A LINEAR COLLIDER IN THE TBA SCHEME USING MICROWAVE FREE ELECTRON LASERS

J.Kishiro, K.Ebihara, S.Hiramatsu, Y.Kimura, H.Kurino*, T.Monaka, T.Ozaki and K.Takayama

National Laboratory for High Energy Physics
1-1, Oho, Tsukuba, Ibaraki, 305, Japan
(*) Department of Physics, Tohoku University, Sendai, 980, Japan

Abstract

A 500 GeVx2 high energy linear collider in the two beam accelerator scheme (TBA) has been conceptually designed. The collider can be realized by employing a multi-stage free electron laser (FEL) as a extremely high power microwave source. The stability analysis for a klystron-type FEL in the microwave regime is also described in this article.

Introduction

An accelerator for the high energy physics is requested to increase its energy up to more than 500 GeV. The size of such a high energy linear collider might be more than 30 km and the number of rf sources, such as klystrons, increases to several tens of thousand, if we take conventional technologies. A linear collider employing the free electron laser (FEL) in a multi-stage configuration driven by an induction linac was proposed by A.M.Sessler[1], which is called a two beam accelerator (TBA). A successful single-stage experiment of the FEL had been carried out for the rf frequency of 35 GHz, and the possibility to obtain an 1 GW rf power was also demonstrated[2]. This indicates that the FEL in the microwave regime is one of most promising instruments as a GW order powerful rf source in a future high gradient linac. The collider size might be reduced down to 4 km and a high efficiency of the multi-stage FEL enables us to realize such high energy collider because of the low primary electric power requirement.

A new version of the multi-stage FEL, klystron-type FEL (KFEL), has been also proposed[3] to overcome the difficulties intrinsic in the original version, where the amplified rf signal is removed out in whole at the end of the each stage and the input small signal is fed into the stage independently. An intrinsic-feature of the longitudinal stability of the multi-stage KFEL has been manifested by the macroparticle model[4,5], which enables us to design a 500 GeVx2 linear collider employing a multi- stage KFEL as a high power rf source.

How far can be propagated a kilo-ampere FEL driving electron beam in the steady-state regime, that is an essential key issue of the TBA scheme. The strong beam break-up instability (BBU) and the resistive wall instability[6] has to be investigated and overcome to make the long distance propagation of a high current electron beam possible. The beam transport in the laser assisted ion focusing regime (IFR) might be a promising scheme to avoid these instabilities because of its strong non- linear focusing force.

A R/D work for the linear collider in the TBA/FEL scheme started at KEK and the construction of a single-stage X-band FEL test stand has been completed, which is driven by an induction linac energized with two magnetic pulse compressors. The feasibility of the IFR has been also demonstrated in this test stand[7].

Linear Collider in the TBA/FEL

In contrast to the conventional klystron, the FEL easily generates the rf power of order of GW capable of producing the accelerating field of several hundred MV/m. The breakdown limit is expected to be so higher than 1 GV/m at 30 GHz[8,9] that we take the accelerating gradient of 300 MV/m at 17 GHz. The rf frequency of 17 GHz seems to be adequate by taking into account the local over voltage less than 500 MV/m, because to reduce it the attenuation factor τ should be less than 0.9 and the restriction to τ requires the rf frequency less than 18 GHz.

The filling time T_f of the accelerating structure is strongly limited because of the short pulse duration of the FEL driving beam, it takes about 100 nsec so T_f is assumed to be 90 nsec in this design.

The optimization of the required rf power in the linac has been done by using the expression developed by Z.D.Farkas[10], and shows that the peak power in a unit length of the structure is minimized and given as follow:

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

Equation (1) shows the minimum peak power for the case of $a/\lambda = 0.0939$, where a and λ are the cavity aperture and the wavelength, respectively, and the group velocity in the unit of light velocity is taken to be v_g/c=0.809 %. The smaller is the group velocity, the shorter accelerating section we have to make, so that it should be taking into account of the practical size of the section.

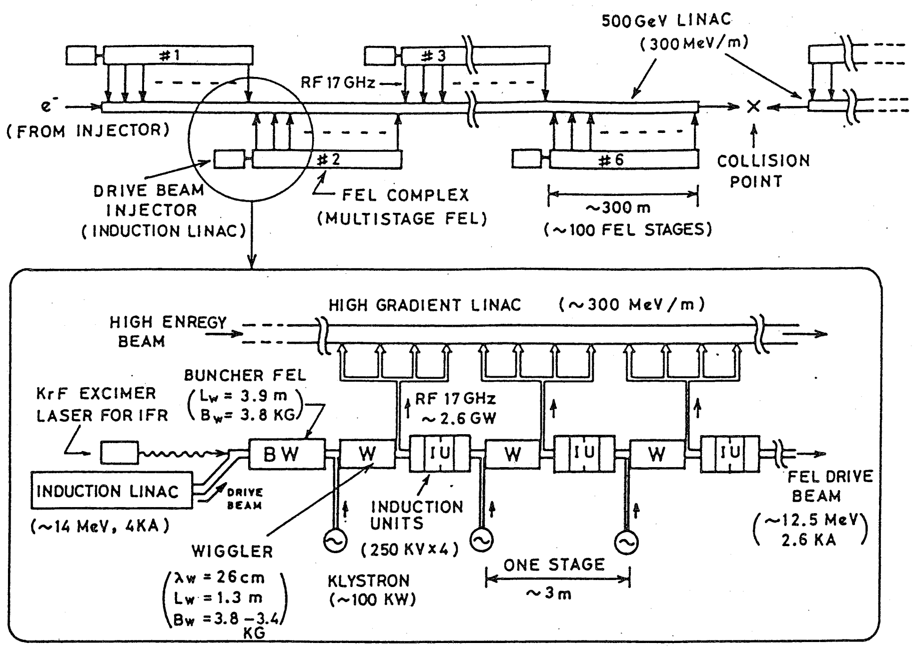

Fig.1 Conceptual illustration of the 500 GeVx2 linear collider in the TBA/FEL regime.

The most significant parameter is a/λ which should ranges from 0.094 to 0.163 in order to minimize the peak power. According to this range, we take $a/\lambda = 0.134$ which provides the section length of 75 cm. This design_fit a practical FEL period length, 3 m. The output power larger than 2.6 GW should be generated in each FEL stage and divided into four to energize the 75 cm accelerating structure.

Fig.1 illustrates the conceptual design of the 500 GeVx2 linear collider in the TBA/FEL concept employing the multi-stage KFEL, which is driven by an induction linac of E_0 ~14 MeV with ~100 nsec pulse width. Since the multi-stage FEL performance is made efficient by driving a bunched beam, a buncher FEL is placed at the upstream of the normal FELs. The wiggler field has a constant gradient taper, which provides either the rf power enhancement and the longitudinal beam stability. It has to be re- compensated the beam energy, $\Delta E = 1$ MeV, which goes into the rf power in each FEL, by employing a induction accelerator unit. A period of the FEL stage has the length of 3 m, in which 1.3 m is occupied by the wiggler magnet and the remnant is reserved for both the energy compensation induction unit and the instruments for rf/beam monitors.

Stability of the KFEL

The capability of the multi-stage FEL as a rf source for linac is strongly dependent on the stable rf generation in each stage. The fluctuations in the rf power and phase may cause the difficulties in the desired linac performance.

To manifest essential features of the longitudinal stability[4] and output rf phase's sensitivity against injection errors[11], we have developed extensive computer simulations and the macroparticle analysis where the gain of a KFEL has been proved to be dominated by the universal gain equation:

$$y'' = -\sqrt{e^{-2y} - (y')^2} + e^{-2y} - 2(y')^2 \tag{2}$$

where y is proportional to e_s (normalized signal field) and primes represent the derivative with respect to the normalized wiggler distance s. Following the macroparticle approach in Ref. 4, the spatial evolution of beam energy, pondermotive phase, and output rf phase are described in recursion forms from period to period:

$$\gamma_a^{n+1} = \gamma_a^n - \frac{k}{4}[\frac{eZ_0 J}{mc^2}]\frac{a_w^2(0)}{(\gamma_a^n)^2}\frac{\exp\left[2y(|b(\gamma_a^n)|L_w)\right]}{|b(\gamma_a^n)|^2} + \Delta\gamma \tag{3}$$

$$\psi_a^{n+1} = \psi_a^n - |b(\gamma_a^n)|L_w + \Delta\phi_s \tag{4}$$

$$(\phi_s)_{out}^n = (n-1)\Delta\phi_s + \int_0^{|b|L_w} e^{-y(s)}\sqrt{1-(y'(s))e^{2y(s)}}ds \tag{5}$$

where J is a beam current density, Z_0 is the resistivity in vacuum, a_w is a normalized wiggler field-strength divided by the wavenumber, L_w is a wiggler length,

$\Delta\gamma$ is the energy gain, - $|b(\gamma_a^n)|L_w$ is the beam phase-advance through the n-th wiggler,respectively. And eq.(5) has initial conditions:

$$e^{y(0)} \propto \frac{e_s(0)}{J}$$

$$y'(0) = \frac{\sin\psi_a^n}{e^{y(0)}}$$

Assuming a current error ΔJ where $\Delta J = J_0 - J$, the recursion formula (3) for a small deviation from the designed value γ_0 is written in a linearized form of:

$$\delta_{n+1} = (1-\mu)\delta_n - \Delta\gamma\frac{\Delta J}{J_0} \quad (6)$$

$$(\delta_n = \gamma_n - \gamma_0)$$

with:

$$\mu = \frac{2\Delta\gamma}{\gamma_0}\left[\frac{1+\frac{\gamma_0^2}{\gamma_s^2}}{1-\frac{\gamma_0^2}{\gamma_s^2}} - \frac{\omega_s}{c^2}\frac{aw^2}{\gamma_0^2}y'(|b(\gamma_0)|L_w)\right] \quad (7)$$

Its solution is:

$$\delta_{n+1} = (1-\mu)^{n+1}\left[\delta_0 + \left(\frac{\Delta\gamma}{\mu}\right)\left(\frac{\Delta J}{J_0}\right)\right] - \left(\frac{\Delta\gamma}{\mu}\right)\left(\frac{\Delta J}{J_0}\right) \quad (8)$$

The small deviation is known to reach an equilibrium state, $-\frac{\Delta\gamma}{\mu}\frac{\Delta J}{J_0}$ when $0 < \mu < 2$. This yields a shot-to-shot fluctuation in the output rf power of $\frac{1}{\mu}\frac{\Delta J}{J_0}$. Fig.2 demonstrates how the energy deviation is damped for $\Delta J = 0$. The output rf power is stabilized in the similar way. Although the fluctuations in the pondermotive phase and rf phase tend to decrease associated with stabilizing of γ_a^n, the shift in the rf phase ϕ_s is inevitable due to a combination of eq.(4) and the initial conditions; however, the shift is less sensitive to injection errors and its magnitude is tolerable for a typical example. These characteristics have been confirmed with multiparticle computer simulations.

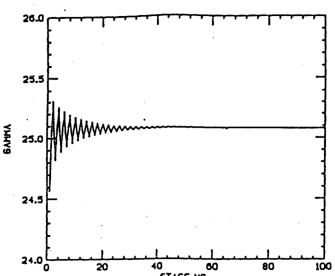

Fig.2 Energy deviation damping in the multi-stage KFEL.

Meanwhile, stability of the bunch shape itself is also studied by investigating a motion of microparticle moving around the macroparticle[12]. The motion of the microparticle around the macroparticle is described by a kind of Hill's equation, and the exact solution of it shows that the bunch subject to the periodic transient process is not destroyed. Thus the intrinsic stability of the KFEL has been established.

However, the transit process between the buncher FEL and the normal FELs is demonstrated only by a computer simulation, and which shows that a fractional part of the beam is lost due to phase-space mismatching caused from the long tail generated in the buncher FEL (Fig.3).

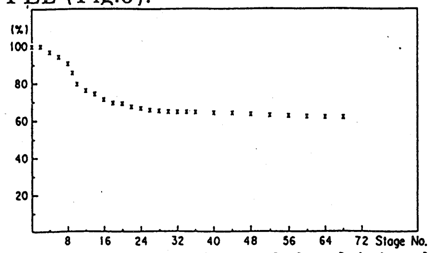

Fig.3 Trapping efficiency of the driving beam in the multi-stage KFEL

These loss have to be stational in order to get a constant rf power in the regular FELs and maintain the constant phasing of the rf signal. Eventually, the conversion efficiency from the beam power to the rf power will reach more than 84 % for 100 stage KFEL.

Summary

A linear collider of 500 GeVx2 is designed by beeing encouraged by the stability analysis for the beam bunch in FEL. The linac size can be reduced to about 2 km by employing six FEL complexes as the high power rf sources. The high power of 2.6 GW at 17 GHz is not difficult to generate if we take FEL, which is driven by an induction linac of 14 MeV. A combination of the induction linac and the energy recovery units are energized with the magnetic pulse compressors at a repetition rate of more than 1 kHz and promises a luminosity of $\geq 1\text{x}10^{33}$ $\text{cm}^{-2}\text{sec}^{-1}$ in a single bunch operation.

REFERENCES

1. A.M.Sessler, AIP Conf.Proc. No.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 Reg. and Ind., Nucl. Instr. and Meth. B40/41(1989)1064
4. K.Takayama, Phys. Rev. Lett. 63(1989)516
5. A.M.Sessler *et al.*, Proc. of the XIV Int. Conf. on High Energy Accelerator, 1989, Tsukuba, Japan
6. K.Takayama, Phys. Rev. A39(1989)184
7. H.Kurino *et al.*, Proc. of the XIV Int. Conf. on High Energy Accelerator, 1989, Tsukuba, Japan
8. P.B.Wilson, SLAC-PUB-2674, 1985
9. R.B.Palmer, SLAC-PUB-4295, 1987
10. Z.D.Farkas, SLAC-PUB-4722, 1988
11. K.Takayama, to be published.
12. K.Takayama and S.Hiramatsu, Proc. 11th Int. FEL. Conf.