Particle Accelerators, 1990, Vol. 31, pp. 75–81
Reprints available directly from the publisher
Photocopying permitted by license only

CONCEPTUAL DESIGN OF A LINEAR COLLIDER IN THE TBA/FEL REGIME

S. HIRAMATSU, K. EBIHARA, Y. KIMURA, J. KISHIRO, T. OZAKI, K. TAKAYAMA
National Laboratory for High Energy Physics,
1-1 Oho, Tsukuba, Ibaraki, 305, Japan

H. KURINO
Tohoku University, Sendai, Miyagi, 980, Japan

Abstract The stability analysis for a klystron-type free-electron laser in the microwave regime, which eliminates the number of problems intrinsic in the original version of the TBA/FEL, has demonstrated the possibility of multi-staging. A 500 GeV×2 linear collider employing such a multi-stage FEL as a microwave source has been conceptually designed with an accelerating gradient of 300 MeV/m.

INTRODUCTION

For a TeV-class linear collider, an extremely high power rf source is required in order to limit its length to a reasonable size. A linear collider employing the free-electron laser (FEL) in a multi-stage configuration driven by an induction linac, a so-called two-beam accelerator (TBA/FEL), was proposed originaly by A. M. Sessler.[1] As a successful single-stage experiment of 35 GHz and 1 GW has been demonstrated,[2] the FEL in the microwave regime is one of the most promising candidates as a powerful rf source for the future high gradient linac. Recently, to eliminate the problems intrinsic in the original version, a multi-stage configuration of klystron-type FELs (KFEL) has been proposed as a new version of the TBA/FEL,[3] where a small rf signal of order of 100 kW is fed in at the start of each period and amplified by the FEL to the GW order power, and the rf is removed out at the end of the period.

In this report we propose a 500 GeV×2 linear collider employing a multi-stage KFEL based on the stability analysis by the macroparticle model where an intrinsic feature of the longitudinal stability of the multi-stage KFEL[4,14] has been manifested. The essential key issue of the two-beam accelerator concept is how far a kiloampere driving beam can be propagated in the steady state regime; the strong beam break-up instability (BBU) and resistive wall instability[5] will prevent the long distance propagation of a high current electron beam. Beam transport in the laser assisted ion focusing regime (IFR) is considered in the proposed TBA/FEL to avoid these instabilities.

As a R/D work for the linear collider in the TBA/FEL regime, a test stand of the X-band FEL, which is driven by an induction linac energized with magnetic pulse compressors, has almost completed at KEK.[6] In this test stand a preliminary beam transport experiment in the IFR has been successfuly demonstrated,[7] and experimental investigations are planned on the microwave FEL in the IFR.

RF POWER REQUIREMENT IN THE LINAC

The accelerating rf field in the linac is required to be highest possible and consistent with breakdown. As the breakdown limit is expected to be higher than 1 GV/m at a rf frequency higher than 30 GHz,[8] we assume the linac could be operated at the average accelerating field of E_0=300 MV/m without breakdown at f=17 GHz. Supposing an ~100 nsec pulse width of the induction linac for driving FELs, the filling time T_f of the accelerating structure is asuumed to be 90 nsec. If we require less than 500 MV/m for the local accelerating field, the attenuation parameter τ should be less than 0.9 which restricts the rf frequency to be less than ~18 GHz.

In order to save rf power, we have optimized the power requirement using the analytic expressions of the structure parameters developed by Z. D. Farkas for the SLAC-type $2\pi/3$ mode disc loaded accelerating structure.[9] For a given attenuation parameter τ and a section length L, the peak power per unit length P_0/L is minimized for $a/\lambda=0.163$, where a is the disk aperture and λ the wavelength, respectively, and is given by

$$\left(\frac{P_0}{L}\right)_{min}=3.75\times\frac{\tau^{2/3}}{(1-e^{-\tau})^2}\,[L(m)]^{1/3}\,[E_0(GV/m)]^2 \quad (GW/m), \tag{1}$$

where the group velocity in light velocity units is $v_g/c=5.01\%$.
For $E_0=300$ MV/m, f=17 GHz and $T_f=90$ nsec, Eq. (1) gives $(P_0/L)_{min}=1.04$ GW/m, $\tau=0.834$ and L=1.35 m.

Since T_f is restricted by the induction linac, it may be usefull to derive the minimum peak power requirement for a given T_f and τ. In this case, P_0/L is minimized at $a/\lambda=0.0939$, and

$$\left(\frac{P_0}{L}\right)_{min}=7.03\times\frac{\tau^{2/3}}{(1-e^{-\tau})^2}\,[T_f(nsec)]^{1/3}\,[E_0(GV/m)]^2 \quad (GW/m), \tag{2}$$

where $v_g/c=0.809$ %. It should be noted that the peak power requirement given by Eq. (2) is 76 % of that given by Eq. (1) for the same T_f and τ. Equation (2) gives $\tau=0.843$ and $(P_0/L)_{min}=0.79$ GW/m; however, a small group velocity requires a short section length of $L=21.8$ cm, which is too short for a practical linac design. For saving peak power, a/λ should be chosen in the range of $0.094<a/\lambda<0.163$. Here we present the structure parameters with $L=75$ cm which fits a practical FEL period length. For this section length, we obtain $v_g/c=2.78\%$ and the power requirement of $P_0/L=0.88$ GW/m. Table 1 summarizes three designs of the structure parameters. Hereafter we consider the TBA/FEL based on the case 3 design in Table 1. Supposing the 3 m-long FEL period, the output power of each FEL stage must be larger than 2.6 GW and is divided into four linac sections.

TABLE I Structure parameters in the SLAC-type $2\pi/3$ mode disk loaded structure for $E_0=300$MeV/m at $f=17$ GHz and $T_f=90$ nsec.

	1	2	3
a/λ	0.163	0.0939	0.134
τ	0.834	0.843	0.840
v_g/c (%)	5.01	0.809	2.78
L (cm)	135	21.8	75
P_0/L (GW/m)	1.04	0.79	0.88

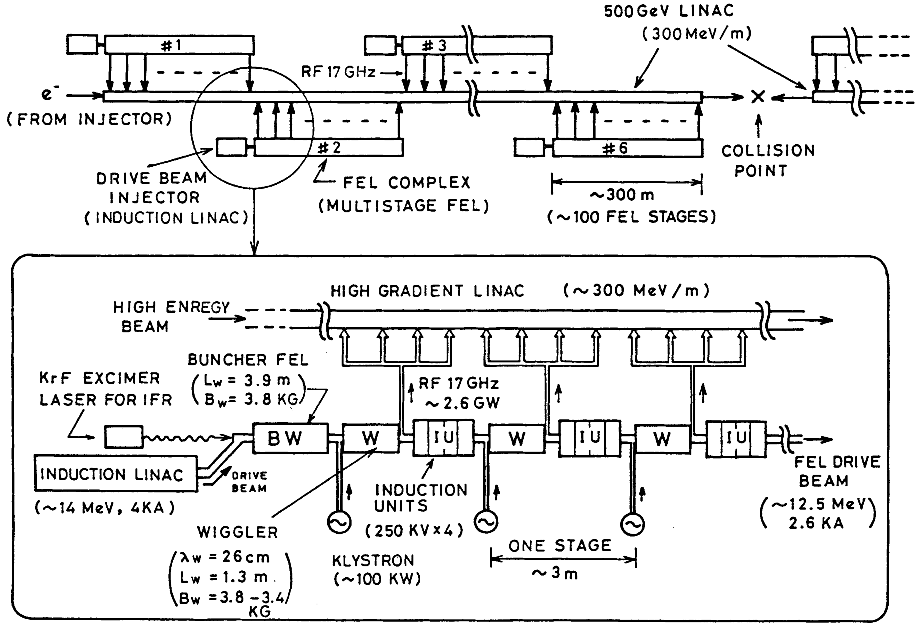

FIGURE 1 Conceptual illustration of the 500 GeV×2 linear collider in the TBA/FEL regime.

In Fig. 1 is conceptually illustrated the 500 GeV×2 linear collider in the TBA/FEL concept employing the multi-stage KFEL, which is driven by an induction linac of $E_0 \sim 14$ MeV with ~100 nsec pulse width. Since the subsequent multi-stage FEL performance becomes possible for initially bunched beams, the FEL driving beam is injected into the buncher FEL. In order to provide the longitudinal stability of the driving beam, a constant gradient tapered wiggler is employed. The part of beam energy which is converted into microwave power in each FEL is recompensated with the reacceleration unit by $\Delta E = mc^2 \Delta\gamma = 1$ MeV after passing through the wiggler region. A 3 m-long single period consists of a 1.3 m long tapered wiggler with $\lambda_w = 26$ cm and four 250 kV induction units. A beam current of $I \gtrsim 2.6$ kA is required to satisfy the peak power requirement of 2.6 GW/3m.

MULTI-STAGE FEL

Essential nature of coherent longitudinal motion coupled with the rf's spatial-evolution have been self-consistently manifested by means of the macroparticle approach (MPA)[4,10] where a rigid bunch is assumed and the macroparticle corresponds to its center. According to the MPA, the period-to-period evolution of beam energy γ_a and pondermotive phase ψ_a of the MP, and output rf's phase ϕ_s are described in a recursion form and the solutions are given by

$$\delta_{n+1} = (1-\mu)^{n+1} \{\delta_0 + (\Delta\gamma/\mu)(\Delta J/J_0)\} - (\Delta\gamma/\mu)(\Delta J/J_0),$$

$$\psi_a^{n+1} = \psi_a^{n} - |b(\gamma_a^n)| L_w + \Delta\phi_s(\text{constant}),$$

$$(\phi_s)^n_{out} = (n-1)\Delta\phi_s + \int_0^{|b|L_w} e^{-y(s)} \{1-(y'(s))e^{2y(s)}\}^{1/2} ds,$$

$$b(\gamma_a^n) = k_w - \delta k_s - (\omega_s/2c)\{b_w(0)/k_w\gamma_a^n\}^2,$$

$$\mu = \frac{2\Delta\gamma}{\gamma_0} \left\{ \frac{1+\gamma_0^2/\gamma_s^2}{1-\gamma_0^2/\gamma_s^2} - \frac{\omega_s}{c} \frac{a_w^2}{\gamma_0^2} y'(|b(\gamma_0)|L_w) \right\},$$

where δ_n is a small deviation from the designed value γ_0 ($\delta_n = \gamma_a^n - \gamma_0$), ΔJ is the injection current error ($\Delta J = J - J_0$), $y(s)$ and $y'(s)$ are the universal gain function and its derivative, and other notations are same as in Ref. 4. If the stability condition $0 < \mu < 2$ is satisfied, the deviation δ will reach an equilibrium state $-(\Delta\gamma/\mu)(\Delta J/J_0)$ and $(\phi_s)_{out}$ is stabilized in a similar way. Thus it turns out that a KFEL is intrinsically stable against injection errors or perturbations through periods. In Fig. 2 is shown an example of the energy deviation damping and in Fig. 3 the stable region on the parameter plane of $\Delta\gamma/\gamma_0$ and $b_w(0)/\gamma_0 k_w$.

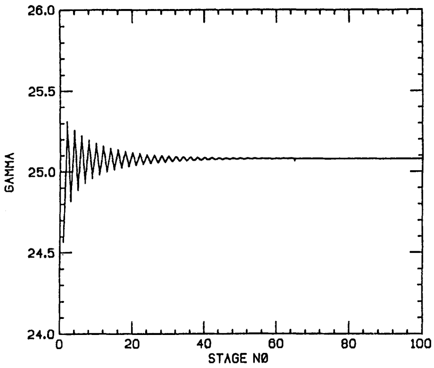

FIGURE 2 Energy deviation damping in the multi-stage KFEL.

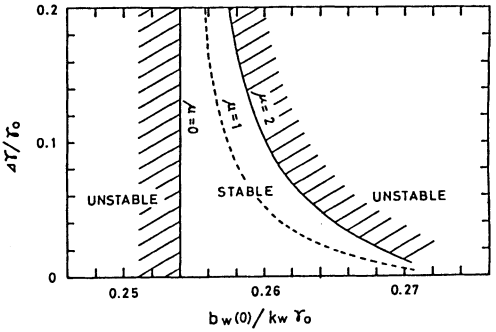

FIGURE 3 Stable region.

The assumption of a rigid bunch has also been ensured by stability analysis of a microparticle.[10] The motion of the microparticle around the MP is dominated by a kind of Hill's equation,

$$\xi'' + G\left[e^{y(s)}\left\{1-(y'(s)e^{y(s)})^2\right\}^{1/2}\delta(s) - H\right]\xi = 0,$$

where ξ is the oscillation amplitude of the microparticle ($\xi = \psi - \psi_a$), G is a function of FEL parameters, and H is relevant to longitudinal space charge forces. Solutions of the above equation have been shown to be bounded over a wide-range of KFEL parameters. The fact means that a bunch subject to the periodic transient process is not destroyed.

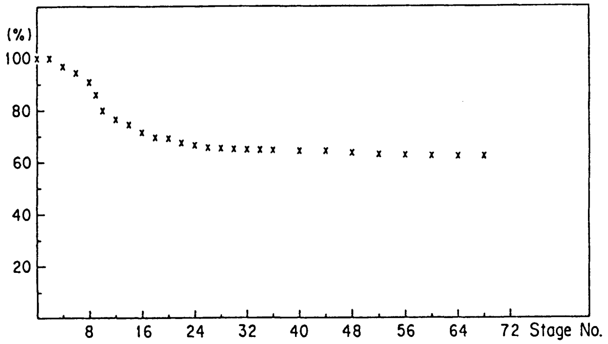

FIGURE 4 Trapping efficiency of the driving beam in the multi-stage KFEL.

The theory established by the MPA has been reconfirmed by multi-particle simulations. However, there is an important feature that can be demonstrated only by simulation: a fraction of beam injected from the FEL buncher into the regular FEL region is lost due to phase-space mismatching which originates from a long tail generated in the buncher FEL but the trapping efficiency saturates beyond 20 stages as seen in Fig. 4. Eventually the conversion efficiency from the beam power to the rf power will reach more than 84% for multi-staging that exceeds 100 for the present example.

TRANSVERSE STABILITY OF THE DRIVING BEAM

Another key issue in the TBA/FEL is the long distance propagation of multi-kiloampere beam. Although a large energy spread is produced in the driving beam from the synchrotron oscillation in a large rf bucket, a phase mix damping for the beam break-up (BBU) and resistive wall instability can not be expected since the wavelength of the synchrotron oscillation is the same order as the betatron wavelength in the multi-stage FEL.[5]

The BBU may be the most severe problem for high current beam propagation; in fact, for a beam current of $I=2$ kA at an energy of $\gamma=25$, a theoretical estimation gives the following growth lengths,

$$L_R = 2\pi(2/3)^{3/2}(\sigma\,\mu_0)^{1/2}(\gamma b^3/\lambda_\beta)(I_0/I)\,\tau^{-1/2} = 1.4 \text{ km},$$

$$L_{BBU} = (2L_g k_\beta \gamma/\omega_\lambda Z_\perp)(I_0/I) = 90 \text{ m}.$$

where the transverse coupling impedance of the induction gap of $Z_\perp = 4\times 20\,\Omega$ at a mode frequency of $\omega_\lambda = 2\pi\times 800$ MHz ($\omega_\lambda Z_\perp = 0.45$ cm^{-1}), $\lambda_\beta = 2$ m, a period length of $L_g = 3$ m, $b = 5$ cm, and a pulse length of $\tau = 100$ nsec are assumed. And numerical simulation indicates some optimistic feature for BBU.[11] One of the possible ways to suppress the BBU growth is to introduce a spread in the betatron wavenumber caused by nonlinearity as seen in beam transport in the IFR.[12] The BBU growth in this example can be suppressed by a phase mix damping with $\Delta k_\beta/k_\beta = \pi/k_\beta L_{BBU} = 1.1\%$.

In addition, beam guiding in the IFR may require no extra magnets for phase space matching between a reacceleration unit and a FEL wiggler, and will have no serious problems for the FEL performance in the microwave regime.[13] Although the hose instability may cause some problems because the beam energy is almost constant along the multi-stage FEL, it is expected that a strong nonlinearity in the IFR will damp even the hose instability within a few betatron wavelengths. A preliminary estimation in the IFR shows that the normalized beam emittance less than 0.5 cm•rad is necessary to prevent beam head erosion and to keep a reasonable equilibrium beam size .

SUMMARY

A linear collider of 500 GeV×2 in the TBA/FEL regime has been proposed. Such a linac is accompanied with six FEL complexes. An accelerating gradient of 300 MeV/m will be achieved with the rf power of 2.6 GW at 17GHz fed from KFELs. Each multi-stage FEL driven by an induction linac of ~14 MeV consists of ~100 FEL stages ~300 m in length. An induction linac and the energy recovery units are energized with magnetic pulse compressors at a repetition rate of more than 1 kHz, which promises a luminosity of $\gtrsim 1\times10^{33}$ $cm^{-2}sec^{-1}$ in a single bunch operation. The collider will have a total length of about 3.5 km+(final focus length) and the average electric power consumption of ~370 MW is estimated. If the collider is operated less than 500 Hz in a multi-bunch mode, the average power will be saved within 200 MW. IFR beam transport is considered as one of the possible ways to avoid BBU. A detailed investigation is required on the emittance growth taking into account the nonlinear features of IFR.

REFERENCES

1. A.M.Sessler, Proc. Workshop on Laser Acceleration of Particles, AIP Conf. Proc. 91 (1982) 154.
2. T.J.Orzechowski et al., Phys. Rev. Lett. 57 (1986) 2172.
3. A.M.Sessler et al., Proc. 10th Int. Conf. Appl. Acc. in Res. and Ind., Nucl. Instr. and Meth. B40/41 (1989) 1064.
4. K.Takayama, Phys. Rev. Letters, 63 (1989) 516.
5. K.Takayama, Phys. Rev., A39 (1989) 184.
6. S.Hiramatsu et al., Proc. 10th Int. FEL Conf.(to be published); KEK Preprint 88-72, 1988.
   J.Kishiro et al., contributed to this conference.
7. H.Kurino et al., contributed to this conference.
8. P.B.Wilson, SLAC-PUB-2674, 1985.
   R.B.Palmer, SLAC-PUB-4295, 1987.
9. Z.D.Farkas, SLAC-PUB-4722, 1988.
10. K.Takayama and S.Hiramatsu, Proc. 11th Int.FEL Conf. (to be published).
11. D.H.Whittum and G.A.Travish, private communication.
12. G.J.Caporaso et al., Phys. Rev. Lett. 57 (1986) 1591.
13. K.Takayama and S.Hiramatsu, Phys. Rev. A37 (1988) 173.
14. A.M.Sessler et al., contributed to this conference.