объединенный
институт
ядерных
исследований
дубна

E9-93-134

E.L.Saldin*, E.A.Schneidmiller*, M.V.Yurkov

ALTERNATIVE CONCEPT OF A RF POWER SUPPLY FOR TeV LINEAR COLLIDERS*

Submitted to «Nuclear Instruments and Methods
in Physics Research A»

---

*Automatic Systems Corporation, Smyshlyaevskoe Shosse 1a, Samara 443050, Russian Federation

1993

1. Introduction

It is widely accepted nowadays in the physical community that new generation of linear electron-positron colliders of TeV range should be a linear one [1-4]. To achieve a reasonable length and cost of such a collider, an accelerating gradient of the order of 100 MeV/m is needed. There exists a good consent about the choice of accelerating structure for linear colliders, it is accepted now that it should be the travelling wave structure. It was demonstrated that the required accelerating gradient can be achieved at the present level of accelerating *R&D* [5].

Nevertheless, there are a lot of problems to be solved prior to the constructing of a full-size collider. One of the main problems unresolved till now is the problem of a reliable *RF* power source. There are two main trends to solve this problem. One of them assumes to use the traditional approach with klystron technique to feed accelerating structures (X-band projects developed at Protvino, SLAC and KEK [1,2] and S-band project at DESY [3]). Another approach exploits an idea of a two-beam accelerator (CLIC project at CERN [4]). In this paper we present a novel concept of the *RF* power supply for linear colliders based on the phased array antenna technique.

2. Formulation of the problem

The main common feature of almost all the projects consists in the choice of short *RF* wavelength in X-band for VLEPP, NLC and JLC projects and in K_α-band for the CLIC project. Such a choice of wavelength is the consequence of the fact that the required peak and average *RF* power are scaled with the *RF* wavelength as $\lambda^{1/2}$ and λ^2, respectively. To provide high average accelerating gradient, the length of accelerating section is usually chosen equal to $l \approx l_e/4$, where l_e is the damping length corresponding to the attenuation of the *RF* field amplitude by factor e ($e = 2.71828\ldots$). The damping length l_e is connected with the other parameters of the accelerating section by the relation $l_e = \lambda Q v_g/\pi c$, where v_g is the group velocity of the wave in the waveguide and Q is the quality factor.

To achieve the required level of the accelerating field strength in the accelerating structure, the RF pulse duration should not be shorter than the filling time $\tau \simeq 4l/v_g \simeq \lambda Q/\pi c$. For example, for JLC project we have the length of accelerating section $l = 0.7$ m and the required RF pulse duration $\tau \simeq 90$ ns. Accelerating gradient $d\mathcal{E}/dz = 100$ MeV/m is achieved at the peak RF power $P \simeq 120$ MW [1]. For the CLIC project these parameters are equal to: $l = 0.27$ m, $\tau \simeq 35$ ns, $d\mathcal{E}/dz = 80$ MeV/m and $P \simeq 15$ MW [4]. The analysis of the collider projects shows that in all cases the filling time of the single accelerating section $\tau \simeq 30 \div 100$ ns is much less than acceleration duty cycle $T = L/c$, where L is the half-length of the collider. For example, at $L \simeq 10$ km we get $T \simeq 30\mu s$ and $T/\tau \simeq 300 \div 1000$.

Let us consider in detail the operation of accelerator exploiting klystron technique. Each klystron feeds its own accelerating section, the total number of klystrons is equal to L/l and is of the order of 15000 for X-band accelerator with the length $L \simeq 10$km. The klystron pulse duration is assumed to be as short as possible, i.e. of the order of the filling time τ. Each klystron is switched on with the prescribed delay, pumps the accelerating section during the time interval τ and is switched off just after the passage of electron beam through the accelerating section. For the deeper realizing of the linear collider operation it is convenient to imagine the following visual picture. At any moment of acceleration cycle, the length of the accelerator section, commutated to the switched on klystrons, is equal to $c\tau$ and is usually of the order of $3 \div 30$ m. The spot of RF excitation moves along the accelerator with the velocity of light c and the electron (positron) beam moves near the back front of this spot.

This simple picture reveals that maximal peak RF power necessary for acceleration, is equal to $Pc\tau/l$ and it is by T/τ times less than the integral peak power of all klystrons. Remembering that factor T/τ is rather large for all the projects, $T/\tau \sim 10^3$, one can conclude that traditional klystron technique is not optimal for TeV linear colliders. So, there is a necessity to design such an RF supply which gives the possibility to commutate the full output RF power to the section of length $c\tau$ and commutate this power along the accelerator with the velocity of light c.

3. Phased array antenna as a RF source for linear collider

One of the possible ways to design an optimal RF supply is based on the concept of a two-beam accelerator. A variant of this scheme is being studied theoretically and experimentally at CERN (CLIC project [4]). In this scheme RF power is generated by drive beam in the travelling wave structures. Another variant of two-beam accelerator scheme based on a free electron laser technique, is developed by Sessler with co-authors [6, 7].

It should be noted that designers of powerful radar systems face similar problems as designers of the future generation linear colliders. Namely, they all need a reliable and powerful RF source with short wavelength, high peak RF power and high repetition rate. To solve the radar problems, a unique technique based on the concept of phased array antenna has been developed [8]. In this paper we propose to use these technique for the linear collider design. We propose to replace the "imaginary" spot of RF excitation moving along the accelerator by means of the real spot from a microwave radiator. The microwave radiator is assumed to be a multielement phased array antenna which focuses and scans the RF beam along the accelerator with the speed of light c. The phased array antenna consists of a large number of radiating elements placed in the nodes of rectangular grid with a step $\lambda/2$. Each radiating element is assumed to be an open waveguide end. Signal amplitudes and phases of elements are controlled independently. From the radiotechnical point of view the phased array antenna is a device matching separated RF sources with an open space which plays the role of a feeder in the case under consideration. There are three evident advantages of using the phased array antenna. First, it enables one to sum up the power of many small RF sources in the single powerful RF beam. Second, the use of the open space as a feeder makes it possible to provide high RF power flux unachievable in usual feeders. And third, the system is extremely reliable with respect to the breakdown of elements. Even a breakage of a large number of elements does not interfere drastically with the operation of the whole system.

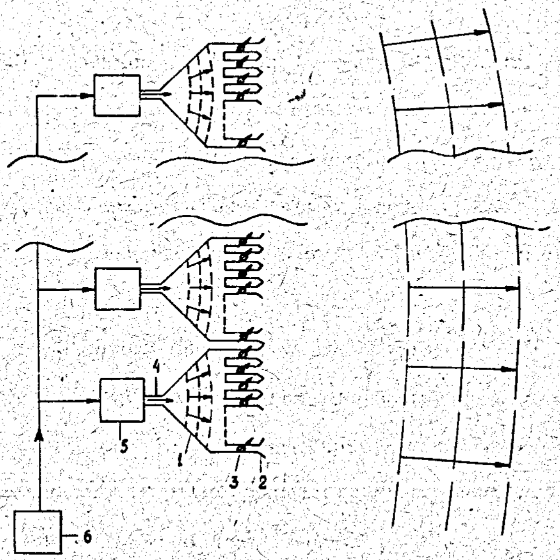

Fig.1. Transmitting phased array. Here: (1) - matching horn; (2) - radiating element; (3) - phase shifter; (4) - waveguide; (5) - RF amplifier; (6) - master oscillator

The phased array antenna is arranged as follows (see Fig.1). RF power is produced by a large number of RF amplifiers controlled by a common master oscillator. The RF power from each amplifier is fed to some number of antenna radiating elements. To divide the RF power among the radiating elements, many types of power dividers may be used, but at a large number of antenna elements the divider of quasi-optical type is the most appropriate. The transmitting array is assumed to be a feedthrough one. Such an array consists of input and output radiators connected by means of phase shifters. To provide a compact arrangement of the array, each phase shifter transverse dimension should not be larger than $\lambda/2 \times \lambda/2$. In this case it can be placed immediately behind the radiating array element. For instance, a typical X-band phase shifter has the following characteristics: transmitting peak RF power $\sim$ 1 kW; transmitting average RF power $\sim$ 10 W; commutation time $\sim$ 100 ns; RF power losses $\sim$ 0.3 dB; weight $\sim$ 10 g.

To provide the optimal RF beam focusing on the receiving antennas, the latter should be placed in the Fresnel diffraction zone, i.e. at $R < S^2/\lambda$, where S is the maximal transverse dimension of the transmitting array. We assume in the further consideration the Fresnel number $N_F = S^2/(\lambda R)$ to be rather large, $N_F \gg 1$. In this case the feedthrough array works as a microwave adaptive lens directing the RF beam to remote receivers. The wave front on the transmitting array is controlled by the steering parameters (amplitudes and phases) of its radiating elements. As a result, a fast scan of the focused RF focal spot along the accelerator is performed.

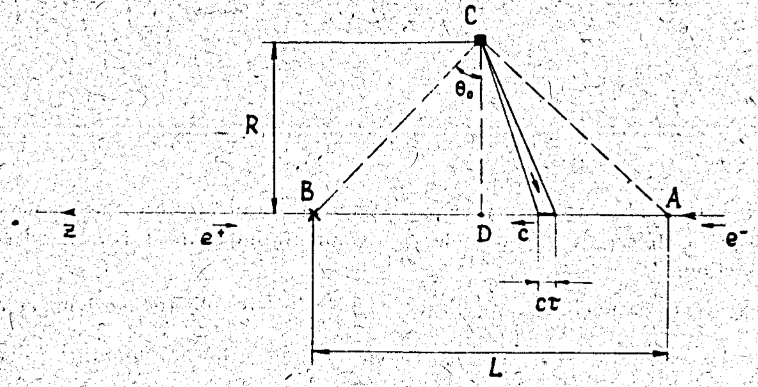

Fig.2. Scheme of RF power supply for a linear collider using the phased array antenna technique

One of the simplest configurations of the proposed RF power supply scheme is presented in Fig.2. Of course, this scheme is not optimal, but it allows one to understand the main features of the proposal. Electrons (positrons) are accelerated along the z axis. The acceleration begins at point A and ends at the interaction point B. The half-length of the accelerator is equal to $AB = L$. The transmitting array is placed at point C symmetrically to the accelerator ends at the distance $CD = R$ from the accelerator.

Angle $\angle ACD = \angle BCD$ is the scanning angle θ_0 and usually does not exceed 60^0 for flat arrays.

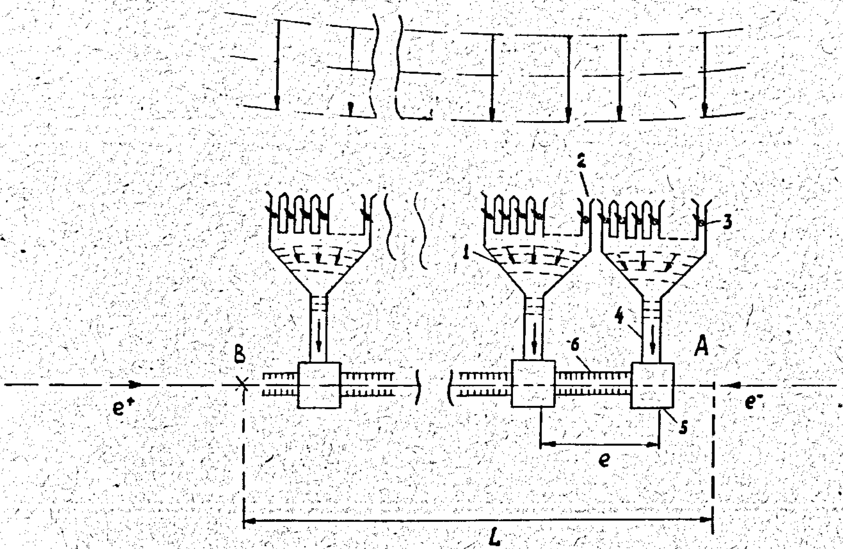

Fig.3. Receiving phased array. Here: (1) - matching horn; (2) - receiving element; (3) - phase shifter; (4) - waveguide; (5) - commutating element; (6) - accelerating section.

Focused RF radiation of the transmitting array is received by the receiving array. The latter has the form of a strip located near and along the linear collider. It consists of L/l separated rectangular antennas, each connected with its own accelerating section (see Fig.3). The receiving antenna is a self-phased array one. The technique of self-phased antennas is widely used now for radar applications. The principle of its operation consists in correction of the receiving signal phase in such a way that summation of the signals received by different antenna elements is performed in phase. It should be noted that the usage of the self-phased antenna technique enables one to organize the optimal matching of the open space and accelerating section. Furthermore, it makes it possible to diminish significantly the influence of such harmful factors as atmospheric inhomogeneities, precipitation, vibrations, etc.

To estimate the transverse dimensions of the transmitting and receiving antennas, we shall use the methods of physical optics and approximation of continuous antenna aperture (which is valid at a large number of antenna elements). We assume the phase front of the focal spot at the receiving antenna to be a plane one. The RF field amplitude distribution on the receiving antenna along the transverse coordinate has the Gaussian profile $\psi = A\exp(-x^2/w_o^2)$. Along the longitudinal direction z the focal spot has the size $c\tau$, which is much more than the transverse one, i.e. $w_o \ll c\tau$. As a result, the maximal linear dimension of the transmitting antenna depends only on the choice of the RF focus spot size w_o.

It is well known from the theory of Gaussian beams that at the distance R from the focal spot the field amplitude distribution remains Gaussian, and its width w and wavefront curvature b are given with the expressions [9]:

$$b = R[1+(\pi w_o^2/\lambda R)^2], \qquad w = w_o[1+(\lambda R/\pi w_o^2)^2]^{1/2}.$$

So, the focal spot of the size w_o and plane wavefront at the receiving antenna take place when field distribution at the transmitting antenna obeys the Gaussian distribution law with the width w and phase front curvature b (remembering that the transverse dimensions of the transmitting and receiving antennas must be greater than $2w$ and $2w_o$, respectively).

So, the choice of the value w_o and the distance R gives the value of linear dimension S of the transmitting antenna. The transverse dimension of the receiving antenna is defined by the value of w_o. At the same time, the distance R should not be too small obeying the condition that the scanning angle θ_0 must be less than 60°, i.e. R should be chosen $R \simeq 0.3L$ (see Fig.2).

It should be noted that the influence of such effects as RF field absorption, dispersion and attenuation in the medium between the transmitting and receiving antennas, should be taken into account. The detailed analysis has shown that these effects influence insignificantly the operation of the proposed RF power supply system if the distance between the transmitting and receiving antennas does not exceed several kilometers. Another helpful factor is that the chosen RF frequency bands (10 GHz for NLC and

JLC and 30 GHz for CLIC) are placed inside the so-called atmospheric windows and attenuation per one kilometer is of the order of 0.01 dB and 0.05 dB, respectively [8].

In conclusion of this section we should emphasize that the scheme presented in Fig.2 aims to illustrate the proposal, and, of course, it may be nonoptimal from the practical point of view. We realize that there are no universal solutions of the problem of the *RF* power supply for TeV linear colliders. Our proposal solves the problem of the *RF* supply itself but some novel problems should be solved, namely the problem of radiation safety and the problem of compact arrangement of the system. A comprehensive analysis of these problems is the subject of a special study but as for the latter one, it may be easily solved by means of installation of additional redirective arrays, thus reducing the transverse dimensions of the system.

4. Numerical example

To illustrate the proposed *RF* supply scheme, we choose the parameters of the linear collider which are close to the CLIC parameters [4]. We assume the *RF* wavelength to be $\lambda = 1$ cm , the collider half-length $L = 10$ km, $c\tau = 10$ m, the accelerating section length $l = 0.25$ m, the accelerating gradient $d\mathcal{E}/dz = 80$ MeV/m, the distance between the transmitting array and accelerator $R = 3$ km, and the width of the Gaussian beam at the receiving array $w_o = 1$ m. The duty cycle of this accelerator is equal to $T \simeq 30\mu s$ at the repetition rate $f \simeq 3$ kHz (duty factor 10). To achieve the required accelerating gradient in the single accelerating section, the peak *RF* power $P = 15$ MW is needed and, consequently, the peak *RF* power 600 MW is necessary to feed the accelerating section of length $c\tau$.

The transmitting phased array is a plane one with transverse dimensions 40 × 40 m. It consists of $6 \cdot 10^7$ waveguide radiators which are placed in the nodes of rectangular grid with the step 0.5 cm. Each radiator is controlled by its own phase shifter providing the transmission of the peak *RF* power ~ 15 W and average *RF* power ~ 1.5 W.

The receiving antenna is of the form of a strip with transverse dimensions 4 m × 10 km. It consists of 40000 separate modules with dimensions 4 × 0.25 m, each feeding its own accelerating section. The receiving module represents a horn with a phased array antenna at its entrance. The number of receiving elements in the module is equal to 40000. Each receiving element consists of input and output radiators connected with the phase shifter providing the transmission of the peak *RF* power ~ 500 W and average *RF* power ~ 0.04 W.

There are 15000 *RF* amplifiers (peak power 40 kW, average power 4 kW, duty factor 10) commutated into the transmitting phased array antenna. Each amplifier feeds 4000 radiators located at the area 30 × 30 cm. The matching of the amplifier waveguide with the radiators is performed by means of a horn. If the transverse dimensions of the amplifiers are rather small (less than 30 × 30 cm), they may be placed immediately behind the antenna to reduce the length of matching waveguides.

It should be noted that there is no need to develop principally new types of amplifiers for the proposed *RF* power supply scheme, devices with close parameters are widely used elsewhere. For example, the travelling wave tube VTA-5700 designed by "Varian" has an output peak *RF* power 30 kW and an average power 9 kW (duty factor 3) at a frequency of 35 GHz. The tube weight (with solenoid) is equal to 160 kG, diameter 37 cm, length 63 cm, amplification coefficient 50 dB, and accelerating voltage 47 kV.

5. Conclusion

In the present paper we have proposed a novel scheme of the *RF* power supply for TeV-range linear colliders based on the phased array antenna technique. The *RF* power of a large number of amplifiers is commutated by a multielement electronically scanned array. Then *RF* power feeds through the air feeder to the receiving arrays of the collider located in the Fresnel diffraction zone. Finally, the receiving arrays transmit the received *RF* power to the accelerating sections of the accelerator. The advantages of the proposed scheme are as follows. First, the required peak *RF* power is diminished by three orders of magnitude. Second, there is no need to develop principally new *RF* sources, well-developed reliable serial amplifiers may be used. And third, the system is extremely reliable with respect to the breakdown of elements. Even breakage of a large number of elements does not interfere drastically with the operation of the whole system.

In conclusion we should note that the phased array technique was developed intensively for needs of radar applications. In some way designers of radar devices and future generation linear colliders face many common problems, namely they need a reliable *RF* devices with a short *RF* wavelength, a high peak power and a high repetition rate. A lot of work has been done to solve this problem for radar applications. As a result, very powerful technique of the phased array antenna was developed. And we hope that application of this technique for the *R&D* of the future linear colliders is quite possible.

Acknowledgments

We are extremely grateful to V.P. Sarantsev for support in our work. We also would like to thank Yu.N. Ulyanov for many useful discussions and recommendations.

References

[1] Status Reports of JLC and VLEPP are given in: 2nd International Workshop "Next Generation Linear Colliders", held at National Laboratory on High Energy Physics (KEK), Tsukuba, Japan, March 28 - April 5, 1990

[2] R.D. Ruth, The Development of the Next Linear Collider at SLAC, SLAC-PUB-5729, 1992

[3] T. Weiland et al., Status Report of a 500 GeV *S*-Band Linear Collider Study, DESY 91-153, 1991

[4] W. Schnell, The CERN Study of a Linear Collider in the TeV Range, CERN SL/91-49, 1991

[5] M.A. Allen et al., Phys. Rev. Lett. **63**(1989)2472

[6] A.M. Sessler, Proc. Workshop on the Laser Acceleration of Particles, eds. C. Joshi and T. Katsouleas, AIP Conf. Proc. **91**(1982)154

[7] A.M.Sessler et al., Nucl. Instrum. and Methods **A306**(1991)592

[8] M.I. Skolnik, Radar Handbook. McGraw-Hill Book Company, 1970

[9] D. Marcuse, Light Transmission Optics. Van Nostrand Reinhold, New York, 1972

Received by Publishing Department
on April 16, 1993.