HIGH GRADIENT S-BAND CRYOGENIC ACCELERATING STRUCTURE FOR RF BREAKDOWN STUDIES*

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Abstract

Operating accelerating gradient in normal conducting accelerating structures is often limited by rf breakdowns. The limit depends on multiple parameters, including input rf power, rf circuit, cavity shape, cavity temperature, and material. Experimental and theoretical study of the effects of these parameters on the breakdown physics is ongoing at SLAC. As of now, most of the data has been obtained at 11.4 GHz. We are extending this research to S-band. We have designed a single cell accelerating structure, based on the extensively tested X-band cavities. The setup uses matched TM_{01} mode launcher to feed rf power into the test cavity. Our ongoing study of the physics of rf breakdown in cryogenically X-band accelerating cavities shows improved breakdown performance. Therefore, this S-band experiment is designed to cool the cavity to cryogenic temperatures. We use operating frequencies near 2.856 GHz. We present the rf design and discuss the experimental setup.

INTRODUCTION

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 to develop NLC/GLC [1–4]. For several kilometer long linacs, the breakdown probability needs to be very small, $< 10^{-6}$/pulse/meter[5].

Presently, most of the data on rf breakdowns is obtained with X-band accelerating structures[4, 6–9]. We know that breakdown statistics depend on pulse heating [10], the peak electric and magnetic field [11], and the peak Poynting vector[12]. However, properties of rf breakdown at other frequencies has not been satisfactorily studied. For example, at S-band, there has been relatively few experiments with published breakdown rates [13, 14].

One of the current hypotheses explains the statistical behavior of rf breakdown in X-band accelerating structures by generation and movement of dislocations under stresses created by rf magnetic and electric fields [9, 10]. This dislocation movement should dramatically change under 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 evidence of 250 MV/m accelerating gradients and 500 MV/m peak surface electric fields in X-band copper cavities at 45 K[15].

The TOPGUN collaboration would like to apply these findings to an ultra-high gradient S-band rf photoinjector [16]. With a significantly larger gradient the beam brightness of an electron photoinjector will be improved by over an order of magnitude. To design and build a practical S-band photoinjector, we first need to extend the knowledge on rf breakdowns to this frequency. We designed an experimental setup that includes a cryogenically cooled copper single-cell-SW accelerating structure.

DESIGN CONSIDERATIONS

In our breakdown experiments, we have tested more than 50 single-cell accelerating cavities at X-band[5]. We propose to use the same approach at S-band.

To reduce price and complexity for the test setup, the cavity will be fed by a TM_{01} mode launcher[17], that is connected to the cavity by a circular waveguide with radius of 1.81 in. The mode launcher will serve as the rf coupler. We propose to use the same configuration in the TOPGUN S-band photoinjector[18].

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 was kept the same as in the X-band cryo experiments, $a/\lambda = 0.105$. The electric field on axis in the middle cell was tuned to be twice that of the outer cells.

The difference between the cryo S-band and cryo X-band cavities are two-fold: the outer diameter of the cells in the S-band design are rounded to increase the Q_0, and the S-band design is more overcoupled. The choice of the coupling value will be discussed later.

DESIGN PARAMETERS

SUPERFISH[19], a 2D finite element electric field solver, was used to design the geometry of the S-band accelerator cavity, and verified with HFSS[20], a 3D finite element electric field solver. The geometry is shown in Fig. 1. The on-axis electric field in the cavity for the π mode are shown in Fig. 2. The peak axis in the middle cell is twice that of the outer cells. Table 1 lists the dimensions shown in Fig. 1 .

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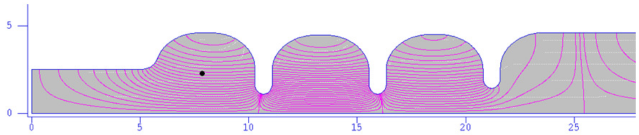

Figure 1: Geometry of accelerating cavity. Axis are in units of centimeters. RF power is coupled in from the right of the diagram.

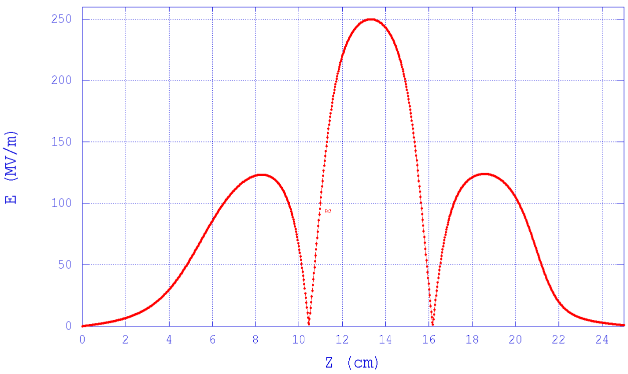

Figure 2: On-axis electric field of the cavity, scaled to 250 MV/m, calculated by SUPERFISH.

Frequency

The frequency of the SLAC 5045 S-band klystron can be set between 2856 ± 10 MHz[21]. Therefore, the resonant frequency of the cavity must be within this bandwidth from room temperature to 20 K. The frequency of the π mode at room temperature was chosen to be 2.85 GHz. As the cavity is cooled to 20 K the frequency will increase to 2.859 GHz. The predicted temperature dependence of the frequency is shown in Fig. 3.

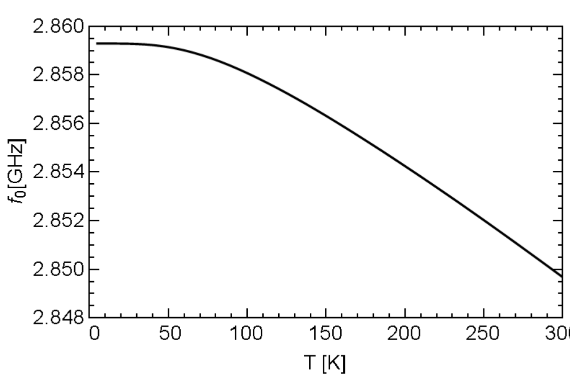

Figure 3: Theoretical prediction of the temperature dependence for the π mode frequency.

Coupling

At cryogenic temperatures Q_0 will increase to more than 90,000. We calculate this using our measurement of the S-band coper rf surface resistance[22]. Figure 4 shows the expected temperature dependence of Q_0.

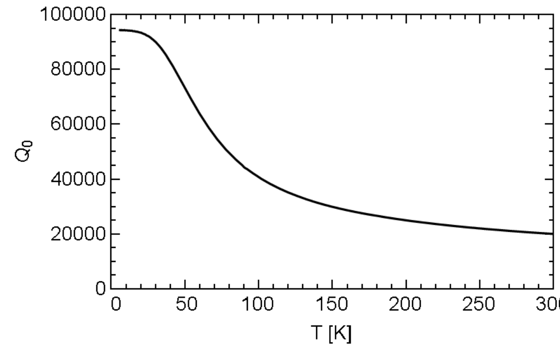

Figure 4: Expected Q_0 of the single cell accelerating cavity at different temperatures based on our measurements of a S-band TM_{01} cavity[22].

Because of the change in the Q_0, the rf coupling, β will also change by a factor of 4.7 from room temperature to cryogenic temperatures. We have chosen to use a 15 MW 3.5 μs klystron pulse for this experiment. Using this rf pulse we would like to choose a coupling that will allow the maximum possible accelerating gradient to be reached.

We calculated the expected gradients achieved by the S-band set up using the following equation,

$$E_0[t] = \sqrt{\frac{4\beta Z P_{\text{in}}}{(1+\beta)^2 L}} \left(1 - e^{-\frac{2\pi f_0 (1+\beta) t}{2Q_0}}\right),$$

where E_0 is the gradient in the central cell, and $L = 0.13$ cm is the length of the cell.

Figure 5 shows calculations for the accelerating gradient for the given rf input pulse at three different choices of β. We calculated the expected gradients achieved by the S-band set up using the following equation,

$$E_0[t] = \sqrt{\frac{4\beta Z P_{\text{in}}}{(1+\beta)^2 L}} \left(1 - e^{-\frac{2\pi f_0 (1+\beta) t}{2Q_0}}\right),$$

where E_0 is the gradient in the central cell, and $L = 0.13$ cm is the length of the cell.

From these results we have chosen the room temperature coupling to be $\beta = 1$.

RF Parameters

We calculated parameters for the π mode of a periodic accelerating structure with the same dimensions as the middle cell of our cavity. Table 1 contains these rf parameters calculated at room temperature.

Figure 6 shows a calculation of the frequency response of the designed accelerator cavity. This calculation includes the effect of the mode launcher. Since the mode launcher is a very broadband device, it has little effect.

Thermal Calculations

The capacity of the cryocooler to remove heat from the S-band system is limited, therefore, we need to understand and

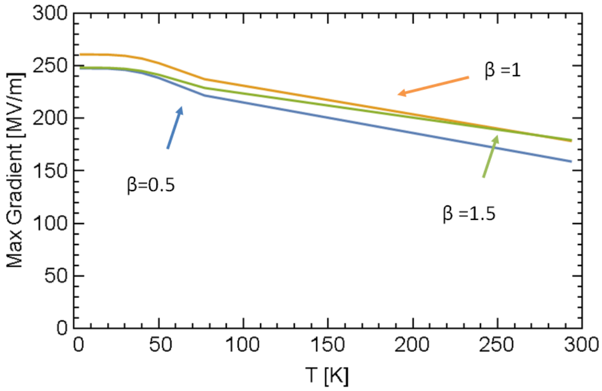

Figure 5: The max gradient reached at different temperatures for three different coupling betas at room temperature. Critical coupling was chosen, since it has the larger gradient achieved.

Table 1: RF properties for a periodic cell calculated at room temperature. Values are normalized to an accelerating gradient of 100 MV/m.

Quality factor (Q_0)	19,989
π mode frequency f_0	2.85 GHz
Stored energy (U)	10.2 J
Shunt Impedance (Z)	57.4 MΩ/m
Max Magnetic Field (H_{max})	275 kA/m
Max Electric Field (E_{max})	195.8 MV/m
Losses in one cell	9.165 MW
$H_{max}Z_0/E_{acc}$	1.036
Coupling β	1.0

minimize the heat deposited in the cavity. To calculate the energy dissipated per pulse we used the equation $P_{dissip}[t] = \omega_0 U[t]/Q_0$ to find the dissipation as a function of time, and then integrated this function over the pulse length of the klystron. The amount of energy dissipated is acceptable since the cryocooler that we are using can remove around 40W at 10K.

The pulse heating was calculated from the diffusion equation assuming the thermal properties of copper are static at the starting temperature of the pulse. This is a bad assumption for 4K, which was therefore not computed. For other temperatures this appears to be a good assumption, since the pulse heating is only on the order of 10 degrees changed.

Table 2 shows the calculated gradient, power dissipation, and rf pulse heating for our S-band experiment.

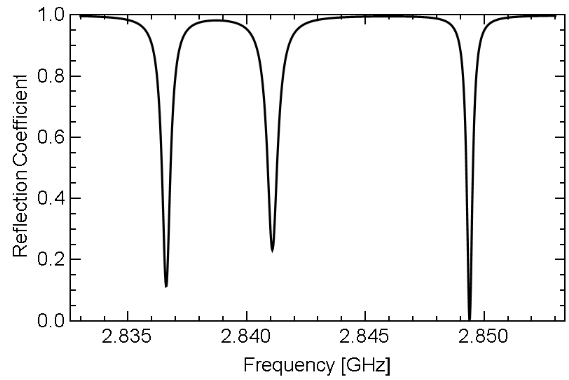

Figure 6: Expected results from a frequency scan for the S-band single cell cavity from a network analyzer. This includes effects from the mode launcher

Table 2: Coupling and Gradient reached at different temperatures for the S-band cryo accelerating structure. Also included are pulse heating and rf surface losses per pulse. Data for 15 MW 3.5 μs flat pulse

Temp. (K)	4	20	30	40
$Q_0/Q_{300\,K}$	4.66	4.62	4.46	4.12
Coupling β	4.66	4.62	4.46	4.12
Pk. Elec. (MV/m)	261	261	260	257
Ener. Diss./Pulse (J)	9.50	9.57	9.87	10.60
ΔT (K)		8.62	7.52	7.92

Temp (K)	50	77	293
$Q_0/Q_{293\,K}$	3.64	2.54	1
Coupling β	3.64	2.54	1
Pk. Elec. (MV/m)	253	237	179
Ener. Diss./Pulse (J)	11.82	15.97	28.83
ΔT (K)		17.67	24.84

CONCLUSION

We have presented a design for a cryogenic S-band accelerating structure. We designed the experiment so that at cryogenic temperatures the cavity will reach peak electric fields of 250 MV/m with a 15 MW 3.5 μs input klystron pulse. We designed the cavity to be critically coupled at room temperature. At 30 K the Q_0 will reach more than 90,000. The thermal load from rf heating in the cavity will allow pulse repetition rates of a few Hz. We plan to investigate rf breakdown physics at S-band. This work will show the viability of the TOPGUN project of creating an ultra-high gradient cryogenic copper rf photoinjector.

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