Simultaneously Optimizing Heat Load and Trip Rates in the CEBAF Linacs

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Outline

• Problem
  • Background and Motivation

• Optimization Problem
  • Formulate the optimization problem
  • Optimization method: Genetic Algorithm (GA)

• Earlier Work on the Subject
  • Arne’s JLab Tech Note: GA optimization attempt
  • Geoff’s BTeam Talk: Lagrange multipliers approach

• Results
  • Make contact with earlier work on the subject

• Summary
• **Problem**
  - What is the optimal configuration of cavity gradients needed to maximize science and minimize cost of operation (electricity bill)?
  - Monthly electricity bill for JLab is measured in millions of dollars – a large part of it is cryogenics
    
    *Even modest improvements in cooling may translate into millions in savings*
  - Cooling (cavity heat load) and interrupted operation time (trip rates) are competing objectives – multi-objective optimization problem

• **The goal here:**
  - Provide a set of feasible solutions showing the trade-offs between competing objectives
Formulating the Optimization Problem

- **Independent variables:**
  - Operating cavity gradients $G_i$ [MV/m]
  - Old setup: 160 cavities per linac
  - Search space domain $[3, \text{DRVH}_i]$; below 3 MV/m control system unstable

- **Objective functions (minimize):**
  - **Objective 1:** Cavity heat load
    \[
    P[W] = \sum_{i=1}^{N\text{cavities}} G_i[V/m]^2 \frac{L_i}{c_i Q_i}
    \]
  - **Objective 2:** Trip rate [per hour]
    \[
    T(G_i) = 3600 \sum_{i}^{N\text{cavities}} \exp [A + B_i(G_i - F_i)]
    \]

  - $L_i$: Length of the cavity in meters [C25/C50: $L=0.5m$, C100: $L=0.7m$]
  - $c_i$: Constant [C25/C50: $c=960 \Omega/m$, C100: $c=968 \Omega/m$]
  - $Q_i$: Cavity quality factor [measured]
  - $A$: Unitless constant of the trip model $A=-10.26813067$
  - $B_i$: Model trip slope
  - $F_i$: Fault gradient [MV/m]

- **Subject to constraints:**
  - Energy gain $E$ within 2MeV of the prescribed:
    \[
    \left| E - \sum_{i}^{N\text{cavities}} G_i L_i \right| < 2
    \]
Formulating the Optimization Problem

- We model PVDIS Run from 2009 to make contact with earlier work
- *The GA approach is not tied to a particular configuration*
- *lem.dat* file provides all information needed for the simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>Loaded Q</th>
<th>DRVH&lt;sub&gt;i&lt;/sub&gt;</th>
<th>PASKsigma</th>
<th>No trip model</th>
<th>Parameters used in the simulation</th>
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<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td>( F_i ) [MV/m]</td>
<td>( B_i )</td>
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<td>NL02-1</td>
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<td>12</td>
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<td>9.8</td>
<td>0.057</td>
<td>7.63, 1.19</td>
<td>1.50E+009, 0.5</td>
</tr>
</tbody>
</table>
Optimization Method: Genetic Algorithm

- This is a **high-dimensional, non-linear, multi-objective** optimization problem
- Traditional, gradient-based methods (Newton, conjugate-gradient, steepest descent, etc...) are **not globally convergent**:
  - Get stuck in a local minimum and never come out
  - Final solution depends on the initial guess
  - Direct multi-objective optimization not possible
- Genetic algorithm (GA) is what is needed here: **globally-convergent, multidimensional, multi-objective, robust, non-linear optimization**
- Platform and Programming Language Independent Interface for Search Algorithms (**PISA**) from ETH Zürich and Alternate **PISA** (**APISA**) from Cornell
- We used GAs before on a number of problems in accelerator physics [Hofler, Terzić, Kramer, Zvezdin, Morozov, Roblin, Lin & Jarvis 2013, PR STAB 16, 010101]
- GA simulation is only as accurate as its function evaluator
Earlier Work on the Subject: Arne’s GA Simulation

• Used *perl-based* GA algorithm (for details see JLAB-TN-12-057)
  • *perl* is an interpreted language $\rightarrow$ slow (> 1 day for 150 generations)
    • From the footnote – acknowledgement that we can do better: 
      “Improvements in execution speed of the GA would be possible utilizing a compiled programming language.”
  • From the abstract – study concluded that the GA is *not worth the effort*:
    “The GA yielded a voltage distribution that achieved similar reduction in heat load to the manual approach. The study also suggests that a genetic algorithm is too slow for the real-time needs of CEBAF operations.”

• *Arne’s work provides an important proof-of-concept*

• Key differences between *Arne’s* and *this* implementation
  • 90% of initial population of gradients is ±2 MV/m from initial value
  • Focused on the *premier individual* from each generation (top fitness)
  • Interpreted perl
  • Unbiased sampling of the entire allowed search space \([3, \text{DRVH}_i]\)
  • Provide a Pareto-optimal front of feasible solutions (enable trade-off)
  • Compiled C++
Earlier Work on the Subject: Geoff’s BTeam Talk

- Use Lagrange multipliers to minimize the *heat load only* or *trip rates only*
- Single-objective optimization problem:

**Minimize:**

\[ P(G_i) = \sum_{i=1}^{N_{\text{cavities}}} \frac{G_i^2 L_i}{c_i Q_i} \]

**Subject to:**

\[ T(G_i) = 3600 \sum_{i} \exp[A + B_i(G_i - F_i)] = \text{const.} \]

\[ E - \sum_{i} G_i L_i = 0 \]

**Lagrangian:**

\[ \mathcal{L}(G_i, \lambda) = P(G_i) + \lambda \left( E - \sum_{i}^{N_{\text{cavities}}} G_i L_i \right) \]

\[ \frac{\partial \mathcal{L}(G_i, \lambda)}{\partial (G_i, \lambda)} = 0 \]

\[ \Rightarrow \frac{\partial \mathcal{L}(G_i, \lambda)}{\partial \lambda} = 0 = E - \sum_{i=1}^{N_{\text{cavities}}} G_i L_i \]

\[ \Rightarrow \frac{\partial \mathcal{L}(G_i, \lambda)}{\partial G_i} = 0 = \frac{\partial P(G_i)}{\partial G_i} - \lambda L_i \Rightarrow \frac{\partial P(G_i)}{\partial G_i} = \text{const.} \Rightarrow \frac{G_i}{Q_i} \equiv k_1 \]

\[ k_1 = E/ \left( \sum_{i=1}^{N_{\text{cavities}}} Q_i L_i \right) \]

\[ \Rightarrow \frac{\partial \mathcal{L}(G_i, \lambda)}{\partial G_i} = 0 = \frac{\partial T(G_i)}{\partial G_i} - \lambda L_i \Rightarrow \frac{\partial T(G_i)}{\partial G_i} = \text{const.} \Rightarrow B_i \exp[A + B_i(G_i - F_i)] \equiv k_2 = \text{const.} \]
Earlier Work on the Subject: Geoff’s BTeam Talk

• Single-objective analytical solutions with Lagrange multipliers are pedagogic, but also somewhat useful
  
  • *Give us the limits of the optimization and a reasonable configuration*

Solution A:
Minimize Heat Load
Disregard Trip Rates
Heat Load ~ 1015 W
Trip Rate ~ 6x10^9 per hour

Solution B:
Minimize Trip Rates
Disregard Heat Load
Heat Load ~ 1405 W
Trip Rate ~ 0.74 per hour

Theoretical limits

Not too far off
Earlier Work on the Subject: Geoff’s BTeam Talk

- Single-objective analytical solutions with Lagrange multipliers are pedagogic, but also somewhat useful

  *Give us the limits of the optimization and a reasonable configuration*

Solution A:
Minimize Heat Load
Disregard Trip Rates
Heat Load ~ 948 W
Trip Rate ~ 4x10¹⁴ per hour

Solution B:
Minimize Trip Rates
Disregard Heat Load
Heat Load ~ 1437 W
Trip Rate ~ 0.2 per hour

Theoretical limits

Not too far off
Results

- **GA simulation:** 512 ind. per gen. on MacBook Pro 2.7 GHz Intel Core i7
- Pareto-optimal front – textbook behavior
  - Longer simulation, more generations – better results (front creeps down)
  - Execution time rough estimates: 5 minutes per 1000 generations
• **GA simulation:** North Linac, 512 ind. per gen., 16000 generations

\[ G_i/Q_i = \text{const.} = 1.62 \times 10^{-3} \]

**Solution A:**
Minimize Heat Load

\[ B_i \exp [A + B_i (G_i - F_i)] = \text{const.} = 1.24 \times 10^{-6} \]

**Solution C:**
Minimize Trip Rates
Results

- **GA simulation:** South Linac, 512 ind. per gen., 16000 generations

  - Outliers: Low-Q cavities (as in Geoff’s talk)
    - $G_i/Q_i$
    - $B_i \exp[A + B_i (G_i - F_i)]$

  - **Solution A:**
    - Minimize Heat Load
    - $G_i/Q_i = \text{const.} = 1.52 \times 10^{-3}$

  - **Solution C:**
    - Minimize Trip Rates
    - $B_i \exp[A + B_i (G_i - F_i)] = \text{const.} = 3.68 \times 10^{-7}$
Comparison to Arne’s Results: North Linac

Arne’s Tech Note (Fig. 2)

Trip Rate = 5
Minimum heat load 1285 W

Our Study

Trip Rate = 5
Minimum heat load 1094 W
(7% from the theoretical minimum of 1015 W)

Reduced heat load by 15% in the North Linac
Comparison to Arne’s Results: South Linac

Arne’s Tech Note (Fig. 5)

- Trip Rate = 5
- Minimum heat load 1150 W

Our Study

- Trip Rate = 5
- Minimum heat load 1017 W
  (7% from the theoretical minimum of 948 W)

Reduced heat load by 12% in the South Linac
Summary

• Presented a GA-based multi-objective optimization tool
  • Simultaneous optimization of the heat load and trip rates
  • Provides an entire Pareto-optimal front of solutions
• Performance of C++ prototype:
  • Full simulation: < 3 hours, but can be made faster if needed
  • “Quick peek”: 5-20 minutes
• Can serve as a diagnostic tool pointing out “delinquent” cavities
• Made contact with Arne’s first implementation
• Geoff’s Lagrange multipliers approach provides useful asymptotes

• For PVDIS run, and required ceiling of 5 trip rates per hour, obtained
  • 15% reduction in power consumption in the North Linac
  • 12% reduction in power consumption in the South Linac