Application of Quasi-optical Approach to Construct RF Power Supply For TeV Linear Colliders

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Abstract

An idea to use quasi-optical approach for constructing RF power supply for TeV linear e^+e^- colliders is developed. RF source of the proposed scheme is composed of a large number of low-powerful RF amplifiers commutated by quasi-optical elements. RF power of this source is transmitted to the accelerating structure of the collider by means of quasi-optical waveguides and mirrors. Conceptual project of 2×500 GeV X-band collider is considered. Accelerating structure of the collider is standard travelling wave one and RF source is assumed to be composed of 0.7 MW klystrons. All equipment of such a collider is placed in a tunnel of 12×6 m^2 cross section.

1 INTRODUCTION

The most popular approach to construct TeV linear collider assumes to develop standard klystron and accelerating structure technology operating in X-band [1]. It is assumed in all the projects that one klystron feeds one or several accelerating structures of the linear collider. To provide high average accelerating gradient ~ 100 MV/m, the length of accelerating section is usually chosen to be about of $l \sim 0.5 - 1$ m, klystron pulse duration $\tau \sim 100$ ns and klystron peak output power $P \sim 100$ MW. So as the half-length of 1 TeV linear collider is about of $L \sim 10$ km, the required number of klystrons is about of $2-4\times10^4$. During acceleration cycle of the linear collider, $T_c = L/c \sim 30$ μs, each klystron is switched on only once during time period $\tau \sim 100$ ns and number of simultaneously switched on klystrons is of the order of $c\tau/l$. So, the required peak RF power for the electron beam acceleration is about of $Pc\tau/l$ which is by $L/c\tau \sim 300$ times less than total peak RF power of all klystrons. One can obtain that a choice of standard klystron technique is not optimal for design of linear colliders of TeV energy range. First, a huge number of high-power klystrons is needed which may limit a reliability of the linear collider operation. Second, a high-cost RF equipment operates with extremely low duty factor.

In ref. [2] a novel approach to solve the problem of RF power supply for Tev-range linear colliders was proposed which is based on quasi-optical technique. That scheme of RF power supply was based on the use of phased array antenna as a summator and commutator of RF power of a large number of low-powerful amplifiers. This electronically scanned array transmits RF power through the air to the receiving array which feeds accelerating structures and is located in the vicinity of the accelerator. The length of accelerating structure commutated to the RF power supply at any moment of time is equal to $c\tau$. As a result, at the same number of klystrons, as in the traditional approach, the requirement on the peak power of each klystron is reduced by $L/c\tau$ times.

In the present paper we develop the quasi-optical approach aiming the goal to find such physical and technical solutions which will enable one to place RF supply using constraints accepted in linear collider projects. We extend our study with application of such quasi-optical elements as open mirror waveguide, lens waveguide, quasi-optical RF summator and plasma mirror.

We should emphasize that proposed approach does not reject all previous experience stored by powerful research groups during last decade: it entirely agrees with generally accepted solutions of linear collider design: injection system, accelerating structure, final focus, etc. The peculiarity of our approach is in the proposal of a novel concept of RF power supply.

2 LINEAR COLLIDER SCHEME

The main feature of the proposed scheme is that it uses quasi-optical summator as an RF power supply, quasi-optical microwave transmission line for transporting RF radiation, microwave deflectors as commutating elements and lens lines with directional couplers as RF power dividers.

The collider scheme is arranged as follows (see Fig.1).

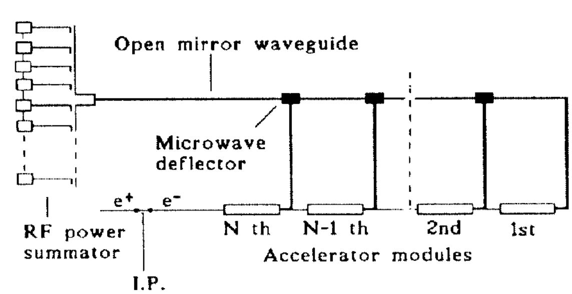

Figure 1: Linear collider scheme

The accelerator is sectioned into N identical modules. Each module consists of a large number of accelerating sections. RF power from the RF power supply is transported to the accelerator modules via microwave transmission line and is commutated to them by microwave deflectors. RF power supply operates in a pulsed mode and produces N pulses of duration τ during the accelerator duty cycle. Time interval between pulses is equal to $T \simeq (c^{-1} + v_z^{-1})L/N$, where v_z is the group velocity of the wave along the axis of the microwave transmission line.

The duty cycle of the accelerator proceeds as follows. The first RF pulse is transported via the microwave transmission line to the first (injector) accelerator module. During the time period T between the RF pulses, the first microwave deflector is switched on and the second RF pulse is directed to the second module. Prior to arrival of the third RF pulse, the second microwave deflector is switched on and directs it to the third module, etc. Distribution of the RF power among accelerating sections of each module is provided by means of the lens line with directional couplers (see Fig.2). As a result, such a system provides commutation of the RF power along the accelerator with the velocity of light c. It is seen that the presented linear collider scheme has benefit in the required peak RF power by N times with respect to traditional scheme based on klystron technique.

Detailed study of the key elements of the proposed linear collider scheme is presented in ref. [3].

RF power source is constructed on the base of serial low-power amplifiers using quasi-optical RF power summator technique which has been developed for needs of radar applications. The main element of quasi-optical RF power summator is quasi-optical directive coupler which has the form of wire grid placed at the angle of 45^0 with respect to the quasi-optical waveguide axis. To make an arrangement of the RF source to be more compact, the RF summator scheme is designed using tree-like structure.

Microwave transmission line has a form of an open periscopic mirror waveguide. For X-band RF wavelength range, at transverse dimensions of the waveguide about of 2×3 m^2 and at the distance between the pairs of mirrors about of 15 m, diffraction losses are negligibly small with respect to the heat losses. For copper mirrors, the heat losses are about of 3×10^{-4} per one mirror.

Plasma mirror is used as microwave deflector. The principle of its operation consists in reflection of electromagnetic wave from plasma layer. It may be realized technically in the form of plane gas volume inclined by the angle of 45^0 with respect to the waveguide axis. We assume to use external electron beam to provide steering the plasma mirror. The rising time of such a device (which is given with the relaxation time of the plasma into the equilibrium state of free electrons) is of the order of several hundreds of nanoseconds. After turning off the external electron beam the electron-ion recombination takes place and the microwave deflector comes to the initial state after a time period about of several milliseconds.

Lens waveguide with directional couplers is used as RF power divider (see Fig.2). It is composed of identical, even spaced long-focus lens. Such a waveguide provides stable transportation of the TEM-mode. To divide RF power among the accelerating sections, directional couplers are installed in each waveguide period. Each coupler consists

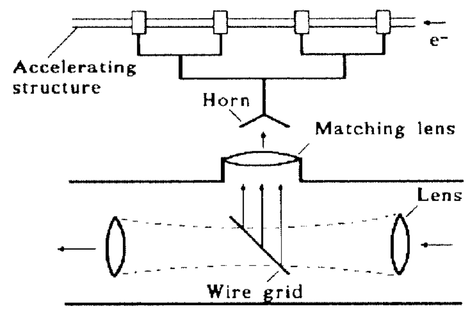

Figure 2: RF power divider

of wire grid and matching dielectric lens and feeds several accelerating sections via single-mode waveguides. The latter ones have time delayer providing synchronization of adjacent accelerating sections.

3 CONCEPTUAL PROJECT

To illustrate proposed scheme, we present conceptual project of 2×0.5 TeV linear collider operating in X-band. All the accelerator and RF equipment may pe placed inside the single underground tunnel with transverse dimensions about of 12×6 m^2 (see Fig.3).

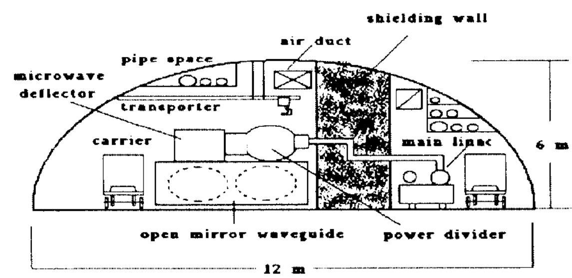

Figure 3: Placement of equipment in the accelerator tunnel

3.1 Linear accelerator

Linear collider consists of two linear accelerators: one for electrons and another for positrons. The length of each accelerator is $L = 10$ km. Parameters of the accelerating sections are chosen as follows: RF wavelength $\lambda_{RF} = 3$ cm, length of accelerating section $l = 0.7$ m, filling time $\tau = 0.1$ μs. Average accelerating gradient 50 MV/m is achieved at the peak RF power $P = 30$ MW per one accelerating section. The duration of the accelerating cycle is equal to $L/c \simeq 33$ μs and repetition rate is equal to 300 Hz. It is assumed that each accelerator is divided into $N = 100$ identical modules.

3.2 RF power supply

We assume RF power supply to be quasi-optical summator which sums up the power of 15000 RF amplifiers which operate in a pulsed mode providing 100 pulses of 0.1 μs duration within accelerator duty cycle. The time period between pulses is equal to $\simeq 0.6$ μs. Each RF amplifier provides 0.7 MW and 2 kW of the peak and average output RF power, respectively. Parameters close to those required are provided by X3030 klystron developed by the Varian for space communications. It operates in a CW mode with 1 MW output power at a frequency 8 GHz. Its efficiency is equal to 50 %, amplification factor is equal to 35 dB and accelerating voltage is equal to 110 kV.

3.3 *Microwave transmission line*

Microwave transmission line is periscopic open mirror waveguide. To provide total RF power losses to be small, the distance between the pairs of mirrors and radius of mirrors are chosen to be equal to $d = 15$ m and $R = 1$ m, respectively. The peak RF power flux on the mirror surface is of the order of 0.3 MW/cm^2 which corresponds to the strength of the surface electric field about of 10 kV/cm. So, we may conclude that electric durability of this open mirror waveguide is rather large.

Maximal RF losses occur for the first RF pulse which travels through the full length of the transmission line. The number of reflection in this case is equal to $2L/d \simeq 1200$ and total RF power losses are equal to 40 %. The RF power losses, averaged over all the RF pulses are about 20 %. Maximal heat losses occur in the first mirror and are about of 8 kW.

3.4 *Microwave deflectors*

Plasma mirror is used to provide commutation of powerful RF beam [3]. Plasma mirror presents plane chamber filled with gas mixture (He at 2 torr pressure and Hg vapor). Side walls of the gas chamber are made of quartz glass of 1 cm thickness. Plasma mirror is switched on by the sheet electron beam ($E \sim 200$ keV, $I \sim 4.5$ kA) which is produced by pulsed diode mounted in the wall of gas chamber and is injected into the chamber through Ti foil (foil thickness ~ 10 μm). The electron beam cross section inside gas volume is equal to 150×3 cm^2 ($j_b = 10$ A/cm^2) which results in the rate of the free electron production $S \simeq 10^{19}$ cm^{-3}s^{-1}, recombination factor $\gamma \simeq 10^{-6}$ cm^3/s, relaxation constant $\tau_d \simeq 300$ ns and equilibrium electron density $n_o = (S/\gamma)^{1/2} \simeq 3 \times 10^{12}$ cm^{-3}. Such a plasma totally reflects electromagnetic wave with the frequency of 10 GHz (penetration depth of radiation into plasma is about of 0.3 cm).

The heat RF losses in the chamber walls are equal to 0.005 dB and the reflection losses - 0.005 dB per one deflector. Taking into account the number of microwave deflectors to be equal to 100, the averaged RF losses are equal to 0.5 dB.

3.5 *RF power dividers*

The RF lens lines (see Fig.2) are placed along the accelerator modules and their number is equal to $N = 100$, the number of accelerator modules. The length of each RF lens line is equal to 100 m. The RF lens line consists of polystyrene lenses and is placed inside the tube with diameter 1.2 m filled with the air at atmospheric pressure. The distance between lenses in the waveguide is equal to 3 m, focus distance is equal to 1.5 m and their maximal thickness is equal to 6 cm. The lens aperture equal to 1 m provides the diffraction losses to be negligibly small.

RF power losses per one lens are equal to 0.013 dB (including 0.005 dB reflection losses) and average RF losses in the lens RF line are equal to 0.2 dB. Another source of the RF power losses is the losses in the directional couplers which match the RF lens line with the single-mode waveguides of the accelerating sections. The value of these losses is about of 0.2 dB per one directional coupler.

3.6 *RF power losses*

Total RF power losses of the proposed linear collider scheme are composed of losses in the quasi-optical RF power summator (10 %), heat losses in the microwave transmission line (20 %), heat and reflection losses in the microwave deflectors (15 %), heat and reflection losses in the RF lens lines (5 %) and losses in the directional couplers matching the RF lines with the accelerating sections (5 %). For the total RF power losses we obtain the value about of 55 %.

Total average RF power required for 2×0.5 TeV linear collider is about of 2×30 MW. Assuming the klystron efficiency to be about of 50 % and efficiency of a high-voltage system to be about of 80 %, we obtain that electric power consumption will be of the order of 150 MW.

3.7 *Perspectives*

Replacement of 0.7 MW klystrons with 3 MW klystrons will allow one to double the accelerating gradient and increase the center-of-mass energy of the linear collider up to 2 TeV.

4 CONCLUSION

In this paper we have presented novel linear collider scheme based on application of quasi-optical approach for constructing RF power supply for TeV linear colliders. The example presented shows that quasi-optical approach forms a firm base for constructing linear collider of TeV energy range at the present-day level of accelerator and RF technique R&D.

5 REFERENCES

[1] Status Reports of NLC, JLC and VLEPP are given in: "Proceedings of the LC'92 ECFA Workshop on e^+e^- Linear Colliders (July, 25 - August , 2, 1993, Germany)", MPI-PhE/93-14, ECFA 93-154

[2] E.L. Saldin, E.A. Schneidmiller and M.V.Yurkov, Nucl. Instrum. and Methods **A344**(1994)255

[3] E.L. Saldin et al., preprint JINR E9-94-94, Dubna, 1994