Experimental Results on a Gas-Loaded Free-Electron Laser

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Wavelength tuning of 0.4 μm has been obtained by the addition of 100 Torr of H_2 gas to a vacuum free-electron laser operating in the near infrared. This experiment demonstrates that a relativistic electron beam from an rf linac can propagate in a partially ionized gas with sufficient quality to achieve free-electron laser action. The picosecond pulse structure of the beam is believed responsible for the avoidance of plasma instabilities. Gain and wavelength measurements are consistent with theoretical expectations.

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The concept of the addition of a gas dielectric to a free-electron laser (FEL) arose from research on stimulated Cherenkov radiation.[1] Slowing down of an electromagnetic wave by the refractive index of the medium allows synchronous interaction with a relativistic electron beam without the need for any structure such as a wiggler. However, there must be a finite Cherenkov angle θ_C between the beam and wave propagation vectors to provide a cumulative energy interaction. This angle gives rise to a walkoff of the electron beam and to a first-order emittance term, $\theta_C\epsilon$, in the random phase spread, where ϵ is the angular divergence of the electron beam. By periodically reversing the transverse component of electron velocity, a wiggler offers two advantages over the simple Cherenkov interaction: Walkoff is eliminated and the effect of divergence is reduced to second order in ϵ. It was also recognized that small concentrations of gas added to a vacuum FEL should give continuous tuning toward shorter wavelengths without changing γ, the beam energy, in contrast to the relatively high pressures required for the Cherenkov effect.[1]

The synchronism condition for an FEL, when filled with a gas of refractive index n, is given by[2]

$$n-1+\lambda/\lambda_w=(1+a_w^2)/2\gamma^2, \qquad (1)$$

where λ_w is the wiggler period and a_w is the dimensionless wiggler parameter.[3] From Eq. (1) it is seen that the gas makes it possible to tune the wavelength simply by a change in the gas pressure. In addition, a lower beam energy is required to produce a given wavelength so that a smaller and less costly accelerator suffices.

For hydrogen, which provides the highest value for n for a given amount of scattering,[4]

$$n-1=10^{-6}P_{\text{atm}}\frac{273\text{ K}}{T_{\text{K}}}\left[21.1+\frac{12.7\times10^3}{111-\lambda_{\mu\text{m}}^{-2}}\right], \qquad (2)$$

where P_{atm} is pressure in atmospheres, T_{K} is temperature, and $\lambda_{\mu\text{m}}$ is operating wavelength in microns. This equation combines the dielectric effects of the vibrational bands associated with the electronic transition in H_2 at 1216 Å into a single resonance and, therefore, cannot be used too close to this wavelength.

A gas may have detrimental effects on electron-beam propagation, caused by interactions with the plasma produced from collisional ionization of the gas.[5] However, previous observations of plasma instabilities[6] were with beam-pulse durations longer than a nanosecond and kiloampere currents, whereas the beam in this experiment, produced by an rf linac, is only tens of amperes and of picosecond duration, a time that is too short for the growth of these instabilities. This conclusion was tested in an experiment[7] in which the beam was transmitted through 1 m of hydrogen at pressures from 1 to 950 Torr. The beam was fully transmitted at all pressures, with no deviation in position and no reverse current flow. Multiple, small-angle scatterings cause the beam emittance to increase with distance in accordance with the Highland formula.[2] For a 40-MeV beam traversing 1 m of hydrogen at 150 Torr, there is an rms divergence of 1 mrad. This effect on beam size and phase deviation is incorporated in the gain calculations.

In the gas-loaded FEL experiment shown in Fig. 1 an existing, vacuum FEL,[8] with the parameters listed in Table I, was modified to allow the addition of gas. The beam enters the laser through a 1.3-μm-thick, 7-mm-

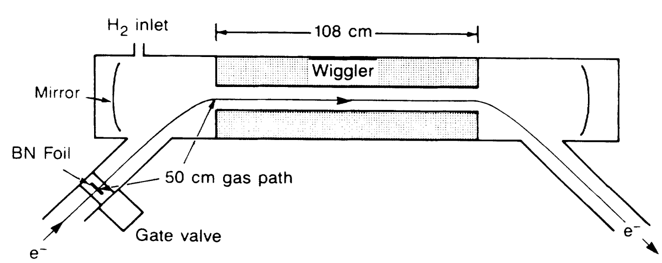

FIG. 1. Experimental arrangement to allow the addition of gas to the FEL. The BN foil is 1.3 μm thick and is placed 50 cm in front of the wiggler to avoid interference with the optical mode.

TABLE I. FEL operating parameters used in the gas-loaded FEL experiment.

Wiggler length	108 cm
Wiggler period, λ_w	2.3 cm
Optical wavelength (in vacuum), λ_0	4.15 μm
Wiggler parameter, a_w	0.94
Electron energy	36.5 MeV
Normalized beam emittance	7π mm·mrad
Peak current	10–40 A
Micropulse duration	0.5–2 ps
Micropulse repetition period	350 ps
Macropulse duration	2–4 μs
Macropulse repetition rate	15 Hz

diam, boron nitride foil, which separates the hydrogen-filled region of the wiggler from the vacuum of the accelerator. To avoid interception of the optical wave by the foil, the latter is placed 50 cm upstream from the front end of the wiggler. The foil's surface is coated with a 50-Å layer of titanium to prevent charge buildup, and the foil is mounted on a gave valve to permit introduction of the foil and gas without opening of the system once the vacuum FEL is adjusted to oscillation. With the addition of a small amount of gas ($\simeq 1$ Torr), beam refocusing is required to compensate for the effect of space-charge neutralization, but only slight additional focusing is needed as the pressure is increased to 100 Torr. Cavity mirror repositioning is necessary to maintain a constant optical path length as the refractive index increases so that the returning wave overlaps subsequent electron bunches.

Net gain was measured from the rise time of the optical output in the small-signal regime. Saturation could not be reached at higher pressures, where the gain is lower, because of a change in beam energy over the macropulse, which limited the usable portion of the macropulse. Since cavity loss, including output coupling, was 4.9% in all cases, this has been added to the measured gain values to obtain the electronic gain, the quantity plotted in Fig. 2. The theoretical curve, which has been normalized to gain without gas but with the foil, takes account of the effects of the emittance increase from scattering in the foil and gas.[9] The two points shown at zero pressure were measured at the beginning and near the end of the run, after a brief accelerator shutdown and restart, and are indicative of the degree of reproducibility of the data.

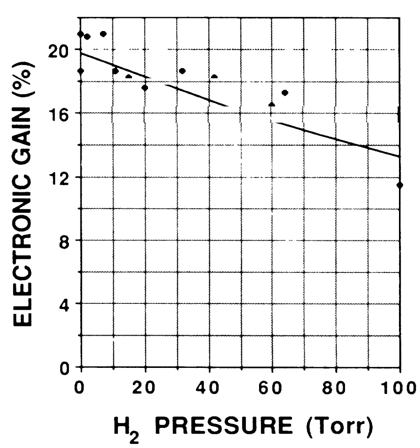

FIG. 2. Comparison of measured and calculated gain for the gas-loaded FEL. Operating parameters are $\gamma = 72$, $a_w^2 = 0.9$, $\lambda_w = 2.3$ cm. Solid curve, calculated gain, which has been normalized to the value without gas but with the foil in place.

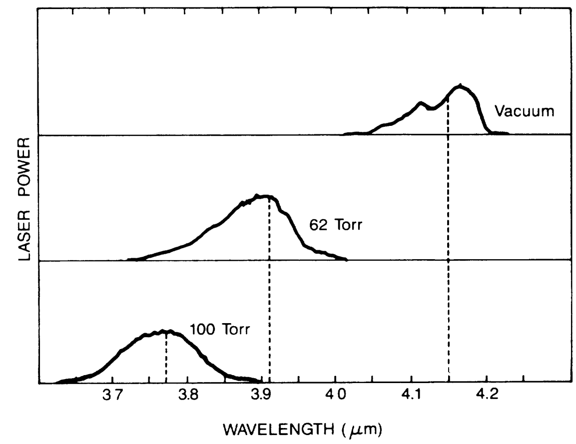

FIG. 3. Optical power spectra measured at H_2 fill pressures of 0, 62, and 100 Torr. Dotted lines, wavelengths calculated from Eqs. (1) and (2). The power scales at different pressures are not normalized with respect to each other. In vacuum there are two peaks in the spectrum resulting from a change in beam energy during the macropulse. With gas the gain is lower, so that there is insufficient time for power buildup at a second frequency. The spectra in gas are somewhat broader than in vacuum. This is a consequence of not reaching saturation, resulting in a bandwidth that is intermediate between spontaneous emission and laser action.

Figure 3 gives the spectra of the optical output for three values of pressure, and shows that the wavelength shift due to the gas is in good agreement with Eqs. (1) and (2). The wavelength shift can be expressed as

$$\Delta\lambda = -\lambda_w (n-1), \tag{3}$$

and for $\lambda_w = 2.3$ cm, $\Delta\lambda = -0.4$ μm at a pressure of 100 Torr of hydrogen. Since $\Delta\lambda$ is independent of the wavelength λ_0 of the FEL in vacuum, except for the dispersion in refractive index, a shorter λ_0 gives a larger fractional shift for the same pressure.

Further work will be directed towards our achieving a broader tuning range by increasing the gas concentration, as shown in Fig. 4. The synchronism condition for the phase-slip mode is given by Eq. (1), while the phase-advance mode results from our slowing down the wave sufficiently to have the electrons gain one optical

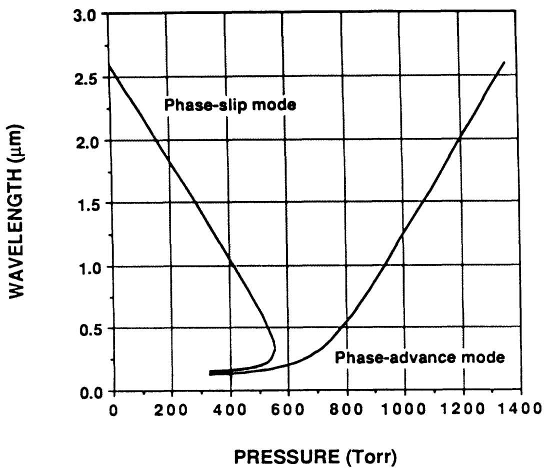

FIG. 4. Wavelength as a function of H_2 gas pressure calculated for fixed FEL parameters: $\gamma = 85$, $a_w^2 = 0.63$, $\lambda_w = 2.3$ cm. These curves are obtained from a simultaneous solution of the synchronism condition with the refractive-index dispersion for hydrogen.

cycle per wiggler period, and corresponds to the subtraction, rather than the addition of λ/λ_w in Eq. (1) to $n-1$. This mode would not normally be used since it requires higher gas pressure; however, for a planar wiggler the conventional phase-excursion correction to the gain $(J_0 - J_1)^2$ is replaced by $(J_0 + J_1)^2$ for this mode.[10] Since the argument of Bessel functions $J_{0,1}$ increases with λ_w/λ, there is a strong numerical advantage to replacement of the phase-slip with the phase-advance mode at short wavelengths where the pressure difference between the two modes becomes small. The curves in Fig. 4 are obtained from a simultaneous solution of the synchronism condition with the refractive-index dispersion for hydrogen. With use of H_2, the shortest attainable wavelength is ≈ 1300 Å, and with He the wavelength could be as short as ≈ 600 Å.[11] The possibility of changes in refractive index occurring during a macropulse as a result of heating of the gas at higher pressures has been examined.[10] This leads to a limitation on macropulse length to of order 100 μs, since the time for transfer of vibration and rotation to translational energy in H_2 is a few milliseconds.[12] High average power can be obtained by increased repetition rate provided the time between macropulses is longer than the thermal equilibrium time with the walls of the FEL chamber. Peak power breakdown and Brillouin scattering have been considered[2] and been found not to be significant for the picosecond micropulses of 10-MW saturation power typical of linac FEL operation.

At higher pressures it proves advantageous to redesign the mirrors to reduce the Rayleigh length and place the optical spot minimum at the entrance to the wiggler. (For the FEL parameters listed in Table I, it is desirable to change the optical cavity for pressures greater than 300 Torr.) The optical beam spread and the curvature of the wave fronts then provide a better match to the increase in electron-beam radius and to its angular divergence, both of which result from multiple scattering by the gas. Calculations[9] made for such a configuration and with the phase-advance mode lead to a gain of 20% down to $\lambda = 0.3$ μm. If it proves possible to eliminate the 50-cm gas column between foil and wiggler shown in Fig. 1, for example, by the placement of the foil at the wiggler entrance, then a gain increase by nearly an order of magnitude is predicted.

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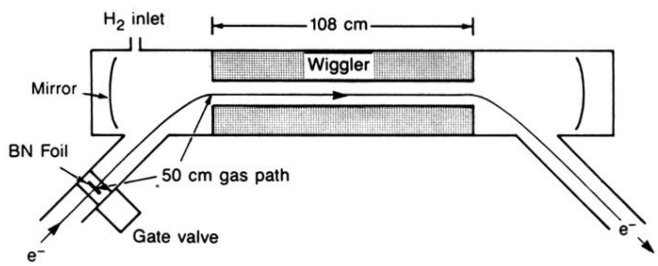

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