

# Wiggler focused relativistic sheet beam propagation in a planar free-electron laser configuration

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The propagation of a relativistic sheet electron beam through a spatially periodic magnetic field (wiggler) has been studied experimentally. The wiggler serves two purposes; it provides beam focusing as well as the magnetostatic pump for the free-electron laser (FEL) interaction. Experiments conducted to study sheet beam generation and propagation in a short-period (1 cm) planar wiggler are presented. A 500 keV, 7 A sheet electron beam was propagated through a 3.2 mm waveguide with negligible losses due to intercepted current. In addition, the first observation of wiggler-induced radiation was obtained from the sheet beam FEL in a short-period wiggler oscillator configuration.

Sheet electron beams offer several potential advantages over cylindrical beams since they can carry a large current yet have a small current density. Although the current density is space charge limited, there is no limit on the total beam current since one dimension may be arbitrarily wide. These features make sheet electron beams attractive for use in certain applications including gas laser excitation<sup>1</sup> and plasma chemistry reactors.<sup>2</sup> Furthermore, a sheet electron beam may be well suited for use in high-power coherent microwave and millimeter-wave radiation sources since an electron beam with a very large geometrical aspect ratio will allow good coupling to millimeter-wave structures while still carrying a large total beam current.<sup>3</sup>

A high-power radiation source would require some form of beam focusing to prevent significant beam expansion from space-charge self-fields and to confine the electron beam to an interaction region. A sheet beam immersed in an axial guide field may be unstable due to velocity shear across the beam.<sup>4</sup> This instability may be suppressed by increasing the axial magnetic field<sup>5</sup> but this field may also tend to suppress any useful transverse interactions used to extract beam energy. A wiggler can be used to provide an alternative method of beam focusing.<sup>6</sup> Previously, an experimental demonstration of wiggler-focused sheet beam propagation was reported without any evidence of disruptive instabilities<sup>7</sup>; however, a significant fraction of the beam was intercepted by the surrounding waveguide.

This letter describes a detailed investigation of the intercepted beam current and thus is relevant in determining the suitability of wiggler-focused sheet beams for use in a high power ( $\sim 1$  MW) free-electron laser (FEL). Applications of this type of radiation source are space-borne radar and electron-cyclotron resonance heating (ECRH) of fusion plasmas.<sup>8</sup> The cost, complexity, and size of this FEL may be minimized by the use of short-period wigglers<sup>9</sup> ( $\sim 1$  cm) and modest electron beam energies ( $< 1$  MeV) to generate high-frequency ( $> 100$  GHz) radiation.

A short-period planar wiggler (Fig. 1) magnet has a transverse magnetic field ( $\hat{y}$ ) component which decays exponentially from the wiggler face, making it necessary to propagate the electron beam close to the wiggler for signifi-

cant FEL coupling to occur. To increase the transverse magnetic field, two wiggler pole pieces are separated by a small gap through which the beam is propagated in a rectangular waveguide. Since wiggler focusing requires a strong magnetic field ( $> 0.1$  T) for beam energies and current densities of interest (0.5–1.0 MeV and 15–150 A/cm<sup>2</sup>, respectively) the air gap must be kept small, typically less than half of the wiggler period. If the gap is too small, however, some of the beam electrons may be intercepted by the waveguide leading to excessive heating of the structure, especially in a high average power device. Hence, a critical issue for high average power sheet beam FELs are beam stability and beam interception by the waveguide walls.

A sheet electron beam was generated by a field emission cathode and injected into a waveguide located in the gap of the wiggler (Fig. 1). A rectangular slit was machined through the anode plate to aperture a sheet (1 mm by 35.5 mm) electron beam. The width of the beam could be reduced by symmetrically blocking the outer areas of the slit. The anode slit provided an emittance filter by collimating the beam to the small ballistic angle of divergence allowed by the

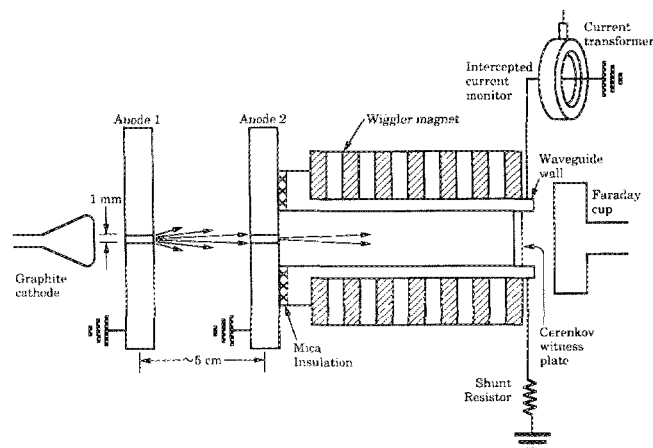


FIG. 1. Experimental sheet beam FEL configuration showing cathode, masking anode(s), waveguide, wiggler, and shunt resistor for measurement of intercepted beam current. Intercepted current was also measured by replacing the resistor with a wire passed through a current transformer.

dimensions of the aperture ( $\pm 4.5^\circ$ ). A pulse line accelerator provided an approximately 35 ns electron beam with current in the range 1–100 A, depending on the width of the beam. The energy of the electron beam was determined to be approximately 500 keV from a series of electron range penetration measurements.<sup>10</sup> The current density profile of the beam was found by symmetrically blocking the outermost areas of the slit. The spatially averaged current density was measured to be approximately 350 A/cm<sup>2</sup> in the center of the beam and decreased to approximately 150 A/cm<sup>2</sup> near the edges. Measurements of the beam density by a small-area current-collector probe suggest that on a very localized scale the actual injected current density might exceed the spatial average by as much as a factor of 5. After exiting the slit aperture, the beam propagated through a waveguide placed in the gap between wiggler pole pieces.

A ten-period electromagnet wiggler with 1 cm period was used.<sup>9</sup> The magnetic fields of the electromagnet wiggler are limited by magnet saturation and by the maximum current available from the power supply [3 kA (rms)]. For the particular wiggler and power supply used in the experiment, on-axis measurements of flux density have shown the maximum attainable field to be approximately 0.2 T with less than  $\pm 5\%$  variation between periods. Previously, it was found that the electron beam accumulated a net drift or deflection in the wiggler plane ( $\hat{x}$ ) as the beam propagated through a uniform wiggler.<sup>7</sup> To eliminate wiggler-plane drift by the electron beam, a short entrance taper was selected for which the flux density of the first half-period of the wiggler was reduced to  $\sim B_w/2$ . It was verified experimentally that the beam did not drift appreciably in the wiggler plane during propagation through the ten periods of the wiggler. Measurements using Cerenkov witness plates to image the beam showed it to propagate through the wiggler void of any disruptive instabilities.

To good approximation, a wide planar wiggler produces a two-dimensional magnetostatic field,<sup>9</sup> an axial component in the direction of beam propagation ( $\hat{z}$ ) and a component in the narrow transverse dimension ( $\hat{y}$ ) across the wiggler gap. As the streaming electron beam with velocity  $v \approx v_{z0} \hat{z}$  enters the wiggler, the interaction of the streaming velocity with the transverse flux density,  $B_y$ , leads to a "wobble" or "quiver" velocity  $v_x$  in the wiggler plane ( $\hat{x}$ ). Once an electron acquires some  $v_x$ , the coupling between the quiver velocity and the periodic axial flux density,  $B_z$ , produces an inward force in the narrow dimension ( $\hat{y}$ ) which focuses beam electrons toward the center of the wiggler gap. Thus, both components of the wiggler field are important for the purposes of beam focusing in the narrow dimension of the magnet gap. Two mechanisms exist which tend to defocus the beam: entrance conditions of the wiggler and self-space-charge repulsion of beam electrons.

For beams which have a small current density (tenuous), the ballistic motion of a single electron under the influence of the wiggler focusing fields can be found analytically<sup>7</sup> to satisfy the differential equation

$$\frac{d^2 y}{dt^2} = -\omega_\beta^2 y, \quad (1)$$

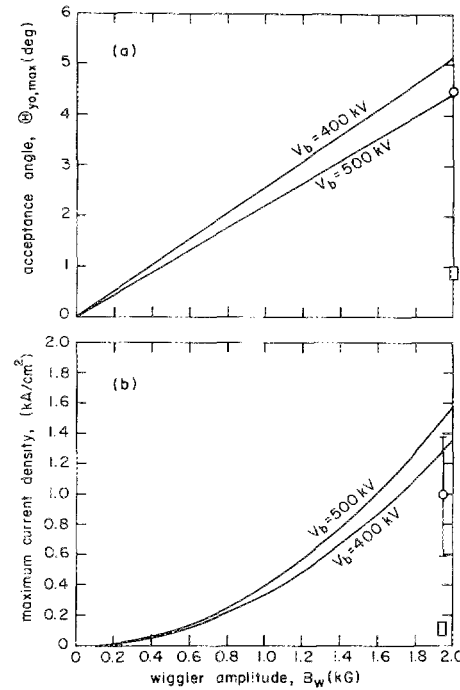


FIG. 2. Theoretically estimated electron beam parameters for negligible intercepted current as a function of wiggler strength. The open circles represent experimental parameters from the single-anode beam and the open rectangles represent that of the double-anode beam. (a) Injected beam divergence angle; (b) Injected beam current density.

where  $\omega_\beta$  is the betatron frequency defined as

$$\omega_\beta = \Omega_w / \gamma \sqrt{2}. \quad (2)$$

Here  $\Omega_w = eB_w/m_e$ , where  $B_w$  is the on-axis transverse flux density,  $m_e$  is the electron rest mass, and  $e$  is the electron charge. The electron trajectory described by Eq. (1) is a sinusoid whose amplitude depends on parameters of the beam electrons at the entrance to the wiggler, such as energy and injected divergence angle. The amplitude of the betatron motion is

$$Y_\beta = (v_{x0}/\omega_\beta) \Theta_{y0}, \quad (3)$$

where  $\Theta_{y0}$  is the beam's initial angle of divergence on injection and is defined as  $\Theta_{y0} \approx \tan \Theta_{y0} = v_{y0}/v_{z0}$ . For FELs with interaction region lengths exceeding one-quarter of the betatron period, beam interception by the waveguide occurs if the amplitude of the betatron oscillation exceeds half of the waveguide height ( $b_{rf}/2$ ). This imposes a limit on allowable beam divergence angles at injection for negligible waveguide interception,<sup>7</sup>

$$\Theta_{y0} < \frac{b_{rf}}{2} \frac{\omega_\beta}{v_{z0}}. \quad (4)$$

Maximum allowable injected divergence angles are shown in Fig. 2(a).

For dense electron beams, expansion due to self-space-charge fields may be significant. However, confinement is still possible if the current density of the beam ( $J_{\text{beam}}$ ) satisfies the condition<sup>7</sup>

$$J_{\text{beam}} < \frac{m_e \epsilon_0}{e} \left( \frac{\gamma_z^2}{2\gamma} \right) \Omega_w^2 v_{z0}, \quad (5)$$

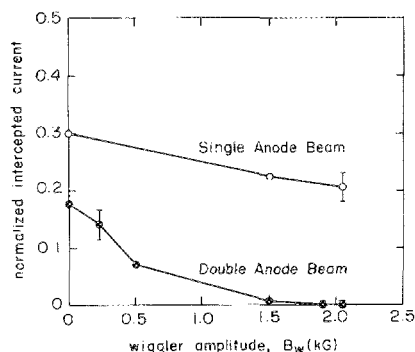


FIG. 3. Intercepted currents for both single-anode and double-anode experimental configurations of beam generation. The open circles represent data from the single-anode electron beam; the closed circles represent data from the double-anode electron beam.

where  $\epsilon_0$  is the permittivity of free space,  $\gamma_z = [1 - (v_z/c)^2]^{-1/2}$ , and  $\gamma = [1 - (v_0/c)^2]^{-1/2}$  is the electron relativistic mass factor. The maximum beam current density with negligible wall interception is shown in Fig. 2(b).

Waveguide intercepted current was measured by two methods (see Fig. 1). First, the intercepted current collected on the waveguide walls was dropped across a shunt resistor. The intercepted current was also measured directly by a current transformer. Calibration performed with a fast rise time pulse generator showed the two methods to be in good agreement and to have sufficient bandwidth.

Initially, it was observed that even in the presence of a 0.2 T wiggler magnetic field approximately 20% of the injected beam current was collected on the waveguide walls (Fig. 3). Both the ballistic and space-charge mechanisms were probably responsible for the intercepted current. The divergence angle of the beam on injection due to the geometric collimation provided by the slit exceeded the limits set by Eq. (4). Furthermore, the localized current density near the center of the beam was on the order of the limits set by Eq. (5).

The maximum divergence angle and the current density of the beam were simultaneously decreased by adding a drift region and a second slit aperture after the first anode. The presence of the drift region between anodes allowed the beam to expand due to its space charge and thus reduce the localized current density. The spatially averaged beam current density measured in the center of the beam was reduced from  $\sim 350$  to  $\sim 65$  A/cm<sup>2</sup>. The drift space also acted to decrease the angle of divergence of the beam injected into the wiggler by approximately a factor of 6. As can be seen in Fig. 3, under these conditions the intercepted current was reduced to well below a fraction of 1% of the injected 7.2 A of beam current. This fraction of a percent represents the limits of signal-to-noise ratio in the accelerator FEL configuration. Thus, within the limits of measurement resolution, no intercepted current was observed in the improved experimental configuration.

Finally, a cavity was added to the experiment and wiggler-induced radiation was observed for the oscillator configuration. A rectangular cavity was formed by closing off the downstream open end of the waveguide. Although

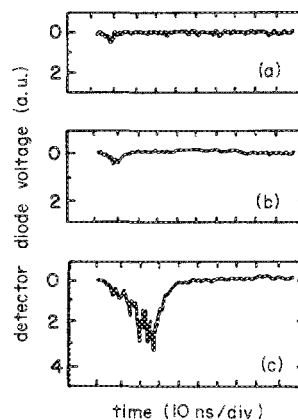


FIG. 4. Oscilloscope traces of the microwave detector signal from the oscillator cavity. (a)  $B_w = 0$  T; (b)  $B_w = 0.08$  T; (c)  $B_w = 0.15$  T. [It was verified that most of the signal was in the V band (40–60 GHz) of frequencies.]

the duration of the electron beam was too short (35 ns) to allow radiation in the oscillator to reach saturated levels, the pulse duration did allow sufficient time for multiple cavity oscillations. Radiation was coupled out of the cavity by a waveguide coupler directly to a crystal microwave detector.

Wiggler-induced radiation was observed for a reduced electron beam energy of  $\sim 350$ – $400$  keV. As expected of the FEL interaction, the microwave power increased as the strength of the wiggler field was increased. Typical traces of the diode detector voltage showing this trend are shown in Fig. 4. Simplified calculations estimate that the reduced energy beam should have a FEL interaction with the TE<sub>01</sub> waveguide mode at grazing intersection resulting in a wide-band instability. This grazing intersection should occur in the V band (40–60 GHz) at about 43 GHz. Sections of cutoff waveguide were placed before the detector to determine the band of the radiation from the oscillator cavity. It was verified that much of the microwave power from the cavity was in the V band. This is the first observation of wiggler-induced radiation from a sheet beam FEL oscillator, using a short-period wiggler.

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