SUMMARY OF WORKING GROUP 1
ON "SEMI-CONVENTIONAL" HIGH-FREQUENCY LINACS

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1. INTRODUCTION

Radio-frequency linear accelerators consist of two main parts: the accelerating structure and the source of rf power. The first topic includes all questions of type of structure, choice of frequency, wake fields, alignment tolerances, focusing and the choice of basic collider parameters. The second topic includes different types of dc to rf power converters and two-beam schemes. Our discussions proceeded along these main lines.

There was complete agreement that a superconducting main accelerating structure would be the ideal solution if it could be given an accelerating gradient at least approaching 100 MeV/m at acceptable refrigeration power. Basic development work on rf superconductivity (including the new high-temperature materials) should be much encouraged, therefore. However, given the very limited gradients obtained with present-day technology and proven materials the discussion then turned to normal-conducting (Cu) main structures exclusively. Superconducting cavities are, however, interesting candidates for drive linacs in two-beam schemes.

2. ACCELERATING STRUCTURES

There appeared to be a complete consensus that travelling-wave structures are the best choice for the main linac. The reasons are not fundamental but the practical advantages over standing-wave structures make travelling waves the method of choice at the high frequencies and short fill times required in an rf linear collider.

The well-known disc-loaded guide is still a good choice of structure at the high frequencies considered here as it offers a good compromise - probably the best obtainable - between the conflicting requirements of high shunt impedance, high shunt impedance over Q, low ratio of peak-to-axial fields and acceptable wake fields requiring the largest possible aperture. Disc-loaded structures for up to 35 GHz have been made and tested. Fabrication may be by electroforming or by brazing techniques. Assembly from radial, comb-like, segments spanning the full length of a section has also been proposed.

At any chosen frequency the beam-aperture (which is also the coupling aperture) should be increased over scaled dimensions from existing linacs, although this means a sacrifice in shunt impedance and peak-to-accelerating field ratio. The main reason is the predominant role of the beam-induced wake fields discussed below. Another reason is the need of a high group velocity required to arrive at a reasonable section length in spite of a short fill time.

Interesting variants of the disc-loaded guide may have asymmetric apertures (even slits, thus forming a "muffin-tin structure") for creating anisotropic wake fields or for rf focusing or side-slits propagating deflecting modes. This will be discussed below.

3. THE CHOICE OF FREQUENCY

Normal-conducting accelerating structures have to be pulsed and cannot conserve stored energy from one pulse to the next. Therefore an upper limit to the rf-to-beam efficiency of energy transmission is the fraction η of stored energy extracted by a beam pulse. This fraction is given by

$$\eta = \frac{eN\omega r'}{E_0} \left(\frac{E_{acc.}}{E_0}\right)$$

where the term in brackets (the ratio of actual accelerating field $E_{acc.}$ over the field E_0 at vanishing beam loading) will always be made close to unity. The pulse population N (the bunch population in single-bunch operation) is limited by beam-beam interaction in the final focus and is in the 0.5 to 1 × 10^{10} range in most designs. The shunt impedance per unit length over Q, r', is proportional to frequency ω making η proportional to ω^2/E_{acc}.

Thus, inescapably, reaching a high accelerating gradient at good efficiency implies going to the highest frequency possible.

The choice of frequency is, however, conditioned by other considerations, Table 1 giving an overview. The most serious limitation to an increase of frequency comes from wake fields.

Table 1

Considerations in the choice of frequency

1.	Acceleration gradient	$\sim f^{7/8}$	(high frequency preferred)
2.	Peak power	$\sim f^{1/2}$	(high frequency preferred)
3.	Average power	$\sim f^2$	(high frequency preferred)
4.	Efficiency	$\sim f^2$	(high frequency preferred)
5.	Structure fabrication complexity		(low frequency preferred)
6.	Wake-field effects	$W_L \sim f^2$ $W_T \sim f^3$	(low frequency preferred)

4. WAKE FIELDS

Each bunch induces longitudinal and transverse-deflecting wake fields as it passes through the accelerating structure. The wakes left behind by downstream particles act on the upstream part of the same bunch. Longitudinal wakes lead to energy loss and energy spread. Dipole wakes may amplify accidental transverse oscillations (due to misalignment of accelerating structures or quadrupoles) so as to cause severe emittance blow-up or even beam loss.

For given structure geometry longitudinal wake potentials scale with ω^2, transverse ones with ω^3; however it is more logical to scale at fixed aperture, since the wakes depend almost entirely on aperture and other parameters change only slowly with frequency at fixed aperture.

Up to at least 30 GHz - generally considered an upper practical limit for the choice of frequency - the effects of transverse wakes can be cancelled by the introduction of a large spread in transverse wave number ("Landau damping"). This spread is most naturally obtained via the natural chromaticity of the focusing lattice by creating or tolerating an energy spread. A large spread might also be obtained directly, without requiring a concomitant energy spread, by rf focusing. In any case, however, a large spread in transverse wave numbers within the bunch aggravates the problem of alignment tolerances, discussed below.

5. ALIGNMENT TOLERANCES

The focusing elements along the linac have to be kept aligned within very tight tolerances in order to conserve the minute values of normalized transverse emittance (from a few times 10^{-6} m down to a few times 10^{-8} m) required in a linear collider. An automatic control system, sampling orbits during a few beam pulses and correcting subsequent ones, is required in any case. Pulse-to-pulse jitter is not felt to be a fundamental problem in view of the rapid decrease of amplitude with frequency in typical spectra of ground vibration.

If the spread of transverse wave numbers within the bunch is small an orbit deviation of many times the transverse beam radius can be allowed before eventual measurement and correction. If, however, the fractional spread of wave numbers is large, an initially coherent oscillation rapidly smears out into irrecoverable emittance blow-up. To avoid this, a tolerance smaller than the beam radius - of the order of a micrometre - has to be kept and it has yet to be demonstrated that this is possible in practice. This is, in fact, the situation around 30 GHz accelerating frequency where the damping of transverse wake fields requires transverse spreads of several per cent at least.

6. COLLIDER PARAMETERS

The considerations concerning the choice of frequency, wake fields and tolerances have led to two typical choices of parameters, given in Table 2.

Table 2

Typical choices of collider parameters for single-bunch operation

Energy per linac		500	1000	GeV
Frequency	$\omega/2\pi$	17	29	GHz
Alignment tolerance (approx.)		40	1	μm
Energy extraction	η	1.2	8	%
Bunch population	N	8×10^{9}	5.4×10^{9}	
Repetition rate	f_{rep}	200	5800	Hz
Beam power	P_b	0.13	5	MW
Normalized emittance	ε_{nxy}	$2.5\times10^{-6}/2.5\times10^{-8}$	3×10^{-6}	m
Amplitude function at collision point	β^*	20/0.04	3	mm
Beam size at collision point	$\sigma^*_{x,y}$	190/1	65	nm
Bunch length	σ_z	26	300...500	μm
Energy spread (after correction)	$\Delta E/E^*$	0.15	0.5...2	%
Luminosity		1.3×10^{33}	1.0×10^{33}	$cm^{-2}s^{-1}$

The first choice (pertaining to a possible SLAC collider for which 11.4 GHz frequency is also being seriously considered) puts the main emphasis on feasible linac alignment tolerances and a small final energy spread, so as to facilitate the design of the final focus system. This design features a 100/1 horizontal-to-transverse emittance ratio, a very flat beam at the final focus and a short bunch. On the other hand, the low energy extraction and concomitant low beam power lead to very small values of the vertical emittance, of the vertical value of β^* and, especially, of the height of the final beam spot.

The second choice (for CLIC at CERN) emphasizes high rf-to-beam efficiency and beam power at the expense of very tight transverse tolerances along the linac.

It will be noted that the divergence of opinion about the choice of frequency has shrunk to about a factor of two. The choice is, however, influenced by one's preference for a particular power source, individual dc to rf converters being favoured by a low frequency, two-beam schemes by a high one.

7. MULTIBUNCHING

Other things being equal the luminosity could be increased by a substantial factor if multiple bunches per beam pulse could be employed. It appears, however, that regenerative beam break-up due to wake fields makes this very difficult. To overcome this problem a proposal was made to equip the accelerating structure with longitudinal slits in the outer wall, so as to let transverse deflecting modes be propagated away. Transverse Q factors will have to be depressed to values of a few tens at most, but this does not seem impossible. The longitudinal slits might be created by assembling an accelerating section from precision machined comb-like segments.

8. FOCUSING

The problems of transverse focusing and concomitant diagnostics were discussed. Permanent magnet quadrupoles form a convenient solution but pose problems if - as is likely - an energy range of more than two-to-one has to be covered without major reconstruction.

Radio-Frequency Quadrupole (RFQ) focusing, by means of asymmetric apertures being placed alternately vertically and horizontally at suitable period lengths, would obviate the need for precision quadrupoles and give a large energy range automatically. The RFQs might provide their own diagnostics in the form of beam-induced higher modes. The main feature of rf focusing is a very large spread of transverse wave numbers within the bunch. This might be seen as an advantage (for damping the wake fields) or a disadvantage (for tolerances) depending on the parameters chosen.

9. DC TO RF POWER CONVERTERS

Traditionally linear accelerators are powered by a large number of dc to rf power converters distributed along the linac. In order to extend this scheme to the higher frequency, shorter pulse and much higher total peak power of a linear collider a large variety of solutions has been proposed, including: Klystrons, Sheet Beam Klystrons, "Klystrinos" (small klystrons merged with the accelerating structure), Lasertrons, Microlasertrons, Ribbon Lasertrons, Free Electron Lasers, Cyclotron Auto Resonance Masers etc.

A Gyroklystron for 10 GHz and 40 MW, with a pulse length of 2 μs, is under development at Maryland University. It is expected that this tube will have a gain of 60 dB and be more than 45% efficient. It is expected to achieve 1% rf phase stability. Extension to 100-300 MW should be possible in the next generation (which will not differ significantly from the tube presently under development).

Radio-frequency pulse compression must be added to convert excess pulse length into increased peak power (SLAC). Note, however, that pulse compression requires very long lengths of low-loss waveguide. Thus 1 μs requires ≈ 1,00 ft per compression unit. Pulse compressions are needed for regular klystrons and for gyroklystrons.

A FEL has given well over 1 GW pulse power at 35 GHz, and with a pulse width (determined by the drive beam) of 15 ns. The efficiency of conversion from beam power to rf power was 40%. Thus the FEL has already been demonstrated (in contrast with the other schemes considered here) to produce copious amounts of power.

Lasertrons, albeit at frequencies below 10 GHz, are under development at KEK, LAL, Orsay and SLAC. The lasertron demands a very good vacuum (so as to maintain the photo cathode) and, hence, necessitates "windows" for the rf and careful vacuum techniques. Whether or not modulators are required, so as to be able to hold the accelerating voltage, is still to be determined. Since a major aspect of the lasertron concept is to do away with the modulators (so as to save on cost), it is important to settle this point. Above 10 GHz a sheet-beam-lasertron is required (so as to break the typical scaling law of all tube-like devices and get large power from the lasertron). Development work on this conecpt is under way in Texas.

A SLAC/LLNL/LBL collaboration aims at employing the beam from a 1.5 MeV induction unit for klystron-type power generation in the 10 GHz range. This might be viewed as a transition to the Relativistic Klystron Two-Beam scheme described below. A common problem with individual dc to rf converters is the very large number of converters required to power a typical collider.

10. TWO-BEAM ACCELERATORS

Instead of the multitude of pulsed dc generators, cathodes and electron guns, a continuous drive beam running along the main linac (or at least a good fraction of it) may be employed. The drive beam supplies energy to the main linac at regular intervals via transfer structures. The drive beam energy is restored, at the same or different intervals, by accelerating structures forming a "drive linac". Free electron lasers (FEL) and direct rf decelerating sections have been proposed as transfer structures, induction units and superconducting rf accelerating cavities as drive linacs.

In the original Two Beam Accelerator (Fig. 1) of LBL/LLNL the drive linac is formed by induction units and the transfer structure by FEL wigglers, the microwave radiation being collected in an overmoded smooth waveguide. Pulsed power at the gigawatt level has indeed been extracted from an FEL unit and a five-cell high gradient structure has been powered to 180 MV/m. Difficulties are being encountered with phase control, microwave extraction from the waveguide and the necessity of letting the collector waveguide traverse the gaps of the induction unit.

These difficulties might be avoided by bunching the low-energy drive beam and extracting energy by means of the longitudinal fields of resonant cavities, this scheme being called the Relativistic Klystron (Fig. 2). Longitudinal and transverse beam dynamics and transfer cavity design are being studied at LLNL/LBL.

Superconducting cavities at low UHF frequency (Fig. 3), drive beam energies in the gigavolt range and travelling wave sections as transfer structures are the main features of the Two-Stage rf scheme studied at CERN. The superconducting drive cavities hold the promise of high efficiency, even energy recuperation from the high gradient structure. The ultra-relativistic drive beam avoids all problems of phase control and the complications of longitudinal dynamics, provided the tightly bunched high energy drive beam can be efficiently generated. The travelling-wave transfer structure is under study at CERN; Fig. 4 shows a scale model.

11. CONCLUSIONS

During the last few years impressive progress has been made in understanding the details of radio-frequency linear colliders. The consensus of opinion about basic design parameters has sharpened to about the span covered by Table 2. The most fundamental outstanding questions concern the choice of rf power source from a large variety of proposals and the general problem of transverse alignment tolerances throughout the linac and in the final focus.

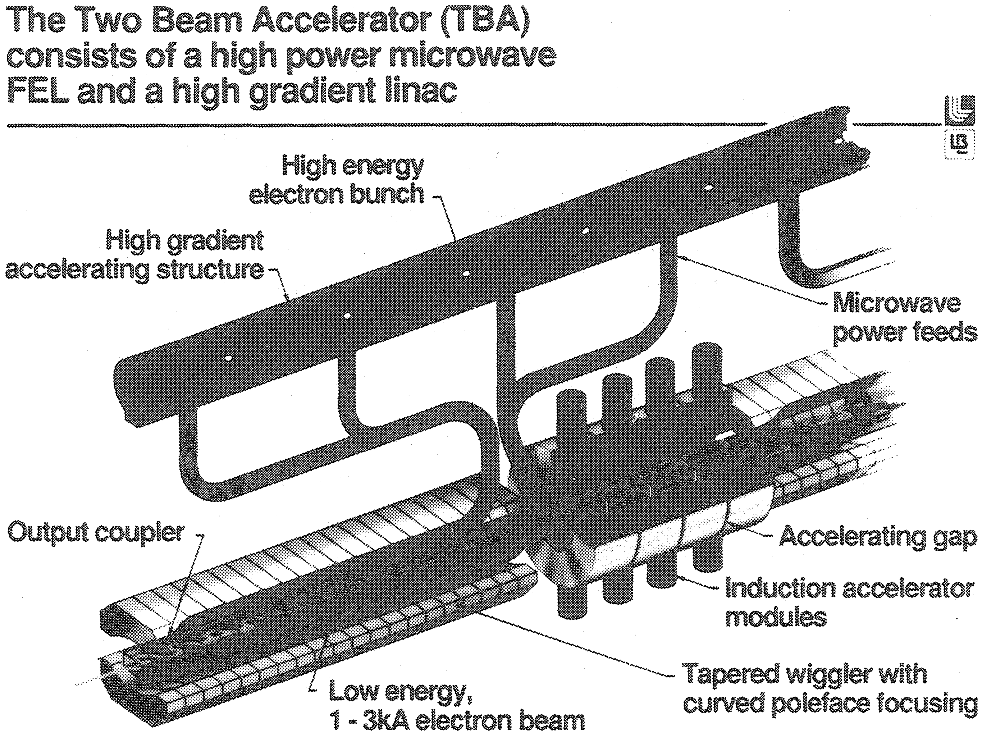

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Fig. 1 Two-beam accelerator consisting of induction units as drive linac and FEL undulators as transfer structure.

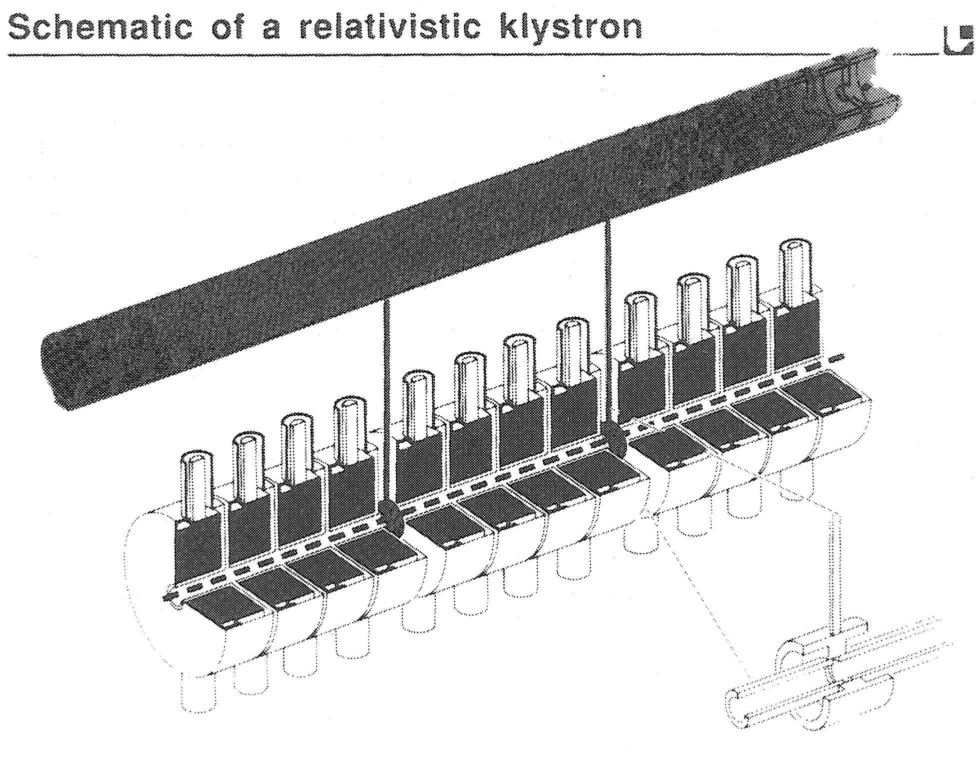

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Fig. 2 Relativistic klystron consisting of induction units as drive linac and decelerating cavities as transfer structure.

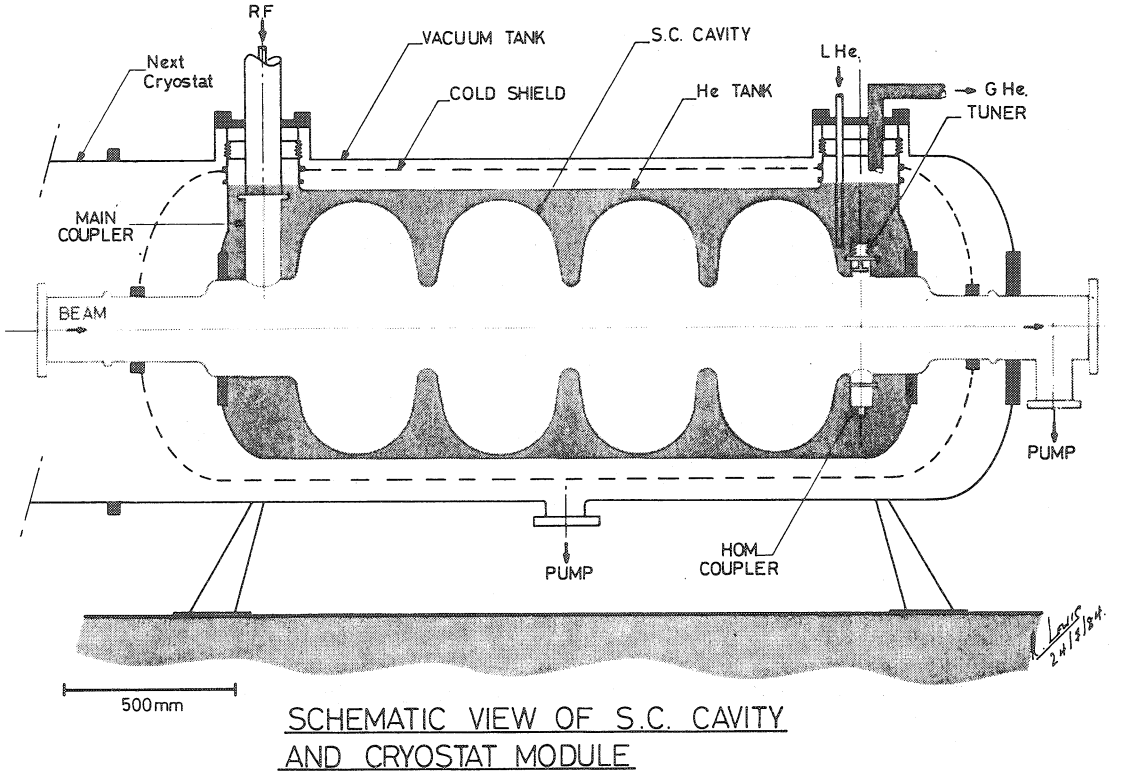

Fig. 3 Four-cell, 350 MHz, superconducting cavity (the LEP 2 prototype) suitable for an RF drive linac.

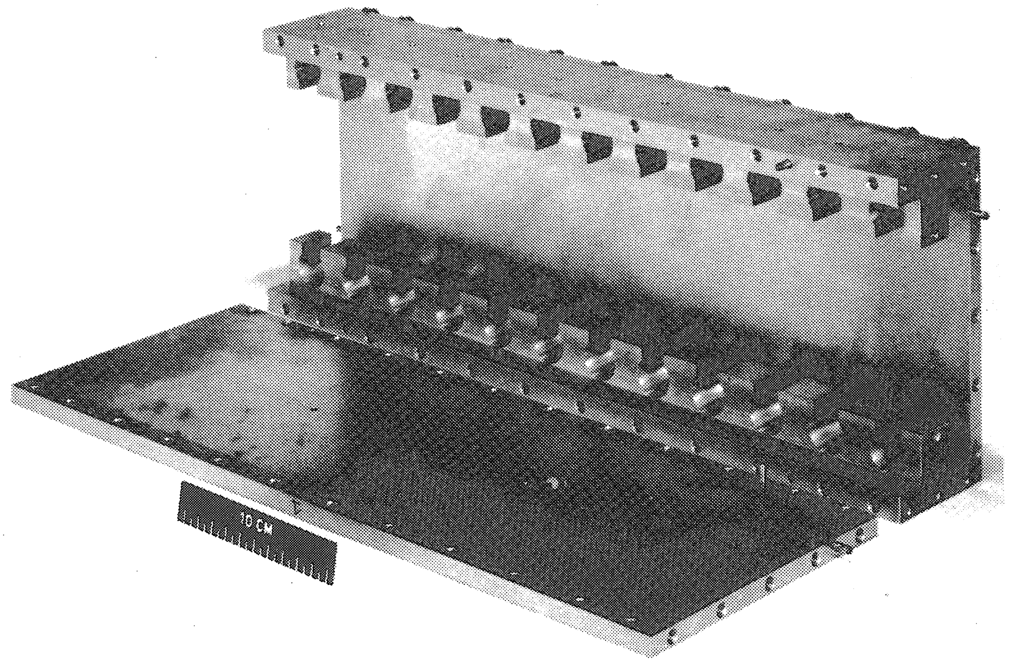

Fig. 4 Scale model of a travelling wave transfer cavity developed at CERN.

Discussion

H. Hora, Sydney

Since there was the question about wiggler-free FELs, I would like to mention the scheme of inverting our experiment [1] where up to 80% efficiency can be achieved from pumping the laser amplifier by the kinetic energy of electrons or clusters, radially injected into the laser pulse [2].

[1] B.W. Boreham and H. Hora, Phys. Rev. Lett. 42, 776 (1979).

[2] H. Hora et al. "Beams 83" Conf. Sept. 83, Briggs & Toepfer eds (LLNL).
H. Hora et al. "1st Colloq. X-ray lasers" Aussois, April 86, P. Jaegle ed. 47, C6-165 (1986).

K.-J. Kim, LBL

Are copper linacs thought to be better than superconducting linacs at the present time?

Reply

Currently, superconducting linacs do not have enough gradient, and thus are not practical. The room temperature superconductor might be promising for high gradient in the future, but nobody knows yet.