THE TRIUMF OPTIMIZATION PLATFORM AND APPLICATION TO THE E-LINAC INJECTOR*

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Abstract

Multi-objective genetic algorithms (MOGA) have demonstrated their usefulness for the global optimization of accelerator design using Elegant [1] and Astra [2]. A MOGA platform developed at TRIUMF seeks to expand the capabilities of such tools by allowing multiple simulation engines to be used. The TRIUMF optimization software platform was applied to the transport design of an injection line leading from a cryomodule to the beam dump. The optimization involves two simulation engines, Astra and MAD-X, and demonstrates the ability for the platform to handle multi-engine optimization for a realistic problem. Results of the optimization are shown.

INTRODUCTION

A software platform for global optimization was created at TRIUMF [3]. The platform uses Multi-Objective Genetic Algorithms (MOGA) [4] as a wrapper around simulation engines. MOGA creates an initial population, with each member of the population some combination of randomly chosen variables. For each of a fixed number of iterations, the members are assigned a density, based on how well they satisfy the optimization constraints and objectives. Members are then randomly chosen, with a bias based on the density function, to 'breed' new members (by mutation, crossing variables, etc). Such algorithms are suitable for global optimization because they ignore the geometry of the search space, and given a large enough population and long enough running time, will always find the global optimum. In accelerator design, MOGA codes are wrappers for simulation engines such as Astra [5]. Each member of the population is an individual Astra run with different input variables such as magnet strengths and RF phase. Constraints and objectives are set on the Astra outputs, such as emittance and bunch length.

Previous single-engine MOGA codes [1, 2] have demonstrated their usefulness for accelerator design. However, since different engines are more useful in different situations, as listed in Table 2, modern accelerators require multi-engine simulations to encompass the wide range of design parameters. This motivates the TRIUMF code platform (Fig. 1), designed to handle multi-engine problems with arbitrary topology descriptions. The code was tested and performed satisfactorily in trial problems in a parallel-capable Linux environment [3].

The ARIEL/e-linac [6] project currently underway at

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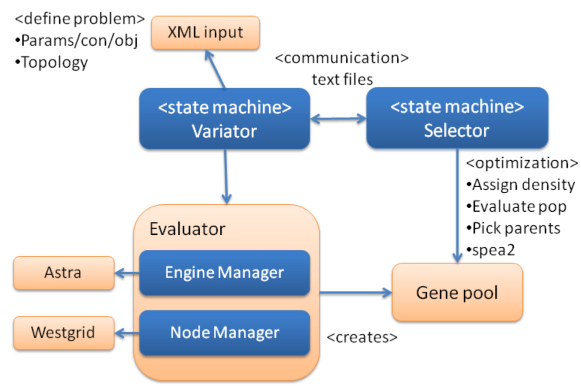

Figure 1: The architecture is based on A Platform and Programming Language Independent Interface for Search Algorithms [7]. The main components of the design are Variator, Selector, and Evaluator. Variator is a state machine which reads from the input file and defines the optimization problem. Evaluator handles the direct evaluation of all individuals in the population, including assigning and managing jobs to network nodes [8], and running the engine executables. Selector is a state machine which calculates the density, i.e. fitness, of the individuals and selects those for reproduction. The benefits of such a framework is decoupling between the algorithm, the problem definition, and the wrapper.

TRIUMF sees the possibility of operating a machine in dual rare isotope (RIB) and light source operation (FEL) (Fig. 2). The assortment of problems present in such a machine and the coupling between parameters, especially the machine settings shared by the low intensity RIB and high intensity FEL beams, means it would be difficult to separate the simulation into individual modules. The prementioned problems leads to a design requiring the use of multi-engine simulations. The optimization platform was created in preparation as a wrapper for such simulations. A sample of anticipated problems is listed in Table 1.

TRIUMF E-LINAC: INJECTOR CRYOMODULE TO DUMP

We demonstrate the platform capabilities in a realistic and practical problem for TRIUMF's e-linac project [6]. The injector consists of 300 keV beam from a thermionic gun going through a buncher and accelerated to 10 MeV through the injection cryomodule (ICM), which houses a 9-cell superconducting cavity. For the current stage test plan, the beam after the ICM terminates on a beam dump. Three

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Table 1: Different aspects of a dual RIB/ERL (Fig. 2) machine requires different and specific treatment. Information courtesy of Y.C. Chao.

Section	Issues	Objectives	Constraints
Injector Complex - gun, cryomodule, simultaneous transport of low intensity RIB and high intensity FEL CW beams	Space charge, phase space preservation, RF bunching and capture	Emittance (longitudinal, transverse), beam profile, momentum spread, transmission, robustness - both beams	Hardware limitation, acceptance (longitudinal, transverse), cost
Injection Merger - injected and recirculated beams, collimation	Longitudinal space charge, phase space preservation, momentum tail collimation	Emittance (longitudinal, transverse), transmission, tunability	Hardware limitation, acceptance (longitudinal, transverse)
Linac - acceleration of low and high intensity beams, energy recovery, transport of 3 different beams	Energy gain, phase space preservation, energy recovery, beam breakup	Beam properties, RF efficiency, instability threshold, transmission, robustness - all 3 beams	Hardware limitation, acceptance (longitudinal, transverse), cost (construction, operation)
RF Separation	Loss less transport	Beam properties, phase space preservation, robustness, tunability	Hardware limitation, acceptance
Arcs - transport, longitudinal manipulation, chromatic control	Phase space manipulation and preservation	Beam properties, transmission, robustness, tunability	Hardware limitation, acceptance (longitudinal, transverse)
Chicane	Phase space manipulation	Beam properties, CSR, tunability	Hardware limitation, acceptance (longitudinal, transverse)
FEL - wiggler, optical cavities	Beam-FEL interaction	Beam properties, FEL efficiency and performance, tunability	Hardware limitation, acceptance (longitudinal, transverse)
Global			Real estate, cost

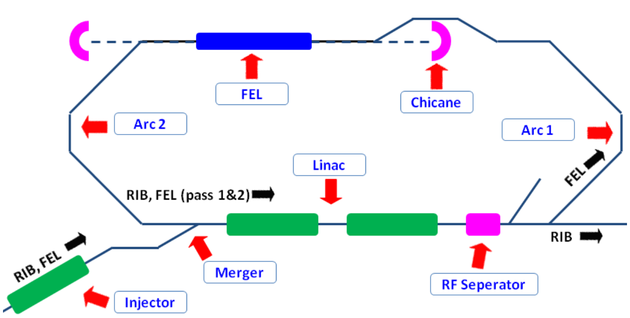

Figure 2: Layout of the upgraded e-linac including dual low intensity rare isotope beam and high intensity beam for light source operation. Many issues need simulations, and is unlikely to be done by a single engine.

solenoids (S1, S2, S3) are placed upstream of the ICM, and one solenoid and two quadrupoles (S4, Q1, Q2) are placed downstream (Fig. 3). A space of 2.5 m is allocated for the dump line from the end of the cryomodule and the entrance of the dump. The objectives are

- want the beam size to be large (≈1 cm) at the dump to minimize heating,
- between S4 and Q1, want the beam size to be minimized, so the beam pipe can be narrowed at this 'neck' to prevent backscatter at the dump from damaging equipment upstream,
- undemanding magnet settings in order to achieve the beam size requirements, and
- feasibility study to determine whether the 2.5 m space reserved from the ICM end to the dump is sufficient to accomplish the above goals.

The variables comprising the search space, i.e. to be optimized, are

- S3 strength,
- S4 strength and position,
- Q1 strength and position, and
- Q2 strength and position.

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Table 2: Comparison of a few common simulation engines and their capabilities [9]. Astra is traditionally used at TRIUMF for modeling the e-linac injector, but its dipole modeling is not optimal, therefore another engine should be used for the merger and dogleg modeling. With the future upgrade of the e-linac into an ERL, a combined MAD/Genesis can be used to model the transport and also radiative properties through the FEL.

Engine	Field Map Required	Space Charge	Radiation Field Interaction	3D	Matrix/Tracking
Astra	1D	yes		limited	tracking
GPT	1D-3D	yes		yes	tracking
MADX	no	yes			both
Elegant		no			both
CSRTrack	multipole	yes	yes		tracking
Genesis			yes		tracking

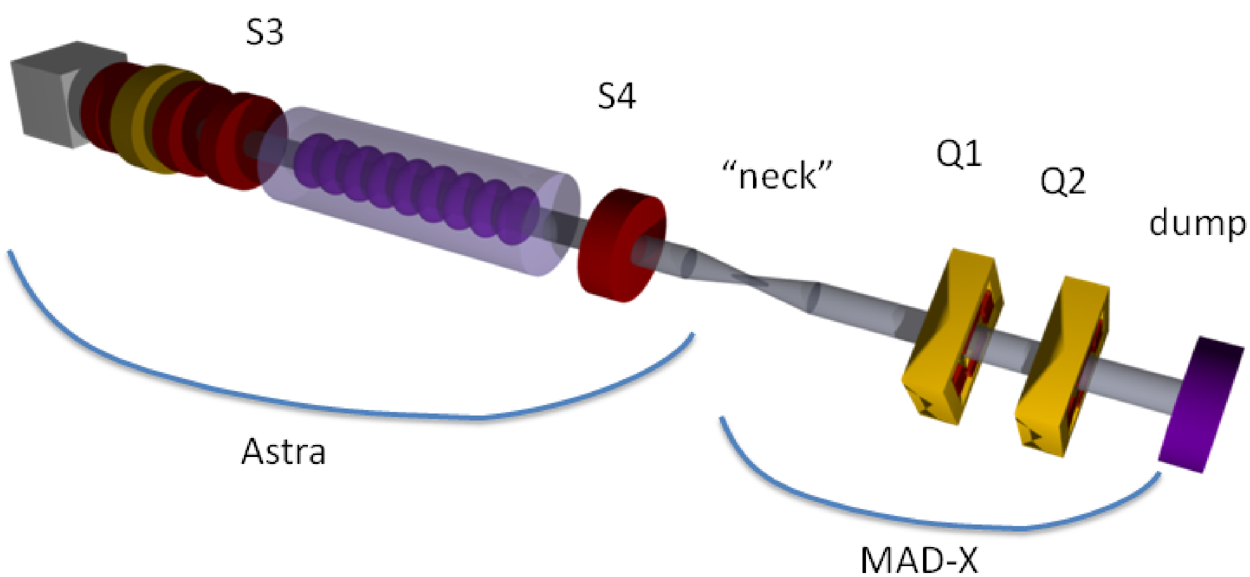

Figure 3: Astra is used to track the 300 keV beam from the exit of the gun to the neck point. The reasons for choosing Astra is 1) at the low 300 keV section, Astra is very easy to use to model space charge effects, and 2) Astra was the traditional engine used for modeling this part of the injector. After the beam accelerates to 10 MeV through the cryomodule and passes the neck point, tracking switches to MAD-X. MAD-X’s tracking by Twiss parameters provided a significant boost to the running time of the optimization.

The majority of the magnets and buncher parameters upstream of the ICM are fixed for optimal transport and minimal beam loss through the ICM. Solenoid 3, although upstream of the ICM, was allowed to vary to determine whether it helps with focusing at the neck point.

Optimization was performed to determine if the layout is feasible. Concerns were raised with the preliminary design. In particular, the end of the ICM wall to the dump is 2.5 m. One goal of the optimization was to determine whether objectives can be satisfied within this distance, or if the dump line should be lengthened [10]. The main limitation is solenoid 4, a custom Niowave 20 cm magnet, which has limited focusing ability. Whether a neck can be achieved so close to S4 is a major question. In addition to the optics, space on the transport line must be made for diagnostics.

SIMULATION SETUP

Tracking starts from the gun exit with a beam distribution generated from GPT [11]. Astra is used to track the beam through the ICM and S4 up to the neck point, and MAD-X [12] for the 10 MeV section from the neck, through the quads, to the dump. MAD-X is used for the tracking through the quads because, 1) after the ICM at 10 MeV, the beam is not as sensitive to collective space charge effects, therefore using MAD-X’s Twiss parameter tracking provides a significant decrease in tracking time, and 2) MADX provides convenient tools for the extraction of beam parameters and transfer matrices for analysis.

For optimization, the problem requires a two-vertex topology, with each member of the population consisting of the Astra tracking and the MAD-X tracking (Fig. 4). The optimization platform takes care of joining the two

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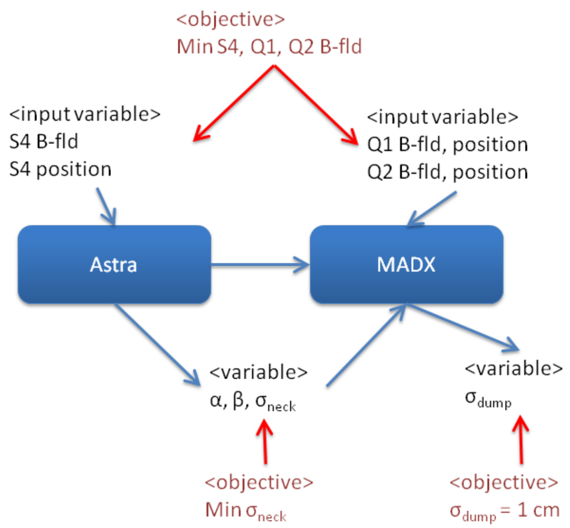

Figure 4: The two-vertex topology of the problem. MAD-X executes in sequence after Astra.

vertices, extracting the beam parameters at the end of the Astra tracking to be used as the input for MAD-X tracking. Twiss parameters are tracked for the MAD-X portion rather than a particle distribution. Only transverse properties are critical for the transport to the dump, therefore the longitudinal properties are ignored. The code also oversees unit conversions, as Astra uses [eV] while MAD-X uses [GeV]. All input for the optimization program is defined through XML (Fig. 5). The extraction of variables from engine outputs is done through python code (Fig. 6). The user can modify the python code, allowing mathematical manipulation of any combinations of variables. Other optimization settings are listed in Table 3.

Table 3: List of optimization settings for the ICM to dump line. Total running time is 15 hours. From previous experience, running time on Westgrid can vary depending on how busy it is.

Setting	Value
Population size	2000
Parent size	20
Generations	1600
Environment	Westgrid
Number of nodes	20

SIMULATION RESULTS

The objectives were easily satisfied within the search space, therefore optimal designs were selected from the solutions that required the least demanding magnet settings. The greatest demands are on the quadrupoles (Fig. 7), as no solutions exist with small field values for both quads. A list of selected individuals are shown in Table 4. A sample plot of the beam size is shown in Fig. 8, which easily satisfies the objectives. The results, particularly of the quadrupole strength and position, is consistent with results derived from an independent study [10], and lends credibility to the optimization engine.

```
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        <Param name="s_S4"      min="4.2"      max="5.0"      unit="m" />
        <Param name="K1_Q1"     min="0"        max="150"      unit="dimensionl
        <Param name="K1_Q2"     min="-150"     max="0"        unit="dimensionl
        <Param name="s_Q1"      min="5.65"     max="6.05"     unit="m" />
        <Param name="ds_Q1Q2"   min="0.0"      max="0.5"      unit="m" />
</ParamList>

<NDParamList>
        <NDParam name="E_n"     unit="MeV"          comment="" />
        <NDParam name="betx_n"  unit="m"            comment="" />
        <NDParam name="bety_n"  unit="m"            comment="" />
        <NDParam name="alfx_n"  unit="dimensionless"            comment="" />
        <NDParam name="alfy_n"  unit="dimensionless"            comment="" />
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        <NDParam name="sigmax_2"        unit="m"           comment="" />
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        <Objective direction="equals" value="0.01" param="sigmay_2" />
        <Objective direction="minimize" param="B_S4" />
        <Objective direction="minimize" param="K1_Q1" />
        <Objective direction="maximize" param="K1_Q2" comment="defocusing, so 0
</ObjectiveList>

<Topology>
        <Vertex name="a1" type="ASTRA" inputdir="2069X" prereqs="" timeout="600"
        <Vertex name="mad" type="MADX" inputdir="mad" prereqs="a1" timeout="60"
</Topology>
```

Figure 5: XML input for the ICM to dump problem. In addition to defining the decision variables, constraints, and objectives, the input file also specifies connecting variables (variables extracted from the output of Astra and used as the input to MAD-X), and the topology. Note in the bottom Topology tag, the MAD-X vertex lists the Astra vertex as a prerequisite, specifying that the two engines execute in sequential order. Other parameters, including the number of nodes to use, number of generations, file save/load, and unit conversions, are also defined in this file (not shown).

```
# neck, also transition between astra and mad
file1 = "%s/input.0559.001" % sys.path[0]
if os.path.isfile(file1):
        d1  = astra.ReadAstraFile(file1)
        common.SetValue("betx_n", astra.GetBetax(d1))
        common.SetValue("bety_n", astra.GetBetay(d1))
        common.SetValue("alfx_n", astra.GetAlphax(d1))
        common.SetValue("alfy_n", astra.GetAlphay(d1))
        common.SetValue("E_n", astra.GetE(d1))
        common.SetValue("emitx_n", astra.GetXemitrms(d1))
        common.SetValue("emity_n", astra.GetYemitrms(d1))
        common.SetValue("sigmax_n", astra.GetSigmaxrms(d1))
        common.SetValue("sigmay_n", astra.GetSigmayrms(d1))
```

Figure 6: Custom python code for the Astra vertex, which runs after the Astra executable finishes. The code extracts variables that are used as connecting variables to MAD-X, e.g. $betx\_n$ (beta at neck), or in objective functions, e.g. $sigmax\_n$ (beam size at neck). Library functions are given for extracting common properties, e.g. emittance.

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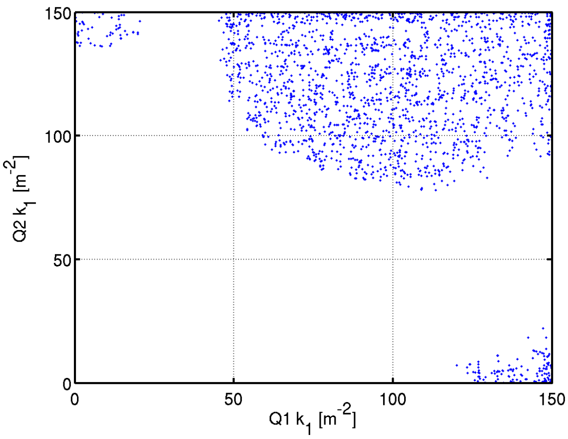

Figure 7: Solution space for quadrupole strengths. No combination of small values can minimize both quads. A k-value of 70 translates to KL = 2300 G. The island in the bottom right with large Q1 and small Q2 corresponds to solutions with Q1 close to the neck point. Here the beam size is very small and the quad does not have much effect. Effects of both quads are therefore minimized and the beam drifts to the dump with $\sigma_x \approx \sigma_y$. The island to the upper left is similar. Why the two islands survived selection is not clear, as they do not satisfy the requirement of large σ_{dump}, but is likely due to minimizing quad strengths as objectives. Table 4 lists designs selected from individuals in the center region of the plot.

CONCLUSIONS

The TRIUMF optimization platform was applied to a multi-engine simulation of the e-linac ICM to dump transport line. Preliminary results are encouraging to the usefulness of the platform. In the near future, the platform will be used on CSR problems and other sections of the e-linac.

Table 4: Individuals selected from the optimized gene pool. For reference, the neck point is defined as z = 5.59 m. End of cryomodule is at 4.09 m. Many individuals satisified the problem objectives. The above were chosen based on magnet restrictions: Sol4<100G, Q1<3000G, Q2<3300G. The quad restrictions causes $\sigma_{dump,y}$ to be smaller smaller than $\sigma_{dump,x}$.

Individual	**1**	**2**	**3**	**4**
Sol4 [G]	49	10	27	6
Sol4 location [m]	4.655	4.630	4.640	4.662
KL, Q1 [G]	2855	2533	2566	2763
KL, Q2 [G]	3029	2895	3204	3167
Q1 location, after neck [m]	0.091	0.086	0.095	0.092
Q2 location, after Q1 [m]	0.319	0.416	0.452	0.312
emit_neck (geometric) [um]	0.411	0.411	0.411	0.411
σ_{neck} **[mm]**	0.669	0.670	0.670	0.670
$\sigma_{dump,x}$ **[mm]**	11.09	10.56	11.11	10.73
$\sigma_{dump,y}$ **[mm]**	7.84	7.02	7.25	8.23

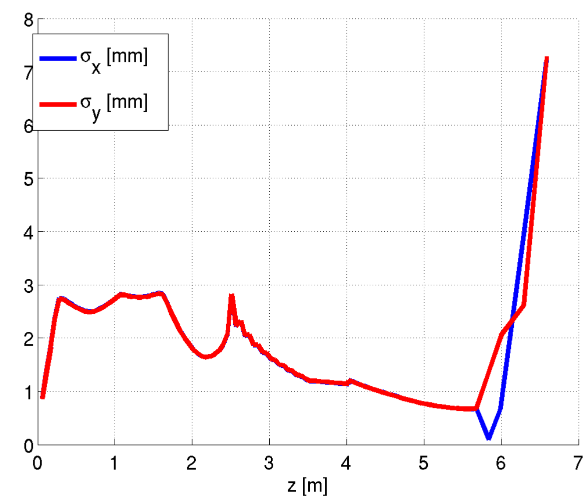

Figure 8: Beam size of one individual in solution space. It satisfies the requirements of small σ_{neck} (z=5.6 m) and large σ_{dump}. The beam pipe can be narrowed at the neck point to prevent backscattering at the dump from damaging the cryomodule upstream. Longitudinal profile of the beam was not studied, as it is not critical to the design objectives.

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