

# FURTHER DEVELOPMENT OF THE V-CODE FOR RECIRCULATING LINEAR ACCELERATOR SIMULATIONS\*

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## Abstract

The recirculating Superconducting Darmstadt Linear Accelerator S-DALINAC, installed at the institute for nuclear physics (IKP) at the TU Darmstadt, consists of a 10 MeV injector and a 40 MeV linac. Utilizing two recirculations, the linac can be used up to three times, leading to a maximum energy for nuclear physics experiments of 130 MeV. In this paper the further developments of the moment based simulation tool V-Code enabling it to simulate recirculating machines are presented along with simulation results of the first recirculation of the S-DALINAC.

## INTRODUCTION

The Superconducting Darmstadt Linear Accelerator S-DALINAC is designed to allow nuclear- and astrophysical experiments with electron beams in an energy range from 1 up to 130 MeV and with low beam currents up to  $60 \mu\text{A}$ . The electrons are emitted from a 250 keV thermionic gun or from a new 100 keV spin-polarized electron source that is currently installed. In order to prepare the particles for the acceleration with superconducting cavities the beam is bunched in the chopper and prebuncher section.

The bunches produced are first accelerated up to 10 MeV within the injector linac and then deflected by 180 degrees into the main linac. The main linac section is composed of 8 standard 20-cell cavities and can provide an energy gain of 40 MeV. Using the beam lines of the first and second recirculation shown in Fig. 1 the main linac can be passed up to three times, leading to a maximum bunch energy of 130 MeV.

This recirculating layout along with the few beam diagnostic instruments makes it pretty complicated to find an accurate setup for the various beam line elements. Fast online beam dynamics simulations can advantageously assist the operators because they provide a more detailed insight into the actual machine status.

The moment approach allows to implement a beam dynamics simulation tool that is much faster than classical beam dynamics simulation codes tracking numerous macro particles and at the same time more accurate than matrix based beam dynamics codes. In addition, the accuracy of a moment based code can be adapted continuously by considering higher order moments and by representing the particle distribution by several sets of moments each of them defining a subset of the particle distribution.

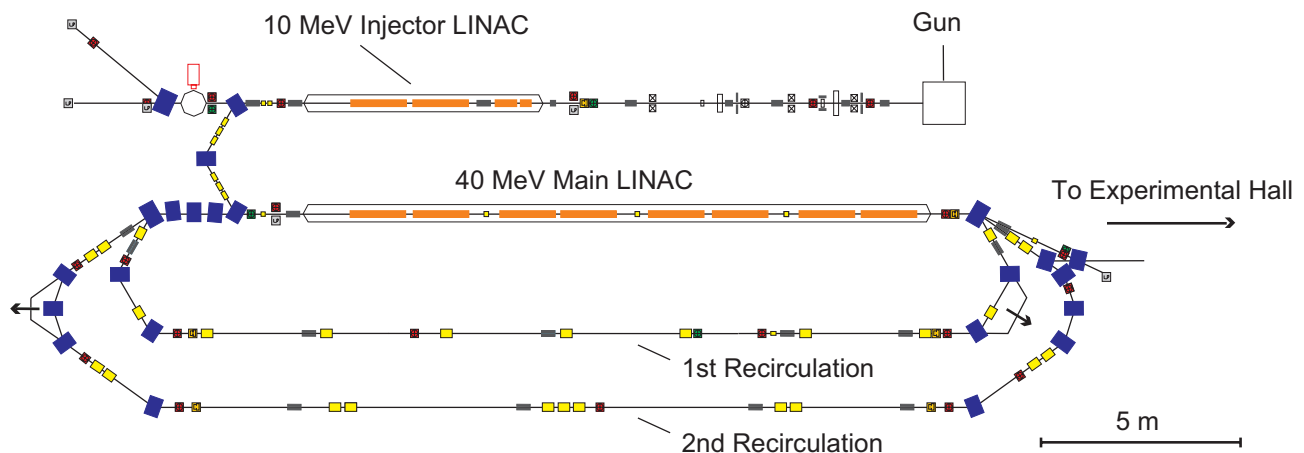


Figure 1: Schematic representation of the Superconducting Darmstadt Linear Accelerator S-DALINAC.

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## MOMENT APPROACH

The moment approach to beam dynamics consists in representing the particle distribution function  $f$  in the 6-dimensional phase space  $\Omega$  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 the first order raw moments  $\mu \in \{x, y, z, p_x, p_y, p_z\}$  and 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  $n = l_1 + \dots + l_6 \in \mathbb{N}, n \geq 2$ .

By this choice one automatically obtains the center of mass position and a translatory invariant description of the shape of the particle distribution function.

By means of the Vlasov equation a time evolution equation can be stated for each moment. Then, this set of ordinary differential equations can efficiently be evaluated with standard time integration methods if proper initial conditions are given and all essential external forces are known. These forces can be determined if the electric field strength and the magnetic flux density are known. 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. A more detailed description of the numerical model is given in [1] and [2].

## IMPLEMENTATION

Based on the moment approach the fast online beam dynamics simulation tool V-Code has been implemented and gradually extended at TEMF. One intention for this further development was to be able to simulate the entire beamline of the S-DALINAC, inclusively the two recirculations.

### Beamline Representation

Within V-Code an accelerator beamline is represented as a consecutive chain of several independent beam line elements along a straight axis  $z$ . In order to reproduce the recirculations a reference path has to be settled for the bending magnets. This path defines the length of the magnet along  $z$ . The actual bunch position is then determined via a normal projection onto the reference path. More details about the implementation of bending magnets in the V-Code are given in [3]. Drift spaces between beam forming elements are represented by beamline elements which are free of external electromagnetic fields.

### Path Length Adjustment

In order to match the path length of the recirculated beam with the phase of the accelerating fields inside the cavities the path length can be adjusted mechanically in the S-DALINAC beamline. This is done by extendable bows within the first and the second recirculation. Within V-Code this path length variation is implemented through drift spaces with a variable length placed in front of and behind the movable beamline elements.

### Repassed Beamline Elements

During the recirculations several beam line elements are passed multiple times by the beam. Within the V-Code beamline elements that are passed  $n$ -times are placed  $n$ -times along the beamline representation. Each of these virtual instances of the true beamline element have to be linked in order to provide parameter changes in one instance to the rest of them. Due to the fact that the particles have a different energy on each passage they are deflected on different trajectories. This implies that the different instances of a dipole bending magnet need to have different reference paths. An example of a dipole magnet with three different trajectories is shown in Fig. 2.

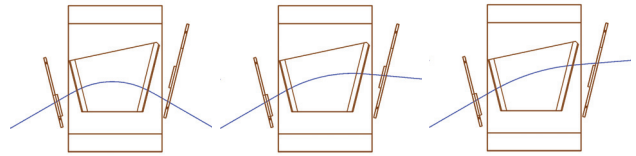


Figure 2: Computational model of one of the S-DALINAC dipole magnets. The magnet is passed three times during the recirculations and thus three reference paths are needed.

## SIMULATION

In order to simulate a beamline the exact setup of the machine has to be known. Therefore, the dimensions and the alignment of the dipole and quadrupole magnets in the two recirculations of the S-DALINAC beamline were measured. These measurements were used to state a V-Code input file and served to determine the reference paths and the field distribution within the magnets.

### Beamline Setup

The recirculations of the S-DALINAC are composed of eight standard 20-cell cavities, five types of quadrupole magnets with different effective lengths and five types of dipole bending magnets. The bending magnets are installed in different orientations and passed with different energies. This leads to 17 different reference path definitions for the dipole magnets.

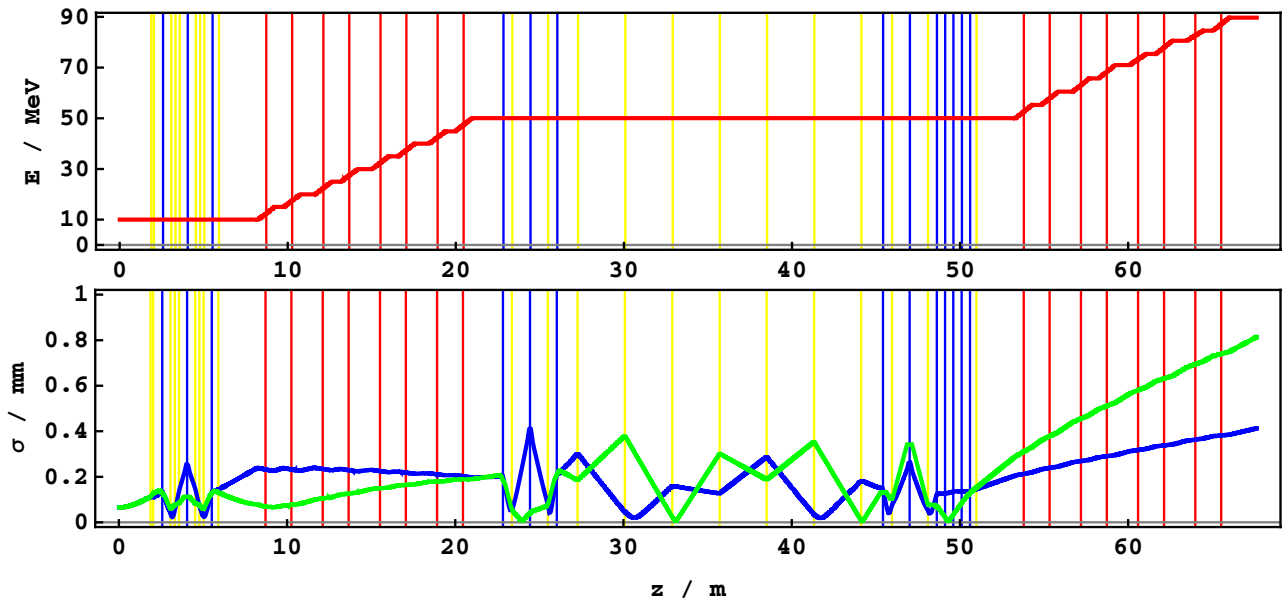


Figure 3: V-Code simulation of the bunch energy (red) and the horizontal (blue) and vertical (green) bunch dimensions inside the S-DALINAC. The simulation was started after the injector and the 10 MeV bunch was then accelerated two times within the 40 MeV main linac. The thin vertical lines mark the positions of the quadrupole magnets (yellow), of the dipole magnets (blue) and of the superconducting cavities (red).

Within the 20-cell cavities the field characteristics were already known from previous work [4]. The field distribution along the reference paths of the dipoles and the quadrupole strength along the axis within the quadrupoles were extracted from field calculations with the magneto-static solvers included in CST PARTICLE STUDIO [5].

### Initial Conditions

Within the S-DALINAC beamline no diagnostic device exists that is able to measure at one position all the bunch parameters required to initialize the V-Code properly. Therefore the simulations for this contribution were initialized with experience values from the operation of the S-DALINAC. The simulation was started after the injector section with a 10 MeV bunch with the following dimensions:  $\sigma_x = 0.060$  mm,  $\sigma_y = 0.060$  mm,  $\sigma_z = 0.014$  mm and a transversal bunch divergence of 0.1 mrad. For later application an end to end simulation would lead to more accurate bunch parameters.

### CONCLUSIONS

In Fig. 3 the simulation results calculated with the V-Code are shown. One can observe that the particle bunch is applicatively transported through the beamline of the first recirculation and properly matches the accelerating phase of the cavities on both passages through the main linac. Up to now the simulation ends after the second passage through the main linac section. But the V-Code beamline for the second recirculation of the S-DALINAC can be stated accordingly. The presented simulation results were calculated on a 3.06 GHz Xeon processor in approximately one second.

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