

SRF PERFORMANCE OF CEBAF AFTER THERMAL CYCLE TO AMBIENT TEMPERATURE *

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Abstract

In September 2003, in the wake of Hurricane Isabel, JLab was without power for four days after a tree fell on the main power lines feeding the site. This was long enough to lose insulating vacuum in the cryomodules and cryogenic systems resulting in the whole accelerator warming up and the total loss of the liquid helium inventory. This thermal cycle stressed many of the cryomodule components causing several cavities to become inoperable due to helium to vacuum leaks. At the same time the thermal cycle released years of adsorbed gas from the cold surfaces. Over the next days and weeks this gas was pumped away, the insulating vacuum was restored and the machine was cooled back down and re-commissioned. In a testament to the robustness of SRF technology, only a small loss in energy capability was apparent, although individual cavities had quite different field-emission characteristics compared to before the event. In Summer 2004 a section of the machine was again cycled to room temperature during the long maintenance shutdown. We report on the overall SRF performance of the machine after these major disturbances and on efforts to characterize and optimize the new behavior for high-energy running.

INTRODUCTION

CEBAF was conceived as a 4 GeV machine and achieved it's design energy soon after initial cool-down in 1991-1993. Since that time the energy has been steadily increased by helium processing and gradual relaxation of operational constraints to almost 6 GeV. Because such improvements were possible the original plan to refurbish two cryomodules per year was not implemented. However as cavities were raised to ever higher gradients many were pushed into the regime of heavy field emission. The CEBAF cryomodule design utilizes a cold ceramic window close to the cavity that exhibits cyclic charging up and discharging when the cavities are run in this way. Cold-window discharge often triggers either a waveguide arc, if the flashover is on that side, or cavity breakdown if the flashover is on the beamline side. In either case the machine fast shut down (FSD) is triggered and the beam is shut off. Each such event takes an operator intervention to recover and restore beam and costs some operational time. Each cavity related FSD is logged and over time detailed models of cavity arc rate vs gradient have been developed. The Linac Energy Management program (LEM) uses these models to balance the gradients in all cavities to minimize the total machine arc rate. Using these methods the machine energy was increased to 5.85

GeV in 2002 for physics running with a test run achieving 6.0 GeV for a short period. When Hurricane Isabel blew through in September 2003 and the resulting power outage resulted in the warm up of all the cavities the arc rate models had to be re-established from scratch and in many cases were quite different from those developed previously.

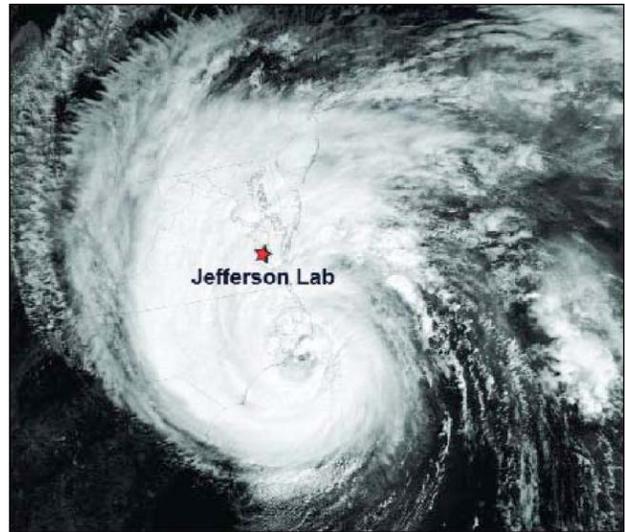


Figure 1: Hurricane Isabel, September 2003.

Another feature of the CEBAF cryomodule is the use of indium joints with super-fluid helium on one side and beam-line or waveguide vacuum on the other. Each time the module is thermally cycled these joints are stressed and there is a risk of a leak developing. Helium or air leaks to the waveguide may be accommodated by actively pumping the waveguide or bypassing the cavities, but helium leaks to the beam-line vacuum require periodic warm up to outgas the module or, in the worst case, removal of the module from the machine.

THERMAL HISTORY

Since the initial cool down in 1991-1993 most of the modules in CEBAF had never been warmed up. One module (North Linac zone 11) had developed a helium to beam-line vacuum leak during a servicing warm-up. This required periodic slight warm up of it and its neighbor in zone 10 to ~24 K to remove the cryo-pumped helium. A number of modules were warmed to about 30K for replacement of their warm RF windows as part of a long term upgrade program.

In September 2003 all the modules were warmed up to ambient after the insulating vacuum was lost during the power outage following the hurricane. Cryo-pumped gas from many years of operation was released and pumped away. After the machine was stabilized and vacuums re-

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established the machine was cooled down again beginning on October 8th and all but one module were returned to service. North Linac Zone 5 developed a new helium to waveguide vacuum leak requiring four cavities to be bypassed. Once stabilized the remaining half of this module was also returned to service. One other cavity developed an open field-probe cable and could not be recovered. By the end of October all remaining cavities had been checked out with at least some RF. Cavities were then pushed systematically to develop new arc rate models. Initial results were encouraging and showed that 5.5 GeV operation should be achievable with low trip rates and 5.75 GeV (needed for some scheduled experiments in 2004) should be possible with elevated but manageable trip rates. Physics operation resumed in November 2003.

During a routine shutdown in August 2004 the linacs were warmed to 4K and transferred to the standby refrigerator while maintenance was performed on the main helium liquefier. Unfortunately this system, which had not been used for some time, was unable to accommodate the static heat load and eventually nine modules were warmed up to shed load until the system stabilized. Also four more modules were warmed to 30K for warm window replacement. New arc-rate models had to be developed for all the affected modules.

COMPARISON OF ARC RATES

Before/after hurricane Isabel

Before Isabel the machine had been running at 5.5 GeV. At about 5 RF trips per hour, see figure 2, most of which were in the north linac since the south had a little spare capacity. That trip rate would have increased to about 12/hour at 5.75 GeV. Immediately after Isabel with freshly out-gassed cavities the trip rate appeared to be actually a little lower, even with the five cavities bypassed, however as the machine settled in (perhaps cryo-pumping a fresh layer of gas onto the surfaces), the trip rate climbed to higher levels than before the storm.

Fearing that the upcoming 5.75 GeV physics run might be in jeopardy the operations group, engineering group and the RF performance integration team put in a concerted effort to reduce the trip rate by developing better arc rate models, eliminating or raising other limits on good cavities where possible, optimizing the way LEM balanced the cavity gradients and trying to keep all recoverable cavities up as much as possible. Dedicated blocks of time for RF recovery were built into the schedule in case they were needed, and were used for beam studies or physics running if they were not. At the same time efforts were made to speed up the recovery time after a trip to minimize time lost to physics. By July 2004 the RF trip rate had been beaten down to about 15/hour.

August 2004 standby refrigerator event

The unscheduled warm up of nine modules plus the warm window work re-randomized many of the field

emission models. After a period of stabilization and arc model development the rate was re-established to be still about 15/hour. In fact some cavities had regained performance lost after the storm and with further tuning the trip rate fell to as low as 10 RF FSD per hour at 5.75 GeV in January 05 with all usable cavities on. For each cavity bypassed the trip rate rose about 1 per hour.

February 05, another one bites the dust

Unfortunately this good luck didn't hold and during the February 05 down the module in north linac zone 3 developed a terminal helium-beamline vacuum leak while cooling down after warm window work. Since the north linac was already the weaker of the two a module was moved over from the south linac into this zone and the dead module returned to the test lab for refurbishment. After recovery from this down the machine came back at ~15 RF FSD per hour at 5.75 GeV. Since then it has crept up to about 18 per hour as cavities have been bypassed for various reasons, which is just about the limit for acceptable operation. The present 5.75 GeV run is scheduled to end in May 2005, after which the energy will drop to 4.5 GeV and stay low for the rest of the year.

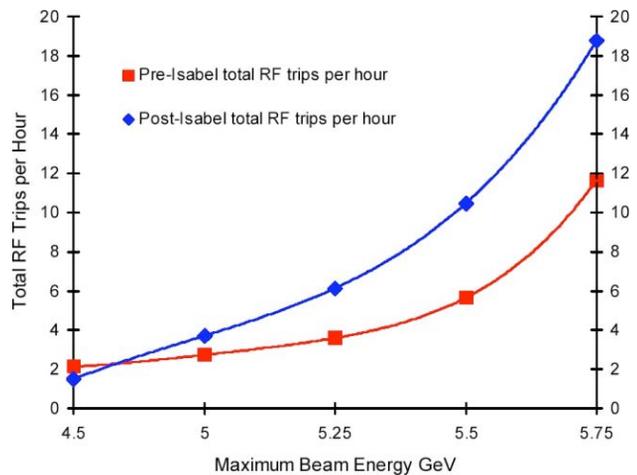


Figure 2. Trip rates before and after hurricane Isabel.

Correlations

It is interesting to compare the trip rates of individual cavities before and after these thermal cycles [2]. Figure 3 shows a comparison of the once-per-day trip rate gradient of all cavities with arc rate models before and after the full thermal cycle. A linear fit (forced through zero), shows an average loss of about 10% of useful gradient, which is consistent with observed performance. Also apparent from the data is the large scatter with many cavities improving significantly, only slightly outweighed by those that degraded.

A similar comparison of the 13 cryomodules warmed up in the August 2004 event shows a net gain in performance. The mechanism for this redistribution is not understood.

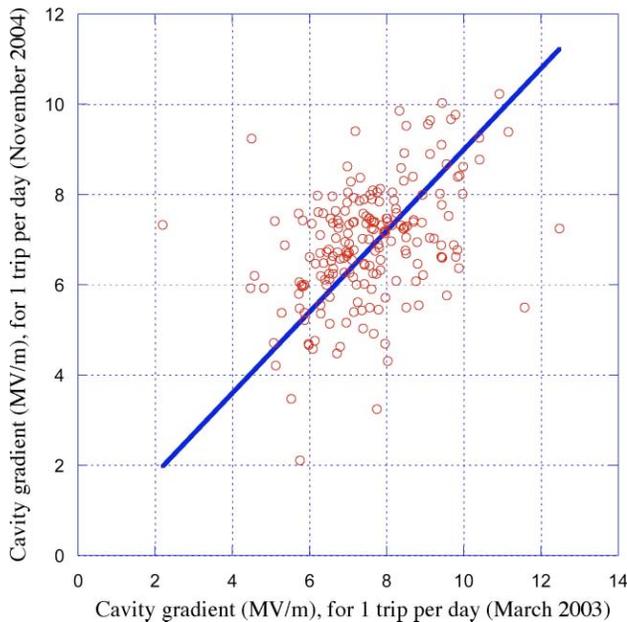


Figure 3. Comparison of pre- and post- hurricane gradients. Blue line: $y = 0.9x$ (zero intercept forced).

HELIUM PROCESSING

Helium processing was an effective part of raising the energy of CEBAF from 4 GeV to almost 6 GeV, however most recent attempts have had mixed results, in once case significantly degrading cavity performance. Some form of high-power helium processing or pulsed-power processing may be effective in pushing existing modules further but it is not without risk. We will investigate such methods off-line in the future when a suitable module is taken out for refurbishment.

CRYOMODULE REFRUBISHMENT

Clearly with recent increases in field emission from thermal cycles and other sources the performance of CEBAF as built has peaked. With the accumulation of leaks and other cavities lost to wear and tear after many years of hard service the time has come to implement the cryomodule refurbishment program that was envisioned right from the beginning. The first module has already been removed from the machine and is being dismantled in the test lab. Tooling from the original production run has been refurbished and improved and will be used to reprocess the original cavity pairs extracted from the modules. With state of the art cleaning and processing techniques it is hoped to raise the average gradient of the refurbished modules to at least 12.5 MV/m or 50 MV per module (half the output expected of the new upgrade modules). Since the lowest performing modules in service provide less than 20 MV/pass this will be a useful increase. Most of the major cryomodule components will be reused, however “dog-leg” waveguides will be installed in the couplers to shield the cold window from the beam. This has been shown to be effective in

eliminating field-emission induced arcing at the cold window [3], although we endeavor to operate refurbished cryomodules free of field emission. Refurbishment of the six worst performing or damaged modules should be enough to provide a robust 6 GeV machine, with low trip rates, to underpin the 12 GeV upgrade. Thereafter at least one module per year should be reworked to keep up with attrition. The schedule for rework will be dictated by funding.

NEW CRYOMODULES

The first full prototype of the 12 GeV upgrade-style cryomodule, a.k.a. “Renaissance” [4], will be installed later this year, joining the intermediate-prototype that is already in service. Although it will not be run at its full potential until all new RF is installed it will still add a much-needed boost to the machine availability. It will also allow one or more original modules to be taken out to feed the refurbishment process.

CONCLUSIONS

Thermal cycling of cryomodules in CEBAF has a profound effect on their arc rate performance and carries significant risk of mechanical failure. After thermal cycling of the whole machine after hurricane Isabel there was a significant re-distribution of field emission induced arc trips that necessitated rebuilding of all the arc rate models in the machine. Almost 10% of useable gradient was thought to be lost, though some of it was recovered by operational improvements. Subsequent warm-up of 13 modules produced further randomization but no ultimate loss in performance, in fact a slight gain. A program of cryomodule refurbishment has been started and should provide a path towards a stable 6 GeV machine to underpin the 12 GeV upgrade.

ACKNOWLEDGEMENTS

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