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X-band Prebunched FEL Amplifier

Kazuyoshi Saito[1], Ken Takayama[2], Toshiyuki Ozaki[2], Junichi Kishiro[2], Kiyokazu Ebihara[2], Shigenori Hiramatsu[2]

[1] Hitachi Research Laboratory, Hitachi, Ltd.
7-2-1 Omika, Hitachi, Ibaraki, 319-12, Japan
[2] National Laboratory for High Energy Physics (KEK)
1-1 Oho, Tsukuba, Ibaraki, 305, Japan

Abstract

We have designed and constructed a prebunched free-electron laser (FEL) amplifier consisting of a prebuncher and a standard FEL. Microwave power saturation with a short wiggler length was realized by the prebunched beam. We also examined the microwave phase evolution. It was found the adjustable range of the output microwave phase by changing the input microwave phase was restricted within a narrow band due to spontaneous emission radiated by the prebunched beam.

1. Introduction

We developed the X-band FEL [1-3], which is a candidate for possible high power microwave sources (~1GW) for future linear colliders and other applications. We tried a new sort of FEL experiment in which the FEL is driven by a prebunched beam [4-7]. The experimental configuration is that of a standard FEL accompanied by a prebuncher. Hereafter we call this a prebunched FEL. In this paper we describe the prebunched FEL experiment which has two important purposes. The first is to realize a compact / efficient FEL with a large gain per wiggler length. By attaining the power saturation with a short wiggler length, we can enhance the power through the remaining length by tapering the wiggler field. The second purpose is to experimentally control the output microwave phase by changing the phase of the seed microwave to the wiggler. Achieving the latter purpose is a crucial issue in FEL physics in a multi-stage FEL which is driven by a bunched beam in the FEL-TBA linear collider [8].

2. Prebuncher

A schematic view of the prebunched FEL amplifier is shown in Fig.1. The prebuncher is placed between the downstream induction unit (IDU) and the wiggler. An electron beam of 1.5MeV/850A generated by the induction gun is prebunched at the same frequency as that of the FEL (9.4GHz) before entering the wiggler. An input microwave signal is amplified through the wiggler due to the FEL interaction (*stimulated operation regime*). Even if no microwave signal is inputted, the strong spontaneous emission radiated by the prebunched beam should be amplified in the same way (*superradiant operation regime*).

Considering the limited magnitude of the available microwave power, we have adopted a prebunching section with a two-cavity configuration as illustrated in Fig.2. It is similar to the bunching section of a conventional klystron. The input cavity is excited in the TM010 mode with a fraction of the power introduced from the external magnetron, leading to modulation in the beam-velocity to some degree. Velocity-modulation gradually becomes current-modulation. The gain cavity, placed 9cm downstream the input cavity, is excited by induced current-modulation and can give the driving beam further velocity-modulation. To get the current-modulation of 30% at the wiggler entrance, the cavity gap voltage of 170kV is required according to a theoretical estimation. In the two-cavity configuration, the input cavity requires a microwave power of 15kW to achieve the gap voltage of 170kV in the gain cavity. The maximum surface electric field can be reduced to 13MV/m in the gain cavity when beam-loaded, which should be sufficiently low enough to avoid surface breakdown. The same sized pill-box cavities without nose cones are employed for the input and gain cavities.

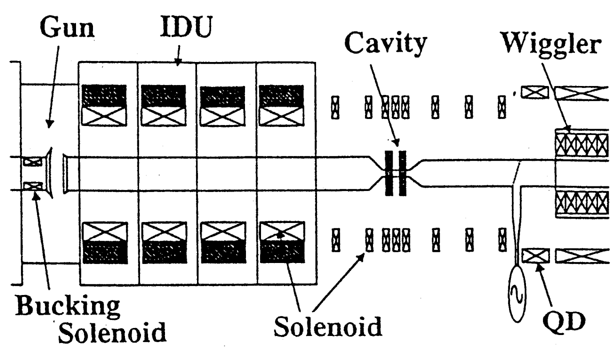

Fig.1 Configuration of the prebunched FEL amplifier.

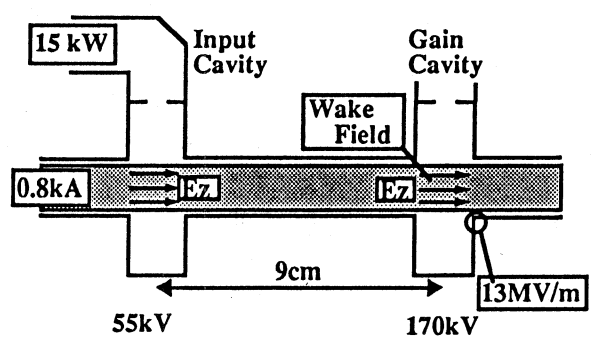

Fig.2 Prebunching cavities.

3. Prebunching Experiment

A magnitude of current-modulation attained at the entrance of the wiggler was measured in the first step of the prebunched FEL experiment to optimize and evaluate the prebuncher system. A bunch-monitoring cavity immersed in an axial magnetic field was installed at the location corresponding to the wiggler entrance. The magnitude of current-modulation was determined from the microwave power extracted from this cavity. Its external-Q (Q_{ext}) is designed to be much smaller than the unloaded-Q (Q_u) and the beam-Q. Under this approximation, the AC beam current I_{ac} is estimated from the extracted power $P_{out,mon}$ by the following relation

$$I_{ac} = \frac{2}{TTF(0)}\sqrt{\frac{Q_u}{R_{sh}}\frac{P_{out,mon}}{Q_{ext}}} ,$$

where R_{sh} is the shunt impedance and TTF(0) is the transit time factor for a particle passing through the cavity center. This method is not so precise, but it is sufficient to estimate the fundamental component of modulation. Figure 3 shows the experimental results in which the maximum current-modulation of 45% was achieved with an input power of 35kW and the dependence of the current-modulation on the input power seemed to be fairly consistent with the design calculation. Current-modulation beyond 45% was limited in practice by pulse-shortening phenomena at the gain cavity.

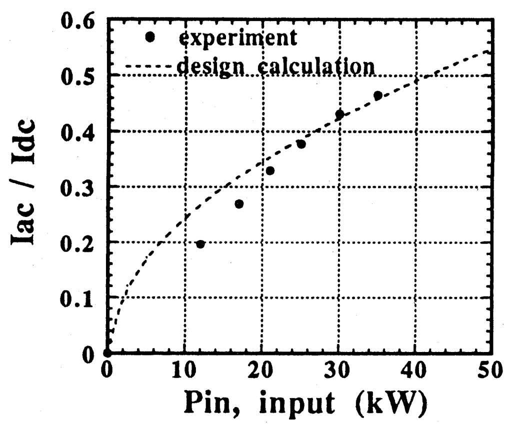

Fig.3 Current-modulation attained at the wiggler entrance.

4. FEL Experiment

4.1 Superradiant Operation Regime

In this regime, a prebunched beam of 1.5MeV/DC750A was introduced into the wiggler and the transmission efficiency through the wiggler was 70%. Figure 4 shows the power evolution measured at the wiggler field of 1.25kG for two cases of current-modulations of 45% and 10%. Both results indicated stagnation in power-growth at the wiggler length of 0.4m. They had different saturation levels and saturation distances; 120MW/1.1m and 150MW/1.5m, respectively. These features could be well-reproduced by simulations. The field growth stagnation was caused by debunching. The prebunched beam is debunched once and again bunched due to space-charge oscillation and partially trapped in the pondermotive potential. Without the space-charge effect, a significant part of the prebunched beam would be trapped in the pondermotive potential without any serious debunching.

To increase the output power beyond the saturation level, we carried out tapered FEL experiments. Simulations told us that an output power over 350MW can be achieved with appropriate tapered wiggler fields. However, an enhanced output power has not been observed yet, probably due to poor beam transport in the wiggler. The beam loss was rather severe around the resonant field (~1.4kG), where the beam should be well-bunched and trapped in the pondermotive potential ideally. Although the saturation power was a maximum for the wiggler field of 1.25kG, at which the beam loss was mitigated, the bunch structure in the pondermotive potential becomes rather elongated due to mismatching in the longitudinal phase space, resulting in poor efficiency of the wiggler field taperings.

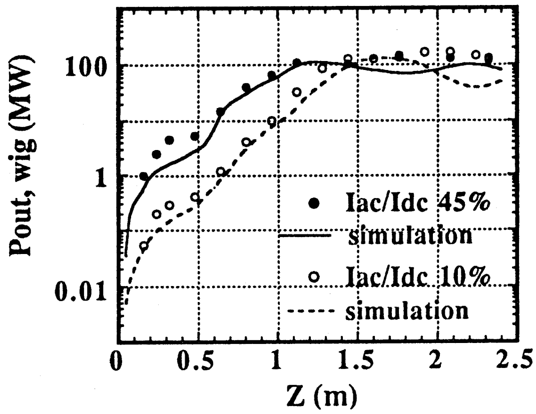

Fig.4 Microwave power evolutions in the case of superradiant operation.

4.2 Stimulated Operation Regime

(a) Power evolution

A seed power of 60kW was introduced into the wiggler through a microwave input coupler with beam-passing metal-mesh which reduced the transmitted beam-current to DC500A. Figure 5 shows the power evolution for current-modulation of 40%. Its initial growth was very sensitive to the phase relation between the seed microwave and the current-modulation. When both were in-phase, the field evolution was quite similar to that in the superradiant operation regime. When both were in anti-phase, a rapid damping in power was observed at the initial stage of the wiggler and beyond that the power grew quickly. The current-modulation being larger, the field recovery became quicker and the power-evolution curve in the case of the anti-phase approached that of the in-phase after the quick recovery. This is quite clear from the fact that the microwave power P_{RF} at the initial stage of the wiggler may be approximated as

$$P_{RF} \propto A_R^2 \approx A_{R,IN}^2 + A_{R,PB}^2 + 2 \cdot A_{R,IN} \cdot A_{R,PB} \cdot \cos\theta,$$

where θ is the phase difference between the seed microwave field $A_{R,IN}$ and the prebunched superradiant emission $A_{R,PB}$. The prebunched superradiant emission $A_{R,PB}$ grows rapidly and surpasses the seed microwave field $A_{R,IN}$ after a few wiggler periods for our beam parameters in the (high-gain) Raman regime. If cosθ is negative, the microwave power P_{RF} drops rapidly from the seed power due to the last term and soon increases again due to the second term. These features can be well-reproduced by simulations and are quite different from those of prebunched FELs operating in the low-gain regime [5][7]. In the case of low-gain prebunched FELs including an optical klystron, the second term is negligible, because $A_{R,PB} << A_{R,IN}$. If $\cos\theta$ is negative, the power gain is negative namely $P_{RF} < P_{RF,IN}$.

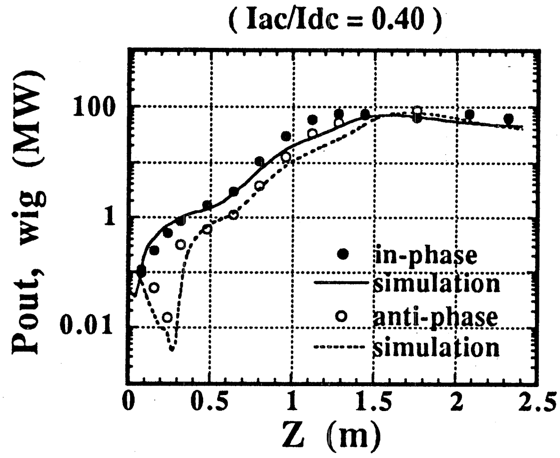

Fig.5 Microwave power evolutions in the case of stimulated operation.

(b) Phase evolution

Microwave phase was measured with a double balanced mixer using a magic tee. The phases of input and output microwaves of the wiggler were measured with reference to the magnetron's output microwave phase. Figure 6 shows the experimental results of phase evolution for current-modulation of 15%. Initial phase variations are caused by a complicated mechanism, because intense FEL interaction starts in the matching section where a non-resonant up-tapering field is present for beam-orbit matching. However, we note that the initial phase difference of 180° decreased to 80° due to FEL interaction with the prebunched beam.

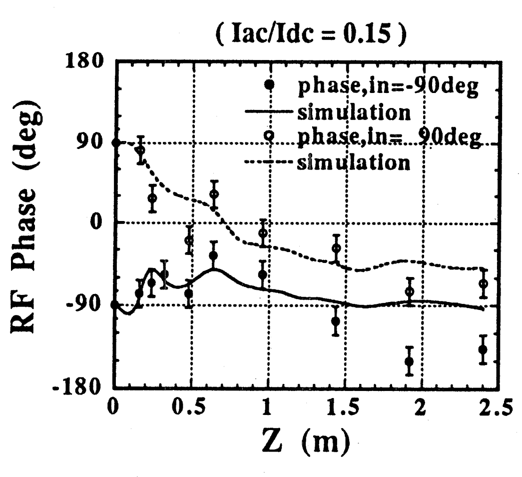

Fig.6 Microwave phase evolutions for different initial phases of the input microwave. The zero phase is when the beam bunch-center is located at the maximum decelerating field of the input microwave.

The response of the output microwave phase was examined for the change of the input microwave phase of the wiggler. Figure 7 plots the experimental results of the adjustable range of the output microwave phase when we changed the input microwave phase from 0° to 360° every 30°. We can say that the current-modulation being higher, the output microwave phase was determined by the superradiant emission of the prebunched beam. The adjustable range of the output microwave phase became restricted within a narrow band. When the current-modulation became higher than 30%, the adjustable range was limited to less than 40° for the input microwave power of only 60kW. These phenomena were expected based on the simulations.

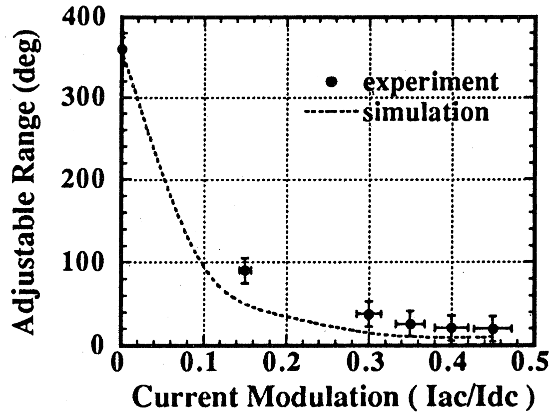

Fig.7 Adjustable range of the output microwave phase by changing the input microwave phase.

5. Conclusion

The saturation power of 120MW was attained at the wiggler length of 1.1m by a 1.5MeV prebunched beam with a 45%-modulated DC750A current. However, FEL performances were deteriorated by beam losses in the wiggler.

The controllability of the output microwave phase was examined by changing the phase of the input seed microwave to the wiggler. When the current-modulation of the injection beam (1.5MeV-DC500A) was higher than 30%, the adjustable range was limited to less than 40° by the input microwave power of only 60kW.

References

[1] K.Takayama, J.Kishiro, K.Ebihara, T.Ozaki, S.Hiramatsu and H.Katoh, Nucl. Instr. and Meth. A358(1995)122.

[2] K.Takayama, J.Kishiro, K.Ebihara, T.Ozaki, S.Hiramatsu and H.Katoh, J. Appl. Phys. 77(1995)5467.

[3] K.Takayama and T.Monaka, AIP Conf. Proc. "Tamura Symposium on Accelerator Physics (1994)".

[4] G.Dearden et al., Nucl. Instr. and Meth. A318(1992)230.

[5] G.Dearden, E.G.Quirk, A.I.Al-Shamma'a, R.A.Stuart and J.Lucas, Nucl. Instr. and Meth. A341(1994)80.

[6] I.Schnitzer and A.Gover, Nucl. Instr. and Meth. A237(1985)124.

[7] M.Cohen, A.Kugel, D.Chairman, M.Arbel, H.Kleinman, D.Ben-Haim, A.Eichenbaum, M.Draznin, Y.Pinhasi, I.Yakover and A.Gover, Nucl. Instr. and Meth. A358(1995)82.

[8] A.M.Sessler, AIP Conf. Proc., 91(1982)154.