RECENT IMPROVEMENTS TO SOFTWARE USED FOR OPTIMIZATION OF SRF LINACS*

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Abstract

This work describes a software tool that allows one to vary parameters and understand the effects on the optimized costs of construction plus 10 year operations of an SRF linac, where operation costs includes the cost of the electrical utilities but not the labor or other costs. The program includes estimates for the associated cryogenic facility, and controls hardware. The software interface provides the ability to vary the cost of the different aspects of the machine as well as to change the cryomodule and cavity types. Additionally, this work will describe the recent improvements to the software that allow one to estimate the costs of energy-recovery based linacs and to enter arbitrary values of the low field Q_0 and Q_0 slope. The initial goal when developing the software was to convert a spreadsheet format to a graphical interface and to allow the ability to sweep different parameter sets. The tools also allow one to compare the cost of the different facets of the machine design and operations so as to better understand tradeoffs. An example of how it was used to independently investigate cost optimization tradeoffs for the LCLS-II linac will also be presented.

SOFTWARE DESCRIPTION

The software allows one to vary the input costs and operating parameters in order to meet requirements of the machine and regionally driven cost metrics. It is described more fully in references [1] and [2]. There are three variations of the program. The first two allow one to sweep the RF frequency for a selected gradient and beam current. In one variation the cryomodules are not causal in that the calculations use a fractional number of cavities and keep the active length per cryomodule constant. The second variation maintains a relatively constant active length per cryomodule by increasing the number of cells per cavity and cavities per cryomodule with user selectable break points. The third model allows the user to select from a number of different cryomodule types or to provide their own cryomodule parameters (number of cavities, frequency, active length per cavity, shunt impedance, etc.). In all cases the program is meant to give trends, cost minimums, etc. but not to provide an absolute cost for developing and building a linac, as a detailed estimate must take into account matters such as detailed design tradeoffs, local costs, schedules, etc.

Input – Output Parameters

The majority of the input parameters are shown in Figure 1. There are two general terms for cryogenic losses. The first is static losses associated with each of the SRF cryomodules, transfer lines, its associated valve box, and per kilometer transfer line losses. These are user inputs to the program. The second is RF driven, or dynamic, losses which are determined on a cavity by cavity basis. Q_0 losses include the electromagnetic field losses in the cavity walls, RF induced 2 K heat load in the fundamental power couplers, higher order mode couplers, bellows, etc. There are three different approaches for determination of Q_0. Q_0 losses are determined based on the cavity geometry, operating temperature, material type and processing techniques which are all input variables to the program. This information can be used to calculate Q_0 losses based on a statistical analyses of vertical test results performed at Jefferson Lab over the past 20 years[3]. Alternately, once one has selected a frequency and cavity type, one can enter a baseline Q_0 value and slope into the program. The third method which is fully described in reference [4] is based on the field-dependent BCS RF surface resistance model of Xiao with the electron mean free path set to 50 nm. Care must be taken when considering Q_0 calculations based on these methods as there are degradations between vertical tests and cryomodule tests, as well as long term degradation of the Q_0 under operational conditions.

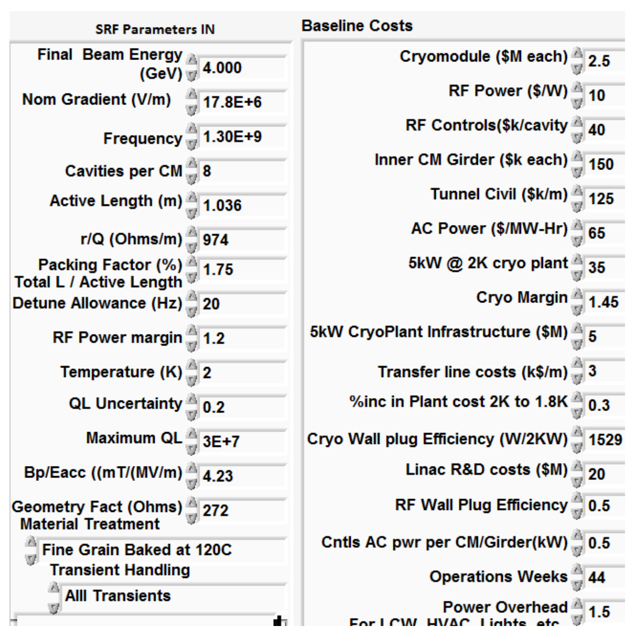

Figure 1: User input screen for input variables.

The output parameters include items such as the total construction costs, operating costs, and SRF parameters.

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They are calculated for each value of the swept input variable. They are available in the form of graphs as well as in a text file. Figure 2 shows a typical graphical interface with pull down menu shown for one of the graphs.

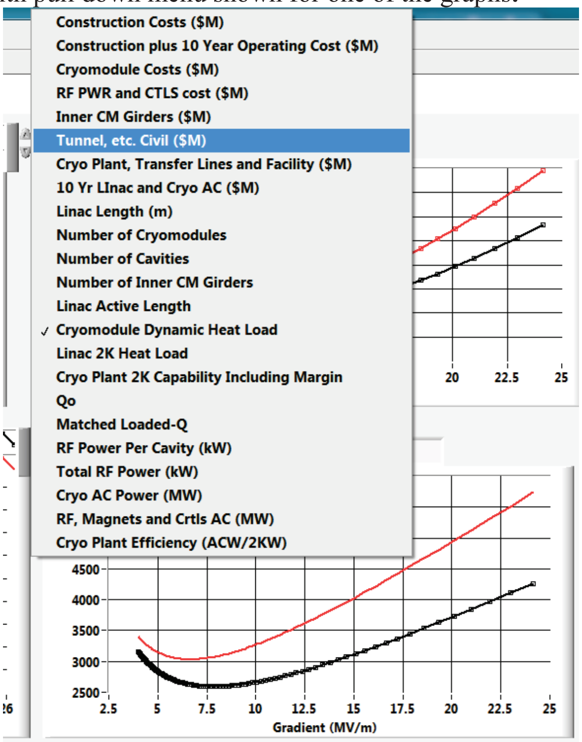

Figure 2: Typical output plots and selector control for plots showing output parameter list.

Calculating Loaded-Q and RF Power

The matched loaded-Q is the loaded-Q such that the installed RF power is minimized. The selected loaded-Q values depend on the whether the RF power can maintain gradient regulation under all transient beam loading conditions or only in a steady-state condition. It is calculated based on equations found in references [1] and [2]. Once the matched loaded-Q is determined, it is used along with the detune frequency budget, the uncertainly in the loaded-Q and the remainder of the cavity parameters to calculate the permutations on the forward power necessary for operation at each point in the parameter sweep. The maximum value of this data set is used as the minimum RF power required. This is multiplied by the RF power margin to determine the RF power required by each cavity. Another recent addition to the program allows one to enter the ERL beam current parameters as well as the tune-up beam, which is not energy recovered and is often the limiting factor for RF power requirements in applications using ERLs.

Cryogenic System Costs

The baseline plant and infrastructure costs were based on the 5 kW at 2 K plant that was built as part of the CEBAF 12 GeV upgrade [5]. One major assumption is that the ratio of 50 K shield power to 2 K power is similar to that in CEBAF. Another critical aspect of the actual costs is that the plant was designed by, major components procured by, and the system integrated by Jefferson Lab staff. Were the plant to be procured as a turn-key plant the costs would likely be significantly higher. The procurement, installation and commissioning costs scaling is given in Equation (3):

$$Cost_{Power} = Cost_{2.05K}\left(\frac{Power_{2.05K}}{5{,}000}\right)^{0.7} \qquad (3)$$

where $Cost_{Power}$ is the overall cost of a 2.05 K plant at $Power_{2.05K}$, and $Cost_{2.05K}$ is sum of the two input cost parameters of 5 kW at 2 K Plant costs and 5 kW Plant Civil costs.

The wall plug efficiency, being the ratio of the total AC power divided by the 2.05 K power, was determined by plotting the wall plug efficiency achieved by several existing plants used at accelerators [6] and generating a third order fit between 800 W and 5 kW at 2 K. It includes all AC power including warm compressors. Cooling towers, HVAC, lighting, etc. are included as part of a separate line item based on the overall power budget. The wall plug efficiency changes between 2.0 K and 1.8 K take into account the Carnot work and Carnot efficiency and adds another 20% to the power requirement. The plant cost was increased linearly by 30% between 2.05 K and 1.8 K [7]. It should be noted that these are just estimates and it is critical that any final design of the cryogenic plant be closely coordinated with the design of the cryomodules in order to optimize the overall cost [8, 9].

Figure 3 shows the cost and efficiency estimates used for the cryogenic plant as a function of "2 K" power. The steps at 5 kW and 3.8 kW for the 2 K and 1.8 K systems were based on the practical aspect of building and shipping the components [5]. The primary issue is shipping an assembled cold box by truck. Above these power break points the plant must be split into two sections. The efficiency steps up to match that of the smaller plant.

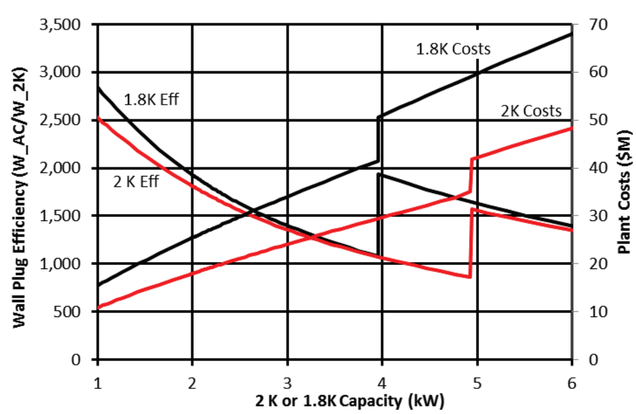

Figure 3: The wall plug efficiency and facility plant procurement costs for a helium refrigerator operated at 2.0 K and 1.8 K.

RESULTS

Descriptions of the results of linac costs as a function of operating frequency were provided in references [1] and

[2]. In general, for a 2 GeV linac using Q_0 values calculated based on historical vertical test measurements, the cost is optimized between 700 MHz and 1 GHz. This optimum is a strong function of the assumed value of Q_0 and may change depending on the required energy, cavity microphonics, and cavity efficiency.

The following figures are the results for the LCLS-II linac, which is a 4 GeV, 300 µA linac. The plan is to build it using XFEL style cryomodules containing 8, 9-cell cavities. It should be noted that in order to obtain the Q_0 in the model of 2.7×10^{10}, one would need to process the cavities using the newly developed nitrogen doping process [10, 11]. In addition to the Q_0 heat load, an extra 10% was added to the cryogenic margin to address the extra heat load due to HOM losses as well as the extra heat load due to the 5 K cooling circuits. Two cases are presented; one with full civil construction costs included and a second with minimal civil construction costs which is the case for LCLS-II.

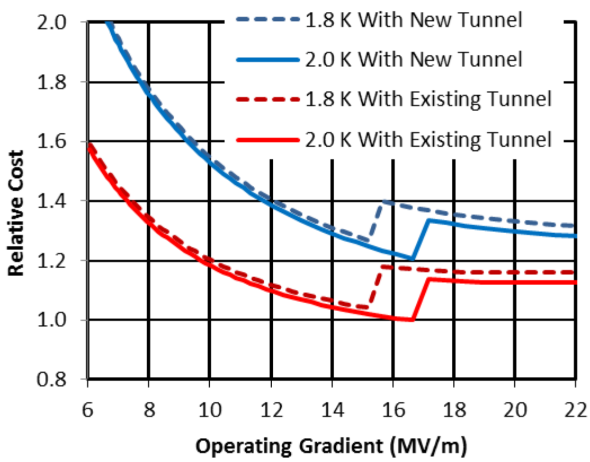

Figure 4: Relative cost of a 4 GeV linac plus 10 years of electrical power as a function of gradient and temperature for the case of using an existing accelerator enclosure and building a new accelerator enclosure.

Figure 4 indicates that there is a slight cost advantage in operating the machine at 2.0 K and that having an existing accelerator tunnel would save approximately 20% on the linac costs. Further it indicates that the optimum operating point is about 16 MV/m. Figure 5 shows the relative cost breakdown for the same cryomodule configuration for the case including the cost of an accelerator enclosure. One can see that the cost drivers at the lower gradients are the cryomodule and civil construction costs. At higher gradients there is a step increase in cryogenic costs as the system exceeds a 5 kW or 3.8 kW cryogenic plant rating for 2.0 K and 1.8 K operating points, respectively. After that point the combination of the cost of the cryogenic facility and the 10 year electrical power costs become a significant fraction of the cost.

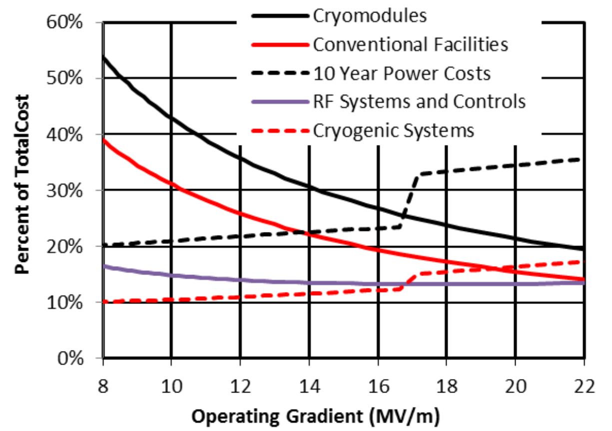

Figure 5: Relative cost breakdown for the components used in determining the cost for the XFEL-style cryomodule based linac operated at 2.0 K including building an accelerator enclosure.

CONCLUSIONS

These tools allow one to better understand the tradeoffs relating to the top level design parameters of an SRF linac. They allow one to make adjustments to the baseline costs, cavity parameters, machine packing factors, etc. on the fly and to get a quick feedback as to the impact. The cost estimates for the individual items within the program will need to be determined on a machine by machine, and location by location basis. Any use of the results of the simulation in its current state should be done with care. For example, simple things such as inclusion of field emission onset, or Q-slope changes at lower frequencies, can dramatically change the optimum operations frequency, as both would tend to degrade high field operations. Inclusion of high field Q-slope will lead to increases in costs at the higher field levels and may lead to lower optimized field. Although we have made good progress in developing the tools for understanding machine cost tradeoffs, more work is necessary in order to understand all of the impacts of the different parameters.

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