QUASI-OPTICAL 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 into phased array antenna. 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 composed of the klystrons with 2 MW and 2 kW peak and average output power, respectively.

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 $2-4 \times 10^4$. 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 and lens waveguide.

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.

Linear collider scheme

The proposed scheme uses phased array antenna as an RF power supply and commutating device, quasi-optical microwave transmission lines for transporting RF radiation, and lens lines with directional couplers as RF power dividers.

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

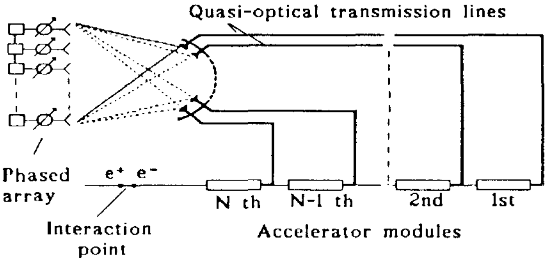

Fig. 1: Linear collider scheme.

The accelerator is placed in the underground tunnel and 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 N microwave transmission lines. Transmission lines

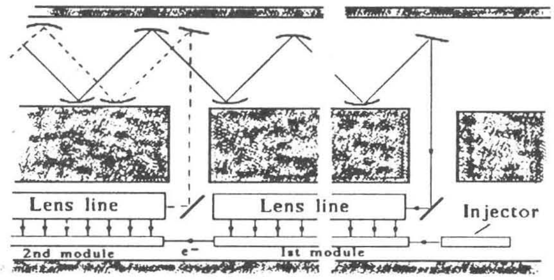

Fig. 2: Transfer of RF power from microwave transmission lines to the accelerator modules.

are placed inside the surface gallery and are connected with the accelerating modules via vertical shafts (see Fig.2). 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 1st the microwave transmission line to the first (injector) accelerator module. During the time period T between the RF pulses, the phased array antenna is switched and second RF pulse is directed to the second transmission line, 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.3).

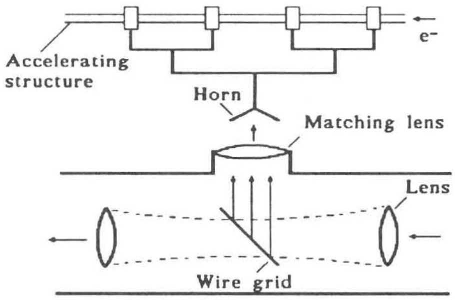

Fig. 3: RF power divider.

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 phased array antenna techniques which has been developed for needs of radar applications.

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.

Lens waveguide with directional couplers is used as RF power divider (see Fig.3). 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 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.

Conceptual project

To illustrate proposed scheme, we present conceptual project of 2×0.5 TeV linear collider operating in X-band.

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 $N = 33$ identical modules.

RF power supply

The RF power supply is a phased array antenna which is parallel to the earth surface and is of rectangular form with transverse dimensions 100×100 m^2. Radiating elements form a rectangular grid with the step $\lambda/2 = 1.5$ cm. 15 000 RF amplifiers are commutated to the array. They operate in a pulsed mode and produce 33 pulses of 0.1 μs duration within the acceleration cycle. The time interval between pulses is equal to $T \simeq 2$ μs. Each RF amplifier has peak and average RF power 2 MW and 2 kW, respectively.

Each RF amplifier is joined to a part of antenna with dimensions 80×80 cm^2 comprising of 2600 radiating elements. Each radiating element is controlled by separate phase shifter which should provide transmission of peak and average RF power 0.5 kW and 0.5 W, respectively, at commutation time 2 μs.

Such an RF power supply may be constructed using serial klystrons. For instance, the parameters close to those required are provided by the four cavity klystron X3030 developed by the Varian (CW mode, 1 MW output power at a frequency 8 GHz, efficiency 50 %, amplification factor 35 dB and accelerating voltage 110 kV). The latter parameter is an extremely important one. Indeed, the use of klystrons with low accelerating voltage together with their compact placement will enable one to simplify significantly a high-voltage system and make all the system to be reliable and effective.

As for phase shifters, the devices with the close parameters are manufactured by microwave industry. A typical semiconductor phase shifter of X-band provides transmission of 1 kW peak RF power and 10 W average RF power at commutation time 0.1 μs.

Microwave transmission line

The RF power from the RF power supply is transmitted to each of 33 accelerator modules by means of 33 microwave transmission lines. 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. Transverse dimensions of the pair of mirrors of the periscopic mirror waveguide are equal to 2×4 m^2. As a result, all of the 33 microwave transmission lines may be placed inside the surface gallery with the 4 m x 70 m^2 cross section.

The peak RF power flux on the mirror surface is of the order of 1 MW/cm^2 which corresponds to the strength of the surface electric field about of 18 kV/cm. So, we may conclude that electric durability of this open mirror waveguide is rather large.

Maximal RF losses occur in the longest transmission line which feeds the first accelerating module. 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 lines are about 20 % and the averaged heat losses in one mirror are about of 250 W.

RF power dividers

The RF lens lines (see Fig.3) 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 300 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.

Electric power consumption

Total RF power losses of the proposed linear collider scheme are composed of losses in the phase shifters of the phased array antenna (10 %), heat losses in the microwave transmission line (20 %), heat and reflection losses in the RF lens lines (15 %) 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 50 %.

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.

Perspectives

Replacement of 2 MW klystrons with 8 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.

One of the visible disadvantages of the proposed linear collider scheme is a rather bulky system of the microwave transmission lines. One of the possible ways to reduce their dimensions is the use of lens waveguides with extremely low losses. It may be realized by the use of artificial dielectric as a material of the lenses or the use of the step-index dielectric waveguides [3]. Estimations shows that in this case the microwave transmission line can be placed in the tube of 1 m diameter and all the RF transporting system can be placed inside several technical tunnels placed along the main accelerator tunnel.

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.

References

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