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J.D. Fuerst and W.H. Hartung

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

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## **DISSIPATED POWER MEASUREMENTS IN THE A0 SRF CAVITY SYSTEM**

J. D. Fuerst and W. H. Hartung

Fermi National Accelerator Laboratory  
Batavia, IL, 60510, USA

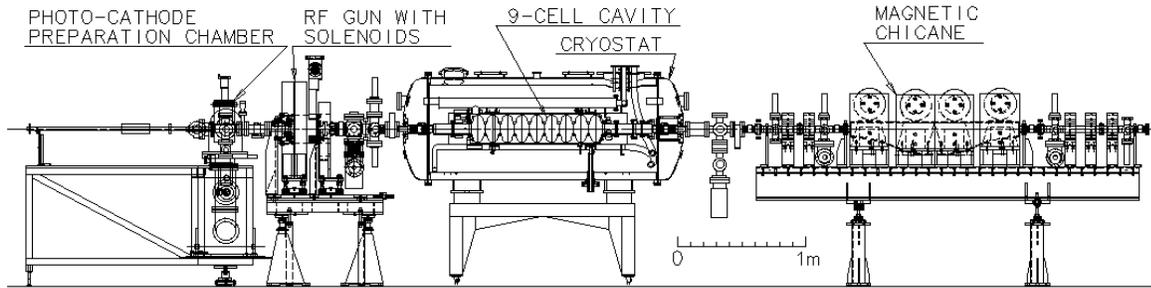
### **ABSTRACT**

Fermilab operates a single TESLA 9-cell superconducting RF cavity in support of a photoelectron R&D beam line. Power going into the 1.8K cryogenic system via static heat leak and RF dissipation is measured from the rate of rise of the pressure in the helium bath. This paper describes the techniques used to determine the cryostat heat load and the RF performance of the cavity.

### **INTRODUCTION**

A photo-injector has been constructed at Fermilab to produce a low-energy (14-18 MeV) electron beam with high charge per bunch (8 nC), short bunch length (1 mm RMS), and small transverse emittance ( $<20$  mm mrad)<sup>1</sup>. The facility was used to commission a photo-cathode RF gun for the TESLA Test Facility (TTF) Linac at DESY<sup>2</sup>. At present, the Fermilab machine is being used for R&D in bunch length compression and fast beam diagnostics; experiments in plasma wake field acceleration and channelling acceleration are in preparation.

Beyond the 4 MeV delivered by the RF gun, acceleration is done by a 9-cell superconducting cavity. The 1.3 GHz cavity also provides a position-momentum correlation for subsequent bunch length compression. The cavity was built by industry for TTF, tested at DESY, and then sent to Fermilab where it accelerated its first beam in October 1998. The maximum beam energy so far is 18.5 MeV, measured with a spectrometer<sup>3</sup>. The cavity is one of several with low quench field, attributed to contamination in the equator welds. Measurements of the cryogenic performance of the cavity and cryostat were done between periods of beam operation, as will be discussed herein.

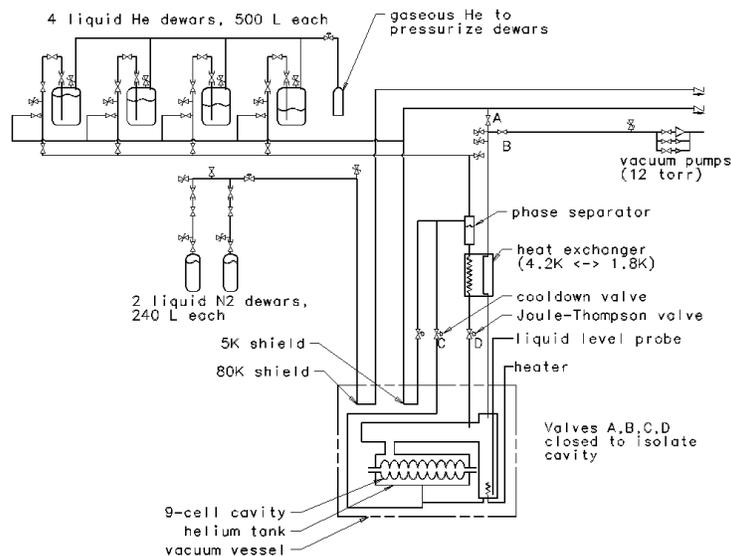


**Figure 1.** Elevation view of the Fermilab A0 Photo-injector beam line.

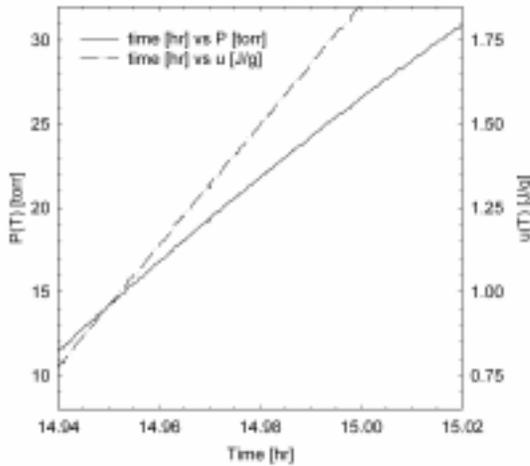
## SYSTEM DESCRIPTION

The photo-injector beam line is shown in Figure 1. The cryostat is a copy of that used for the TTF capture cavity<sup>4</sup> and operates in a saturated bath of 1.8K helium II. Liquid helium is supplied from a manifold to which as many as four 500 liter helium dewars may be connected. The helium tank is radiation shielded and heat intercepted at 5K and 80K. Helium boil-off gas exhausts to the atmosphere through several vacuum pumps which maintain the cavity bath at 1.6 kPa (12 torr). Figure 2 shows a schematic of the cryogenic system.

The cavity and RF system were designed for pulsed operation at 10 Hz repetition rate with a 500  $\mu$ s fill time and an 800  $\mu$ s "flat top" of constant field. The input coupler is optimized for the heavy beam loading provided by a train of 800 bunches of 8 nC each, spaced 1  $\mu$ s apart. Thus, without the beam, the cavity is highly over-coupled (the external Q can be adjusted between  $10^6$  and  $10^7$ ), and the RF power dissipation cannot be determined with any accuracy from RF measurements. Cryogenic loss measurements must therefore be used instead. The amplitude and phase of the cavity field are regulated via a digital control system developed for TTF<sup>5</sup>.



**Figure 2.** Schematic of the cryogenic system for the 9-cell superconducting RF cavity.



**Figure 3.** Rise in helium bath pressure and saturated liquid internal energy with supply and return valves closed.

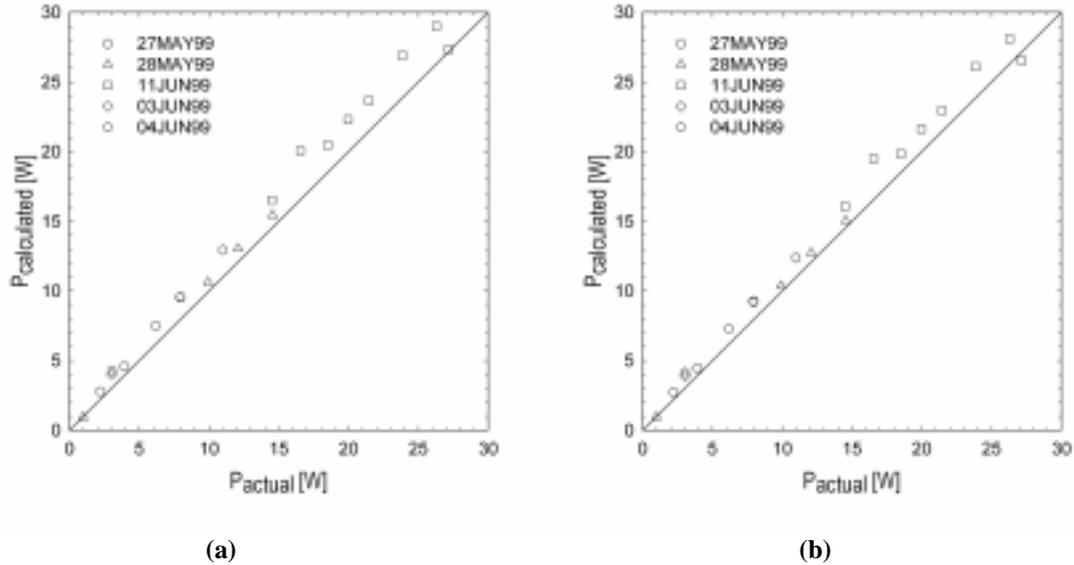
## MEASUREMENT TECHNIQUES

Several techniques, varying in accuracy and simplicity, exist for measuring the RF power dissipation to the cryogenic system.<sup>2</sup> We chose a slight modification of a method used at TJNAF for the CEBAF cryomodule commissioning<sup>6</sup> whereby the cryogenic system supply and return valves are shut while three distinct heat loads are applied to the cavity cryostat. First, RF power is applied over some pressure interval. Next, the RF is switched off and the pressure is allowed to rise further under the influence of the static heat load. Finally a known power level is applied to the bath through a resistance heater as the pressure rises still further. For small  $\Delta p$ , the rise in pressure over time is almost linear and the power dissipated by the RF can be inferred directly. In contrast to the CEBAF cryomodules, for which the pressure rise was on the order of a few millitorr over several minutes, the pressure rise for our system was several torr for each data point. This is due to the large volume difference between the systems (about 20 liters of liquid for our system vs. several hundred liters at CEBAF) for comparable static heat loads.

Plots of heater power against  $\Delta p/\Delta t$  show inconsistencies in slope, particularly among data gathered on different days. For example, the isolation valves (particularly the LHe supply valve "D" in Figure 2) don't appear to seal completely when closed, causing error. The "3-point" measurement technique reduces error associated with valves as well as error caused by slow changes in the system. The calibration data (known heater power and static heat load alone) for each RF data point is taken before the isolation valves are opened again.

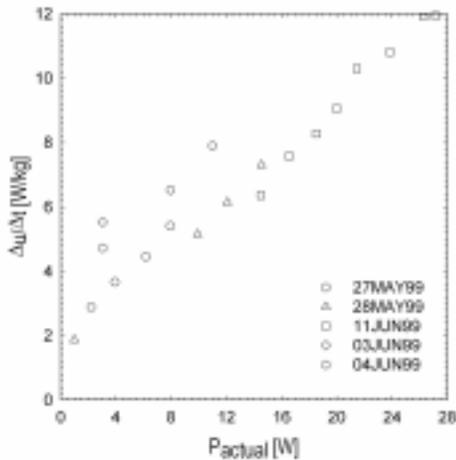
As the observed  $\Delta p/\Delta t$  is not constant, we evaluate the system's change in internal energy instead. Our cryostat contains 21.5 liters saturated liquid, 6 liters saturated vapor, and 11.5 liters superheated gas. The superheated gas temperature is about 4K. By adding up the internal energy of the helium in these three regions at 9 torr (1.2 kPa) and at 21 torr (2.8 kPa), we find that 2700 Joules of energy are added to the helium between 9 and 21 torr. Under static conditions, it takes about 225 s for the pressure to rise between these two values, implying a static heat load of 12 W. Evaluating the saturated liquid component alone, we find an energy change of 2590 Joules, giving an 11.5W static load. Figure 3 shows the rise in system pressure as well as the rise in saturated liquid internal energy over time with the helium supply and return valves closed. Several "3-point" test measurements were done in which a known heater power

was substituted for the RF dissipation. The heater power was inferred from the measured pressure rise.

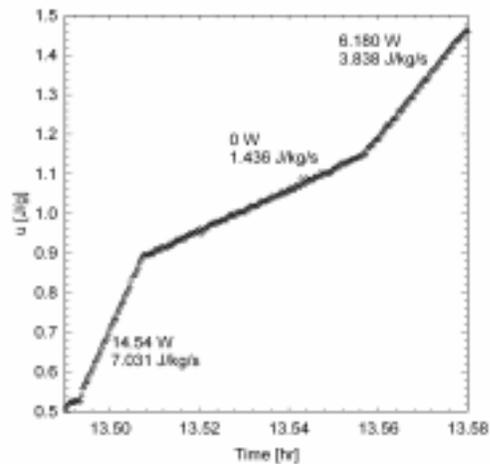


**Figure 4.** Calculated vs. actual power from  $\Delta p/\Delta t$  data (a) and  $\Delta u/\Delta t$  data (b). The solid line corresponds to the case in which the calculated power is equal to the actual heater power.

Figure 4a shows a plot of actual vs. calculated power using  $\Delta P/\Delta t$  data while Figure 4b shows the same plot using  $\Delta u/\Delta t$  data. If we plot heater power vs.  $\Delta u/\Delta t$  (Figure 5) for the data of Figure 4b, we see the cumulative effects of valve position error, slow changes in system equilibrium, etc. This scatter is reduced using the "3-point" analysis technique. Nevertheless, our analysis technique systematically overpredicts the dissipated power by less than one watt at low power and about three watts at high power, with maybe one watt scatter in the data. We have not corrected the data for this effect.



**Figure 5.** Heater power vs.  $\Delta u/\Delta t$  for the data of Figure 4b, showing scatter between data sets.



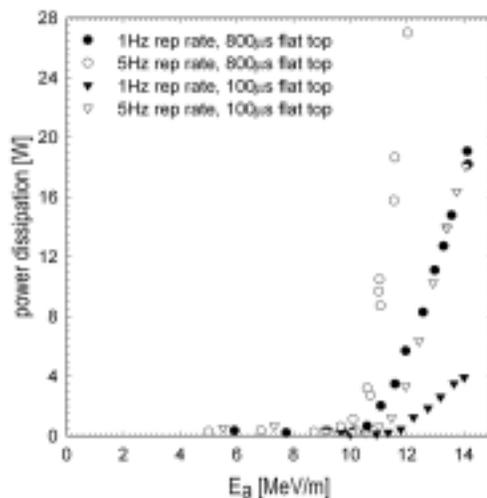
**Figure 6.** Data collected with heater settings of 14.54W and 6.18W, separated by static load.

The cavity was typically tuned to be on resonance at 11 torr bath pressure. RF data were collected between 9 and 13 torr. The RF control system was used to maintain a constant field level in the cavity, even as the resonant frequency shifted with the changing bath pressure. Static heat load data was taken from 13 to 17 torr, and the control heater data was taken from 17 to 21 torr. Figure 6 shows a single set of three measurements for a control data point (that is, using the heater instead of RF).

## MEASUREMENT RESULTS

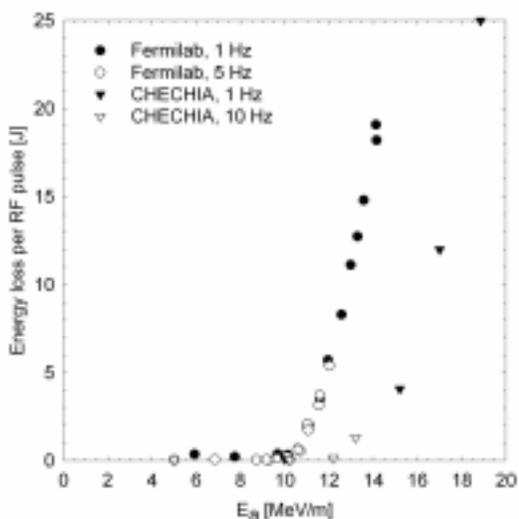
Figure 7 shows the power dissipated into the helium as a function of cavity field level for several different RF input parameters. Initial tests of this cavity in a vertical dewar at DESY<sup>7</sup> indicated that the CW quench field was about 13 MeV/m. Dissipation into the cryogenic system begins to become noticeable as the accelerating gradient  $E_a$  exceeds 10 MeV/m. The attainable gradient was limited by trips in the RF interlock system. Dissipation rates above 20W caused fairly rapid pressurization of the helium tank making data difficult to collect. In any case, these rates approach the sustainable capacity of the helium vacuum pumps and are beyond the expected operating envelope. As can be seen in Figure 8, the scaling with repetition rate is as expected: for a given flat top duration, the energy loss per RF pulse is approximately the same, whether the repetition rate is 1 Hz, 5 Hz, or 10 Hz. Figure 8 also compares the cavity performance at Fermilab with earlier performance in the CHECHIA horizontal cryostat at DESY. Note the degradation in performance with time, perhaps caused by particulate contamination during the removal at DESY, handling, and subsequent installation at Fermilab. High peak power pulsed processing may allow us to reverse this degradation.

The data are most easily collected if the isolation valves seal completely and reliably. We also believe it is best if the volume trapped between the isolation valves is kept to a minimum and kept cold, to maximize the fraction of energy residing in the liquid



**Figure 7.** Average power dissipated in the cavity cryostat as a function of cavity accelerating gradient for several sets of RF parameters.

Finally, we learned early on that the response from our cavity pressure transducer was overly sluggish, caused by a long thin sensing line. Relocation of the room temperature transducer closer to the tap allowed us to see the small but rapid changes in bath pressure caused by changing heat loads.



**Figure 8.** Comparison of cavity performance at Fermilab (June 1999) and DESY (April 1997). The CHECHIA data was obtained via measurement of the helium gas flow rate. The flat top duration is 800  $\mu$ s in all cases. Dissipated power is divided by the repetition rate to give energy dissipation per RF pulse.

## CONCLUSIONS

A TTF 9-cell cavity is being used at Fermilab for a high-brightness electron photo-injector. The dissipation as a function of gradient was measured for several combinations of repetition rate and flat top duration. The dissipated power was measured by closing isolating valves on the supply and return sides of the helium cryostat and allowing the system to pressurize under the influence of the heat load. Following TJNAF, we collected calibration data with each RF data point ("3-point" measurements) in order to reduce the measurement error. This technique can be adapted to our system, in spite of the rate of pressure rise being about 100 times larger. The results indicate that the high-field losses in the cavity are presently higher than in initial measurements at DESY. However, accelerating gradients up to 10 MeV/m are possible without noticeable power dissipation in the cryogenic system.

## ACKNOWLEDGMENT

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