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# OPERATIONAL OPTIMIZATION OF LARGE-SCALE SRF ACCELERATORS\*

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## Abstract

Unlike other types of accelerator subsystems, because of the flexibility in setting the gradient in each cavity, an SRF linac has many operational degrees of freedom. The overall linac has an operational envelope (beam voltage and current) that depends on acceptable reliability, cryogenic capacity, and RF power budget. For economic and end-user physics reasons, one typically wants to run as close to the edge of the operational envelope as possible. With about 160 cavities in each of the CEBAF linacs, we have been forced to treat this problem in a very general way, and satisfy other non-fundamental needs as energy lock and rapid recovery from failures. We present a description of the relevant diverse constraints and the solution developed for CEBAF.

## 1 GOALS

We seek a method for choosing the accelerating voltage for a large set of cavities, such that the behavior of the set as a whole is optimized. The aggregation of cavities has exactly four properties that we care about: the total voltage delivered to the beam, the amount of beam current it can carry while maintaining voltage regulation, the amount of cryogenic losses, and the frequency of trips. The optimization could, in general, be based on any restrictions and figures of merit that depend on these four quantities. In practice, the simplest arrangement is satisfactory, where individual parameters can be fixed, constrained, or floating.

## 2 PRELIMINARIES

Table 1: notation

|          |                                   |
|----------|-----------------------------------|
| $V$      | Cavity voltage                    |
| $I$      | Beam current                      |
| $W$      | RF power                          |
| $R_c$    | coupling impedance, $Q_L(R/Q)$    |
| $R_d$    | dissipation impedance, $Q_0(R/Q)$ |
| $\delta$ | Detune angle, radians             |

Table 1 shows the notation used. The operating voltage of the SRF cavities at CEBAF is constrained by four very specific limitations:[1, 2]

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### 2.1 Hard limit

During commissioning, a safe upper bound for operation is determined. This may be a safe margin below a quench, or the point at which X-ray fluxes are deemed dangerous for long term operation of equipment near the cavity. If nothing else, it is the highest field achieved during commissioning, since there is no positive evidence showing safe operation above that point.

### 2.2 RF Power budget

Given a long series of assumptions about the cavity and its RF system, it is straightforward to compute the amount of RF power required to run the cavity at any specified gradient and beam current. Given a value for available RF power (at which there is still adequate gain for feedback), and the overall linac beam current, an upper limit on the each cavities voltage can be computed. This expression is postponed until later in the paper.

### 2.3 Trip limit

Given trip rate as a function of voltage (assumed to be well known)  $R(V)$ , the formal condition of balance is that all cavities limited by this phenomenon have the same value of  $\partial R/\partial V$ . This means that shifting a Volt of beam energy gain from one of these cavities to another will not change the total machine trip rate.

### 2.4 Cryogenic capacity limit

Given cryogenic dissipation as a function of voltage (assumed to be well known)  $C(V)$ , the formal condition of balance is that all cavities limited by this phenomenon have the same value of  $\partial C/\partial V$ . This means that shifting a Volt of beam energy gain from one of these cavities to another will not change the total machine cryogenic dissipation. This limit has not yet been an issue at CEBAF, but will soon become one as the energy is pushed to 6 GeV and beyond. The cryogenic limit will become severe in the planned energy upgrade.

## 3 SYNTHESIS

Given a complete description of each cavities capabilities, and the three global constructive parameters  $I$ ,  $\partial R/\partial V$ , and  $\partial C/\partial V$ , a setpoint voltage for each cavity can be computed, which is the lowest of the four limits. This set of

cavity voltages represents one possible complete and balanced accelerator configuration.

These three constructive parameters completely span the space of rational configurations, so choosing a setup involves a search in these three dimensions, a great improvement over the 160 cavities in each linac at CEBAF. Of course, CEBAF's users and operators can not be expected to choose  $\partial R/\partial V$  and  $\partial C/\partial V$  by themselves to give the desired linac energy, stable cryogenic operation, and tolerable trip rate. Software has to be constructed to aid them in that search. That magic word "search" implies the ability to compute derivatives, so that the process can converge rapidly.

The expression for the power needed for a given voltage, current, and detune angle is

$$W = \frac{1}{4R_c} |(1 + j\delta)V + R_c I|^2$$

The expression can be inverted to find the cavity voltage limit due to available RF power

$$V = \frac{1}{1 + \delta^2} \left[ \sqrt{4WR_c(1 + \delta^2) - I^2 R_c^2 \delta^2} - IR_c \right]$$

In this case  $I$  is considered the globally tunable parameter.

$$\frac{\partial V}{\partial I} = -\frac{R_c}{1 + \delta^2} \left[ \frac{IR_c \delta^2}{\sqrt{4WR_c(1 + \delta^2) - I^2 R_c^2 \delta^2}} + 1 \right]$$

This technique works as long as one can construct a unique cavity voltage limit from  $t_R = \partial R/\partial V$  (this can be thought of as a "tune parameter"), and the function  $V(t_R)$  for each cavity is non-pathological, so that small changes in  $t_R$  can be used to make small changes in total linac energy. The implementation to date assumes

$$R(V) = e^{a+bV},$$

where  $a$  and  $b$  empirically parameterize observed trip rates. From this we derive

$$V(t_R) = \frac{1}{b} \left[ \ln \frac{t_R}{b} - a \right]$$

$$\frac{\partial V}{\partial t_R} = \frac{1}{bt_R}$$

$$\frac{\partial R}{\partial V} = be^{a+bV}.$$

This technique also requires that one can construct a unique cavity voltage limit from  $t_C = \partial C/\partial V$  (this can be thought of as another "tune parameter"), and the function  $V(t_C)$  for each cavity is non-pathological, so that small changes in  $t_C$  can be used to make small changes in total linac energy. The implementation to date assumes

$$C(V) = \frac{V^2}{R_d},$$

where  $Q_0$  is measured at the time of cavity commissioning. From this we derive

$$V(t_C) = \frac{1}{2} t_C R_d$$

$$\frac{\partial V}{\partial t_C} = \frac{1}{2} R_d$$

$$\frac{\partial C}{\partial V} = \frac{2V}{R_d}.$$

Each of the above expressions is written in the single cavity form. The voltage  $V$  actually selected for a cavity is the lowest of  $V(I)$ ,  $V(t_R)$  and  $V(t_C)$ . The overall ensemble  $R$  and  $C$  are clearly summations of the individual cavity amounts, where the actual cavity voltage is used for each cavity. The ensemble derivatives  $\partial V/\partial I$ ,  $\partial V/\partial t_R$ , and  $\partial V/\partial t_C$  need some care—a cavity only contributes to the sum corresponding to its limit.

## 4 SPACE EXPLORATION

As mentioned earlier, a rational ensemble setup is based constructively on the values of the three tune parameters,  $I$ ,  $t_R$ , and  $t_C$ . Four "result" terms are  $V$ ,  $I$ ,  $R$ , and  $C$ . One expects that any three of these may be specified, and the fourth solved for (along with the tune parameters, and therefore the exact setup). While in general a set of non-linear equations can be quite pathological, or at least have multiple solutions, the monotonic relations we have chosen between, e.g.,  $t_R$ ,  $R$ , and  $V$  make it very generally true that solutions, when they exist, are unique. It is, of course, true that asking to solve for unreasonable values of the "result" terms will give a null answer.

The current implementation allows searches for any three given values of  $V$ ,  $I$ ,  $R$ , and  $C$ . One can also directly provide  $I$ ,  $t_R$ , and  $t_C$ .

## 5 GRITTY DETAILS

Other functionality than the pure theory has to be accreted to the core before the lab has a usable software tool:

- Acquisition and control of all the input
- Operator override of specific troublesome cavities
- Computation and setting of the quadrupoles (sensitive to the energy profile down the linac)
- Smooth changes to the cavity gradient (don't overrun the tuners or the module heaters)
- Operator interface

The implementation of all these requirements was purposefully quite modular. The inner math program has no user interface or control system dependence; those features are implemented as separate programs, with simple data streams and handoff rules between them.

A fringe benefit of this modularity is that the (debugged, ready-to-run) inner math program is available for scans of parameter space. A total of 67 lines of sh and perl suffice

to generate figures 1 through 4 by repeatedly invoking the math program to do the actual calculations.

These figures show that the nominal relationship between voltage and cryogenic load ( $C \propto V^2$ ) breaks down when the machine operates near its voltage or RF power maximum. Similar slices can be taken for other combinations of beam current, trip rate, beam energy, and cryogenic losses.

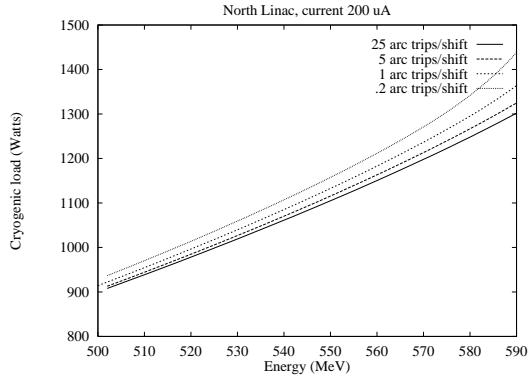


Figure 1: Variation with energy of the Cryogenic Load generated by CEBAF's North Linac, with RF headroom to sustain 200  $\mu$ A beam loading and various trip rates.

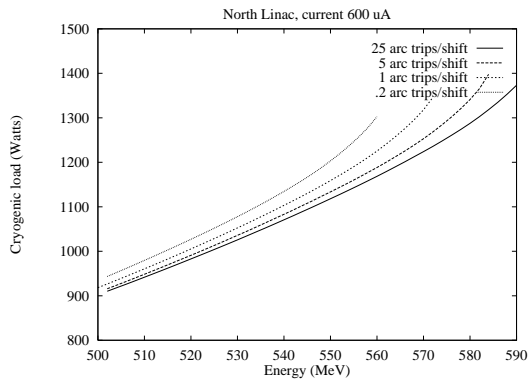


Figure 2: Variation with energy of the Cryogenic Load generated by CEBAF's North Linac, with RF headroom to sustain 600  $\mu$ A beam loading and various trip rates.

## 6 CONCLUSIONS

It is interesting to note that no single phenomena even represents a majority limitation in the machine under our current high energy setups (5.5 GeV, 600  $\mu$ A). This could be construed as a sign of several poorly controlled manufacturing steps (such as the wide range of cavity voltages showing onset of field emission). It can also be argued that this is a natural consequence of efficient design where most subsystems are not overdesigned[3] (such as with the sizing of the cryogenic refrigerator).

This pattern of large, complex systems, bounded by a complex envelope, is likely to recur in the accelerator com-

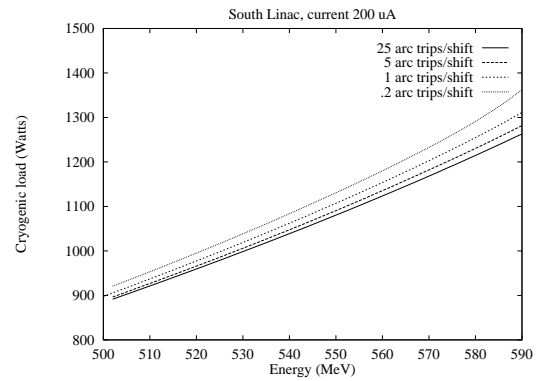


Figure 3: Variation with energy of the Cryogenic Load generated by CEBAF's South Linac, with RF headroom to sustain 200  $\mu$ A beam loading and various trip rates.

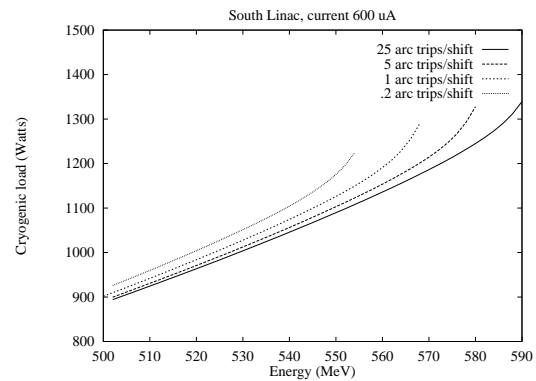


Figure 4: Variation with energy of the Cryogenic Load generated by CEBAF's South Linac, with RF headroom to sustain 600  $\mu$ A beam loading and various trip rates.

munity. Modern trends of careful design and simulation, applied to large, costly projects, will tend to create situations where many phenomena interact in the final operation of the device. Work such as this can make an important contribution to actually achieving performance at the edge of the predicted envelope.

While more complex models would improve the realism of the simulated performance, the dominant source of error at the moment seems to be our inability to accurately measure some of the parameters of the simple model. One lesson to the designers and builders of large scale systems, therefore, is the necessity of embedding adequate in-situ measurement capability.

## 7 REFERENCES

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- [3] Henry Petroski, "To Engineer is Human," Random House, New York, 1992 and "The Deacon's Masterpiece," by Oliver Wendell Holmes, referenced and copied therein.