QUALITY FACTOR IN HIGH POWER TESTS OF CRYOGENIC COPPER ACCELERATING CAVITIES*

A. Cahill†, J. Rosenzweig, UCLA, Los Angeles, California
V.A. Dolgashev, M. Franzi, S. Tantawi, S. Weathersby, SLAC, Menlo Park, CA

Abstract

Recent SLAC experiments with cryogenically cooled 11.4 GHz standing wave copper accelerating cavities have shown evidence of 250 MV/m accelerating gradients with low breakdown rates. The gradient depends on the circuit parameters of the accelerating cavity, such as the intrinsic and external quality factors (Q_0, Q_E). In our studies we see evidence that Q_0 decreases during rf pulse at 7-70 K. This paper discusses experiments that are directed towards understanding the change of Q_0 at high power.

MOTIVATION

Accelerating gradient is important for future rf linacs, larger gradients decreases the accelerator length. RF breakdown is one of the major factors limiting the operating accelerating gradient. The statistical nature of rf breakdowns was discovered during work on NLC/GLC [1–4]. For several kilometer long linacs, the breakdown probability needs to be very small, $< 10^{-6}$/pulse/meter[5]. Presently, X-band structures are the most studied in terms of rf breakdowns [4, 6–9]. We know that breakdown statistics depend on pulse heating [10] and a numerous list of other factors, such as the peak electric field, the peak magnetic field [11], and the peak Poynting vector[12].

One of the current hypotheses explains the statistical behavior of rf breakdowns in X-band accelerating structures by generation and movement of dislocations under stresses created by rf magnetic and electric fields [13]. This dislocation movement should dramatically change at cryogenic temperatures and this should be reflected in the statistical behavior of the breakdown rate. Recent experiments at SLAC were performed with copper accelerating cavities cooled to cryogenic temperatures to investigate this claim. These experiments have shown preliminary evidence of 250 MV/m accelerating gradients and 500 MV/m peak surface electric fields with 10^{-3} per pulse per meter breakdown rates at 45 K[14]. The cavity was designed using rf surface resistance measured at low temperature and low power[15, 16]. During high power measurements we noticed a reduction of Q_0. This change in Q_0 brings uncertainty to our calculation of the gradient. To know the gradient precisely we need to understand the physics of the reduction in Q_0. In this paper we discuss our experimental work directed towards this understanding.

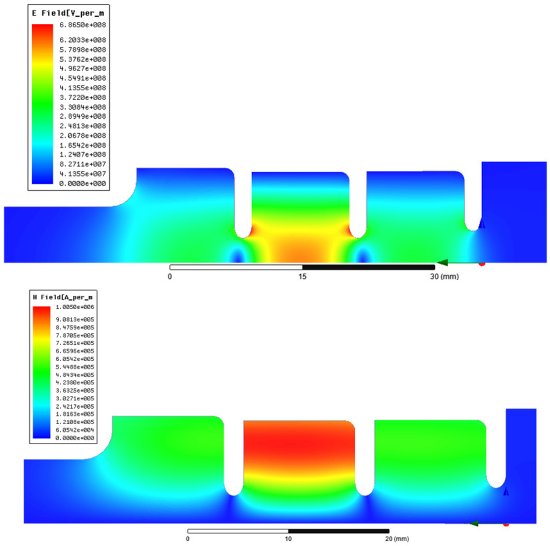

Figure 1: Electric and magnetic fields. 10 MW input at 95K.

EXPERIMENTAL METHODS

In this experiment we used the same cavity as described in [17]. To localize rf breakdowns to a single cell, one cell of the test structure has high electric and magnetic fields, to mimic those of a full length accelerating section [5]. There are two cells on each side of the test cell to remove any effects from the coupling to the waveguides on either end of the structure. The ratio of the radius of the irises adjacent to the central cell, to the wavelength is, $a/\lambda = 0.105$. The electric field on axis in the middle cell was tuned to be twice that of the outer cells. A diagram and field map of the cavities is shown in Fig. 1. RF power is coupled into the structure by a TM_{01} mode launcher, connected by a circular waveguide. The cavity can be cooled to 7 K when placed inside the cryostat.

Low Power Measurements

After an initial run at high power to study breakdown statistics as mentioned previously, the cavity was disconnected form the klystron. At this time we measured the rf properties of the cryo cavity using a network analyzer. The network analyzer was attached to a WR-90 rf window that was connected to the TM_{01} mode launcher and coupled to the cavity. To find the Q_0 from the frequency scan of the network analyzer we fit the data with a resonant circuit model. There was also a dispersion term to account for the effect from the waveguide connecting the network analyzer to the accelerating cavity. Figure 2 shows the fitted Q_0 versus temper-

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* Work Supported by DOE/SU Contract DE-AC02-76-SF00515 and DOE SCGSR Fellowship

† acahill@physics.ucla.edu

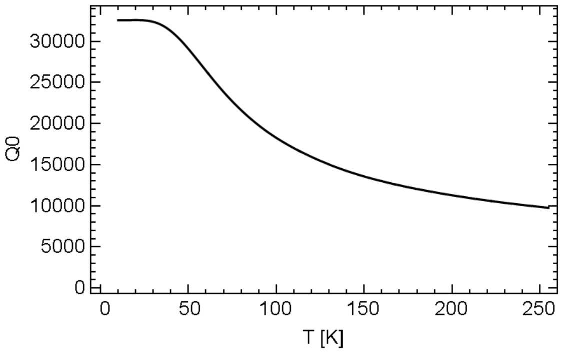

Figure 2: Low power measurement of the Q_0 versus temperature

ature of the π mode for the cryo cavity from the data. The external quality factor, $Q_E = 15,273$

High Power Measurement

The system is powered with an XL-5 klystron that can generate up to 50 MW of rf power near 11.424 GHz and a pulse length up to 1.5 μs[18]. The klystron power is transported to the accelerating cavity by both TE and TM waveguides. Near the cavity there is a 3dB hybrid to reduce reflections from and to the klystron. After the hybrid are two directional couplers; two being used to reduce the directivty of a single directional coupler. After the directional coupler is the previously mentioned mode launcher, that couples the rf power into the accelerating caivty, through a circular waveguide.

We placed both a frequency downmixer and a peak power meter (PPM) on two of the directional coupler arms, one that couples to forward power and one to reflected power from the cavity. Both the mixer and the PPM are used since the PPM cannot record the phase of the rf signals but gives a calibrated power reading.

There are two beam current monitors in the system, one below the mode launcher, and the other attached to the accelerating cavity, on the opposite side of where the rf power is coupled in.

For this experiment we set the input rf shape so that the accelerating gradient is flat after 150 ns of charging time. To achieve this, we start the input rf pulse with 150 ns of higher power, and then decrease the power in a step function to a lower value. This second value is calculated using the low power Q_0 and coupling factor (β) to keep the gradient inside the cavity constant. We use the dark current measurement to verify that the accelerating gradient is flat, since field emission has a sttrong dependence on gradient. We recorded data at pulse lengths from 100-800 ns, 1,5, and 10 Hz repetition rates, 10,25,45, and 292 K operating temperatures, and input powers ranging from 50 KW-3 MW. Pulse length nad input power refer to the length of time that the accelerating gradient is flat, and the power during this time.

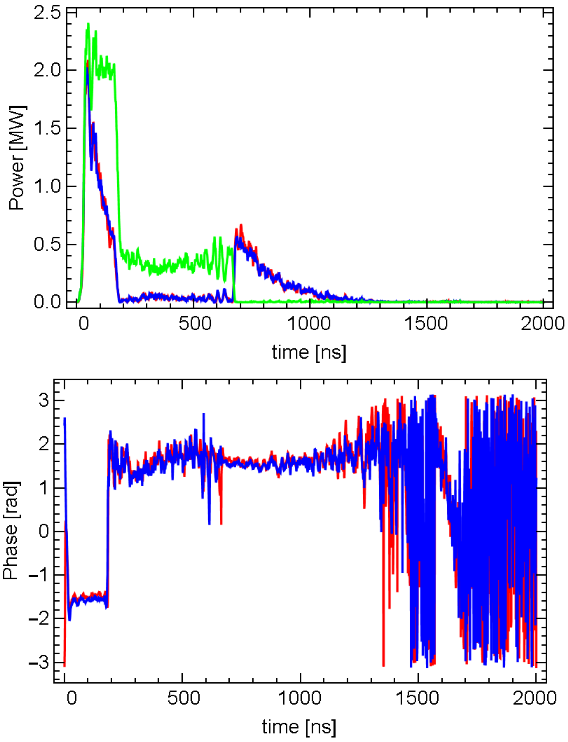

Figure 3: Measurement (Red) and calculation (blue) for 0.32 MW, 500 ns, 5Hz, 25 K input rf pulse. The input rf piulse is in green. The calculated response matches the measured signal for a $Q_0 = 32,533$.

RESULTS

The results presented in this paper will be at 25 K and 5 Hz. At powers below 0.5 MW the reflected data matches a calculation of the expected reflected signal in both amplitude and phase, where $Q_0 = 32,533$. Figure 3 is a comparison of the simulation and measurement for 0.35 MW and 500 ns pulse length and the amplitude and phase both match correctly. At larger input powers there is a deviation between the expected reflected signal and the actual measured signal. During the flat gradient section of the pulse, the phase is different than expected, and during the decay, after the input pulse ends, the amplitude is smaller than expected. Figure 4. shows the results for 2.6 MW 500 ns, where blue is the calculated response, and red is the measured signal.

We measured the Q_0 of the accelerating caivty after the rf pulse by fitting the decay to an exponential function. The measured Q_0 for 5 Hz, 500 ns, 25 K, 2.6 MW pulse is 20,300. We note that this method is inaccurate for two reasons: because the cavity is overcoupled with copuling β near 2, the time decay constant is dominated by the external quality facor. Second, reflections from the klystron can interrupt what should be a pure exponential. The drop in Q_0 was also observed at 10 K and 45 K, but not at room temperature. Figure 5 shows an example at room temperature, where there is no drop in Q_0. This deviation from the expected signal increases with increasing input rf power, so for a 5 Hz, 500 ns, 25 K, 1.5 MW pulse the $Q_0 = 26,800$. The drop in Q_0 dur-

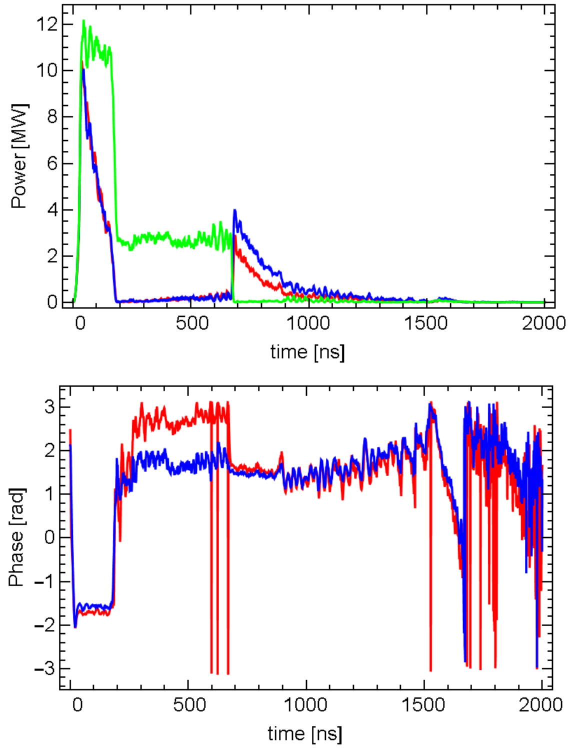

Figure 4: Measurement (Red) and calculation (blue) for 2.6 MW, 500 ns, 5Hz, 25 K input rf pulse. The input rf piulse is in green. There is a deviation from the expected phase during the inpur pulse, and a deviation in the amplitude after the rf pulse.

ing the rf pulse also increases with increasing pulse length as shown in Fig. 5 for 25 K, 5 Hz, 2.6 MW input rf pulses. The decrease is from $Q_0 = 28,080$ at 100 ns,$Q_0 = 24,700$ at 300 ns, to $Q_0 = 20,300$ as stated previously for 500 ns.

DISCUSSION

We believe that the drop in Q_0 at the end of an input rf pulse can be explained by rf pulse heating on the surface of the copper. As the surface of the copper heats, the surface resistivity increases, dropping the Q_0. For example, when starting from 25 K, an increase of 65K intemperature would decrease the Q_0 from 32,500 to 20,000 if we use the measurements of Q_0 from the earlier section of this paper. A simple calculation from the equations shown in [19] give a pulse heating of over 32 K. However, this calculation does not take into account the effect of changing temperature on the thermal and electrical propoerties of the copper, where the increasing rf surface resistance would have a positive feedback effect. Therefore, we speculate that a 65 K tempearture rise is possible.

A decrease in Q_0 at high power was observed before in [20], however, they did not specify that the Q_0 changes during the rf pulse, and made the measurements at a different frequency and temperature. They did find that the Q_0 decreased with increasing magnetic field, which the rf pulse heating does as well. Another group measured X-band accelerating structures at liquid nitrogen temperatures and did not see a decrease in Q_0. However, the peak power they used was only 0.6 MW, most likely too small to observe the decrease in Q_0 due to rf pulse heating.

CONCLUSION

We described a set of experiments directed towards understanding the reduction in Q_0 at high power in cryogenically cooled accelerating copper X-band structures. We have shown that the response of the cavity at 25 K differs from the response calculated with constant Q_0. This deviation gets larger with increasing input rf power starting around 0.5 MW, and with increasing pulse length from 100-800 ns. We speculate that this deviation stems from a change in the Q_0 during the rf pulse that itself comes from an increase in the surface temperature due to rf pulse heating. We have measured the decrease in Q_0 by finding the decay time constant in the reflected signal and found that indeed the Q_0 is smaller than the value measured at low power, $Q_0 = 32,533$. Data analysis is ongoing and will be published at a later date.

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