IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

30-53 MHz SUPER CAVITIES FOR 10-GeV ACCELERATION IN THE FERMILAB BOOSTER RING

Q. A. Kerns, M. P. May, H. W. Miller, J. S. Reid*†

INTRODUCTION

Here we describe techniques to increase the normal operating voltage of Fermilab Booster Cavities by 33-1/3%. The previous barrier of 22.5 kV was a limiting threshold above which destruction of many of the cavity components occurred. Areas discussed are a spark protection system, improved anode blocking capacitor characteristics, modifications made to critical areas of the cavity which spark, and RF power amplifier requirements.

SPARK DETECTION SYSTEM

We have observed that ARCS in the RF cavity are not self-extinguishing, but, especially with the powerful regulating loops, arcs persist for RF "ON" time, and do severe damage to copper surfaces, involving as much as 1500 Joules. By detecting the spark early and gating off all power, the spark energy is limited to that stored in the system, 0.1 Joule, and we are able to "bake-in" the system to progressively higher voltages. That is, sparking of limited energy actually improves the voltage hold off capability.

Description of Spark Detector

Figure 1 is a diagram of the spark sensor, and Figure 2 is a photo of the unit.

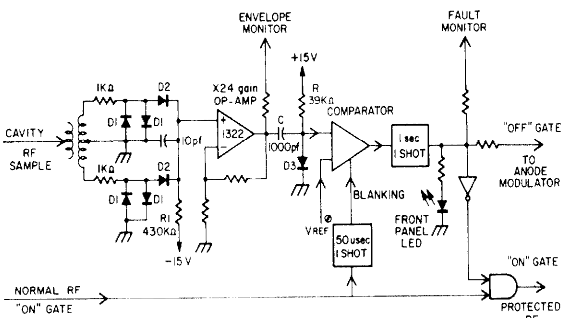


Fig. 1. Simplified Schematic of Spark Sensor.

Fig. 2. Complete Spark Sensor Assembly.

A sample of a few volts RF from the cavity is fed to a full-wave rectifier (Diodes D2) after limiting by diodes D1. Owing to the forward conduction characteristics of D1, the envelope response of this peak detector is approximately logarithmic over 40 dB and may be observed at the point labeled "Envelope Monitor".

*Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.

†Operated by Universities Research Association, Inc., under contract with the U. S. Department of Energy.

On receiving a normal RF "ON" gate, the cavity RF envelope rises and follows a programmed amplitude. During the first 50 μs of the RF envelope, the spark detector is inactived by the blanking signal to allow for computer-automated tune-up of ferrite bias starting current. Diode D3 is normally conducting via R and +V. Only if the cavity envelope decreases amplitude can D3 be turned off and the comparator fired. Furthermore, the rate of envelope decrease must equal or exceed a set threshold to fire the comparator and 1-shot, simultaneously gating off RF drive and anode power to the 160 kW Power Amplifier. The standard setting for V_{REF} and the chosen constants R, C, and V are such that the RF amplitude must fall a) at least 1 dB and b) at a rate of at least 2 dB/microsecond, to shut off the power amplifier. On the other hand, the RF may increase at any rate without being misinterpreted as a fault. Settings a) and b) were arrived at after a test program of deliberately initiated sparks at various places in a Booster cavity and in a power amplifier on the test stand, and confirmed by Booster operation.

During the course of developing the spark detector system we explored a) acoustic detection (microphones), b) optical detection (multiplier phototubes, PIN photodiodes, photo transistors), and c) RF detection. All these methods worked. Method a) suffers from speed-of-sound delays and conferred measurably less protection of sparked surfaces. Method b) requires careful gain adjustment and is tricky because spilled beam can appear to any of the light sensors as a flash of light and therefore shut off the system. We did, nevertheless, determine that PIN photodiodes, especially, are usable and live at least a year in the tunnel environment. Method c) was chosen because it was least difficult to apply and gave adequate protection in our tests.

SUPER CAVITY PROGRAM

Mechanical and Quality Control Steps

Twenty Booster Cavities, 18 of which are needed in the machine in order to make the required RF volts/turn and two spares were modified to "30 kV Super Cavities", Figure 3. Because of the residual radioactivity present, a special "Hot Shop" was set up to handle the modification which took one year using people who still had to do routine machine maintenance.

Cavities were completely stripped, parts machined as necessary, tuners rebuilt using new low loss ferrite, parts thoroughly cleaned, electrical joints tin-plated, and mode damper mounts added before final assembly.

Measurements and tests done on the final assembled cavity to ensure its performance included water flows, bus bar electrical joints, RF monitor calibration, high voltage running, spurious mode plots and RF leakage.

Higher Frequency Modes

At 30 kV two higher order modes aggravate cavity gap arcing. An 82 MHz "end-to-end" mode (non-tuneable with ferrite tuner) developed an out of phase voltage from one gap to the other. We added coupling loops that selectively damp the out of phase mode while removing little fundamental power from the cavity.

The other offensive mode is an overtone above the fundamentally tuned frequency of the cavity. Both gaps resonate in phase and if the overtone and second

0018-9499/79/0600-4111$00.75 © 1979 IEEE

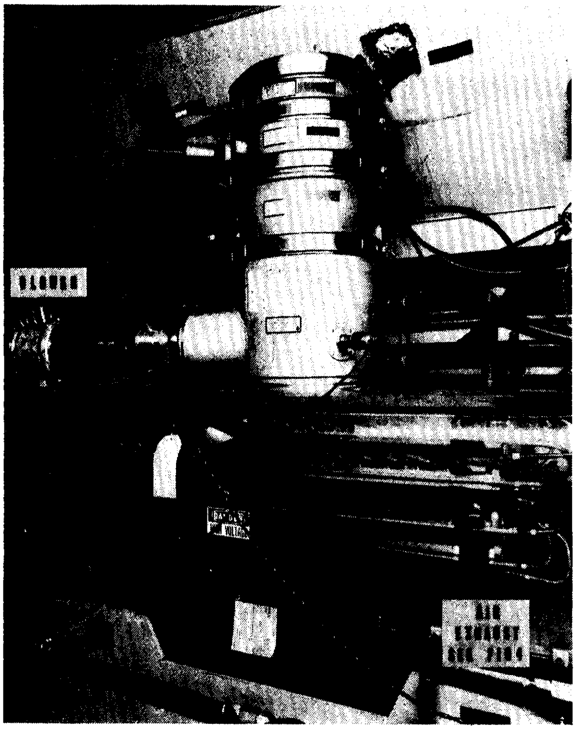


Fig. 3. Booster Super Cavity installed in tunnel.

harmonic of the fundamental drive frequency approach each other, a large second harmonic gap voltage is developed. Adding capacitive loading near the gap ends of the drift tube serves to push the overtone away from the second harmonic so they will never approach or cross each other as the fundamental is tuned.

Air Circulation

Filtered air is blown in thru a snout in the power amplifier, around the anode blocking capacitor, and out each end of the three tuners (Figure 4). The blower serves two purposes. The air flow provides additional cooling for the anode blocking capacitor and, it keeps ozone from building up around the power amplifier, blocking capacitor, drift tube and tuners. If corona or a spark should occur, the air circulating will blow the ionized air out and prevent a recurring arc.

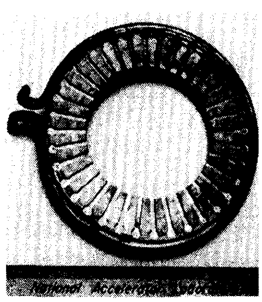


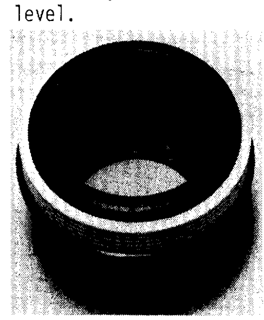
Fig. 4. Modified End Ring for air discharge at each end of tuner.

BLOCKING CAPACITOR

For several years, a blocking capacitor of simple design has been used in Booster cavities. The capacitor is assembled using a monolithic ceramic cylinder of 99.5% alumina as the dielectric. The choice of dielectric material provides high radiation resistance and low dielectric loss. Copper 102 cylinders, shrunk on the outside and expanded against the inside diameter of the ceramic, form the two capacitor electrodes. Clamping fingers on the inside copper and a bolt flange on the outside electrode provide the means to coaxially mount the blocker between a power amplifier and the cavity. Copper thickness of 0.09 inches provides a good thermal path to carry heat from the copper surfaces to the clamped electrical connections which are water cooled.

The blocker design proved adequate at booster cavity operating voltages below 25 kV. At 30 kV operation however, there was excess heating. Although the copper electrodes are fitted to the bare ceramic with a 0.014 inch interference, minute gaps can exist between the ceramic and copper due to manufacturing imperfections. Corona discharge in these gaps at high RF power levels causes excessive heating. This expands and loosens the copper (a runaway condition). Figure 5 shows a picture of the blocker along with required design parameters for 30 kV operation.

Two improvements were implemented in the blocker system to meet the 30 kV requirements. The ceramic was metalized over the entire surface where the copper is in contact. Air, blowing on the outside diameter of the assembly, removes ozone due to corona and provides additional cooling. Characteristics are compared for the blocker assembled with bare ceramic and with metalized ceramic in Table I. The bare ceramic assembly is less lossy at low power than the metalized one. However, the power dissipation calculated from Q is only of academic interest above 22.5 kV where, for the bare ceramic, corona heating dominates. The increased corona threshold of the metalized ceramic blocker significantly reduces RF heating at the higher voltage level.



BLOCKER DESIGN PARAMETERS

Capacitance	1000 pf
RF Current	$565A_{rms}$ 53 MHz
DC Stress	30 kV/200 mils
Dielectric	99.5% Alumina
Ceramic	10.7" Dia. x 5.6" H.

Fig. 5. Assembled metalized blocker with design parameters.

TABLE I. BLOCKING CAPACITOR CHARACTERISTICS

	Bare Ceramic	Ceramic Metalized
Capacitance 1 kHz	1062 pf	1190 pf
Q at 53 MHz	2316	1753
Corona Threshold 60 Hz peak	3.5 kV	14 kV
Temperature Rise[1] Water Cooled	Local Hot Spots > 100°C	25.6°C
Temperature Rise[1] Water & Air Cooled	Local Hot Spots > 100°C	16°C
Power Loss[2] Calculated from Q	180 watts	226 watts
Ceramic Loss[2,3] Q > 10,000	< 40 watts	< 40 watts

1) Temperature measurements made at 30 kV, 53 MHz & 50% duty cycle.
2) Power loss calculated for above conditions assuming no Corona heating.
3) See Ref. 3.

160 kW POWER AMPLIFIER

In the Fermilab Booster Synchrotron, the driving point impedance of the cavity varies as a function of the tuning frequency. (Approximately 1.6 kΩ at 30 MHz to 8 kΩ at 53 MHz.) The maximum RF power required from the power amplifier to drive the cavity occurs early in the Booster cycle while the RF gap voltage is still increasing. The gap voltage is equal to the product of the power amplifier RMS current, the driven impedance, and the appropriate amplifier to gap step-up ratio.

For the 30 kV Super Cavities, the required RMS drive current early in the cycle is substantially greater than for previously standard 22.5 kV cavities. This increase in the required current required a moderate modification to the existing 100 kW power amplifiers.[1,2] Figure 6 compares the Super Cavity gap voltage with a 160 kW Power Amplifier and the standard cavity with its 100 kW Power Amplifier as a function of booster frequency. Operation at 160 kW pushes the final power amplifier tube to above some maximum rated parameters but so far we see no degradation in final tube reliability.

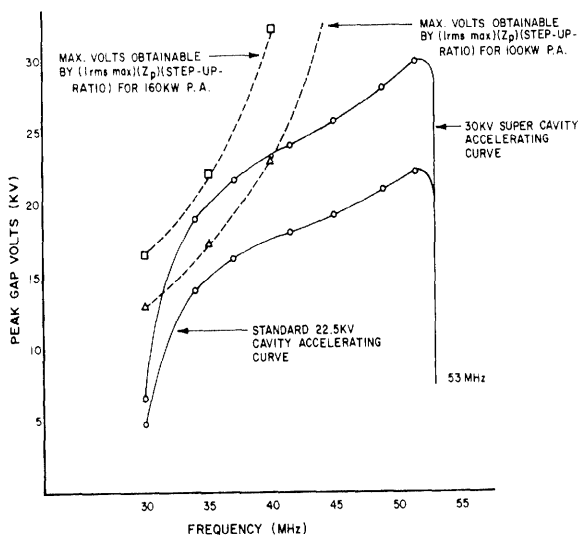


Fig. 6. Booster Cavity available gap voltage with 100 kW and 160 kW Power Amplifier.

It is too early to tell what long term reliability at 160 kW power level will be. A number of measures are being taken to improve reliability. One of the major problems has been the failure of tubes in the cascode driver portion of the power amplifier within a very short period of time after being installed in the machine. (Not necessarily related to the higher power amplifier.) We believe a lot of these early failures (< 1 month running time) were due to poor quality tubes. This brought about an extensive screening program with the development of a modular 40 tube "Tube Tester and Bake-In" rack. All new tubes are cycled thru this testing rack which is equipped with individual fast crowbars to prevent possible tube destruction should one arc. This now enables us to weed out potentially bad tubes.

We feel the addition of this careful tube screening program along with better quality control, addition of fast power supply blocking circuits, and a scheduled tube replacement program (about 600 tubes/year) will help in keeping the reliability and power output high.

REFERENCES

1. Q. A. Kerns and H. W. Miller, "100 kW RF Power Amplifier", IEEE Transactions on Nuclear Science, V. MS-18, No. 3, June, 1971, p. 246.

2. H. W. Miller and J. S. Reid, "Immediate Steps to Increase Power Amplifier Output", Internal Fermilab Memo, August, 1978.

3. J. F. Bridges et al., "Dielectric Property Measurements on Large Alumina Vacuum Seals Used on Fermilab Accelerator RF Cavities", IEEE Transactions on Nuclear Science, V. NS-22, No. 3, June, 1975, p. 1296.