Self-amplified Emission in a Hybrid-FEL

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Abstract

Experiments on self-amplified microwave emission were performed at the hybrid-FEL test-stand. The injector has a two-cavity buncher which can be operated as a klystron. Without feeding external input RF power, the output from the cavities was measured. Also, the power evolution in FEL without input was measured. These are reported in section 1 and 2, respectively.

1. Auto-bunching and Emission in Cavities

There have been many experiments on the auto-bunching (self-excited bunching) of high-current beams through cavities. At first, M. Friedman reported on the auto-bunching phenomenon (ref. 1). The frequency of the bunching was 500 MHz. The degree of amplitude modulation exceeded 80%. The beam had a current of 15 kA and a voltage of 500 kV for 50 ns duration. I.A. Grishaev also observed auto-bunching of 300 MHz (ref. 2). The auto-bunching occurred at a current in excess of 6 kA; the amplitude of the modulation increased with increasing the current. However, K. Minami had not observed the auto-bunching because the beam was only on the order of 100 A and the frequency, 2830 MHz, was too high (ref. 3).

A bunched beam generates coherent emission. The cavity extracts power from the beam, and further bunches the beam. Self-amplified emission is observed in cavities.

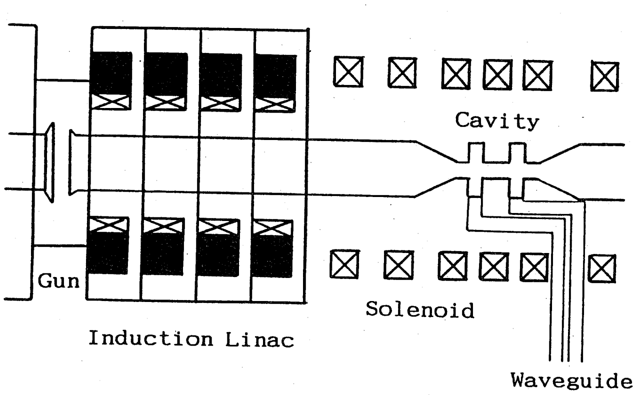

Fig.1:FEL injector

1.1 Setup for experiments

Figure 1 shows the injector for prebunched beam FEL experiments (refs. 4 and 5). The injector consist of a 1.6-MeV induction linac and a prebuncher. The linac consists of eight induction cells. The electron source is a carbon cathode. The gap between the cathode and the anode is 10 cm. The beam is emitted under a strong electric field. The beam is transported by a solenoid magnetic field. The prebunching system consists of an input cavity and an idle cavity. These are analogous to those of a klystron.

In auto-bunching experiments, the beam had a kinetic energy of 1.5 MeV with a 50 ns duration. The beam current at the exit of the induction linac was 497A, and the current was 328A at the exit of the prebuncher. To pass the beam through the narrow apertures of the cavities, the solenoid field near to the cavities was strengthen to 3 kG, compared to 0.4 kG in the other region.

The beam profile can be expressed by an envelope equation. A simulation with a normalized emittance of 0.1 $cm \cdot rad$. was consistent with the experiments. An emittance measurement performed at 700 keV was 0.41 $cm \cdot rad$. (ref. 6). The improvement is considered to be due to the R&D work on the geometrical shape of the cathode and anode.

The prebuncher is of conventional design, except that the velocity (v) of 1.5 MeV beam is $0.967c$, which is close to the velocity of light (c). The cavities use the TM_{010} mode. The radius of the cavity is 26.77 mm, the radius of the beam aperture is 15 mm, and the length is 10.2 mm. The distance (drift space) between the cavities is 90 mm. Both cavities have the port connected to the waveguide. The RF source to excite the cavity is a 9.4 GHz magnetron. The detected signal from the cavity is observed by a oscilloscope outside the shield.

Under the usual buncher operation, about 40 kW was fed into the first cavity, the output power of 150 kW was extracted from the second cavity. Therefore, the power gain of this two-cavity klystron was 6.1. This agrees with the value which is expected from the usual small-amplitude klystron theory.

1.2 Measurements of the Wake Field in the First Cavity

The first cavity was connected with a long waveguide and terminated at a calibrated diode. The wake field from the beam was measured. Figure 2-a shows 20 successive shots. The voltage on the diode changed at each shot. The average voltage was 35 mV. The noise level was about 5 mV. The power corresponding to the voltage of 35 mV was 37 mW.

The power could be estimated as follows. Consider a beam with radius b passing through a cylindrical cavity with inner radius a and length l. The current is assumed to be linearly increasing. The induced field (E_z) is given by the vector potential (A_z);

$$E_z = -\frac{\partial A_z}{\partial t}.$$

Here, A_z is a solution of the following wave equation, which has a driving term:

$$\Delta A_z - \frac{1}{c^2}\frac{\partial^2 A_z}{\partial t^2} = -\frac{1}{\varepsilon_0 c^2} j_0 \frac{(vt-z)}{Tv} \qquad (0 \le r \le b),$$

where T is the rise time of the current, and j_0 is the current density. Expanding the vector potential and the current in terms of the normal mode series of the cavity, and substituting them into the wave equation, we obtained a solution of A_z. The excited electric field on the axis of the cavity is (by reference (3))

$$E_z = 480 \cdot I \cdot \frac{J_0(kr)}{a^2 k J_1^2(ka)} \left\{ \frac{3\left(1-\frac{1}{\pi}\right)^2}{2\omega^2 T^2} + \frac{l^2}{8v^2T^2} \right\}$$

and the power is

$$P = E_Z^2 \left(\frac{\pi \varepsilon_0 \omega l a^2 J_1^2(2.405)}{Q_E} \right),$$

where $I = \pi b^2 j_0$ is the total current; J_0 and J_1 are Bessel functions.

The Q-value was 4300, and the external Q-value (Q_E) was 550. A power of 32mV was obtained by assuming a build-up time of 70 ns. This nearly agrees with the experimental value of 37 mW.

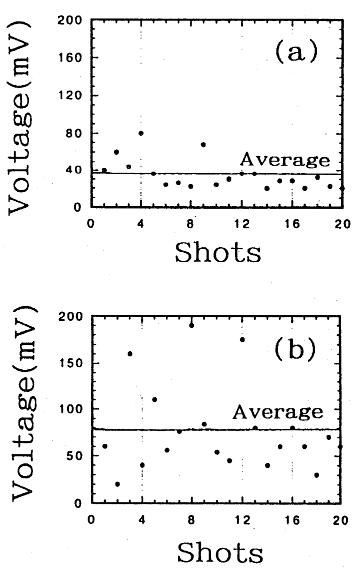

Fig.2: Power from cavity

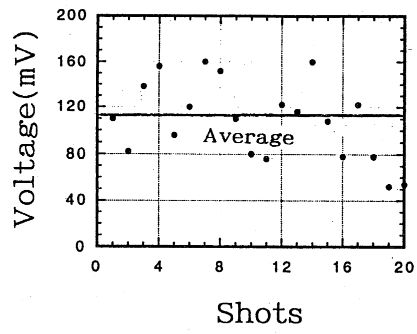

Fig.3: Amplifier experiment

1.3 Measurements of the Power from the Second Cavity

The power from the second cavity was measured in the absence of any input RF power to the first cavity. Figure 2-b shows 20 successive shots. The average voltage was 77.5 mV, which corresponds to 114 mW. The power gain to that from the first cavity was 3.1. This gain was about half that of the usual high-power two-cavity klystron operation (as described above). Thus, these results demonstrate that self-amplified emission occurred in the cavities.

1.4 Experiments as an Amplifier with Low Input Power

As the input source, a Gunn diode was used. A microwave power of 9 mW was launched into the first cavity via an isolator. The power from the second cavity was measured. The average voltage in 20 shots (Fig.3) was 115.5 mV. It corresponds to 200 mW at the exit of the second cavity. The power gain was 4.3.

As easily can be seen, the variation in the Fig.3 is smaller than the variation in Fig.2-b. The standard deviation of Fig.3 ia 47 mV, and the ratio to the average power is 61%. Also, those of Fig.3 are 30.4 mV and 27%, respectively. It can be understood that the external input power stabilize the output power.

2. Self-Amplified Spontaneous Emission in FEL

The Self-Amplified Spontaneous Emission (SASE) in FEL has attracted much interest in recent years. FELs in the oscillator mode can not be operated in the soft X-ray region because of a difficulty concerning mirror fabrication with high normal reflectivity and high power-endurance. The use of SASE eliminates the need to use mirrors. On the other hand, FELs in the single-pass amplifier mode, like the KEK X-band FEL, require an input source. Since the SASE-mode FEL does not need any input sources, the frequency of the output can be varied by controlling the beam energy and the wiggelr field.

In the SASE-mode FEL, the electron beam through wiggler will be self-bunched due to interaction with its own radiation field. The radiation starts from the beam noise. If the wiggler is made long enough, and the beam intensity is large, the spontaneous emission starts to be amplified by the beam, itself, and the radiation grow exponentially.

2.1 Setup for Experiments

The electron beam is generated in the induction linac, and the beam is guided through a 15-period planar wiggler with a period length of 16 cm. The field in each period can be independently controlled by varying the charged voltage of the capacitors in the pulsed power supplies. The maximum field is 2 kG. The electron beam undergoes a wiggling motion and interacts with a RF wave in an oversized waveguide (110 mm × 55 mm). The input RF source is a magnetron. The magnetron was turned off in the SASE experiments.

2.2 SASE from 750 keV Beam

In 1989-92, FEL experiments using a 750 keV beam were performed. The beam source was an one-stage induction linac with 4 cells. The output RF power was passed though a RF-window and radiated in an anechoic room. A receiving horn picked up the signal. The output signals were not stable because of a fluctuation of the voltage on the induction linac.

SASE had been observed. The maximum power was 15 kW, and the average was 4 kW. Fig. (4) shows the evolution of SASE. The average SASE gain was 33.6 dB/m while the amplified gain was 20.3 dB/m.

2.3 SASE from 1.5 MeV DC Beam

In 1.5 MeV beam FEL experiments, the RF system was improved. The output RF power was absorbed into a long dummy load. The known fractions of the power were extracted by a directional coupler, which was installed in front of the dummy load. The attenuation from the high-power line to the entrance of the calibrated diode was 88.6 dB. The least-observable RF power was about 5 kW.

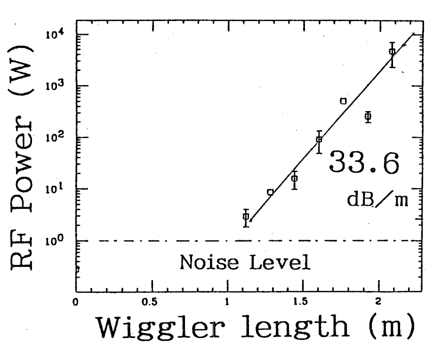

Fig.4:Evolution of SASE

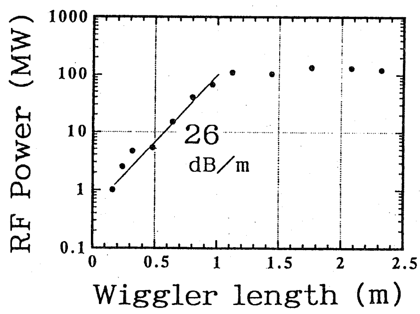

Fig.5:Prebunched beam experiment

The obvious signal on SASE had not been observed. Several reasons exist. The new RF monitor could not observe signals in the low-power region. Further, the fraction of the beam begins to hit the wall of the waveguide above the 1.2 kG wigger field. The center of the FEL resonance seems to exist at about 1.4 kG. The observed signal may be caused by such a chopped beam.

2.4 RF Evolution by 1.5 MeV Prebunched Beam

As described above, SASE starts from the noise field in the beam. Therefore, the emission field is expected to evolve from the self-field in the prebunched beam as well.

The prebunched beam was produced by cavities (described in section 1). A beam having current modulation of 45% was introduced into the wiggler. The wiggler field was 1.25 kG. The current was 730 A at the entrance of the wiggler and 500 A at the exit. Fig.5 shows the power evolution (ref. (5)). The average gain was about 26 dB/m. The power exceeded 100 MW. The saturation length was 1.1 m, which is short compared with that of 1.9 m in the case of DC beam.

Acknowledgments

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