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**This paper was prepared for submittal to the
Thirteenth International Free-Electron Laser Conference
August 25-30, 1991, Santa Fe, New Mexico**

August 1991

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Predicted Performance of an Induction Linac Driven
FEL Amplifier Designed for Radar Applications at 94 GHz*

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ABSTRACT

The saturated performance of an Induction Linac Driven FEL operating at 94 GHz with peak microwave powers in excess of 2 GW is evaluated using a self-consistent 3D waveguide mode-particle interaction code. The code includes the effect of AC longitudinal space charge and DC transverse space charge with the resulting prediction that operation is not possible below 2.5 MeV with a 2 kA beam and 10 cm wiggler. A design based around a 4 MeV beam predicts peak power in excess of 2.4 GW over a 10% bandwidth with output phase varying linear with frequency.

1. Introduction

There is interest in developing a 94 GHz FEL amplifier as the microwave source for an imaging radar. The radar is required to operate at a power of 2 GW peak, 5 MW average with a bandwidth of at least 5%. The beam to power the FEL is provided by an induction linear accelerator operating in the range 2-5 MeV and 1-2 kA with 1 μ sec pulses. The requirement for high average power leads to the choice of a 10 cm period linear polarized wiggler with curved pole pieces for focusing and capable of generating up to 4 kilogauss transverse field. It is practical from the point of view of accelerator design to operate at lower voltages and higher currents consistent with high microwave conversion efficiency. In order to determine a reasonable operating voltage, it is important to include both AC and DC space charge effects in the FEL computer models since these effects can greatly degrade

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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performance at lower voltages. A 3D self-consistent microwave FEL code has been developed in order to design and predict the performance of an FEL satisfying the above radar requirements. In Sec. 2, a brief description of the computer model is given. Section 3. shows the effects of AC and DC space charge on determining the design. Finally, in Sec. 4. a 94 GHz FEL design is presented with predictions of power, mode purity and phase versus frequency.

2. Computer Model

A self-consistent 3D microwave FEL code has been developed with the following features:

- (i) Non-wiggle averaged exact 3D particle orbits.
- (ii) Initial particles set up to fill a 4 volume in phase space uniformly corresponding to a specified beam emittance. Realistic initial focusing and entrance conditions can be modelled. A spread in gamma due to space charge depression is included.
- (iii) Fields are expanded in a complete set of TE and TM modes in arbitrary waveguide geometry.
- (iv) AC space charge is included up to 5th harmonic in $[\omega t - kv_z]$. This is rigorously derived by summing up the E_z fields of all nonresonant TM modes.
- (v) DC space charge forces are included by solving for the DC radial electric field and potential in the center of mass frame using gauss's law.
- (vi) External 3D magnetic fields are those of a curved pole piece tapered wiggler or straight pole piece with quadrupole focusing.

The particle equations of motion for the transverse positions, momenta, phase $\psi = (\omega t - k_L z)$ and gamma (γ) as functions of z are given by:

$$\frac{dx_p}{dz} = \frac{U_x^p}{U_z^p}, \quad \frac{dy_p}{dz} = \frac{U_y^p}{U_z^p}, \quad \frac{d\psi_p}{dz} = \frac{\omega \gamma_p}{U_z^p c} - k_L$$

$$\frac{dU_x^p}{dz} = -\frac{eE_x}{mc^2} \frac{\gamma_p}{U_z^p} - \frac{U_y^p}{U_z^p} \frac{eB_z}{mc^2} + \frac{eB_y}{mc^2}$$

$$\frac{dU_y^p}{dz} = -\frac{eE_y}{mc^2} \frac{\gamma_p}{U_z^p} - \frac{eB_x}{mc^2} + \frac{U_x^p}{U_z^p} \frac{eB_z}{mc^2}$$

$$\frac{d\gamma_p}{dz} = -\frac{e}{mc^2} \frac{\vec{U}^p \cdot \vec{E} \text{ (microwave)}}{U_z^p}$$

$$\gamma_p = \gamma_p^* - \frac{e\Phi_p}{mc^2} \quad \text{where: } \psi_p \text{ is particle phase} = (\omega t - k_z z)$$

Φ_p is DC space charge potential

$$U_z^p = \sqrt{\gamma_p^2 - 1 - (U_x^p)^2 - (U_y^p)^2}$$

The generalized field equations for arbitrary waveguide geometry are given in terms of the complex wave amplitude $V(z)$ by:

$$\vec{E} = \sum_i R_e \left\{ V_i(z) e^{j\omega t - jk_z^i z} \right\} \sqrt{Z_i} \vec{e}_i(x, y)$$

$$+ \hat{z} \sum_i \underbrace{I_m \left\{ V_i(z) e^{j\omega t - jk_z^i z} \right\} k_c^i / (k_0 \sqrt{Z_i})}_{\text{TM modes}} \cdot \vec{e}_z(x, y) + \vec{E} \text{ (space charge)}$$

$$\vec{B} = \sum_i R_e \left\{ V_i(z) e^{j\omega t - jk_z^i z} \right\} \frac{1}{\sqrt{Z_i}} \cdot (\hat{z} \times \vec{e}_i(x, y))$$

$$+ \hat{z} \sum_i \underbrace{I_m \left\{ V_i(z) e^{j\omega t - jk_z^i z} \right\} k_c^i (\sqrt{Z_i} / k_0)}_{\text{TE modes}} \cdot b_z^i(x, y)$$

$$\frac{dV_i(z)}{dz} = \frac{2}{N_p} \exp(-j\Delta k_i z) \cdot \frac{2\pi I_0 \sqrt{Z_i}}{c} \sum_p e^{-j\psi_p} \frac{\vec{U}_\perp^p}{U_z^p} \cdot \vec{e}_i(x_p, y_p)$$

$$+ \frac{2}{N_p} \exp(-j\Delta k_i z) \cdot \frac{2\pi I_0 k_c^i}{k_0 \sqrt{Z_i}} \sum_p e^{-j\psi_p} e_z^i(x_p, y_p) \left\} \quad \text{TM modes only}$$

$$\text{Power} = \frac{c}{4\pi} \frac{|V_i|^2}{2} \quad \epsilon(xy) = \text{normalized waveguide transverse functions}$$

The evaluation of the AC space charge field is obtained by analytically summing the axial components of the TM modes and gives the same expression as that used in the "FRED" code.[1] The DC space charge fields are obtained from gauss's law. These fields are given explicitly as:

AC Axial E field

$$E_z = \sum_m \frac{4\pi j \rho_m}{m(k + k_w)} e^{jm[\omega t - (k + k_w)z]} \cdot \left[1 - \frac{4}{(mgr_b)} - \left(\frac{r}{r_b}\right)^2 - f_m I_0(mgr) \right]$$

$$f_m = -2[I_0(mga) K_2(mgr_o) - K_0(mga) I_2(mgr_b)]$$

$$g = \frac{(k + k_w)a}{\gamma}$$

a = guide radius

r_b = beam radius

$$\rho_m = -\frac{4I_0}{\pi r_{fc}^2 N_p} \sum_p e^{-jm\psi_p} = \text{mth harmonic of charge density}$$

DC space charge potential

$$\frac{e\Phi}{mc^2} = -\frac{2eI_0}{mc^3} \ln\left(\frac{a}{r_b}\right) - \frac{2eI_0}{mc^3} \int_r^{r_b} \frac{N(r')}{N_{Tr'}} dr'$$

3. Effect of AC and DC Space Charge on FEL Design

It is desirable for practical reasons to lower the accelerator voltage while still maintaining efficiency and frequency. The physics of FEL interaction indicated that the "bucket height" decreases with decreasing voltage and increasing AC space charge assuming fixed frequency.[2] If the spread in γ due to DC space charge depression is much greater than the bucket height, FEL performance is severely reduced. This is expressed mathematically by:

$$(\Delta\gamma)_{\text{Bucket}} = \left\{ \left(\frac{4e\gamma}{mc^2k_W} \right) \left[E_{\text{RF}} \sqrt{\frac{ck_W}{\omega} - \frac{1}{2\gamma^2}} - E_{\text{sp}} \right] \right\}^{1/2} > .088 I_0 (\text{kiloamps})$$

spread due to DC
space charge

where $E_{\text{sp}} = \text{AC space charge field} = 4\mu c\rho_m/\omega$

$E_{\text{RF}} = \text{RF electric field}$

$I_0 = \text{Beam current}$

Computer simulations were performed at various voltages and the power optimized as illustrated in Fig. 1. FEL performance is severely degraded at 2 kA as one lowers the voltage to 2.5 MeV. Figure 2 shows that this is due to the combined effects of both AC and DC space charge fields. The AC space charge fields reduce the bucket height decreasing gain and bunching. The effect of DC space charge at 2 kA results in sufficient spread in γ so that the reduced bucket no longer can contain the electrons. In order to develop a conservative robust design where space charge effects do not present problems, the voltage was chosen to be 4 MeV. Table I gives the basic design parameters for the proposed 94 GHz FEL.

4. Performance Predictions for FEL Design

Simulations were done using the parameters of Table I to evaluate the amplifier characteristics at saturation at 1000 watts drive. Typical simulation results are shown Fig. 3. The first 1.9 meters is a linear gain region with the eigenmode made up of 80% TE_{01} mode and 20% in TE_{21} , TE_{41} , and TM_{21} . The remaining 2.1 meters consists of a linear taper of 3% decrease per wiggler period. The final output power is almost entirely in the TE_{01} mode. Figure 4 shows that the effect of the DC space charge is to cause the beam to expand 40% more in the tapered region than it would otherwise. This puts extra restriction on how much tapering can be done before the beam gets near the waveguide wall and thus restricts the maximum achievable efficiency. FEL performance is summarized in Fig. 5 which shows power, phase and mode purity as a function of frequency. One observes that there is a frequency range

of almost 10 GHz where the phase varies linear with frequency and the power is within 1 dB of maximum with mode purity greater than 96%.

5. Conclusions

A conservative design has been developed for a 94 GHz FEL amplifier for radar applications demanding high average power. The basic performance characteristics are:

peak power	≥ 2.4 GW
average power	5 MW
1 dB bandwidth	10%
phase linearity bandwidth	10%
mode purity over bandwidth	$\geq 96\%$

References

- [1] E.T. Scharlemann, W.M. Fawley, B. Anderson, and T.J. Orzechowski, "Comparison of the Livermore Microwave FEL Results at ELF with 2D Numerical Simulation," Nuclear Instruments and Methods in Physics, Research A250 (1986) 150-158.
- [2] V.K. Neil, "Effects of Longitudinal Electric Self-Field on Acceptable Energy Spread in a Free Electron Laser," UCID-179851, LLNL, November 27, 1978.

- Figure 1 Maximum power out versus beam voltage. Current fixed at 2 kA. Frequency fixed at 94 GHz. Linear field tapered down to 20% of maximum wiggler field.
- Figure 2a Bunch parameter $\langle e^{i\psi} \rangle$ versus distance with and without AC and DC space charge. Voltage = 2.5 MeV Current = 2 kA
- Figure 2b Gain versus distance with and without AC and DC space charge. Voltage = 2.5 MeV Current = 2 kA
- Figure 3 Power and mode purity (% TE₀₁) vs distance with magnetic taper. Voltage = 4 MeV Current = 2 kA
- Figure 4 Effect of DC space charge on beam expansion in linear taper region. Voltage = 4 MeV Current = 2 kA
- Figure 5 Power, phase and mode purity vs frequency at saturation. Drive power = 1000 watts.

Figure 1

Figure 2a,b

Figure 3

Figure 4

Figure 5

Table 1 FEL design parameters

Voltage	4 MeV
Current	2kA
Beam brightness	3×10^8 amps/(m-rad) ²
Wiggler period	10 cm
Wiggler field	2.69 kilogauss
Waveguide width	3.5 cm
Waveguide height	4.0 cm
Total Wiggler length	4 meters
Center frequency	94 GHz
Taper length	2.1 meters
Taper strength	3%/wiggler period
Drive power	1000 watts

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