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 underlying coupler breakdowns. The simulations and their results are discussed in this paper.

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™ [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 \( \psi \) 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 \( \Re(E(z)) \) and
\( \Im m(E(z)) \) along the z axis of the structure.

3. The program reads the saved fields, calculates \( R(z) \)
and \( \psi \) and then writes an HFSS macro with geometry
for the next iteration.

4. The program uses a two parameter optimization algo-


This program can use any structure dimensions in the
parameter search, but usually the chosen dimensions are di-

mension of the coupler cell, opening of the waveguide-to-
coupler iris, and diameter of next-to-coupler cell. For typ-
ical geometries one such iteration takes from 8 to 30 min-
utes on a two-processor 900 MHz Pentium computer. More
accurate calculations require more time. A typical cou-
pler 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 exact periodic structure
do not prevent a good match.

**Matching of SW structure couplers**

SW \( \pi \) 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 fre-
quency and loaded Q of the coupler cavity only.

HFSS in eigenvalue mode was used for these calcula-
tions. Magnetic boundaries were applied on the interface
between coupler and adjacent cells to simulate \( \pi \) mode.
Waveguide, connected to the coupler cell, was terminated
with a matched load. With these boundary conditions the
HFSS eigenvalue solver directly calculates resonant fre-
quency 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 calcu-
tation 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 ± 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 calcu-
lated 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 pro-
portional to \( \rho^{-1/3} \), where \( \rho \) is the distance to the corner
[14]. Fields calculated with HFSS on such a corner will de-
pend on mesh size and will not converge. At the same time,
field between the sharp edges will converge. A 2D electro-
static 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 \( k = 1.04 r^{1/3} \) for iris
width of 0.8 mm and the edge rounding \( r \) [mm]. This fac-
tor for 76 \( \mu \)m rounding is \( \sim 2.5 \). Direct HFSS calculations
of couplers with 76 \( \mu \)m 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 \( H_\parallel \) [5].
The pulse temperature rise \( \Delta T \) is given by :

\[
\Delta T = \frac{|H_\parallel|^2 \sqrt{t}}{\sigma \delta \sqrt{\pi \rho' c_k k}},
\]

where \( t \) is the pulse length, \( \sigma \) is the electrical conductivity,
\( \delta \) is the skin depth, \( \rho' \) is the density, \( c_k \) 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 \( \Delta T =
430|H_\parallel|^2 \sqrt{t} \), where \( \Delta T \) is in °C, \( H_\parallel \) in MA/m, and \( t \) is in
\( \mu s \). In this simplified model, nonlinearities of the metal’s
physical properties are neglected.

**RESULTS**

Coupler breakdowns limited the performance of all re-
cently 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: in-
crease the iris rounding to reduce magnetic surface fields.
To determine the sufficient rounding one NLC proto-
type 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 dif-
ferent rounding were matched. The results for two struc-
tures with 70 MV/m unloaded gradient and NLC pulse
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$\degree$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$\degree$C calculated temperature rise but no breakdowns was autosipped. 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 $\mu$m 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 $\sim$2 MV/m. The calculated pulse temperature rises are 270$\degree$ and 160$\degree$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.

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 multilactor 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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REFERENCES