HIGH MAGNETIC FIELDS IN COUPLERS OF X-BAND ACCELERATING STRUCTURES*

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INTRODUCTION

Increasing the accelerating gradient is an important issue for linear accelerators. Among phenomena that limit the gradient is rf breakdown in accelerating structures. Breakdowns have been frequently observed in coupler cells of accelerating structures and have been attributed to the electrical field enhancement noted in simulations. Several solutions have been proposed to reduce this enhancement [1, 2]. For example, increasing the group velocity in the coupler and adjacent cells, and shaping of the coupler cell to reduce maximum surface electric fields below the fields in the structure. Little attention was paid to enhancement of the magnetic field in the couplers although the possibility of damage due to pulse heating was mentioned in [3].

The limit imposed by rf pulse heating and thermal fatigue was discussed in [4, 5], but the connection between the high rf magnetic field and coupler breakdowns was realized only recently in high gradient experiments with traveling wave (TW) and standing wave (SW) 11.4 GHz accelerating structures [6, 7, 8]. These experiments are part of extensive experimental and theoretical program underway at SLAC, FNAL and KEK to develop structures that reliably meet the Next Linear Collider and Japanese Linear Collider (NLC/JLC) requirement of 50 MV/m loaded (65 MV/m unloaded) gradient operation.

Experiments There is overwhelming experimental evidence that the waveguide-to-coupler irises in couplers are prone to breakdowns for low group velocity TW and SW structures [9]. The maximum gradient in all of these structures was limited by breakdowns in couplers. The damage was concentrated in input couplers [10].

The breakdowns produce mechanical shock. Shock waves were registered by acoustic sensors installed on the input coupler of a TW structure. The data have shown that the location of the source of the acoustic signal is correlated to the location of waveguide-to-coupler-cell irises [11].

A video-camera was used to obtain images of the arcs in the SW structures. Averaging of more than 100 images again shows that the visible arc location corresponds with the location of the waveguide-to-coupler-cell irises [8].

An autopsy of a TW structure has shown that the inner edges (cell side) of the waveguide-to-coupler-cell irises are eroded while the outer edges (waveguide side) are almost intact. The damage was roughly uniform over the height of the irises [12].

Detailed electrodynamic simulation was made in order to understand the physics underling coupler breakdowns. The simulations and their results are discussed in this paper.

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COUPLER SIMULATIONS

A coupler cavity is designed to provide rf power flow from waveguide to the accelerating structure. Design of the coupler is a complex 3D electrodynamic problem. To find the rf magnetic field and calculate the pulse temperature rise the existing couplers had to be modeled with a more accurate code than the code they were originally designed with. Since both TW and SW accelerating structures were tested, couplers for both types were simulated. First, the couplers were matched. The matching procedures for couplers of TW structures and SW structures are different: a TW structure coupler should match waveguide to an infinitely long periodic structure; a SW structure coupler should provide specified loaded Q. Second, the maximum surface rf magnetic field should be determined. In the couplers the field reaches maximum on the edges of the waveguide-to-coupler iris. Then the maximum pulse temperature rise due to the magnetic field is estimated.

Matching of TW structure couplers

An efficient automated procedure has been developed for the simulation of existing TW structure couplers, new couplers designs, and for study of how cell shape effects the magnetic and electric fields. A C++ program optimizes coupler dimensions using the commercial frequency-domain code Ansoft HFSS^{TM}[13]. The matching procedure uses a method based on properties of periodic structures to calculate reflection from the coupler for known on-axis electric field. This method was developed for time domain simulations by N. M. Kroll *et al.* [1]. To find the reflection three points on z axis separated by structure period P were used, with complex electric fields at $E(z-P)$, $E(z)$, and $E(z+P)$. Intermediate quantities are

$$\Delta(z) \equiv (E(z+P) - E(z-P))/E(z),$$
$$\Sigma(z) \equiv (E(z+P) + E(z-P))/E(z).$$

Phase advance per cell ψ is found from equation $\cos\psi = \Sigma(z)/2$. The reflection is

$$R(z) = (2\sin\psi - j\Sigma(z))/(2\sin\psi + j\Sigma(z)).$$

Here $j = \sqrt{-1}$. One frequency point calculation of a model made of 4 to 6 cells and one coupler cell gives the coupler reflection directly. More than 4 cells is needed if the structure is tapered. Reflection from the excitation port is irrelevant so there is no need for a second coupler. The structure does not have to be symmetrical from beginning to end as in [1]. The following algorithm is executed during coupler matching:

1. The program reads a text file of coupler and cell dimensions and optimization parameters. Then it

writes an HFSS macro that is later executed by post-processor and a macro for 3D modeler to generate the first structure geometry.

2. The program starts HFSS and waits until HFSS has finished calculating and saving $\Re e(E(z))$ and $\Im m(E(z))$ along the z axis of the structure.
3. The program reads the saved fields, calculates $R(z)$ and ψ and then writes an HFSS macro with geometry for the next iteration.
4. The program uses a two parameter optimization algorithm and repeats steps 2 and 3 until the desired coupler reflection is found.

This program can use any structure dimensions in the parameter search, but usually the chosen dimensions are diameter of the coupler cell, opening of the waveguide-to-coupler iris, and diameter of next-to-coupler cell. For typical geometries one such iteration takes from 8 to 30 minutes on a two-processor 900 MHz Pentium computer. More accurate calculations require more time. A typical coupler is matched with an overnight run of the program using lower accuracy faster iterations. Then the match is verified with several more accurate runs, which at the same time provide tolerance analysis for manufacturing. Typical final R achieved is 0.02...0.06.

The whole procedure is robust and never failed to match a coupler. Such sources of error as finite accuracy of field calculation in HFSS or slight variations of tapered structure dimensions from dimensions of an exactly periodic structure do not prevent a good match.

Matching of SW structure couplers

SW π mode structures were recently high power tested at SLAC [8]. Each structure has 14 uniform cells with the coupler cell located in the middle. The coupler matching of such a structure is reduced to adjusting the resonant frequency and loaded Q of the coupler cavity only.

HFSS in eigenvalue mode was used for these calculations. Magnetic boundaries were applied on the interface between coupler and adjacent cells to simulate π mode. Waveguide, connected to the coupler cell, was terminated with a matched load. With these boundary conditions the HFSS eigenvalue solver directly calculates resonant frequency and loaded Q. First, the loaded Q is adjusted with a change of the waveguide-to-coupler cell iris opening; then the coupler is tuned to resonate at the working frequency by changing the coupler cell diameter. Typically 6 to 10 iterations are enough to tune the coupler with total calculation time of one to two hours. The match is verified by calculating the reflection coefficient of the whole structure assuming it is made of copper.

Magnetic fields on sharp edges

The radius of the waveguide-to-coupler cell iris edge was specified on the drawing at $76 \pm 25\mu$m. Width of the iris is 0.8 mm. Direct calculation of this small rounding is rather time consuming and was done only for several couplers. For the rest of the couplers, the magnetic field was calculated using an analytical extension of the numerical result.

Usually, the couplers were simulated without the waveguide-to-coupler cell rounding. On a $90°$ corner the normal magnetic and electric fields have a singularity proportional to $\rho^{-1/3}$, where ρ is the distance to the corner [14]. Fields calculated with HFSS on such a corner will depend on mesh size and will not converge. At the same time, field between the sharp edges will converge. A 2D electrostatic model was built to determine field enhancement on the corner compared to field between edges. A precision 2D boundary-element code was used [15]. Fitting of the results gives the amplification factor $k = 1.04r^{1/3}$ for iris width of 0.8 mm and the edge rounding r [mm]. This factor for 76 μm rounding is ~ 2.5. Direct HFSS calculations of couplers with 76 μm rounding agree with this simple model.

Pulsed heating

RF heating of a metal surface was calculated with a 1D model using calculated tangential magnetic field $H_{\|}$ [5]. The pulse temperature rise ΔT is given by :

$$\Delta T = \frac{|H_{\|}|^2\sqrt{t}}{\sigma\delta\sqrt{\pi\rho' c_\epsilon k}},$$

where t is the pulse length, σ is the electrical conductivity, δ is the skin depth, ρ' is the density, c_ϵ is the specific heat, and k is the thermal conductivity of the metal. For copper at a frequency of 11.424 GHz the temperature rise $\Delta T = 430|H_{\|}|^2\sqrt{t}$, where ΔT is in °C, $H_{\|}$ in MA/m, and t is in μs. In this simplified model, nonlinearities of the metal's physical properties are neglected.

RESULTS

Coupler breakdowns limited the performance of all recently tested structures with sharp edged couplers. Some of the couplers were cut open after the test. Damage to edges observed on the microscope images was correlated with calculated pulse temperature rise of about 100°C. But to predict the breakdown behavior using the calculated pulse temperature rise was difficult. All structures have shown threshold-like breakdown behavior with the input rf power and pulse width similar to that given in [8]. The calculated pulse temperature rise for the threshold varied between 60 to 150°C, but not all couplers with similar rf magnetic fields where breaking down.

Rounded irises

After the source of coupler breakdowns was traced to high magnetic fields on the sharp edges of the waveguide-to-coupler cell irises, an obvious solution followed: increase the iris rounding to reduce magnetic surface fields. To determine the sufficient rounding one NLC prototype structure was matched by couplers with different iris rounding. That structure is 60 cm long, constant gradient, with initial group velocity (v_g) of 3% of speed of light (c) and 150° phase advance per cell. Several couplers with different rounding were matched. The results for two structures with 70 MV/m unloaded gradient and NLC pulse

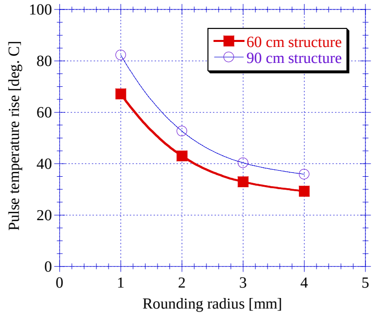


Figure 1: Dependence of maximum pulse temperature rise *vs.* waveguide-to-coupler iris rounding for 60 cm and 90 cm long accelerating structures. Dots — simulation, curves — polynomial fit.

width of 400 ns are shown in Fig.1. The shorter structure needs 70 MW of input power while the longer one needs 96 MW to reach this gradient. The temperature rise for the 90 cm, $v_g = 0.03c$ structure has been scaled up from 60 cm structure results since both structures have the same input couplers. Iris rounding of 3 mm was chosen for the new couplers to keep the pulse temperature rise far below 100° C. Couplers for several structures with such rounding were designed, built and high power tested. Performance these structures was not limited by coupler breakdowns [16]. At the same time, new coupler designs have been developed to considerably decrease the pulse temperature rise and surface electric field [17].

Electric fields

A coupler that had more than 150°C calculated temperature rise but no breakdowns was autopsied. The coupler had damage on the the iris edges. This damage was roughly uniform along the height of the iris but looked very different from damage in couplers with breakdowns. This observation prompted a closer look at the surface electric field.

This edge surface electric field is commonly ignored since it has much lower amplitude than the maximum field in the cell. A real structure with irises and beam pipes always has electric field on outside cell diameters contrary to an idealized case of a pill-box cavity with TM001 mode. The sharp edges on the waveguide-to-coupler iris enhance this field.

Input and output couplers of a 60 cm structure with initial $v_g = 0.03c$ were simulated using HFSS. The couplers were modeled with 80 μm rounding. The surface electric field distribution on the iris edges is shown in Fig. 2. For unloaded gradient of 70 MV/m the input coupler has 13 MV/m maximum field on the edge, the output couplers has ~2 MV/m. The calculated pulse temperature rises are 270° and 160°C respectively. During the high power test the input coupler was breaking down, but output did not.

SUMMARY AND DISCUSSION

After the source of coupler breakdowns was traced to sharp edges of the waveguide-to-coupler irises the problem was solved with new low magnetic field coupler designs.

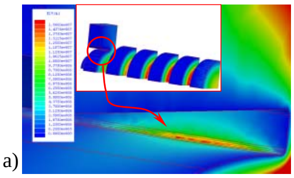
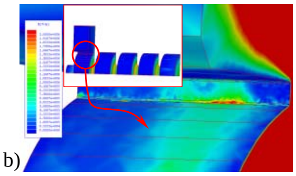
a)  b) 

Figure 2: Surface electric field distribution on the edge of 60 cm, $v_g = 0.03c$ structure: a) input coupler, maximum edge field ~13 MV/m; b) output coupler, maximum edge field ~2 MV/m.

The damage observed on the coupler edges and the breakdown behaviour suggests that the breakdown trigger is related to *mechanical fatigue* of the copper surface. In the the model described in [18] the mechanical fatigue accumulates with each pulse and after certain number of pulses a macroscopic change occurs (similar to creation of a dislocation). This model needs an additional assumption that this macroscopic change triggers the rf breakdown. It seems that the moderate electric fields ($\sim$ 10 MV/m) on the edges are an essential part of this trigger. The physics of the surface heating also needs verification, since other effects, like single surface multipactor discharge in strong rf magnetic fields, could increase the surface temperature in addition to the Joule heating due to rf currents.

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