APPLICATION OF NON-ISOCHRONOUS BEAM DYNAMICS IN ERLS FOR IMPROVING ENERGY SPREAD AND BEAM STABILITY*

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Abstract

Non-isochronous recirculation is the common operation mode for synchrotrons or microtrons. In such a non-isochronous recirculation scheme the recirculation paths provide a non-zero longitudinal dispersion while the accelerating field is operated at a certain phase off-crest with respect to the maximum. In few turn linacs like ERLs and in microtrons non-isochronous beam dynamics can be used to reduce the energy spread by cancelling out any rf-jitters coming from the linac cavities. To do so the longitudinal phase advance needs to be tuned to a half-integer number of oscillations in longitudinal phase space. Then the total energy spread after main linac acceleration conserves 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. Such concept provides an inherent beam stability and has been introduced many years ago [1,2] and proven to work successfully in a few-turn recirculator already [3]. We will present beam dynamics calculations for the application of nonisochronous beam dynamics in single- and multi-turn energy recovery linacs at different longitudinal working points.

INTRODUCTION

Short recirculating electron linacs and in particular energy recovering linacs (ERLs) are operated with an accelerating phase in a way that electrons are accelerated in the maximum of the accelerating field (on crest). In few-turn recirculators with on crest acceleration the electrons are accelerated in the maximum of the accelerating field 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. It is reached when electrons of different energies need the same time of flight through the optics ($\mathrm{d}t/\mathrm{d}E = 0$). This can be described using the momentum compaction factor of the recirculating lattice. In the special case of ultra-relativistic electrons ($v \approx c$) isochronicity is achieved when the path length of all electrons is equally long ($\mathrm{d}l/\mathrm{d}E = 0$) independent from their energy. Usually amplitude and phase jitters of the accelerating cavities are not correlated so the resulting energy spread is mainly determined by the short bunch length for an electron linac operated on crest. In the special case of a superconducting few-turn linac, like most ERLs are, the RF jitters can add up coherently throughout the small number of linac passages. As a result every electron experiences the same errors in every pass through the linac. The reason is the large time constant of field variations in the superconducting accelerating cavities compared to the short time of flight of the ultra relativistic electrons through the accelerator.

This adding up can be overcome by changing the longitudinal working point to a non-isochronous one. This operation mode is the only stable one for accelerators with many revolutions like synchrotrons or microtrons. On a non-isochronous longitudinal working point the

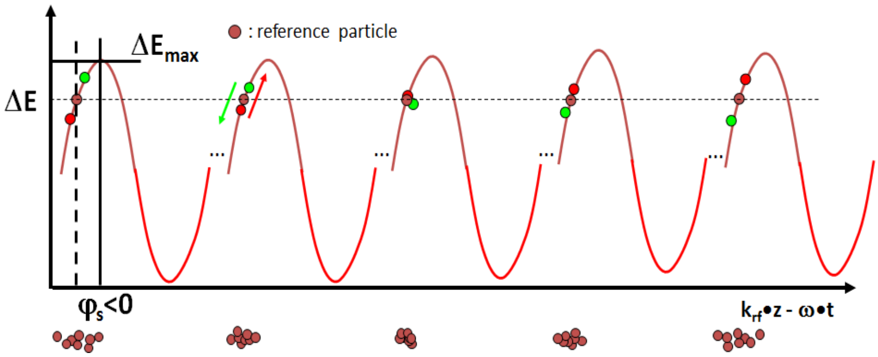

Figure 1: Illustration of synchrotron oscillations of electrons on a non-isochronous working point in a five-pass recirculating linac [4]. The particles perform exactly a half synchrotron oscillation throughout the acceleration process. It can be seen that the particles in front and back of the bunch 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. [5]

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recirculation paths provide a certain longitudinal dispersion $\mathrm{d}l/\mathrm{d}E = D_L \neq 0$ while the accelerating field is operated at a synchrotron phase $\Phi_S \neq 0$ (off crest) with respect to the maximum of the accelerating field. During the different turns the electrons perform synchrotron oscillations in the longitudinal phase space. 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 [1,2]. This concept has been tested successfully in a three pass superconducting linac reducing its energy spread and enhancing its stability [3,5]

Figure 1 illustrates this error cancellation on a half-integer longitudinal phase advance through an example given for a five-pass linac. [5]

WORKING POINTS FOR MESA

The MESA accelerator under construction at Johannes Gutenberg-Universität Mainz [6] will be a superconducting recirculating linac running in two completely different operation modes, an external beam mode and a multi-turn ERL mode. It has a double sided layout with vertical beam separation and vertically stacked return arcs.

Using the external beam mode the polarized electrons can be accelerated to a maximum energy of 155 MeV and to a maximum beam current of 150 µA in three passes through each linac module. In ERL mode maximum beam energy of 105 MeV and maximum beam current of 1 mA are planned using each cryomodule two times for acceleration and deceleration. In a later construction stage of MESA this beam current shall be increased to a maximum of 10 mA.

External Beam Mode

In external beam mode a non-isochronous recirculation scheme is planned for operation. For finding the optimum pair of the parameters D_L and Φ_S tracking simulations using a matrix code like presented in [7] have been performed with the MESA layout. According to the problem given above the two parameters D_L and Φ_S were varied independently and the beam was tracked through the complete acceleration process calculating new energies and longitudinal poitions for every electron after each acceleration or recirculation step. The input electron distribution has been taken from [8]. At the end of every iteration step the resulting RMS energy spread of the extracted beam was calculated. The result of this simulation, a hill plot of the resulting energy spread with respect to the varied parameters, is shown in Fig. 2, revealing areas of improved energy spread beside the isochronous longitudinal working point. A closer look on the acceleration process reveals that the bunch performed a half synchrotron oscillation throughout the acceleration process. The optimized working point for the external beam mode yields to a relative energy spread of $\Delta E_{rms}/E = 5.5 \cdot 10^{-5}$ (isochronous: $\Delta E_{rms}/E = 3.4 \cdot 10^{-4}$) when setting the parameters to $D_L = -2.6$ mm/% and $\Phi_S = -5.8°$.

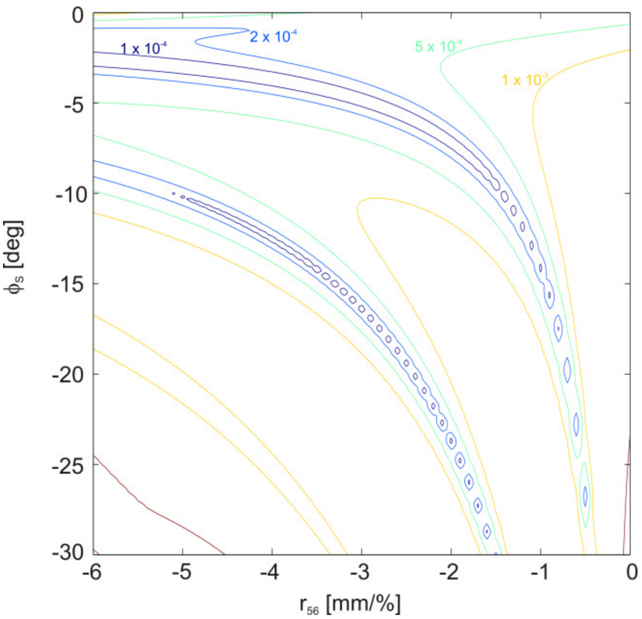

Figure 2: Hillplot of the resulting energy spread at extraction for different sets of longitudinal dispersion and synchrotron phase. The contours mark lines of equal height. Within the dark blue curves the minimum of the energy spread can be determined to $D_L = -2.6$ mm/% and $\Phi_S = -5.8°$.

ERL Mode

In ERL mode the decelerating bunches are needed to provide sufficient RF power for the accelerating ones. So a recirculating scheme with acceleration off crest can result in a huge loss of recovering efficiency as the decelerated bunches excite an RF wave with wrong phase and magnitude with respect to the desired one (see Fig. 3). This results in an additional need of RF power. For that reason for MESA the beamline will be constructed in a way that it allows isochronous and non-isochronous operation. The injector simulations at 1 mA beam current (bunch charge 0.77 pC) show a rather filamented longitudinal phase space and long bunches [8]. Therefore the injector has been optimized for either best energy spread or shortest bunch length [8]. Using an isochronous operation point with on crest acceleration for the ERL mode the resulting energy spread at the experiment is mainly determined by the bunch length of the injector beam. An energy spread of $\Delta E_{rms}/E = 7.2 \cdot 10^{-4}$ has been calculated using the injector beam optimized for best energy spread at 5 MeV injection energy. This value can be improved a lot to $\Delta E_{rms}/E = 1.99 \cdot 10^{-4}$ using the short bunch setting in isochronous mode.

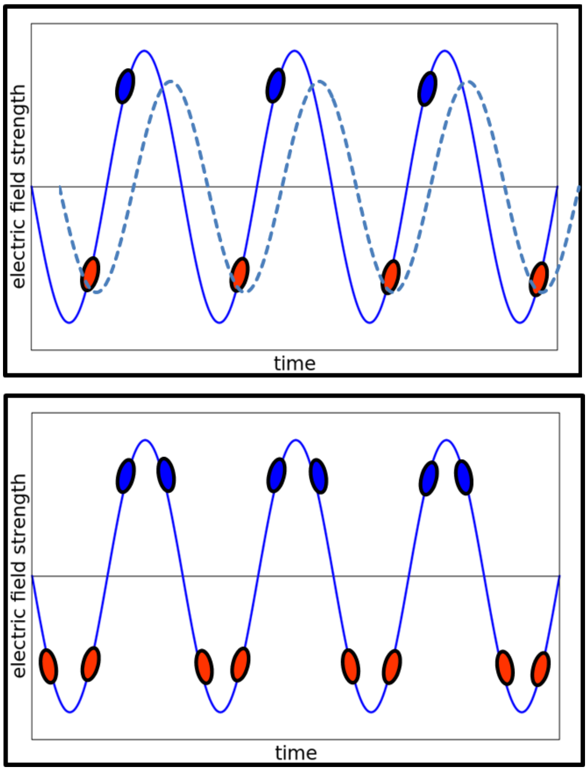

Figure 3: Bunches in two different ERL operation modes. The accelerated bunches are plotted in blue, the decelerating bunches in red. In the common mode like used in forward recirculation without energy recovery (upper part) the decelerated electrons would excite an RF wave with wrong phase and magnitude resulting in a high demand of RF power to compensate. The lower part of the figure shows the reflecting non-isochronous ERL operation mode with acceleration and deceleration on either side of the accelerating/decelerating field. Here the excited wave is in phase with the required one.

The double sided layout of the MESA accelerator with two acceleration linacs allows another non-isochronous operation mode for ERLs. As the total number of linac passes and recirculation arcs each add up to a number of four the phase space can be rotated half way throughout the first two linac passes already. The second two linac passes then can be used to rotate the phase space back to its initial orientation by using the other edge of the acceleration field and another sign of longitudinal dispersion. This acceleration scheme allows to benefit from the stabilization as mentioned above [1,2] but also distribute two bunches on each edge of the accelerating field in acceleration and as well in deceleration (see Fig. 3). The additional RF power for ERL operation is only needed to compensate the additional dynamic losses of the RF cavities. In first results of the tracking simulations the energy spread could be improved to $\Delta E_{rms}/E = 8.9 \cdot 10^{-5}$. The parameters for the best setting have been calculated to $D_{L\_1st} = +1.55$ mm/%, $D_{L\_2nd} = 0$ mm/% and $D_{L\_3rd} = -6.45$ mm/% at a synchronous phase of $\Phi_S = \pm 8.3°$.

SUMMARY AND OUTLOOK

Using non-isochronous recirculation can reduce the energy spread of the electron beam in few-turn recirculators significantly. For MESA such an operation mode is planned for the external beam and under investigation for the ERL mode. In ERL mode the presented reflecting longitudinal beam dynamics show promising first results but need to be investigated more precisely in the future.

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