ON THE LIMITATIONS OF ACCELERATING GRADIENT IN LINEAR COLLIDERS DUE TO THE PULSE HEATING

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Abstract

In this work, we consider the limitation of the maximal accelerating gradient in linear colliders due to the pulse heating by the RF magnetic field at the cavity walls. Heating of the thin surface layer creates pulse mechanical stresses which may cause destruction of the inner surface of the cavities within a limited period of time. Because of this limitation the accelerating gradient can't exceed 300 MV/m even for frequences over 40 GHz, despite the fact that other factors allow to reach substantially higher gradients.

1. INTRODUCTION

In the longer-range future electron-positron linear colliders with 5-15 TeV center of mass energy will be in growing demand for high energy physics studies. A high accelerating gradient will be required to maintain a reasonable overall length of this collider.

The accelerating gradient is strongly correlated with the operating frequency - the energy stored per meter of accelerating structure varies approximately as $(G_o\lambda)^2$, where G_o is the unloaded gradient and λ is the RF wavelength. Hence, it is possible to design high energy colliders keeping the length and AC power within a reasonable bounds by operating at higher frequences [1].

Several factors must be taken into account in scaling a linear collider to higher frequences. Basic factors are a breakdown threshold, "dark current" capture threshold and problems caused by pulse heating by the magnetic fields at the accelerating cell walls. As for the breakdown and "dark current" capture thresholds, these factors make it possible to increase the gradient up to 250 MV/m for a frequency 34.3 GHz or up to 500-600 MV/m for a 91.4 GHz frequency [1]. At the same time a strong magnetic field on the cell walls causes the temperature increase by 110-510 ^{0}C in a pulse. Pulse heating of the thin surface layer creates pulse mechanical stresses which may result in destruction of the inner surface of the accelerating cavities within a limited period of time.

It will be shown below that the life time of the accelerating structure i.e. the number of pulses the structure can sustain without surface destruction appears acceptable only if the pulse heating does not exceed ~150 ^{0}C.

2. PULSE HEATING AND MECHANICAL STRESSES

A high frequency magnetic field on the cavity walls causes pulse heating. The temperature rise at the end of a pulse of duration τ_p is [1]

$$\Delta T = \frac{R_s}{K}\left(\frac{D\,\tau_p}{\pi}\right)^{1/2}\left(\frac{G_0}{Z_H}\right)^2 . \qquad (1)$$

Here R_s is the surface resistance, K is the thermal conductivity and D is the thermal diffusivity, given by $D=K/C_s\rho$, where C_s is the specific heat, ρ is the density (D=1.15 cm /sec and K=3.95 W/cm/ ^{0}C for copper). Z_H is an impedance defined as $Z_H = G_o/H_s$, where H_s is the peak surface magnetic field. Formula (1) is derived on the assumptions that R_s, D, C_s and ρ do not change with temperature and the depth of thermal diffusion is far bigger than skin depth. The latter is valid for the range of parameters which is of interest (f= 11.4-91.4 GHz, τ_p=12-250 ns) where the skin depth is 0.2-0.6 μm and thermal diffusion depth is 3.5 - 17 μm.

Mechanical stresses appears in the thin (3 - 17 μm) surface layer of metal due to the pulse heating. When the rise in temperature is above a “safe” value (ΔT_s), the mechanical stress grows large enough to create microscopic damages in the metal. The damage accumulates with each suceeding pulse and the cavity surface is destroyed after the certain number of pulses (n). It is possible to define ΔT_s and n from the theory developed in the 70’s by researches in the USSR to investigate the distruction of collectors and other parts of the microwave tubes resulting from the pulse heating by an electron beam [2-4].

In practice, the destruction of the metal surface occures when the mechanical stress exceeds its elastic limit. From this, the approximate value of the "safe" temperature rise can be written as [2]

$$\Delta T_s = \frac{2\sigma}{\alpha E} , \qquad (2)$$

where σ is an elastic limit, α is coefficient of linear expansion and E is Young's modulus. For copper $\alpha=16.5\cdot10^{-6}/^0$C, $\sigma= 1.2\cdot10^4$ N/cm^2 , $E=1.31\cdot10^7$ N/cm^2 and a "safe" pulse heating is only T_s ~110 ^{0}C !

Once the pulse heating exceeds this limit, plastic deformation occurs in the metal, which leads to accumulation of defects causing destruction of the heated surface after n pulses [3,4], given approximately by [2]

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TABLE 1

Frequency (GHz)	$G_0 \sim \omega^{5/6}$ (MV/m)	$\tau_p \sim \omega^{-1.5}$ (ns)	$\Delta T \sim \omega^{1.42}$ (^{0}C)	$T_0 = 27\ ^0$C		$T_0 = 77\ ^0$C	
				n	and life	n	and life
11.424	100	250	23				
22.848	180	90	61				
34.272	250	50	112				
45.696	320	30	165	$3.6 \cdot 10^{10}$	14 years	$2.5 \cdot 10^{9}$	1 year
57.120	380	22	225	$1.5 \cdot 10^{9}$	3500 hours	$1.8 \cdot 10^{8}$	420 hours
68.544	440	17	290	$1 \cdot 10^{8}$	230 hours	$1.8 \cdot 10^{7}$	42 hours
79.968	500	14	370	$9.8 \cdot 10^{6}$	23 hours	$2.6 \cdot 10^{6}$	6 hours
91.392	560	11	440	$1.4 \cdot 10^{6}$	3 hours	$4.7 \cdot 10^{5}$	1 hour
102.816	620	9	520	$2.6 \cdot 10^{5}$	36 min	$1 \cdot 10^{5}$	14 min
114.240	680	8	600	$6 \cdot 10^{4}$	8 min	$3 \cdot 10^{4}$	4 min

$$n \sim \frac{U - 50T_0}{16.7U} \cdot \exp\left(\frac{U}{6(T_0 + \Delta T)}\right), \qquad (3)$$

where U is heat of evaporation of the material (76320 cal/mole for copper), T_0 is the temperature before the pulse start (^{0}K).

3. RESULTS

The calculations made are for NLC - like TW accelerating structure with $Z_H = G_o/H_s$=307 Ohms [1] for frequences from 11.424 GHz (NLC) to 114.24 GHz (10xNLC). The increase in surface resistance due to the temperature rise and the accumulation of microdamages [5] was not taken into account.

To consider the influence of temperature before the pulse start, the exact value of which depends upon the design, the calculations were made for two values of T_o - 300 ^{0}K (27 ^{0}C) and 350 ^{0}K (77 ^{0}C). Keeping in mind that the life time of the collider must be about 20 years at a repetition rate of 120 pulse/sec and for 6000 hours of operation per year, the requirement is that the accelerating structure should at least stand the number of pulses n $\sim 5 \cdot 10^{10}$ without destruction.

The results of the calculations are shown in TABLE 1.

One can see from the Table that the temperature rise at the end of the pulse should not exceed, say, $\Delta T \sim 150\ ^0$C, than G_0 ~300 MV/m at a frequency of 40 GHz. It can be shown that for fixed ΔT, the gradient will increase with frequency as $G_0 \sim \omega^{1/8}$. G_0 can not exceed 330 MV/m at 91.4 GHz. It is obvious, that pulse heating limits the maximum value of RF fields in the cavities of microwave sources at a level lower than that in accelerating structures, because the pulse duration in the former is 4-16 fold as long.

4. CONCLUSION

The surface destruction of accelerating cells due to the pulse heating limits the gradient to about 300 MV/m and, consequently, decreases the attractiveness of linear colliders with a frequency substantially higher than 34.3 GHz.

More accurate experimental measurements of the maximal acceptable pulse heating for different materials may possibly be made at the NLC frequency (11.4 GHz) where the 50 MW klystrons with a pulse of 1.5 μs are available.

5. ACKNOWLEDGMENTS

This work is supported by the Department of Energy, Division of High Energy Physics. The author also would like to thank Dr. B. Persov for helpful discussion and Dr. A. Ganguly for careful reading the manuscript.

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