

INTEGRATION OF THE MOMENT-BASED BEAM-DYNAMICS SIMULATION TOOL V-CODE INTO THE S-DALINAC CONTROL SYSTEM*

Sylvain Franke**, Wolfgang Ackermann, Thomas Weiland,
TEMF, Technische Universität Darmstadt, Darmstadt, Germany

Ralf Eichhorn, Florian Hug, Christian Klose, Norbert Pietralla, Markus Platz
IKP, Technische Universität Darmstadt, Darmstadt, Germany

Abstract

Fast and accurate beam-dynamics simulation programs within accelerator control systems can advantageously assist the operators and provide a more detailed insight into the actual machine status. The V-Code simulation tool implemented at TEMF is a fast tracking code based on the moment approach. In this contribution an overview of the numerical model is presented together with implemented features for its dedicated integration into the control system of the superconducting linear accelerator S-DALINAC.

INTRODUCTION

The Superconducting Darmstadt Linear Accelerator S-DALINAC [1], installed at the institute for nuclear physics (IKP) at the Technische Universität Darmstadt is designed to allow nuclear- and astrophysical experiments with electron beams in an energy range from 1 MeV up to 130 MeV with beam currents up to $60 \mu\text{A}$. The electrons are emitted from a 250 keV thermionic gun or alternatively from a recently installed source for 100 keV spin-polarized electrons.

The beam is bunched in the chopper and prebuncher section in order to prepare the particles for the acceleration within the radio frequency cavities. The provided bunches are first accelerated up to 10 MeV within the injector linac and subsequently deflected by 180 degrees into the main linac. This main linac section is composed of 8 superconducting 20-cell cavities and is designed to provide an energy gain up to 40 MeV. The main linac can be passed up to three times using the beamlines of the first and second recirculation, leading to a maximum bunch energy of 130 MeV.

The layout for beam recirculation shown in Fig. 1 together with the few beam diagnostic instruments render it quite complicated to find optimum settings for the individual beamline elements. Fast online beam-dynamics simulations can 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 on the one hand much faster than classical beam-dynamics simulation codes which track numerous macro particles and on the other hand more accurate than matrix-based beam-dynamics codes.

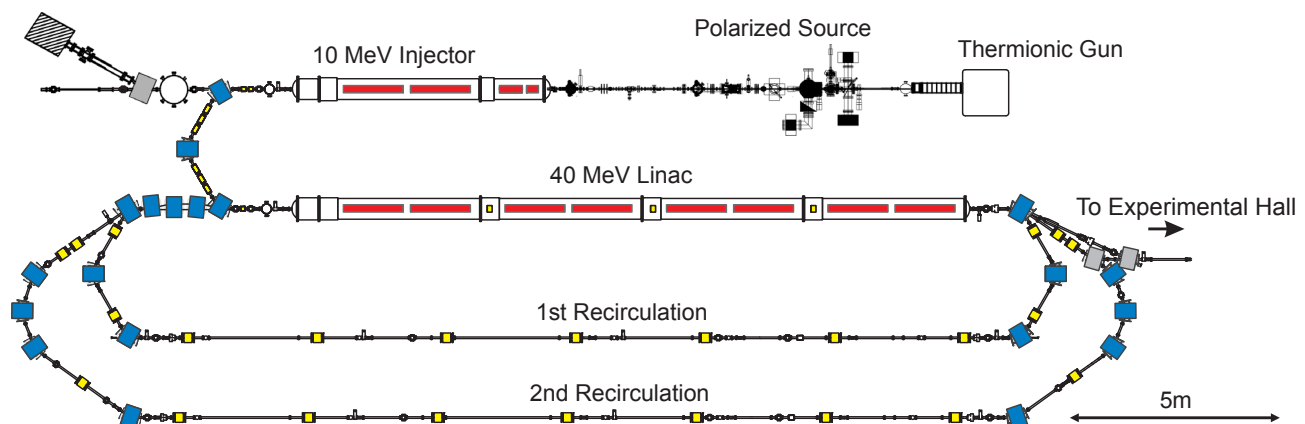


Figure 1: Schematic layout of the Superconducting Darmstadt Linear Accelerator S-DALINAC.

* Work supported by DFG through SFB 634.

** franke@temf.tu-darmstadt.de

THE MOMENT APPROACH

The moment approach to beam-dynamics 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 momenta p_x, p_y, p_z by a discrete set of characteristic moments [2].

Moment Definition

The 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 $n = l_1 + \dots + l_6 \in \mathbb{N}, n \geq 2$.

Following this idea one automatically obtains the center of mass position and a translatory invariant description of the shape of the particle distribution [3].

Moment Evolution

A fundamental time evolution equation can be stated for each moment $\langle \mu \rangle$ by means of the Vlasov equation:

$$\begin{aligned} \frac{\partial \langle \mu \rangle}{\partial \tau} = & \left\langle \frac{\partial \mu}{\partial \langle \vec{r} \rangle} \right\rangle \left\langle \frac{\vec{p}}{\gamma} \right\rangle + \left\langle \frac{\partial \mu}{\partial \langle \vec{p} \rangle} \right\rangle \left\langle \frac{\vec{F}}{m_0 c^2} \right\rangle \\ & + \left\langle \frac{\partial \mu}{\partial \vec{r}} \frac{\vec{p}}{\gamma} \right\rangle + \left\langle \frac{\partial \mu}{\partial \vec{p}} \frac{\vec{F}}{m_0 c^2} \right\rangle \end{aligned} \quad (2)$$

This set of ordinary differential equations can efficiently be evaluated with standard time integration methods [4] if proper initial conditions are given and all essential forces are known.

Force Calculation

The Lorentz force $\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$ specified in the fundamental time evolution equation (2) can be evaluated as a sum of forces resulting from superposed external fields and internal space charge effects. A numerically useful way to provide all external field components in the vicinity of the particle distribution is given by a paraxial approximation using a series expansion of the external fields. For the calculation of internal space charge forces a model assuming a certain particle distribution can be applied to reconstruct the distribution within the bunch from the moment description. An alternative approach consists of representing the particle distribution through multiple interacting sets of moments in a multi-ensemble environment [5].

IMPLEMENTATION

The beam-dynamics simulation tool V-Code has been implemented at the Computational Electromagnetics Laboratory (TEMF) at the Technische Universität Darmstadt on the basis of the moment approach.

Beamline Representation

For applying the moment approach even to a long accelerator beamline it is useful, especially in terms of an efficient memory management, to represent the beamline as a consecutive chain of several independent beamline elements along a straight axis. 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 defined. This path fixes the length of the magnet along the projected axis within V-Code. The actual bunch position within the bending magnets is then determined via a normal projection onto the reference path [6].

Recirculations

Several beamline elements are repassed multiple times by the beam during the two recirculations. Beamline elements that are passed n times are placed n times along the beamline representation within the V-Code. Proper reference paths have to be defined for all instances of a bending magnet that is passed by the beam at different energies during the recirculations.

The length of the S-DALINAC beamline can be adjusted mechanically in order to match the path length of the recirculated beam with the phase of the fields inside the cavities. This is realized by means of extendable bends within the first and the second recirculation. In 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.

Overlapping Fields

The proximity of some beamline elements leads to overlapping fringe fields between consecutive elements. The V-Code database of disjunctive beamline elements has to be extended accordingly.

The fundamental time evolution equation (2) can be separated into drift terms and transport terms. The drift terms represent the fundamental internal feedback and depend on the momentum whereas the transport terms consider the interaction with the external forces. If linear materials can be assumed, the specified force can be evaluated as a sum of forces resulting from various superposed fields and it is also allowed to apply one transport term for each overlapping field component [7]. This approach was implemented in a new enveloping macro element which enables the user to combine all beamline elements with overlapping fields.

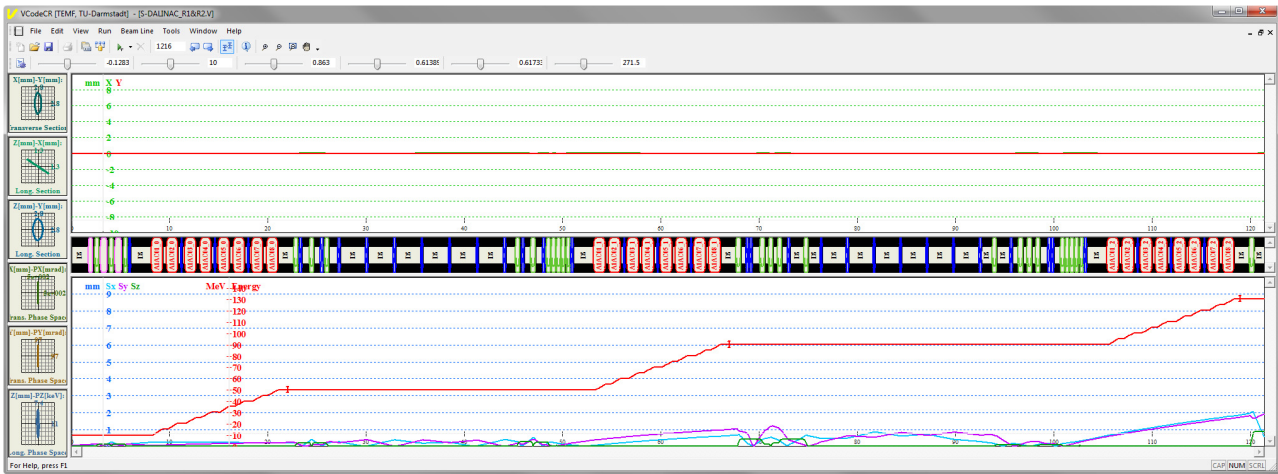


Figure 2: Screenshot of the V-Code graphical user interface showing simulation results for the S-DALINAC recirculating machine. The simulation was initiated right after the injector and the corresponding 10 MeV bunch was subsequently accelerated three times within the main linac. Reference markers for 50, 90 and 130 MeV beam energy are displayed.

User Interface

A comfortable and clearly arranged graphical user interface is essential in order to provide the operators of the accelerator a utile simulation tool. Figure 2 shows a screenshot of the V-Code user interface. Several beam parameters like the position of the center of mass in x and y direction, the dimensions of the beam σ_x , σ_y and σ_z in Cartesian coordinates and the energy are displayed along the longitudinal axis z in the panes above and below the representation of the beamline. On the left side six phase space projections on different planes can be observed at any position in time.

The user interface also provides access to each parameter of the various beamline elements by double clicking on a specific element in the beamline representation. Another way to tune the settings of the beamline elements is implemented via arbitrary assignable sliders in the menu bar.

Online Simulation

Supplementary to the possibility to manipulate the parameter setup of the beamline elements within the V-Code through the user interface an online simulation mode has been implemented. Within this operating mode the parameter settings are read from an external source. This external source may be either an other software tool or for example the control desk of the accelerator machine.

Markers

During each simulation run the actual bunch parameters at the interfaces between the consecutive beamline elements can be stored. These specific sets of moments can be used as initial start ensembles for upcoming simulations of subsets of the beamline. This feature helps to further speed up the iterative process of finding an optimal machine setup.

Reference Markers

In order to additionally assist the operator, reference markers can be displayed on top of the simulation data. This can be used for instance to superimpose expected data or measurement data received from a diagnostic device installed within the beamline.

Automatic Beam Adjustment

Finding an optimal parameter setup for the S-DALINAC beamline is a laborious task as the number of variable parameters is very large. The V-Code opens up the possibility to analyze a multitude of parameter sets in a reasonable time. This procedure can be automated by implementing objectives and evaluation rules. Further, a connection between the V-Code and the accelerator diagnostic software allows to take into account measured parameters in the automated optimization process. A promising prototype for an automatic beam adjustment algorithm applying the V-Code has been published in [8].

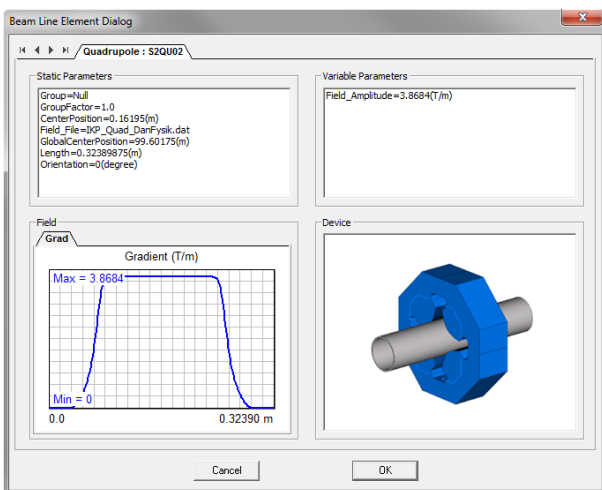


Figure 3: Dialog providing access to all static and variable parameters of a quadrupole. In addition the distribution of the quadrupole strength and a schematic representation of the magnet are displayed.

APPLICATION

The V-Code has to be accurately initialized with the geometrical setup of the beamline, the field distribution within the various beamline elements and an initial set of moments for its dedicated application within the S-DALINAC control system.

Initialization

The S-DALINAC beamline shown in Fig. 1 consists of over 100 beam guiding elements and for each of them the electromagnetic fields have to be provided. The field distribution along the reference paths of the dipoles, the quadrupole strength along the axis within the quadrupoles and the accelerating electric field within the cavities were extracted from field calculations with the appropriate solvers included in the CST STUDIO SUITE [9].

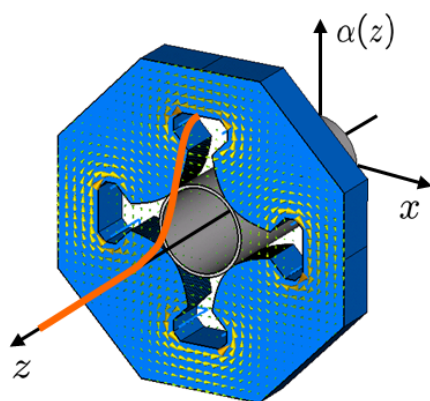


Figure 4: Computational model of a quadrupole magnet together with the extracted quadrupole strength $\alpha(z)$.

The position of the beamline elements within the V-Code beamline is defined by the length of the field data sets of the consecutive beam guiding elements and drift space elements which represent intervals without external electromagnetic fields.

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. Nevertheless, the measured bunch data can be used to ensure the bunch parameters achieved from start-to-end simulations.

Simulation Results

The V-Code was initialized with values provided by experienced operators of the S-DALINAC in order to examine its applicability to simulate the recirculating setup. The simulation was started right after the injector section with a 10 MeV bunch with the 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. Results of this simulation are displayed in the screenshot in Fig. 2. More details concerning the simulation of the S-DALINAC recirculations are published in [10].

SUMMARY

The moment approach together with a paraxial field approximation allows the implementation of a fast and accurate beam-dynamics simulation tool. Changing the order of moments or the number of applied ensembles permits to adapt the simulation to the required accuracy while keeping the simulation times in an acceptable level. With the help of the reference-path concept this code can be used to simulate even recirculating machines like the S-DALINAC. With its customized graphical user interface the V-Code is designed to assist the operators in finding an optimal setup for the accelerator beamline.

REFERENCES

- [1] R. Eichhorn: Optimierung des Strahltransportsystems und experimentelle Umsetzung verschiedener Methoden zur Gütemessung am S-DALINAC, Dissertation, Darmstadt, Germany, 1999.
- [2] P.J. Channell: The Moment Approach to Charged Particle Beam Dynamics, *IEEE Trans. Nucl. Sci.*, NS-30, No. 4, Page 2607, 1983.
- [3] M. Krassilnikov, A. Novokhatski, B. Schillinger, S. Setzer, T. Weiland, W. Koch: V-Code Beam Dynamics Simulation, Proceedings of the 6th International Computational Accelerator Physics Conference (ICAP 2000), September 2000.
- [4] W. Ackermann, T. Weiland: Efficient Time Integration for Beam Dynamics Simulations Based on the Moment Method, Proceedings of ICAP 2006, Chamonix Mont-Blanc, France, October 2006.
- [5] S. Franke, W. Ackermann, T. Weiland: A Fast and Universal Vlasov Solver for Beam Dynamics Simulations in 3D. Proceedings of the 10th International Computational Accelerator Physics Conference, San Francisco (ICAP 2009), September 2009.
- [6] S. Franke, W. Ackermann, B. Steiner, T. Weiland, J. Enders, C. Hessler, Y. Poltoratska: Implementation of Fringe Field Dipole Magnets into the V-Code Beam Dynamics Simulation Tool, Proceedings of the 11th European Particle Accelerator Conference (EPAC 2008), Genoa, Italy, June 2008.
- [7] S. Franke, W. Ackermann, T. Weiland, J. Enders, C. Heler, Y. Poltoratska: Handling Overlapping Fields Within the V-Code Beam Dynamics Simulation Tool. Proceedings of the 2009 Particle Accelerator Conference (PAC 2009), Vancouver, Canada, May 2009.
- [8] C. Klose: Entwicklung und Implementierung von Algorithmen zur automatisierten Strahleinstellung am S-DALINAC, Diss., Darmstadt, Germany, 2010.
- [9] CST AG - Computer Simulation Technology, Bad Nauheimer Str. 19, D-64289 Darmstadt, Germany, <http://www.cst.com>.
- [10] S. Franke, W. Ackermann, T. Weiland, T. Quincey, F. Hug, P. Görgen, C. Klose, M. Platz: Further Development of the V-Code for Recirculating Linear Accelerator Simulations, Proceedings of the XXV International Linear Accelerator Conference (LINAC 2010), Tsukuba, Japan, September 2010.