IMPROVING ENERGY SPREAD AND STABILITY OF A RECIRCULATING FEW-TURN LINAC*

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Abstract

A non-isochronous recirculation scheme which helps cancelling out errors coming from the RF-jitters in a recirculating linac will be presented. Non-isochronous recirculation is the common operation mode for synchrotrons or microtrons. In such a scheme the recirculation arcs provide a non-zero longitudinal dispersion, while the particle bunches are accelerated at a certain phase off-crest with respect to the maximum of the accelerating field. In few-turn linacs and microtrons such beam dynamics can be used to reduce the energy spread. To do so the longitudinal phase advance during the complete acceleration and recirculation process needs to be set to a half-integer number of oscillations in phase space. Then errors from linac RF-systems cancel out and the energy spread remains closely to the value at injection. In addition to the improved energy spread the beam stability of few-turn recirculators can be increased as well using such a system.

We will present operational experience with the non-isochronous recirculation system of the twice recirculating superconducting accelerator S-DALINAC operated at TU Darmstadt including beam-dynamics calculations and measurements of the energy spread.

INTRODUCTION

For most electron linacs the accelerating phase is chosen in a way that electrons are accelerated in the maximum of the accelerating field (on crest). In few-turn recirculators which are using only a small number of recirculating beamlines acceleration on crest while choosing an isochronous longitudinal working point still is the conventional mode of operation. On such an 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 (± 1°) using achromatic and isochronous recirculation paths. Isochronicity is a property of beam optics and can be described as all electrons need the same time of flight through the optics ($\mathrm{d}t/\mathrm{d}E = 0$) For ultra-relativistic electrons ($v \approx c$) isochronicity can also be described by $\mathrm{d}l/\mathrm{d}E = 0$ meaning that the length of the flight paths of all electrons is independent from their energy. Usually amplitude and phase jitters of the cavities are not correlated and the resulting energy spread is mainly determined by the short bunch length for an electron linac operated on crest. But in a few-turn linac these errors can add up coherently throughout the small number of linac passages in a way that every electron sees the same errors

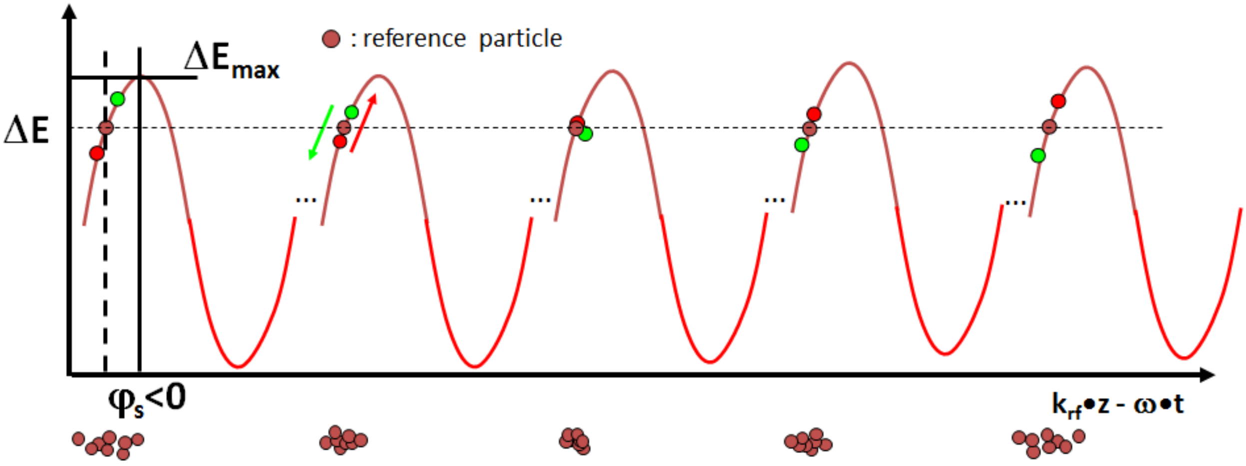

Figure 1: Illustration of synchrotron oscillations of electrons on a non-isochronous working point in a five-pass recirculating linac [1]. The particles perform exactly a half synchrotron oscillation throughout the acceleration process. It can be seen that the particles in front and back of the bunch add up energy errors within the first two linac passes. Nevertheless these errors are compensated during the last two passes in a way that the sum of all errors for every particle adds up to zero at the end of the acceleration process. The phase advance for a concrete recirculating linac would be determined by the choice of the parameters D_{L} and Φ_{S}.

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in all passes through the linac due to the large time constant of field variations in the accelerating cavities compared to the short time of flight of the ultra relativistic electrons through the accelerator.

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 certain longitudinal dispersion $\mathrm{d}l/\mathrm{d}E = D_\mathrm{L} \neq 0$ while the accelerating field is operated at a synchrotron phase $\Phi_\mathrm{S} \neq 0$ (on edge) with respect to the crest of the accelerating field. The electrons then perform synchrotron oscillations in the longitudinal phase space. A quite large phase advance per turn is chosen to cancel out the RF jitters. Compared to synchrotrons, where small integer multiples of synchrotron oscillations need to be avoided in order to provide stability, in few-turn recirculators or microtrons these resonances are desired. In fact half or full integer numbers of synchrotron oscillations lead 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 completely [2,3].

Figure 1 illustrates this error cancellation on a half-integer longitudinal phase advance through an example given for a five-pass linac. In the next section we will present the application of a non-isochronous working point at the superconducting two-fold recirculator S-DALINAC.

S-DALINAC

Operating since 1987 the Superconducting DArmstadt LINear ACcelerator (S-DALINAC) is providing electron beams for nuclear- and astrophysical experiments at the university of Darmstadt [4]. The linac accelerates beams of either unpolarized or polarized electrons [5] to energies from 1 up to 130 MeV at beam currents from several pA up to 60 µA. The layout of the S-DALINAC (valid until end 2015) is shown in Fig. 2. Since end 2015 a third recirculation beamline is under construction [6] and will be commissioned by summer this year. As all experiments and calculations presented in this contribution have been carried out at the twice-recirculating machine we here present the old layout only.

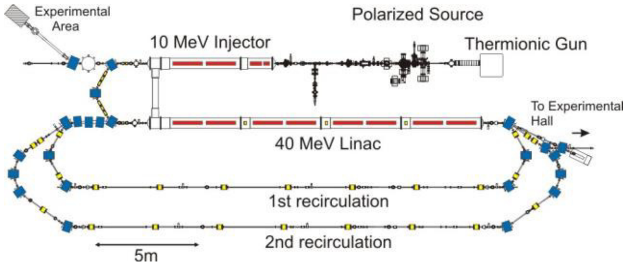

Figure 2: Floor plan of the S-DALINAC (valid until end 2015).

Acceleration in the injector and main linac is done by superconducting elliptical cavities with a quality factor of $Q_0 \approx 10^9$. All SC cavities are operating at a frequency of 3 GHz on a maximum accelerating gradient of 5 MV/m. The main linac consising of 8 standard 20-cell cavities is designed for providing a maximum energy gain of 40 MeV per turn. 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 the electron scattering experiments a relative energy spread of better than $\pm 1 \cdot 10^{-4}$ is required.

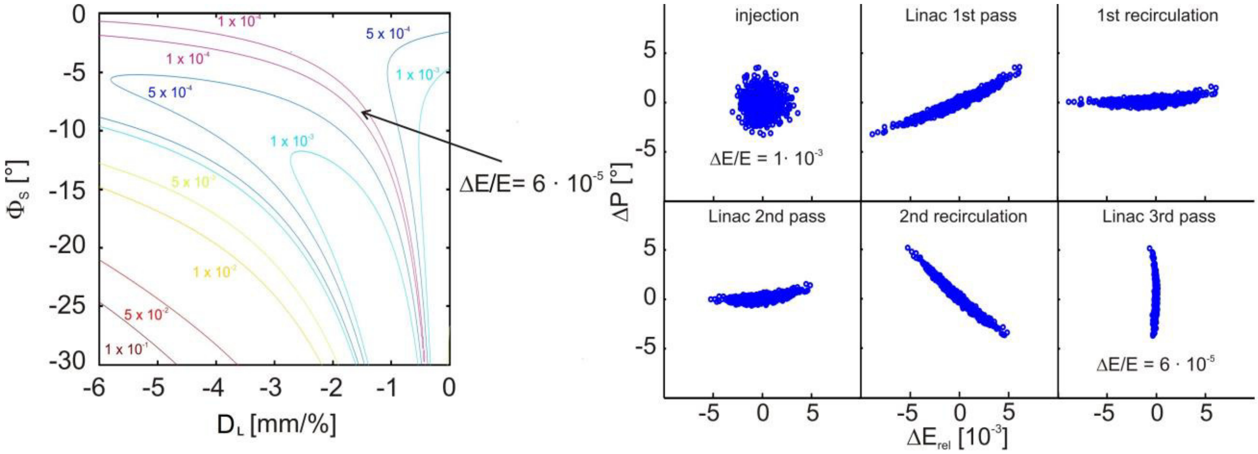

Figure 3: Hillplot of the resulting energy spread at extraction for different sets of longitudinal dispersion and synchrotron phase (left). The RF jitters (*rms*) in the simulations have been set to $\pm\,3 \cdot 10^{-4}$ in magnitude and to ± 0.3° in phase for these simulations, which corresponds to the operational values of the S-DALINAC control system [11]. Beside an isochronous working point there exist areas of a reduced energy spread. The minimum has been determined to $D_\mathrm{L} = -1.5$ mm/% and $\Phi_\mathrm{S} = -9.5°$. On the right side a bunch of 5000 particle has been tracked through the linac using these optimized parameters. The particles perform a half oscillation in longitudinal phase space ending up on a reduced energy spread through cancelling out the RF jitters of the main linac. [10]

The usability of a non-isochronous recirculation scheme at the S-DALINAC has been investigated already through several numerical simulations [7-10] like the ones given in Fig. 3 and verified experimentally as well [10]. The optimum parameters of the new longitudinal working point for the twice recirculating layout have been determined to D_L = -1.5 mm/% and to Φ_S = -9.5° respectively and lead to a reduction of the rms energy spread to $\Delta E/E = 6.03 \cdot 10^{-5}$ in simulations which satisfies the requirements mentioned above very well.

OPERATIONAL STABILITY ON THE NEW WORKING POINT

The compensation of the RF jitters using non-isochronous beam dynamics can be illustrated best assuming one linac cavity running out of control (see Fig. 4). With the isochronous operation mode the energy spread increases rapidly, while the non-isochronous beam dynamics manage to compensate the errors almost completely. This calculation fits very well to the operational experience gained at S-DALINAC during the last few years. Using non-isochronous working points the accelerator runs much more stable and reliable.

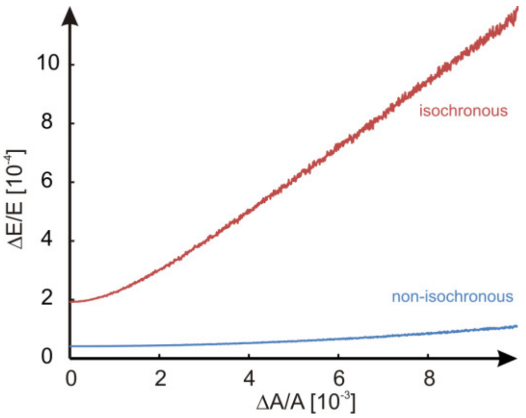

Figure 4: Dependence of the rms energy spread after 3 linac passes from a magnitude error of one single linac cavity, while all remaining cavities stayed at a 10^{-4} error level. When cavity control gets worse the energy spread in isochronous mode is strongly affected while in non-isochronous mode the error can be compensated.

MEASUREMENT OF THE ENERGY SPREAD

The presented beam dynamics simulations [7-10] as well as optimizations on the recirculation optics [8-10] and an improved beam diagnostics [12] allowed to operate the accelerator on its new non-isochronous working point successfully. In order to investigate the energy resolution of the beam an electron scattering experiment on a thin gold target has been performed. The beam energy has been 75 MeV. The measured line-width (*FWHM*) depends on three statistically independent errors: the contributions of the energy straggeling inside the target (1 keV), the resolution of the spectrometer system (22.5 keV) and finally the contribution of the energy spread of the electron beam. So the total linewidth measured at the spectrometer calculates like:

$$\Delta E_{total}^{\;2} = \Delta E_{target}^{\;2} + \Delta E_{spectrometer}^{\;2} + \Delta E_{beam}^{\;2}$$

The obtained data is shown in Fig. 5. The total energy spread could be reduced from $\Delta E \approx$ 120 keV in the isochronous mode to $\Delta E \approx$ 30 keV in the non-isochronous mode which corresponds to beam contributions (*FWHM*) of 117 keV (isochronous) and 21.5 keV (non-isochronous). Both spectra have been measured for the same run-time of 30 minutes until the same amount of statistics (integrated counts in peak) has been collected. The improved energy spread on the non-isochronous working point results in a smaller width and an increased height of the peak. Both measures are of great importance for precision nuclear physics experiments carried out at S-DALINAC.

SUMMARY AND OUTLOOK

Using non-isochronous recirculation can reduce the energy spread of the electron beam in few-turn recirculators significantly. In addition the operational stability on such a working point is improved with respect to operation on an isochronous working point with acceleration on crest. In future additional experiments are planned to systematically investigate the effect of different longitudinal working points for the S-DALINAC with 3 recirculations and 4 linac passes on the energy spread and compare the data with similar simulations like shown in Fig. 3.

In addition, the concept of using a non-isochronous working point to reduce the energy spread of multi-pass linacs might be interesting in ERLs as well. But here the applicability of the concept needs to be investigated carefully in future because of the decreasing efficiency of energy recovery at off crest acceleration.

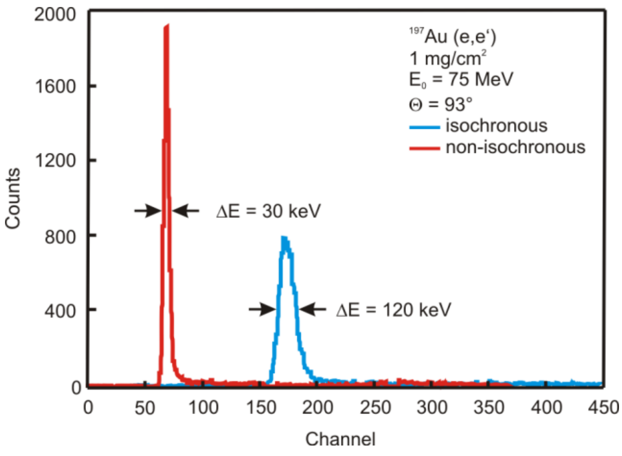

Figure 5: Energy spread of the beam obtained by elastic scattering on a thin gold target. Blue: isochronous; Red: non-isochronous recirculation. For better visibility the blue spectrum has been shifted in horizontal direction.

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