ENERGY STABILITY OF ERLS AND RECIRCULATING LINACS

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Abstract

Energy recovery linacs can be seen as a hybrid between a linear and a circular accelerator. It has been shown in the past that an appropriate choice of the longitudinal working point can significantly improve the energy stability of a recirculating linac. In this contribution we will expand the concept of energy recovery linacs and investigate the energy spread of the beam as well as the recovery efficiency stability which can be a more demanding quantity in a high current ERL.

INTRODUCTION

The principle of phase focusing in longitudinal phase space is well known and essential for the operation of circular machines like synchrotrons and storage rings. It is also applied in low and medium beta linear accelerators. However with high beta linacs, the acceleration of the particles is usually done on-crest.

Recirculating linacs and energy recovery linacs usually also use on-crest acceleration with a beam transport system tuned to isochronisity. In that case, the machine has no inherent longitudinal stability, and as a result the bunch length and the stability of the RF field inside the accelerating cavities determine the energy spread of the beam.

As pointed out earlier for recirculating linacs [1,2], the choice of an off-crest synchronous phase together with a non-isochronous beam transport system can offer a longitudinal stability, thus reducing the effects of amplitude and phase jitter of the accelerating cavities in the linac. We will apply this concept to energy recovery linacs and also investigate the role of path length variations that may be caused by thermal drifts.

LONGITUDINAL TRACKING

Concept

For our simulations we assumed a particle distribution entering a linac at low energy. This beam is assumed to be accelerated 5 times and decelerated again. The linac is modelled to have several cavities operated and powered individually at a certain gradient and at a given synchronous phase, which we define with respect to the maximum field. Each cavity is assumed to have a certain field stability in terms of amplitude and phase jitter. The recirculation arcs are represented by their longitudinal dispersion and are assumed to have an integer (half integer for the highest energy arc before the beam is decelerated again) wavelength. For some of the simulations, a random error to the path length was added to simulate thermal effects. Figure 1 gives a layout of the machine scenario.

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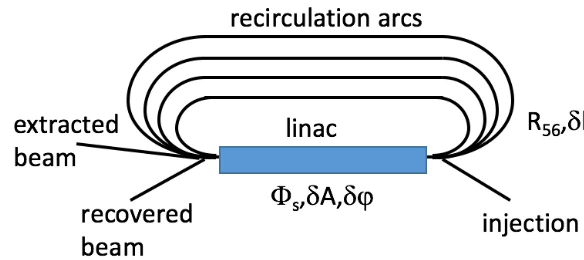

Figure 1: Recirculating linac/energy recovery linac scenario calculated within this paper. R_{56} and Φ_S are the parameters under which the linac and the arcs are operated. δA and δφ are the jitters that are applied to the cavity fields and δl is the random path length variation.

The particle bunch was tracked through the machine within an “inner” calculation loop. This sent a single particle bunch through a simulated linac for N passes. We used an “outer” calculation loop to reiterate the “inner” loop with randomized jitters in the cavity field as well as in path length variation. Every data point given represents the outcome of the outer loop calculation, which is an overlay of all phase space distributions. It represents the beam properties to be expected when accelerating many bunches. Our code was programmed in Python® to assure quick execution. All parameters are easy to change, and a reference (“ideal”) particle is tracked to ensure consistency. We also benchmarked our code by reproducing results from earlier calculations.

Parameters

We ran our simulations using realistic parameters and a configuration planned for the C-BETA project [3]. The injection energy in this case is 6 MeV, the energy spread was assumed to be 10^{-3} and the phase spread to be 0.5°. We represented the beam by 1000 particles with Gaussian distributions in energy and phase.

The linac in the case of the C-BETA linac houses six cavities, oscillating at 1.3 GHz and providing a gradient of 6 MV. Random errors for the phase between ±0.5° and for the amplitude between $\pm 10^{-4}$ were assumed. For every inner loop a constant but different amplitude and phase error was allotted to every cavity. This is due to the fact that the fluctuations of the field are typically driven by microphonics and occur on the time scale of milliseconds or more, while the accelerated beam passes through the machine in some 100 microseconds or less. For calculations with path length variations, we assumed individual contributions for every recirculation, being constant within the inner loop. In the outer loop, field errors and path length contributions were re-assigned and the resulting phase space can be seen as an average over a period of several seconds (or several hours in case of the thermal drift calculation).

RECIRCULATING LINAC

We assumed the machine depicted in fig. 1 being operated as a recirculating linac and the beam being extracted after 5 linac passes. The usual operation for such a machine is to tune the recirculations to isochronisity and have the particle accelerated on-crest.

RF Errors Only

As a first step to investigate the stability of the beam parameters of the extracted beam we assumed amplitude (10^{-4}) and phase (0.5°) jitters for the cavities inside the linac. We then calculated the energy spread of the extracted beam as a function of the parameters longitudinal dispersion (r_{56}) and synchronous phase (Φ_S). The result is plotted in fig. 2. We found that a reduction in the energy spread by more than a factor of 2 can be achieved if a non-isochronous longitudinal working point is chosen. The optimum point, however, is on the second "annihilation" resonance. Similar results have been published before and have been confirmed experimentally [4].

The benefit can be even greater if the RF control is less stable. Choosing a longitudinal working point can also be a measure to relax RF control requirement which might be very demanding for high Q_L cavities.

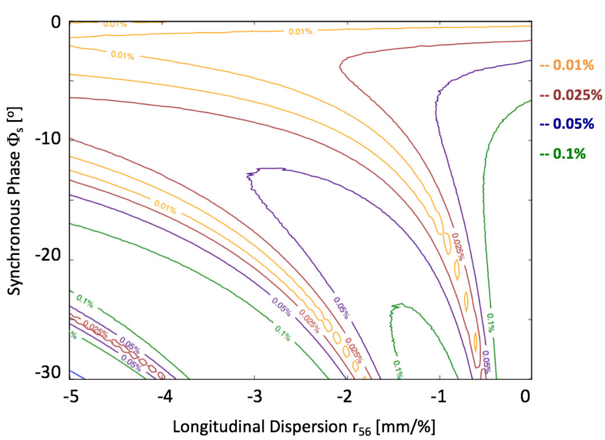

Figure 2: Hill plot of the energy spread as a function of longitudinal dispersion and synchronous phase after 5 linac accelerations. The lowest energy spread is $3.9{\cdot}10^{-5}$ for r_{56}=-3.4 mm/% and Φ_S=-17.1°, more than a factor of 2 in reduction compared to $8.3{\cdot}10^{-5}$ for the isochronous/ on-crest case (r_{56}=0 mm/%, Φ_S=0°).

RF Errors and Path Length Variations

Driven by the idea that a longitudinal working point offers stability against phase variations of the RF cavities we started investigating reinjection phase variations. These reinjection phase variations can be caused by thermal drifts in the recirculations, increasing or decreasing the total length of the path. Making no specific assumption on the reason for this path length variation which in

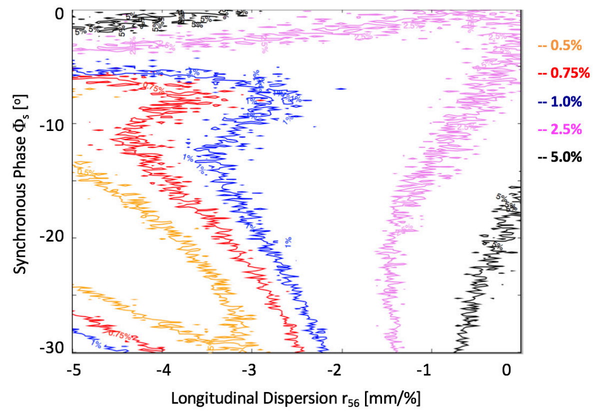

Figure 3: Hill plots of the energy spread as a function of r_{56} and Φ_S. This calculation was performed applying RF jitters and random path length variations between ±5 mm.

practice can be caused by steering drifts or by expansion/ shrinkage of the whole machine, we assumed 3 scenarios of a random change of the path length between ±1, ±5 or ±10 mm, individually allotted to each recirculation path and treated as uncorrelated. Again, variations were reassigned in the outer-loop calculation. Results as shown in fig. 3 can be seen as long time stability of the beam parameters. We found that for a 5 mm variation of the path-length, going from the isochronous operation to the optimum longitudinal tune (r_{56}=-4.9 mm/% and Φ_S=-19°) can reduce the energy spread by almost a factor of 10 (from $2.3 \cdot 10^{-2}$ to $2.82 \cdot 10^{-3}$).

Table 1 summarizes our findings and compares the optimum longitudinal working point to the isochronous. As one can see for larger path length variations non-isochronous operation becomes more favourable.

Table 1: Calculated energy spread for different values of random path length variations, given for the optimum longitudinal working point (r_{56},Φ_s), compared to isochronous/ on-crest.

δl [mm]	r_{56} [mm/%]	Φ_S [°]	σ_E (opt.)	σ_E (iso.)
1	- 4.3	- 1.4	$6.51 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
5	- 4.9	- 19.0	$2.82 \cdot 10^{-3}$	$2.3 \cdot 10^{-2}$
10	- 4.8	- 20.6	$4.40 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$

ENERGY RECOVERY CALCULATION

For an energy recovery linac, the energy spread of the accelerated beam might not be of so much interest, and experiments or the user of the beam may accept a slightly higher energy spread. However, longitudinal stability might be of paramount importance as the machine itself needs to be highly efficient in recovering the beam energy, or it will run out of RF power in the linac section. For C-BETA we calculated that the required energy recovery efficiency might be as high as 99.9 %. The JLAB FEL had a similar figure of 99.5 %, where it has been found

ISBN 978-3-95450-169-4

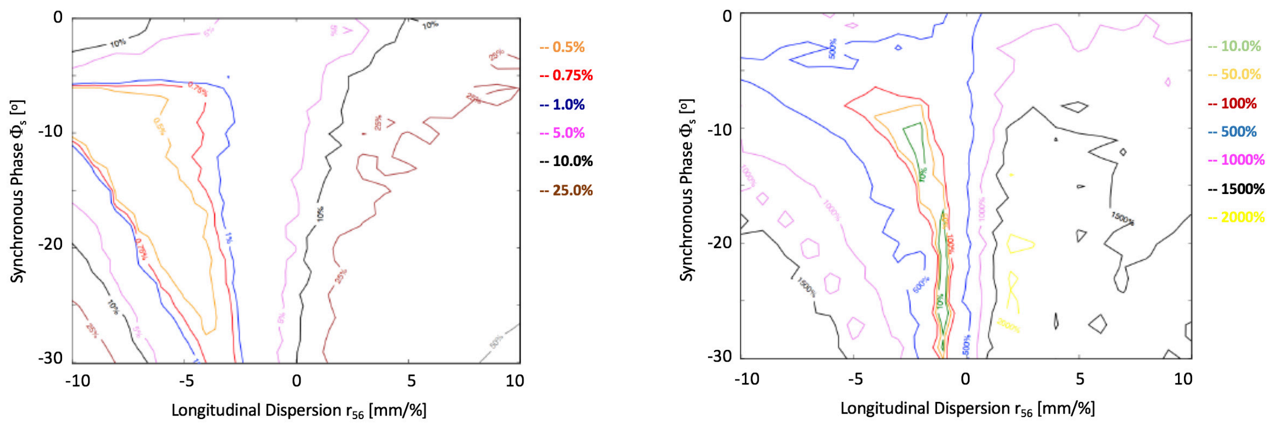

Figure 4, left: energy spread of the highest energy beam as a function of the longitudinal working point assuming only path length variations of 5 mm. Right: energy deviation from the injection energy after energy recovery. A 0% deviation means full energy recovery. This plot indicates that a working point which is minimizing the energy spread at full energy leads to poor energy recovery efficiency and vice versa.

that adjusting and keeping the recirculation path length is a critical quantity [5].

In the following calculations we will therefore focus on the average energy the beam will have after deceleration. To understand the role of path length variations we ran our calculations with the RF jitter turned off. Results are given in Fig. 4 for a 5 mm path length variation. As can be seen, having a small energy spread of the accelerated beam and achieving full energy recovery are conflicting goals: longitudinal tunes which help the beam on acceleration to stay compact in phase space lead to an extensive smear-out on deceleration.

However, our simulations reveal quite interesting results: if left uncompensated, an isochronous machine with a 5 mm path length variation leads to a decelerated beam with an average (calculated) energy of ~36 MeV. In reality this would exceed the momentum acceptance of the machine and result in a complete beam loss.

Again, choosing an appropriate longitudinal working point improves the stability of the machine dramatically.

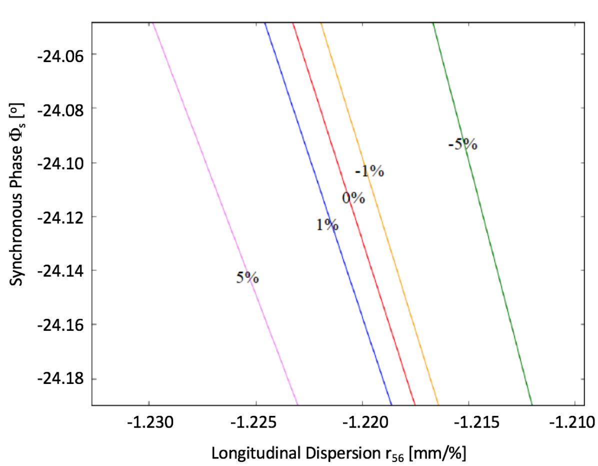

Figure 5: Magnified region of fig. 4 (right) indicating a line of perfect energy recovery (0% energy deviation). By slight variation of the synchronous phase one is able to find optimum performance.

Figure 5 shows a magnification of the small energy deviation region of fig. 4 (right). It reveals the existence of a contour of full energy recovery, even with the 5 mm path length variation. In conclusion, this means a longitudinal tune is also able to stabilize an energy recovery linac against thermal drifts.

SUMMARY

We have expanded the concept of non-isochronous recirculation to energy recovery linacs. Our calculations focused on energy recovery efficiency, the role of path length variations and measures to compensate them passively by the choice of the tune. We demonstrated that there is always a better longitudinal tune than the isochronous/on-crest working point, depending on the details of the machine and the target quantity.

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