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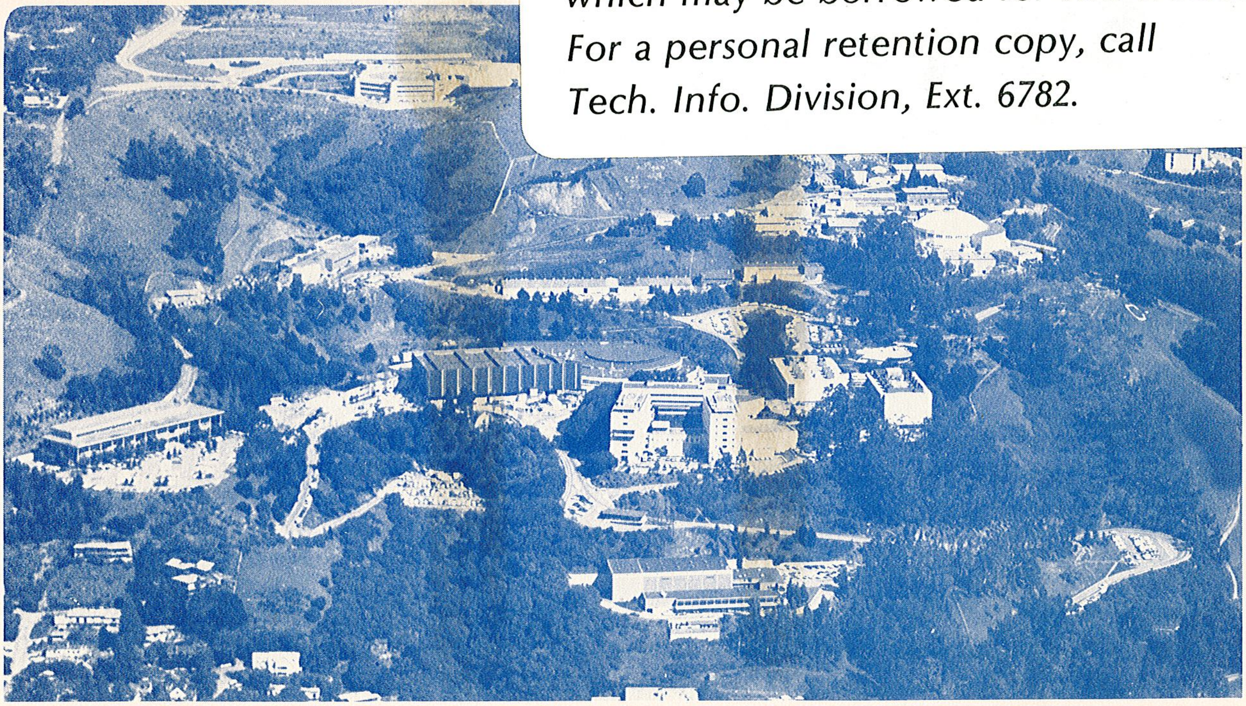

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A NEW, RUGGED, HIGH POWER COCKCROFT-WALTON POWER SUPPLY*

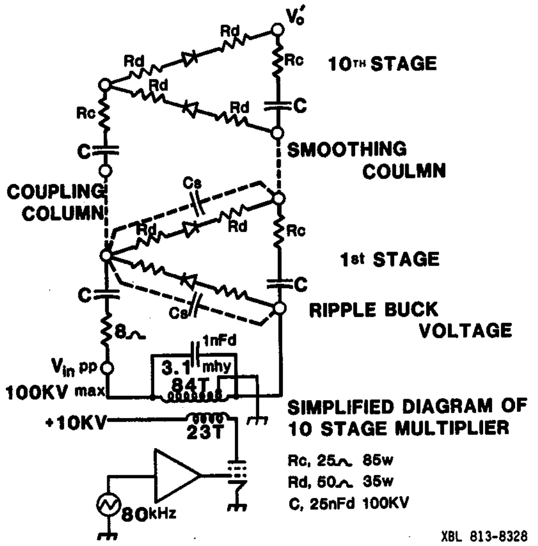
J. Hinkson, G. Behrsing, E. Hazelton, W. Hearn, H. Lancaster**

Abstract

A ten foot (3 m), ten-stage air-insulated Cockcroft-Walton power supply designed and built at LBL has been tested to 900 kV at the SuperHILAC. Operating at 80 kHz, the power supply features low ripple, moderate stored energy, 10 ma average current, and no bouncer requirement for pulsed loads. Other system features include: inexpensive generating voltmeters and a capacitive pick off for monitoring and regulation in lieu of costly resistance dividers, "home-made" semiconductor rectifier modules, excellent component protection against sparking, and easy maintenance. This report describes design, construction, and testing of the high voltage system.

Introduction

The high intensity uranium beam injector for the SuperHILAC includes a Wideroe Linac and a 750 kV pre-injector. The pre-injector high voltage power supply described in this report is a half-wave cascade voltage multiplier. It was tested to 900 kV in October 1980. As of this writing, the beam accelerating column has not been installed so no tests with beam loading have been conducted.



XBL 813-8328

Design

The parameters considered in the design of the Cockcroft-Walton (C-W) were:[1]

V_o	Theoretical DC output voltage
V'_o	Actual DC output voltage
V_{inpp}	AC input voltage, peak-to-peak
N	Number of decks (two sections per deck)
f	Operating frequency
I	DC load on power supply
C	Coupling capacitor
C_s	Stray capacitance per section
$\delta V'_{opp}$	Ripple voltage due to circulating current, peak-to-peak
ΔV_o	Voltage drop due to load current
δV_{opp}	Voltage ripple due to load, peak-to-peak

1. The highest voltage required for preacceleration of $^{238}U^{+5}$ is 750 kV. A maximum design voltage of 900 kV insures stable operation at 750 kV.
$V'_o = 900$ kV

2. The maximum beam current is 20 ma for 14 ms at a duty cycle of 50%. I_{avg} is 10 ma maximum.
$I = 10$ ma

3. The lowest operating voltage required is 500 kV. The maximum load induced ripple, δV_o, is taken as 0.1% V'_o minimum to limit beam energy spread.
$\delta V_o = 500\ V_{pp}$

4. The multiplication efficiency decreases as the number of decks is increased. A loss of about 5% occurs with 10 decks. With 20 decks a loss of 17% occurs. With all factors considered, a value of 10% for N was chosen. This permitted the use of available capacitors.
$N = 10$

5. The operating frequency affects ΔV_o and δV_o, that is, the higher the frequency, the lower the voltage drop and ripple due to load. Circulating current increases and rectifier efficiency due to recovery time decreases with increasing frequency. An operating frequency of 100 kHz was chosen as the highest in consideration of rectifier efficiency. Actual operation is between 80 and 90 kHz.
$f = 85$ kHz

6. The coupling capacitor value is determined by the load induced ripple requirement

$$C = \frac{I_{pk}}{f\delta V_o} \times \frac{N(N+1)}{2} = 25.9 \times 10^{-9}\ \text{fd}$$

An oil filled, extended foil, 100 kV, 25 nfd capacitor is used. It is tubular in shape, 12.7 cm in diameter and 61 cm long.
$C = 25$ nfd

7. The stray capacitance per deck, C_s, affects multiplication efficiency and circulating current in the C-W. It was measured on a two deck model of the C-W.
$C_s = 10\text{–}20$ pf

8. The load induced droop $\Delta V_o = I/fC \times N/3\ (2N^2+1)$. This is voltage droop that will occur with a DC load of I amperes. The C-W drive circuitry must have sufficient overdrive capability to correct for the droop. With a pulsed load the drive circuitry must have sufficient bandwidth to correct the droop during the pulse. For the system described here, the uncorrected droop is about 3 kV at a load of 10 ma DC.
$\Delta V_o = 3$ kV.

9. The required input voltage to the C-W for 900kV output is

$$V_{inpp} = \frac{V'_o\sqrt{C_s/C}}{\tanh\left(2N\sqrt{C_s/C}\right)} = 94.75\ \text{kV}$$

$V_{inpp} = 95$ kV

10. The ripple voltage due to circulating currents, $\delta V'_o$, is not affected by the load but is proportional to the ratio C_s/C. This ripple voltage is bucked out by bouncing the return side of the C-W a few kV's 180° out of phase with the ripple. Surge protection resistors in series with the C-W smoothing capacitors cause a phase shift of the bucking voltage and prevent the ripple from being reduced to zero. By returning the C-W to ground through a few turns of the C-W drive transformer, the ripple was reduced to 500 V pp. The uncompensated magnitude of this ripple is

$$\delta V'_o = \frac{V'_o\ 2\sqrt{C_s/C}}{C}\ \frac{\cosh 2N\sqrt{C_s/C} - 1}{\sinh\sqrt{C_s/C}\ \sinh 2N\sqrt{C_s/C}} = 3.55\ \text{kV pp}$$

11. Total voltage drop across the rectifiers is about 4 kV. This is allowed for in the C-W drive system.

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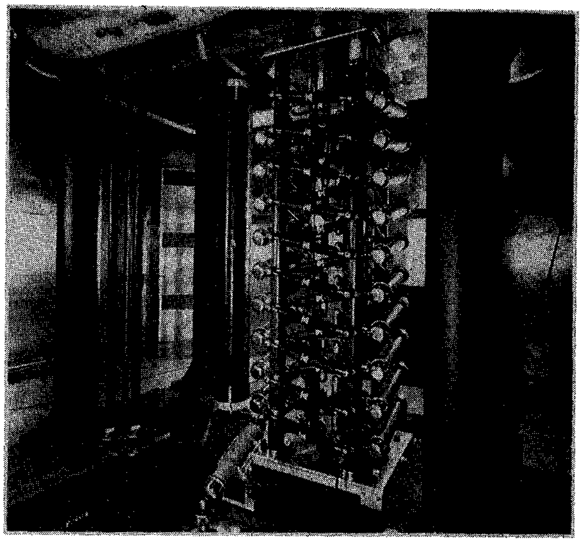
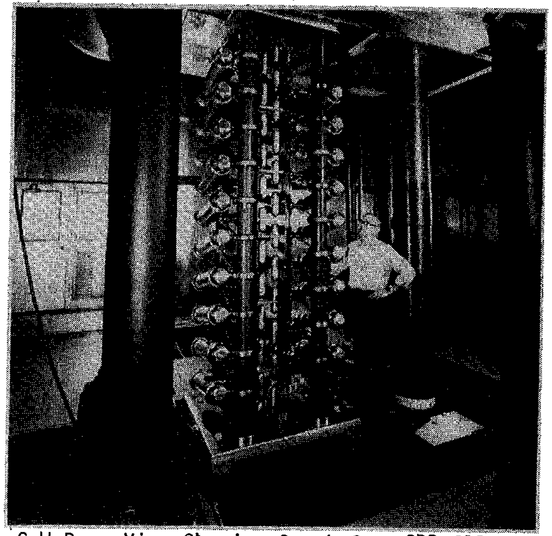
The C-W stack is driven by an air core transformer with an 84 turn secondary shunt resonated with four vacuum capacitors totaling 1 nfd. The stray capacity of the C-W increases the shunt capacitance. The system is resonant at 80 kHz with C-W connected, and at 90 kHz with the C-W disconnected. The calculated C-W shunt capacity is about 270 pf or about 13 pf per section. The transformer has been tested to 105 kV pp without the C-W being driven. The transformer was designed for 10 kW average and 20 kW peak load.

The 23 turn transformer primary is driven by two parallel 4CW25k tetrodes operating class B. A 10 kV, 50 kW power supply provides plate power. The tetrodes are driven by a solid state amplifier with a gain of about 100. The driver also supplies negative grid bias. A voltage controlled oscillator (VCO) which is phase locked to the transformer resonant frequency provides input to the driver amplifier. The C-W output voltage is adjusted by controlling the level of the VCO output.

Two generating voltmeters (GVM) mounted in a wall of the pre-injector enclosure measure the voltage gradient between the high voltage terminal and the wall. One GVM is used for high voltage monitoring. The other provides feedback for voltage regulation in the DC to 50 Hz bandwidth. A capacitive pickoff plate mounted near the GVMs is used for higher frequency feedback signals.


CBB 811-856

C-W Front View


C-W Rear View Showing Spark Gaps CBB 811-854

The pickoff plate is also used for spark detection. It is assumed that any sudden drop of 50 kV or more in the C-W output is caused by a spark. If a spark is detected, the VCO output is clamped to zero for about 5 s, and then allowed to ramp up slowly to its former value. If 5 sparks occur within 2 minutes, the system is automatically shut down. Another protection circuit measures the C-W V_{inpk}/V'_0 ratio. If the ratio changes significantly, the system is shutdown.

Construction

The 4 legs that support the C-W components are composed of sections of solid PVC rod 13 cm in diameter. Between each rod is an aluminum ring 20 cm in diameter and 5 cm thick. The PVC rods are joined through holes in the center of the rings. The vertical separation between each ring is 23 cm, yielding a maximum operating gradient of 4 kV/cm along the surface of the plastic.

The rectifier modules are connected to the rings with 7.6 cm diameter balls. Rods connected to the rings support the capacitors. Stainless steel solution bowls were fitted over the capacitor connections to shield the mounting apparatus.

The capacitor damping resistors are connected to the rings with balls also. The resistors limit capacitor current during a spark down. Because all the reactive current in C_s flows through the first stage resistors they become quite warm. These ceramic power resistors are able to run safely up to 200°C.

A spark gap assembly stands in the middle of the C-W stack. Spark gap electrodes are arranged so that each rectifier module is protected by a horizontal gap and each capacitor/resistor network is shunted by a vertical gap. The gaps are set to spark at 100 kV.

To safely ground the C-W and short each capacitor, 4 grounding bars pivoted at the C-W base are attached to each capacitor connecting rod.

A novel automatic grounding system is being tested. Mercury is pumped up two plastic columms attached to the spark gap electrodes. While not 100% fail safe, this system will make manual grounding of the C-W less hazardous.

There are 20 rectifier modules in the C-W. Each module is composed of 25, 10 kV silicon rectifiers, type CLR10. The rectifiers are wound in a helix over a plastic mandrel and terminated on each end with 50 ohm ceramic power resistors. The resistor-rectifier assembly is cast in a dense thermally conductive epoxy. The finished rectifier module is 61 cm long and 7.6 cm in diameter. Sockets in each end of the rectifier module are used for connection to the C-W.

All of the CLR10 rectifiers were tested for recovery time and reverse leakage. All rectifiers had recovery times of about 300 ns. The reverse leakage measured in some 700 units varied widely, so the 25 rectifiers for each module were picked from groups for which the leakage varied no more than a factor of two.

The GVM consists of a 3600 RPM split phase small motor, a 20 cm dia. printed circut board, a two blade aluminum rotor and a 1 Meg ohm load resistor. The printed circut board is etched in the shape of the rotor to yield two isolated electrodes which are connected to the resistor. The remainder of the board is ground plane. The rotor is positioned close to the board so as to periodically cover the electrode. The motor shaft is grounded by a brush assembly. At a gradient of 5 kV/cm, this GVM yields about 10 μa peak to peak. The GVMs are placed in a corona-free area away from the preinjector accelerating column.

Calculations to determine breakdown voltage between conducting surfaces[2] were performed to determine electrode and component radii. Given a maximum height of 3 meters, N determined the maximum separation between deck components. The breakdown voltage between components had to be higher than that of the spark gaps. The rectifier modules were considered to be parallel cylinders with 3.8 cm radius and 20 cm separation between surfaces. Their ends were not considered. The calculated breakdown between rectifiers was 300 kV. The sphere-to-sphere breakdown voltage for the rectifier mounting balls was calculated to be 158 kV. The component mounting rings were conservatively regarded as parallel cylinders formed by the radiused edges of the rings. Having assumed a 1.3 cm radius and 23 cm separation, the breakdown voltage was calculated to be 175 kV. The capacitors were calculated to spark to each other at 300 kV. The solution bowls on the ends of the capacitors were regarded as 13 cm diameter spheres. They were calculated to spark to each other at 120 kV. Breakdown tests were performed on two completely assembled decks. The rectifier module mounting balls were the weakest points, breaking down at 115 kV DC. The literature[2] states that a 20% reduction in breakdown voltage would be expected for sinusoidal voltage above 61 kHz. This would imply a 92 kV breakdown in the AC side of the C-W stack and an 80 kV breakdown in the AC side spark gaps. However, at ~90 kV/deck, no sparking in the C-W was seen until the terminal house flashed over. At that time, sparking was confined to the spark gaps.

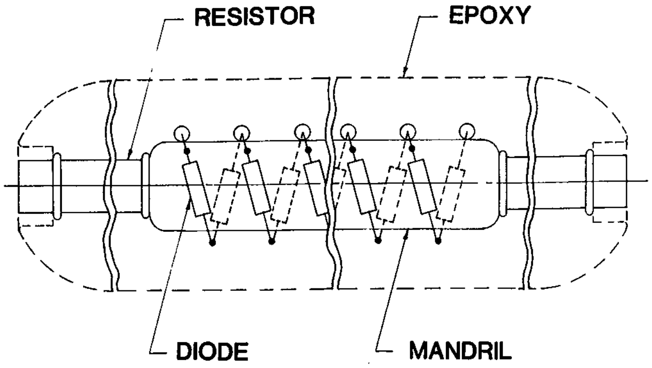
Testing

The C-W was run at 200 kV as measured by a resistance divider. The GVMs were calibrated at this level. The C-W was run up to 750 kV where some sparking from the terminal house corners to ground occured. After the terminal house was cleaned and smoothed, the C-W could be run up to 900 kV. At that level, long strings of corona could be seen coming from the terminal house corners. A complete discharge always followed soon after the corona appeared. When the high voltage tests were made, the environmental control system for the enclosure was not yet installed. Operation above 750 kV is expected to be more reliable when temperature and humidity are controlled.

Reliability

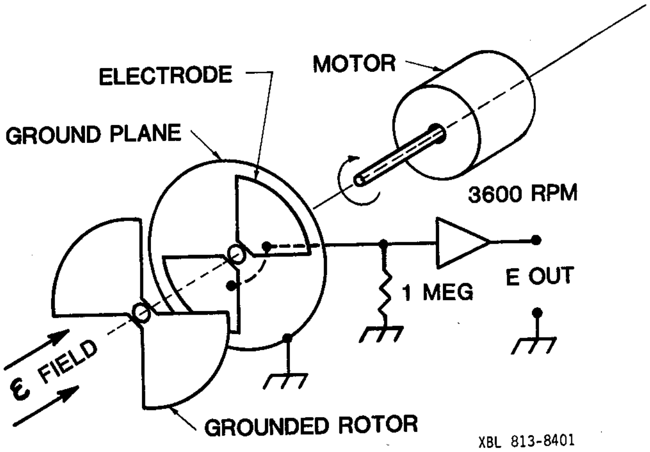
Since October 1977 a 9 stage C-W, which is the prototype of the C-W described here, has been running at between 650 kV and 740 kV for about 4000 hours per year. Because this power supply runs very near its sparking potential, and that of the terminal house and accelerating column, a great deal of sparking has occurred. The capacitors and resistors are the same as those in the new C-W. There have been no failures of these components. The rectifier assemblies consist of ten Unitrode type UDC15 modules in series with 50 ohm ceramic power resistors on each end. The rectifier assembly is potted in a clear silicon rubber compound. One of these rectifiers has failed. Four prototype rectifiers using the CLR10 diode were installed in the C-W. Two of the rectifiers were potted in a clear epoxy. Both have failed, one very soon after installation and the other after about 1000 hours of operation. The other two rectifiers were plotted in dense thermally conductive epoxy. Both have survived for at least 1000 hours.

Usually series strings of silicon rectifiers in high voltage applications have series resistors to limit fault currents and shunt capacitors to evenly distribute inverse voltage.[1] The shunt capacitors can contribute significantly to C_s and therefore to higher C-W ripple. We believe that by matching diodes for reverse leakage and recovery time the capacitors can be eliminated. The resistors used in our rectifier modules were chosen to limit the short duration fault current to a safe value.



XBL 813-8400

C-W Rectifier



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Generating Voltmeter

Conclusion

A new high power voltage multiplier has been constructed and tested to 900 kV DC. It is designed for the severe service imposed by a high intensity heavy ion beam pre-accelerator. Excellent reliability is expected because of the successful operation of a similar system for many thousands of hours.

References

[1] "Ultra-high Voltage DC Power Supplies for Large Currents", G. Reinhold, manuscript for a lecture held on July 2, 1974, for the High Voltage Technology Seminar at the Federal Institute of Technology in Zurich, Switzerland. (The German version of this article was published in SEV Bulletin No. 14 of July 19, 1975.)

[2] "Design Considerations and Data for Gas-Insulated High Voltage Structures", D. B. Hopkins, LBL, presented at the 6th Symposium on Engineering Problems of Fusion Research, San Diego, Nov. 1975.