Title

THE DEVELOPMENT OF 2000-AMPERE DIODES FOR HIGH CURRENT PERRITE BIASING SUPPLIES

Authors

Tusting, R.F.
Katz, J.E.
Kerns, Q.A.

Publication Date

1967-03-17

UCRL-17457

University of California

Ernest O. Lawrence
Radiation Laboratory

THE DEVELOPMENT OF 2000-AMPERE DIODES FOR HIGH CURRENT FERRITE BIASING SUPPLIES

DISCLAIMER

For Proceedings of the 1967
U. S. National Particle Accelerator Conference
Washington, D. C., March 1-3, 1967

UCRL-17457
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

THE DEVELOPMENT OF 2000-AMPERE DIODES FOR HIGH CURRENT FERRITE BIASING SUPPLIES

R. F. Tusting, J. E. Katz, and Q. A. Kerns

March 17, 1967

UCRL-17457

THE DEVELOPMENT OF 2000-AMPERE DIODES FOR HIGH CURRENT FERRITE BIASING SUPPLIES*

R. F. Tusting, J. E. Katz, and Q. A. Kerns

Lawrence Radiation Laboratory
University of California
Berkeley, California

Summary

Ferrite tuning circuits of the RF system for the 200-GeV machine require specialized components, because of the requirements for high current and for reliability under pulsing conditions. The present status of the LRL program to provide high-current supplies for ferrite biasing is described here.

I. Introduction

The RF systems of the 200-BeV accelerator[1,2] will be tuned through the range of 29 to 52 MHz as protons are accelerated from an injection energy[3] of 200 MeV to a final energy of 200 GeV. Tuning will be accomplished by loading the RF systems with ferrite, and electronically controlling the permeability with high-current dc biasing supplies. Currents in the range of 0.5 to 50 kA are to be provided by the various (main synchrotron and injector synchrotron) ferrite-saturating supplies.

In view of these requirements (including especially the ability to cycle many times without premature failure), we have tested an evaluated various commercial diodes which are individually rated for 500 A and 1 kA (for the high current units) and 20 A (lower current units).

The above-mentioned needs, together with the results of our testing program, led to the development of 2-kA rectifier diodes. Their first use will be in a 24 kA, 5-volt dc supply currently under construction at LRL, Berkeley. This supply will be used in a ferrite-testing program and as a design prototype for ferrite-saturating supplies for the 200-GeV accelerator. Later design work may suggest a somewhat different dc current requirement, but would embody the concepts of the 2-kA diodes.

II. Requirements of Rectifiers for Ferrite Biasing Supplies

Components used in a high-energy particle accelerator such as the 200-GeV machine will be carefully chosen to ensure that they will provide satisfactory service within a demanding environment where stray electrical interference is present and unscheduled shutdowns will be costly. Reliability, economy, and long life are the essential characteristics required of rectifiers to be used in the ferrite-biasing supplies. In one year of operation, the main synchrotron will be cycled approximately 10^7 times and the injection synchrotron nearly 10^8 times.

A primary requirement of the rectifiers, in addition to suitable ratings, is that they respond well to our cycling or pulsing applications. The thermal, mechanical, and electrical stresses generated by cyclic operation are generally more damaging than those encountered in continuous operation. Later we will discuss how various diodes responded to cyclic operation.

It is instructive to list a few critical requirements of the rectifiers. The p-n junction area should have highly uniform characteristics so that the current density is uniform and hot spots do not develop. Low junction voltage drop and ohmic resistance (both bulk and contact) are necessary for cool operation and high forward-surge-handling capacity. Joints and contacts must withstand the cyclic stresses associated with differential coefficients of expansion, and the ratings of the device must be based realistically on the limitations of the package.

Low forward-voltage-drop rectifiers are desirable so that conversion efficiency is high and cooling requirements are low. An ability to handle forward and reverse surges is also required. Although line filtering will be employed, the rectifiers must be able to tolerate moderate line transients without becoming damaged or causing other parts of the system to fail.

III. Testing Program

In view of our requirements of reliability under cyclic operation and a general lack of data on the performance of high current rectifiers under such conditions, we initiated the diode-testing program described in the next few paragraphs. We know that gradual deterioration is to be expected in our application (even though ideally the diodes would last indefinitely). Since we have every reason to believe that the diodes will eventually fail, the problem is not whether they will fail, but how soon and in which ways.

We want to elucidate the mode of failure, or tendency toward failure, under expected conditions of service. The region of failure may be either in the bulk junction, over the silicon surface, or in the connecting joints of the package--diodes may fail for reasons such as thermal fatigue, fracture of some bond, surface contamination, puncture under electric field, or melting. Our testing program adopted involves measuring the following characteristics of the diodes.

---

*Work done under the auspices of the U. S. Atomic Energy Commission.

A. Capacitance vs inverse voltage (varactor characteristics),

B. Forward voltage drop vs dc forward current,

C. Inverse current vs inverse dc voltage.

After these characteristics are carefully measured and recorded (as discussed a few paragraphs below), we are in a position to subject the diode to electrical and mechanical stresses and to detect (by later repeating the measurements) small changes in the characteristics. Knowing the changes, we can adopt ratings giving suitable operating life under our conditions.

We tested a range of rectifiers, some having a rating as small as 20 A, through those having a rating of 2000 A. Varactor characteristics of small rectifiers ($C \leq 300$ pF at zero volts bias) were measured with a Tektronix LC meter (type 130), modified so that capacitance could be read out on a frequency counter. High-capacitance diodes were measured with an impedance bridge (General Radio Type 1608-A) an an external dc bias supply. A high-input impedance digital voltmeter is used to measured inverse voltage. Expected errors of less than 1% allowed us to detect small changes in junction geometry.

The voltage-current characteristics of the diodes, both forward and reverse, were measured with digital meters and a semiautomatic type-out system. With the present measurement system, a change in forward voltage of a few millivolts is obvious, and in this way incipient failures in joints can be readily detected.

Inverse leakage current was measured for inverse voltages ranging from a few millivolts to the peak-inverse rating of the rectifier. The V-I characteristics at low inverse voltage are continuous with the forward characteristics, and for voltages less than a few millivolts, the diode has the characteristics of a resistor, the properties of which are equivalent to a parallel combination of the bulk junction and the surface leakage paths. The essential point here is that at very low voltage, the combination behaves as a linear resistor.

The data obtained from the semiautomatic type-out system was digested by a computer program DIODE. We developed DIODE to do the handling, calculating, and plotting of the three different types of data corresponding to the varactor, forward, or inverse characteristics described above.

Scaling of the plot coordinate systems was automatically handled by DIODE, to accommodate diode-characteristic data that range over many orders of magnitude. For example, see Fig. 1 where the maximum inverse current is approximately 600 nA, and Fig. 2 where the maximum inverse current is approximately 4 mA. The automatic scaling may be suppressed in order to amplify a small portion of a diode characteristic plot. For example, millivolt changes in a diode forward characteristic curve may be displayed by expanding the forward voltage scale. See Figs. 3 and 4.

IV. Cycling Procedure

Diode specimens tested were of the types listed in Table I; all were silicon devices. The samples, for which test data is present, have been assigned letter designations as indicated in the left-hand column of Table I. The Motorola single-cell rectifiers (an example of which is designated diode C) are the same type as those used to build up the multicell rectifiers E and F.[4] The same semiconductor pellet was used to make rectifiers with average forward current ratings whose values, varying from 1.5 to 35 A, depend on the package used.

Table I. Rectifier diodes tested.

Diode	Type	Current rating	Number tested
A and B	Delco 1N1192A (single cell)	22 A	8
C	Motorola (single cell)	22 A	18
D	General Electric A296B (single cell)	500 A	2
E	Motorola MR1290 (multiple cell)	1 kA	4
F	Motorola SR1691 (multiple cell)	2 kA	14

The small rectifiers were cyclically stressed by connecting in series the diodes being tested. The forward current through the series of diodes was turned on for five seconds and then off for five seconds. The forward current during the on period was held at a constant value, which depended on the particular diode string under test. The value of the forward on current was set at specific values in the range from 22 to 90 A. See Figs. 5 and 6. During the off period, the forward current was less than 0.1 A.

For the high-current rectifiers, the cycling procedure was as follows: A pair of diodes to be tested was connected in a 60-Hz full-wave rectifier configuration, then operated on for one second and off for one second. During the on period, the average dc current delivered by the pair of rectifiers was 2 kA for the 1000-A rectifiers and 800 A for the 500-A rectifiers. During the off period, the currents were approximately 5% of the above values.

In addition to the cyclic stressing described above, selected rectifiers were tested for forward and reverse surge handling capacity. Again, careful measurements before and after testing allowed us to detect early stages of degradation. The type E diodes displayed excellent stability in their forward characteristics (see Fig. 4), although inverse leakage current increased significantly with age (see Fig. 2). The type D rectifiers behaved just the opposite: the inverse V-I characteristics were very stable but the forward voltage drop progressively increased with time (refer to Figs. 1 and 3). In all cases, the varactor characteristics did not change within the small limits of experimental error. This fact is significant because it shows the p-n junction itself did not degrade.

V. Development of 2-kA Diodes

On the basis of the above results, we decided to concentrate on developing multi-cell rectifiers for the ferrite bias supplies. The flat pack construction permits low circuit inductance and facilitates maintenance--it is easy to replace a single 2-kA diode. Because our application involves low voltage, the inverse leakage currents are less important than stable forward characteristics. Future use of a few large-area rectifiers in parallel is not ruled out, but they will have to compare favorably with available multi-cell units.

To build one 24 kA, 5-V supply using a 12-phase system required twelve 2-kA rectifiers. The manufacturer agreed to make 14 units to LRL specifications. As well as having a higher current rating than the MR1290, the diodes incorporated a number of design improvements. The differences between the MR1290 type devices and the LRL 2-kA rectifier (SR 1691) are tabulated in Table II. Both types have measured forward drops of 955 mV (± 10 mV) at twice rated forward current. See Fig. 7 for a typical forward characteristic curve for a 2-kA diode and Figs. 8 and 9 for photographs.

Measurements on individual single cells of the type used to build the 2-kA rectifiers showed them to be very vulnerable to inverse voltage surges. A few microjoules of inverse energy can cause permanent damage to such cells, whereas cells of the same size but containing avalanche-protected junctions should be able to handle millisecond pulses of several joules. Because the present rectifier technology cannot achieve this in the cells used, inverse transient protection is obtained by connecting a 2-by-2 in. selenium surge protector (Klip-Sel) in parallel with each diode array.[5] The Klip-Sels are able to pass repeated 200-A inverse surge currents while limiting the inverse voltage to less than 100 volts, without becoming damaged. The selenium cells are mounted against the anode plate of the rectifier, the cathode connection being made by a 0.003-inch thick tin strap (refer to exploded view of the cell and mounting hardware, Fig. 9).

Table II. Comparison of rectifier characteristics.

	MR1290 series	SR 1691
Rated average forward current (A)	1000	2000
Rated peak repetitive reverse voltage (V)	50 to 400	100
Number of parallel cells	45	100
Spacer material	Nylon	Ceramo-plastic[a]
Spacer bolt material	Nylon	Steel
Width of bus bars (in.)	4	6
Number of bolt holes per terminal	2	5
Shape of water cooling tubing	S	Spiral
Plate-to-tubing contact length (in.)	15	50
Weight (lb.)	4.25	9.5
Overall dimensions (in.)	8×4×1-3/4	10×6×1-3/4
LRL assembly drawing number		9W2914

[a] Supramica 500, Mycalex Corp. of America

VI. Future Work

The testing program described in Sec. III and IV is being continued; the diodes under test have so far undergone 14 million test cycles.

We are continuing to survey the field for diode most suited to our needs, since it is clear that p-n junction device technology is advancing.

At present, low-reactance transformers are being constructed for the previously mentioned 24-kA supply. The transformers are designed with integral high-current terminals for direct diode mounting. We plan to report on the supply performance with its associated high-current feedback control system at a later time.

Acknowledgments

The authors express their thanks to John Newcomb, a District Sales Manager of General Electric, for his assistance in obtaining the A296B rectifiers, and to Edward Richez, Product Manager of Rectifiers, Motorola, Phoenix, for his assistance in obtaining rectifiers for testing and for his cooperation in the SR 1691 development program.

References

1. Lloyd Smith, Super-Energy Accelerators, IEEE Trans. Nucl. Sci., NS-12 No. 3 June, 1965.
2. F. B. Selph and J. M. Peterson, Selection of Injector Synchrotron Parameters to Minimize Cost of the 200 BeV Accelerator, Paper G-18 of this Conference.
3. J. M. Peterson, Choice of the Injection System for the 200 BeV Accelerator, Paper F-24 of this Conference.
4. The Semiconductor Data Book, Motorola, Inc., Semiconductors Products Division, 1966.
5. International Rectifier Corp. Catalog B-66. Similar surge protectors are manufactured by others, for example, General Electric and Sarkes Tarzian.

Figure Captions

Fig. 1. Inverse characteristics of diode D, single cell, 500-A rating.

Fig. 2. Inverse characteristics of diode E, multiple cell, 1-kA rating.

Fig. 3. Forward characteristics of diode D, single cell, 500-A rating.

Fig. 4. Forward characteristics of diode E, multiple cell, 1-kA rating.

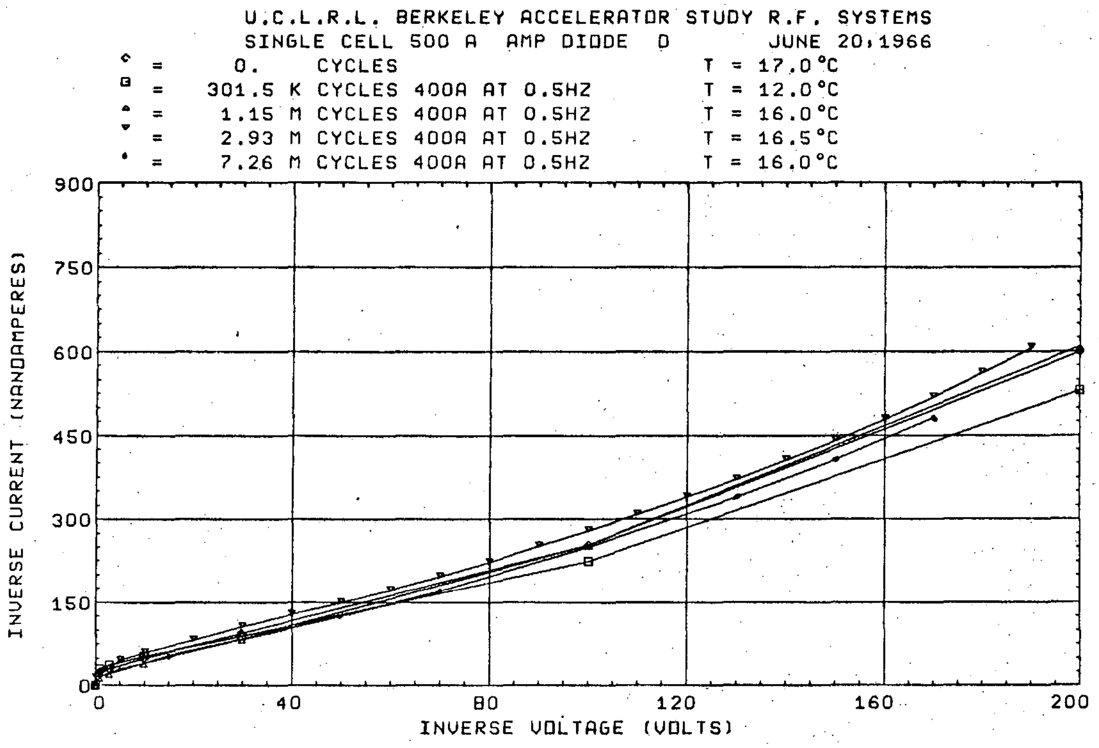
Fig. 5. Forward characterisitcs of diode B, single cell, 22-A rating.

Fig. 6. Forward characteristics of diode C, single cell, 22-A rating.

Fig. 7. Forward characteristics of diode F, multiple cell, 2-kA rating.

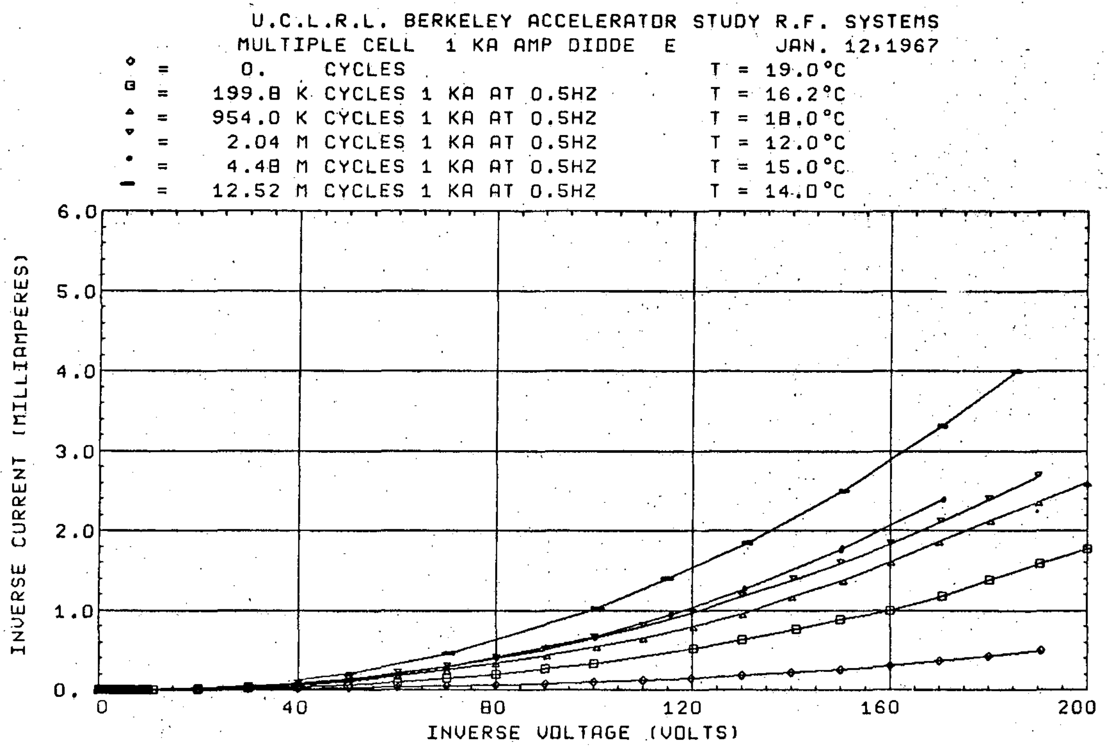
Fig. 8. SR 1691, 2-kA rectifier.

Fig. 9. Exploded view of surge protector mounting hardware and the SR 1691 rectifier.



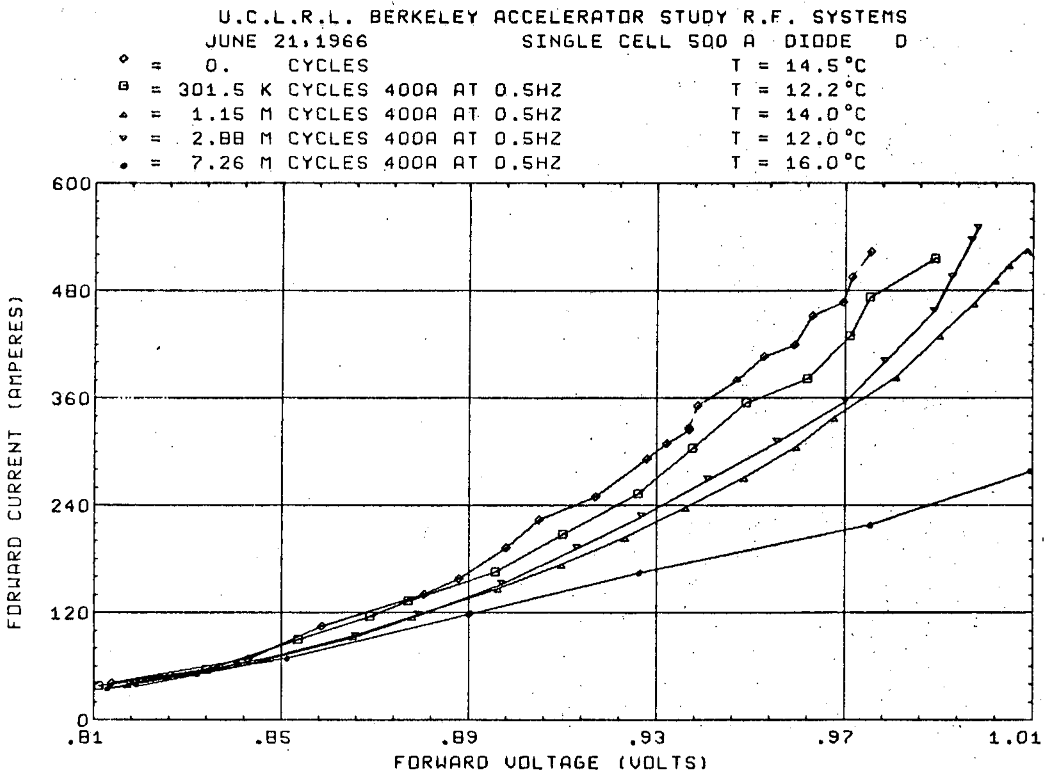
XBL 673-1291

Fig. 1



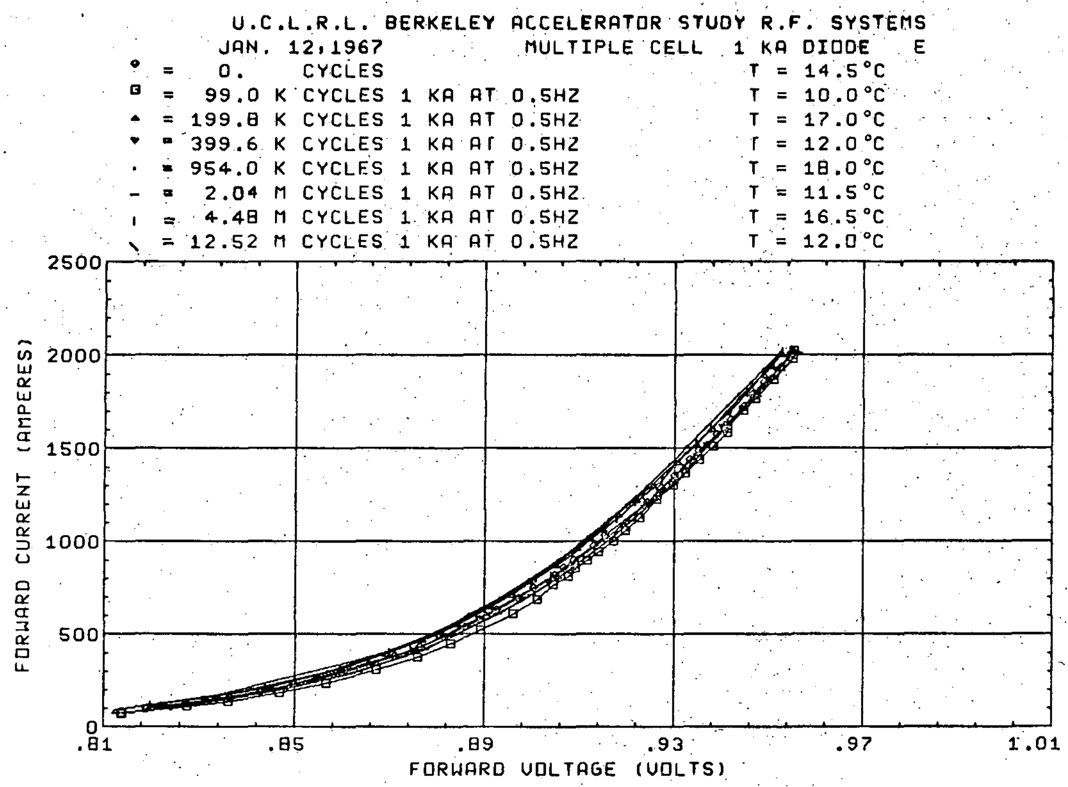
XBL 673-1290

Fig. 2



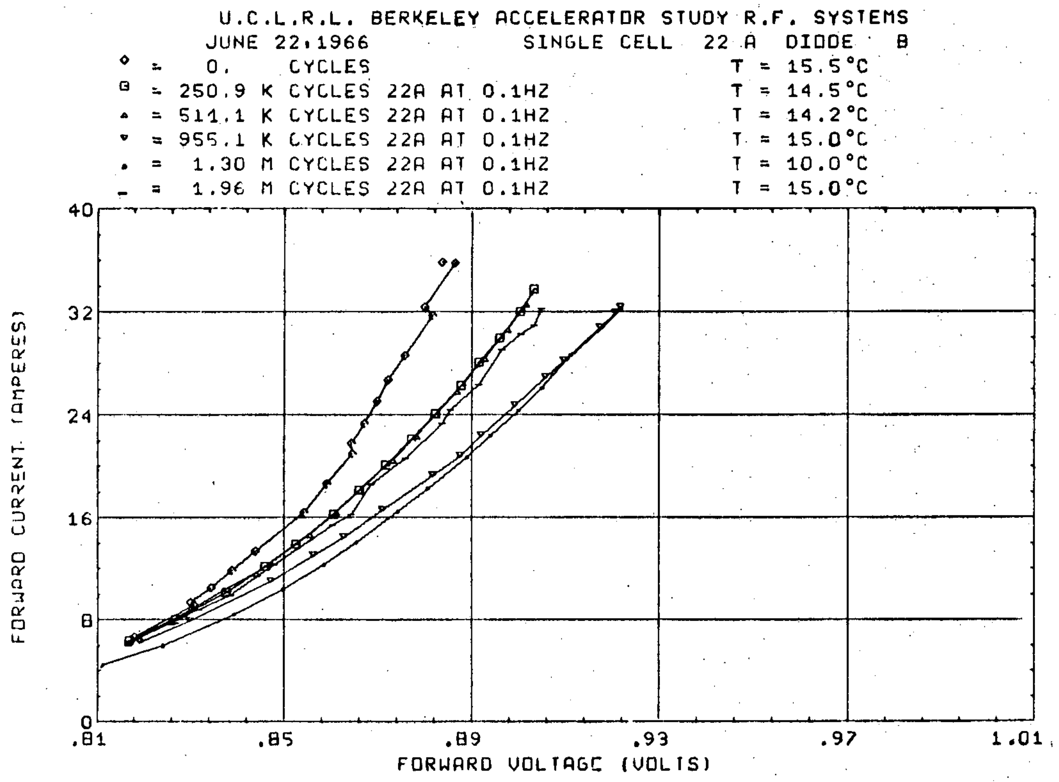
XBL 673-1292

Fig. 3



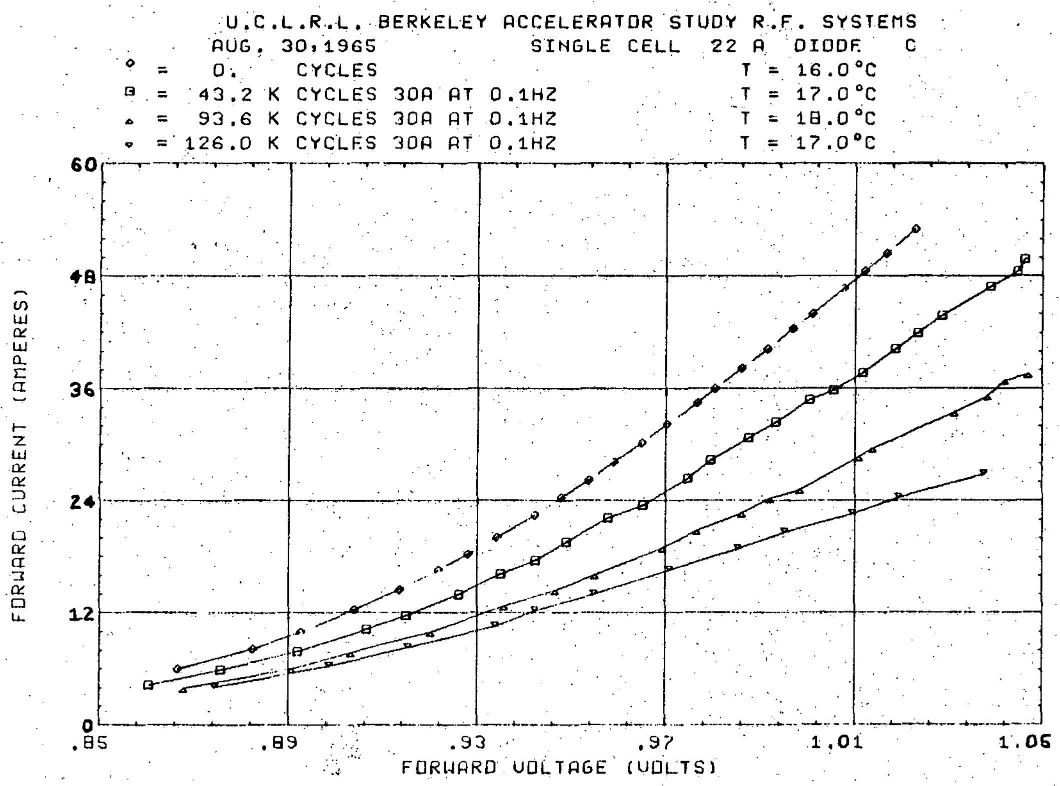
XBL 673-1293

Fig. 4



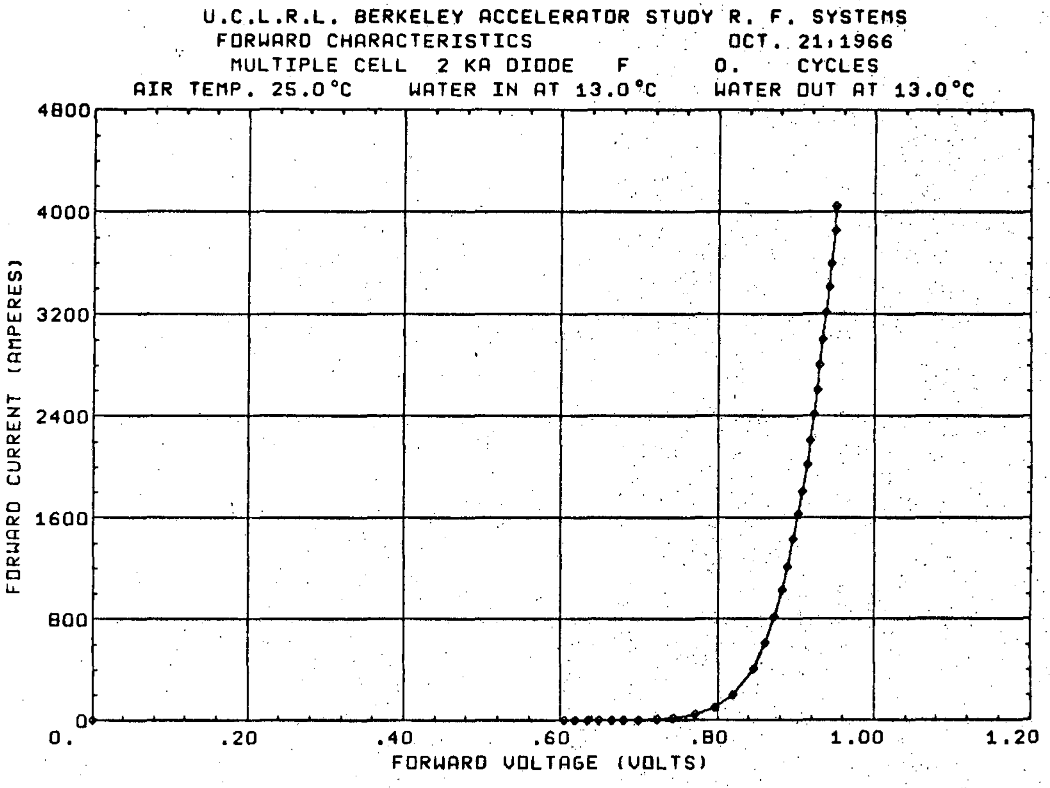
XBL 673-1294

Fig. 5



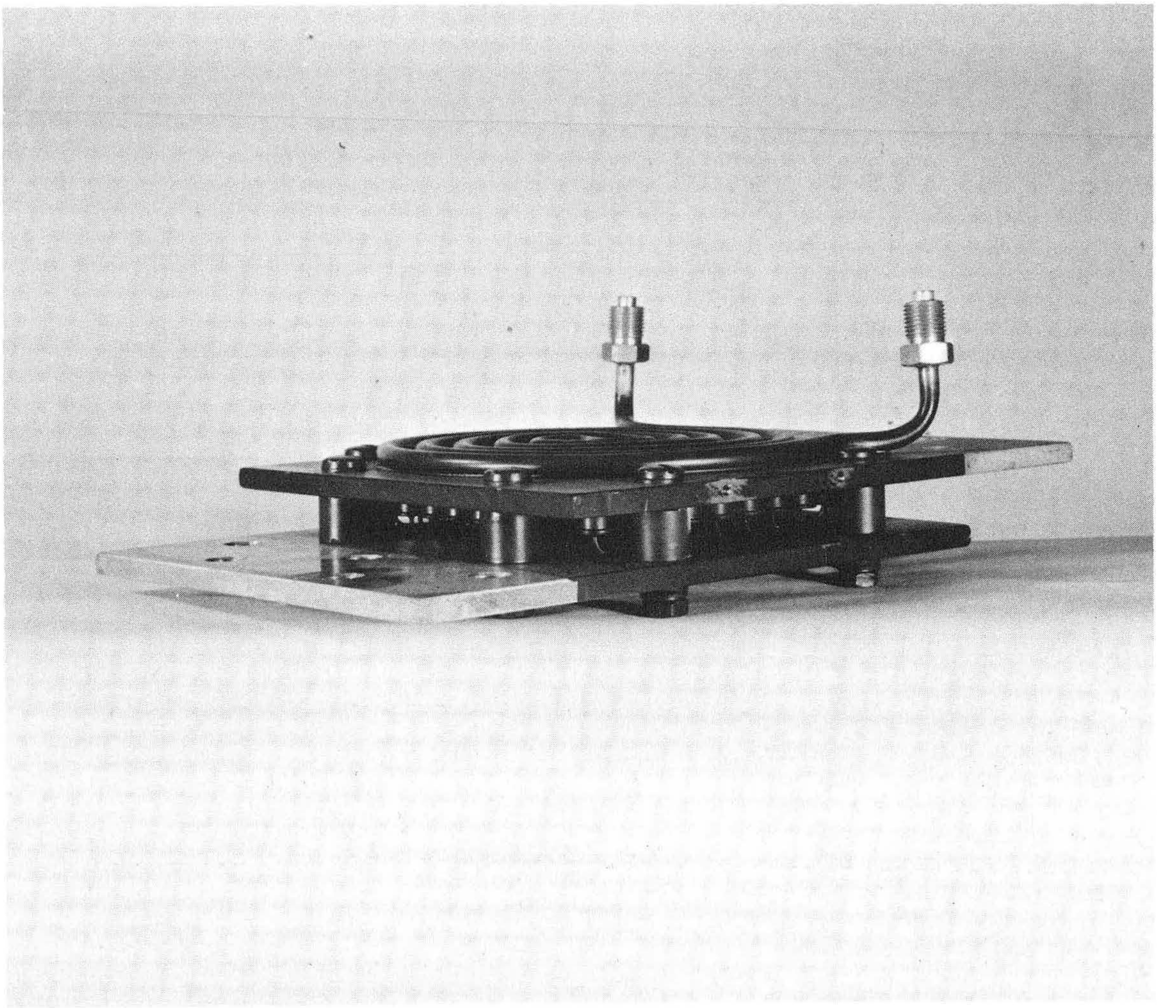
XBL 673-1295

Fig. 6



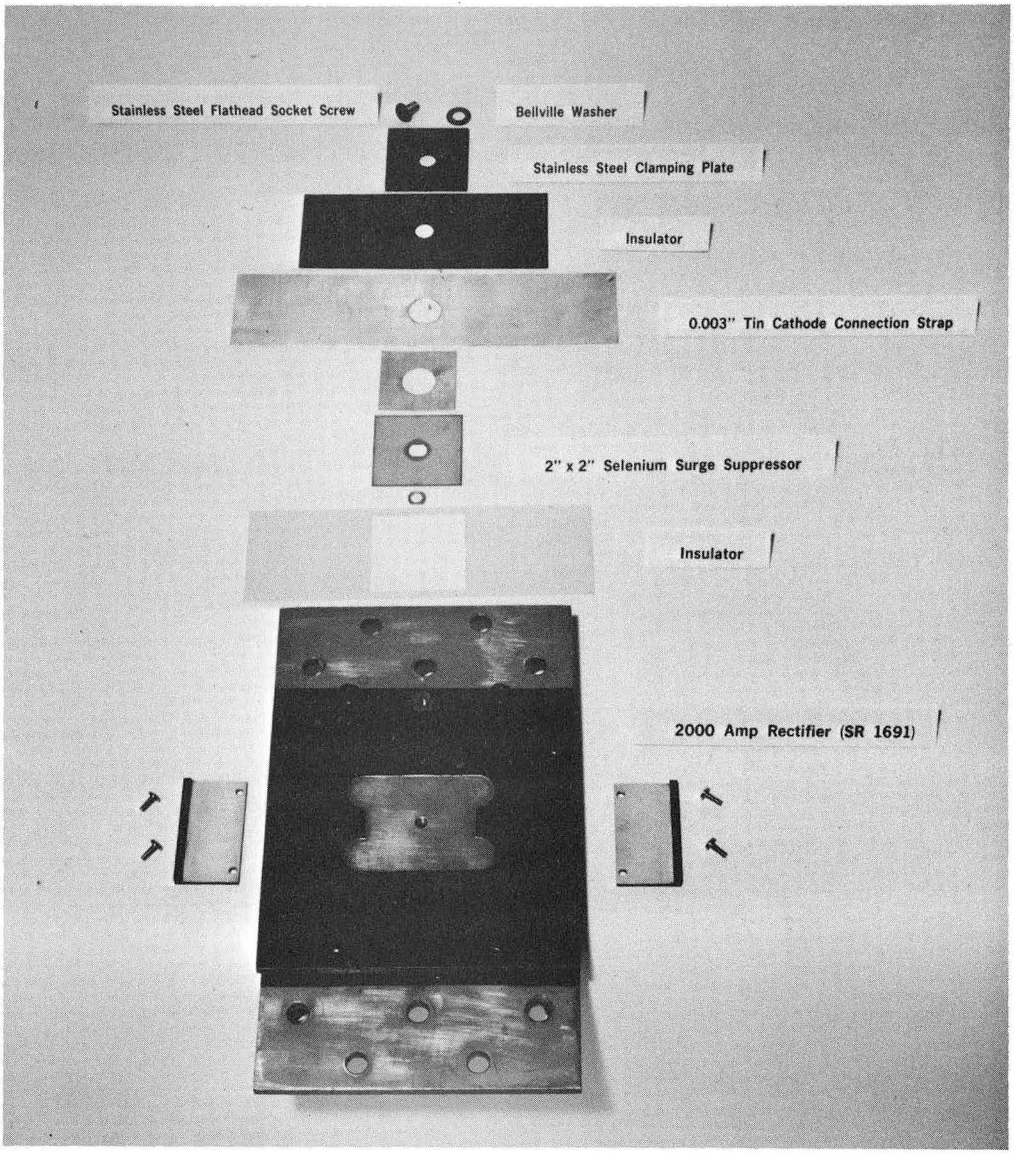
XBL 673-1296

Fig. 7



BBH 673-97

Fig. 8



BBH 673-98

Fig. 9