

## JLAB HURRICANE RECOVERY

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### *Abstract*

Hurricane Isabel, originally a Category 5 storm, arrived at Jefferson Lab on September 18, 2003 with winds of only 75 mph, creating little direct damage to the infrastructure. However, electric power was lost for four days allowing the superconducting cryomodules to warm up and causing a total loss of the liquid helium. The subsequent recovery of the cryomodules and the impact of the considerable amount of opportunistic preventive maintenance provides important lessons for all accelerator complexes, not only those with superconducting elements. The details of how the recovery process was structured and the resulting improvement in accelerator availability will be discussed in detail.

### **HURRICANE ISABEL**

Unusually, we had a full week's notice of a Category 5 hurricane moving towards the Virginia/North Carolina coast, and the predictions were remarkably accurate (warnings are usually much less precise). Every possible preparation was taken before the lab was evacuated on Sept. 17, 2003. Isabel crossed the shoreline about 200 miles south of the laboratory as a Category 1 hurricane on September 18. When it arrived in Newport News, Isabel's strength had reduced to a Tropical Storm with maximum wind speeds of 75 mph. By the next morning, the storm had passed but had inflicted major damage to the area's electrical distribution system.

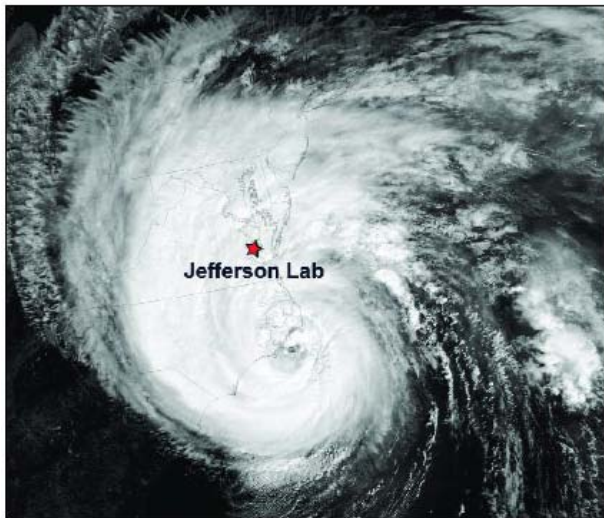


Figure 1: Isabel

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### *Initial Damage*

One tree damaged an air-handling unit on top of one of the CEBAF surface buildings, and many trees went down in the wooded areas of the lab site. This was full the extent of the visible damage to the lab infrastructure due to the hurricane. But more importantly, a tree outside the lab fell on the main power line to the accelerator site, removing all electrical power from the site – most notably from the Central Helium Liquefier (CHL). Because of the extensive damage to the electrical distribution network throughout the area, restoring the power grid took nearly four days. This allowed the entire cryogenics plant to warm up and approximately 65,000 liquid litres of helium were lost. The superconducting cavities (338 in CEBAF, 3 in the FEL) warmed up to at least 180K and many to room temperature.

### *Initial Response*

Our first instinct was to restore the power and the CHL as quickly as possible. However, after some thought, it was decided to carry out aggressive preventive maintenance on the electrical substations and the CHL before energizing anything. The substations had not had preventive maintenance for about five years, and the CHL had operated continuously for more than twelve years.

### *Schedule*

A detailed recovery schedule was developed with the active participation of all the groups involved. It was regularly updated and improved and contained about 500 entries. It was very useful to predict a date when Physics could be resumed (December 2), and is being used to plan the recovery from other long maintenance periods.

## **CRYOGENIC RECOVERY**

### *CHL*

The helium transfer lines had been installed and operational for twelve years. The O-rings are only guaranteed for fifteen years, so every O-ring in the transfer lines was replaced. The insulating vacuum spaces were also pumped out to remove the cryo-pumped contaminants that had accumulated over the years. An enormous amount of other maintenance was also carried out, including cleaning, checking, recalibrating and re-installing all the CAMAC crates and electronics.

Nine truckloads of gaseous helium were needed initially to replace the lost helium inventory. The CHL was ready to start cooling down cryomodules by Oct 8, three weeks after the hurricane.

## Cryomodules

Most cryomodules had never been warmed up since installation in the tunnel. Warming the cryomodules expands all the internal components, and the eight-cavity string expands by several mm. We were worried about opening one of the internal indium vacuum seals (64 per cryomodule) as this could introduce a helium leak into the cavity beamline vacuum, so every module was examined for internal leaks and then pumped down, requiring every pump cart in the laboratory. Five out of 328 cavities could not be recovered. Four were because of superfluid leaks; one was due to an open probe cable.

### Cryomodule Cool Down to 4K

Cryomodule cool down began on October 8. The two Injector cryomodules and all twenty cryomodules in the North Linac were cooled to 4K in blocks of 5 to 10, the first time this had been attempted (previously, modules had always been cooled alone). The twenty cryomodules in the South Linac and the two FEL cryomodules followed a day later. All cryomodules were cooled at a rate of about 150 K/hour to avoid Q disease (formation of niobium hydride at around 60-80K by precipitation of hydrogen dissolved in the niobium).

### Cryomodule Cool Down to 2K

Most of the CEBAF and FEL cryomodules were cooled simultaneously from 4K to 2K, requiring 10,000 gallons of liquid helium to complete the helium inventory. Since this was the first time that liquid helium (rather than gas) had ever been used, it required learning a new technique. No further problems were unearthed and the CHL has worked reliably since then.

## ACCELERATION PERFORMANCE

### Cryomodule Recovery

All cavities were raised to the minimum stable operating gradient of 2 MV/m on October 22/23, demonstrating that all the RF systems, cryogenics, cryomodules, interlocks, and safety systems were working correctly, a major milestone! All cavities except five were successfully brought online. NL05 (North Linac cryomodule 5) cavities 1,2,3,4 and NL12 cavity 2 were taken permanently offline. Cryomodule NL05 will be replaced by a new 12 GeV prototype cryomodule, scheduled for completion in July 05. All cavities were then brought up to 5 MeV/m (roughly two thirds of the nominal operating value) to look for, and address, vacuum problems in the warm window region.

### RF Cavity Arc Trips

There are two windows in the original CEBAF cavities, one at liquid helium temperature and one at room temperature. The cold windows tend to arc at high gradients due to charging of the window by electrons created by field emission in the cavity. The RF and the beam must be shut off to protect the cavity (a trip). The

trip rate depends exponentially on the accelerating gradient, determining the maximum beam energy.

The trip rate is strongly affected by the cavity surface conditions, particulates, adsorbed gasses, etc. It was expected that warming up the cavities would desorb gases, leading to an improvement in the trip performance, while cavity leaks and other degradations could reduce the cavity performance. It was an open question as to whether the final performance would be better or worse than before.

### Assessing RF Cavity Trip Performance

All the cavities were set to a high gradient, based on their previous performance, and the trip rate was calculated after a day's operation. All the cavities were then set to a low gradient, and again the trip rate was calculated after a day. The data was then fitted to a Fowler-Nordheim function [1].

This process provides parameters to LEM (the Linac Energy Management program), the online program that calculates the optimum settings for the linac energy as a function of beam current and cryogenic cooling capacity. Finally, the cavities were set to 5.5 GeV, and the performance compared to prediction. The data in Figure 2 demonstrate our ability to deliver 5.5 GeV beam for the present Physics program at about 10 trips per hour. However, the Physics program needs 5.75 GeV in September 2004, and this will only be met at an increased trip rate ~20/hour. We therefore initiated a detailed evaluation of every effect that limited the beam energy.

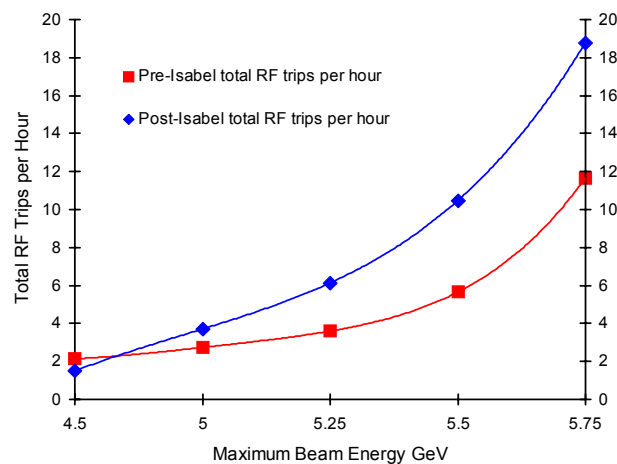


Figure 2: RF Trip rate as a function of beam energy

### Temperature Interlocks

Temperature monitor interlocks on the input warm windows limited the gradient in a large number of cavities (about 70 out of 300). Detailed studies, both in the lab and *in situ*, showed that the interlock settings for the new ceramic windows could be relaxed compared to the older polyethylene windows. Relaxing these interlock settings resulted in a gain of about 50 MeV in maximum beam energy.

## BEAM SET-UP

Rather than attempting to restore beams as quickly as possible, we again decided to take the time to carefully set up the beam, addressing many problems that had been plaguing us for many years. This process took several weeks because there were two very demanding experiments scheduled to begin immediately after the recovery: the G0 experiment that required a different pulse structure, and the Hypernuclear experiment that required a very tight energy spread ( $< 3 \times 10^{-5}$ ) [2]. All beams were set up by November 25, followed by a one-week collaborative commissioning period with the Users to demonstrate that all of the required beam specifications were being met. G0 beam properties were measured daily and were stable, including regular measurements of helicity-correlated effects. We were able to deliver G0 beam that met all specifications. We were also able to demonstrate the ability to simultaneously deliver beams for the hypernuclear experiment in parallel with G0 [3, 4].

## ACCELERATOR AVAILABILITY

### Accelerator Down

The “Accelerator Down” metric captures the fraction of time that the accelerator is unable to support the research program. This metric is purely hardware driven and does not include time it takes to tune up the beams to the User. In Figure 3, the “Accelerator Down” metric is averaged over a one-month period and plotted for the last two years. The difference in downtime before (14.3%, in red) and after (10.3%, in blue) the hurricane indicates a 4.0% net improvement. We attribute this to the preventive maintenance carried out following the hurricane.

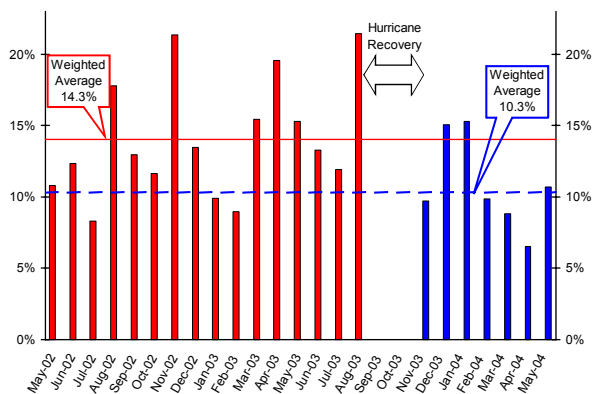


Figure 3: “Accelerator Down” versus time, showing monthly data before (in red) and after (in blue) hurricane recovery

### Availability for Physics

The “Accelerator Down” metric does not capture everything important to Users. CEBAF is a very complex accelerator that simultaneously serves three experiments. The “Accelerator Availability for Physics” is the total hours that the User reports to be acceptable divided by the total number of experimental hours scheduled. The “Availability for Physics” metric is lower for

simultaneous operation of multiple experiments, and even lower for an experiment requiring a major upgrade in accelerator capability (e.g. tighter beam specifications, new bunch pattern, higher polarization).

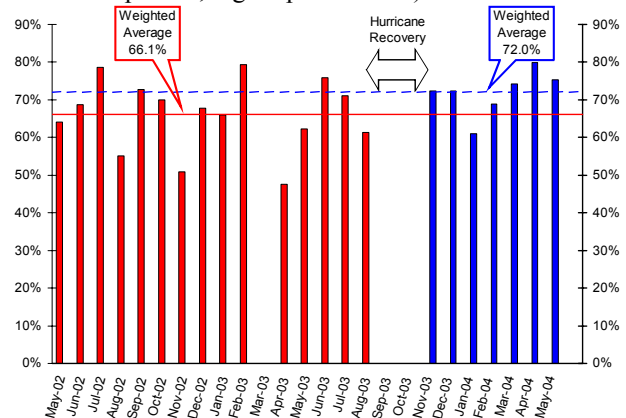


Figure 4: “Availability for Physics”, showing monthly data before (in red) and after (in blue) hurricane recovery

In Figure 4, the “Accelerator Availability for Physics” metric is averaged over a one-month period and plotted for the last two years. The average availability before (in red) is 66.1%, and after the hurricane (in blue) is 72.0%, an improvement of 5.9%. This is a big improvement since the good performance following the hurricane coincided with the most difficult experiments ever mounted at JLab. We attribute this both to the preventive maintenance and to the extra time spent setting up the accelerator to the best of our ability. The Users were also satisfied with the result as improved beam quality more than outweighed the time lost in establishing the beams.

## SUMMARY

This report cannot do justice to the enormous effort that was invested by Jefferson Lab staff in recovering the accelerator and all the associated systems. Operation of the machine since December has been above historical values, both in capability and reliability. This is because 1) the time spent on preventive maintenance of almost every component improved accelerator hardware reliability and 2) the time spent on accurate beam set-up provided a solid, reproducible base for operations.

## REFERENCES

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