MEASUREMENTS OF RF BREAKDOWNS IN BEAM DRIVEN MM-WAVE ACCELERATING STRUCTURES*

Massimo Dal Forno[1†], Valery Dolgashev[1], Gordon Bowden[1], Christine Clarke[1], Mark Hogan[1],
Doug McCormick[1], Alexander Novokhatski[1], Bruno Spataro[2], Stephen Weathersby[1], Sami Tantawi[1]
[1] SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[2] INFN/LFN, Frascati (Roma) 00044, Italy

Abstract

We studied the physics and properties of rf breakdowns in high gradient traveling-wave accelerating structures at 100 GHz. The structures are open, made of two halves with a gap in between. The rf fields were excited in the structure by an ultra-relativistic electron beam generated by the FACET facility at the SLAC National Accelerator Laboratory. We observed rf breakdowns generated in the presence of GV/m scale electric fields. We varied the rf fields excited by the FACET bunch by moving structure relative to the beam and by changing the gap between structure halves. Reliable breakdowns detectors allowed us to measure the rf breakdown rate at these different rf parameters. We measured radiated rf energy with a pyro-detector. When the beam was off-axis, we observed beam deflection in the beam position monitors and on the screen of a magnetic spectrometer. The measurements of the deflection allowed us to verify our calculation of the accelerating gradient.

INTRODUCTION

Accelerating gradient is one of the crucial parameters affecting the design, construction and cost of the next generation of linear accelerators. To reach high gradient acceleration above the state of the art of 100 MV/m, several problems such as vacuum rf breakdowns must be overcome [1, 2]. During the development of the Next Linear Collider/Global Linear Collider the statistical nature of rf breakdown became apparent [3, 4, 2]. It was found that when accelerating structures are exposed to constant rf power and pulse shape, the number of rf breakdowns per pulse is nearly constant. The breakdown rate depends on pulse heating [5] and other factors, such as the peak magnetic field [6], the peak electric field, and the peak Poynting vector [7]. Presently X-band accelerating structures are the most studied in terms of rf breakdowns [2, 8, 9]. Currently, research in accelerating structures is moving towards higher rf frequencies because of the expected higher gradients. However, data on breakdown statistics above 40 GHz is not available [10, 11, 12].

In this paper we present a quantitative measurement of rf breakdowns and gradients in a mm-wave copper travelling wave structure. The major goal of our study is to determine the breakdown properties and specifically how the rf breakdown rate changes with rf parameters at these high frequencies. Moreover, when the electron beam travels off-axis, a deflecting field is induced in addition to the longitudinal field. We measured the deflecting forces by observing the displacement of the electron bunch. A set of 120 GHz travelling wave constant impedance accelerating structures was designed, built and tested [13]. The structures were excited by the ultra-relativistic electron beam generated by FACET [14].The studied structure is open, made of two separate metal blocks. It is 10 cm long and composed of 125 coupled cavities. Cavities are milled into the flat face of each block. The two halves are placed together, with a gap between, forming an open accelerating structure (see Fig. 1(a)). Fig. 1(b) shows one half of the structure, and Fig. 1(c) shows the geometry of one quarter of the vacuum volume of a regular cell. The 'x' direction is horizontal, while the 'y' direction is vertical. The fundamental mode is synchronous with the speed of light at a phase advance per period close to $2\pi/3$. RF parameters for the fundamental accelerating mode are listed in Table 1. They were calculated for a beam on the central axis, using the method described in [13]. The peak electric and magnetic fields are calculated on the surface. Their distribution, for the fundamental mode, is shown in Fig. 2. During the experiment we varied the rf parameters of the structure by remotely changing the gap. With larger gap the pulse length is determined by the group velocity and structure length, and with smaller gap and thus higher attenuation the pulse length is equal to the decay time [13]. Accelerating gradient was varied by horizontally scanning the beam position with respect to the structure center axis. To reliably detect breakdowns we used a diagnostic tool which we call "arc-detector" [13]. The two metal halves were electrically insulated from ground and each other. RF breakdowns generate electron and ion currents that induce a voltage between the two halves, which were measured with an oscilloscope. When the electron beam trajectory moves horizontally off-axis it excites deflecting fields, however when the beam trajectory moves far beyond the corrugations, the deflection disappears. We simulated wakefields excited by a Gaussian bunch with $\sigma_z = 50\ \mu m$ and charge 3.2 nC using CST Particle Studio [15] and GdfidL [16]. The integrated accelerating and deflecting voltages in the 10 cm long structure are shown in Fig. 3. These results are in good agreement with other wakefield calculations made with a method developed by A. Novokhatski [17, 18, 19, 20]. When the

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* Work supported by the US DOE under contract DE-AC02-76SF00515.

† dalforno@slac.stanford.edu

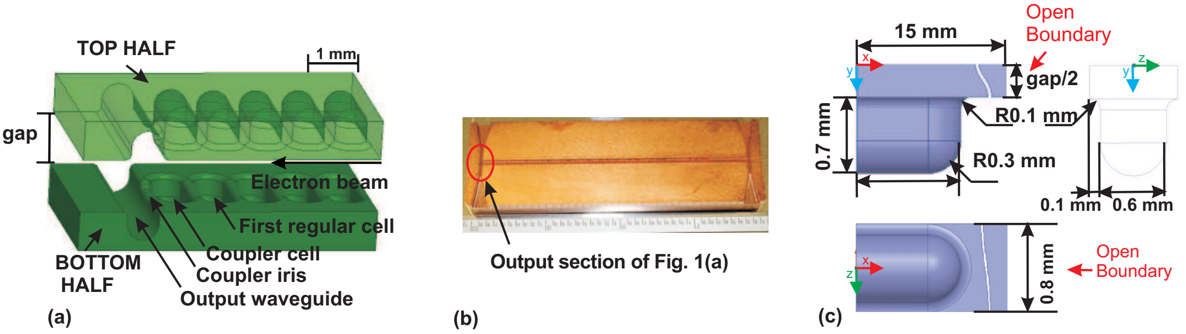

Figure 1: Solid model of the output section of the mm-wave travelling wave accelerating structure, including output coupler and waveguides (a), photo of the copper half structure (b), geometry of one quarter of the vacuum part of the regular cell (c).

Table 1: RF parameters of the fundamental mode in the travelling wave copper accelerating structure. RF fields and power are normalized to 1 nC bunch charge. The beam is on the central axis. The peak electric and magnetic fields are calculated on the surface, "$1m.$" means for the fundamental mode only.

Gap	Frequency	Shunt impedance	Loss factor	Group velocity	Pulse length	Output power	Accelerating gradient	E_{peak} surface	H_{peak} surface
	f	R_s	κ	v_g/c	τ_p	P	E_{acc}	$E_{max,1m.}$	$H_{max,1m.}$
mm	GHz	$M\Omega/m$	MV/nC/m	%	ns	MW	MV/m	GV/m	MA/m
0.2	140.28	449	47.45	0.21	2.34	0.03	95	0.2	0.4
0.3	136.27	398	41.60	0.85	2.36	0.105	83	0.19	0.356
0.5	130.30	298	31.15	3.54	2.37	0.34	62.5	0.174	0.347
0.7	126.01	222	23.50	7.65	4.03	0.58	47	0.16	0.34
0.9	122.66	166	17.87	12.42	2.35	0.75	36	0.15	0.3
1.1	119.93	128	13.89	17.48	1.57	0.88	28	0.12	0.23
1.3	117.59	99	10.97	22.44	1.15	0.94	22	0.11	0.2

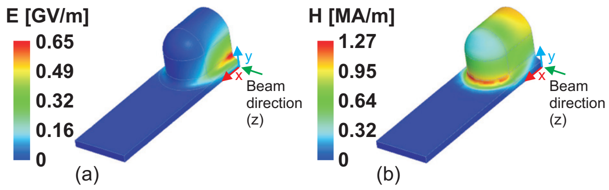

Figure 2: Plot of the electric field (a) and magnetic field (b) of the fundamental mode over one quarter of period of the regular cell (gap = 0.2mm), at synchronous frequency. These fields are calculated for a bunch charge of 3.2 nC and 50 μm long in an infinite travelling wave structure.

beam trajectory is close to the central axis there is no deflecting voltage. The deflection appears only as two spikes which are far from the structure center and close to the edge of the cavities.

EXPERIMENTAL RESULTS

The structure was installed in the vacuum chamber located in the experimental FACET section. A camera located after the vertically bending magnet records the screen image of the bunch at each pulse. The beam optics between the test structure and the camera converts the horizontal kick angle θ_x, generated by the structure, to a horizontal beam displacement Δx, given by:

$$\Delta x = R_{12} \cdot \theta_x = R_{12} \cdot \frac{eV_x}{E},$$

where e is the electron charge, R_{12} (= 14 m) is the optics coefficient that converts a beam horizontal angle into a beam horizontal displacement, given by the deflecting voltage V_x and the beam energy E. By measuring Δx on the diagnostic screen, the deflecting voltage is determined. The FACET beam had an energy E = 20.35 GeV, a charge of 3.2 nC and an RMS bunch length of about 50 μm. To vary the structure properties and gradients, we first remotely set the gap between the two blocks and then horizontally moved the structure position with respect to the beam, changing the gradient. During a horizontal scan we could clearly observe horizontal deflection of the beam centroid, from which the deflecting voltage was calculated using R_{12}. Figure 4 shows this analysis of a horizontal scan. Vertical error bars correspond to standard deviation of the centroid positions caused by transverse position jitter of the FACET bunch, pulse to pulse variation of the bunch shape and rf breakdowns. We believe that good correspondence between the simulated and measured deflecting voltages confirms our simulations of the accelerating voltage.

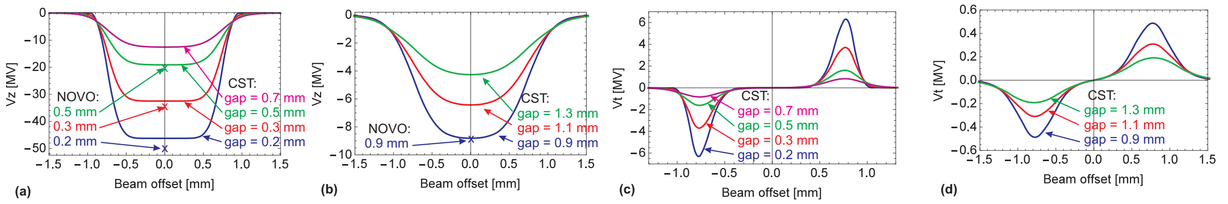

Figure 3: Deceleration voltage (a-b) and transverse voltage (c-d) as a function of the horizontal beam-structure displacement, for different gaps. The fields are generated by a 3.2 nC bunch with $\sigma_z = 50\ \mu m$ in 10 cm long structure. The solid lines are calculated with CST, the ‘X’ points with the code “NOVO”.

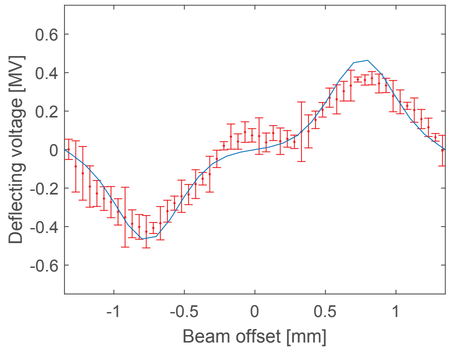

Figure 4: Measurement of beam deflection in a horizontal scan with gap = 0.9 mm. Blue line is the simulation.

With the known gradient and data from the “arc-detector”, we put the beam on the central axis and exposed the structure to a large number of pulses. The breakdown rate results are 0.66 1/(pulse m) with 3200 pulses and E_{peak} = 0.57 GV/m considering the sum of all modes (gap = 0.9 mm), and 0.38 1/(pulse m) with 500 pulses and E_{peak} = 0.47 GV/m considering the sum of all modes (gap = 1.1 mm). Our tests were done in a large vacuum chamber, as a consequence, the vacuum pressure was $7 \cdot 10^{-7}$ Torr. We conjecture that rf conditioning and a lower vacuum pressure could reduce the measured breakdown rate.

DISCUSSION

In this experiment we studied physics of rf breakdowns in mm-wave metallic travelling wave accelerating structures. The breakdown rates are relatively high for the field levels and pulse lengths as compared to values extrapolated from x-band experiments [2, 10]. X-band structures were conditioned by more than 10^8 rf pulses, typically without beam and vacuum pressures below 10^{-8} Torr. In this experiment the rf field is excited by the FACET beam so the number of pulses was limited to $< 10^6$ and the vacuum level is $7 \cdot 10^{-7}$ Torr. The breakdown rate is expected to improve with a better vacuum and more conditioning time. Moreover the beam halo was intercepted by the structure and a few times, the whole beam was dumped into the structure due to linac faults. All of the above could contributed to a relatively high breakdown rate. These experiments are the first yielding quantitative measurements of rf breakdown rate in this parameter space. It will take many more experiments to understand the physics of it.

CONCLUSIONS

In conclusion we report experimental measurements of rf breakdown statistics and deflecting forces in a copper travelling wave accelerating structure at sub-THz frequencies. The breakdown rate results are 0.66 1/(pulse m) with E_{peak} = 0.57 GV/m (considering the sum of all modes), and 0.38 1/(pulse m) with E_{peak} = 0.47 GV/m (considering the sum of all modes). This structure can be used as either a wakefield-driven or an rf powered accelerating structure. For the latter one, a gyroklystron would be a practical rf drive source.

ACKNOWLEDGMENT

We thank the experiment crew: Brendan O’Shea, Spencer Gessner, Oliver Williams, Chris Pearson, Erik Adli, Carl Lindstrom, Michael Litos. We thank Vitaly Yakimenko and the FACET team for their excellent support.

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