ACCELERATOR ARCHEOLOGY - THE RESURRECTION OF THE STANFORD MARKIII ELECTRON LINAC AT DUKE*

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In the early 1960s, the Mark III accelerator at the Stanford High Energy Physics Laboratory was used as the prototype test-bed for the SLAC Two-Mile accelerator. In the mid 1980s the accelerator was dismantled and a large part of it was transported to the Duke University Free-Electron Laser Laboratory to form the basis of the injector for the 1-GeV Duke Storage Ring. The plan was to use the original accelerator sections and some rf equipment with new magnetic optics, vacuum system, gun and a modern control system. The first 295-MeV portion of the linac is now operational at Duke. The linac currently consists of eleven sections from the old linac with a single-cell rf gun. Our guiding principal has been one of economy and simplicity. We have not attempted to restore the accelerator to its original form, but have added modern components where necessary. We discuss some of the more interesting features of the linac, and how we have given new life to this venerable machine here at Duke.[*]

INTRODUCTION

The Mark III electron linear accelerator underwent many incarnations at the Stanford High Energy Physics Laboratory following its initial construction beginning in 1949. A description of the history up to the mid 1960s is given in reference [1]. During 1963 and 1964 the Mark III was reconfigured to its final form using new constant-gradient accelerator sections that had been developed for the SLAC Two-Mile Accelerator. By March 1964 the accelerator had 32 SLAC sections and beams of up to 1.2 GeV were being produced. The nuclear physics program on the Mark III continued until 1970. After that time the accelerator was operated occasionally as a calibration source for various nuclear detectors. The accelerator was dismantled in November 1985 under the supervision of its last operator Don Lee. One of the accelerator sections became the core of what has become known as the Mark III Free-Electron Laser, originally at Stanford, now at Duke. In 1989, 26 of the accelerator sections were shipped to the Duke University Free-Electron Laser Laboratory. During 1993-94 eleven of the sections plus an rf thermionic gun were configured into the initial 295-MeV phase of the injection linac for the Duke Storage Ring.

In its Duke incarnation, the Mark III linac retains only the accelerator sections and rf loads of the Stanford machine. Much of the original equipment at Stanford was not suitable for use in a modern machine. Examples of such equipment included 1960s vintage oil diffusion pumps and early versions of the SLAC klystrons (12 MW peak power!).

When the accelerator was dismantled it was found that many of the sections had been contaminated by back-streaming pump oil. The rf-drive cells of many of the sections could best be described as appearing to be coated with an amber/black colored varnish that had a finely crazed surface. We vacuum-baked the sections to 400°C for 5-10 days and then cleaned the rf input irises and cavity noses. The remaining coating was confined to the outer walls of the cells.

Structure type	SLAC traveling wave
RF frequency (MHz)	2856.76
Number of sections	11 + gun
Section temperature (°C)	30.2
Gun	Thermionic RF with α-magnet
Klystron type	ITT 2960
Number of Klystrons	3
Number of sections per klystron	4
Peak rf power per klystron (MW)	34
RF Macropulse length (μs)	2
Achieved energy (MeV)	295
Nominal injection energy (MeV)	283
Macropulse current (mA)	40
E-beam macropulse length (ns FWHM)	50-1000
Energy spread (macropulse) (%)	0.2
Energy jitter (%)	< 0.1%
Macropulse rep. rate (Hz)	2

Table 1 Characteristics and measured performance of the Duke Injection Linac

By the end of its life at Stanford, because of various component failures, the Mark III could only reach 275 MeV. At Stanford there had been one 12-MW klystron per section. At Duke the plan was to use one 30 MW klystron for four sections. Even though the planned power per section at Duke (for most of the sections) was less than that at Stanford, there was some concern that the sections would be difficult to

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condition to full power. These fears proved to be largely unfounded. All of the sections, except for one, conditioned in a matter of days. The one recalcitrant section took approximately 3 months to reach full power. The first linac section at Duke has been operated at 15 MW input power.

At Duke the linac is housed in a 150-m long tunnel. In its present phase the linac is 47 m long. First beam reached the end-station of the Duke Linac on October 21, 1994. The design energy of 250 MeV was reached on November 1, with first injection into the storage ring on November 2. The linac beam energy reached 295 MeV with 20 mA of beam loading by April 1995. The nominal conditions for ring injection have been 283 MeV at 40 mA. Our plans are to add a further 22 sections (14 Mark III vintage plus 8 new) to the linac to reach a final energy of 1.2 GeV.

RF SYSTEM

The present accelerator is powered by three ITT 2960 S-band klystrons. The accelerator sections are grouped into clusters, with each cluster powered by a single klystron. The first cluster consists of the gun and three accelerator sections with the remaining two clusters consisting of four sections each. The power is split approximately as follows: gun 2 MW; fists section 14 MW, all others 7 MW. The nominal energy increment per section is given by $\Delta E\ (\mathrm{MeV}) \approx 10\sqrt{P}$, where P is the section input power in MW. The maximum observed beam energy of 295 MeV (with 0.02 A of beam loading) is very close to the predicted value for the available rf power. This indicates that, in spite of their age, the accelerator sections are performing a originally specified at Stanford over thirty years ago.

The waveguide is aluminum WR-284 pressurized to 26.2 PSIG with SF_6. This was chosen because of the reduced expense compared with evacuated waveguide. We have had no significant problems with waveguide arcing. The rf power is split using 4-port 3-dB hybrid couplers. We could only afford one high-power phase shifter, which we use to shift the phase between the gun and the first section. To phase the sections within a cluster we constructed simple remotely actuated mechanical “waveguide phase adjusters” i.e. push-pullers that squeeze or expand the waveguides as necessary to adjust the phase[7]. These allow $\pm 15^\circ$ phase adjustment range for each accelerator section. Initially the phase was set with the help of low-power phase measurements. Once the linac was operational we adjusted the phase shifters for maximum energy. This setting was done only once and resulted in an energy increase of about 1.4% over the low-power settings. We monitor the rf power using simple magnetic loops at the output of each accelerator section just before the rf loads.

The rf drive is provided by a Sperry SAS-61 2-kW klystron. When distribution losses were taken into account, the SAS klystron was unable to provide the 300-W drive necessary for each klystron. We adopted a novel approach to rf distribution. We used the SAS to drive one of the ITT klystrons then we split off a few kW of the high-power output to provide the drive for the other klystrons. This system works very well in practice. The rf output of the klystron has been flattened by appropriate tuning of the modulator pulse forming networks.

Two of the ITT klystrons have had an unusual history. Even though they had never been operated since leaving the manufacturing plant, they both developed leaks while in storage at Duke. It is likely that the interiors of both tubes were at atmospheric pressure for about one year. Lacking the funds to pay for refurbishment of the tubes, we chose to repair the klystrons in house[8]. The first step involved diagnosing the source of the vacuum leaks. One tube was found to have a leaking rf output window, the other a failed joint in the line leading from the klystron body to the vacuum pump. The tube with the leaking window provided the greatest challenge. Replacing the window was beyond our capabilities. We chose to add a second window by adapting an accelerator-section input window to provide a second window for the klystron, with an evacuated section in between the windows. As a precautionary measure, we added a 20-l/s ion pump to the tube in addition to the existing 2-l/s pump. Once the tube was sealed, pumped and leak-checked, the next step was to attempt to recondition the barium dispenser cathode.

The first prerequisite was to bake the tube to 450 °C. This was done over a period of nine days. The ultimate pressure was less than 1×10^{-9} torr. The cathode heater power was then turned on very slowly, reaching a maximum power of 400 W after twenty-two days. Preliminary emission tests at 500 V indicated a very good cathode perveance of 1.8 μPervs.

We then moved the tube to our 2-μs, 300-kV test modulator. The HV conditioning went very quickly 0 to 270 kV in twenty minutes. We found the peveance to be 1.9 μP at 250 kV. We determined a saturated gain of 52.2 dB at 280 kV and 33 MW output power in a 2-μs pulse at 10 Hz. The performance of the tube met or exceeded the manufacturers specifications in all respects. The tube has been in almost daily use at full power and a 1-Hz repetition rate since October 1994. We have had no problems with the additional rf window on the tube.

The second leaking tube was also repaired and now operates on a daily basis along with its companion.

For future upgrades to the linac we plan to modify some old SLAC klystrons manufactured by RCA. Many of the tubes that we have in-house are capable of producing no more than 20 MW in their present condition. We believe that if we replace the existing oxide cathodes on these tubes with new dispenser cathodes, we will be able to achieve performance specifications similar to that of the ITT tubes.

ELECTRON GUN

The electron gun used on our linac is the same single-cell thermionic rf gun that was previously used on the MKIII FEL at Stanford and later at Duke[2,3]. For injection into the storage ring a short multi-nanosecond pulse is required[4]. This pulse is generated by chopping the electron beam with a pulsed electrostatic kicker at an energy of 1 MeV just after the gun. We can generate electron macro-bunches with an FWHM of 50 ns and 40 mA current.

The storage ring operates at an rf frequency of 178 MHz and a bucket spacing of 5.5 ns. The present system delivers approximately 0.2 nC per ring bucket and fills approximately 10-15 buckets per fill. Ideal operation requires a single-bunch injection of 1-2 nC of charge with a pulse width of less than 5 ns. The timing uncertainty should be less than 1 ns. It would appear that a photocathode system using an inexpensive pulsed nitrogen laser (337 nm) might be a considered for producing such pulses. The present cathode is LaB_6 whose quantum efficiency has been measured to be 2.5×10^{-4} at 337 nm[5].

Nitrogen lasers are commercially available for under $ 7000 that can produce 100-500 μJ of 337-nm light in 1-5 ns long pulses with sub-ns timing jitter[5]. Under ideal circumstances such lasers could produce between 17 an 85 nC per pulse (2-14 linac buckets) at the cathode. The transmission efficiency should be approximately 20% to the ring. (Half the charge generated will be accelerated and up to 40% of that will make it through the gun alpha-magnet.) The huge overhead in optical energy available makes this an attractive option. The peak optical power density on the cathode would be no more than 0.5 MW/cm^2, so surface damage would not be a problem. The system cost would be < 7 k$ not including transport optics and diagnostics. We are considering this as an upgrade to our system.

OTHER SYSTEMS

The control and diagnostic systems are lean and effective. A description of the control system is given in a companion paper[9].

The electron beam diagnostic system is very simple. Current is monitored using six beam current toroids and one fast stripline wall-current monitor. Beam position and match are monitored using six chromium-doped aluminum-oxide insertable screens viewed by inexpensive vidicon cameras. Energy is monitored with two nine-degree magnetic spectrometers, one after the first accelerator section (35 MeV) and one at the end of the linac. Pulse temporal structure is monitored by two methods. One uses a photomultiplier tube that looks at the synchrotron radiation from the electron beam as it bends in the high energy spectrometer. The other method uses a fast stripline wall-current monitor at the high-energy end of the machine.

The magnetic lattice consists of quadrupole pairs between each accelerator cluster. Each quadruple has integral two-axis steering. Each accelerator section is covered with μ-metal sheet to block stray magnetic fields.

In contrast to the original vacuum system, with its welded flanges, we installed the latest in HV conflat hardware with copper gaskets. All pumping is done with 20-l/s ion pumps, one per accelerator section.

CONCLUSION

As is evident from the description above the guiding principal in our design and construction philosophy has been one of strict economy. Wherever possible we have procured equipment from government surplus. We estimate that our total expenditure on external procurements for the construction of the linac so far is under 1M$. This has resulted in a reliable system that has exceeded specifications, and given new life to a venerable accelerator.

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