relative energy measurements, independent of precise knowledge of the pion mass.

We are grateful for help by the Nevis synchrocyclotron staff members throughout this experiment, and by Dr. M. Holland, Dr. S. Cheng, and Dr. D. Stromswald in beam construction at the initial stage of the experiment. This research was supported in part by the National Science Foundation and the U. S. Department of Energy.

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Proposed Free-Electron Laser Stimulated by Traveling Microwave Radiation

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(Received 15 November 1978)

A free-electron laser excited by traveling microwave radiation is suggested and discussed. Some desirable features of the microwave free-electron laser are given.

Recently, the first operation of a free-electron laser was reported by Deacon *et al.*,[1] soon after the stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field had been successfully observed by Elisa *et al.*[2] The apparatus of this laser consists of a superconducting double helix to produce a transverse and circularly polarized periodic static magnetic field of 2.4 kG, a beam of 43-MeV electron bunches traveling along the axis of the helix to interact with the periodic magnetic field, and a pair of mirrors located at the ends of the interaction region to provide feedback. The stimulated emission of bremsstrahlung in a spatially periodic magnetic field, on the basis of which this magnetic free-electron laser was constructed and tested, was first analyzed by Madey[3] and Madey, Schwettman, and Fairbank.[4] However, some authors have subsequently shown,[5-8] and also it is now known,[9] that magnetic free-electron lasers are purely classical devices.

If the periodic static magnetic field in the apparatus is replaced by a traveling microwave as the source of excitation, the apparatus becomes a microwave free-electron laser. Since microwave radiation is coherent, when a bunch of electrons is backscattered (antiparallel scattered) by a microwave, the electrons will be stimulated to oscillate coherently and to emit coherent radiation in the direction of the electron beam with a shorter wavelength and a higher intensity than that of the microwave, depending on the electron velocity and the number of electrons in each bunch. The physical process of the interaction is basically a Compton type of scattering. The microwave free-electron laser has some desirable features which deserve to be considered and studied. For examples: (1) A large scattering cross section is available in the backscattering process. (2) The wavelength of the stimulated radiation can be easily varied by varying the wavelength of the microwaves without changing the velocity of the electron beam. Hence the microwave method will provide extra tuning convenience. (3) The wavelength and the wave shape in each period of a microwave can be maintained more uniformly than that of a periodic static magnetic field. As a result, a narrower linewidth and a better line shape of the stimulated radiation can be obtained with a microwave stimulus. (4) Since the polarization of the stimulated radiation is the same as that of the microwave used, stimulated radiation of a desired kind of polarization can be generated by using a microwave of the same kind of polarization. (5) Either antiparallel or parallel scattering can be performed with a traveling microwave, which is a directional quantity specified by its direction of propagation. As a classical device, the output (scattered) wavelength and power of a microwave free-electron laser should be dictated by classical electrodynamics.

The Compton type of scattering in classical electrodynamics has been discussed by Chan[10,11] and by Chan and Lee[12] for the scattering of a free electron by a coherent electromagnetic plane wave. When a beam of electrons of charge e, mass m, velocity $\vec{\beta}_0=\vec{v}_0/c$, and total energy $\mathcal{E}_0=\gamma_0 mc^2$ with $\gamma_0=(1-\vec{\beta}_0^{\,2})^{-1/2}$ is backscattered by a microwave beam of wavelength $\lambda_m=2\pi c/\omega_m$, direction of propagation $\vec{n}=-\vec{\beta}_0/\beta_0$, and electromagnetic field $\vec{E}$ and $\vec{B}=\vec{n}\times\vec{E}$, we have $\vec{\beta}_0\cdot\vec{E}=\vec{\beta}_0\cdot\vec{B}=\vec{\beta}_0\cdot\vec{A}=0$, where $\vec{A}$ is the vector potential. According to theory,[10] the wavelength of the scattered wave $\bar{\lambda}_s$ in a direction $\vec{n}_s$ making an angle θ with respect to the direction of $\vec{\beta}_0$ is given by

$$\bar{\lambda}_s(\theta)/\lambda_m=[(1-\beta_0\cos\theta)/(1-\beta_0)+\bar{D}\cos^2\tfrac{1}{2}\theta][(1+\beta_0)\gamma_0]^{-2}, \tag{1}$$

where $\cos\theta=(\vec{\beta}_0\cdot\vec{n}_s)/\beta_0=-\vec{n}\cdot\vec{n}_s$ and $\bar{D}=e^2\langle(\vec{A}-\vec{A}_0)^2\rangle/m^2c^4$. Note that Eq. (1) takes the form of Compton wavelength shift for $\beta_0=0$ and is reduced to a two-step Doppler effect $\bar{\lambda}_s(\theta)/\lambda_m=(1-\beta_0\cos\theta)/(1+\beta_0)$ for $\bar{D}=0$. In the case of a linearly polarized microwave with direction of polarization $\vec{m}$, $\vec{E}=\vec{m}E_0\times\cos(\omega_m\tau+\varphi)$, phase φ, and advanced time $\tau=t+z/c$ with $\vec{z}=c\vec{\beta}_0 t$, we have $\bar{D}=(e\lambda_m E_0/2\pi mc^2)^2$. When $\theta=0$,

$$\bar{\lambda}_s(\theta=0)/\lambda_m=(1+\bar{D})/[(1+\beta_0)\gamma_0]^2. \tag{2}$$

For a microwave of $\lambda_m=3.0$ cm and power density equal to 100 MW/cm^2, we have $E_0=1.94\times10^5$ V/cm and $\bar{D}=0.0329$. For an electron beam of total energy 43.5 MeV, we have $\gamma_0=85.15$, and $\beta_0=0.999\,931$. Consequently, $\bar{\lambda}_s=1.069$ μm.

Since the electrons are forced to oscillate coherently by the microwave, the power differential scattering cross section $d\sigma_P/d\Omega$ (called $d\sigma_I/d\Omega$ by some authors[13]) is given by[11]

$$\frac{d\sigma_P(\theta)}{d\Omega}=\frac{(Nr_0)^2(\lambda_m/\bar{\lambda}_s)^6}{(1+\beta_0)^6\gamma_0^{\,6}}\left[\frac{1-\beta_0\cos\theta}{1-\beta_0}+(\bar{D}-2)\cos^2\tfrac{1}{2}\theta\right]^2, \tag{3}$$

where N is the number of electrons in each bunch and $r_0=e^2/mc^2$, the classical electron radius. For $N\cong10^8$, $d\sigma_P(\theta=0)/d\Omega\cong1.49\times10^4$ cm^2. However, Eq. (3) is quite sensitive to $\lambda_m/\bar{\lambda}_s$, which is itself a function of θ. According to Eq. (1), $\bar{\lambda}_s(\theta=0.3°)=1.274$ μm, and hence $d\sigma_P(\theta=0.3°)/d\Omega\cong3.27\times10^3$ cm^2, which is about 22% of that at $\theta=0$. Therefore, most of the power radiated is confined within $\theta=\pm0.3°$.

The differential power radiated is given by $dP=\bar{S}(d\sigma_P/d\Omega)d\Omega$, where $\bar{S}=cE_0^{\,2}/4\pi=(\pi mc^2/r_0\lambda_m^{\,2})\bar{D}$, the magnitude of the Poynting vector or the power density. For $\theta=0$, we have

$$dP(\theta=0)=\frac{\pi N^2 r_0 mc^3}{\lambda_m^{\,2}}[(1+\beta_0)^6\gamma_0^{\,6}]\left[\frac{\bar{D}(1-\bar{D})^2}{(1+\bar{D})^6}\right]d\Omega. \tag{4}$$

Under the suggested experimental condition, $dP(\theta=0)=1.5\times10^{12}d\Omega$ (watt). It is interesting to note from Eq. (4) that $dP(\theta=0)\propto\gamma_0^{\,6}\propto\mathcal{E}_0^{\,6}$ and also $dP(\theta=0)\propto\bar{D}(1-\bar{D})^2/(1+\bar{D})^6$ with maximum value at $\bar{D}=0.131$. These two predicted features are indirectly supported by the experimental observations reported by Friedman and Herndon[14] with a spatially rippled magnetic field.

By means of a pair of plane mirrors at the ends of the interaction region, not only the stimulated radiation from each electron bunch can be stored in the cavity to provide a quasisteady flow of output radiation, but also the feedback process could reject most of the unwanted radiation which is emitted at $\theta>0$ and with longer wavelength than that at $\theta=0$. If the overall alignment of the apparatus can be achieved better than 0.03° (= 0.52 mr), the spectrum of the output power should be better than 1.069(+2) μm. Since $\theta\leqslant0.03°$ is equivalent to a $\Omega=8.6\times10^{-7}$ sr acceptance of the detection system, the total power radiated into this solid angle from each electron bunch is expected to be $P\approx1.3$ MW.

We have shown that the classical theory gives a favorable condition to the possibility of microwave free-electron lasers. Experimental investigation of this possibility is of great significance, not only as a device for the production of high-power coherent radiation, but also as a fundamental process for the interaction of free electrons with coherent radiation, which has attracted a great deal of theoretical interest and attention some years ago.[15]

The author wishes to thank Dr. H. S. Lau for his helpful discussion.

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Radial Distribution of Nonneutral and Neutral Electron Clouds Confined in a Magnetic Mirror

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(Received 11 July 1978)

The radial distribution of a nonneutral electron cloud confined in a magnetic mirror was measured. The cloud is compressed by the magnetic field to a final radius of 4 mm from an initial radius of 4.5 cm with a final kinetic energy of 0.3 MeV and 2×10^{11} electrons. The radial distribution of the cloud is hollow up to 150 μsec after injection. When the cloud is neutralized by a background plasma, filling in of the center does not occur.

There has been a considerable interest in the last years in the behavior of nonneutral plasmas. Part of this interest comes from the possibility of using the electrostatic fields of these plasmas for collective ion acceleration. Nonneutral electron plasmas confined in magnetic mirror fields were investigated at the University of Maryland[1] for a few years. A few groups around the world have investigated the concept of the electron ring accelerator.[2-5] The use of a toroidal confinement scheme was also investigated for similar purpose[6,7] and lately, a toroidal collective focusing ion accelerator using a magnetically confined electron cloud has been constructed at the University of California at Irvine.[8,9]

Levy[10] has shown that an infinitely long, magnetically confined, hollow electron column can be unstable against electrostatic surface waves. These diocotron[10] oscillations, which are unique to nonneutral plasmas will tend to diffuse the inner and outer boundaries of the hollow column. When this occurs, electrons will effectively cross magnetic field lines. In the present investigation the dynamical behavior of the radial distribution of an electron cloud confined in a magnetic mirror was measured directly for the first time. This was done for neutralized as well as nonneutralized electron clouds.

In the system described here an electron could with average electron energy of about 8 keV is injected into a magnetic mirror. Part of the electrons are trapped and then compressed and accelerated by the increasing magnetic field. The magnetic field is then crowbarred and an equilibrium of the nonneutral electron cloud trapped in the magnetic mirror is achieved.