OPTIMIZATION OF THE RF CAVITY HEAT LOAD AND TRIP RATES FOR CEBAF AT 12 GEV*

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Abstract

The Continuous Electron Beam Accelerator Facility at Jefferson Lab has 200 RF cavities in the north linac and the south linac respectively after the 12 GeV upgrade. The purpose of this work is to simultaneously optimize the heat load and the trip rates for the cavities and to reconstruct the Pareto-optimal front in a timely manner when some of the cavities are turned off. By choosing an efficient optimizer and strategically creating the initial gradients, the Pareto-optimal front for up to 15 cavities turned off can be established in about 20 seconds.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab provides a continuous polarized electron beam of up to 12 GeV for nuclear physics experimental use in the four experimental halls. CEBAF has two linacs, North and South. Each linac contains 25 cryomodules, each with eight elliptical superconducting radio frequency (SRF) cavities. A total of 200 cavities are implemented in each linac. The configuration of the gradients of the cavities has a dominating effect on the trip rates and the heat consumption of the cavities [1, 2]. Low trip rate is required for stable machine operation, while low heat consumption reduces the operation cost. Previous study [2] on the optimal gradient set for CEBAF at 6 GeV shows that the trip rate and the heat load are competing objectives, and that a set of optimal solutions shows the trade-off between them can be found using the Generic algorithm (GA).

In this report, we implement GA on the newly updated CEBAF at 12 GeV. More important, we investigate how to efficiently create a new gradient profile when some cavities are turned off, based on the result with all the 200 cavities in operation. The optimization that starts from those strategically selected individuals converges to the new optimal results faster than those starting from the ones randomly created. For up to 15 cavities turned off, the new optimal settings for the gradients can be found in a timely manner, which makes it possible to adapt the optimization algorithm into the CEBAF online control system.

SIMULTANEOUS OPTIMIZATION OF HEAT LOAD AND TRIP RATE

Problem Description

The heat load of the CEBAF RF system is calculated as

$$P(\boldsymbol{G}) = \sum_{i=1}^{N_c} \frac{G_i^2 L_i}{c_i Q_i(G_i)}, \tag{1}$$

where N_c is the cavity number, $\boldsymbol{G} = (G_1, G_2, \ldots, G_{N_c})$ the cavity gradients, L_i the cavity length, c_i the shunt impedance, Q_i the measured cavity quality factor. G_i is measured in MV/m and restricted in [3, D_i], with D_i the maximum gradient for each cavity. $L_i = 0.5$ m, $c_i = 960$ Ω/m for the C25/C50 cavities, and $L_i = 0.7$ m, $c_i = 968$ Ω/m for the C100 cavities. In general, Q_i is a function of the gradient G_i. But in the following calculation, Q_i is treated as a fixed number for each cavity. The trip rate (per hour) has an exponential model [3] as

$$T(\boldsymbol{G}) = 3600 \sum_{i=1}^{N_c} \exp[-10.268 + B_i(G_i - F_i)], \tag{2}$$

where B_i is the model trip slope and F_i the fault gradient. Both B_i and F_i are obtained by fitting the history data in the trip record. Those cavities without enough recorded data are treated as if they never trip. The energy gain through each linac should be within a tolerance τ_E to the prescribed energy E_{linac}, which is 1150 MeV. The value of τ_E is 2 MeV [1, 2] in the following if not specified. To simultaneously minimize the heat load and the trip rate, we need to solve a multiobjective, multidimensional, constrained optimization problem, described as

$$\begin{aligned} &\text{Minimize } P(\boldsymbol{G}), T(\boldsymbol{G}) \\ &\text{Subject to } \left|E_{\text{linac}} - \textstyle\sum_{i=1}^{N_c} G_i L_i\right| < \tau_E, \\ &\qquad\qquad 3 \le G_i \le D_i. \end{aligned} \tag{3}$$

Optimization with All Cavities On

The PyGMO/PaGMO package [4] was used to solve the optimization problem in Eq. (3). The package provides a convenient Python interface for a collection of efficient optimizers developed in C++. After investigating some of the optimizers, we choose nsga_II (Non-dominated Sorting Genetic Algorithm) for the best efficiency. It is straightforward to implement the optimizer on the problem in Eq. (3) and find the Pareto-optimal front (PF). Shown in Fig. 1 are the PFs for the both linacs, each operating with all the 200 RF cavities on, after running nsga_II for 30,000 generations with 128 individuals. An individual is a group of valid gradients that satisfy the constraints and a PF is composed of 128 individuals in each generation, each of which is not inferior to any others. The PF gives us a guide to find the gradients with the lowest energy cost for an expected trip rate or the lowest trip rate for an expected energy cost.

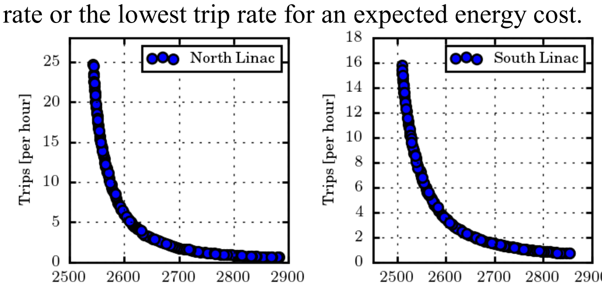

Figure 1: PF with all the 200 cavities.

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Optimization with Some Cavities Off

In practice, we may not be able to use all the cavities, so we need to find the PF again when some cavities turn off. One can start the optimization from randomly generated individuals for each different group of cavities, but this is usually not very efficient. Now the question is, knowing the PF with all the 200 cavities (PF200), can we find a fast way to construct the new PF with n cavities off (PFm, $m = 200 - n$)?

In [2], it is shown that starting with the initial population using the gradients in PF200, one can reduce the computation time for PF199 or PF198 by half. However, using the gradients in PF200 with fewer cavities will reduce the energy gain. When there are many cavities off, the energy constraint in Eq. (3) may not be satisfied, hence those individuals are not good candidates any more. Especially, when a penalty method is used to handle the constraints, the optimizer may fail if all the individuals violates the constraint. An easy fix is to scale up the gradients so that the energy gain satisfies the constraint. The procedure could be described as follows: (1) Calculate the difference, δE, between the desired energy gain with the supplied energy gain by the available cavities; (2) Calculate the rate: $R = \delta E / E_{\text{Linac}}$; (3) Set the new gradients as $G_{i,\text{new}} = \min((1+R)G_i, G_{i,\max})$; (4) Repeat from step (1) until the energy constraint is satisfied. The individuals generated by this method are shown in Fig. 2, with up to 15 cavities turned off for both linacs. As one can see, when n is small, the individuals form a concave curve similar to the PF. As n increases, the individuals have a clear tendency to fall into the high trip rate region. For the north linac, when n is larger than 10, the individuals do not form a concaved curve any more, although they are probably still better than the ones generated randomly. An example of the PF185s for the both linacs is shown in Fig. 3. The lowest trip rate is about 20/hour for the north linac and 10/hour for the south linac. From the perspective of machine operation,

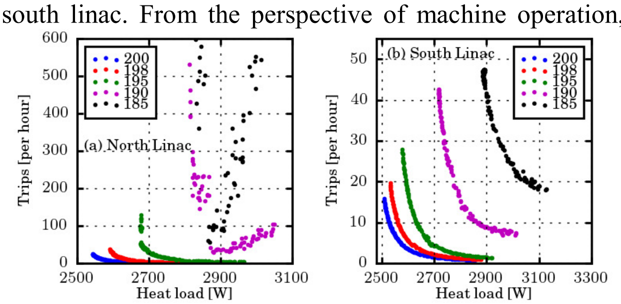

Figure 2: Initial population by gradient scaling.

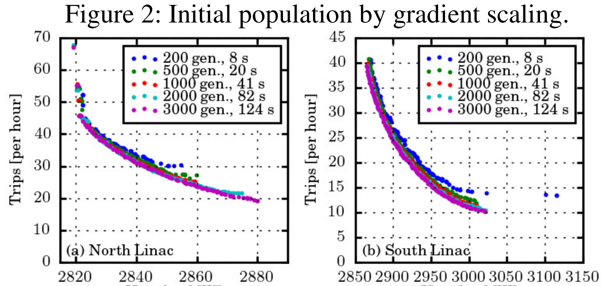

Figure 3: PF185 obtained from the initial population by gradient scaling.

individuals with smaller trip rate are preferred. The new question is how to create initial population of individuals with smaller trip rates, which helps to further extend the PF to the low trip rate region.

In the following, we discuss two possible ways to generate individuals with low trip rates. One way is to use the derivatives of $P(\boldsymbol{G})$ and $T(\boldsymbol{G})$ with respect to the gradients $\boldsymbol{G}$ as a guide when we rescaling the gradients for energy constraint. Both derivatives can be calculated easily from Eq. (1) and Eq. (2). We choose $dP/d\boldsymbol{G}$ because the trip rate data is not complete and $dT/d\boldsymbol{G}$ cannot be calculated for some cavities. $dP/d\boldsymbol{G}$ tells us how much the heat load will change when the gradient changes. It also implicitly indicates the change of trip rate. Because the heat load and the trip rate are competing objectives, a larger increase of the heat load tends to result in a smaller increase of the trip rate. So in order to generate individuals with lower trip rates, we should make larger increase of gradient for cavities with larger $dP/d\boldsymbol{G}$. The revised rescaling algorithm includes the following steps: (1) Calculate the energy difference δE; (2) Calculate the derivative of heat load for each cavity $\frac{dP}{dG_i} = \frac{2G_iL_i}{c_iQ_i}$; (3) The change of gradient for each cavity is $\Delta G_i = \left(\frac{dP}{dG_i}\right)^2 K$, with $K = \frac{\delta E}{L_i}\left(\frac{dP}{dG_i}\right)^{-2}$ and L_i is the length of the i-th cavity; (4) Set the gradient for each cavity as $G_{i,\text{new}} = \min(G_i + \Delta G_i, G_{i,\max})$; (5) Repeat from step (1) until the energy constraint is satisfied. The individuals generated by the improved scaling algorithm are shown in Fig. 4. Clearly these individuals have lower trip rates if compared with those generated by simple scaling in Fig. 2. The difference is significant for $n > 10$. The PF with 15 cavities off we achieved starting from these individuals are shown in Fig. 5. The lowest trip rate for the north linac is brought down from 20/hour to 8/hour, that for the south linac from 12/ hour to 4.5/hour. The other way is to find

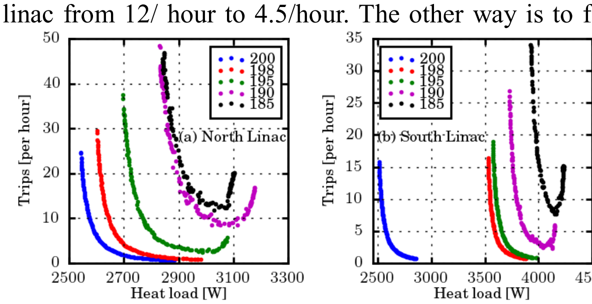

Figure 4: Initial population by gradient scaling guided with heat load derivatives.

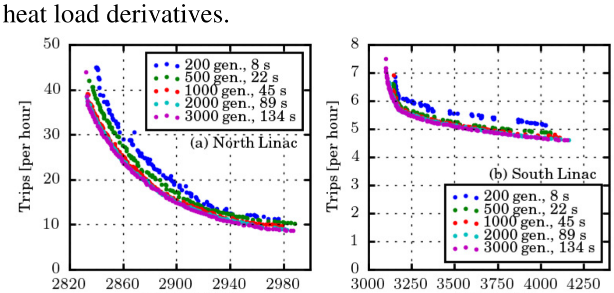

Figure 5: PF185 obtained from the initial population by gradient scaling guided by heat load derivatives.

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some individuals with small trip rate and add them into the initial population. If we want to get the lowest trip rate without caring about the heat load, this single-objective optimization can be solved by the Lagrangian multiplier method. Given the total energy, the optimized gradients that give the minimum trip rate can be calculated as in [2]. We can select a few (multiple of four as required by the optimizer) energies within the energy constraint, calculate the gradients for minimum trip rate, and add these gradients into the population generated by the simple scaling method. During the optimization, the information of these individuals with minimum trip rates will be transferred to the other individuals, thus the PF will be brought down to the low trip rate region. Optimization for the same group of cavities with 15 down as in Fig. 3 and Fig. 5 has been repeated. The PF185s were plotted in Fig. 6. For the north linac, the lowest trip rate is 8/hour. For the south linac, the lowest trip rate is 5/hour.

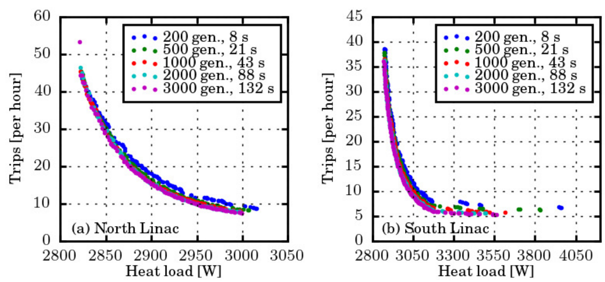

Figure 6: PF185 obtained from the initial populations including four trip rate minimized individuals.

Comparing the PF185s in Fig. 3 Fig. 5 and Fig. 6 achieved from different initial populations, there are a few points we want to note here. (1) The simple scaling methods works well when the number of cavities turned off is small. If there are more than 10 cavities turned off, the PF obtained from the simple scaling individuals tends to lose the low trip rate region. (2) The PF can be extended to the low trip rate region by using the improved scaling method or by adding a few individuals with lowest trip rate into the initial population. For the north linac, the performance of the two methods is very similar. For the south linac, PF by the improved scaling method missed the higher trip rate (lower heat load) region, while the PF by the other method covers a more extensive region. (3) The PF after 500 generations of nsga_II is very close to the PF after 3000 generations, and may be good enough in practice. It takes about 20 seconds to run nsga_II for 500 generations with 128 individuals on a laptop PC with Intel i7-3630QM 2.4 GHz CPU, which allows us to build up a fast response optimization system.

Compare with the Current System

In the following, we compare the two-objective optimized results with the result from the current LEM program [1], which only minimize the trip rate.

The first example is the north linac with 195 cavities in operation (5 turned off). The gradients by the LEM program provides an energy gain of 1050.43 MeV. The heat load is 2984.51 W and the trip rate is 1.57/hour. The PF195, with $\Delta E \leq 0.5$ MeV, is calculated and presented together with the LEM result in Fig. 7 (left). As expected, the LEM result, which minimizes only the trip rate, is close to the low trip rate tail of the PF195. From the PF195, we pick an individual having the same trip rate with the LEM result. The energy of this individual is 1049.50 MeV and the heat load is 2938.35 W. For a very small energy deviation, the heat load is reduced by 46.16 W. In Fig. 7 (right), we compare the change of the gradient of each cavity for the selected individual with the LEM result. There is one cavity with a change larger than 60%, two between 20% and 30%, 14 between 10% and 20%, and all the others less than 10%.

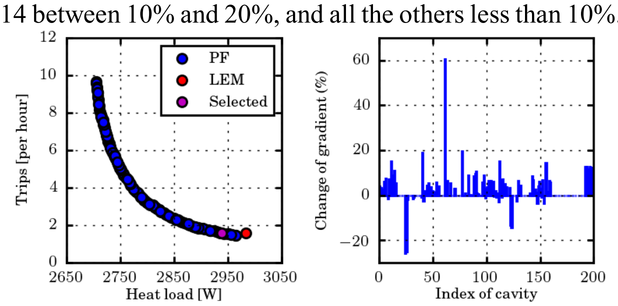

Figure 7: Compare PF with LEM result for the north linac

The second example is the south linac with 187 cavities in operation (13 off including a whole cryomodule of eight cavities). The LEM result provides an energy gain of 1045.62 MeV. The heat load is 2972.37 W and the trip rate is 2.09/hour. As shown in Fig. 8(left), the LEM result lies close to the low trip rate tail of the PF187. An individual on the PF187 with the same trip rate can be found, which provides an energy gain of 1045.54 MeV. The heat load is 2929.29 W, 33.08 W lower than that of the LEM result. Comparing the required changes in, one gradient changes more than 40%, one between 20% and 30%, five between 10% and 20%, and all the others less than 10%. For both cases, the heat load can be further reduced if a higher trip rate is acceptable.

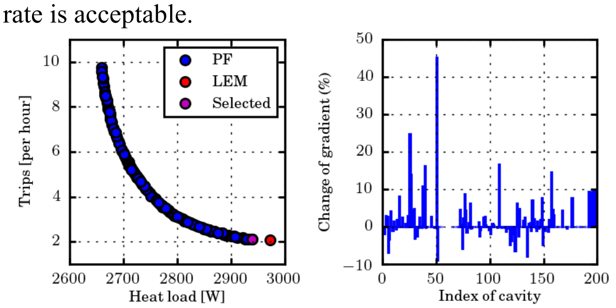

Figure 8: Compare PF with LEM result for the south linac.

SUMMARY

We implemented the GA (nsga_II) algorithm to simultaneously optimize the heat load and the trip rate of the CEBAF 12 GeV RF system. Based on the PF found for all the 200 cavities in operation, the new PF covering a wide range, with up to 15 cavities turned off, can be found in about 20 second, if we strategically create the initial population. Comparing with the current LEM program, we see the PFs for the two-objective optimization provide a guide for heat load reduction, keeping the trip rate in reasonable level.

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