TRIUMF-VECC ELECTRON LINAC BEAM DYNAMICS OPTIMIZATION

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Abstract

The TRIUMF-VECC Electron Linac is a device for gamma-ray induced fission of actinide targets, with applications in nuclear physics and material science. A phased construction and commissioning scheme will eventually lead to a 50 MeV, 10 mA CW linac based on superconducting RF technology. Using this linac to deliver high intensity electron beams for applications such as an energy-recovered light source is a possibility integrated in the design study. The multitude of design and tuning parameters, diverse objectives and constraints require a comprehensive and efficient optimization scheme. For this purpose we adopted the genetic optimization program developed at Cornell University as a prototype. Feature extensions were developed to accommodate specifics of the Electron Linac design, provide framework for more generic and integrated design process, and perform robustness/acceptance analyses. In this report we will discuss the method and its application to the design optimization of the Electron Linac. [4].

OVERVIEW

TRIUMF and VECC of Kolkata, India are signing an MOU to jointly develop Injector Cryo-Modules for an electron linac (E Linac) for radioactive ion beam (RIB) production via photo-fission of ^{238}U. This provides a source of neutron-rich isotopes complementary in character to those produced by proton beams.

The E Linac accelerates 10 mA CW e^- beam (16 pC/bunch) to 50 MeV with 1.3 GHz superconducting RF cavities housed in three cryo-modules. The beam is generated at a 100 keV grid-modulated thermionic gun with a 650 MHz pulse structure. A normal conducting buncher and two 1.3 GHz SRF single cell cavities provide graduated bunching and longitudinal matching into the main accelerating structure. Transverse focusing is provided by solenoids or quadrupoles.

Table 1: Beam parameters for the E Linac

RIB 16 pC per bunch	**100 keV**	**10 MeV**
RMS ε_N transverse (μm)	7.5	12.5
Bunch length (cm)	2.8 (±20°*)	0.6
Energy spread	±1 keV	±40 keV
High brightness 100 pC per bunch	**200 -300 keV**	**50 MeV**
RMS ε_N transverse (μm)	1.0	10.0
Bunch length (mm)	4.0	1.0
Energy spread	±0.5 keV	±50 keV

Coupled to a high brightness photo injector, the E Linac can potentially be used in applications beyond RIB production, such as an X-ray source through Compton scattering. It is therefore interesting and relevant to investigate if, and how, the same configuration can deliver both the 16-pC/bunch RIB beam and a 100-

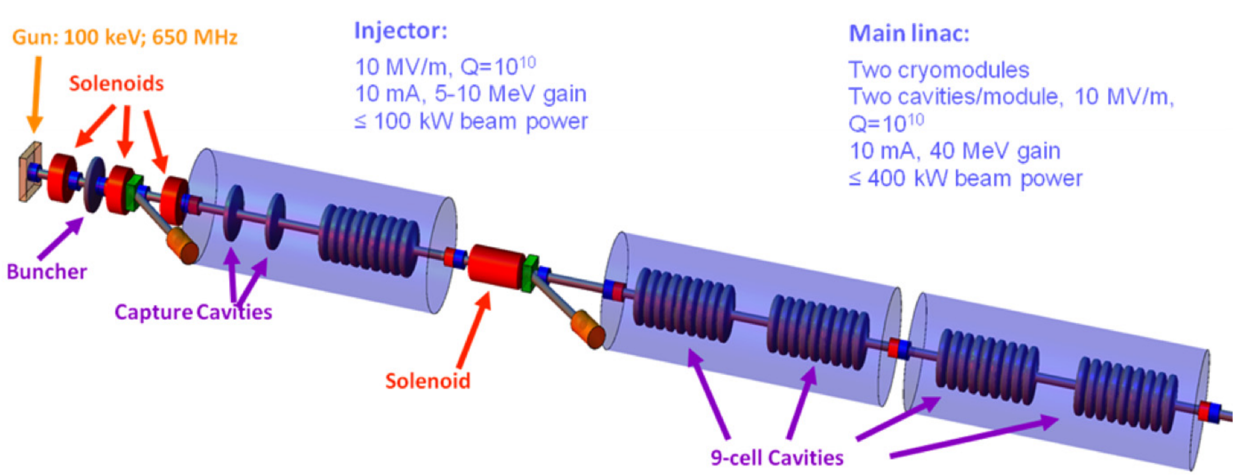

Figure 1: Schematic of the TRIUMF E Linac.

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pc/bunch high brightness (HB) beam, achieving final beam specs suitable for their respective applications. The commissioning plan may dictate different setup parameters at the front end for optimized performance at different stages of the project. Such questions can best be answered by a systematic optimization program accounting for a broad variety of objectives and constraints.

Beam dynamics modeling is done with Astra [1], Parmela [2] and Track [3]. To explore the multi-dimensional parameter space in a systematic and comprehensive manner, a genetic optimization program, originally developed at Cornell University [4], was adopted and modified to run on the Western Canada Research Grid [5]. A typical optimization involves the selected evolution of design parameters (tuning parameters and element locations), toward progressively improved design objectives (beam parameters and performance measures such as beam loss), subject to constraints mostly reflecting limitations in geometry and hardware.

OPTIMIZATION - GENETIC ALGORITHM WITH PARETO DOMINATION CRITERION

A genetic algorithm is superior in its robustness against near singularities in the modeling process. The particular algorithm adopted performs selection based on the Pareto domination criterion, with the additional advantage of allowing overview of multiple competing objectives, and avoidance of artificial cut-off in constrained parameters. This algorithm has proved quite competent in achieving design goals set for the current study. Figure 2 shows a well defined Pareto front plot representing trade-off between 3 competing objectives from a typical sufficiently evolved run.

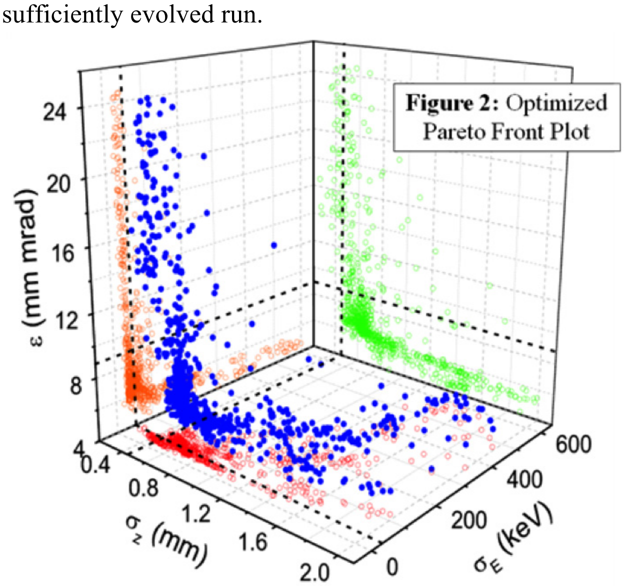

Figure 2: Optimized Pareto front plot.

OPTIMIZED SOLUTIONS

The genetic algorithm was used to find the following E Linac configurations. Figure 3 shows a 50 MeV RIB solution where the nonlinearity in the RF waveform (a T_{655} term) was used to cancel the nonlinear momentum compaction due to non-relativistic dynamics at low energy (a T_{566} term) while performing efficient bunching and acceleration at the same time. The normalized longitudinal emittance decreased by ~50% from the otherwise inevitable peak growth. Figure 4 shows a 10 MeV high bunch charge solution where the reduction in transverse emittance was accomplished through realignment of longitudinal slices in the transverse phases space by optimized RF focusing.

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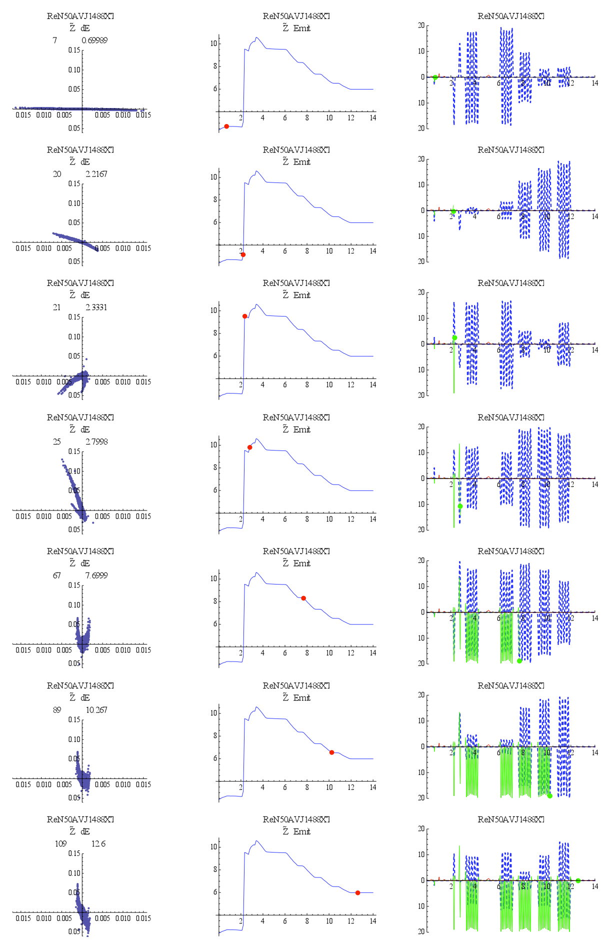

Figure 3: Longitudinal space 100 keV -50 MeV RIB; Left: Phase space distribution E (MeV) vs Z (m); Center: ε^N_Z in keV-mm vs distance in m; Right: Progress of beam along Z and RF waveform.

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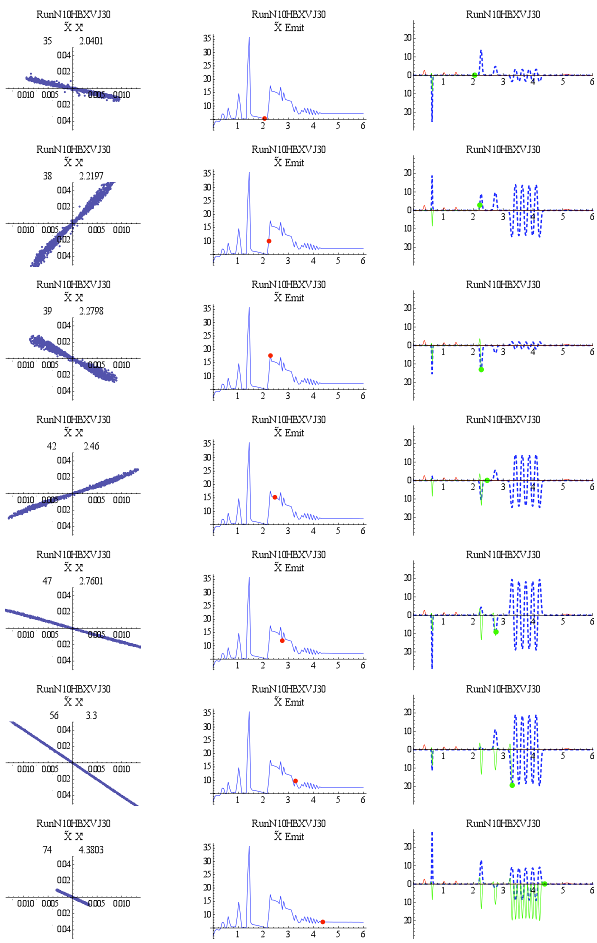

Figure 4: Transverse space 200 keV -10 MeV HB; Left: Phase space distribution X' (rad) vs X (m); Center: ε^N_X in mm-mrad vs distance in m; Right: Progress of beam along Z and RF waveform

APPLICATION OF THE METHOD

Besides providing globally optimized solutions for a given configuration, this method proved valuable in resolving other design issues and providing insights into the underlying physical mechanism of solutions. A few examples are shown in the following.

- Performance comparison between different designs: As the level and detail of optimization can be controlled better than many other methods, one can compare the relative merits of different designs <u>optimized to the same level</u>. Figure 5 shows such comparisons between different choices of the capture cavity configurations, and between different geometries of the design.
- Solving for externally imposed design goals: The method can be trivially extended to solve for design parameters satisfying externally imposed design goals, or provide insight on trade-off between parameters in meeting such goals through Pareto-front plots. Figure 6 shows a case where exact solutions can be obtained for given design goals in terms of beam parameters, and in the case of over-constrained goals, the Pareto front mapping out best-achievable options in the parameter space.

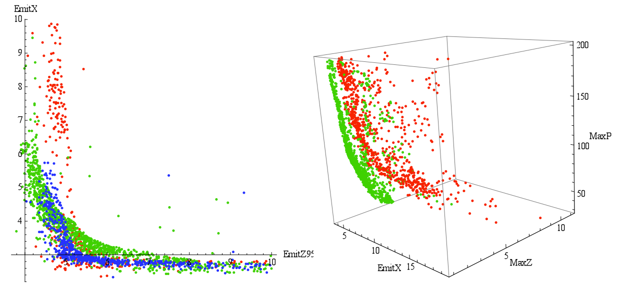

Figure 5: Left: Pareto fronts for β=0.7+β=1.0 capture cavities (red), β=0.7+β=0.85 (green) and β=0.7+β=0.7 (blue). Right: Pareto fronts for 1.55 m inter-buncher-capture distance (red) and 1.05 m inter-buncher-capture distance (green).

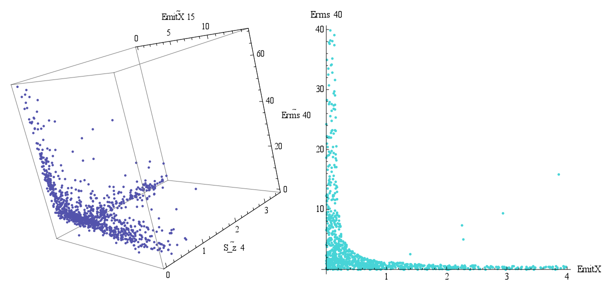

Figure 6: Left: Trade-off among solutions attempting to satisfy 3 parameters at the same time: ε^N_X = 15 mm-mrad, σ_Z =4 mm & σ_E =40 keV. Right: Solutions attempting to satisfy 2 parameters: ε^N_X = 15 mm-mrad & σ_E =40 keV, as well as additional constraints.

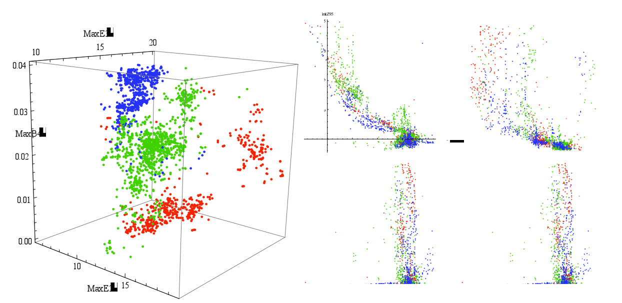

Figure 7: Left: Distribution of capture cavity fields (MaxE(2/3): MV/m) & last solenoid field (MaxB(4): T) optimized for 3 different capture configurations**.** Right: Various correlations between buncher field (MaxE(1): MV/m), first solenoid field (MaxB(1): T) and longitudinal & transverse emittances.

- Correlation between parameters: Due to its ability to efficiently carry along high dimension of parameters, and the large statistics readily available from the globally optimized gene pool, this method provides insight into correlation and interplay between variables, objectives and constraints. Figure 7 shows an example of the different optimization strategies, in terms of the capture cavity fields and solenoids, for the 3 capture configurations described in Figure 5, and another example of how final beam parameters are correlated to various tuning parameters.
- Exception handling of design. Figure 8 shows the compromise in performance of various designs when one of the capture cavities is not used. Again the comparison is more rigorous because all cases are <u>optimized to the same level</u>. It also shows, through inspection of the optimized gene pool, that in such exception cases the second capture cavity has to do more acceleration at the expense of bunching, and the opposite for the 9-cell cavity, in order to achieve improved beam parameters. It is also clear that the first capture cavity (β=0.7 in all cases) is more important than the second capture cavity. This is mostly due to its more favorable distance to the buncher in satisfying the longitudinal matching condition.

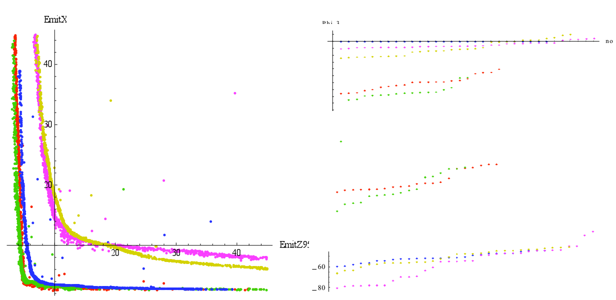

Figure 8: Left: Performance comparison between normal and exception cases: red: β=0.7+β=1.0 capture cavities, green: β=0.7+β=0.7, blue: 1st capture only (β=0.7), pink: 2nd capture only (β=1.0), olive: 2nd capture only (β=0.7). Right: Corresponding RF phases for the 2nd capture & the main (9-cell) cavities.

EXTENSION OF THE METHOD

Extension to the optimization program for the current design effort, either developed or under development, include the following:

- A generic framework based on python scripts allowing the definition of optimization objectives and constraints through user defined operation on arbitrary code-generated files.
- Method to incorporate different design prototypes into a single selection process subject to common selection criteria. This can be useful when other criteria such as cost become relevant.
- A flexible structure based on XML and python scripts allowing evaluation of a design by arbitrary processing modules. This extends the concept of model into an integrated design process where for example, Astra, is only one of many modules called on to return a complete set of performance metrics as input to the selection mechanism. This feature has been used for efficient benchmarking between Astra and Track.
- These modules can be invoked in parallel or in series in a single optimization run. In the former case complementary performance metrics can be obtained from different modules, while in the latter the user can perform high level analysis on raw simulated parameters, or end-to-end optimization over an integration of successive components.
- The optimization program is being integrated as a tuning component in the study of machine acceptance and robustness, where one defines the part of parameter space spanned by input beam and machine error that can be handled by tuning within operating range. In this context local-minimum algorithms such as the Levenberg-Marquardt method may be considered as an efficient alternative.

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