DESIGN OF A HYBRID FEL AMPLIFIER

Kazuyoshi Saito[1], Shigenori Hiramatsu[2], and Ken Takayama[2]

1 The Graduate University for Advanced Studies at KEK
2 National Laboratory for High Energy Physics in Japan (KEK)
Tsukuba, Ibaraki, 305 Japan

Abstract

We have developed an X-band FEL for future linear colliders, and now designing a hybrid FEL consisting of a pre-bunching system and a standard FEL system. The pre-bunching system injects 30% density-modulated 800A beams to the wiggler, resulting in the saturation output power of 70MW with the wiggler length of 1.3m. We can examine FEL performances driven with bunched beams in this hybrid FEL system.

Introduction

We have developed the ion-channel guided X-band free-electron laser [1][2] which is a possible high power RF source for future linear colliders. Recently we attained the peak output power of 20MW with a 1.5MeV- 400A electron beam injected from the induction gun; however, the saturation has not been observed because of several reasons. A certain way to achieve rapid FEL amplification with a relatively short wiggler distance is to employ driving beams modulated in longitudinal density at the same frequency as that of the FEL. This is a design study of the hybrid FEL consisting of a pre-bunching system and a standard FEL system. Essential features of a microwave FEL amplifier driven with bunched beams, which is a final scheme in a multi-stage FEL of the TBA/FEL [3][4] such as rapid phase following and sinusoidal gain evolution which have been theoretically predicted [5][6] will be realized in the hybrid FEL amplifier though it is less than perfect.

The pre-bunching system consists of input and idling cavities analogous to that of a klystron. The input cavity is energized with an external RF source and excited in TM010 mode. Interaction of slightly modulated beams with the idling cavity will lead to further modulation in the longitudinal direction. Beam loading in the input cavity and beam-to-wakefield interactions in the idling cavity have been examined by using an analytical approach and numerical simulations. Multi-particle simulations through the complex of devices (1.6MV induction gun, pre-bunching system, wiggler) taking account of magnetic beam guiding instead of ion channel guiding have been performed. Bunching simulations have been also carried out to obtain the suitable initial beam conditions at the entrance of the wiggler, under which FEL simulations have been done to examine interactions of bunched beams with inputted traveling waves.

Magnetic Guiding System

We have so far employed an ion channel focussing for beam guiding. The ion channel focussing is surely an attractive scheme of beam guiding, however, it is not compatible with the cavities requiring high vacuum conditions. Hence, we need select a conventional magnetic guiding scheme instead.

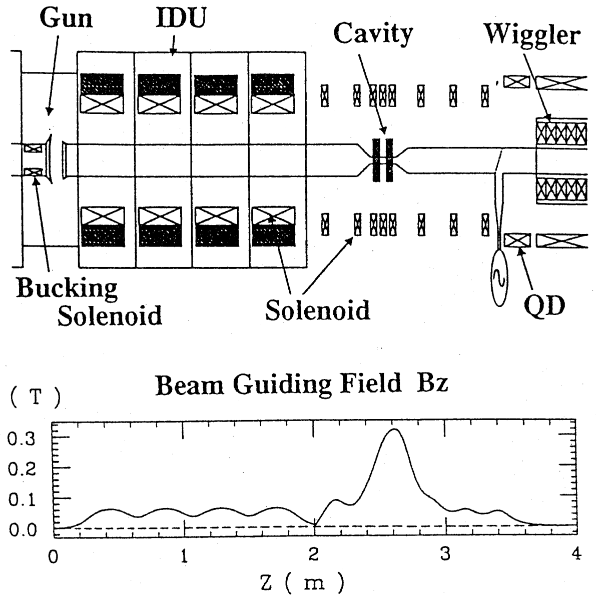

Fig.1 Hybrid FEL System

Initial Condition (at Anode) :
$E_b = 1.6\,\mathrm{MeV}$, $\Delta E_b/E_b = \pm 10\%$,
$I_b = 1\,\mathrm{kA}$, $\varepsilon_n = 4\,\mathrm{mm{\cdot}rad}$,
$R = 2.0\,\mathrm{cm}$, $R' = -40\,\mathrm{mrad}$

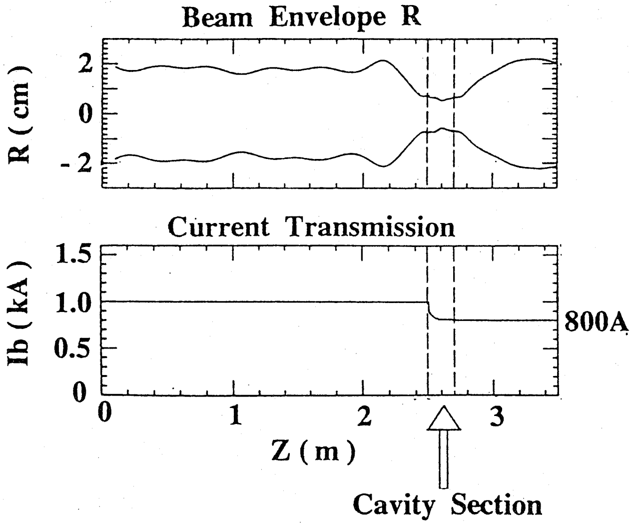

Fig.2 Beam Transport

The hybrid FEL system is illustrated in Fig.1, which also shows the magnetic guiding system. The magnetic guiding system is comprised of beam-guiding solenoids and a quadrupole magnet matching the beam phase space to the acceptance of the wiggler. A bucking solenoid is installed to cancel the magnetic field on the cathode surface. Several solenoids are disposed to converge the beam in the cavity section and expand it again smoothly to moderate the longitudinal space charge effect preventing the beam bunching. Figure 2 shows the beam transport from the anode to the wiggler, which is obtained by multi-particle tracking. We can transport 800A beams to the wiggler with the focusing field of 0.32T in the cavity section. The multi-particle simulations also show we can transprt 650A beams to the exit of the wiggler by adjusting the matching quadrupole field, wiggler field tapering and its externally applied quadrupole field.

Pre-bunching System

We selected the same sized pill-box cavities for both the input and idling cavities. Table 1 describes the cavity design parameters. Figure 3 shows the cavity structure and the electric field distribution. The cavity design was performed using the SUPERFISH code.

The cavity is connected to a beam pipe with large inner diameter enough to realize a good transmission of relatively large emittance beams from the induction gun.. The large apertures of the cavity cause the poor field confinement and the large transit angle despite of its small gap length, resulting in the reduction of the effective accelerating/decelerating field experienced by beams. And besides, beam loading is no longer negligible due to bunching effect in the cavity itself. A large input RF power is therefore required to get the desired beam-bunching, which leads to the increase of the maximum surface field strength of the cavity. To realize 30% density-modulated beams, the cavity gap volatge of 170kV is required. If we use the input cavity only, the required input RF power is up to 150kW and the maximum surface electric field is up to 25MV/m (when beam unloaded).

Figure 4 illustrates the principle of the two-cavities configuration. The input cavity is energized with an external RF source and excited in TM010 mode, which velocity-modulates the beam to some degree. Velocity modulation gradually turns into density modulation . The idling cavity is in turn oscillated in TM010 mode with the beam density-modulated slightly but enough, which further velocity-modulates the beam tightly. The idling cavity using the beam self-bunching effect is therefore useful for the reduction of a burden for the input cavity. The input cavity requires only 8kW to achieve the gap voltage of 170kV in the idling cavity. The maximum surface electric field can be reduced to 13MV/m (in the idling cavity when beam-loaded).

Bunching and FEL Simulations

Bunching simulations were carried out based on the 1D disk model including space charge effect , which is often used for klystron designs. Figure 5 illustrates the beam modeling and shows the comutational results. A beam is divided into a number of discrete disks of charge, the equation of motion of which we solve numerically.

Table1 Cavity Design Parameters

Mode	TM$_{010}$
Resonant Frequency : fr	9.4GHz
Beam Apertures	15mm
Shunt Impedance : Rsh	3.7MΩ
Transit Time Factor : TTF	0.41
Quality Factor Q	
Wall Loss : Qu	9000
Beam Loading : Qb	510
External Q : Qext	490

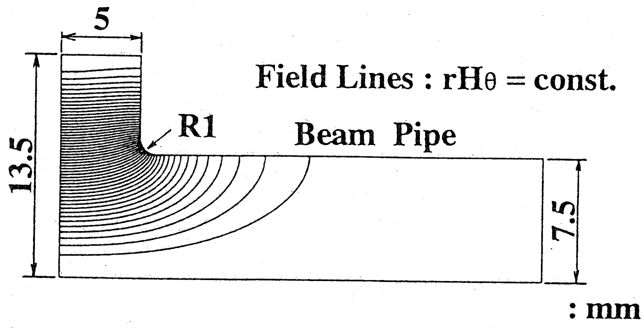

Fig.3 Cavity Structure and Field Distribution

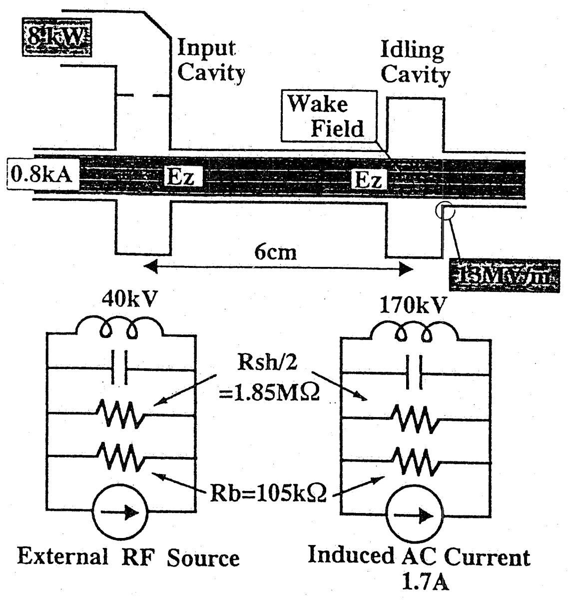

Fig.4 Two-Cavities Configuration and Equivalent Circuits

The computational results show the traces of individual disks in the longitudinal phase space. We can see the maximum density-modulation of 30% occurs at the drift length of 1.2m, where we will place the entrance of the wiggler. The modulation wave is nearly sinusoidal due to space charge effect.

We analysed FEL performances by 1D FEL simulation, using the beam conditions obtained by other simulations; average beam current of 700A, average beam radius of 2cm by multi-particle tracking, and the amplitude of density modulation of 30% by bunching simulation.

We examined the self-amplified spontaneous emission (SASE) by bunched beams. The rapid field growth is found near the entrance of the wiggler. Within 2 wiggler periodes, the RF power rises up to 1MW (in the case of 30% density-modulated beams), followed by a linear gain evolution of 22dB/m, and reaching the saturation level of 70MW at the wiggler length of 1.3m.

Figure 6 shows the simulational results when a traveling wave of 100kW is inputted into the wiggler. In the case that the traveling wave is just in phase to the beam modulation wave, namely when the bunching center is positioned in the decelerating phase, the rapid field growth appears like the case of SASE. On the other hand, in the case that the traveling wave is just out of phase to the beam modulation wave, the RF field starts to grow after its rapid decrease. The initial field evolution is thus affected by their phase difference.

We are now examining the feasibility to control the output RF phase by adjusting the input RF phase, which is a critical issue of the TBA/FEL. Preliminary results show the controllable range of the output RF phase is only ± 20 degrees in the case of the 30% density-modulated beam and the 100kW input RF. IF a few MW RF source is available, the controllable range is expected to be more than ± 60 degrees. The bunching becoming tighter, the input RF power required to control the output RF phase ought to be larger.

Conclusion

We have designed the hybrid FEL system consisting of a pre-bunching and a standard FEL systems. The pre-bunching system enables the injection of 30% density-modulated 800A beams, resulting in the saturation output power of 70MW with the wiggler length of 1.3m . We have also confirmed the initial field evolution is strongly influenced by the phase difference between the input RF and the beam modulation wave.

References

[1] T.Ozaki *et.al.*, Nucl. Instr. and Meth. A318(1992)101
[2] J.Kishiro *et.al.*, Particle Accelerators 31(1990)83
[3] A.Sessler, AIP Conf. Proc. No.91, New York 1982
[4] S.Hiramatsu *et.al.*, Nucl. Instr. and Meth. A285(1989)83
[5] K.Takayama, Phys. Rev. Lett. 63(1989)516
[6] K.Takayama, *et.al.*, Nucl. Instr. and Meth. A320(1992)587

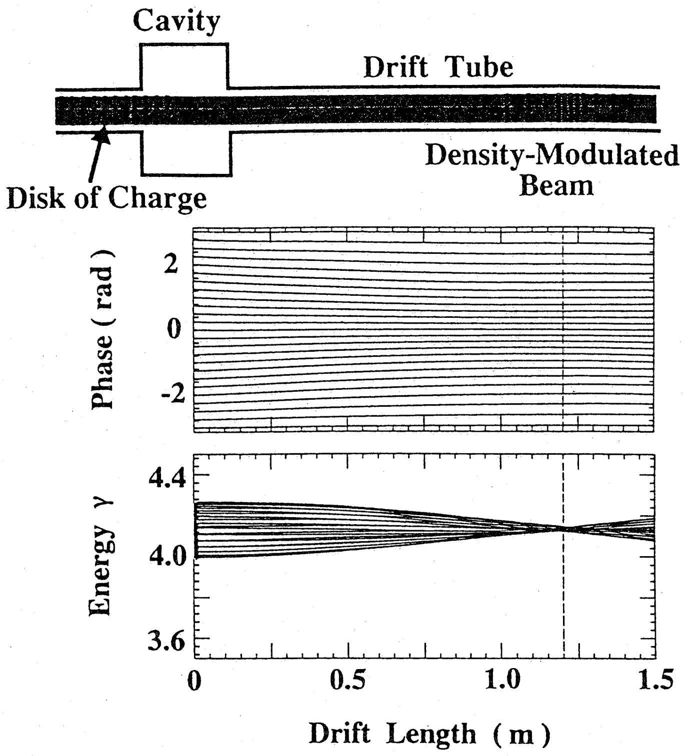

Fig.5 Beam Bunching

$I_b(\psi) = 700\,(1+0.3\sin\psi)$ [A],
$R_b = 2$ cm ,
$E_b = 1.6$ MeV , $\Delta E_b/E_b = \pm 10\%$,
$B_w(z) = 0.14\sin(k_w z)$ [T] ,
$\lambda_w = 16$ cm ,
$f_r = 9.4$ GHz , TE_{01} Mode ,
$P_{RF,in} =$ 100kW

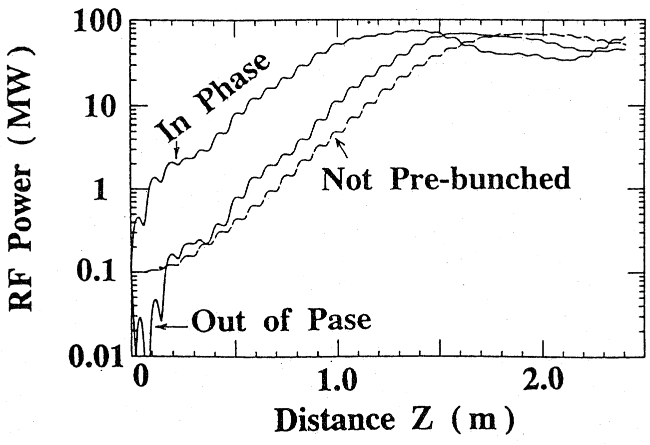

Fig.6 RF Amplification with an Inputted RF