CERN – European Organization for Nuclear Research
European Laboratory for Particle Physics

CLIC Note 498
PS/AE Note 2001-010

A 30 GHZ BEAM DRIVEN HIGH GRADIENT SINGLE CELL CAVITY TEST

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Abstract

In December 1999 a first 30 GHz high gradient experiment [1] was performed using a single cell excited directly by the high-charge drive beam of the CLIC Test Facility (CTF II) [2]. Since this experiment showed quite promising results (peak surface fields of 300 MV/m were measured) it was decided to remeasure the cavity with improved vacuum, diagnostics and data acquisition. In addition an experiment was prepared to cool the cavity with liquid nitrogen and heat it with a hot air gun. The electrical breakdown behaviour was measured as a function of the cavity temperature. The breakdown threshold was found to be at a maximum surface field of 380 MV/m and remained unchanged in the accessible temperature range between 100 K to 500 K. Large data samples were taken to provide statistics of unforseen delays and frequency shifts that occur during breakdown events

Geneva, Switzerland
10 August 2001

1. Introduction

The Compact Linear Collider (CLIC) [3] currently being studied at CERN aims for an average accelerating gradient of 150 MV/m using 30 GHz travelling wave accelerating structures with an RF pulse length of 130 ns. In such a structure the maximum surface field can exceed the accelerating gradient by a factor 2 to 3 depending on the design of the cavity and is thus in the 300 to 500 MV/m range. In CTF II high gradient experiments using a 30 GHz power extraction structure are limited to a pulse length of 16 ns.

The use of standing wave single cell cavities powered directly by the drive beam enables investigations of very high surface fields for longer pulse durations. Cavities are driven by 12 to 24 electron bunches having a 3 GHz time structure and they then ring freely while decaying exponentially according to their loaded quality factor. The advantages of this approach are a simple experimental set-up, low cost and a fast turn-around time. However there are also some particularities like the presence of the drive beam, the special pulse shape and the standing wave field pattern.

The first single cell cavity experiment revealed some very surprising breakdown features. The RF frequency was observed to shift up during the energy dissipation and a delay of 10 to 60 ns was measured between the onset of breakdown and the time when the field maximum occurred. The second experiment using the same cavity focused on obtaining statistical distributions of these two features.

The explosion of RF heated dust particles is one model, which was inspired by the original experiment [4] and was able to explain the short delay times. Because some possible mechanisms of initiation of electrical breakdown are associated with some sort of heating process (heating dust particles, ohmic heating of copper tips or heating by electron bombardment) an experiment was set up to investigate the effect of the cavity temperature on breakdown behaviour.

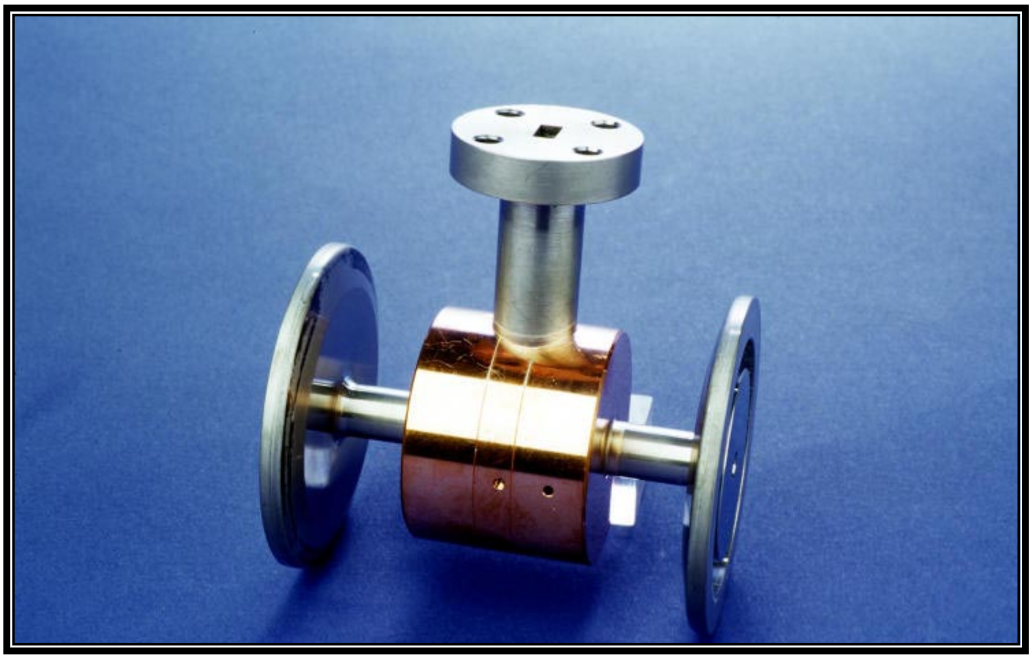

Figure 1: Photo of the 30 GHz high-gradient single-cell cavity.

3. High gradient single cell experiment

The vacuum was improved to 10^{-9} mbar for the second experiment since it was probably very poor during the first one (~ 10^{-6} mbar). To reduce outgasing and limit the oxide layer, the cavity was vacuum fired at 600 °C for two hours and in-situ baked at 140 °C for two days. The experimental set up consists of a TM_{010}-mode pill-box with a small coupling aperture to a WR28 waveguide (see Fig.1).

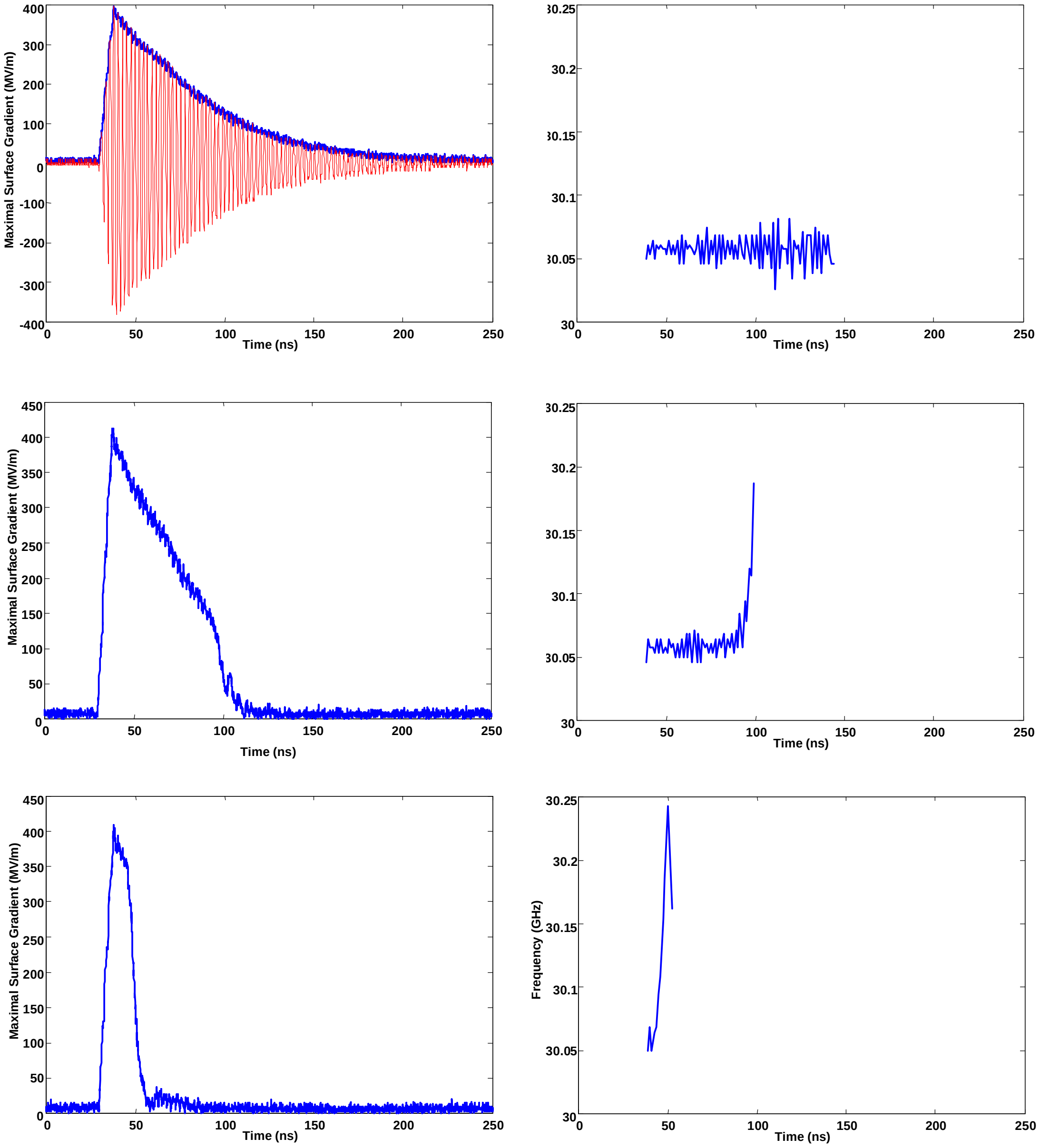

Figure 2: Typical RF pulses (left column) and corresponding plots of resonant frequency of the cavity during the pulse (right column).

The power coupled out of the cavity is measured with a -57 dB vacuum-to-air directional coupler before being dumped in a vacuum high power load. A more detailed description of the cavity and the set up can be found in [1]. The cavity was driven with an 8 ns long bunch train with a total charge > 100 nC. After excitation, the field in the cavity decays according to its loaded quality factor (Q_L = 3800). The coupling factor was measured to be β = 0.33 leading to an unloaded Q of Q_0 = 5054. The 30 GHz cavity output signal is mixed down to an intermediate frequency (IF) of 500 MHz and captured on a fast scope. In this way amplitude and frequency are measured. In order to improve the time resolution a second detection electronics was developed using an IF of 1 GHz. Utilizing a higher IF frequency gave more confidence in the shape of the measured waveforms but didn't reveal new information.

Typical measured signals are shown in Fig.2 with and without breakdowns. Plots of frequency, determined by analysing zero-crossings, during the RF pulse are shown to the right. The top left plot shows a 500 MHz raw signal and the corresponding envelope for a typical pulse without breakdown. One sees that the resonant frequency stays constant during the pulse. The two following rows in Fig. 2 show an example of RF breakdown events occurring at different delays after the field maximum was reached (60 ns in the middle row and 10 ns in the bottom row). The resonant frequency of the cavity shifts up considerably during energy dissipation in a breakdown event (150 MHz in the middle row and 200 MHz in the bottom row). The definition of a breakdown event in this paper is the very fast dissipation of the available stored energy in the cavity. It appears as a shortening of the RF pulse.

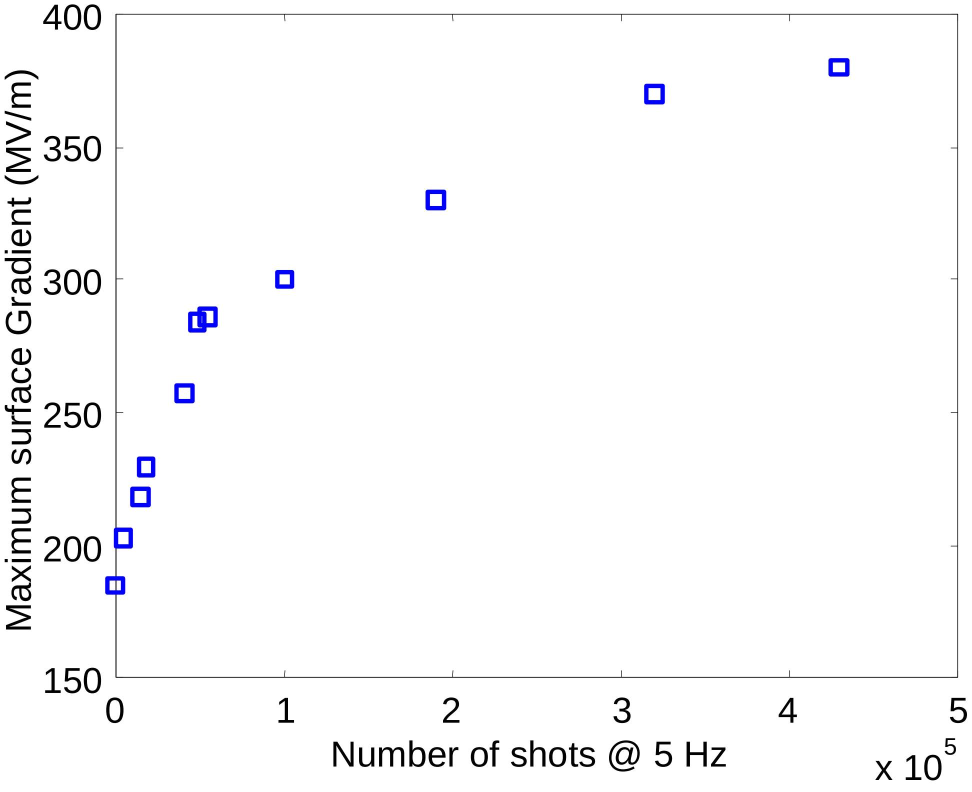

Figure 3: Conditioning history of the 30 GHz single cell cavity.

The cavity was conditioned for a few days at a repetition rate of 5 Hz to accumulate about $5\cdot10^5$ pulses as shown in Fig.3. Although the conditioning of the cavity was stopped because of time limitations, the plot in Fig.3 reveals some sort of saturation in the conditioning progress. The maximum surface field in the cavity for stable operation was found to be 380 MV/m.

4. Frequency shift and delayed breakdown

Breakdown events in such a single cell cavity can be characterized by the frequency shift Δf and the delay τ of the energy dissipation after the field maximum. The breakdown events happened up to 60 ns after the field maximum, but the statistical analysis showed that most of the events occurred about 10 ns after the maximum. The maximum frequency shifts measured were about 250 MHz while the average shift was 110 MHz. It was found that breakdowns can occur as single events but are most often observed in limited periods of continuous breakdown on every pulse. Usually the first breakdown in a series produces a bigger frequency shift than the subsequent ones. Very delayed breakdowns (up to 60 ns) are rare and seem to occur more frequently in the transition between no breakdown and continuous breakdowns. An example of the distribution of the parameters discussed above is shown in Fig. 4.

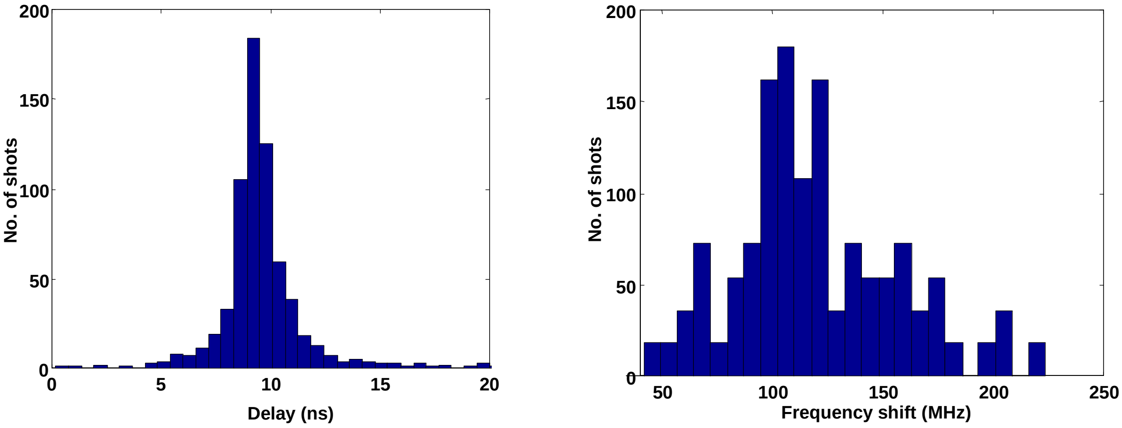

Figure 4: Distributions of measured frequency shift and delay observed for breakdown events in the single cell cavity.

The frequency shift towards higher frequencies could be interpreted as a sign of massive electron loading or plasma formation. For a flow of free electrons across the gap of the cell the frequency shift would be [5]:

$$\frac{\Delta\omega}{\omega}=\frac{e^2 n_e \lambda^2}{8\pi^2 \varepsilon_0 m_e c^2}$$

The frequency shift is proportional to the electron density n_e and to the wavelength λ squared. This electron current corresponds to an additional parallel inductance. A second approach would be to assume not only free electrons but the formation of a neutral plasma. The frequency of the cavity filled by a plasma would change due to the plasma frequency ($\omega_p^2 = e^2 n_e/\varepsilon_0 m_e$) yielding $\omega^2 = \omega_0^2 + \omega_p^2$ [6]. For $\Delta\omega << \omega$ this leads to the same results as the pure electron loading description.

A frequency shift of 200 MHz corresponds to an electron density of $n_e = 1.5\cdot10^{17}$ m^{-3} or $3\cdot10^{10}$ electrons. If the stored energy of about 30 mJ in such a cavity is dissipated by electron acceleration across the gap, about $2\cdot10^{11}$ electrons are needed.

The observed delays for the discharge indicate that the process needs typically 10 ns to develop the conditions that lead to sudden energy dissipation. It seems to be most natural that this phenomenon is due to some sort of heating process. From pulsed DC experiments [7] it is known that mechanisms like explosive electron emission on the cathode or melting by electron beam impact on the anode can have similar short time scales. As shown in [4] RF heating of dust particles combined with run-away thermal electron emission would also occur on a time scale of 10 to 20 ns. As a consequence one might expect that the cavity temperature could affect the breakdown level.

5. Temperature scan

The cavity was attached to two copper blocks, which are directly cooled by a flow of liquid nitrogen. The breakdown behaviour was then measured while the cavity warmed backup to room temperature, which took a few hours. In a similar way the cavity was heated and the breakdown level was measured as it cooled down to room temperature. A simple hot air gun served for heating the cavity above room temperature. The resonant

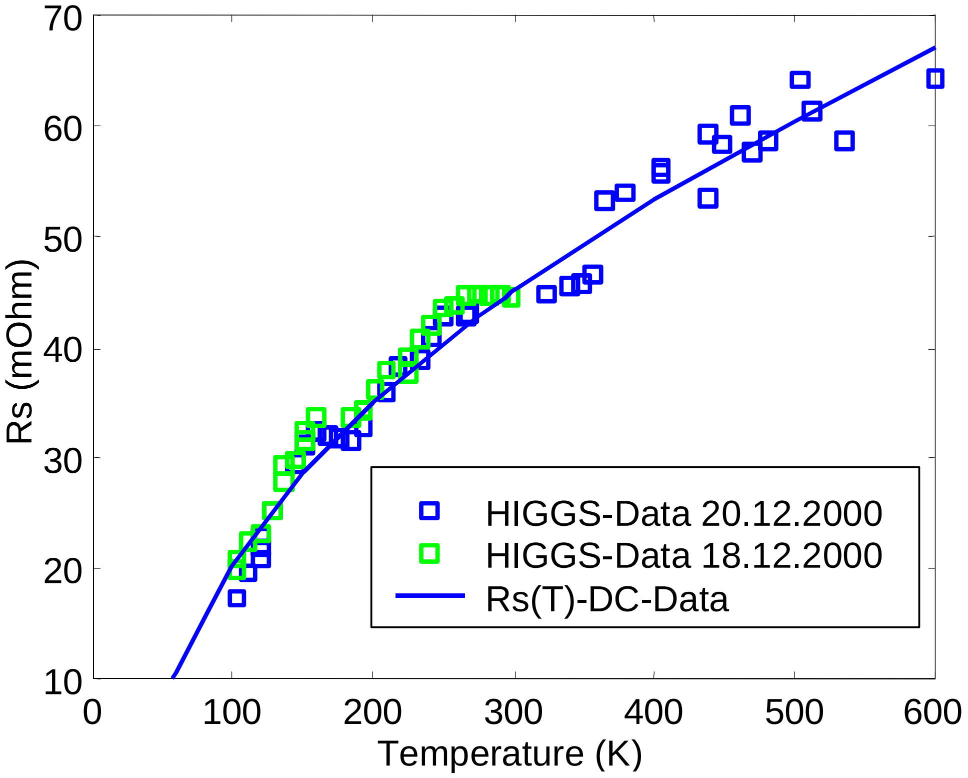

Figure 5: Measured surface resistance and published data for DC-experiments.

frequency shift due to the temperature changes was consistent with a simple thermal expansion using data found in the literature. This shift of the resonant frequency therefore turned out to be the most accurate measurement of the cavity temperature because it was measurable on every shot together with the RF power data. A copper/constantan temperature sensor attached to the cavity confirmed the temperature readings but was much slower and showed some dependence on the insulation of the cavity. To compensate for the shift of the resonant frequency of the cavity, the bunch-to-bunch distance within the train had to be adjusted to assure efficient power production at 30 GHz. Since the external Q of the cavity is expected to remain constant as the cavity expands and contracts, the unloaded Q and the surface resistance at the different temperatures can be calculated. Figure 5 shows a comparison of the measured surface resistance and published data for DC experiments. The measured data is consistent with the DC-data found in the literature, confirming that the assumption of a constant external Q was valid and that we actually reached the temperatures indicated on the inner cavity surface. The unloaded Q varied by a factor of 3 over the temperature range, this is shown in Fig.6 together with a fit of the expected $\nu^{-1/2}$ dependence.

The change in the quality factor implies also a large variation for several parameters that are suspected to be important for electrical breakdowns such as the power dissipated on the surface or the integrated power during a pulse. The main result from this experiment however was that the maximum surface field without breakdowns remained constant within the accuracy of the measurement. The breakdown threshold as a function of temperature is plotted in Fig.7. No significant temperature dependence was found on breakdown delays or frequency shift.

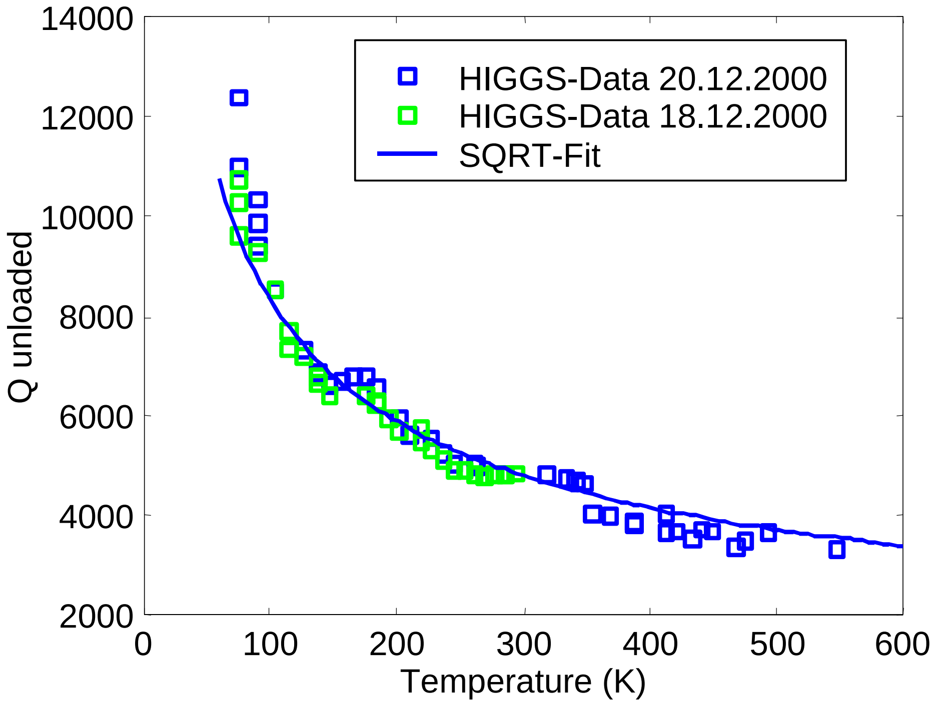

Figure 6: Unloaded Q as a function of temperature.

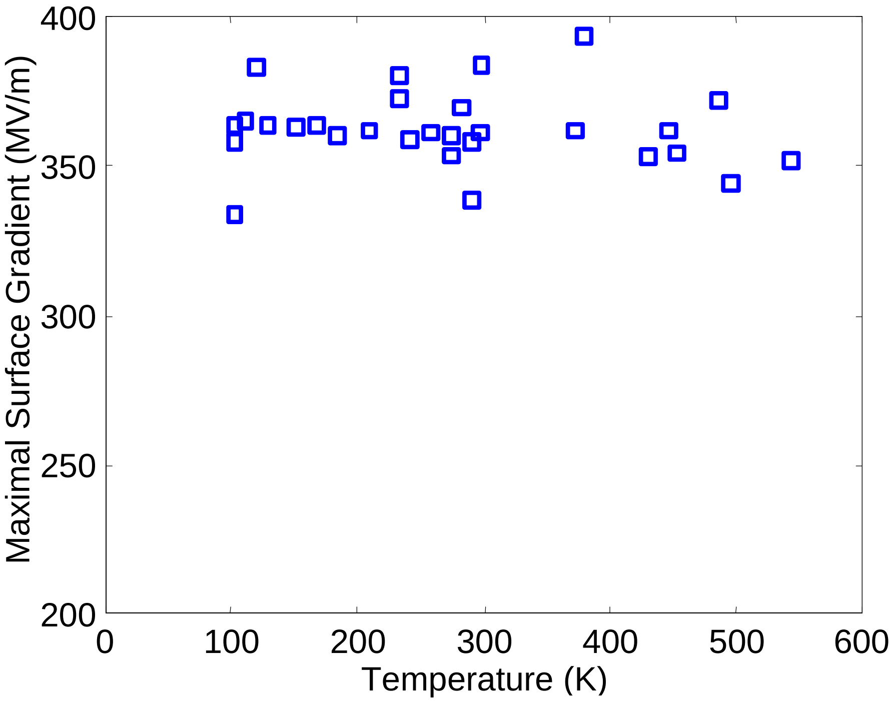

Figure 7: Maximum surface gradient as a function of the cavity temperature.

6. Conclusion and Discussion

The breakdown threshold of a 30 GHz single cell cavity directly driven by the electron beam showed no significant dependence on the cavity temperature. In the entire measured temperature range between 77 K and 550 K the surface gradient remained constant to within 10 % (which corresponds to the accuracy of this experiment). The maximum surface field at room temperature after about $5 \cdot 10^5$ pulses was found to be 380 MV/m. Breakdown events were found to be characterised by a delay of the energy dissipation and a frequency shift during the discharge. The maximum surface field improved from 300 MV/m to 380 MV/m with respect to the first high gradient test of this cavity. This improvement could be due to the much better vacuum but is probably just due to longer conditioning time.

The cavity was inspected with an optical endoscope after the high gradient test. The surface in the high electrical field region appears to be rougher compared to the optical surface quality obtained after diamond machining. Since the resolution of the endoscope is not sufficient an autopsy and inspection with SEM is planned to assess any possible damage. The RF parameters of the cavity were remeasured and found to be unchanged after the test.

The independence of breakdown behaviour with cavity temperature can be either interpreted as a result showing that the relevant mechanism for electrical breakdown doesn’t involve a heating process at all or the heating process is too fast in this experiment to modify the breakdown threshold.

In the first case a mechanism like multipacting could play a role. Preliminary estimations have revealed that two-point multipactoring across the longitudinal gap should be investigated in more detail as a possible candidate to explain the measured threshold.

From the observed frequency shifts during a breakdown event it seems obvious that electrons play an important role in the energy dissipation mechanism. Electrons will cross the longitudinal gap in one half of a RF period (16 ps). If we assume that the impact of these electrons heats up the surface to the melting point in about 10 ns, the heating rate would be 100 K/ns. Thus the difference of ± 200 K would be within our time resolution, and would support the second interpretation. Heating and subsequent explosion of emission-tips in pulsed DC experiments is also known to be an extremely fast process, which leads to breakdown in less than 10 ns [7].

A particularity of this experiment is the exponential decay of the RF field with a time constant proportional to Q_L. The time constant of the decay was varied by more than a factor of two therefore it seems that only the first nanoseconds with the highest surface gradients are important for triggering the breakdown events.

We believe nevertheless that the results from these beam driven single cell experiments are also relevant to our high gradient studies of multicell travelling wave accelerating structures. It turns out that the surface gradient 14 ns after the maximum in the single cell (~ 300 MV/m) is very well comparable with the values obtained with the CLIC prototype structures [7]. This statement is illustrated in Fig. 8 where a HIGGS field decay curve

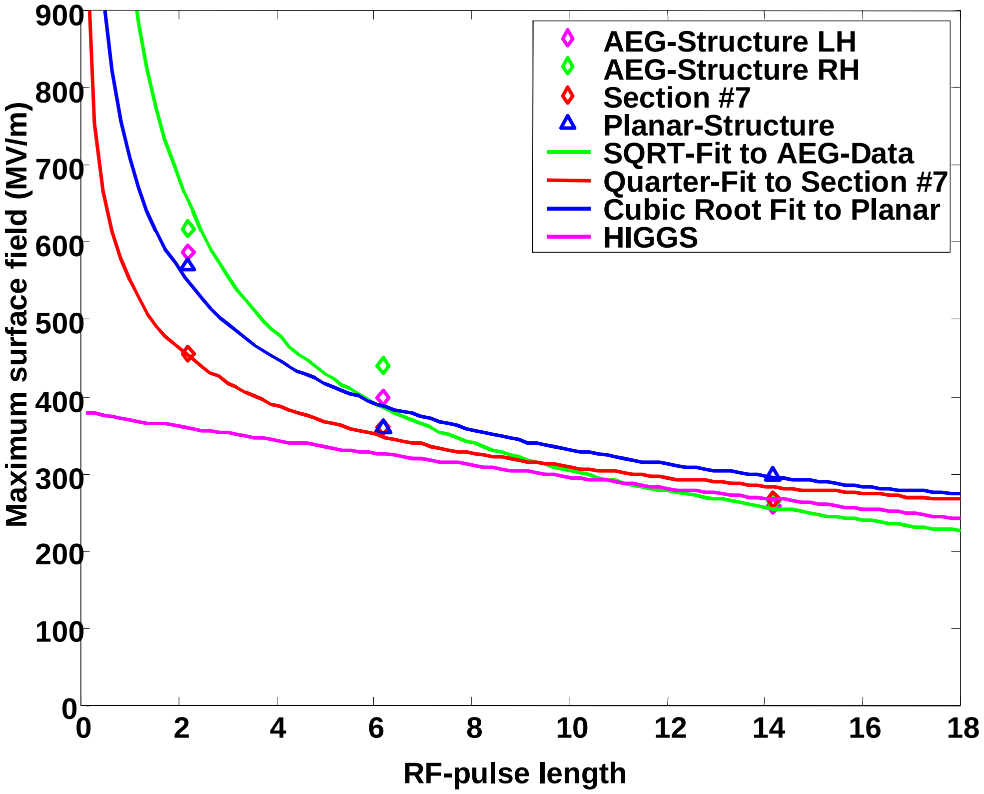

Figure 8: Comparison of RF pulse length dependence of surface gradients measured on CLIC prototype accelerating structure and a HIGGS surface-field decay curve.

was added to a plot showing the RF pulse length dependence of the achieved gradients for different accelerating structures [8].

7. References

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8 Appendix I

Please note that the surface fields quoted in references [1] and [4] are unfortunately wrong by a factor $\pi^{0.5}$ due to a calibration error, which was discovered during the second experiment.

9. Appendix II

Power and field calibration

In order to determine field levels in the cavity a complete calibration of the RF network is required. The Q_{ext} of the coupling determines the part of the RF energy deposited in the cavity by the drive beam that is coupled out of the cavity. A vacuum-to-air directional coupler picks up a small fraction of this signal while the main part is absorbed in a vacuum load. The 30 GHz signal is then transported by a waveguide into the klystron gallery. In the gallery, the signal amplitude can be adjusted with a rotary attenuator to match the input power requirements of a microwave mixer, which converts the signal down to 500 MHz. The output signal of the mixer is amplified and transported with low-loss cables to the control room where the waveform is digitised on a fast oscilloscope.

During the calibration the following quantities are measured:

- The loaded Q and the coupling factor β of the cavity using a network analyser.

· The attenuation between the cavity output flange and the non-vacuum side of the directional coupler also with the network analyser (*dcatt [dB]*).

· The attenuation of the waveguide from the directional coupler to the input of the mixer box in the gallery (*wgatt [dB]*).

· The signal amplitude on the scope in the control room as a function of the 30 GHz input power of the mixer box (*calibbox* $[W/V^2]$). A synthesizer is used to provide a reference input power source. A frequency scan is also made.

The value of the rotary attenuator in the gallery will be called (*gallatt [dB]*)

From cavity simulations using for example HFSS or URMEL we need:

· The ratio between maximal surface gradient and maximal gradient on axis
$E_s/E_{zmax} = 1.1$ (URMEL)

· The ratio between gradient and stored energy
$E_{zmax}/W^{0.5} = A = 17.635 \cdot 10^8\ [V\ m^{-1}\ J^{-0.5}]$ (URMEL)

· The expected surface field as a function of drive beam charge
$E_{surf} = 3.894\ [MV/m] \cdot q/[nC]$ (see Fig. 9)

The RF power coupled out of the cavity is then given by using the envelope of the 500 MHz signal:
$P_{RF} = calibbox \cdot 10^{((dcatt+wgatt+gallatt)/10)} \cdot envelope^2\ [W]$

The stored energy is given by:
$W = Q_{ext}/\omega_0 \cdot P_{RF} \quad (J) \quad$ with $Q_{ext} = (1/\beta + 1) \cdot Q_L$

Finally the maximum surface field is given by:
$E_{surf} = E_s/E_{zmax} \cdot A \cdot W^{0.5}\ [V/m]$

As a consistency check during operation the field levels expected from the drive beam charge were compared to those determined from the RF calibration. An example of such a comparison is shown in Fig.9.

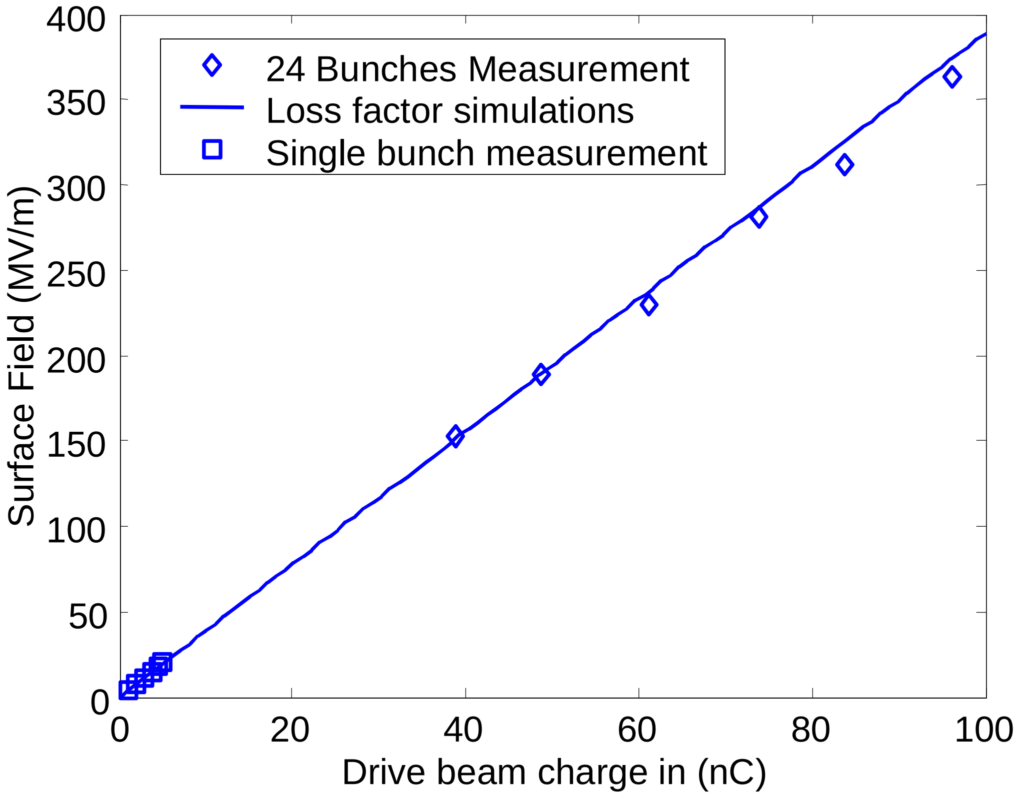

Figure 9: Comparison of measured and simulated loss factor for the 30 GHz single cell cavity. The agreement between the simulations and the measurement is very good ($Es_{\text{simulated}}$ / Es_{measured} =1.02). The inefficiency due to bunch length and multi bunch effects appears to be negligible.