MEASUREMENTS OF ULTIMATE ACCELERATING GRADIENTS IN THE SLAC DISK-LOADED STRUCTURE* (Part I)[†]

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1. Introduction

The design of future linear colliders depends on a number of crucial factors, one of which has to do with the accelerating structure and the electric field gradients attainable therein. It is not clear at this time whether various trade-offs¹ between accelerator length, energy consumption, availability of power sources, frequency, alignment tolerances and other parameters will dictate the choice of a medium gradient (20-50 MV/m), a high gradient (100-250 MV/m) or a super-high gradient (~ 1 GV/m). The work reported here describes measurements made to study the maximum attainable accelerating gradients in a conventional SLAC disk-loaded accelerator section of the constant-gradient type running at 2856 MHz. The objective was to reach an accelerating gradient of at least 100 MV/m. The accelerating gradient at which the SLAC disk-loaded waveguide runs routinely is ~ 9 MV/m (36 MW tubes without SLED) and ~ 12 MV/m with SLED I (2.5 μ sec pulse). With 50 MW tubes and SLED II (5 μ sec) the gradient will increase to over 20 MV/m. The highest accelerating gradient ever measured until recently at SLAC dates back to undocumented experience with a

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[†] Some of the measurements described in this report are being repeated with upgraded experimental equipment. They will be published in Part II if new information becomes available.

short accelerator section in a resonant ring used to test RF components during the construction period (1962-1966) of the linear accelerator. It is believed that at that time, this short section reached an accelerating gradient of 46 MeV/m with no obvious signs of breakdown.

To reach 100 MV/m in a conventional 3 m constant-gradient section, one would need a klystron with a peak power output of 900 MW. Since such a tube is not available, we decided to use a short standing-wave section in which the resonant fields would be allowed to build up. The design criteria for this section, the fabrication, matching and tuning, the experimental set-up and the results are described below.

2. Design Criteria

Standing-wave accelerators are generally built in the π -mode or some variation thereof so that both forward and reflected waves contribute to the acceleration of a synchronous particle. In the case of this experiment, however, we were not interested in accelerating electrons but rather, in testing a $2\pi/3$ -mode SLAC-type of section to its maximum field. We took advantage of the availability of short six-cavity stacks, already brazed onto a coupler, to speed up the experiment (see Fig. 1). These stacks were actually the input and output segments of the SLAC 3 m sections which consist of a total of 84 regular cavities and two coupler cavities. These stacks were brazed separately and then joined onto the center portion (74 cavities). We chose the output stack because it has a lower group velocity and a higher field intensity for a given power input, and we capped it off at the end opposite to the coupler to make it resonant. Thus our standing-wave section consists of seven cavities.

The conceptual passage from standing waves to traveling waves and vice versa can be understood by referring to Fig. 2 and Ref. 2. One of the main differences, as shown in Fig. 2(a) and 2(b), is that in the traveling wave the E and H fields are in time phase whereas in the standing wave they are in time quadrature.

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To calculate the field parameters in our standing-wave section conservatively, we used the SUPERFISH program on the lowest field cavity (No. 79) of the constant-gradient stack. The parameters of this cavity are:³

$$2a = 1.99 \text{ cm}$$

$$2b = 8.192 \text{ cm}$$

$$r/Q = 47.4 \text{ ohms/cm for the traveling wave}$$

$$Q = 13712.6$$

where $2a$ is the iris diameter, $2b$ is the cavity diameter, r is the shunt impedance per unit length and Q is the usual loss factor. The SUPERFISH program can calculate the standing-wave fields for the Neuman-Neuman or Dirichlet-Dirichlet

Fig. 1. Resonant structure used for these experiments. Test points indicate locations of thermocouples used to monitor temperatures during operation.

(a) Traveling Waves, $\beta_0 d = 2\pi/3$

(b) Standing waves, $\beta_0 d = 2\pi/3$, for boundaries at $z=0$ and $z=3d$

Fig. 2. Traveling waves and standing waves in the SLAC structure with their respective field amplitudes in arbitrary units. Note that E_z is taken on-axis and E_r and H_ϕ are off-axis.

boundaries shown in Fig. 2(b). The calculation is performed for one and one-half cavities for a length L of 5.25 cm as shown in Fig. 3. For the Neumann-Neumann condition, the following results are obtained:

- Resonant frequency $f = 2855.76$ MHz.

Standing wave $R/Q = 124.4$ ohms for length L (5.25 cm).

This value is half of the value for the traveling wave because twice the energy is stored for the same accelerating field.

Fig. 3. Standing-wave amplitudes of E_z , E_r , and H_ϕ in cavity as calculated by SUPERFISH. E_z is on-axis, E_r , and H_ϕ are off-axis.

SUPERFISH calculates that when the average of the peak axial field over L expressed as

$$\frac{\int_0^L |E_z(z)| dz}{L} \text{ is } 1 \text{ MV/m} ,$$

the energy acquired by a particle riding synchronously at the velocity of light with the traveling-wave component is

$$\left| \int_0^L E_z(z) e^{j(\omega z/c)} dz \right| = 0.038 \text{ MV}$$

The corresponding energy stored in the section of length L is

$$W = 6.453 \times 10^{-4} \text{ Joule} ,$$

the power dissipated is

$$P_D = \frac{\omega W}{Q} = 844 \text{ watts} ,$$

the maximum axial field (in this case at $z = 0$) is

$$\{E_{z,SW}\}_{max} = 1.916 \text{ MV/m} ,$$

and the maximum surface field at the edge of the first disk is

$$\{E_{s,SW}\}_{max} = 2.81 \text{ MV/m} .$$

From these quantities we can calculate the average accelerating field

$$\bar{E}_{acc} = \frac{0.038 \text{ MV}}{L} = 0.723 \text{ MV/m}$$

and the ratios

$$\frac{|E_{z,SW}|_{max}}{\bar{E}_{acc}} = 2.65 \quad \frac{|E_{s,SW}|_{max}}{\bar{E}_{acc}} = 3.89$$

For Dirichlet-Dirichlet boundaries, the corresponding ratios are

$$\frac{|E_{z,SW}|_{max}}{\bar{E}_{acc}} = 2.19 \quad \frac{|E_{s,SW}|_{max}}{\bar{E}_{acc}} = 3.21$$

Note that the above $|E|_{max}$ are maxima reached by the standing wave which can be viewed as the sum of two traveling waves, one traveling to the right ($e^{+j\beta z}$), the other to the left ($e^{-j\beta z}$). For a particle traveling to the right on crest at the velocity of light, the first wave alone produces acceleration. Because of the periodic nature of the structure, the fields are actually made up of summations of space harmonics of amplitude a_n of which only the first (a_0) travels at the velocity of light. The standing waves can be expressed as

$$\begin{aligned} E_{z,SW} &= e^{-j\omega t} \sum_{n=-\infty}^{n=+\infty} 2a_n \cos \beta_n z & (\text{Neuman}) \\ E_{z,SW} &= e^{-j\omega t} \sum_{n=-\infty}^{n=+\infty} 2a_n \sin \beta_n z & (\text{Dirichlet}) \end{aligned} \quad (1)$$

where

$$\begin{aligned} \beta_n &= \beta_0 + \frac{2\pi n}{d} \\ \beta_0 &\doteq \frac{\omega}{c} \\ d &= \text{periodic length} \end{aligned}$$

and where the a_n 's are functions of the radial propagation constant

$$k_{r,n}^2 = \left(\frac{\omega}{c}\right)^2 - \beta_n^2$$

We can see that were it not for the space harmonics, the ratio $|E_{z,SW}|_{max}/\bar{E}_{acc}$ would simply be equal to 2, whereas here it is 2.65 and 2.19 respectively: the higher space harmonics ($n \neq 0$) enhance the local field but do not produce any cumulative acceleration.

Now, remember again that the purpose of our experiment was not to accelerate electrons but to create fields in our standing-wave structure that would simulate those which would yield accelerating fields of 100 MV/m in a traveling-wave structure. Given the above factor of 2 multiplier and the fact that power scales as $|E|^2$, we see that it is enough to supply the 1-1/2 cavity cell with that power which yields $E_{acc} = 50$ MV/m. For our stack of seven cavities, that power was calculated to be 17.06 MW. Note that the 100 MV/m accelerating field conditions are only fulfilled in every third cell, as we will see below. The equivalent traveling-wave fields for a power input P_{in} in MW are

$$\begin{aligned} E_{z,TW} &= \sqrt{\frac{P_{in}}{17.06}} \times 100 \text{ MV/m} \\ E_{z,TW} &= \sqrt{\frac{P_{in}}{17.06}} \times 194.5 \text{ MV/m} \end{aligned} \quad (2)$$

3. Fabrication, Matching and Tuning

Four mechanical modifications were made to complete the fabrication of the standing-wave section. The first was to braze sixteen (instead of the usual eight) cooling tubes around the section to improve the cooling. The second was to drill small holes (by EDM) into the wall and disks of the section (see Fig. 1) to insert thermocouples for temperature monitoring. The third was to cap off the last cylinder (cavity 79) with a disk of diameter $2a = 0.7617$ in. and a subsequent plate to provide a reflection plane and a vacuum seal. The fourth was to braze an extra matching iris into the input coupler (see Fig. 4) to critically couple the section for maximum power delivery. A coupling coefficient of $\beta = 1.08$ was obtained for an iris opening $S = 0.78$ in.

Tuning of the section was done by the usual nodal shift technique.³ A dielectric bead was then pulled along the axis of the section and the power reflected by the bead was plotted, as shown in Fig. 5. Note that cavities 83 and 80 are the ones that reach maximum field; the coupler and the other cavities do not.

Fig. 4. Cross-section of coupler cavity showing extra brazed-in matching iris to obtain critical coupling.

Fig. 5. Power reflected by bead as a function of axial position (in arbitrary units). This power, if it were measured with a perfect square-law crystal, would be proportional to $|E_z|^4$ because the reflection coefficient of the bead is proportional to $|E_z|^2$ and the reflected power scales as the square of the reflection coefficient.

4. Experimental Set-Up

A block diagram of the experimental set-up used to perform the measurements is shown in Fig. 6. The RF system consisted of a low-level variable frequency oscillator, a pin-diode modulator, a 20 W traveling-wave amplifier, a pulsed sub-booster amplifier and an XK-5 klystron which supplied up to about 36 MW of peak power to the accelerator section. The variable frequency oscillator was needed because the temperature of the section changed as the input power was increased, and the oscillator had to be retuned to keep the section resonant. The trigger system was used to vary the repetition rate and the pin diode allowed us to adjust the length of the RF pulse. The forward and reflected powers were monitored by means of two modified Bethe-hole couplers. A 60 ℓ /sec vacuum pump was used on the section. At the beginning of the tests, the section had its vacuum separated from the vacuum of the rectangular waveguide by means of a ceramic window. Later on, the window broke and it was removed. A residual gas analyzer was used to monitor the gasses emitted during RF processing and operation, and a multipoint thermocouple reader allowed us to monitor the temperature of the section at various points (see Fig. 1). A photodetector was used to display the instantaneous radiation emitted by the section during each pulse. Figure 7 shows the part of the experimental set-up which was located inside the radiation vault.

5. Experimental Results

Because of equipment limitations, the experiments were done with an RF pulse length of 2.5 μ sec and a maximum repetition rate of 120 pps. The cooling water flow was set at 15 gpm and the input water temperature was 83° F. Figure 8 shows the temperatures monitored in the section as a function of average power dissipated. All variations appear to be linear. Test points 2 and 3 are in successive disks, and test point 4 is in the outer wall. As we see, test point 2 rose twice

Fig. 6. Block diagram of experimental set-up.

Fig. 7. Photograph of experimental set-up inside radiation vault. Note accelerator section with water-cooling manifold in lower left-hand corner.

as fast as test point 3 because the fields in cavity 83 (see Fig. 5) were higher than in cavity 82. This, of course, would not happen in a traveling-wave structure because all cavities would undergo the same excitation and power dissipation. Figure 9 shows the resonant frequency of the section as a function of average power dissipated. Note that the variation was not quite linear. The resonant frequency at very low power level was ~ 2856.8 MHz.

It should be mentioned that the average powers plotted in Figs. 8 and 9 were indeed the powers delivered to the section, after subtraction of the reflected power from the forward power measured by the directional couplers in Fig. 6. The ratios of reflected-to-forward energy or average power for a critically coupled cavity can be expressed as⁴

$$\frac{\bar{P}_{ref}}{\bar{P}_{for}} = \frac{T_C}{T_P} \left(1 - \frac{1}{2} e^{-2T_P/T_C} \right) \quad (3)$$

where T_P is the length of the RF pulse and $T_C = 2Q_L/\omega$ or Q_0/ω since the loaded Q_L of the cavity is equal to $Q_0/2$. For our experiment, T_P was $2.5 \mu\text{sec}$ and $T_C \sim 0.75 \mu\text{sec}$. The ratio calculated by expression (3) was monitored throughout the measurements by means of the directional couplers.

Before the RF tests were started, the section was baked at roughly 250°C for 36 hours. The pressure after bake was 10^{-8} Torr. The RF was then turned on gradually to let the section outgas. Figures 10(a), (b), (c) show forward (top) and reflected (bottom) wave shapes. In the absence of breakdown, the reflected wave shapes exhibited the pattern one would expect from a critically coupled resonant system, with roughly equal reflections at the beginning and at the end of the pulse. The wiggles within the pulse were probably due to a combination of ripple from the PFN in the modulator and internal reflections within the section as it filled and emptied. At the beginning of the RF tests, the window mentioned earlier was fractured and underwent considerable

Fig. 8. Temperatures as a function of average power dissipated in accelerator section for the test points shown in Fig. 1.

Fig. 9. Resonant frequency as a function of average power dissipated in accelerator section.

$P_{in} = 28 \text{ MW}$ $2 \times 10^{-7} \text{ Torr}$
No Breakdown
(a)

$P_{in} = 30.2 \text{ MW}$ $8 \times 10^{-7} \text{ Torr}$
Notice Breakdown
(b)

$P_{in} = 30.2 \text{ MW}$ $2 \times 10^{-7} \text{ Torr}$
No Breakdown
(c)

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Fig 10. Forward and reflected wave shapes.

electrical breakdown. After it was removed, only minor RF processing was required and the power input to the section was easily increased up to 28 MW [see Fig. 10(a)]. The pressure was roughly 2×10^{-7} Torr. When the power input was somewhat abruptly increased to its maximum attainable, namely 30.2 MW, the pressure rose to about 8×10^{-7} Torr and the section exhibited the breakdown shown in Fig. 10(b). After some further processing and pumpdown back to 2×10^{-7} Torr, the breakdown disappeared and the stable condition shown in Fig. 10(c) was obtained without difficulty. The outgassing as observed by the RGA revealed only the presence of some water, nitrogen, fluorine and methane. Using expressions (2), the equivalent traveling-wave accelerating fields were:

$$E_{r,TW} \sim 133 \text{ MV/m}$$

$$E_{s,TW} \sim 259 \text{ MV/m} \quad .$$

The klystron output power could not be increased further. Note that the above fields were reached and maintained after the standing-wave structure was fully charged, roughly 1.5 μ sec into the 2.5 μ sec pulse. The results reported here are similar to those given for the single cavity tests described in Ref. 5.

As the RF power was increased during all the above tests, considerable* x-ray radiation was observed in the vault around the section. Field emission was clearly present and the resulting radiation as the electrons were accelerated in the section and hit the end-plates could be monitored on an oscilloscope as a function of time within the pulse. The radiation had the same general time-variation as the fields. After completion of the tests, blue spots from the radiation could be seen externally on the axis of both stainless steel end-plates. One of the end-plates was then removed and the inside of the section was inspected carefully with a boroscope. No internal damage was observable on the copper surfaces.

* No absolute measurements were made.

As this Part I of our work is being published, a second series of measurements with improved equipment is about to begin. If new information becomes available, it will be published in Part II.

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