NON-PLASMA BASED ADVANCED METHODS OF ACCELERATION

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Introduction

The development of advanced acceleration mechanisms will provide new capabilities for science. At the present time, discussions are centered on particle physics where advanced accelerators are the only route to electron-positron collisions at energies significantly above that of LEP. Cost effectiveness in this application leads to requirements which can be stated roughly as:

i. high acceleration gradient for a reasonable length machine,

ii. small transverse emittances for a small collision spot,

iii. small longitudinal emittance to minimize chromatic aberrations while working in the quantum beamstrahlung regime,

iv. stable, reproducible operation.

These requirements may be unique, and an acceleration technique inappropriate for this may be suitable in some other application. However, since end-use requirements have an important influence and these have been enumerated only for high energy linear colliders, this talk will concentrate on advanced accelerators for particle physics. There are other survey talks at this conference which may have more general remarks [1,2]

In a linear collider the beam power, center-of-mass energy, luminosity, and beamstrahlung parameter fix the longitudinal and transverse beam dimensions, the collision frequency, and number of particles [3]. The accelerator must be designed to minimize costs while reaching the needed energy with the needed beam quality.

RF Driven Accelerators

Short RF wavelength, λ, is favored for a high gradient [3,4] and a high energy extraction efficiency because, for a given gradient, the RF energy to fill the structure depends on wavelength as λ^2. At S-band the energy extraction efficiency is so small that the only realistic possi-bility is superconducting RF where the RF energy can be stored between beam pulses. Thus there are two general approaches, a normal conducting accelerator with wave-length shorter than S-band, and a superconducting accelerator operating at S-band. Contributions to this conference deal with the optimum choice of λ and structure design [5].

For X-band and K-band accelerators efficient, high peak power RF sources and new methods for accelerator component manufacture must be developed. If a given RF tube design is scaled with λ, the peak power capability varies as λ^2 [6]; this follows from Child's Law and the cathode radius being proportional to λ [7]. However, peak power requirements fall as $\lambda^{1/2}$, and new power sources are needed. These could be tubes such as ring or sheet beam klystrons [8] or gyroklystrons [9]. An experimental investigation of a third possibility, a virtual cathode device is also being reported [10]. An alternative approach, the "two-beam" accelerator replaces many RF tubes with a low energy, high current beam running parallel to the high energy beam [11]. Energy is extracted from the low energy beam by either Free Electron Laser (FEL) sections [11,12] or sections resembling klystron output gaps [13,14]. Either induction or superconducting RF linacs replace the lost energy. The promise of the FEL, induction linac combination has been demonstrated in recent experimental work [15], and FEL power sources for this wavelength region are a major topic at this conference [16].

For these wavelengths the typical transverse dimensions of the accelerator are of order one centimeter. Feature sizes, such as the hole in a disk loaded waveguide, must be a small of this full transverse size and tolerances a fraction of that. In addition, careful consideration must be given to cooling and thermal properties. Some initial work led to a small section of λ = 8.6 mm waveguide which achieved a gradient of 180 MeV/m [17]. Several papers submitted to the conference deal with the fabrication of short λ components [18].

As the wavelength decreases the effects of wakefields become more serious. When the ratio of bunch length to wavelength is held constant, longitudinal wakefields scale as $1/\lambda^2$ and deflecting ones as $1/\lambda^3$ [3]. These wakefields are the cause of longitudinal and transverse emittance blow-up with the transverse being more serious. Strong focusing and Landau damping introduced through momentum spread can control the transverse blow-up [19], and with sufficient momentum spread this is adequate. The problem then becomes the design of a final focus which can handle a large momentum spread (an example particle physics requirements having implications about appropriate acceleration mechanisms). Transverse emittance blow-up has been studied with analytical calculations, two-particle models, and computer simulations [5,20]. The results are not consistent; this seems to be caused by different approximations about wakefields and the energy spread within the bunch. Since results are not consistent, conclusions about the suitability of an accelerator with λ = 1 cm are not clear at the present time.

In addition to emittance blow-up wakefields combined with injection errors, etc could make stable operation difficult. Ultimately calculations of all these effects must be based on experimental results. There are a number of papers submitted to the conference on experimental beam dynamics studies in the SLC [21]; these are an important contribution to understanding and solving limitations from beam dynamics.

At wavelengths shorter than K-band work has concentrated at λ = 10 μm where a CO_2 laser is a natural power source for prototype tests. While possible power sources for a collider and emittance growth are unsolved issues, structure fabrication has received the most attention. The emphasis has been on the design, prototyping, and RF model studies of various open structures [22]. These were chosen because of the applicability of techniques such as etching and greater ease of introducing power into the accelerator. The successful manufacture of small sections of accelerator is an encouraging beginning for the study of very short wavelength near-field accelerators.

At long wavelengths linear colliders based on superconducting RF have been considered [23,24,25]. This offers the possibility of storing the energy between beam pulses and thereby increasing efficiency. Acceleration of multiple beam pulses per RF pulse has also been considered for room temperature cavities [12], but this has two disadvantages which arise

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because the beam pulses must be closely spaced to avoid wall losses: the need for several bunches in the interaction region at the same time [26], and inter-bunch wakefields. In contrast, with superconducting RF the time between bunches can be long, and through the use of external loads, the Q's of fundamental and higher modes can be orders of magnitude different. This avoids the inter-bunch wakefields.

The disadvantage of a superconducting, high energy linear collider is that of cost; at the present level of performance the cost would be prohibitive. With improvements in gradient and Q to greater than 25 MeV/m and 3×10^{10} (progress is discussed in [27]) and by employing a macroscopic duty cycle of about 10%, the costs are still high. Independent estimates for a collider with 2 TeV center-of-mass energy are 6,500MSF [24] and \$5,000,000 [23]. Even these costs, which which are based on the assumption of improved gradient and Q, may prove too great.

Wakefield Accelerators

In wakefield accelerators a low energy, high current beam accelerates a high energy, low current beam. In contrast with two-beam accelerators both beam travel in the same structure. In [28] it was shown that the maximum transformer ratio, R, is limited

$$R = \frac{\text{Gradient x Stopping Distance}}{\gamma_1} = \frac{\Delta\gamma_2}{\gamma_1} \leq 2 - \frac{n_2}{n_1}$$

where the n_1 and γ_1 , n_2 and γ_2, are the number of particles and energy of the leading, low energy beam and the trailing, high energy beam respectively. This result holds for a symmetric, collinear, rigid driving bunch. In that case the maximum energy gain of the trailing bunch is twice the drive beam energy.

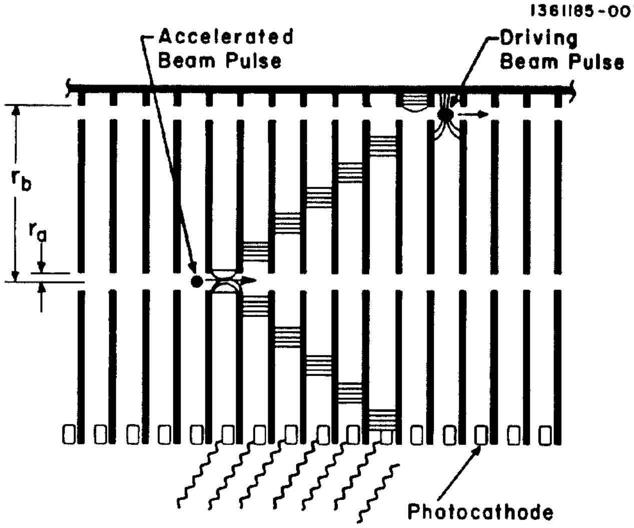

Figure 1: The DESY wakefield transformer [30] and the switched power accelerator [41] are sets of disks illustrated in section view. Fields generated at r_b by either an annular drive beam or light striking annular photocathodes propagate towards the center and accelerate the high energy beam.

The DESY Wakefield Transformer [29] achieves a substantially better transformer ratio through the use of an annular driving beam coaxial with the high energy beam. The wakefield transformer (Fig. 1) is a set of disks with a hole of radius r_a in the center for the high energy beam. The driving beam, a ring of radius r_b, travels on the outside of these disks. For a high transformer ratio r_b/r_a must be large. The wakefield of the driving beam propagates towards the center of the disk structure which is a radial transmission line with increasing characteristic impedance. This results in an increased voltage and, therefore, a high acceleration gradient and transformer ratio. Subsequent reflections of the pulse can be used to accelerate positrons.

This concept is being tested in an ambitious experiment at DESY [30]. In this experiment a laser driven gun produces both a 1 μC annular drive beam and a low charge, about 0.01 μC, test beam. The gun is followed by a 500 MHz, 8 MeV linac, a high energy buncher which compresses the beam longitudinally, and the wakefield transformer with an expected transformer ratio R = 10. The experiment incorporates extensive diagnostics. A gradient in excess of 100 MeV/m is expected over a transformer length of 0.42 m. The status of the experiment, as reported at a conference in August, 1986 [31], was: 1) most of the equipment was in place with the expectation that all parts would be completed in Sept.,1986; 2) problems such as linac multipactoring and errors in manufacturing had been identified and were being fixed; 3) measurements of the drive beam quality were in progress. Studies concentrated on increasing the beam current and improving the azimuthal uniformity of the beam.

Azimuthal uniformity is important in the wakefield transformer because misalignment and/or nonuniformity will generate strong deflecting forces on the accelerated beam [32,33]. In addition, since the transformer ratio depends on r_b/r_a and the drive beam should not be excessively large, a small value of r_a is used. This implies large wakefields for the high energy beam which could lead to emittance growth. These problems are being studied by computer simulation [33].

A second approach to exceeding the limit $R < 2$ is using a collinear geometry and a drive beam with a unsymmetric longitudinal distribution. If this is done the maximum gradient decreases unless the number of particles in the drive bunch is increased proportionally to the bunch length [34]. This can be avoided with trains of driving bunches. Both equal bunches with variable spacing and evenly spaced bunches of different charges have been investigated [34]. The former gives the optimum performance but is more difficult to produce. The plasma wakefield accelerator [28,35] is the collinear wakefield accelerator which has received the most attention; plans include using an unsymmetrical drive bunch [36].

The accelerators discussed above are dependent on generating high current electron drive beams with special properties such as ring shape or an unsymmetrical longitudinal distribution. Generation of high current, high quality electron beams is a major topic at this conference [37].

The "Wakeatron" uses a collinear, symmetric, proton bunch as the drive beam [38]. Even though very high energy, the protons are not ultrarelativistic, and the wakefields within the bunch lead to mixing of longitudinal positions. This results in the energy loss being averaged over the entire bunch; this lowers the energy loss per drive beam particle. The accelerator structure resembles a disk loaded waveguide; for a high gradient and large transformer ratio closely spaced disks with small holes are used. Emittance blow-up in such a structure is a concern. Paper [39] deals with recent advances in the wakeatron concept. Some aspects of collinear wakefield acceleration related to the wakeatron will be tested at the advanced accelerator test facility at Argonne [40].

Switched Power Accelerators

In the switched power linac [41] the driving beam of the wakefield transformer is replaced an annular photocathode (Figure 1). This cathode is charged to a high voltage and then switched with a pulse of laser light. The charge on the cathode is discharged to the disk, and the resultant pulse propagates towards the center. The initial charging voltage is transformed to a higher value as in the wakefield transformer. Typical parameters are a charging voltage of 80 kV which is increased by a factor of twenty [42]. For such parameters r_b = 120 mm and r_a = 1 mm. Gas, avalanche transistor, and solid state switches are being considered also [42], but the laser switched photodiode has received the most attention.

The efficiency of the photodiode switch has been studied with MASK, and the single pulse switching efficiency is around 10%. Space charge effects are important. By forming a closed cavity and using multiple pulses efficiency approaches 50% [42]. (This observation is the basis of the "microlasertron" power source [43].) Experimental studies of such switches are underway at Brookhaven.

A large scale model is being used for measurements of the transformer ratio and the deflecting fields produced by azimuthal nonuniformity of the pulse. Results from these model studies are being reported at this conference [44].

Conclusions

The concepts reviewed above are receiving substantial attention in the accelerator community as witnessed by the numerous contributions to this conference. Experiments and simulations aimed at proving essential features are in progress, and based on results a few concepts may advance to a stage requiring detailed engineering and prototype construction. It is hoped that this will be the subject of future meetings.

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