ENGINEERING DESIGN OF THE INTERACTION WAVEGUIDE FOR HIGH-POWER ACCELERATOR-DRIVEN MICROWAVE FREE-ELECTRON LASERS

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Abstract

Linear induction accelerators (LIAs) operating at beam energies of a few million electron volts and currents of a few thousand amperes are suitable drivers for free-electron lasers (FELs). Such lasers are capable of producing gigawatts of peak power and megawatts of average power at microwave frequencies. Such devices are being studied as possible power sources for future high-gradient accelerators and are being constructed for plasma heating applications. At high power levels, the engineering design of the interaction waveguide presents a challenge. This paper discusses several concerns, including electrical breakdown and metal fatigue limits, choice of material, and choice of operating propagation mode.

Introduction

In recent years, much work has gone on at Lawrence Berkeley Laboratory (LBL) and at Lawrence Livermore National Laboratory (LLNL) directed at using LIA-driven FEL amplifiers as high-power microwave sources for future high-energy accelerators[1-3] and for plasma heating applications.[4-6] One design for a 17-GHz, 1-TeV electron-positron linear collider[3] requires from each of 553 FEL sections a peak output power level of 5.0 GW and an average power level of 54 kW. The Intense Microwave Prototype (IMP) FEL at LLNL, nearing completion, is designed to produce a few gigawatts of peak power at 140 GHz. The IMP will be used for electron cyclotron resonance (ECR) heating in the Microwave Tokamak Experiment (MTX). Also under construction for MTX ECR heating is the wiggler and other hardware for upgrading IMP to a 250-GHz, 8.0-GW (peak), 2.0-MW (average) capability. For ECR heating in the Compact Ignition Tokamak (CIT) and the International Thermonuclear Experimental Reactor (ITER), FEL designs call for driving-beam parameters of 13-15 MeV, 3.0 kA, 70 ns, and 10 kHz. For CIT and ITER, such devices are to generate about 14 GW (peak), 10 MW (average) at 280 GHz and 10 GW (peak), 7.0 MW (average) at 560 GHz, respectively.

The FEL interaction waveguide (IW) is the pipe through which the wiggled electron beam and the growing microwave field propagate. It is an oversized waveguide, typically with a size of a few centimeters. At the high peak and average power levels mentioned above, many questions arise regarding the performance limitations, reliability, lifetime, and mechanical design of this key system component. Several of these issues are examined below.

Interaction Waveguide Concerns

Figure 1 shows the electron beam, electric field pattern, and mode commonly used in single-pass FELs with linear wigglers using circular-, elliptical-, or rectangular-shaped IWs. These are shown oriented for the usual horizontal wiggle motion of the electron beam. A 3 x 10-cm rectangular IW used in LLNL's ELF experiments produced ~1.5-GW peak power at 35 GHZ. The same size of guide is being studied for use in a 17-GHz two-beam accelerator that will produce ~5.0 GW of peak power.[1] For the 140/250 GHz IMP FEL discussed earlier, a 3.25-cm-diam circular IW must reliably propagate 8.0 GW of peak power and up to 2.0 MW of average power for 0.5 s.

The threshold power level for electrical breakdown is a natural first concern when dealing with high power waveguides. For the modes shown in Fig. 1, the peak power is related to the electric field in vacuum by

$$P_{P(GW)} \simeq 5.0 \times 10^{-5}\, d^2_{(cm)} \left(\frac{\lambda}{\lambda_g}\right) E^2_{P\,(MV/cm)} \qquad \text{[circular]}$$

and

$$P_{P(GW)} \simeq 6.6 \times 10^{-5}\, a \times b_{(cm)} \left(\frac{\lambda}{\lambda_g}\right) E^2_{P\,(MV/cm)} \qquad \text{[rectangular]}$$

where λ is the operating wavelength, λ_g is the guide wavelength, $\lambda/\lambda_g = [1-(\lambda/\lambda_c)^2]^{1/2}$, and λ_c is the cutoff wavelength. For the usual case of operation in a highly oversized waveguide, $\lambda/\lambda_g \simeq 1.0$ and the peak electric field, now independent of frequency, is given by

$$E_{P(MV/m)} \simeq 142 \left[\frac{P_{P(GW)}}{d(cm)}\right]^{1/2} \qquad \text{[circular]}$$

and

$$E_{P(MV/m)} \simeq 123 \left[\frac{P_{P(GW)}}{a x b\ (cm)}\right]^{1/2} . \qquad \text{[rectangular]}$$

For an FEL propagating 5.0 GW in a 3 x 10-cm rectangular waveguide, $E_p \simeq 50$ MV/m. In a 3.25-cm-diam circular waveguide propagating 8.0 GW in the TE°_{11} mode, $E_p \simeq 123$ MV/m.

To judge whether or not the foregoing peak field values are excessive, we present Fig. 2, which plots E_p versus frequency and shows limits based on electrical breakdown and surface fatigue. Pertinent scaling factors are also included. Note the plot is for a fixed rf pulse width of 60 ns, a common value

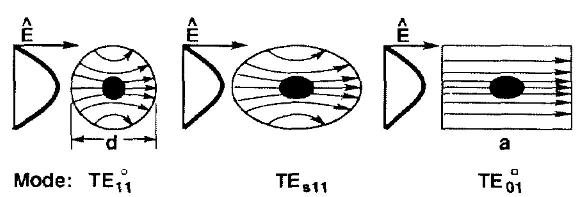

Figure 1. Commonly-used IW cross sections, modes, and optical E-field intensity.

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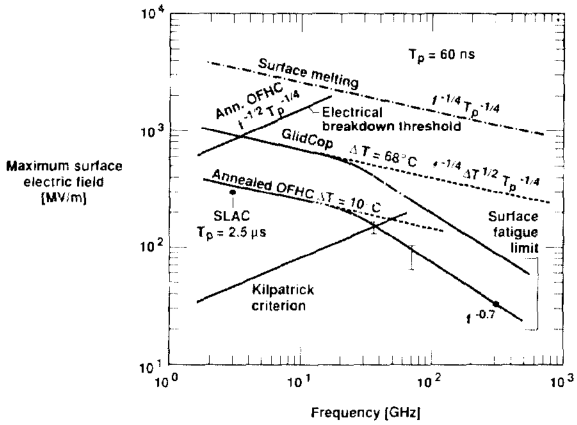

Figure 2. Electrical breakdown and metal fatigue limits on surface electric field for copper.

in induction accelerator designs. Starting with the SLAC electrical breakdown data point of ~312 MV/m at 2.856 GHz and an rf pulse width of $T_p = 2.5$ μs,[7] the limit line for annealed oxygen-free high-conductivity (OFHC) copper has been scaled[8] $f^{1/2}\ T_p^{-1/4}$. As can be seen, the peak E-field values calculated in the previous paragraph fall well below the electrical breakdown limit. The more stringent limit lines shown on the figure, however, are governed by surface metal fatigue, which we now address.

During each pulse of any rf structure designed to operate at a high repetition rate, such as an FEL, the surface temperature is briefly increased over the average bulk temperature by an amount, ΔT, dependent on the operating mode, the material electrical and thermal properties, the dimensions of the structure, the peak pulsed power level, the pulse width, and any active cooling that is effective during the pulse. This last factor is negligible in the short-pulsed devices under consideration. Because of thermal expansion, this temperature change puts metal surfaces under significant compressive stress. This situation is analyzed in detail elsewhere.[9] The stress and temperature change are related as

$$|\sigma| = \frac{E\alpha_{ex}\Delta T}{1-\upsilon} \quad ,$$

where α is the stress, E is Young's modulus, α_{ex} is the coefficient of thermal expansion, ΔT is the surface temperature rise, and υ is Poisson's ratio. A common engineering convention is to design for $\alpha \leq \alpha_{pr}$, where $\alpha_{pr} \simeq 80\%$ of the yield stress. Copper is the best commonly available metal for these applications because of its superior electrical and thermal conductivity. A value of $\alpha_{pr} = 40\ N/mm^2$ (= 5.8×10^3psi) may be taken for annealed OFHC copper. With $E = 17 \times 10^6$ psi, $\alpha_{ex} = 17 \times 10^{-6}/°C$, and $\nu = 0.3$, the corresponding maximum allowable temperature change produced by skin effect and beam interception heating is ΔT = 14°C.

Modern metal-fatigue theory states that when the yield stress is not exceeded, there is only elastic strain (i.e., no plastic strain) and therefore the cyclic life is essentially infinite.[10] Whereas this may be true regarding overall sample failure, no data known to us offers assurance that surface damage such as micro-cracking has not occurred. Such cracks with depths on the order of a skin depth (typically <1.0 μm) would noticeably increase the surface resistance and pulsed ΔT, leading to runaway failure. A reasonable definition of surface lifetime would therefore be the number of cycles to the onset of micro-cracking. To our knowledge, no relationship has been established between this newly-defined lifetime and sample-rupture lifetime shown in fatigue-test summaries.

Figure 3 shows sample-rupture lifetime curves for various types of copper.[11] Typically, the sample stress is cyclically alternated between compression and tension. Since such a test is much more severe than a cyclic compression-only test, the allowable stress is likely to be higher than the results of a compression-tension test would show, perhaps by 20-50%. However, high average power devices will probably operate with a mean bulk temperature in the 100-150°C range, where the yield stress is 15-20% lower than at room temperature. Higher yield-strength copper (e.g., electrolytic tough pitch, or cold worked) can permit higher stresses and ΔT values. However, any annealing step during fabrication will, of course, lower these values. Also, stress softening of such "hard" copper is known to occur and must be examined.

For some FELs, e.g., IMP, a 10^8 cycle lifetime for the IW may be acceptable. For others, a lifetime exceeding 10^{11} or more may be required. Figure 3 indicates the large uncertainty in lifetime beyond ~10^7 cycles. One is therefore faced with the necessity of choosing a stress safety factor with no hard data upon which to base the choice. Obviously, it would be very desirable to have new stress-cycle lifetime data based on, say, a 10% increase in surface resistance, or microwave attenuation.

We are investigating the possibility of correlating data from studies of laser damage to metal mirrors with our present requirements. For example, the peak energy density/pulse in the IMP IW is 0.07 J/cm^2/pulse. This is below the measured threshold for damage to an uncoated copper mirror (~0.5 J/cm^2/pulse) at the 10.6-μm wavelength of a CO_2 laser.

Information pertaining to a promising, relatively new material is included in Figs. 2 and 3. This is type C15715[12] dispersion-strengthened copper, called "GlidCop" by the manufacturer. It permits an operating stress and ΔT several times OFHC values, has a resistivity only ~9% higher than that of OFHC, and has a cost ~3 times that of OFHC. Made with 50-60 μm particles of Al_2O_3 dispersed throughout the copper, it is not likely to have an electrical breakdown threshold as high as that of OFHC. As indicated by Fig. 2, however, the surface fatigue limit rather

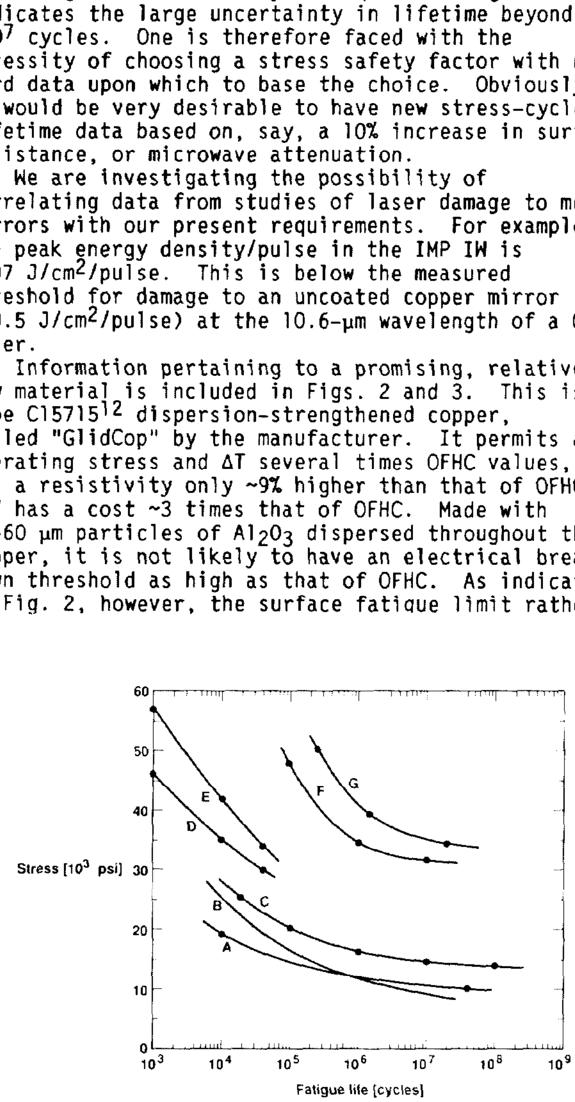

Figure 3. Rupture stress vs cycles to failure.
A,B Annealed OFHC copper
C Annealed electrolytic tough pitch copper
D Annealed copper
E Drawn copper
F C15715 dispersion-strengthened copper (GlidCop)
G C17510 $Cu_{0.4}BeNi$

than the breakdown limit will be dominant for many applications. The C17510 alloy shown in Fig. 3, incidentally, has a resistivity ~39% higher than that of copper and so is not as interesting as GlidCop.

Completing the explanation of Fig. 2, two reference fatigue limit lines are included for room-temperature OFHC and GlidCop with ΔT values of 10°C and 68°C, respectively. At frequencies above ~25 GHz, experimental data indicates that surface resistance values (and therefore ΔT values) are higher than theoretical predictions. Empirically, in this frequency range, the fatigue-limited maximum surface electric field is seen to scale as $\sim f^{-0.7}$ for this constant pulse-width case. These limit lines may be considered infinite lifetime limits if one is somewhat optimistic. In that case, if a lifetime of only 10^8 cycles is satisfactory, the lines may be located higher on the figure. Apparently, no relevant experimental data exists to provide guidance for doing so. However, some guidance is provided by pressure vessel codes which indicate that the stress need only be scaled as the square root of the safety factor chosen for cycle lifetime.

Fortunately, for the highest-power FELs where the uncertainties just discussed are intolerable, operation with a certain less common but desirable mode results in a large margin of safety.[6] This is the hybrid HE_{11} mode.[13] In a circular waveguide it is similar to the TE^{0}_{1} mode except that it has a Gaussian-like distribution of field intensity over the cross section. In the 140-250-GHz range in a 3.25-cm-diam waveguide, the wall-heating power density for the hybrid HE_{11} mode is nearly three orders of magnitude lower than for the TE^{0}_{1} mode. This makes possible the CIT and ITER FELs mentioned earlier in the paper. An additional bonus occurs because the beam wiggle motion couples more strongly to this mode than to the TE^{0}_{1} mode, resulting in higher FEL gain/unit length. The penalty to be paid for this performance is a more complex and expensive waveguide. An inner corrugated wall is required with circumferential grooves on the order of $\lambda/4$ deep with a $\lambda/4$ axial spacing. Such a penalty is not prohibitive, however. Lengthy corrugated waveguides operating at 300 GHz have been demonstrated.

The limited space available here prohibits discussing a number of additional interesting topics such as multipactor, surface preparation, oxidation, and mechanical specifications. These have been examined in depth with regard to the IMP/MTX IW requirements and will, perhaps, be the subject of a future paper.

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