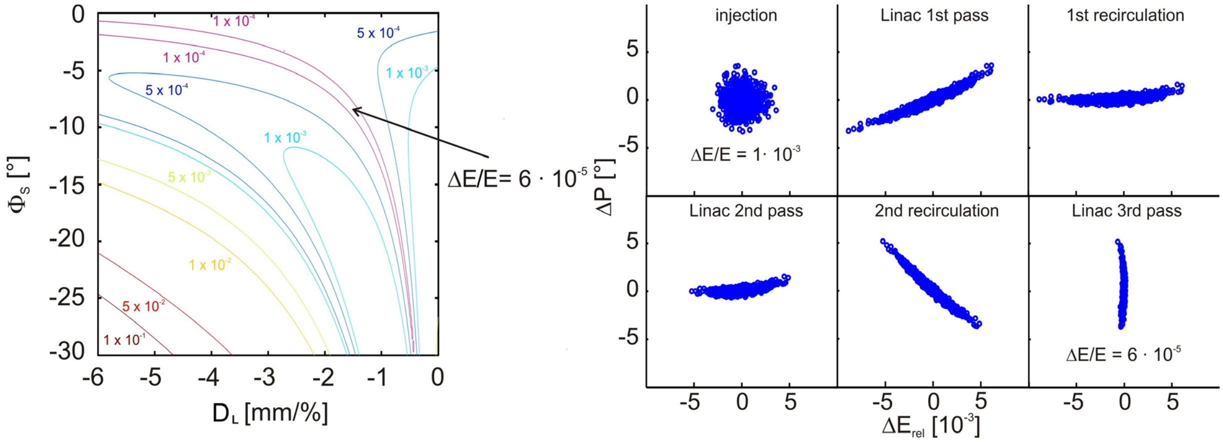

Figure 2: Hillplot of the resulting energy spread at extraction for different sets of longitudinal dispersion and synchrotron phase (left). Beside the isochronous point exist areas of reduced energy spread. The minimum has been determined to D_L = -1.5 mm/% and Φ_S = -9.5° On the right side a bunch of 5000 particle has been tracked through the linac using the optimized parameters. The particles perform a half oscillation in longitudinal phase space ending up on a reduced energy spread.

working point has been determined to D_L = -1.5 mm/% and Φ_S = -9.5° and would lead to a reduction of the energy spread to $\Delta E/E = 6.03 \cdot 10^{-5}$ which satisfies the requirements mentioned above very well. (for more details see [5,6,7])

LATTICE OPTIMIZATION

In order to tune the S-DALINAC to different non-isochronous working points in future optimizations at the recirculation paths had to be carried out. In particular the quadrupole lattice of the recirculation arcs needed to be reviewed 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 are lattices for both arcs in which D_L can be manipulated easily by changing only the quadrupole gradients in the arcs. Keeping these gradients on a fixed ratio in addition D and D' remain at zero at the end of every arc like required. (for more details on this topic see [7,8])

MEASUREMENT OF LONGITUDINAL DISPERSION

The idea of adapting the concept of non-isochronous recirculation for the S-DALINAC was presented many years before [5], while the realisation, especially tuning the machine to the new longitudinal working point, needed some time. One reason was a lack of beam diagnostics developed meanwhile and described in the section below.

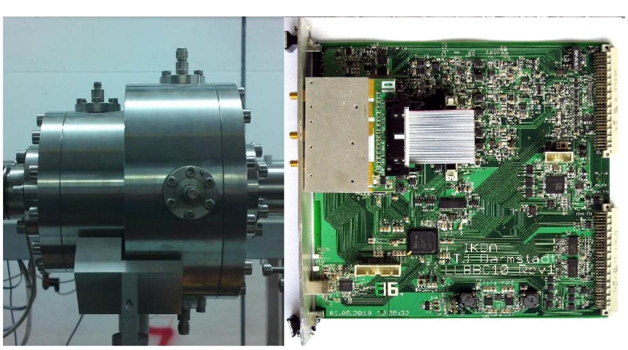

Figure 3: Measurement setup consisting of rf monitor (left) and rf board with FPGA board (right).

For the measurement of the longitudinal dispersion of the recirculation arcs RF monitors located at the beginning of the straight sections behind the last dipoles has been used. Usually, these intensity monitors, which are 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 cw beam excites an oscillation and the RF signals can be coupled out. Matter of interest is the detection of 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 [9] is done on a RF board (see Fig. 3 right) leading to I/Q values describing the relative oscillation phase of the RF monitor. The I/Q values are converted into real phase values on a FPGA board then. This board is also used for setting amplifications and offsets of the measurement. The hardware is mainly part of the new developed digital LLRF system of the S-DALINAC with minor modifications due to the weak signals coming out of the RF monitors [8,9,10].

To determine D_L out of the phase values the time of flight method is used. For every quadrupole setting, corresponding to a certain dispersion D_L the energy of the beam is changed and the phase on the RF monitor is measured. If $D_L \neq 0$ the time of flight in the arc changes with respect to the beam energy and so does the phase. The results of the measurements on both recirculations is shown in Fig. 4.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 including the envisaged value of D_L = -1.5 mm/%.

ISBN 978-3-95450-122-9

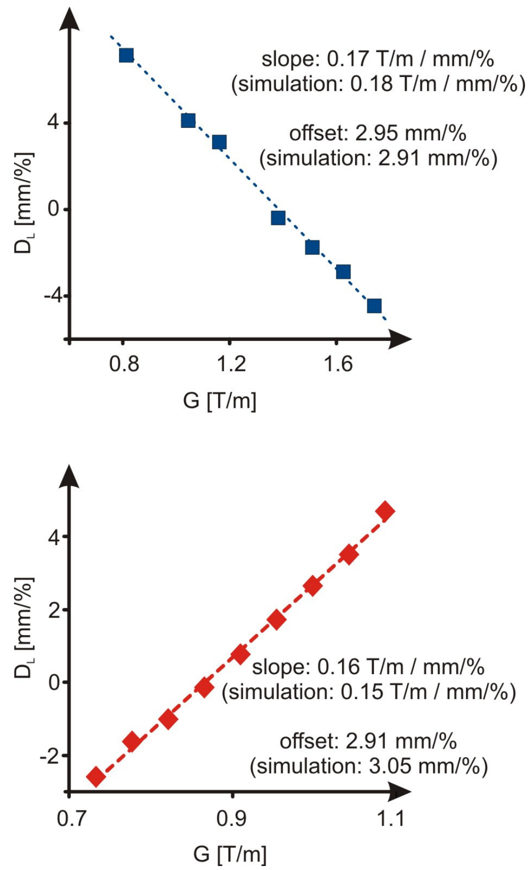

Figure 4: Measured values of D_L in the first recirculation (top) and second recirculation (bottom) for different quadrupole gradients in the arc.

MEASUREMENT OF THE ENERGY SPREAD

Having set up a detection system for D_L and characterized the recirculation arcs allowed to tune the accelerator to its new non-isochronous working point. In order to check the energy resolution of the beam an electron scattering experiment on a thin gold target has been performed. The obtained data is shown in Fig. 5. The energy spread could be reduced from ΔE = 120 keV in the isochronous mode to ΔE = 30 keV in the non-isochronous mode. Both spectra have been measured for about 30 min, which is a typical time between two saves of experimental runs for nuclear physics experiments. After this first proof of principle the following beam time has been successfully performed in the non-isochronous mode.

SUMMARY AND OUTLOOK

Using a new non-isochronous recirculation scheme for the S-DALINAC the energy spread of the electron beam could be reduced significantly. Nevertheless additional experiments are planned to check the effect of different longitudinal working points on the energy spread and compare the data with simulations shown in Fig. 2.

In addition the concept of using a non-isochronous working point to reduce the energy spread of multi-pass linacs might be interesting to overcome beam break-up limits in high current linacs or ERLs as the bunchlength during acceleration is naturally longer which generally leads to weaker excitations of HOMs [11].

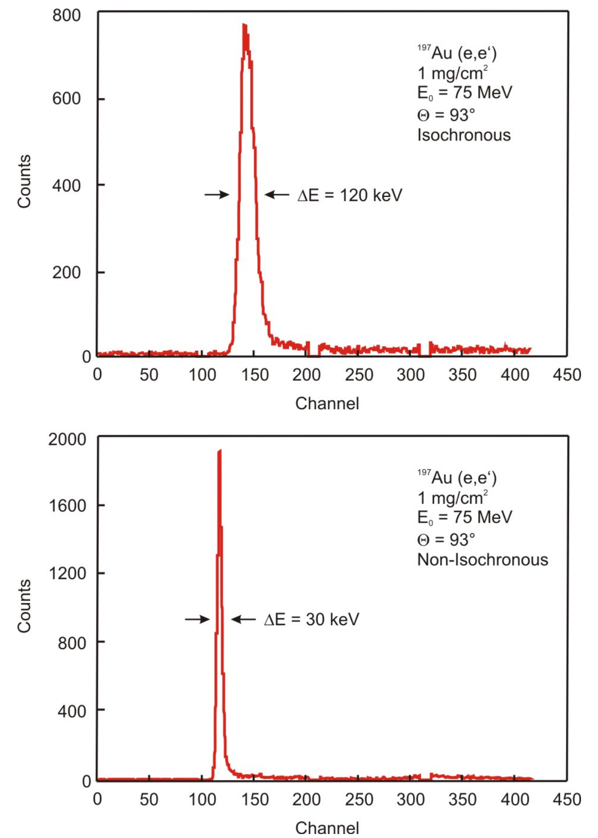

Figure 5: Energy spread of the beam obtained by elastic scattering on a thin gold target. Top: isochronous acceleration. Bottom: Non-isochronous recirculation.

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ISBN 978-3-95450-122-9