

MOMENT-BASED SIMULATION OF THE S-DALINAC RECIRCULATIONS*

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Abstract

In this paper an outline of the numerical model and the implementation of the moment-based beam dynamics simulation tool V-Code is presented together with new simulation results regarding the S-DALINAC recirculations. These simulations demonstrate the applicability of the V-Code to properly reproduce the recirculating layout including the longitudinal beam dynamics within the dispersive sections.

INTRODUCTION

The recirculating Superconducting Darmstadt Linear Accelerator S-DALINAC, installed at the institute for nuclear physics (IKP) at the Technische Universität Darmstadt, consists of a 10 MeV injector and a 40 MeV linac. Utilizing two recirculations, the linac can be used up to three times, allowing nuclear- and astrophysical experiments with electron beams in an energy range from 1 up to 130 MeV. During operation phase- and amplitude-jitters of the accelerating field within the cavities can be observed. As these field variations occur relatively slow compared to the cycle duration a certain particle realizes the same error in each of its passes through the main linac.

So far, the acceleration of the particles within the main linac section is done on crest of the accelerating electric field of the 8 superconducting cavities. Together with an isochronous recirculation scheme, where every particle has the same revolution time L independent of its energy, the field errors coherently add up throughout the three main linac passages. This results in a undesired increase of the energy spread.

In order to reduce the energy spread caused by the observed phase- and amplitude-jitters a new non-isochronous recirculation scheme is currently being investigated at the IKP. This scheme utilizes longitudinal dispersion D_L in the recirculation paths together with an off-crest acceleration as it is done for example in microtrons.

The intended longitudinal dispersion leads to the fact that particles with higher energy re-enter the LINAC earlier, whereas particles with lower energy re-enter the LINAC later. In [1] a phase shift of 7.5 degree and a longitudinal dispersion of -1.5 mm/% were found to be an optimal working point for the two S-DALINAC recirculations. Under these conditions the effects of the phase- and amplitude jitters on the energy spread can almost be compensated.

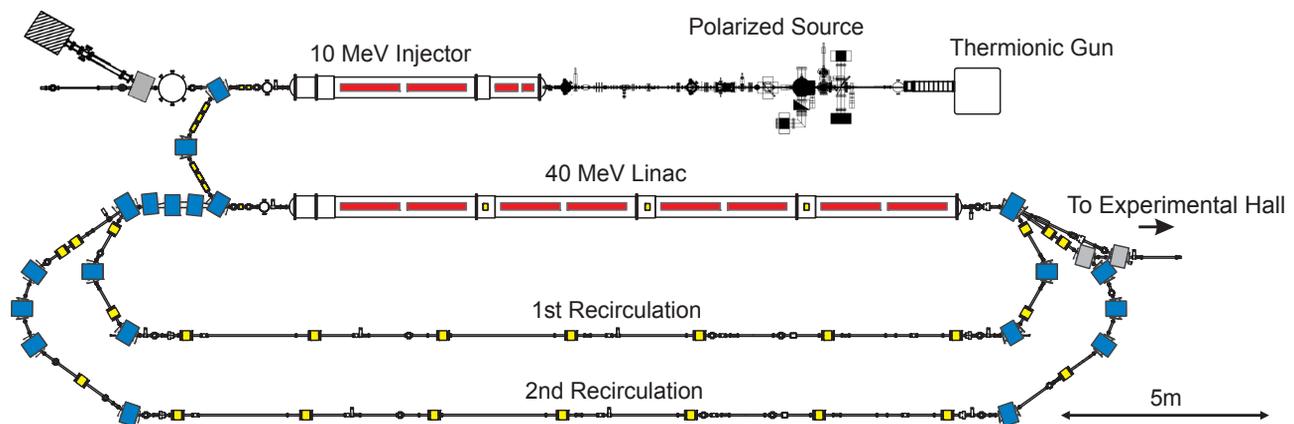


Figure 1: Schematic representation of the Superconducting Darmstadt Linear Accelerator S-DALINAC.

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After several modifications in the layout of the bends, presented in [2], the longitudinal dispersion can be set independently within each bend of the recirculation paths via a simultaneous variation of the gradients G of the installed quadrupoles.

The length of the beamline and the numerous accelerating structures as well as dipole and quadrupole magnets require a highly efficient numerical simulation tool in order to assist the operators by providing a detailed and almost instantaneous insight into the actual machine status. A suitable approach which enables a fast online calculation of the beam dynamics is given by the so-called moment approach where the particle distribution is represented by means of a discrete set of moments or by multiple discrete sets of moments in a multi-ensemble environment. Following this approach the V-Code simulation tool has been implemented at the Computational Electromagnetics Laboratory (TEMF) at Technische Universität Darmstadt.

MOMENT-BASED SIMULATION

The moment approach to beam dynamics [3, 4, 5] consists in representing the particle distribution function f in the 6-dimensional phase space Ω spanned by the Cartesian coordinates x, y, z and the momentums p_x, p_y, p_z by a discrete set of characteristic moments.

These moments are obtained by a weighted integration over the whole phase space

$$\langle \mu \rangle = \int_{\Omega} \mu f(\vec{r}, \vec{p}, \tau) d\Omega. \quad (1)$$

A numerically advantageous choice is given by utilizing the first order raw moments $\mu \in \{x, y, z, p_x, p_y, p_z\}$ together with the centralized moments

$$\mu \in \{(x - \langle x \rangle)^{l_1} \cdot \dots \cdot (p_z - \langle p_z \rangle)^{l_6}, \dots\}$$

for the higher orders $n = l_1 + \dots + l_6 \in \mathbb{N}, n \geq 2$.

With the help of the Vlasov equation a time evolution equation can be stated for each moment. The resulting set of ordinary differential equations can be evaluated efficiently with standard time integration methods if suitable initial conditions are given and all essential external forces are known [6].

These forces can be determined if the electric field strength and the magnetic flux density are known at any position within the beam line. In the vicinity of the particle distribution a numerically useful way to provide all external field components is given by a paraxial multipole series expansion of the external fields.

In order to apply this approach to a long accelerator beamline it is useful especially in terms of an efficient memory consumption to represent the beamline as a consecutive chain of several independent beamline elements along a straight axis z . Drift spaces between beam forming elements are represented by beamline elements which are free of external electromagnetic fields. Within bending magnets a reference path has to be settled. This path defines the length of the magnet along the projected axis z . The actual bunch position is then determined via a normal projection onto the reference path [7].

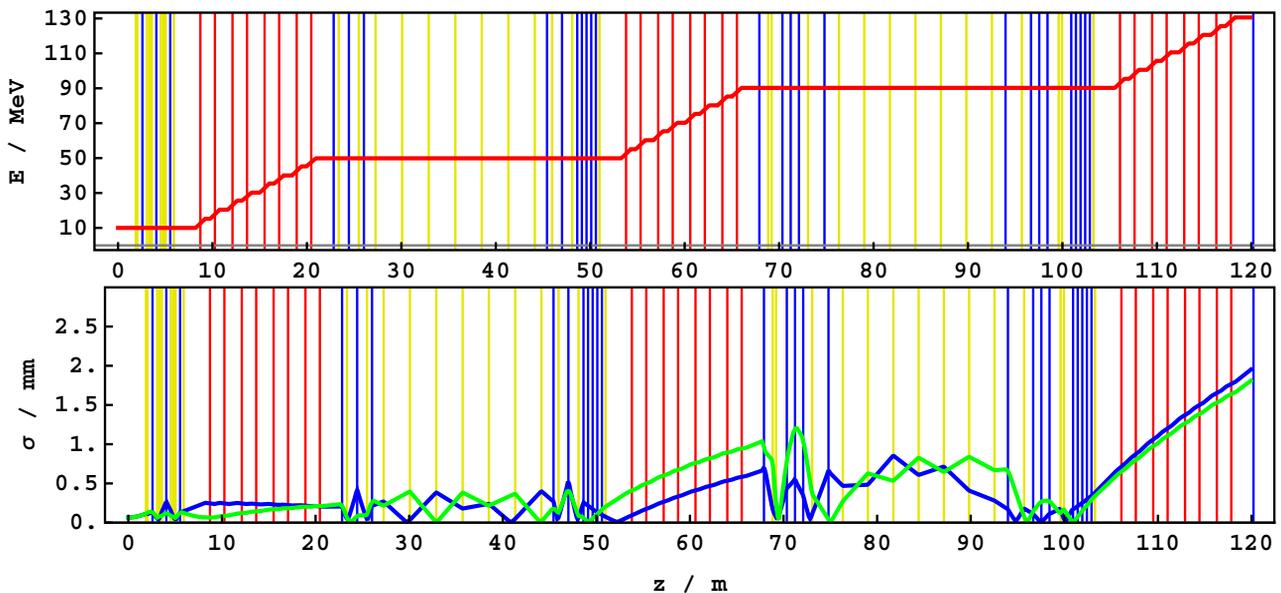


Figure 2: V-Code simulation of the bunch energy (red) and the horizontal (blue) and vertical (green) bunch dimensions within the S-DALINAC recirculating layout. The simulation was initiated right after the injector and the corresponding 10 MeV bunch was then accelerated three times within the 40 MeV main linac. The thin vertical lines mark the positions of the quadrupole magnets (yellow), of the dipole magnets (blue) and of the superconducting cavities (red).

APPLICATION

In [8] the implementation of new features enabling the simulation of the recirculation sections has been presented together with simulation results of the first recirculation path. Following this work the field distribution along the reference paths of the remaining dipoles and the quadrupole strength along the axis within the remaining quadrupoles were extracted from field calculations with the magnetostatic solvers included in CST PARTICLE STUDIO [9].

In Fig. 2 simulation results for the first and second S-DALINAC recirculation path are displayed. One can observe that the particle bunch is properly transported through the beamline of the two recirculations and accurately matches the accelerating phase of the cavities on the three passages through the main linac. The results for this 121 m long section of the S-DALINAC beamline was calculated in approximately 2.6 seconds on a single core of a 2.4 GHz Intel Xeon CPU considering first and second order moments and applying a third order Runge-Kutta time integration method with a step size of 1 mm.

In order to proof the applicability of the V-Code to calculate the longitudinal dispersion within the S-DALINAC recirculations, two point like bunches with slightly different energies were tracked through the first bending arc of the first recirculation. The longitudinal dispersion was then calculating from the difference of the traveling time of the two bunches. In order to accurately resolve these time differences a sufficiently small step size for the integration method is required.

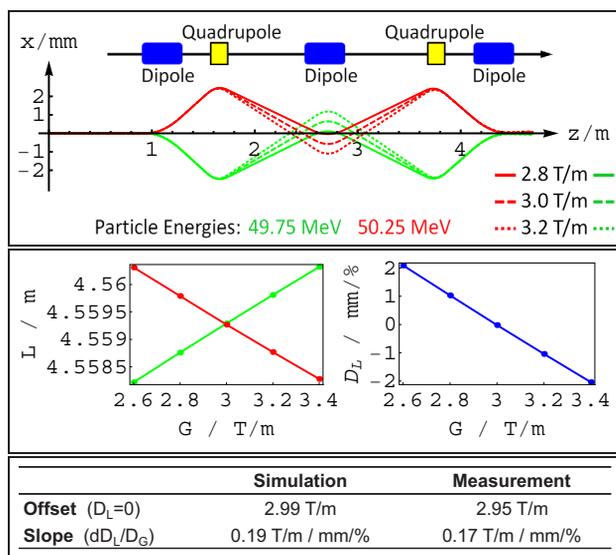


Figure 3: V-Code simulation results of the first bending arc of the first S-DALINAC recirculation.

CONCLUSION

In Fig. 3 the V-Code simulation results for the first bend of the first S-DALINAC recirculation are displayed. The simulations confirm that the longitudinal dispersion of the beam can be tuned via a simultaneous variation of the two quadrupole gradients and are in very good agreement with the measurements of the longitudinal dispersion published in [10].

Moment-based simulations are able to provide a detailed insight into the beam dynamics of recirculating accelerators and in particular of the dispersive sections.

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