

IMPROVEMENTS OF THE LORASR CODE AND THEIR IMPACT ON CURRENT BEAM DYNAMICS DESIGNS

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Abstract

LORASR is a multi-particle tracking code optimized for the beam dynamics design of ‘Combined Zero Degree Structure (KONUS)’ lattices, which can benefit from an adapted input file structure and code architecture. Recent code developments focused on the implementation of tools for machine error studies and loss profile investigations, including also steering correction strategies. These tools are a stringent necessity for the design of high intensity linacs. Thus, the abilities of the present LORASR release allow performing a manifold of checks and optimizations before finalizing the layouts of KONUS-based or conventional linacs. Two representative examples are the MAX-MYRRHA Injector and the GSI FAIR Facility Proton Linac, both under development with strong participation of IAP, Frankfurt University.

This paper presents the status of the LORASR code development with focus on the new features and illustrates the impact on current designs by examples taken from the above-mentioned projects.

MACHINE ERROR TYPES IMPLEMENTED IN LORASR

The LORASR beam dynamics code [1] [2] is maintained and continuously improved at IAP, Frankfurt University. Recent code development focused on the implementation of tools for defining random machine errors, in order to study their effect on the beam dynamics in linacs. The error types implemented so far are described in the following table.

Table 1: Error Type Definitions Available in LORASR

Error Type	Typical Range
Transverse displacements $\Delta x, \Delta y$	≤ 0.1 mm
Lens rotations $\Delta\Phi_x, \Delta\Phi_y, \Delta\Phi_z$	$\Delta\Phi_{x,y} \leq 5$ mrad $\Delta\Phi_z \leq 10$ mrad
Voltage variations $\Delta U_{i,j}$ of single gaps (i) and whole cavities (j)	$\Delta U_i / U_i \leq 5$ % $\Delta U_j / U_j \leq 1$ %
Cavity rf phase variations $\Delta\phi_j$	$\Delta\phi_j \leq 1$ deg

Typical reasons for the occurrence of such errors are failures during the manufacturing, alignment and tuning of the components (*static errors*) or fluctuations (rf source instabilities, mechanical vibrations) during the operation (*dynamic errors*).

Consequently, in LORASR the error settings can be

defined explicitly, as well as statistically distributed.

Manual input is adequate when data from measurements is available (e.g. quadrupole alignment listings or measured gap voltages). In this case, single runs are performed in order to investigate the effects of one particular set of error parameters.

In case of randomly generated error settings many runs (100 to 1000 typically) are needed for good statistics. In LORASR, the random errors are Gaussian distributed and truncated at the 2σ -width. A ‘batch’ processing mode has been implemented: the user defines the number of runs and the starting seed. Results from each run are stored to separate files (sets of runs on different PCs are also possible).

Moreover, an elementary steering correction strategy has been implemented. Steerers are treated as ideal elements with no field limitation.

ERROR ANALYSIS TOOLS AVAILABLE IN LORASR

When operated in the batch mode as described in the previous chapter, LORASR stores all relevant data (error settings and results) of each run in separate files. Thus, all needed information is available for post processing by any statistical software application.

Nevertheless, several error analysis tools related to the collected data were implemented directly to LORASR. The corresponding new plots are as follows:

- Loss profile plots for single runs (Figure 1), as well as for all runs (showing the averaged losses).
- Plot of the maximum beam envelope compounded from all runs, together with the envelope of the nominal case (Figure 2, top; Figure 3).
- Probability distribution of the maximum aperture filling factor (Figure 2, bottom).
- Distribution of the additional relative emittance growth, compared to the nominal run.

In Figure 1 a single run loss profile plot is shown exemplary. The plotted loss profile (= loss rate) is defined as follows:

$$\frac{(dN/N_0)}{dz} = \frac{\text{fraction of locally lost particles}}{\text{path length of local losses}} \left[\frac{1}{m} \right] \quad (1)$$

This quantity with the unit 1/m is not very descriptive, but it is independent of the beam current setting and the related plot provides a realistic representation of the distribution of losses along the beam line. Knowing the initial beam current and the bunch energy along the beam line, the loss rate can be easily converted into a current loss rate dI/dz [A/m] or into the beam power loss rate dP/dz [W/m].

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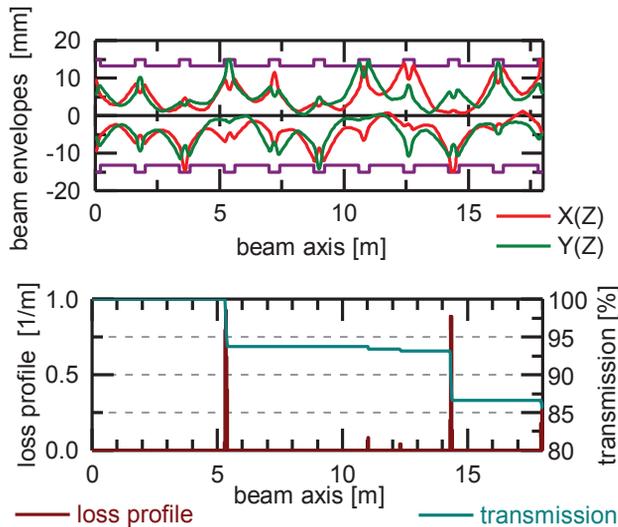


Figure 1: LORASR beam loss plot: the 100% transverse beam envelopes of a single run are shown together with the distribution of losses along the beam line.

In Figure 2 other two new LORASR plots are shown, by also varying the magnitude of the error setting (max. lens displacements).

In the upper plot, each envelope was obtained by overlapping all single run 100% beam envelopes and calculating the contour of this overlap. The result can be regarded as the probability of the beam to “populate” the given aperture when errors are switched on. However, in this plot no information about the density of the aperture filling is given. For such a purpose, the second plot in Figure 2 is better suited: The maximum aperture filling factor of single runs f_{max} defines the closest distance between beam and aperture and is calculated as follows:

$$f(z) = \frac{r_{beam}(z)}{a_{beamline}(z)}; \quad f_{max} = MAX(f(z), z=0..z_{max}) \quad (2)$$

With f_{max} available from each single run, a probability distribution can be calculated. In the numerical example from Figure 2, the content of the plot can be evaluated as follows: The nominal run (red, “no error”) has a filling factor of 70 %. For a certain error value (blue, 0.05 mm) all runs keep within the aperture without losses. When increasing the errors (green, 0.1 mm) only 67% of all runs stay within the aperture and the other 33% have losses.

ERROR STUDY EXAMPLES

Error studies became a stringent necessity in the design phase of high current and especially high duty factor linacs. For such applications, particle losses can lead to severe activation problems or even to quenches in the sc components.

For the present paper, two examples with direct participation of IAP, Frankfurt University were chosen. In both cases, the direct user feedback was very helpful for further developing the LORASR code as presented.

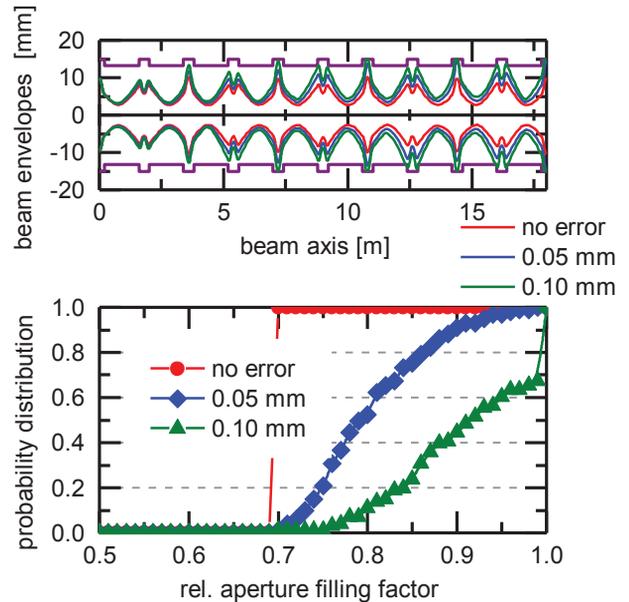


Figure 2: LORASR plot examples: Maximum beam envelope of all runs (top); Probability distribution of the maximum aperture filling factor (bottom).

FAIR Facility Proton Linac

A dedicated 70 MeV, 35 mA (operation) to 70 mA (design) proton injector linac is built in the framework of the FAIR project, in order to fill the synchrotron SIS 18 up to its proton space charge limit. The accelerator layout is based on the KONUS [2] beam dynamics concept and consists of three coupled CH and three standard CH-DTL with quadrupole triplet focusing [3].

Numerous error studies have been performed during the beam dynamics design phase of this linac [4],[5],[6],[7].

The scope and key findings of all these investigations were as follows:

- Definition of manufacturing, alignment and tuning tolerances. The final results were: $\Delta x = \Delta y = 0.1$ mm; $\Delta\Phi_{x,y,z} = 8.7$ mrad; $\Delta U_i / U_i = 5$ % (gaps); $\Delta U_j / U_j = 1$ % (cavity); $\Delta\phi_{rf} = 1$ deg [see ref. 7].
- Detection of “bottlenecks”: The long MEBT at 35 MeV turned out to be particularly sensitive to errors. Thus, a second triplet lens and a steerer were added.
- Total number and positions of steerers.
- Overall accelerator layout: The preferred option with 3 standard cavities at CH section II (instead of 6 coupled CH) showed similar error tolerances and thus could be chosen.

MAX-MYRRHA Injector

In the framework of the MYRRHA Accelerator experiment (MAX) research programme, the beam dynamics design of the 17 MeV, 5 mA proton injector linac has been elaborated and completed at IAP, Frankfurt University. A detailed description of the up-to-date r&d status can be found in a dedicated paper [8].

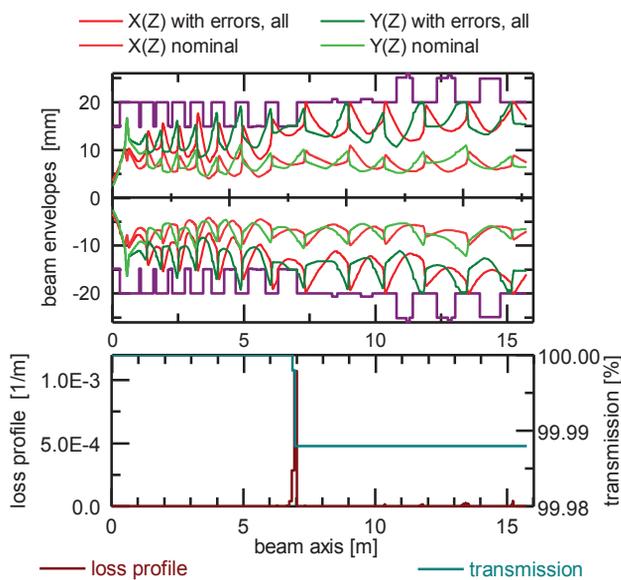


Figure 3: Maximum beam envelope of all runs (top) and distribution of losses (bottom) for the final MAX-MYRRHA Injector design. The applied error magnitudes are as follows: $\Delta x = \Delta y = 0.2$ mm; $\Delta\Phi_{x,y,z} = 1$ mrad; $\Delta U / U = 5$ % (gaps) and 1 % (cavity); $\Delta\phi_f = 1$ deg

The final layout of the proposed linac consists of 7 room temperature CH-DTL with constant phase profile, covering the energy range from 1.5 to 5.9 MeV, followed by 5 sc CH cavities with constant beta profile and an output beam energy of 17 MeV. The focusing channel is based on quadrupole doublet lenses, all placed outside the resonant cavities.

In Figure 3 the beam envelopes with and without errors and the distribution of losses are shown. The error margins have been increased step by step to the values given in the caption of Figure 3, until first losses occurred. The main losses appear at the exit of the rt part of the linac, and the transmission is still at about 99.99 %, although the applied error is quite high ($\Delta x, \Delta y = 0.2$ mm) and no steering correction was used in simulations.

To reach this final result, many iteration steps accompanied by extensive error studies were needed [9]. The scope and key findings of all these investigations were as follows:

- Definition of manufacturing tolerances.
- Adjustment of the overall accelerator layout:
 - Finding the optimum RT – SC transition energy.
 - Finding the optimum density of focusing elements.
 - Comparing the usage of short vs. long multi gap cavities.
 - Comparing the error sensitivity of a doublet vs. a triplet focusing channel.

At this point it should be mentioned that first, extended error studies on an injector for an accelerator driven transmutation facility have been already performed (by using the LORASR code as well) in the framework of the

EUROTRANS project, which can be considered as the predecessor of MAX-MYRRHA. These early injector proposals were characterised by a very compact layout, which could be achieved by applying the KONUS beam dynamics together with high accelerator gradients and short inter tank sections (e.g. by integrating all sc cavities in a common cryostat, together with sc solenoid lenses). The associated error studies lead to tolerance limits very similar to those of the present design [10], [11]. The same concept has been adopted in the early stage of the MAX-MYRRHA injector design, resulting as well into a promising, very compact layout [12]. However, by considering different technical aspects (the integration of many sc cavities in one long cryostat seems challenging; more space is needed in the inter-tank sections; a reduced average acceleration gradient gives safety margins and can improve the beam quality) the present, more conventional concept has been finally adopted [13], [8].

REFERENCES

- [1] R. Tiede et al., “LORASR Code Development”, EPAC 2006, Edinburgh, p. 2194-2196 (2006).
- [2] R. Tiede et al., “KONUS Beam Dynamics Designs Using H-mode Cavities”, Hadron Beam 2008, Nashville, p. 223-230 (2008).
- [3] G. Clemente et al., Phys. Rev. ST Accel. Beams 14, 110101 (2011).
- [4] G. Clemente et al., “Beam Dynamics Layout and Loss Studies for the FAIR P-Injector”, EPAC 2008, Genoa, p. 2701-2703 (2008).
- [5] G. Clemente et al., “Investigation of the Beam Dynamics Layout of the FAIR Proton Injector”, Hadron Beam 2008, Nashville, p. 235-237 (2008).
- [6] G. Clemente et al., “The FAIR Proton Linac: The First Linac Based on a Room Temperature CH-DTL”, Hadron Beam 2010, Morschach, Switzerland, p. 115-119 (2010).
- [7] G. Clemente et al., “Beam Dynamics Error and Loss Investigation of the FAIR Proton Injector”, IPAC 2013, Shanghai, p. 3776-3778 (2013).
- [8] D. Mäder et al., “R&D of the 17 MeV MYRRHA Injector”, MOPP064, these proceedings, LINAC’14, Geneva (2014).
- [9] N. Petry, “Error Studies on the 17 MeV Injector for the MYRRHA Project”, Bachelor Thesis, IAP Frankfurt University, May 2014.
- [10] C. Zhang et al., “KONUS Dynamics and H-Mode DTL Structures for EUROTRANS and IFMIF”, EPAC 2008, Genoa, p. 3239-3241 (2008).
- [11] C. Zhang et al., Phys. Rev. ST Accel. Beams 13, 080101 (2010).
- [12] C. Zhang et al., “From EUROTRANS to MAX: New Strategies and Approaches for the Injector Development”, IPAC 2011, San Sebastián, p. 2583-2585 (2011).
- [13] D. Mäder et al., “Consolidated Design of the 17 MeV Injector for MYRRHA”, SRF 2013, Paris, p. 271-273 (2013).