The Story of 6 GeV at CEBAF

With the spotlight on the CEBAF accelerator's upgrade for future nuclear physics experiments at 12 GeV, it's easy to overlook something important that's being realized as of mid-2009: CEBAF's evolution into a machine that can operate reliably at 6 GeV – 50 percent higher than the 4 GeV energy that was promised when construction began more than two decades ago.

The achievement of routine, stable 6 GeV running is fundamentally important for the laboratory. Not only does the higher energy enable users to probe the nucleus more accurately, but it's crucial for reaching 12 GeV. The upgrade is predicated on starting with a 6 GeV machine.

The achievement is also an interesting story. It goes back more than a quarter of a century.

First Goal Was 4 GeV

Physicists struggle to decide how much energy a planned accelerator must deliver. What will it take, and at what cost to conduct the needed investigations? Those are difficult questions to answer, especially since the scientific territory to be investigated is by definition unknown. What was known when CEBAF was first considered was that to achieve the precision capability needed for the anticipated physics program, the beam on target needed to be continuous, rather than pulsed. Originally, a 2 GeV beam was the goal for CEBAF, but by 1985 the accelerator design had been changed to a 4 GeV machine.

This 4 GeV CEBAF wasn't planned as the superconducting radiofrequency (SRF) machine that exists today. It was to have been a linear accelerator built with conventional "room-temperature" technology. To attain the "continuous" characteristic required for physics, this conventional accelerator was to work in combination with something called a pulse stretcher ring. But by early 1986, the potential advantages of the SRF approach led to its adoption, setting the 4 GeV CEBAF on a path to become the first large-scale application of what was then a brand-new technology.

It was a cautious path. Even today SRF offers plenty of surprises, challenges and unknowns. That's part of why Jefferson Lab's SRF experience and expertise are so valued for other accelerator projects around the world – and it's part of why 6 GeV is a real achievement.

So in the late 1980s, when the accelerator still existed only in its builders' imaginations, there was plenty of reason to be scrupulously careful about putting SRF into action in this new research tool, anticipated by both nuclear physicists and the Department of Energy. The physicists and engineers designing CEBAF worked conservatively, striving to make sure that even if the finished machine didn't do everything exactly right, it would still meet its basic performance specifications – including 4 GeV.

Yet even amid the purposeful cautiousness, they also looked far ahead. They foresaw the need for future improvements, like the evolution to 6 GeV and future upgrades. One of the clearest examples of that foresight was the switch to SRF. First, though, the lab's founders had to deliver and operate a reliable 4 GeV machine.

The key capability, but by no means the only element, in reaching 4 GeV was accelerating gradient, which is simply the accelerator's ability to boost electrons' energy by a given amount within a given distance. The SRF accelerating cavities have to work as part of an enormously complex operation involving not only the cryomodules that contain them, but:

* the injector, where the beam originates,
* the radiofrequency (RF) that powers beam acceleration,
*other support equipment in the service buildings above the tunnel,
* the monitoring and control network centered in the Machine Control Center,
* the Central Helium Liquefier that provides the ultra-low-temperature refrigeration needed for superconducting operation, and
* the magnets that guide and steer the beam around the underground racetrack and into the experimental halls.

When the accelerator was new (and still today) this complexity meant that those who operated CEBAF had to learn, first, what effects limited the accelerator's performance, and second, how to overcome those effects. Eventually, the accelerator became capable of operating reliably at 5.2 GeV, substantially more than originally promised.

Toward 6 GeV

Even then, CEBAF's scientific users looked forward to still higher energy. Standing in the way, however, was the *arc trip rate*. On SRF cavity insulators, a static electric charge builds up during operation. When it eventually arcs or discharges to the cavity itself, the arc causes the cavity automatically to trip off, something like when a switch shuts off a lamp.

Each arc trip means losing a few or many seconds while the cavity is restored to service. If the rate at which these arc trips occur is too high, say, 15 or more per hour distributed over the 320-plus cavities in the accelerator, the accelerator isn't doing its job well enough for users trying to conduct experiments. Get it down to eight or so per hour, and you have smooth sailing.

Each cryomodule has its own trip rate. It was, and still is, vital to determine just how to manage all of the cryomodules around the accelerator to get the most from each cavity while maintaining an acceptable overall arc trip rate. That determination gets made using sophisticated statistical methods that incorporate performance data from each cavity and cryomodule.

The first efforts toward 6 GeV actually began almost a decade ago. But even with the continually improving understanding of the technical choreography involved in operating CEBAF, it was clear that some higher-performing cavities and cryomodules would be required.

'C50' Cryomodule Refurbishment

By 2003, it had become possible to run CEBAF at 5.7 GeV. In September of that year, however, Hurricane Isabel blew into town. Its damage included loss of electrical power to the Central Helium Liquefier, which maintains the cavities inside the cryomodules at their operating temperature of 2 Kelvin, not far from absolute zero.

When the CHL lost electrical power, the cryomodules and the SRF cavities inside them warmed up. It was an uncontrolled – and definitely undesired – warmup. SRF cavities are delicate devices, requiring meticulous preparation and care. The uncontrolled warmup caused harm. This added significantly to a reduction in performance that had started accumulating gradually over years of intense use.

During the years leading up to 2003, though, JLab's SRF scientists, engineers and technicians had learned more and more about the delicate processing of SRF cavities. For example, they had become better able to make cavities ultra-clean before installing them in cryomodules. This improves cavity performance.

So, a formal cryomodule refurbishment program called "C50" began, with the purpose of increasing the accelerator's energy and reliability. The program was called "C50" because the idea was to refurbish 10 cryomodules to make each of them capable of yielding 50 megavolts of acceleration, approximately doubling the original performance. Weaker-performing cryomodules would be removed from the tunnel, reworked using improved processes, and then re-installed as strongly performing cryomodules.

Refurbishment was scheduled at three cryomodules per year. The first C50 goal was to reach 5.75 GeV quickly, but without sacrificing quality. The second was to maintain that energy while continuing to improve the hardware needed to reach 6 GeV. Top priority has been to maximize CEBAF's availability for physics users and, in fact, during 2008 users completed 15 experiments.

The first C50 cryomodule operated in the accelerator in February 2007, leading to 5.1 GeV (less than the 5.2 GeV previously achieved, but even the weak modules removed to begin the refurbishment process had been making some contribution) by June. By October 2008, with six C50 cryomodules re-installed and commissioned, CEBAF had reached 5.9 GeV, but with an arc trip rate worse than 15 per hour. By December, the rate was down to just below 15 per hour. By January 2009, due to to statistical analysis for optimizing accelerator operation, it was down to below 10 per hour – relatively smooth sailing.

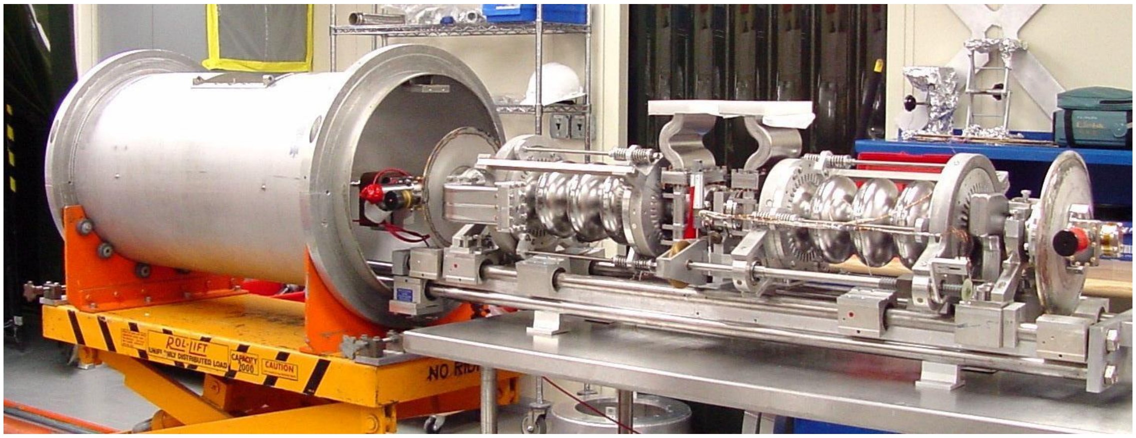
And then on June 15 and 16, CEBAF reached 6.068 GeV, delivering beam at 100 microamperes of current to Hall A. The trip rate was almost 15 per hour, but typically the trip rate starts out high and improves with fine tuning. This test demonstrated that Jefferson Lab does indeed now have a full 6 GeV "beam loaded" CEBAF accelerator.

Looking ahead

Not everything about the achievement of 6 GeV has been perfect. The refurbished cryomodules haven't seen the expected improvement in the quality factor *Q*, a key accelerator performance measure. But with the eighth C50 cryomodule re-installed and commissioned as of April 2009, the ninth C50 re-installed in late summer 2009 and commissioned over the fall, CEBAF successfully completed a two month physics run at 6.068 GeV in November and December 2009. With the tenth C50 installed and commissioned during the 2010 winter accelerator down, the focus is on making 6 GeV operation even more routine, reliable, and robust.

The lab itself was called CEBAF until Thomas Jefferson's name was adopted in 1996. During the 1980s, CEBAF's staff made a 4 GeV promise to nuclear physics users, to the Department of Energy, and to the taxpayers who ultimately pay the bills. Not only has that promise been realized, but it's now being enlarged upon substantially.

Now the achievement of 6 GeV places Jefferson Lab in position to carry out another big promise: to double the energy via the 12 GeV upgrade, thereby greatly multiplying CEBAF's usefulness for science.



This photo shows a reprocessed cavity pair before assembly into a helium vessel to form a cryounit (one-quarter of a cryomodule).