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W-BAND FREE ELECTRON LASERS FOR HIGH GRADIENT STRUCTURE RESEARCH

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Abstract

We analyze two designs for W-Band free electron lasers for application as laboratory instruments in the study of millimeter wave accelerators at high gradient. The first design is based on the linear induction accelerator LELIA (CEA/CESTA, France), employs a 1-kA, 80-ns electron pulse, and corresponds to a helical TE_{11} 200MW W-Band amplifier design. We analyze also a W-Band planar ubitron design making use of a SLAC-modulator, operating with a 480 kV, 300 A, sheet beam gun and producing a 5 MW, 1μs pulse.

1 INTRODUCTION

To reach high gradients in conducting structures a short rf wavelength is required, due to the constraints of *trapping*, *breakdown*, and *pulsed heating* [1]. For copper accelerators, optimized for *[R/Q]*, the scaling for wall quality factor, $Q = 2.7\times10^4 f(\mathrm{GHz})^{-1/2}$, implies a field decrement time, $T \approx 8.6\mu s\, f(\mathrm{GHz})^{-3/2}$, and a natural fill time in the range of 10ns at W-Band (75-110 GHz). Extrapolation of breakdown scalings at S and X Band indicate that this time-scale is sufficiently short that breakdown may well be inhibited up to gradients beyond 1 GeV/m. Trapping of an initially stationary population of field-emitted electrons is diminished at mm-wavelengths, where even at 1 GeV/m, the gradient wavelength product can be held to values routinely employed on certain high-gradient sections at the SLC [2]. The most critical concern at high-gradient is heating due to Ohmic loss in a *single pulse*, for it is conventional wisdom that the pulsed temperature rise ΔT, should be held to 40° K or lower, due to the cyclic stress limit for copper. To appreciate the significance of this constraint, we note the relation between gradient and pulsed temperature rise for a conventional travelling wave structure with attenuation parameter τ ˜1, and optimized shunt impedance,

$$G\left(\frac{\mathrm{GeV}}{\mathrm{m}}\right) = 0.25\left(\frac{\Delta T}{40°\mathrm{K}}\right)^{1/2}\left(\frac{f}{91.4\mathrm{GHz}}\right)^{1/4}.$$

This constraint is, for some ΔT, unassailable, and motivates the design of structures, and powering schemes that escape the bandwidth constraint for conventionally powered, passive structures [1]. Detailed experimental studies are in progress at SLAC to assess in practice the limit on ΔT [3]. Other concerns have been raised, over the years, concerning the use of short-wavelength structures, particularly: fabrication, and wakefields. Fabrication of such structures is now an accomplished fact [4]. Wakefields, it has been demonstrated [5] can be dealt with in a constructive fashion, making use of the structure itself as a beam-position monitor, and permitting, in principle, precision structure alignment.

The immediate implication of this line of research is however, that one needs a W-Band high-power amplifier, as a laboratory instrument at first, and eventually as an accelerator power source. Commercial amplifiers at W-Band provide at most 3-5 kW [6]. Gyroklystron tube research has resulted in 55 kW power levels [7]. A planar ubitron has been operated at 250 kW [8]. Induction linac driven FELs have output 100 MW at 35 GHz[9], and 2 GW at 140 GHz [11]. To produce a 1 GeV/m gradient in a W-Band structure, and regardless of whether it is an active or passive structure, one needs power levels in the range of 200 MW, for pulse lengths of order 10 ns. There are two conceivable ways to accomplish this with externally generated RF. The first is to generate a low power level, in the range of 5 MW, over a longer, 1 μsec pulse, and perform active pulse compression. The second is to generate the 200 MW directly, in a short pulse. We consider each of these in turn. We will analyze two examples, set down the design parameters required, and confirm them with the help of 1D and 3D simulations. We will consider an rf frequency of 91.39 GHz, the 32nd harmonic of SLAC S-Band, 2.856 GHz.

2 PLANAR UBITRON

The mm-wave planar ubitron would be powered by a SLAC modulator, with space-requirements typical of a klystron test-stand in the SLAC Klystron Test Lab. The wiggler parameters we have in mind are close to those of the sheet beam free-electron laser operated at 250 kW, at the University of Maryland [8]. The focusing scheme is different in that a quadrupole will be considered to provide focusing in the horizontal, at the expense of vertical focusing provided by the wiggler. The geometry is similar to that employed for the 30 MW X-Band FEL at KEK [10].

With beam voltage set at 480 kV, consistent with the available modulator, and beam current set at 300 A consistent with the 5 MW requirement (absent tapering), the wiggler wavelength should be in the range of 1.16 cm for optimal gain at 91.39 GHz. With these parameters, the peak wiggler field on-axis, at optimal gain is 5.1 kG, well within the Halbach limit for NdFeB with Vanadium Permendur, provided the pole gap is held to 4 mm (7 kG). Focusing in the vertical is provided by the wiggler itself. One long quadrupole can be employed to focus in the horizontal, at the expense of vertical focusing.

Table 1 Parameters for the planar ubitron.

Wiggler Parameters	
wiggler period λ_w	1.16cm
peak wiggler field B_w	5.5kG
# of wiggler periods N_w	60
desirable tuning range	3kG-7kG
Beam Parameters	
voltage V_b	480kV
current I_b	300A
beam full width $2X$, $2Y$	2cm, 0.2cm
Waveguide & RF	
inner dimension height, width	0.4cm, 4cm
input power, P_{in}	1kW
gain	37dB
required match to output	VSWR<1.002

Parameters are indicated in Table 1, arrived at taking into account the envelope equation, and, for gain calculation, solution of an analytic dispersion relation that incorporates space-charge, emittance, energy-spread, low energy corrections to the relativistic approximation, and waveguide corrections.

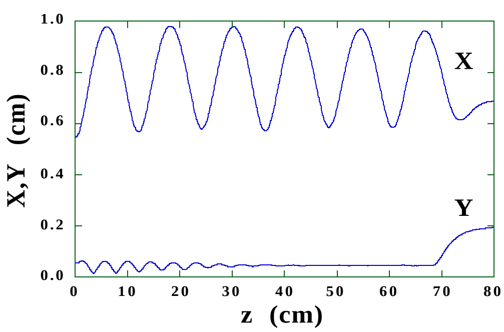

Figure 1 Envelope evolution in the Planar Ubitron.

The 1D scalings provide a gain curve to guide the design. These scalings are being studied numerically with a non-wiggler averaged, particle-in-cell code, incorporating the physical optics as modified by the beam, space-charge, and a realistic wiggler model computed as a sum over coils. This code also provides a feature for tuning of the quad field to maximize transmission, and adjusting of the first two half-period coil currents to minimize betatron launch down the wiggler. Illustrative results for beam transport are indicated in Figure 1.

Beam collection in the first implementation of this design would simply amount to dispersal on the vertical walls of the guide, as the beam exits the wiggler, as seen in Figure 1. Due to the wide sheet character of the beam, and the 5 cm beam spreading length, the heat load is below 50 W/cm^2 at a pulse repetition frequency under 5 Hz.

The gun design for this tube is the most challenging technology feature of the device. The required current density at the entrance plane is 750 A/cm^2. If we ask for a very ambitious cathode loading of 100 A/cm^2, the required convergence is x 7.5 for waist formation near the anode. Taking, as an example, a gun consisting of a section of a cylindrical diode, we find that the unique solution for convergence of 8.1 into a full height of 2 mm corresponds to a cathode radius of 1.247 cm, an anode radius of 0.154 cm, and a half-angle of 40.5°. This solution however corresponds to a field in the gun in excess of 250 kV/cm, too high to be held for 1 µs without arcing. This suggests, at the least, that a simple 2D gun is not likely to be adequate, and opens the problem up to that of 3D gun design, with convergence in both planes, a challenging problem.

3 LIA FEL

Linear induction accelerators have been used successfully in the past to drive free electron lasers operating in the W-band frequency range [9, 10, 11]. Electron beams produced with these accelerators typically have energies ranging from several MeV to tens of MeV, and pulse lengths from tens of nanoseconds to several microseconds. The LELIA accelerator, operated at the Centre d'Etudes Scientifiques et Techniques d'Aquitaine (CESTA) facility, generates a 1 kA, 2.2 MeV beam with an 80 nsec (FWHM) pulse length. Current FEL experiments operate in the amplifier mode, and have shown strong bunching and power production at 35 GHz [12]. This configuration is being studied as a possible bunching device for the drive beam in a two-beam accelerator. Involvement of both the CERN CLIC and the LLNL/LBNL RK-TBA groups is ongoing.

Table 2 Parameters for the LIA FEL

Wiggler Parameters	
wiggler period λ_w	5cm
peak wiggler field B_w	2.7kG
# of wiggler periods N_w	68
Beam Parameters	
voltage V_b	2.2MV
current I_b	900A
beam radius	0.4cm
Waveguide & RF	
inner radius	3.05cm
input power, P_{in}	0.5kW
gain	56dB

We have designed a new helical wiggler for use on the LELIA beamline to drive the FEL resonance at 91 GHz. The parameters are shown in Table 2.

The FEL interaction is simulated with the code WTDI [13]. This code tracks 3D particle motion, and the amplitude and phase of a single frequency vacuum waveguide mode. Space charge effects are included from an approximate analytic model. This allows us to use a relatively small number of particles (4096) in the simulation.

We have modelled the power and phase fluctuations induced by energy jitter in the drive beam. We assume a maximum fluctuation of ±0.1% of the beam energy over the entire pulse. This fluctuation is primarily due to nonlinearities in the pulse forming network that drives the induction cells, and results in variations of both the peak power and the phase of the output radiation from the FEL. The difference in phase development is shown in Figure 2.

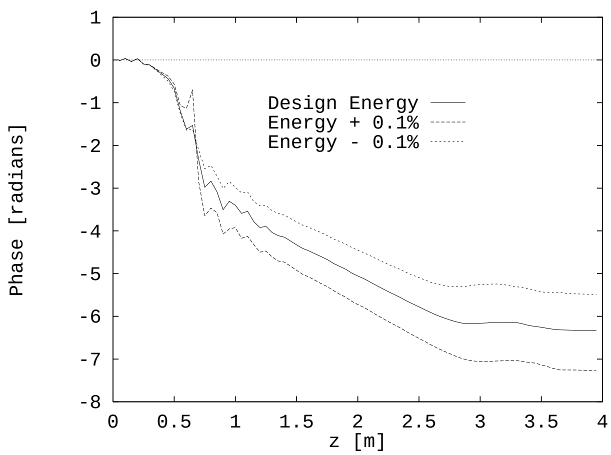

Figure 2 Phase development in the FEL

Clearly, this amount of phase difference over the full pulse length is unacceptable for most applications. Indeed, this has proven to be a fundamental limitation in using FEL's as drivers in two-beam accelerators. However, simple control and feedback systems have been proposed [14] that can reduce this level of jitter to ±0.5% or less, by employing an active compensation circuit to the drive PFN and the input RF signal. In this way, fluctuations in phase may be controlled to with ±2° over a bandwidth of several hundred MHz.

4 CONCLUSIONS

We have seen that, from the point of view of the FEL interaction, the power levels required for high-gradient studies of W-Band structure are achievable with existing facilities in at least two ways. For the Planar Ubitron, the challenge is the gun, and this is a considerable, but not insurmountable challenge. For the induction driven device, the required performance has already been achieved at the ELF facility some 10 years ago.

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