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1. INTRODUCTION

This talk will deal with possible *future* technologies, based on fundamentally new developments and, therefore, still affected by many as yet unsolved problems. In this respect the situation is drastically different for hadrons from that for electrons.

Colliders for protons and heavy ions do not require any basically new developments. Instead we are heading for another round of vigorous extensions of known technologies. The most striking examples are, of course, the SSC and LHC projects. The LHC design - based on the given circumference of the LEP tunnel - pushes harder against the limits of superconducting high-field magnet technology. The LHC¹ magnet now under development is a two-in-one design aiming at a 10 T field. Two routes are being followed in parallel. Either (and more likely) NbTi conductors, similar to the ones already in current use, will be employed but cooled to 1.8 K with superfluid helium. Or, the more familiar 4.5 K cryogenics will be maintained but the coils will be wound with Nb₃Sb conductors and glass-mica insulation. These coils must then be reacted at about 700°C. So far, one-metre models of both kinds have exceeded 9 T field and longer models are in preparation.

A field of about 10 T must, however, be considered a limit at present. The mechanical forces to be contained increase with the square of the field. And at presently-achievable current densities higher field means additional coils at larger distance from the beam with rapidly diminishing returns. The parameters of these proton rings of many tens of kilometres' circumference, containing particle populations in the 10¹⁴ range, do imply the need for careful

attention to beam dynamics and present many serious engineering problems - for instance those concerned with the safe handling of the beam's stored energy.

For electron colliders substantially above LEP energy the situation is completely different. The fourth-power increase of radiation excludes any further extension of the storage-ring technology we have so successfully followed for several decades (a 1 TeV electron in LEP would lose 30 TeV per revolution) and linear machines appear to be the only possible solution. Linear colliders are also being proposed for lower energy very high intensity machines. The basic elements of an e⁺e⁻ linear collider are: the generators for positrons and electrons; storage rings at a few GeV energy for radiation-damping to extremely small values of transverse emittance; pre-accelerators and bunch compressors; the main accelerating structures with gradients of about 100 MeV/m or more; the final focus system. Only the last two items will be discussed here and the emphasis will not be on parameters² and parameter interdependences³ but on an overview of elements of linear-collider technology which are now being actively developed in several laboratories.

2. METHODS OF ACCELERATION AND ACCELERATING STRUCTURES

During the first half of this decade a number of ingenious methods of acceleration at extremely high gradients were proposed. These methods include laser-driven structures, laser-driven plasma beat-waves, beam-driven plasma waves and structures driven by the wake field of a single beam pulse or by single pulses from photo-electric or semiconductor

Table 1
Tentative parameters of e^+e^- linear colliders under study²

<i>Institution</i>		CERN	KEK	Novosibirsk -Serpukhov	SLAC	
<i>Name of project</i>		CLIC	JLC	VLEPP	ILC	TLC
c.m. energy	[TeV]	2.0	1.0	2.0	0.5	1.0
luminosity	$[10^{33}\text{cm}^{-2}\text{s}^{-1}]$	1	1.7	1	1.7	8
number of bunches per pulse		1	15	1	10	10
accelerating gradient	$[\text{MVm}^{-1}]$	80	100	100	93	186
accelerating frequency	[GHz]	30	11.4	14	17.1	17.1
repetition frequency	[Hz]	1700	510	100	360	360
bunch population	$[10^{10}]$	0.5	0.4	10	0.7	1.4
normalized vertical emittance ϵ_y	$[\mu\text{m}]$	0.5	0.1	0.06	0.02	0.03
normalized horizontal emittance ϵ_z	$[\mu\text{m}]$	1.6	3.0	6.0	1.9	2.7
beam height at collision σ_y^*	$[\text{nm}]$	12	3	10	2.4	2.2
aspect ratio at collision		5	100	100	175	177
bunch length σ_z^*	$[\mu\text{m}]$	200	80	700	70	70

switches. However, by the middle of this decade all laboratories interested in potential projects had converged to the principles of classical radio-frequency acceleration. The reason is the hard fact that the accelerating gradient is fundamentally limited by average power consumption to values in the 100 MeV/m range. Such values *are* obtainable from classical RF structures, thus maintaining the RF structure's basic advantages of energy storage and of a well defined field configuration (both expressed by the presence of a substantial Q-factor).

Much higher frequencies than the customary 3 GHz of present-day electron linacs will have to be employed, however. The losses of any non-superconducting accelerating structure preclude the conservation of stored energy between pulses of colliding beams. Therefore, an upper limit to the efficiency of power conversion to the beam is the fraction of stored energy extracted by the beam. This fraction scales with the inverse accelerating gradient and with the structure's cross-section which is proportional to the square of the RF wavelength. A limit to the increase of operating frequency is, however, set by constructional tolerances

and (more fundamentally) by the beam-induced wake fields, self-deflecting wake fields scaling with the third power of frequency. The parameter list given in Table 1 shows that the design frequencies considered by different study groups range from 11.4 GHz to 30 GHz (tentatively adopted by CERN).

The most efficient accelerating structure even at these high frequencies is still the familiar iris-loaded waveguide - probably in the equally familiar form of a travelling-wave structure. And there is a general consensus that the most promising fabrication method (at least for the moment) is still by vacuum brazing of stacks of machined copper cups.

Figure 1 shows a small stack of such precision-machined cups (prior to brazing) for 30 GHz frequency. The aperture is 4 mm, the cavity diameter 8 mm. The required tolerances and surface finish approach, but do not exceed, the possibilities of modern machine tools. At the lower frequencies listed in Table 1 the requirements are relaxed (by roughly the square root of the ratio of frequencies) but the situation is not basically different.

FIGURE 1
Elements of a 30 GHz accelerating structure

The accelerating gradients considered may lead to problems with surface deterioration by occasional arcs or by superficial thermal stress. Serious problems may also arise due to field emission currents ("dark currents") which might affect the symmetry of fields and, thus, give rise to random deflections with concomitant emittance growth. High gradient effects are, therefore, under study at KEK, LAL-Orsay, SLAC and other places.

A substantial improvement might be obtainable by making each beam pulse consist of a rapid succession of several bunches, spaced a certain number of RF wavelengths apart. This increases the effective repetition rate and, thus, the luminosity by the number of bunches per train (a typical number might be ten), yet they share most of the stored energy so that only a small increase of RF pulse length and concomitant energy dissipation is required. The idea is most actively pursued⁴ at SLAC and the TLC and ILC parameters of Table 1 are based on multibunching. Among the problems with this method is the requirement for very strong damping of deflecting modes of resonance in the accelerating structure. This is necessary in order to avoid avalanching bunch-to-bunch deflection ("beam break-up") by wake fields. The only known way⁵ to achieve sufficient damping is to provide radial slots in every (or every second) iris of

FIGURE 2
Model of slotted iris with radial waveguides for the damping of deflecting modes.

the accelerating structure and couple these slots to waveguides which direct any induced deflecting-mode power into absorbing loads. The idea is illustrated by the model shown in Fig. 2.

In this model (CERN) the slots and small rectangular waveguides have been cut by means of electro-erosion, an elegant way of precision machining which leaves, however, the unsolved problem of intolerably sharp edges. It is for this reason that SLAC prefers to compose every iris from four separately machined segments.

3. SUPERCONDUCTING ACCELERATING STRUCTURES

The difficulties clearly implied in the parameters shown in Table 1 could be much alleviated if the main linacs of a linear collider could be made superconducting. Since, in a superconducting cavity structure, stored energy can be conserved at low losses over long periods and the beam's energy extraction may be small, the operating frequency can be low, so that wake field problems are virtually eliminated, and the repetition rate can be made very high. Moreover, the peak-power problem discussed in the next section is completely eliminated since power can now be fed to the structure continuously or in very long pulses.

Unfortunately, at the present state of development, accelerating gradients in superconducting cavities are limited by surface effects to values which are quite unacceptable for a TeV (or even fractional TeV) collider. A record value of surface electric field of 145 MV/m has been reported⁶ for a niobium cavity. This would correspond to about 65 MeV/m accelerating gradient in an appropriate structure. However, in order for the influence of surface defects in this experiment to be overcome, the region exposed to high electric fields was deliberately limited to less than a square centimetre in a geometry quite unsuitable for the acceleration of particles. Laboratory test cavities have, occasionally, exceeded 20 MV/m potential *accelerating* field and 10 MeV/m may have been reached in beam tests.

A real breakthrough in the operation of superconducting cavities in an accelerator has been made in the TRISTAN collider⁷ at KEK where 16 five-cell cavities, generating a total energy gain of 120 MeV have actually been in routine operation for one year and 16 additional cavities have recently been added. The operating gradient there is slightly below 5 MeV/m. Active engineering developments are being carried out in connection with the CEBAF, HERA and LEP2 accelerators, but all aim at realistic accelerating gradients below 10 MeV/m. One is obliged to conclude, therefore, that superconducting main accelerating structures for high energy linear colliders are not a predictable development, however desirable such a development may be.

4. GENERATION OF PEAK POWER

If the fill-time for stored energy in a copper accelerating structure at about 100 MeV/m is to be sufficiently short to escape excessive losses the total peak RF power required for a TeV collider is well above the Terawatt level. No solution has yet been demonstrated to exist for this problem but active development is going on in different laboratories. Three general directions are being pursued; they will be discussed below under the names of *discrete power sources*, the *intermediate solution* and the *two-beam accelerator*.

At least for the lower end of the frequency range considered here *discrete power sources* in the 100 MW range may be developed. The many proposals are based on the known principles of the klystron, the gyro-klystron, the crossed-field generator or of variants thereof. Generally, a high intensity electron beam is being generated in a cathode and a pulsed high-voltage gun. An RF modulation is impressed on this beam and amplified to saturation level by interaction with the RF structure of the device. After extraction of RF power from the beam it is dumped in a collector. The beam current at the gun exit is limited by space charge and by the fact that the cathode area tends to scale with λ^2 . The gun voltage is limited by breakdown. Several proposals aim at overcoming the cathode-area limitation (for instance by employing distributed multi-element devices or a ribbon beam). It is nevertheless difficult to expect power levels above a few hundred megawatts (at the very most) per individual device, even including a small factor of peak-power gain by RF pulse compression. An excessively large number of individual power sources, each with its gun, RF structure and collector and a very large number of high-voltage modulators, is the consequence.

In order to reduce the number of discrete power converters an *intermediate solution* may consist in re-using the high intensity beam several times and over several tens of metres of main linac length^{8,9}. An appropriate device for re-accelerating the beam between extraction points of RF power is the induction unit fed via a magnetic pulse compressor¹⁰. The necessary RF modulation may be impressed on the high-intensity beam in the form of longitudinal bunching or of transverse deflection by static magnetic wigglers. The latter arrangement, which constitutes a single-pass microwave Free Electron Laser (FEL) has, in fact, given over 1 GW pulse power at 35 GHz in an experiment at LLNL¹¹; a dedicated test facility at that laboratory has been proposed¹² and a similar test facility is being commissioned at KEK¹³.

The γ^2 relation between wiggler wavelength and RF wavelength in an FEL limits the electron energy to the order of 10 MeV where phase slip effects limit the

drive-beam length along the main linac. If, however, the drive-beam is given an energy of a few GeV it can stretch all along the main linac thus forming a true *two-beam accelerator* (first proposed by A. Sessler). In this solution¹⁴, which is being studied at CERN, a tightly bunched drive beam of 3 to 5 GeV average energy delivers energy to 30 GHz travelling-wave transfer structures¹⁵ which, in turn, feed RF power to the main linac via waveguides (Fig. 3). The drive beam is being periodically re-accelerated in superconducting cavities fed from continuous wave klystrons at relatively low frequency (350 MHz) and high average power. The superconducting cavities are run at about 10 MeV/m accelerating gradient. An obvious advantage here is the freedom of most of the accelerator tunnel from active high-power equipment other than copper structures and beam transport.

FIGURE 3

A two-beam accelerator.

One problem is the effect of wake fields induced by the intense drive beam in the surrounding walls. Another problem is the generation and pre-acceleration to GeV energies of the required multibunch drive beam containing typically about 10^{12} electrons per one-millimetre bunch. In order to study this problem a test facility, incorporating a laser-driven photocathode, RF gun and bunch compressor, is being built at CERN.

5. WAKE-FIELD PROBLEMS

A serious problem is presented in the main linac by wake fields which are induced in the accelerating structure and act on trailing particles within the same bunch. Dipole wakes scale with the inverse third power of the beam aperture (and, thus, wavelength). They tend to lead to avalanching self-deflection unless the only known remedy - called BNS damping after the

inventors¹⁶ - is applied. This remedy consists of generating a gradient of transverse focusing over the bunch length (typically from a few tens to a few hundred micrometres) so as to focus the tail of the bunch harder than the head. As a result the phase of the deflecting fields is reversed. They now counteract accidental transverse deflections rather than leading to unstable growth. The necessary gradient of transverse focusing may be generated by a deliberate energy spread. A more powerful method, proposed¹⁷ for the especially difficult situation in the 30 GHz scheme of CERN, is the use of radio-frequency quadrupoles. Such quadrupoles can be formed by giving a fraction of the accelerating structures an asymmetric (slit-like) aperture instead of a circular one. Computer simulations¹⁸ have shown that this permits stabilization of the beam even in the rather extreme case of a 30 GHz structure with its 4 mm aperture. The large spread of transverse focusing wavelengths created in this way does, however, aggravate the alignment problem discussed in the next section.

6. TRANSVERSE ALIGNMENT

As can be seen from Table 1 values of normalized vertical emittance below - in most cases far below - one micrometre are required for acceptable luminosity. Although such values of transverse emittance have not been reached yet in an actual storage ring they appear readily achievable theoretically in specially designed damping rings, with¹⁹ or without²⁰ heavy reliance on wiggler magnets. The choice of energy for these rings - typically 2 to 3 GeV - is a compromise between the conflicting requirements of short damping time and small equilibrium emittance due to quantum excitation.

Maintaining transverse emittance values as small as this throughout the linear accelerator is, however, a major problem. Fast servo-controlled beam steering through quadrupoles and accelerating structures, or direct servo-controlled alignment of these elements, remains a necessity even though the *unstable* growth of emittance due to the wake fields will be avoided by BNS damping. The time-scale of such an automatic

alignment system should be made to approach the repetition period. The required precision depends on the amount of BNS damping. If the spread of transverse wave numbers within a bunch is small, errors can be allowed to build up over relatively long distances before correction. By contrast, the strong BNS damping required for the highest RF frequency considered (CERN) makes particles near the head and the tail follow essentially incoherent trajectories. In this case misalignment errors have to be kept everywhere below the beam radius - below one micrometre¹⁸ in fact - if irreversible growth of emittance is to be limited to acceptable values.

Fortunately, electrically controlled movers for micron precision and relatively heavy loads are commercially available. Beam position monitors of micron precision will have to be integral parts of focusing and accelerating elements and development work is under way in several laboratories. Vibrations at frequencies above the possibility of pulse-to-pulse correction are of concern also. Such vibrations may be due to ground motion or the unavoidable flow of cooling water. First series of measurements indicate that on a suitable building site this problem is likely to be manageable by proper design of foundations and supports. Active damping systems, incorporating vibration sensors and actuators in feedback loops, do exist commercially and permit an order of magnitude reduction in r.m.s. vibration amplitude. It is hoped, however, that their use can be restricted to the final focus system.

7. THE FINAL FOCUS SYSTEM

At the place of collisions the beams must be focused to nanometre size - at least in one dimension - in order to achieve adequate luminosity.

The required short focal length quadrupoles can be of "conventional" design in principle - employing permanent magnets, possibly in conjunction with soft-steel poles - but with a very small aperture (half-millimetre radius or less). In any case, the blow-up of transverse emittance due to the quantized radiation loss in the off-centre field, precludes the use of excessively strong final quadrupoles²¹.

Chromaticity correction - focusing all particles to within a bunch length in spite of their unavoidable energy spread and the fact that the focal length of any individual particle lens is proportional to energy - is a serious problem. The only practicable solution is to deflect the beam with dipoles and to place sextupoles at places of finite dispersion. These bends have to be very soft, and thus very long, to limit emittance growth by quantized radiation. A typical design²² for 1 TeV beams has about one kilometre total length and several tenths of a per cent energy bandwidth.

Diagnostics for bringing the beams to collision has yet to be developed. The diagnostics for *holding* them in collision by pulse to pulse automatic correction will clearly be based on beam-beam deflection or on beam-beam radiation ("beamstrahlung") following the pioneer work²³ at the SLAC SLC.

The situation at the collision point is governed by violent electromagnetic beam-beam interaction. A measure for the strength of this interaction is the disruption parameter - the ratio of r.m.s. bunch length to the focal length of the space charge lens presented by a bunch to the oncoming particles. Values of the order of unity are being considered for this parameter. Apart from a small and dubious luminosity gain by pinch enhancement the effects of a large disruption are purely negative; it creates a spray of spent particles which must be directed past the opposite focusing system if damage (or at least background radiation) is to be avoided and it may create unstable bunch-to-bunch growth of deflection in slightly off-centred multibunch trains.

The problem of spent-beam disposal is aggravated and a large energy spread is being created by beamstrahlung, the heavily quantized radiation in the field of the opposite beam. Moreover, this high-energy gamma radiation tends to be converted back to charged particles by pair creation. The resulting electrons and positrons of very large energy spread are still exposed to the space charge field, adding further (and seriously so) to the spent-beam problem. The governing parameter here is Y , the ratio of the classically calculated critical photon energy over the particle energy. Contrary to earlier hopes the intolerable onset of coherent pair production imposes $Y < 0.5$ (say).

Since space-charge compensation by means of four-beam (e^+e^- , e^-e^+) schemes does not look promising, the only practicable way to reduce beam-beam interaction at given cross-section is to employ flat beams in spite of the concomitant tendency towards even smaller beam heights. All tentative sets of parameters now incorporate this remedy, albeit at very different degrees.

So far, the entire complex of final focus design for nanometre beams has been the subject of theoretical study only. However, SLAC have started to build a Final Focus Test Facility²⁴ which aims at a beam height of 60 nm at 50 GeV and should permit a study of many of the engineering problems involved.

8. CONCLUSIONS

While storage rings equipped with superconducting magnets will permit another order-of-magnitude extension of energy for hadrons, the fundamentally new technology of the linear collider is required to make e^+e^- machines break through the 100 GeV barrier. At the present time a rather complete understanding of the many problems involved has been gained and solutions for most of them have been found in principle. Active research and development is going on world-wide in several laboratories, with good qualitative consensus about the directions to follow and much complementarity in detail. More work is, however, required before an actual project can be proposed in full confidence.

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